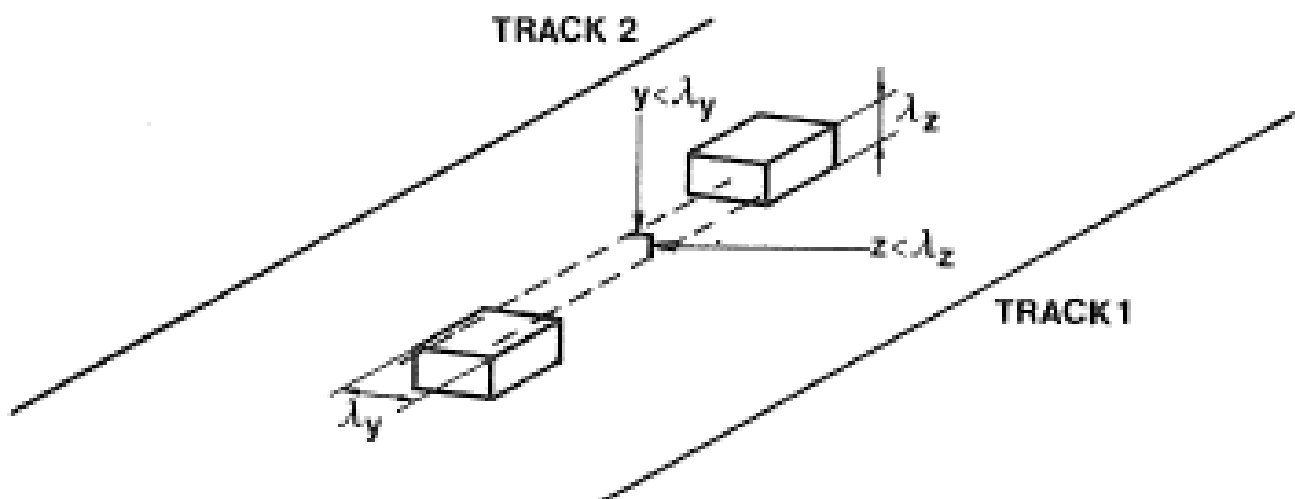


Aircraft Collision Risk Modelling for the Determination of Separation Minima

NLR



$$N_a(x) = 10^7 N_x P_y P_z$$



Aircraft Collision Risk Modelling for the Determination of Separation Minima

Problem area

This document deals with the modelling of aircraft collision risk due to the loss of separation in en-route airspace. The goal of this type of collision risk modelling is to determine safe separation standards/minima and to assess their continuing safe use by means of mathematical models of, and data on, the flight paths of aircraft operating in a given airspace on a specific route structure, as a function of the communication, navigation, and surveillance characteristics of the aircraft population and airspace under consideration. A separation minimum is called safe when the estimated aircraft collision risk meets a specified safety criterion. The basic safety criterion used by ICAO and EUROCONTROL in this context is of the threshold type and is called a Target Level of Safety (TLS).

Description of work

Collision risk modelling basically started from the modelling work of Brian Marks of the United Kingdom's Royal Aircraft Establishment (RAE) who developed the first collision risk model in 1963 in the context of oceanic navigation. The model was based on computing the probability of proximity and the conditional probability of collision given proximity. Marks's approach was modified and enhanced by his co-worker Peter Reich and presented in several RAE internal memoranda which, after further development, were published as a series of three papers in the (refereed) Journal of the Institute of Navigation (UK) in 1966. The work described here provides an overview until 2020.

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Results and conclusions

The Royal Netherlands Aerospace Centre NLR, formerly the National Aerospace Laboratory NLR, has a long history in collision risk modelling. The authors, as a part of their work at NLR, have been involved in the collision risk modelling for the benefit of two International Civil Aviation Organization (ICAO) Panels, namely the Review of the General Concept of Separation Panel (RGCSF) and the Separation and Airspace Safety Panel (SASP), EUROCONTROL, and the African Regional Monitoring Agency (ARMA). Prior to the authors' involvement in aircraft collision risk modelling, other NLR staff was involved in the field, particularly messengers Pool, Simons, Burgerhout, Renes, and Traas.

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Dedicated to innovation in aerospace

NLR-TP-2023-043 | January 2025

Aircraft Collision Risk Modelling for the Determination of Separation Minima

NLR

AUTHOR(S):

J.W. Smeltink
G. Moek

NLR

"This report is based on the work that NLR performed in the past on aircraft collision risk modelling for the determination of separation minima"

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Acronyms

ACRONYM	DESCRIPTION
AAD	Assigned Altitude Deviation
AAMA	Australian Airspace Monitoring Agency
ACAS	Airborne Collision Avoidance System
ACC	Air Control Center
ADS, ADS-B, ADS-C	Automatic Dependent Surveillance – Broadcast, - Contract
AFI	Africa and Indian Ocean (ICAO Region)
AGHME	Aircraft Geometric Height Monitoring Element
AIDC	ATS Interfacility Data Communications
ALARP	As Low As Reasonably Practicable
ANB	Air Navigation Bureau (of ICAO)
ANC	Air Navigation Commission (of ICAO)
ANSP	Air Navigation Services Provider
APCH	Approach
ARMA	AFI Regional Monitoring Agency
ASAS	Airborne Surveillance Applications
ASE	Altimetry System Error
ASEPS	Advanced Surveillance-Enabled Procedural Separation
ASP	Aeronautical Surveillance Panel (of ICAO)
ATC	Air Traffic Control
ATM	Air Traffic Management
ATS	Air Traffic Service
ATMRPP	Air Traffic Management Requirements and Performance Panel (of ICAO)
CAR/SAM	Caribbean/ South American (ICAO Region)
CARSAMMA	Caribbean and South American Monitoring Agency
CD	Communication delays
CDP	Climb and Descent Procedure
CEP	Central East Pacific
CNS	Communication Navigation and Surveillance
CONOPS	Concept of Operations
CPA	Closest Point of Approach
CPDLC	Controller Pilot Datalink Communication
CRM	Collision Risk Modelling or Collision Risk Model
CSE	clock setting error
DCPC	Direct Controller Pilot Communication
DE	Double Exponential (distribution)

ACRONYM	DESCRIPTION
DDE	Double-Double Exponential (distribution)
DFPT	Deviation From Planned Time
DME	Distance Measuring Equipment
EANPG	European Air Navigation Planning Group
ECAC	European Civil Aviation Conference
EGMU, E ² GMU	Enhanced GMU, Enhanced2 GMU
ESAF	Eastern and Southern African (Regional Office)
ETA	Estimated Time of Arrival
EUR	Europe (ICAO Region)
FANS	Future Air Navigation Systems
FIR	Flight Information Region
FL	Flight Level
FMS	Flight Management System
FRT	Fixed Radius Turn
FTE	Flight Technical Error
GDE	Gaussian-Double Exponential (distribution)
GMU	GPS Monitoring Unit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAZID	Hazard Identification
HME	Height Monitoring Element
HMU	Height Monitoring Unit
ICAO	International Civil Aviation Organization
IE	Initial Error
IFFP	Instrument Flight Procedures Panel (of ICAO)
ILS	Instrument Landing System
INS	Inertial Navigation System
IP	Information Paper
ITP	In Trail Procedure
JASMA	Japan Airspace Safety Monitoring Agency
kts	Knots
LORAN	Long Range Navigation
MAAR	Monitoring Agency for Asia Region
MASPS	Minimum Aircraft System Performance Specification
MDG	Mathematicians Drafting Group (of EUROCONTROL)
MIDRMA	Middle East Regional Monitoring Agency
MIG	Mathematicians Implementation Group (subgroup of the NAT SPG)

ACRONYM	DESCRIPTION
MG	Monitoring Group
MLAT	Multilateration
MNPS	Minimum Navigation Performance Specification
MSG	Mathematicians Sub-Group (of RGCSP and SASP)
MSL	Minimum Separation Loss
MWG	Mathematicians Working Group (of the NAT, subgroup of NAT SPG)
NAARMO	North American Approvals Registry and Monitoring Organization
NAT	North Atlantic (ICAO Region)
NATCMA	North Atlantic Central Monitoring Agency
NAT OTS	North Atlantic Organized Track System
NAT SPG	North Atlantic Systems Planning Group
NAT VSG	North Atlantic Vertical Studies Group
NDB	Non-Directional Beacon
NOPAC	North Pacific (ICAO Region)
NLR	Royal NLR - Netherlands Aerospace Centre
OCA	Oceanic Control Area
OCP	Obstacle Clearance Panel (of ICAO)
OE	Overall Error
OPSP	Operations Panel (of ICAO)
OR	Operational Requirement
PANS, PANS-RAC, PANS-ATM	Procedures for Air Navigation Services, - Rules of the Air and Air Traffic Control, - Air Traffic Management
PARMO	Pacific Approvals Registry and Monitoring Organization
PBCS	Performance-based Communication and Surveillance
PBN	Performance-based Navigation
RA	Resolution Advisory
RCP	Required Communication Performance
RCTA	Radio Technical Commission for Aeronautic
RESA	Runway End Safety Area
RF	Radius to Fix
RGCSP	Review of the General Concept of Separation Panel (of ICAO)
RHSM	Reduced Horizontal Separation Minima
RLatSM	Reduced Lateral Separation Minimum
RLongSM	Reduced Longitudinal Separation Minimum
RMA	Regional Monitoring Agency
RMACG	RMA Coordination Group
RNAV	Area Navigation
RNP	Required Navigation Performance

ACRONYM	DESCRIPTION
RNPC	Required Navigation Performance Capability
RPG	Regional Planning Group
RPE	Reporting Period Error
RSP	Required Surveillance Performance
RTE	Rounding/Truncation Error
RVSM	Reduced Vertical Separation Minima
SAATS	Shanwick Automated Air Traffic System
SARP	Standards and Recommended Practices
SARSIG	Safety Analysis & Reduced Separation Implementation Group (of the NAT SPG)
SASP	Separation and Airspace Safety Panel (of ICAO)
SATMA	South Atlantic Monitoring Agency
SATVOICE	Satellite voice
SB	Space-Based
SLOP	Strategic Lateral Off-set Procedures
SPM	Single Period Model
TA	Traffic Advisory
TACAN	Tactical Air Navigation
TC	Type Certificate
TCAS	Traffic Alert and Collision Avoidance System
TLS	Target Level of Safety
TMU	Total vertical error Monitoring Unit
TVE	Total Vertical Error
USRAT	User Requirements for Air Traffic Services
VOR	VHF (Very High Frequency) Omni-directional Range
WG	Working Group
WHL	Whole
WP	Working Paper

1 Introduction

This document deals with the modelling of aircraft collision risk due to the loss of separation in en-route airspace that the authors have been involved in as a part of their work at the Royal Netherlands Aerospace Centre NLR, formerly the National Aerospace Laboratory NLR, for the benefit of two International Civil Aviation Organization (ICAO) Panels (*GM*), namely the Review of the General Concept of Separation Panel (RGCSP) and the Separation and Airspace Safety Panel (SASP), EUROCONTROL (*GM*), and the African Regional Monitoring Agency (ARMA) (*GM and JWS*). The objective of this type of collision risk modelling is to determine safe separation standards/minima and to assess their continuing safe use by means of mathematical models of, and data on, the flight paths of aircraft operating in a given airspace on a specific route structure, as a function of the communication, navigation, and surveillance characteristics of the aircraft population and airspace under consideration. A separation minimum is called safe when the estimated aircraft collision risk meets a specified safety criterion. The basic safety criterion used by ICAO and EUROCONTROL in this context is of the threshold type and is called a Target Level of Safety (TLS). Other safety criteria may also be used, e.g. comparison with a reference system that is deemed safe (ICAO, 1998c) or an *As Low As Reasonably Practicable (ALARP)* criterion (Spouge, 1999).

Chapter 2 elaborates how globally applicable separation standards/minima are developed under the auspices of ICAO. From a process point of view, it discusses the role of the RGCSP, the SASP, and the ICAO Air Navigation Commission (ANC) and it discusses the role of communication, navigation, and surveillance (CNS) from a technical point of view. It will touch upon some major developments in the latter fields, like area navigation, satellite navigation, new means of surveillance based on Automatic Dependent Surveillance (ADS) and multilateration (MLAT), and the transition from technology-based separation standards/minima to performance-based standards/minima. The chapter will also list a number of globally applicable horizontal separation standards/minima and a number of ICAO regulatory and guidance documents regarding the subject.

Traditionally, surveillance was subdivided into procedural surveillance and radar surveillance, where procedural surveillance refers to surveillance based on position reports by flight crew (see e.g. Chapter 1 of ICAO's *Manual on airspace planning methodology for the determination of separation minima* (1998c)¹). Aircraft collision risk modelling and separation can be subdivided in the same manner. The collision risk models to be discussed in this document are basically of the procedural type. Two approaches to modelling the effect of radar surveillance on aircraft collision risk that have been used in ICAO SASP and EUROCONTROL work are outlined in Chapter 2 of (Moek, 2015b). The effectiveness of surveillance is closely coupled to the communication capabilities of the aircraft and the airspace they are operating in, i.e. how quickly can Air Traffic Control (ATC) communicate with an aircraft in case of detection of an adverse situation. In connection with the more recent surveillance methods, the ICAO SASP has started working on collision risk modelling for Advanced Surveillances-Enhanced Procedural Separation (ASEPS) (ICAO, 2020a). Route structures can be decomposed in the horizontal dimension into basic components like straight route segments, turns, parallel routes, and intersections whereas decomposition in the vertical dimension is based on the use of flight levels. Aircraft separation and route spacing minima as well as collision risk models can be distinguished similarly.

¹ Reich (Reich, 1966a, 1966b, 1966c) describes procedural separation standards in the sense that the flying errors (i.e. the imperfections of navigation and piloting) are not monitored from the ground, and the aircrew are entirely responsible for keeping to the tracks and altitudes assigned by air traffic control.

Although there have been some earlier attempts to modelling aircraft collision risk, see e.g. the review by Burt (1999), the development of the Reich collision risk model (Marks, 1963; Reich, 1966a) is generally recognised as marking the start of collision risk modelling for the determination of separation minima². The Reich model was first applied to examine the feasibility of a safe reduction of the 120 NM lateral separation standard between parallel routes in North Atlantic (NAT) airspace in the mid-1960s (Reich, 1966a) and has since then been used in probably all work on the safe spacing of parallel routes in procedural airspace, e.g., approximately 20 years later, the development of the Minimum Navigation Performance Specification (MNPS) concept for the NAT Region and the subsequent reduction of the lateral separation standard (for aircraft at the same flight level) from 120 NM to 60 NM in NAT MNPS³ airspace (Reich, 1966a; White, 1979). This regional lateral collision risk modelling work for the NAT was presented to and endorsed by the ICAO Review of the General Concept of Separation Panel in 1973. A subsequent review of the lateral collision risk model for the NAT was provided by (1993). Annual safety assessment and collision risk modelling for parallel routes in North Atlantic airspace continues to be performed under the auspices of the North Atlantic Mathematicians Working Group (NAT/MWG).

Prior to the authors' involvement in aircraft collision risk modelling, other NLR staff was involved in the field, particularly messengers Pool, Simons, Burgerhout, Renes, and (Moek and) Traas (Burgerhout, 1973; Moek & Traas, 1979; Pool, 1974, 1975, 1979b, 1979a, 1983; Pool & Renes, 1974; Pool & Simons, 1973; Renes & Pool, 1975). To honour this earlier work, a lecture entitled *Historical development of collision risk models for en-route air traffic* given by A. Pool at Princeton University in 1983 has been reproduced in Chapter 3 of this document. The lecture concludes with a look ahead at two main subjects being underway at the time, namely investigation of the possibilities of reducing the vertical separation standard above FL 290 from 2000 feet to 1000 feet (RVSM), and development of a Minimum Navigation Performance Specification for continental airspace, specifically in Europe. Both subjects will be elaborated later in this document. (See Chapters 5 and 6).

Chapter 4 then presents some preliminary aspects of aircraft collision risk modelling, including the definition of aircraft collision risk, modelling aircraft shapes and collision volumes, routes and navigation errors, and closest point of approach between two aircraft. Following this basic material, Chapters 5 – 7 present aircraft collision risk modelling for the lateral, vertical, and longitudinal dimensions respectively.

Chapter 5 introduces the Reich aircraft collision risk model. It begins with the original Reich model for parallel routes in NAT procedural oceanic airspace and sketches a number of subsequent developments, then proceeds with referencing a number of lateral separation standards/minima determined by the ICAO SASP, and concludes with a review of lateral collision risk modelling work performed under the auspices of EUROCONTROL (largely) aimed at the spacing of parallel routes in Europe's radar-controlled airspace.

From a modelling point of view, vertical collision risk between aircraft at adjacent flight levels is very similar to lateral collision risk between aircraft on adjacent parallel routes when the roles of the vertical and lateral dimensions are reversed. Thus, Chapter 6 discusses vertical collision risk assessment based on a such modified version of the (lateral) Reich collision risk model and addresses the first main global development previewed by Pool in his 1983 Princeton lecture (Pool, 1983). One of the authors (GM) of this document has been involved with collision risk modelling for RVSM from the start at EUROCONTROL (Harrison & Moek, 1992), the RGCSF, and, partly, the North Atlantic Mathematicians Working Group (NAT MWG), whereas both

² The Reich model is occasionally referred to as the Reich/Marks model or even as the Marks model (Burt, 1999; Machol, 1975, 1995; Pool, 1983).

³ As of February 4th 2016, NAT MNPS Airspace is called NAT High Level Airspace (HLA). This chapter uses the term MNPS airspace for all work prior to that date.

authors have been involved with RVSM collision risk modelling for the Africa and Indian Ocean (AFI) Region since the start in 2004 (Moek & Smeltink, 2005; Smeltink et al., 2021).

Chapter 7 presents collision risk modelling for the application of longitudinal separation, where two cases are to be distinguished, namely longitudinal separation between aircraft in level flight and longitudinal separation between aircraft in climb or descent. A second sub-division concerns longitudinal separation between in-trail aircraft and longitudinal separation between aircraft on intersecting tracks. As will be seen in this Chapter, the longitudinal case differs from the lateral and vertical cases in that it uses a distribution of nominal entry-separations, all equal to or larger than the longitudinal separation standard/minimum rather than a fixed nominal entry separation equal to the lateral or vertical separation standard/minimum. Like Chapter 5, Chapter 7 will consider longitudinal collision risk modelling work performed over time for NAT procedural oceanic airspace as well as a number of longitudinal separation standards/minima determined by the ICAO RGCSP and SASP.

Two more Chapters complete the document. Chapter 8 takes a more general point of view (more general than a single specific dimension) using the concept of in-crossing rate of an aircraft modelled as a point with respect to a suitably-sized collision volume representing the other aircraft, resulting in the Rice formula (Bakker & Blom, 1993a, 1993b; Bellantoni, 1971; Blom & Bakker, 2002; ICAO, 2009). The previously presented lateral, vertical, and longitudinal aircraft collision risk models can then be shown to be special cases of the collision risk model based on the Rice formula.

Chapter 9, finally, presents some more models based on specific assumptions and/or applications, namely, a general collision risk model based on reliability theory developed by D. Anderson (Anderson, 2005), the gas law model (Alexander, 1970; Endoh & Odoni, 1983), and the Obstacle Clearance Panel/Instrument Flight Procedures Panel (OCP/IFPP) collision risk model (CRM) for ILS operations (ICAO, 1980a).

It should be clear that not each and every existing collision risk model can be treated in this document. Some models that will not be treated are:

- The OCP/IFPP collision risk model for collisions between aircraft and obstacles (ICAO, 1980a);
- Collision risk models for the benefit of determining Runway End Safety Areas (RESAs) (Ayres Jr. et al., 2011; Es et al., 2014);
- Models, if any, for the determination of radar separation minima, but see Section 2.3;
- Collision risk models for ASAS operations, i.e. operations where the responsibility for aircraft to aircraft separation resides in the flight crews (Hoekstra, 2001);
- Burt's 3D collision risk model for radar airspace (Burt, 1999, 2002);
- Rome and Krishnan's collision risk modelling work (Rome, 1993, 1995; Rome & Krishnan, 1990);
- Chenevier's collision risk model for ADS-based ATC (Chénevier, 1993);
- Collision risk models for turns connecting pairs of parallel routes; and
- Collision risk models developed by the SASP MSG since 2012.

It is finally noted that, over the years, only a limited number of individuals and organisations have been involved in collision risk modelling activities in connection with the development of separation minima under the auspices of the ICAO RGCSP and SASP, particularly Airservices Australia, CENA, ENRI, EUROCONTROL, FAA, NATS, and NLR as far as organisations are concerned.

This document is the result of the idea that started in 2009 to make an overview of the collision risk modelling work in which the authors and NLR have been involved. A problem with an overview is that it is difficult to determine where to end and to determine how detailed it should be. As a result, this document is not finished and the authors doubt whether or not it will ever be finished. The current version is a version that is mature enough to be shared in a larger audience. There are definitely improvements to be made. Therefore, the authors welcome suggestions for improvement to be incorporated in the next version.

2 Development of Separation Standards/Minima by ICAO

2.1 Introduction

The first paragraph of Chapter 1 introduced three elements related to the determination of globally applicable separation standards/minima under the auspices of ICAO, namely safety of a separation standard/minimum, the ICAO RGCP and SASP Panels, and the development of separation standards/minima as a function of the communication, navigation, and surveillance (CNS) characteristics of the aircraft population and airspace under consideration. A definition of when a separation standard is considered to be safe was included in the paragraph. This chapter expands on the other two elements in Section 2.2 and Sections 2.3 - 2.4 respectively. Sections 2.3 - 2.4 will touch upon some major developments in the CNS fields, like area navigation, satellite navigation, new means of surveillance based on Automatic Dependent Surveillance (ADS) and multilateration (MLAT), and the transition from technology-based separation standards/minima to performance-based standards/minima. The chapter concludes with a section listing various horizontal separation standards/minima developed by ICAO for global application in en-route airspace (Section 2.5). Appendix B contains a list ICAO regulatory and guidance documents regarding the subject.

2.2 ICAO Panels and the development of separation standards/minima

The modelling of aircraft collision risk due to the loss of separation in en-route airspace have been a central element for two ICAO Panels, namely the Review of the General Concept of Separation Panel (RGCSPP) and the Separation and Airspace Safety Panel (SASP). The RGCSPP was established in 1973 and SASP, established in 2000, can be considered the successor to the RGCSPP.

To put the ICAO Panel work into perspective, it is noted that ICAO is a United Nations specialized agency established by States in 1944 to manage the administration and governance of the Convention on International Civil Aviation (Chicago Convention)⁴ (ICAO, 2015a). From an organizational point of view, ICAO has a sovereign body, the Assembly, and a governing body, the Council. The Assembly is comprised of all Member States of ICAO and meets not less than once in three years and is convened by the Council at a suitable place and time. It has numerous powers and duties. The Council is a permanent body of ICAO responsible to the Assembly and has numerous functions, administers the finances of ICAO, appoints and defines the duties of a number of Committees, and appoints the Members of the Air Navigation Commission (ANC). One of the major duties of the Council is to adopt and approve consensus-driven international Standards and Recommended Practices (SARPs) and to incorporate these as Annexes to the Chicago Convention. The Council may also amend existing Annexes as necessary. The ICAO organization also comprises an Air Navigation Commission (ANC) and an Air Navigation Bureau (ANB). The ANC serves as an independent advisory body to the Council on all air navigation technical matters. It considers and

⁴ Source <https://www.icao.int/about-icao/assembly/Pages/default.aspx> "About ICAO" tab. Last accessed 17 February 2023.

recommends to the Counsel new or amended SARPs and Procedures for Air Navigation Services (PANS). To ensure that these SARPs and PANS will be effective and practical for end-users, the ANC works through established panels of experts in various disciplines who are assigned specific tasks from the overall work programme. The development of SARPs and PANS follows a structured, transparent and multi-staged process, often known as the ICAO “amendment process” or “standards-making process” (ICAO, 2015a). Typically, it takes approximately two years for an initial proposal for a new or improved Standard, Recommended Practice, or procedure to be formally adopted or approved for inclusion in an Annex or PANS.

The panels work in between and at its semi-annual (two-week) meetings through the preparation and discussion of pertinent working papers, information papers, and flimsies. Working papers contain specific proposals for action. Each working paper is normally limited to one specific work programme or agenda item. Information papers comprise content that the originator wishes to bring to the attention of the panel. Typically, the only action required in an information paper will be an invitation to note the contents of the paper. Flimsies are very short papers, generally only one page, containing, for example, suggested text for the panel report. Flimsies are usually initiated and distributed at panel meetings and, where interpretation is provided, copies must be given to the interpreters. After each panel meeting, a meeting report is produced which is submitted to the ANC and shared with other panels. A panel can be subdivided into working groups for specific topic. A rapporteur of a working group leads the working group and reports to the panel on the progress of the working group as required.

The work results in Panel-agreed amendment proposals that are subsequently transferred to the ANC for further processing. Safety assessments (conducted by the SASP) in support of the proposed amendments are documented in ICAO Circulars. Circulars are publications intended to disseminate specialized information to Member States, such as technical studies; analyses, reproductions of or extracts from informative documents supplied by Member States; and reports on the implementation of Standards and Recommended Practices. Appendix B lists a number of circulars relevant to this document.

Today, over 12,000 SARPs have been developed, contained in 16 Annexes to the Chicago Convention, as well as 5 PANS and numerous manuals. Regarding separation standards/minima, Sections 3.3 - 3.4 of Annex 11 (ICAO, 2018a) are of relevance as well as Chapters 5 – *Separation methods and minima*, 8 - *ATS Surveillance Services* (Section 8.7.3), and 13 – *Automatic Dependent Surveillance Contract (ADS-C) Services* (Section 13.5.3) of the PANS-ATM (ICAO, 2016c). Following a recent revision, the current ANC Panel structure comprises 15 Panels, including the SASP which was established in 2000.

2.3 Surveillance and Communication

2.3.1 Surveillance

Returning to communication, navigation, and surveillance as the basic characteristics for aircraft collision risk modelling, surveillance was traditionally subdivided into procedural surveillance and radar surveillance. Procedural surveillance refers to surveillance based on position reports by flight crew. Separation standards/minima under the two types of surveillance, referred to as procedural and radar separation standards/minima, were available in the PANS-ATM in its Chapter 5 – *Separation methods and minima*, and

Chapter 8 – *Radar separation*, up to and including Amendment 4 to the Fourteenth Edition (2001) of the PANS-ATM (applicability date 24 November 2005) (ICAO, 2001). Section 8.7.4, *Radar separation minima*, of the fourteenth edition of the PANS-ATM states that unless otherwise prescribed in accordance with certain paragraphs, the horizontal radar separation minimum shall be 5.0 NM. This minimum may, if so prescribed by the appropriate ATS authority, be reduced, but not below 3.0 NM when radar capabilities at a given location so permit. An RGCSF paper of 1998 (ICAO, 1998b) provides some background information on the 5 NM radar separation minimum and some additional information on radar separation and radar separation minima is provided in references (Dalm, 1987; EUROCONTROL, 1997, 1998).

Other surveillance methods based on Automatic Dependent Surveillance (ADS) and multilateration (MLAT) started to be developed in the early 1960s⁵. In connection with this, SASP performed a comparative assessment on the use of ADS-B surveillance by the Air Traffic Services (ATS), documented in ICAO Circular 311 (ICAO, 2006a). The assessment concluded that ADS-B can be used to provide a 5 NM separation minimum, subject to certain conditions being satisfied. Subsequently, SASP extended its assessment to include MLAT-based services to provide ATS surveillance, subject to certain conditions, and to the use of ADS-B and MLAT for 3 NM separation. The complete set of safety assessments is available in ICAO Circular 326 (ICAO, 2012a). Procedures for ADS-B, ADS-C, ATS Interfacility Data Communications (AIDC), Controller Pilot Datalink Communication (CPDLC), and Required Communication Performance (RCP) were incorporated in the Fifteenth Edition of the PANS-ATM (ICAO, 2007), applicable 22 November 2007, and Chapter 8 of the PANS-ATM was re-titled *ATS surveillance services*, covering radar and/or ADS-B. Paragraph 8.7.3.1 of section 8.7.3, *Separation minima based on ATS surveillance systems*, of the 15th edition of the PANS-ATM states that, unless otherwise prescribed in accordance with certain paragraphs, the horizontal separation minimum based on radar and/or ADS-B shall be 5.0 NM. Paragraph 8.7.3.2 states that the radar separation minimum of paragraph 8.7.3.1 may, if so prescribed by the appropriate ATS authority, be reduced, but not below 3.0 NM when radar capabilities at a given location so permit. ADS-C, at the time used wholly to provide procedural separation, was covered in Chapter 13, *Automatic Dependent Surveillance – Contract (ADS-C) Services*, of the Fifteenth Edition of the PANS-ATM⁶. Paragraph 13.5.3.1 of section 13.5.3 states that ADS-C based longitudinal distance separation minima are detailed at 5.4.2.6.4 of Chapter 5 of the 15th edition of the PANS-ATM. Amendment 4 to the Fifteenth Edition of the PANS-ATM extended the application of the 5 NM horizontal separation from radar and/or ADS-B to radar and/or ADS-B and or MLAT systems and also extended the 3 NM horizontal separation minimum from radar to radar and/or ADS-/ and/or MLAT.

2.3.2 Communication

Despite many developments in data link applications for air traffic control, the primary means of communication between controllers and pilots continues to be voice links provided by analog radios operating in the VHF and HF bands (IATA, 2017). HF voice is used for air-ground communications in remote and oceanic areas outside the range of VHF frequencies. In most cases, an HF radio operator functions as an intermediary between controllers and pilots, transcribing and relaying the contents of HF voice communications. Communication between controllers and pilots can be subdivided into that for routine or strategic purposes on the one hand and communication for tactical purposes, i.e. for the resolution of

⁵ See https://en.wikipedia.org/wiki/Kop%C3%A1%C4%8D_passive_sensor

⁶ The Fourteenth Edition of the PANS-ATM already includes a Chapter 13 entitled *Automatic Dependent Surveillance (ADS) Services* where a note following the chapter heading states that Chapter 13 applies to contract ADS only. Paragraph 13.5.3.1 of this edition states that ADS-based longitudinal distance separation minima are detailed at 5.4.2.6.4 of Chapter 5.

conflicts, on the other. The latter form of communication is relevant to the underlying document. Communication is then a part of the intervention process, which comprises two more components, namely conflict detection and response times of both controllers and pilots/aircraft. The effectiveness of communication in case of (potential) conflicts is highly dependent on the surveillance capabilities at hand. Procedural separation standards/minima, therefore, are to be designed to account for the lack of surveillance-based intervention capability and are thus significantly larger than separation standards/minima based on radar, ADS, or MLAT. See e.g. Burt (2002).

Building the potential occurrence of conflicts into a procedural separation standard/minimum requires data on such occurrences. When such data is available prior to the development of a procedural separation standard/minimum, a certain safety margin may be applied to this data to account for possible limitations of the data. In the absence of any data, conservative assumptions will have to be made. In both cases, it is useful to utilize airspace monitoring and to conduct an a-posteriori safety assessment, e.g. annually, to verify the validity of prior data and/or assumptions and that the applicable TLS is being met. As will be seen in Chapters 5 – 7, data and/or assumptions on (potential) conflicts or operational risk are generally modelled through probability distributions of large lateral, vertical, or longitudinal deviations/errors, in addition to probability distributions of typical, normal, or technical deviations/errors.

Monitoring and a-posteriori (annual) safety assessment have been conducted for lateral and longitudinal separation in some airspaces for a long time, e.g. for the North Atlantic (NAT) Organised Track System (OTS) (White, 1979). Height-keeping performance monitoring and ongoing safety assessment have been a key element of the implementation and continuing safe use of the Reduced Vertical Separation Minimum (RVSM) (ICAO, 2012b) and have been supported with ICAO guidance material for Regional Monitoring Agencies (RMAs) (ICAO, 2011). More formal monitoring in relation to lateral and longitudinal separation started to be addressed by the ICAO SASP in 2011/2012 and has resulted in the development of additional global ICAO guidance manual for RMAs (ICAO, 2017b). This manual, which has a global scope, includes modified portions of a regional guidance document for the implementation and continuing safe use of performance-based horizontal separation minima (Asia & Office, 2010). A second edition of the monitoring manual (ICAO, 2017b) is due in 2020. Three more guidance documents are available for three different cases of communication means, namely where VHF voice communication is not available (ICAO, 2020a), ADS-C (ICAO, 2020b), and RCP 240 communications (ICAO, 2020a).

2.3.3 Performance-based Communication and Surveillance (PBCS)

In a similar spirit as the development of performance-based navigation (PBN) (ICAO, 2013b), see below under the *Navigation* heading, ICAO developed the Performance-based Communication and Surveillance (PBCS) concept. This development took place in two steps. In the first step, global guidance material on performance-based communication was developed in the *Manual on Required Communication Performance (RCP)* (ICAO, 2006b). The purpose of the RCP Manual was to explain the concept of RCP, to identify RCP requirements applicable to the provision and use of air traffic services, and to provide a basis for the application of RCP in a specified airspace. In a similar manner as for PBN, the RCP concept characterizes the performance required for communication capabilities that support Air Traffic Management (ATM) functions without reference to any specific technology and is open to new technology. The RCP Manual includes five RCP types, RCP 10, RCP 60, RCP 120, RCP 240, and RCP 400, with each type being characterized by specific

values for transaction time, continuity, availability, and integrity. The number included in the RCP type denotes transaction time in minutes.

In the second step, the notion of an RCP type was replaced by the notion of an RCP specification and the concept of Required Surveillance Performance (RSP) was added together with the notion of an RSP specification. The second step resulted in the Second Edition of ICAO Doc 9869, which was renamed *Performance-based Communication and Surveillance (PBCS) Manual* (ICAO, 2017c). Parts of regional guidance material developed by the NAT and APAC ICAO Regions (ICAO, 2012c, 2013a) were included in the PBCS Manual. As stated under the *Scope and purpose* heading in the PBCS Manual, the RCP and RSP specifications included are intended initially for ADS-C, CPDLC, and satellite voice (SATVOICE) communications supporting ATM operations in airspace, where procedural separations are being applied. However, the PBCS concept allows for new RCP and RSP specifications for other purposes. For example, the PBCS Manual could be updated to include a new RSP specification that is intended for ADS-B supporting an ATM operation. In general, RCP specifications provide a means of compliance. RCP allocations are provided for SATVOICE when the intended use is to provide an intervention and/or surveillance capability in support of air traffic services that is subject to a specified RCP.

Appendix B to the PBCS Manual provides two RCP specifications, RCP 240 and RCP 400, with the following allocations: RCP 240/D (applicable to the controller intervention capability via CPDLC), RCP 400/D (applicable to the controller intervention capability via CPDLC), RCP 400/V_{RO} (applicable to the controller intervention capability via a radio operator using SATVOICE), and RCP 400/V_{ATC} (reserved). Allocation is understood to be the process of apportioning RCP specification values to the various parts of the system. (Compare the RCP type allocation process described in paragraph 4.2 of RCP manual (ICAO, 2006b).)

Appendix C to the PBCS Manual provides two RSP specifications, RSP 180 and RSP 400, with the following allocations: RSP 180/D (applicable to the delivery of surveillance data via ADS-C), RSP 400/D (applicable to the delivery of surveillance data via ADS-C), RSP 400/V_{RO} (applicable to the delivery of surveillance data via a radio operator using SATVOICE), and RSP 400/V_{ATC} (reserved).

It is noted at the end of sections 2.2.1 and 2.4.1 respectively of the PBCS Manual that RCP and RSP specifications were derived from intervention capabilities used in collision risk modelling, aircraft performance characteristics, conflict detection and resolution capability PANS-ATM, RTCA/EUROCONTROL Standards, and other factors.

It is also stated in paragraph 2.2.2.3 of the PBCS Manual that for separation assurance, the RCP transaction time can be determined by collision risk modelling. Collision risk modelling considers the RCP transaction times in the communications and controller intervention buffer supporting separation assurance. Similarly, it is stated in paragraph 2.4.2.3 of the PBCS Manual that for separation assurance, the RSP data delivery can be determined by collision risk modelling. This method considers the RSP delivery times in the surveillance data delivery supporting separation assurance.

It is finally remarked that guidance and requirements on post-implementation monitoring under PBCS are in Appendix D to the RCP manual (ICAO, 2006b) for controller-pilot data link communications (CPDLC) and automatic dependent surveillance — broadcast (ADS-B), and in Appendix E to the RCP manual for satellite voice communications (SATVOICE).

2.4 Navigation

Having briefly discussed surveillance and communication, it remains to examine the role of navigation in relation to aircraft separation standards/minima and collision risk. Navigation has developed from the use of conventional ground-based navigation aids to area navigation (RNAV) to required navigation performance (RNP) to performance-based navigation (PBN). Ground-based navigation aids and area navigation (as such) are technologies whereas RNP and PBN are performance specifications. Separation standards/minima have been developed on this basis over time.

The *Navigation* section of the URATS document (IATA, 2017) lists the following conventional ground-based navigation aids for the en-route phase of flight,

- Non-Directional Beacon (NDB);
- Distance Measuring Equipment (DME);
- VHF Omni-directional Range (VOR);
- Tactical Air Navigation (TACAN),

in addition to the Global Navigation Satellite System (GNSS) and PBN. A more complete list, including inertial navigation, is available in (Nolan, 2011). Additional references are (Binns, 2018; Powell, J., 1981; Tooley & Wyatt, 2018).

As described in e.g. (EUROCONTROL, 2014), area navigation is a method of navigation which permits aircraft operation on any desired flight path within the coverage of station-referenced nav aids, or within the limits of the capability of self-contained systems, or a combination of these capabilities. It is enabled through the use of a navigation computer and waypoints (coordinates) input to it, either manually or automatically with an integrated database. The navigation computer estimates aircraft position using navigation sensors fitted and compares estimation to defined route to create guidance information. Area navigation became operational in Europe in 1998 (EUROCONTROL, 2014). Guidance material on area navigation was developed by ICAO in the *Manual of Area Navigation (RNAV) Operations* (ICAO, 1991).

In 1988, the ICAO Special Committee on Future Air Navigation Systems (FANS) (Galotti, 1997; ICAO, 1988a) identified that the method most commonly used over the years to indicate required navigation capability was to prescribe mandatory carriage of certain equipment (ICAO, 1999b). This constrained the optimum application of modern airborne equipment and was also foreseen to impose a laborious selection process for ICAO regarding satellites becoming available. To overcome these problems, The FANS Committee developed the concept of required navigation performance capability (RNPC), where RNPC was defined as “*a parameter describing lateral deviations from assigned or selected track as well as along track position fixing accuracy on the basis of an appropriate containment level*”. The RNPC concept was approved by the ICAO Counsel and was assigned to the RGCSP for further elaboration. The RGCSP, in 1990, noting that capability and performance were distinctly different and that airspace planning is dependent on measured performance rather than designed-in capability, changed RNPC to RNP as a statement of the navigation performance necessary for operation within a defined airspace in the form of an RNP type specifying the navigation performance accuracy of all the user and navigation system combinations within an airspace. See the First Edition of the *Manual on Required Navigation Performance (RNP)* (ICAO, 1999b)⁷. In this context, navigation performance accuracy is based on the combination of the navigation sensor error, airborne receiver error, display error, and flight technical error. The RNP type is based on a single navigation performance accuracy

⁷ The *Manual on Required Navigation Performance (RNP)* (ICAO, 1999b) supersedes the *Manual of Area Navigation (RNAV) Operations* (ICAO, 1991).

value that is expected to be achieved at least 95 per cent of the time by the population of aircraft operating within an airspace. The Second Edition of the *Manual on RNP* (ICAO, 1999b) provides five RNP types for general application to en-route operations, namely RNP 1, RNP 4, RNP 10, RNP 12.6, and RNP 20. Paragraphs 2.3.6 and 2.3.7 of the *Manual on RNP* very briefly discuss the relation of RNP to separation minima. Paragraph 2.3.6 emphasizes that RNP alone cannot and should not imply or express any separation standard or minima and that other parameters such as intervention capability, capacity, airspace structure and occupancy or passing frequency (exposure) must be taken into account. The paragraph also states that a general methodology for determining separation minima has been developed by the RGCSP, viz. the *Airspace Planning Methodology manual* (ICAO, 1998c). Paragraph 2.3.7 discusses in some more detail the fundamental parameters to be considered when envisaging a separation standard change.

The fourth and latest development in navigation that needs to be addressed is performance-based navigation or PBN (ICAO, 2013b). As noted under the *History of this manual* heading in the *Executive Summary* of the Third Edition of the *Performance-based Navigation (PBN) Manual*⁸⁹ (ICAO, 2013b), while RNP types identified by a single accuracy value in conformity with the former RNP concept were found to be appropriate for application in remote and oceanic areas, the associated guidance for route separation was not sufficient for continental applications. This was due to a number of factors, including the setting of performance and functional standards for aircraft navigation systems, working within the constraints of available airspace, and using a more robust communication, surveillance and ATM environment. It was also due to practical considerations stemming from the gradual development of RNAV capability together with the need to derive early benefits from the installed equipment. This resulted in different specifications of navigation capability with common navigation accuracy. It was noted that such developments were unlikely to cease as vertical (3D) navigation and time (4D) navigation evolved and was subsequently applied by ATM to increase airspace capacity and efficiency. The above considerations have presented significant difficulties to those organizations responsible for the early implementation of RNAV operations in continental airspace. In solving these, significant confusion has developed regarding concepts, terminology and definitions. Consequently, a divergence of implementation resulted in a lack of harmonization between RNP applications.

On 3 June 2003, the ICAO ANC, when taking action on recommendations of the fourth meeting of the Global Navigation Satellite System Panel (GNSSP), designated the Required Navigation Performance and Special Operational Requirements Study Group (RNPSORSG) to act as the focal point for addressing several issues related to required navigation performance (RNP). The RNPSORSG reviewed the ICAO RNP concept, taking into account the experiences of early application as well as current industry trends, stakeholder requirements and existing regional implementations. It agreed on the relationship between RNP and area navigation (RNAV) system functionality and applications and developed the PBN concept, which will allow global harmonization of existing implementations and create a basis for harmonizing of future operations.

As also set out in the *Executive Summary* of the Third Edition of the *Performance-based Navigation (PBN) Manual* (ICAO, 2013b), the application of RNAV techniques has resulted in improved operational efficiency of navigation applications in various regions worldwide and for all phases of flight. RNAV systems evolved in a manner similar to conventional ground-based routes and procedures. A specific RNAV system was identified and its performance was evaluated through a combination of analysis and flight testing. For domestic operations, the initial systems used VOR and DME for estimating their position whereas for oceanic

⁸ For certain documents, ICAO preserves the document reference number and amends the document title (and Edition number) to emphasize the evolution of the document/topic. This applies e.g. to Doc 4444, PANS ATC/PANS RAC/PANS-ATM, and Doc 9613, RNP Manual and PBN Manual.

⁹ The *Performance-based Navigation (PBN) Manual* (ICAO, 2013b) supersedes the *Manual on Required Navigation Performance (RNP)* (ICAO, 1999b).

operations, inertial navigation systems (INSs) were employed. These “new” systems were developed, evaluated, and certified. Airspace and obstacle clearance criteria were developed based on the performance of available equipment and specifications for requirements were based on available capabilities. In some cases, it was necessary to identify individual models of equipment that could be operated within the airspace concerned. Such prescriptive requirements resulted in delays to the introduction of new RNAV system capabilities and higher costs for maintaining appropriate certification. To avoid such prescriptive specifications of requirements, ICAO developed PBN as an alternative method for defining equipage requirements by specifying the performance requirements.

The PBN concept specifies that aircraft RNAV system performance requirements be defined in terms of the accuracy, integrity, availability, continuity, and functionality, which are needed for the proposed operations in the context of a particular airspace concept. It represents a shift from sensor-based to performance-based navigation. Performance requirements are identified in navigation specifications, which also identify the choice of navigation sensors and equipment that may be used to meet the performance requirements. These navigation specifications are defined at a sufficient level of detail to facilitate global harmonization by providing specific implementation guidance for States and operators. Thus, generic navigation requirements are defined based on operational requirements. Technology can evolve over time without requiring the operation itself to be reviewed, as long as the expected performance is provided by the RNAV system.

During development of the PBN concept, it was recognized that advanced aircraft RNAV systems are achieving a predictable level of navigation performance accuracy, which, together with an appropriate level of functionality, allows for more efficient use of available airspace. It also takes account of the fact that RNAV systems have developed over a 40-year period and as a result there are a large variety of systems already implemented. PBN primarily identifies navigation requirements irrespective of the means by which these are met.

Two fundamental aspects of any PBN operation are the requirements set out in the appropriate navigation specification and the navigation infrastructure (both ground- and space-based) allowing the system to operate.

A navigation specification is a set of aircraft and aircrew requirements needed to support a navigation application within a defined airspace concept. The navigation specification defines the performance required by the RNAV system as well as any functional requirements such as the ability to conduct curved path procedures or to fly parallel offset routes. It should be noted that under PBN, the use of expressions such as RNP type and RNP value defined previously in the *Manual on Required Navigation Performance (RNP)* (ICAO, 1999b) was discontinued.

The PBN concept makes a distinction between RNAV systems and RNP systems. RNAV and RNP systems are fundamentally similar. The key difference between them is the requirement for on-board performance monitoring and alerting. As a result of decisions made in the industry in the 1990s, most modern RNAV systems provide on-board performance monitoring and alerting. Similarly, the PBN concept makes a distinction between RNAV navigation specifications and RNP navigation specifications. A navigation specification that includes a requirement for on-board navigation performance monitoring and alerting is referred to as an RNP specification. One not having such requirements is referred to as an RNAV specification. An area navigation system capable of achieving the performance requirement of an RNP specification is referred to as an RNP system. However, many RNAV systems, while offering very high accuracy and

possessing many of the functions provided by RNP systems, are not able to provide assurance of their performance. Recognizing this, and to avoid operators incurring unnecessary expense, where the airspace requirement does not necessitate the use of an RNP system, many new as well as existing navigation requirements will continue to specify RNAV rather than RNP systems. It is therefore expected that RNAV and RNP operations will co-exist for many years. However, RNP systems provide improvements on the integrity of operation permitting, inter alia, possibly closer route spacing, and can provide sufficient integrity to allow only the RNP systems to be used for navigating in a specific airspace. The use of RNP systems may therefore offer significant safety, operational and efficiency benefits. While RNAV and RNP applications will co-exist for a number of years, it is expected that there will be a gradual transition to RNP applications as the proportion of aircraft equipped with RNP systems increases and the cost of transition reduces.

In elaborating the PBN concept and developing associated terminology, it became evident that the use of RNAV-related expressions could create some complexities. States and international organizations should take particular note of the *Explanation of Terms* and of Chapter 1, Part A, of Volume I of the (Third Edition) of the *Performance-based Navigation (PBN) Manual* (ICAO, 2013b).

While the Third Edition of the *Performance-based Navigation (PBN) Manual* provides the information on the consensus achieved on 2D and approach RNAV applications at the time, the experience of RNP to date leads to the conclusion that as 3D and 4D applications are developed, there will be a need to review the impact of such developments on the performance-based navigation concept and to update the manual accordingly. This update resulted in the Fourth Edition of *Performance-based Navigation (PBN) Manual* published in 2013 (ICAO, 2013b). Both editions comprise two volumes, Volume I, *Concept and Implementation Guidance*, and Volume II, *Implementing RNAV and RNP*. Each of the Volumes I comprises a Part A, *The Performance-based Navigation Concept*, and a Part B, *Implementation Guidance*, whereas each of the Volumes II comprises three parts, Part A, *General*, Part B, *Implementing RNAV*, and Part C, *Implementing RNP*.

Table II-A-1-1 in Volume II of the Third Edition of the *Performance-based Navigation (PBN) Manual* (ICAO, 2013b) shows the navigation specifications and their associated navigation accuracies published in Parts B and C of this volume. The table has been reproduced as Table 2.1 below.

*Table 2.1: Application of navigation specification by flight phase (Reproduced from Table II-A-1-1 in Volume II of the **Third** Edition of the Performance-based Navigation (PBN) Manual)*

Navigation Specification	Flight phase							Departure
	En-route oceanic/ remote	En-route continental	Arrival	Approach				
				Initial	Intermediate	Final	Missed	
RNAV 10	10							
RNAV 5		5	5					
RNAV 2		2	2					2
RNAV 1		1	1	1	1		1 ^b	1
RNP 4	4							
Basic-RNP 1			1 ^{a,c}	1 ^a	1 ^a		1 ^{a,b}	1 ^{a,c}
RNP APCH				1	1	0.3	1	

- The navigation application is limited to use on STARs and SIDs only.
- The area of application can only be used after the initial climb of a missed approach phase.
- Beyond 30 NM from the airport reference point (ARP), the accuracy value for alerting becomes 2 NM.

It has not been attempted to identify the differences between the Third and Fourth Editions of the *Performance-based Navigation (PBN) Manual* (ICAO, 2013b) in any detail. The main difference in the *Executive Summary* text of the two editions seems to be the substitution of “RNAV or RNP” in the Fourth Edition for “RNAV” in the Third Edition where appropriate. Of main interest here are the different navigation specifications available.

Table II-A-1-1 in Volume II of the Fourth Edition of the *Performance-based Navigation (PBN) Manual* (ICAO, 2013b) shows the navigation specifications and their associated navigation accuracies published in Parts B and C of this volume. The table has been reproduced as Table 2.2 below. Note: The original table includes one more column on the left referencing the pertinent chapter in the Manual. This column was left out to save space. A review of five navigation specifications from Table 2.2/Table I-A-1-1, namely RNAV 5, RNAV 1, RNP 1, RNP 2, and Advanced RNP, is provided in (Moek, 2014).

Table 2.2: Application of navigation specification by flight phase (Reproduced from Table II-A-1-1 in Volume II of the *Fourth* Edition of the *Performance-based Navigation (PBN) Manual*)

Navigation Specification	Flight phase							Departure
	En-route oceanic/ remote	En-route continental	Arri val	Approach				
				Initial	Intermediate	Final	Missed ¹	
RNAV 10	10							
RNAV 5 ²		5	5					
RNAV 2		2	2					2
RNAV 1		1	1	1	1		1	1
RNP 4	4							
RNP 2	2	2						
RNP 1 ³			1	1	1		1	1
Advanced RNP (A-RNP) ⁴	2 ⁵	2 or 1	1	1	1	0.3	1	1
RNP APCH ⁶				1	1	0.3 ⁷	1	
RNP AR APCH				1 – 0.1	1 – 0.1	0.3 – 0.1	1 – 0.1	
RNP 0.3 ⁸		0.3	0.3	1	0.3	0.3	0.3	0.3

1. Only applies once 50 m (40 m, Cat H) obstacle clearance has been achieved after the start of climb.
2. RNAV 5 is an en-route navigation specification which may be used for the initial part of a STAR outside 30 NM and above MSA.
3. The RNP 1 specification is limited to use on SATRs, SIDs, the initial and intermediate segments of IAPs and the missed approach after the initial climb phase. Beyond 30 NM from the ARP, the accuracy value for alerting becomes 2 NM.
4. A-RNP also permits a range of scalable RNP lateral navigation accuracies – see Part C, Chapter 4, 4.3.3.7.4.
5. Optional – requires higher continuity.
6. There are two sections to the RNP APCH specification: Part A is enabled by GNSS and baro-VNAV, Part B is enabled by SBAS.
7. RNP 0.3 is applicable to RNP APCH Part A. Different angular performance requirements are applicable to RNP APCH Part B only.
8. The RNP 0.3 specification is primarily intended for helicopter operations.

2.5 Horizontal separation minima in the PANS-ATM

2.5.1 Lateral separation minima

Section 5.4.1, *Lateral separation*, of Chapter 5, *Separation methods and minima*, of the Fourteenth Edition of the PANS-ATM (ICAO, 2016c) (formerly called the PANS RAC)¹⁰ provides five means by which lateral separation may be applied in subsection 5.4.1.2, *Lateral separation criteria and minima*:

- The first means is by reference to the same or different geographic locations and requires position reports which positively indicate the aircraft are over different geographic locations as determined visually or by reference to a navigation aid;
- The second means is by use of the same navigation aid or method and requires aircraft to fly on specified tracks which are separated by a minimum amount appropriate to the navigation aid or method employed. This means provides minima for a) VOR, b) NDB, and c) dead reckoning (DR) in terms of angles between radials or tracks and distance to the facility. Although it is at present virtually impossible to infer how these minima were determined at the time, it should be clear that the accuracy of the different navigation means must have played an important role in the development of the minima. This means also covers d) RNAV operations (by use of the same navigation aid or method);
- The third means is by use of different navigation aids or methods;
- The fourth means concerns RNAV operations where RNP is specified on parallel tracks or ATS routes; and
- The fifth means concerns RNAV operations (where RNP is specified) on intersecting tracks or ATS routes.

No specific minima are given for item d) of the second means or for the third to fifth means but rather the methods to be used to determine appropriate minima. The respective methods are as follows: non-overlapping protected airspace of the two aircraft tracks, non-overlapping protected airspace of the navigation aid(s) or RNP, non-overlapping protected airspace of the tracks or ATS routes, and collision risk analysis. Concerning the fourth means, a note refers to guidance material in (the then prevailing) Annex 11, Attachment B. Provisions for area navigation practices seem to have been incorporated into the PANS-ATM in Amendment 4 of its Tenth Edition with an applicability date of 23 November 1974. Lateral separation on intersecting tracks for RNAV operations where RNP is specified was introduced under Amendment 1 to the Fourteenth Edition of the PANS-ATM with an applicability date of 28 November 2002.

Hajek (2007c) deals with the need to define *protected airspace* at the hand of three questions, namely: what is protected airspace, what is it used for, and how is the size of protected airspace determined? Concerning the first question, it notes in its paragraph 2.2 that the term protected airspace is used in PANS ATM on seven occasions, yet no definition exists. Thus, it proposes protected airspace (horizontal) to be defined as the area in which the aircraft is considered to be contained with a certain degree of probability. Concerning the third question, *how big is it*, Hajek (2007c) notes in paragraph 2.4 ff. that, traditionally, lateral separation has been based on the primary area of airspace derived by the Obstacle Clearance Panel (OCP) for terrain and obstacle protection, i.e. 95% containment or 2σ . For a VOR airway 95% containment is defined by Annex 11, Attachment A. It continues to note that this concept has been successfully applied in the provision of lateral separation in non-radar airspace for over 45 years, but that there is a need to migrate from protected airspace along VOR and NDB routes to RNAV and RNP ATS routes. Hajek (2007c) concludes with the recommendation to define protected airspace for RNP ATS routes as “two times” the navigation accuracy

¹⁰ See the *Historical background* section in the *Foreword* to the Fourteenth Edition of the PANS-ATM.

value (RNP) for one half width of the track and for RNAV routes as “two-and-a-half times” the navigation accuracy value (RNAV) for one halfwidth of the track.

Until approximately the year 2003, intersecting routes were mainly considered in the context of distance-based or time-based longitudinal separation. Nonetheless, a method of determining lateral separation on intersecting tracks by means of collision risk modelling was developed in (Anderson, 2003a). It was called the area of conflict method and was subsequently included in the PANS-ATM, though it doesn’t seem to have been used in practise.

The intersecting-track collision risk modelling work of (Moek, 2008; Moek & Aldis, 2008) differed from the area of conflict method by requiring non-overlapping protected airspaces for the routes at the intersection where the protected airspaces were defined in terms of suitable multiples of the “RNAV or RNP value” (Hajek, 2007c). It was inspired by previous work of the SASP MSG on the extension of VOR lateral separation minima to GNSS navigation (ICAO, 2014a) (see the *15th Edition incorporating Amendments 1-6* entry in Table 2.3 below). According to the PANS-ATM, lateral separation between two VOR aircraft exists when both aircraft are established on radials diverging by at least 15 degrees and at least one aircraft is at a distance of 28 km (15 NM) or more from the facility. When the SASP MSG started work on the extension to GNSS navigation, it was unclear how the VOR lateral separation had been derived in the past. Therefore, the general collision risk model based on reliability theory of (Anderson, 2005) was adapted to an intersecting-track scenario for VOR navigation and subsequently expanded to GNSS navigation. (The ultimate assessment of the tolerability of intersecting-track GNSS collision risk was based on a comparison with VOR risk.) See the summary of this work in chapter 3 of ICAO, 2014). The (Moek, 2008; Moek & Aldis, 2008) work was not continued because the SASP did not proceed with Hajek’s (2007c) definition of protected airspace. (A technical detail of the (Moek, 2008; Moek & Aldis, 2008) work is that the lateral collision risk was calculated over the duration of a level change needed to end or achieve vertical separation plus ten minutes following or preceding the level change (Moek & Aldis, 2009). This may be interpreted as covering only half of the collision risk for a full crossing of two aircraft at an intersection where the risk for a full crossing can be obtained by (manually) summing the risks per inbound and/or outbound pair collision risk tables.)

Table 2.3 illustrates the evolution of lateral separation standards/minima in the PANS/ATM, starting with the 14th Edition incorporating Amendments 1-4 with a first applicability date of 1 November 2001 and an applicability date of 24 November 2005 for Amendment 4 (ICAO, 2016c). The table represents the spirit of the pertinent PANS-ATM text, but the PANS-ATM itself should be consulted for the precise wording. Bullets in the table below correspond to paragraph numbers in the official text. New or amended text between versions is shown in bold. Text deleted is shown by means of strike through. See Appendix B for the documents referenced in the last column of Table 2.3. For some of the editions and/or amendments, there are no changes in Table 2.3 compared to their precursors, but these editions and/or amendments are included to maintain consistency with the editions and/or amendments to be presented in Table 2.5 for the longitudinal separation minima.

For example, there is no change in the lateral separation minima in Table 2.3 until the incorporation of Amendment 6 to the 15th Edition of the PANS-ATM. Amendment 1-7-A incorporated into the 16th Edition of the PANS-ATM concerned a reduction of the 30 NM lateral separation minimum for RNP 4 or RNP 2 aircraft on *parallel or non-intersecting tracks or ATS routes* meeting the PBCS RCP 240 and RSP 180 standards. The corresponding safety assessment was documented in a revised version of ICAO Circular 334, published under

the same title as ICAO Circular 341¹¹. The material on *Lateral separation of aircraft on parallel or non-intersecting tracks or ATS routes* changed to a tabular format with Amendment 8 to the 16th Edition of the PANS-ATM, to distinguish between airspace where SLOP is not authorized, or is authorized up to 0.5 NM, and airspace where SLOP up to 2 NM is authorized.

2.5.2 Longitudinal separation minima

Section 5.4.2, *Longitudinal separation*, of the Fourteenth Edition of the PANS-ATM (ICAO, 2016c) distinguishes five cases, namely:

- a) longitudinal separation minima based on time;
- b) longitudinal separation minima based on distance using distance measuring equipment (DME);
- c) longitudinal separation minima with Mach number technique based on time;
- d) longitudinal separation minima with Mach number technique based on distance using RNAV;
- e) longitudinal separation minima based on distance using RNAV where RNP is specified.

Time-based separation applied in accordance with bullets a) and c) may be based on position information and estimates derived from voice reports, CPDLC or ADS.

Communication is explicitly addressed for the cases b), d), and e) as follows:

- b) Direct controller-pilot communication shall be maintained while such separation is used;
- d) Direct controller-pilot communications should be maintained while such separation is used;
- e) Direct controller-pilot communications shall be maintained while applying a distance-based separation minima. Direct controller-pilot communications shall be voice or CPDLC. The communication criteria necessary for CPDLC to satisfy the requirement for direct controller-pilot communications shall be established by an appropriate safety assessment. A further subdivision of case e) is made based on not using ADS or using ADS.

The longitudinal separation minima provided in section 5.4.2 of PANS-ATM are illustrated in the following table. See PANS-ATM for details under which the different minima per case apply.

Table 2.4: Longitudinal separation minima as a function of the means of providing longitudinal separation (ICAO, 2016c)

Means of providing longitudinal separation	Longitudinal separation minima
a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes
b) longitudinal separation minima based on distance using distance measuring equipment (DME);	20 or 10 NM
c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive
d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM
e) longitudinal separation minima based on distance using RNAV where RNP is specified.	Not using ADS: 50 NM Using ADS: 50 NM or 30 NM

¹¹ ICAO Circulars can only be updated under a new Circular number.

The longitudinal separation minima for case e) are dependent on combinations of RNP type, RNP 10 or RNP 4, communication requirement, direct controller-pilot communications, surveillance requirement, procedural position reports or ADS, and a distance verification requirement/maximum ADS periodic reporting interval. The communication criteria which are used as a basis for the derivation of the longitudinal separation minima under case e) are set out in Appendix 5 to the (then prevailing) *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (Doc 9689) (ICAO, 1998c). Guidance material for CPDLC is contained in the *Manual of Air Traffic Services Data Link Applications* (Doc 9694) (ICAO, 1999a). Note 3 in Section 5.4.2.6.3 of the PANS-ATM (ICAO, 2016c) states that the 50 NM longitudinal distance-based separation minimum in an RNP RNAV environment not using ADS was developed in accordance with a collision risk analysis which dictates conditions under which this separation can be applied¹² (i.e. Appendix 5 to the then prevailing edition of *Manual on Airspace Planning Methodology*). The same applies for the 50 NM and 30 NM longitudinal distance-based separation minima in an RNP RNAV environment using ADS.

As described earlier, see footnote 6 in Section 2.3, automatic dependent surveillance was incorporated into the PANS-ATM under Amendment 1 to its Fourteenth Edition. The 30 NM longitudinal separation minimum and the requirement for ADS to implement this separation minimum were incorporated under the same amendment. The applicability date of this Amendment was 28 November 2002.

Table 2.5 illustrates the evolution of longitudinal separation standards/minima in the PANS-ATM, starting with the 14th Edition incorporating Amendments 1-4 with a first applicability date of 1 November 2001 and an applicability date of 24 November 2005 for Amendment 4. The table represents the spirit of the pertinent PANS-ATM text, but the PANS-ATM should be consulted for the precise wording. Bullets in the table below correspond to subsection numbers in the official text. New or amended text between versions is shown in bold. Text deleted is shown by means of strike through. See Appendix C for the documents referenced in the last column of Table 2.5. For some of the editions and/or amendments, there are no changes in table 2.5 compared to their precursors, but these editions and/or amendments have been included to maintain consistency with the editions and/or amendments presented in table 2.3 for the lateral separation minima.

Amendments 1-2 to the 15th Edition of the PANS-ATM show two changes compared to the 14th Edition, namely one for item b), extending the DME minimum to DME and/or GNSS, and one for item e) strengthening (Not) using ADS to (Not) using ADS-C. There are no changes to the longitudinal separation minima in the additional Amendments 3-5 to the 15th Edition of the PANS-ATM, but there is one addition under Amendment 6 to the 15th Edition, viz. item f). Next, the 16th Edition incorporating Amendment 1-7-A involves three changes, deletion of *Using ADS-C* from item e) and two additions in the form of items g) and h), where the latter provides a PBCS-based replacement for the deletion of *Using ADS-C* from item e). Finally, incorporation of Amendment 8 to the 16th Edition of the PANS-ATM did not involve any changes to the longitudinal separation minima.

¹² The thirteenth edition of the PANS-RAC, i.e. the immediate predecessor to the PANS-ATM, incorporated both an 80 NM and a 50 NM longitudinal distance-based separation minimum in an RNP RNAV environment not using ADS for RNP 20 and RNP 10 respectively with corresponding distance verification requirements of at least 60 and 30 minutes. RNP 20 was subsequently dropped by ICAO.

3 Historical Development of Collision Risk Models for En-route Air Traffic

3.1 Introduction

As set out in Chapter 1, *Introduction*, this chapter has been reproduced from Pool (1983), a lecture entitled “*Historical development of collision risk models for en-route air traffic*”, given by A. Pool at Princeton University in 1983, to honour the earliest work performed on aircraft collision risk modelling at NLR. The lecture will also be used in Section 5.3 to trace some of the later lateral separation developments in the NAT following the pioneering Reich model work (Reich, 1966a). As also set out in Chapter 1, the Princeton lecture concludes with a look ahead at two main subjects being underway at the time, namely investigation of the possibilities of reducing the vertical separation standard above FL 290 from 2000 feet to 1000 feet, and development of a minimum Navigation Performance Specification (MNPS) for continental airspace, specifically in Europe. The first of these subjects will be amply covered in Chapter 6, *Vertical collision risk assessment*, of this document. The second subject did not materialize. Instead, ICAO developed the globally applicable Required Navigation Performance (RNP) concept (ICAO, 1999b), which was subsequently superseded by the Performance-based Navigation (PBN) concept in 2008 (ICAO, 2013b) (cf section 2.4).

3.2 Historical Background

The collision risk models mentioned in the title of this chapter are used to ascertain whether the separation standards used by the Air Traffic Control authorities remain sufficiently safe as the air traffic increases and whether, if the navigation performance seems to have improved, this will allow a decrease of one or more separation standards.

In the early days of aviation the probability that a collision could occur was very low because only relatively few aircraft flew along individually selected routes. In addition, as flying was done at low speed and only in good weather, the pilots would generally see other aircraft in their neighbourhood sufficiently early. The most critical situations might occur near airports, and there the pilots would be especially vigilant.

In the mid-1930s two new developments occurred which tended to increase the probability of mid-air collisions:

- Blind flying became possible and made observations of other aircraft by the pilots more difficult
- Route systems were defined by radio beacons, which meant that more aircraft would fly along the same routes.

At that time, the first separation minima were introduced: first 1000 feet vertical separation and then 10 minutes longitudinal separation between aircraft flying nominally at the same height along the same route.

In the 1950s the fast increase in traffic density was, to a certain extent, compensated by a fast increase in the effectiveness of Air Traffic Control. Especially radar control provided an effective means to prevent collisions. A longitudinal separation standard of 5 NM was accepted for aircraft that were under radar control. In

oceanic areas, where radar control was not possible and where aircraft often fly for many hours without independent checks on their positions, the increase in traffic density led to the implementation of much larger separation standards: 20 minutes longitudinal separation and 120 NM lateral separation, plus the 1000 feet vertical separation that was used worldwide. When jet aircraft came into use, which flew at higher altitudes than all aircraft used previously, it was realized that the accuracy of altimeters (in feet) decreases as the altitude increases. For that reason, the worldwide separation standard was increased to 2000 feet at flight levels above FL290. The numerical values for these separation standards were based on judgement: wise men, often assembled in ICAO meetings, agreed what seemed safe enough and was workable for pilots and air traffic controllers.

That was the situation at about 1960. The very large increase in air traffic density in the 1960s and 1970s started to cause congestion problems in busy areas. Then interested parties began to ask whether the separation standards could be reduced to alleviate this, especially as at the same time the accuracy of the navigation equipment and of the altimeters increased drastically. On the other hand it was realized that the probability of a collision would increase with the number of aircraft that were in the air, so that such decisions should not be taken too lightly. Investigations were then started on how to quantify the “collision risk”, in order to obtain objective criteria. That led to the collision risk models that are the subject of this section.

3.3 History of Collision Model Development

The first steps toward the development of a collision risk model were probably made during the three meetings of the ICAO Vertical Separation Panel between 1956 and 1958 (ICAO, 1956, 1957, 1958). A later review of their work, with some additional material, is given in (ICAO, 1972). The Panel analysed the altimeter errors and collected large quantities of statistical material on error components. It also tried to develop a mathematical model for calculating the collision risk. In this respect, it just fell short of realizing a complete model. Many of their ideas were, however, used in the later development of the Reich model.

In 1962-1963 a second step was made. By that time, the traffic density above the North Atlantic had increased so much that the lateral separation standard of 120 NM caused important economic penalties to flights that could obtain their requested routes or flight levels. The FAA, in cooperation with IATA, set up a large data collection, Operation Accordion. Radars were set up in Newfoundland, in Ireland and on a ship that was positioned in mid-ocean. The radar data of 1000 flights were correlated with the flight logs of the aircraft. The results seemed to indicate that a separation standard of 90 NM would be safe enough (Hirsch, 1964) and convinced the ICAO Special NAT meeting of 1965. ICAO made the necessary legal steps for the implementation. A closer investigation, prompted by a protest from IFALPA, brought about some doubt about the conclusions drawn from the data. It was, for instance, realized that the conclusions were based on the assumption that all aircraft flying across the ocean would show the same performance as the aircraft of the few major airlines that took part in Accordion. Also, the conclusions were not based on an actual calculation of probability but on the reasoning that “relatively few” aircraft had passed the half separation (i.e. 45 NM). On the basis of these doubts, and pushed by actions by the pilots, the separation in the NAT was brought back to 120 NM. Nevertheless, Operation Accordion and the discussions around it proved to be of great importance for further developments. The problems of the assessment of a collision risk had been clearly formulated and the possibilities of large data collections had been shown.

Meanwhile B.L. Marks in the U.K. had developed the principles on which a collision risk model could be based (Marks, 1963). His work was continued by a group of scientists at the Royal Aircraft Establishment headed by P. Reich. They developed a collision risk model for the North Atlantic and indicated how it could be used (summarized in (Reich, 1966a, 1966b, 1966c)). That model, later called the Reich model, was the basis of practically all investigations described in this chapter. A brief description of this model is given in Section 3.4 below. The group also showed that assuming that the probability distribution of the deviation from track was of the “Gaussian” type (as had been done in all previous attempts) would significantly underestimate the collision risk.

The work in this field was continued in the North Atlantic Systems Planning Group (NAT/SPG) that had been set up by the ICAO Special NAT meeting of 1965 and of which all States which had done studies in this field became member. This Group somewhat extended the Reich model and proposed a limit value for the collision risk (called “target level of safety”) which has since then been used as a basis of comparison for the calculated risk (ICAO, 1966, 1967). The States participating in the NAT/SPG organized a large data collection in the NAT area, in which Gander radar, a specially set up radar in Ireland and 3 radar-equipped ships took part. Between March 1967 and July 1968 radar measurements were obtained on more than 14000 flights. The processed results (when interpreted according to the rules laid down by the Group itself) indicated that a separation standard of 90 NM was not safe and that 120 NM was safe (NAT SPG/4 report).

The NAT/SPG then proposed a new layout for the parallel track system used in the North Atlantic Region (ICAO, 1968a). Using the same method and the data from the data collection of 1967-68, it showed that this “composite” track system was very nearly as safe as the “rectangular” system used previously, but could accommodate up to twice the number of aircraft in the same airspace as the old system. The principle is shown in figure 1. The upper figure shows a cross section through the rectangular track system, where all aircraft had 120 NM lateral separation and (above FL 290) 2000 feet vertical separation. The lower figure shows the “composite” system. There all aircraft have the same separations of 120 NM and 2000 feet with aircraft flying at the same altitude and along the same track respectively, but tracks (dotted lines) have been inserted where aircraft have 60 NM and 1000 feet separation with the aircraft on the original tracks. The calculation of the collision risk was based on the fact that the height-keeping errors and the (horizontal) navigation errors could be regarded as being statistically independent, as one was measured by pressure altimeters and the other by navigation equipment based on radio beacons or on inertial navigation systems. This method was implemented by ICAO after approval by the ICAO Fifth North Atlantic RAN meeting in 1970 and was used for nearly a decade.

During the same period the NAT/SPG investigated the possibilities of applying the Reich model to vertical and longitudinal separations. The principles were laid down (ICAO, 1968a), but due to lack of data no definite results were produced at that time.

Meanwhile ICAO had constituted a Panel for the Review of the General Concept of Separation (RGCS Panel). This Panel coordinated a large collection in Europe of lateral deviations from tracks defined by VOR, conducted at Orly, France. The method used by the NAT/SPG was adapted for application to parallel routes in a VOR-defined environment. From the results recommendations were formulated for procedures for choosing the best spacing between such parallel routes. After discussion at the ICAO Ninth Air Navigation Conference (1976) these were incorporated as “Guidance Material” in ICAO Annex 10. The theoretical studies and the data on which this guidance material was based have been published in (ICAO, 1976a). A later data collection in the USA (Colomosa, 1982) provided data which were very similar to those collected in Europe.

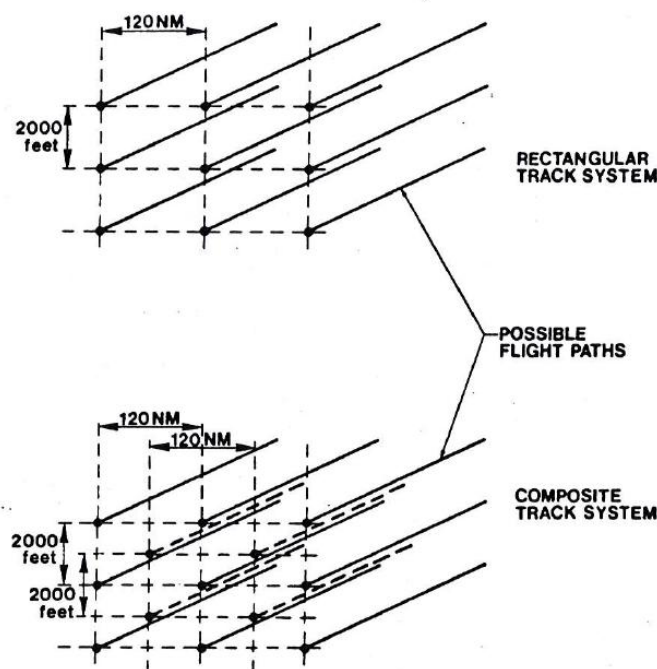


Figure 3.1: Rectangular and composite track systems

Composite separation was, in later years, also applied in oceanic areas outside the NAT Region. After a detailed study (ICAO, 1976b) a composite track system between the USA and Hawaii was tried out for 2 years starting in 1977. At the end of the trials period a new evaluation of the system (ICAO European Office, 1979) showed that a non-composite system with one-way tracks gave more flexibility to this system. That new track system was implemented in 1979. For flights between Alaska and Japan a composite track system was implemented in 1982 (Busch et al., 1977).

The deviations from track of the aircraft coming off the North Atlantic Region have, since the data collection of 1967-68, been continually monitored by radar controllers in Ireland and Canada. If large deviations occur, the operators are asked for details about what has occurred. The reports on the monitoring results are submitted to the NAT/SPG. The first results showed that aircraft navigating on inertial navigation systems (INS) and, in the later years, OMEGA had markedly less large errors than those navigating on LORAN A/Doppler. The operators using this equipment wanted to earn economic advantages from its use. It proved, however, impossible to adapt the NAT route system to two classes of navigation performance. An opportunity to make use of the better performance possibilities came when the military authorities announced that they intended to stop the operation of LORAN A at the end of 1977. The operators which then used this navigation aid would have to re-equip their aircraft. It was decided that from that time onward all aircraft that flew above FL280 in the NAT Region would have to show a navigation performance that was at least as good as that achieved by INS-equipped aircraft at that time. The NAT/SPG developed a Minimum Navigation Performance Specification (MNPS), which all aircraft flying in the NAT area are required to meet. This was not, as had been done in the past, a specification of the equipment that should be on board the aircraft, but a requirement about the actual navigation performance. The operators have to show that their aircraft and flight crew can meet this specification before they are certified to fly in the NAT area, and the actual performance is monitored by radars on both coasts of the ocean. The general principles of this new concept were discussed in and accepted by the ICAO Ninth Air Navigation Conference (1976) and the details were developed during the ICAO Limited NAT RAN Meeting in the same year (ICAO, 1976b). It was developed from the Reich model and the data which had been

collected since 1967 by the monitoring process were used to define the range of shapes of the distributions of lateral deviations that were used in the derivation of the MNPS requirements and to estimate the occupancies. The MNPS was implemented in the NAT Region at the end of 1977 with the composite track system that was in use at that time, although it had been designed for operation with a “60 NM/2000 feet” rectangular system. During an “experimental” period of nearly 2 years the operators and controllers accustomed themselves to working under the new system, while all aircraft coming of the ocean were closely monitored by radar. For every deviation from track larger than 25 NM the causes were closely investigated. From the experiences obtained during that period guidelines for using the MNPS were laid down by ICAO and IATA in a document (ICAO European Office, 1979) that received a very wide distribution. Finally the track layout was changed to the rectangular 60 NM/2000 feet configuration near the end of 1980.

An extension of the MNPS concept to other areas than the NAT Region was developed by a working group of the RGCS Panel in 1980. It is intended for publication as guidance material in one of the ICAO Annexes¹³.

The latest change in a separation standard that was realized on the basis of results from the Reich model is the change in longitudinal separation in the North Atlantic Region. In November 1981, the longitudinal separation standard there was reduced from 15 to 10 minutes. The model and the data which were used are described in (ICAO, 1980b).

The above very briefly reviews (with references to the theoretical and practical results) what has been achieved in the field of development and application of collision risk models. At the present time, a number of projects are still underway, but no referenceable papers have been published yet. The main subjects are:

- Investigation of the possibilities of reducing the vertical separation standard above FL 290 from 2000 feet to 1000 feet,
- Development of an MNPS for continental airspace, specifically in Europe.

In the next two paragraphs these developments will be briefly reviewed.

Throughout the last three decades it has been the feeling of many experts that a reduction of the vertical separation above FL 290 to 1000 feet could be the most effective step towards reducing congestion in air traffic. The Vertical Separation Panel, the NAT/SPG and the RGCS Panel have all spent considerable effort in trying to find out whether (and how) this can be safely done. The problem proves to be more complex than that for the lateral separation, mainly for the following reasons:

- The statistics of height-keeping errors is more complex than that for the lateral deviations, because they are more dependent on the meteorological situation and the presence of turbulence and mountains than the present-day (horizontal) navigation errors.
- Data collections are more difficult and costly. In lateral track-keeping studies data available in ATC surveillance radar systems could be extracted for studies at relatively low cost. For similar data collections on height keeping, measurements with lock-follow radars will have to be made for that specific purpose only.
- Data collected up to now on the accuracy of altimeters seem to indicate that with the best types of altimetry systems now available it may well be possible to reduce the separation standard without compromising safety. Many aircraft flying regularly above FL290, however, still have altimeters of significantly lower quality, which probably are not accurate enough for such a reduction to be safe. It would seem, therefore, that a reduction of the (worldwide) separation standard might require re-equipment of many aircraft.

¹³ See also Chapter 1 of this document (Burt, 1993b). However, rather than developing an extended MNPS concept, a global RNP, Required Navigation Performance concept was developed (ICAO, 1999b). The RNP concept was subsequently superseded by the PBN concept in 2000 (ICAO, 2013b).

Cost-benefit studies (see e.g. (FAA, 1981)) seem to indicate that the economic gains of a reduction in vertical separation above FL290 are so large, that they warrant a costly safety study and the costs of re-equipment that this may make necessary. Therefore, large data collections are being set up now both in Europe and in the USA, which should provide the basis for a definition of the conditions under which a separation standard of 1000 feet above FL290 can be realized.

In Europe, maybe even more than in the USA, congestion occurs on continental air routes. Eurocontrol, in which the ATC organisations of a number of states in Western Europe co-operate, is investigating the possibilities of a continental MNPS based on the performance of modern aircraft equipped with inertial navigation system with multiple-DME updating. It is hoped that then dual-track routes, with aircraft flying at the same flight levels on both routes, can be established with a spacing of the order of 7 NM. In the modelling for this system the effect of radar controller interventions must be taken into account, which will require an important modification of the Reich model. At present the development of a suitable model is being studied and data are collected on the deviations from track of aircraft that use modern navigation systems.

3.4 The Reich model

3.4.1 Preliminaries

Before presenting the principles of the Reich collision risk model, two basic quantities have to be defined: what is collision risk and what value of that collision risk should be acceptable in the route systems considered?

The units in which the collision risk is expressed must be chosen so that the values from different areas can be compared and that they are as well as possible comprehensible to the users. After a detailed discussion (ICAO, 1966, 1967) the NAT/SPG agreed on the following definition, that had already been proposed by Reich: Collision risk is the average number of aircraft accidents due to collision in a certain area per ten million flying hours flown in that area. One collision causes two accidents. This definition has been used for all investigations.

If collision risks calculated by a model are to be used in assessing whether a system will be safe or not, then a limit acceptable value for the collision risk must be agreed. This is a very critical value because it decides, in principle, how many aircraft are allowed to be involved in collision accidents. It is, however, necessary to define a value, because a collision risk equal to zero can only be achieved if not more than one aircraft is allowed in an area at a time. It was tried to define such a value as far as possible independently of the collision risk that actually existed at that time, i.e. to define a value that endangered people to about the same extent as other comparable causes of death. The latest version of the derivation is given in (ICAO, 1976a Section 7). The value adopted, which was called the “target level of safety”, was that no more than 6 aircraft should be involved in collisions during a hundred million flying hours, i.e. a collision risk of 0.6 according to the definition given above.

In the practice of the studies mentioned in Section 3.2 it was found that usually only one of the separations (lateral, longitudinal or vertical) could be investigated at any one time. In those studies 1/3 part of the above value has been used for each separation separately, i.e. a target level of safety of 0.2 has been allowed for each separation.

3.4.2 Derivation of the model equation

The model equation is derived for the case of the assessment of lateral separation in a parallel track system (Figure 3.2), but the basic model equations are equally applicable to other cases. The aircraft are simulated by rectangular blocks with dimensions of the average values of aircraft length (λ_x), span (λ_y) and height (λ_z). The sides of the blocks remain parallel to the tracks. The aircraft nominally fly on different tracks and at the same FL, but due to navigation and altimetry errors they will in general not be exactly on their nominal tracks. A collision can occur in three ways: head-on, vertically or laterally. A head-on collision will only occur if the two aircraft have lost both lateral and vertical separation (i.e. $|y| < \lambda_y$ and $|z| < \lambda_z$) before the x value becomes zero (Figure 3.3). If the probability that $|y| < \lambda_y$ is P_y and the probability that $|z| < \lambda_z$ is P_z then the probability that both will occur simultaneously is $P_y P_z$. If the average number of aircraft that pass aircraft nominally flying on another track during one hour is N_x , then the collision risk as defined above is

$$N_a(x) = 10^7 N_x P_y P_z \quad (3.1)$$

Similar equations can be derived for vertical and lateral collisions, so that the full collision risk equation is

$$N_a = 10^7 (N_x P_y P_z + N_y P_z P_x + N_z P_x P_y) \quad (3.2)$$

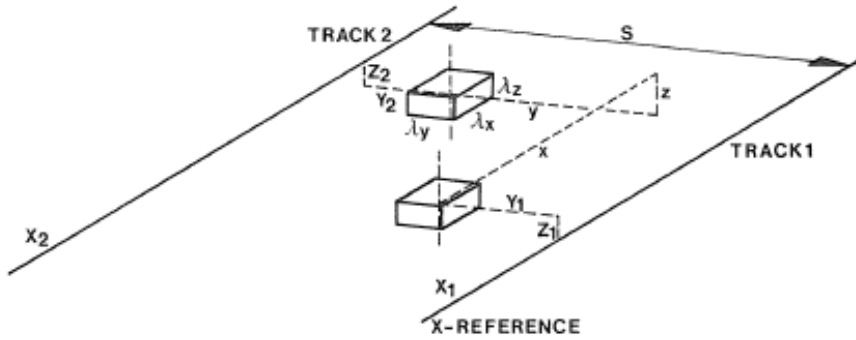
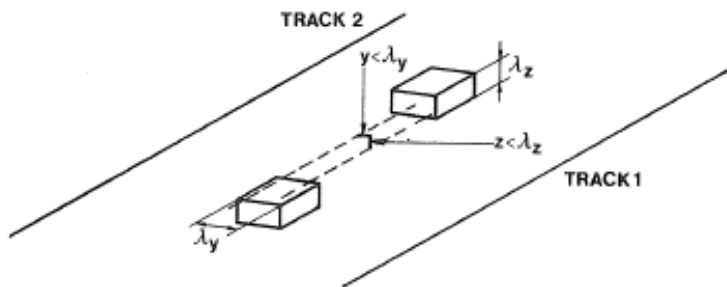


Figure 3.2: Definition of co—ordinates in the Reich model



$$N_a(x) = 10^7 N_x P_y P_z$$

Figure 3.3: A case of simultaneous lateral and vertical overlap

The associated P and N values can be related to each other. The probability P_x that longitudinal overlap will occur, for instance, is equal to the fraction of the total flying time in the area during which longitudinal overlap between aircraft occurs. The number of such longitudinal overlaps is N_x times that total number of flying hours. The relation is, therefore, as follows:

$$N_x = P_x \frac{\overline{|\dot{x}|}}{2\lambda_x} \quad (3.3)$$

where $\overline{|\dot{x}|}$ is the average longitudinal closing speed of the two aircraft or, more precisely, the average of the absolute values of the relative along-track velocity between two aircraft flying on different tracks. Using similar relationships in the other two directions, the above general equation can be written as

$$N_a = 10^7 P_x P_y P_z \left(\frac{\overline{|\dot{x}|}}{2\lambda_x} + \frac{\overline{|\dot{y}|}}{2\lambda_y} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right) \quad (3.4)$$

This is usually called the general Reich model equation. Its derivation requires only very few assumptions, and these are in most cases quite realistic. It can, therefore, be said that this equation is valid for practically all collision risk studies. The parameters are different according to the separation that is studied (lateral, longitudinal or vertical) and for same—direction and opposite—direction traffic on the parallel tracks. If combined risks must be calculated, the model equation becomes the sum of more than one term.

It is far beyond the scope of this lecture to describe the assessment of all parameters in the model equations. A few words will be said, however, about the two most critical parameters: the probability of overlap in the direction of the separation that is studied (P_y in the case of a lateral separation study) and the probability of longitudinal overlap P_x .

The assessment of P_y for lateral separation between parallel tracks spaced by a distance S is explained using Figure 3.4. The upper part of that figure shows a general shape for the probability density function of the lateral distances y between aircraft, nominally flying different tracks, as they pass each other. It has a peak at the nominal distance S and will drop to a very low value at $y = 0$. The probability of lateral overlap P_y is equal to the shaded area below the curve within $\pm\lambda_y$ of $y = 0$. Many thousands of independent measurements are required to define the tail of such a curve with sufficient confidence. It will, in general, require a very lengthy data collection to measure so many points of that curve directly, as aircraft on dual tracks do not pass each other very often. Moreover, in some of the studies it was not possible at all to measure these data directly, as dual—track systems hardly existed at all. In such cases it is necessary to calculate, with a few additional assumptions, the upper curve of Figure 3.4 from measured deviations of aircraft from single tracks. The principle is shown in the lower graph of Figure 3.4. In the studies described in (ICAO, 1976a) these lateral deviations were measured continuously by surveillance radars. It can then be assumed that the aircraft on both tracks will have the same distribution of lateral deviations, and the value of P_y can then be calculated by a mathematical process called convolution. The results of such a convolution must be interpreted with more care than a direct measurement of the relative distances, as several assumptions are implicit in the process. The most important assumptions are, in the case of lateral separation:

- It is assumed that the tracks in the route system that is investigated are parallel. If they are not parallel, using the average distance between the tracks in the calculation will grossly underestimate the risk. If

the smallest distance between the tracks is used, the model will overestimate the risk, but generally to a lesser degree.

- It is assumed that the distribution of lateral deviations from track is independent of the position of the aircraft along the route. This is, for instance, not true for VOR—defined routes, as is shown in (ICAO, 1976a). A more complex model equation has been derived there to cover this case. If this equation is not used, the collision risk may be underestimated significantly.
- It is assumed that the deviations of the aircraft on one track are independent of the position of the aircraft on the other tracks. This is not true if ATC controllers intervene to reduce lateral deviations when there is an aircraft nearby on an adjacent track, and do not intervene when there is no aircraft on the other track. In that case the model will overestimate the risk.

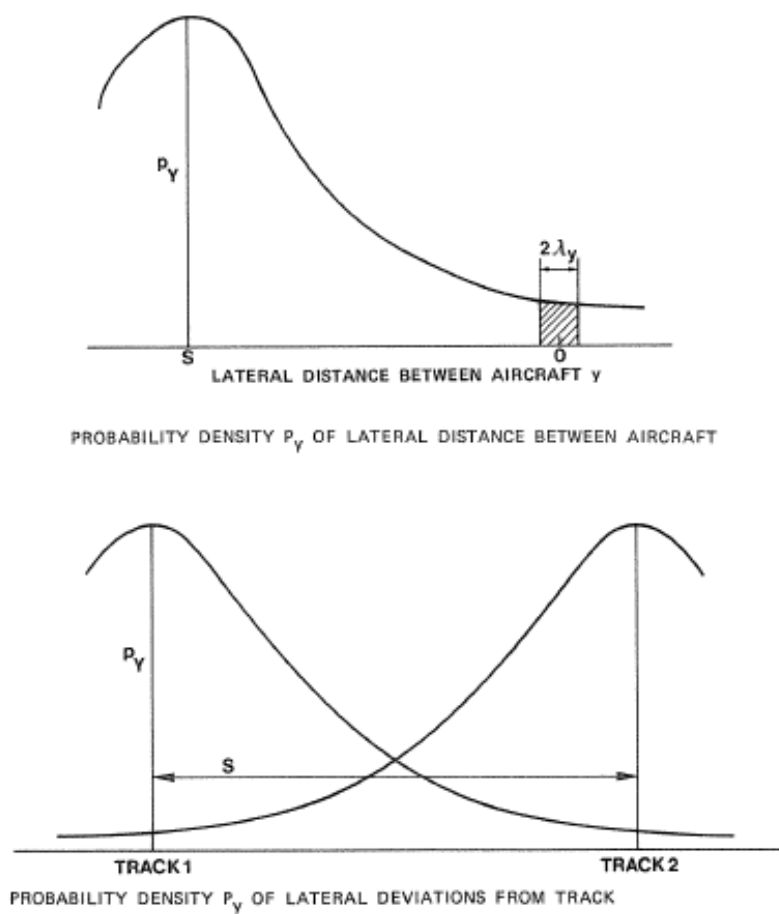


Figure 3.4: Assessment of P_y

The probability of longitudinal overlap P_x is usually calculated using the parameter “occupancy”, which is defined by:

$$E = \frac{S_x}{\lambda_x} P_x \quad (3.5)$$

where S_x is an arbitrary length, usually 120 NM. Occupancy is the average number of aircraft on an adjacent track that are within S_x of an aircraft (all aircraft at the same FL). The occupancy of an existing route system

can be determined from a listing of arrival times of all aircraft at a cross sections through the route system, listed by track and flight level. A problem is, that the occupancy of a system may vary considerably between different times of the day, days of the week, seasons, etc. A reliable occupancy value can, therefore, only be obtained from samples involving many days throughout the year. In the North Atlantic there is the additional problem that the position of the tracks is chosen twice daily on the basis of weather forecasts, whereby the opposite-direction tracks are sometimes located within the main-flow track system, but on other occasions far from the main track system. A simpler, but less accurate, method is to calculate E from data (or forecasts) on aircraft densities as a function of flight level, track and time, that can often be obtained from air traffic authorities. This method is less accurate than the direct method mentioned above. If the traffic on adjacent tracks moves in the same direction, an additional assumption is then implicitly made that the along-track positions of the aircraft on different tracks are uncorrelated. The importance of this assumption can be shown by an extreme example: if all aircraft would be flying side-by-side all the time, the occupancy would be of the order of a thousand times greater than when the longitudinal positions are uncorrelated.

It is very important that all (implicit and explicit) assumptions in the model are carefully checked on their validity. If one is found to be invalid, the model (or the method of data collection) must be adapted in such a way that the assumption is no longer required. This will usually require more data or a more complex method of data collection.

One other general problem should be mentioned. In the discussions above on the assessment of P_x and P_y it has been assumed that they must be determined for an existing route structure. In many cases, however, the object of the model study is to assess the safety of some planned route structure, and the values must be valid for the period after the new system has been implemented. For P_y the logical assumption is, that the distribution of the lateral deviations will then be at least as good as it was at the time when the distribution was measured. For the problem is more difficult: the traffic densities on the different tracks and flight levels of the new system will depend on how the airlines will flightplan in that (not yet existing) system. That is often difficult to foresee. For the changes in the NAT system described in Section 3.2 complex models have been developed to predict the occupancies for the new system (see e.g. (Sheil, 1977)).

3.5 The Minimum Navigation Performance Specification

When thinking about the concept of a Minimum Navigation Performance Specification (MNPS), it became clear that this should be an “inverse” Reich model. The Reich model calculates the collision risk for a given separation value from data on the actual performance of aircraft. In the case of the MNPS the separation value was fixed from the beginning: it had to be 60 NM (1 degree of latitude) because some of the existing navigation equipment could only be programmed in degrees. Then it would be necessary to specify the minimum navigation performance of the aircraft in such a way that the totality of the traffic would not cause the collision risk to increase beyond the target level of safety.

Previous experience in the North Atlantic had made it clear that the actual navigation performance of the aircraft should be the basis of the MNPS, not the manufacturer’s specifications of the navigation equipment. It had been found that the actual distribution of lateral errors was, in many cases, very much different from what could be expected from those specifications. This was not because the specifications were incorrect. It was mainly due to the fact that “blunder errors” occurred due to incorrect procedures in the cockpit or on

the ground which could not have been foreseen when the specification of the navigation equipment was set up. Such blunder errors would very often cause large deviations from track, which would have an important effect on the collision risk. The MNPS should, therefore, be based on the actual performance. Each operator would have to show, in a special certification process, that his aircraft with his crews could meet the MNPS.

Two more logical steps had to be made before the MNPS and the associated certification procedures could be defined:

- In principle the MNPS should be defined in such a way that the overall performance of all aircraft in the MNPS area remained within specified limits. For the certification procedure it would be necessary to define limits for the performance of specific aircraft operated by specific crews. It was decided that in each certification it should be shown that the MNPS requirements were met. It was agreed that this “extra safety” was a welcome bonus.
- Even if all aircraft/crew combinations have been certified before they start operations in the MNPS area, there is a possibility that their performance may deteriorate with time. Such a deterioration in performance had actually been observed in the North Atlantic some time before. Moreover, not all aircraft and all crews could be certified. It was, therefore, decided that radar monitoring of the actual performance of the aircraft would be essential, at least for a very long time after the MNPS operation had started. Actually, it was found during the first years of the MNPS operation that an unexpectedly large percentage of flights showed large errors. The results of the monitoring, together with information supplied by the operators on what actually occurred in each case, have provided a basis for improving incorrect procedures. The results of those investigations have been widely distributed to operators and this has significantly reduced the number of large deviations.

At first sight the task to define the MNPS may seem to be simple: just specify a limit distribution for the deviations from track. There were, however, a few good reasons why this would not be satisfactory. The most important of those are:

- Different aircraft may have different types of distribution which, by themselves, might meet the collision risk requirement. One might have a wide centre part and a very low tail, another might have a somewhat thicker tail but, due to the shape of the remaining curve would still be safe. Previous experience had shown that no general shape can be applied to all aircraft.
- Such a limit distribution function would be difficult to work with. Many people with only a vague understanding of statistics might become confused, and what should be done if the actual curve would only slightly surpass the limit curve at a point that was not essential to collision risk?
- The other parameters in the model equation, of which the occupancy is the most important, must be chosen in such a way that they will be valid for a considerable time after the MNPS is implemented. For the NAT MNPS a period of 10 years has been chosen. These other parameters must also be monitored in order to verify that the predictions used in the calculation remain valid.

Further investigation of the collision risk caused by different curve shapes that were likely to occur showed that it would be sufficient to specify two criteria: the limit probability that the half—separation is exceeded and the limit probability density at the full separation value. As a third criterion the standard deviation of all lateral deviations was added as a general quality guarantee. The derivation of the MNPS criteria is described in detail in (Colomosa, 1982). The final criteria for the NAT MNPS are:

- the standard deviation of the lateral track errors shall be less than 6.3 NM;
- the proportion of the total flight time spent by aircraft 30 NM or more off the cleared track shall be less than 5.3×10^{-4} ;
- the proportion of the total flight time spent by aircraft between 50 and 70 NM off the cleared track shall be less than 1.3×10^{-4} .

It will be clear that a full certification test which proves that the aircraft meet those requirements is a practical impossibility. To prove with high confidence that all three requirements are met would require thousands of test flights. The certification requirements (those of the U.K. and the USA are published in (ICAO European Office, 1979)) require only a relatively limited number of test flights which are mainly used for checking the standard deviation criterion. This is usually supplemented by a qualitative check for ergonomic errors in the cockpit equipment and the cockpit procedures are checked both in the flight manuals and by check pilots who fly in the cockpits on occasional flights.

As already stated above, the detailed analysis of the results of the radar monitoring has resulted in a significant decrease in the frequency of some types of error. The NAT/SPG receives a complete review of all information obtained by radar control stations in Ireland, Canada, the USA, Portugal, France, the UK and Iceland every 3 months and uses that information to improve procedures both in the cockpits and on the ground.

3.6 Conclusion

The statistical methods described in this paper belong to a special branch of the science of statistics: the statistics of rare events. In most other branches of statistics, e.g. those of motor accidents, there is a very large sample of accidents that have actually happened and most statistical work is involved with extrapolation and taking into account trends. Mid-air collisions occur extremely rarely: scientists differ of opinion whether an accident of the types considered here has occurred at all or whether there have been a very few. The collision risk must, therefore, be calculated using models which have as inputs parameters which occur much more frequently, e.g. deviations from the nominal track. If the duration and cost of the data collections, by which the data on these parameters must be obtained, are to be kept within reasonable limits even those data have to be extrapolated. The probabilities that must be found are very low: it has been calculated that, with the present traffic in the NAT Region the target level of safety is equivalent to approximately one collision per 100 years.

It must, therefore, be accepted that the statistical confidence of the collision risk values calculated by the model studies reviewed in this paper is not very high. A few of the assumptions which had to be made in the models are not absolutely exact and the data used in them may not be fully representative for the future, and even the present, environment. These limitations have been realized from the beginning by all who took part in the studies and it was tried to achieve safe answers, notwithstanding all these uncertainties, by close observation of the following ground rules:

- All studies have been made in very close co-operation between mathematicians, engineers and flight operations specialists, so that all sides of the problems could be taken into account.
- Every possible effort has been made to be clear about all explicit and implicit assumptions that were necessary, and to verify them to the extent possible.

- In those cases where no clear answers could be found the assumptions have been chosen so that their effect would be on the cautious side. In some cases, interested parties have complained that the approach chosen was “too” cautious, but in the end all have agreed that the cautious approach was the only one that could be taken.

The work has had an important side issue that should be mentioned here. The enthusiastic and detailed work of specialists from many fields with these models and the close analysis of statistical data that has become (and still becomes) available has made possible a much better understanding of the problems of the operation of the aircraft and the ATC systems. This may not have been the main purpose in the beginning, it has in the end also had an important effect in itself on the safety of air traffic.

4 Preliminaries of Aircraft Collision Risk Modelling

4.1 Introduction

This chapter provides some basic notions and elements used in developing and describing the collision risk models in the following chapters. In order to assist in identifying the commonalities and differences between the models, a uniform notation will be used for all models based on vector notation. Appendix A provides the notation as well as some basic mathematical properties as background information. Following this introductory section, the chapter provides the following sections:

- 4.2 Defining aircraft collision risk;
- 4.3 Collision between two aircraft;
- 4.4 Closest point of approach for straight-line aircraft motion;
- 4.5 Overlap probabilities and aircraft navigation and height-keeping deviations;

4.2 Defining aircraft collision risk

A definitive reference on risk in the late 1970's and beyond is W.D. Rowe's book *An anatomy of risk* (Rowe, 1977), see e.g. Gough (1988). Following Rowe, risk associated with an activity or process deals with harmful consequences, if any, of the activity or process. In general, risk is a function of harmful consequences and the probabilities of these occurring. Numerous excellent books on risk have been published since Rowe's one was published in 1977, see e.g. Aven (2012) for a review of historical and recent development trends regarding the concept of risk. The International Standards Organisation (ISO) and the International Electrotechnical Commission (IEC) define risk as a combination of the probability of occurrence of harm and the severity of the harm, where harm is physical injury or damage to the health of people either directly or indirectly as a result of damage to property or the environment (ISO, 1999)¹⁴. In its dealing with safety management, ICAO has limited the definition to aviation: (safety) risk is the predicted probability and severity of the consequences or outcomes of a hazard where a hazard is defined as a condition or an object with the potential to cause or contribute to an aircraft incident or accident (ICAO, 2016b, 2018b).

Returning to Rowe, in general, risk is a function of harmful consequences and the probabilities of these occurring, which can be expressed formally as

$$Risk = f(\text{harmful consequences, probabilities}) \quad (4.1)$$

There are many ways to define the function $f(\text{consequences, probabilities})$ ¹⁵ but the most frequently used one takes it to be linear in the consequences, i.e.

¹⁴ Although recently, the definition has become more vague: the effect of uncertainty on objectives. Where an effect is a deviation from the expected positive and/or negative.

¹⁵ The adjective harmful has been left out of eq. (4.1) and will also be left out in the remainder of this chapter unless it is critical to maintain it for a proper understanding.

$$Risk = \sum_i C_i \times p_i \quad (4.2)$$

for a discrete (finite or countable) set of consequences C_i with probabilities p_i or

$$Risk = \int C(x) p(x) dx \quad (4.3)$$

for a continuous set of consequences $C(x)$ labelled by the variable x with associated probabilities $p(x)dx$.

For a flight of a given aircraft, measures of the consequences of a collision with another aircraft due to the loss of separation in the applicable dimension could be the numbers of people killed or injured. The corresponding probabilities would be made up of two parts, namely the probability of the aircraft colliding against the other aircraft, and the probabilities of dying or getting injured as a result of the collision. In principle, the latter probabilities would depend, broadly speaking, on the characteristics of the collision dynamics and geometry and on the (structural) design/integrity of the aircraft, and would be difficult to quantify. For this reason, as well as for a few more reasons, e.g. collisions between small(er) and/or larg(er) aircraft, the ICAO RGCSP decided at the time, early 1970s, ((ICAO, 1976a) Section 1 3.4 and Section 7 (Parker, 1996)) to consider as the consequence of a collision between two aircraft due to the loss of separation the full loss of both the aircraft, i.e. the loss of two aircraft hulls. In addition, the probability of this happening, given the occurrence of a collision, was taken as 1 (one). Following this, the RGCSP was left with the problem of determining the probability of a collision occurring between two given aircraft as a result of the loss of separation in the applicable dimension. Statistically, this problem is known as a Bernoulli trial, i.e. a collision between two given aircraft may occur with probability p and may not occur with probability $1 - p$ where $p \ll 1$.

The model can be refined by considering the probability of a collision occurring during the first, second, third, or fourth part of one of the given aircraft's flight and, more generally, during any time interval $[t, t + \Delta t]$ of its flight. As will be seen in Chapters 5 and 6, this time-dependency is not modelled for lateral separation between parallel routes and vertical separation between adjacent flight levels. It is, however, accounted for in the general collision risk model based on reliability theory (Anderson, 2003a, 2005) for longitudinal separation between in-trail aircraft or aircraft on intersecting routes, Chapter 7, and lateral separation for aircraft on intersecting tracks, Section 5.4.2.4.

It is quite possible that the given aircraft under consideration passes more than one other aircraft during its flight and hence to ask after the probability of the given aircraft colliding during its flight against any of these other aircraft. Denoting the number of other aircraft passed N and assuming that the probability of colliding against any of the other aircraft (given that a collision has not yet occurred before) is the same, say p , the binomial distribution model with parameters N and p comes to mind. The expected number of collisions for the given aircraft during its flight then amounts $N \cdot p$. This model, however, is only correct in an approximating sense in that it does not account for the fact that the given aircraft can collide against another aircraft at most once during its flight. This reality can be modelled as follows.

Let C denote the event where the given aircraft collides against another aircraft during its flight, then the probability that this event occurs is given by

$$\begin{aligned} Pr(C) &= p + (1-p)p + (1-p)^2p + (1-p)^3p + \dots + (1-p)^{N-1}p \\ &= p\{1 + (1-p) + (1-p)^2 + (1-p)^3 + \dots + (1-p)^{N-1}\} \end{aligned} \quad (4.4)$$

The expression in brackets is the sum of a geometric sequence with the first term equal to one and quotient (ratio) $1-p$. It thus follows that

$$Pr(C) = p \cdot \frac{1 \cdot (1 - (1-p)^N)}{1 - (1-p)} = 1 - (1-p)^N \quad (4.5)$$

For $p \ll 1$, the right side of eq. (4.5) can be approximated by $1 - \binom{N}{1} \cdot p = 1 - N \cdot p$. Hence,

$$Pr(C) \approx 1 - (1 - N \cdot p) = N \cdot p \quad (4.6)$$

The importance of eq. (4.6) is that it shows that for a collision probability $p \ll 1$, the expected number of collisions based on a binomial distribution with parameters N and p provides a very good approximation to the exact probability of collision for the given aircraft during its flight when it passes N other aircraft. Notice that the approximation based on the expected number of collisions includes the probability of more than one collision occurring, although that probability is very small when $p \ll 1$. Modelling aircraft collision risk comes essentially down to estimating the parameters N and p .

From an ATM system perspective, the risk of a collision over all aircraft pairs, say M , operating in an airspace is of interest. The analysis above for N aircraft pairs involving a given aircraft can be extended to all aircraft pairs and aircraft collision risk modelling comes down to estimating the parameters M and p . Clearly, the number of aircraft pairs M operating in an airspace is dependent on the period of calendar time over which the operations take place.

Thus, Reich (1966a) defined aircraft collision risk as the expected number of collisions over a specified time period $[t_0, t_1]$. The introduction of a specific time period into the definition of aircraft collision risk allows calculating various collision “rates”, e.g. expected number of collisions per calendar year, per flight hour or per nautical mile flown during the specific time period. This element was included in the ICAO RGCSF definition of aircraft collision risk due to the loss of separation in the applicable dimension, namely as the expected number of fatal accidents per flight hour where **two** fatal accidents are to be counted per collision (ICAO, 1976a).

The following section proceeds with making precise the notion of a collision between two aircraft.

4.3 Collision between two aircraft

Obviously, a collision between two aircraft can only occur when their bodies overlap in all three dimensions simultaneously at some point in time. Collisions due to the loss of separation are caused by very rare navigation or height-keeping deviations with very large magnitudes. For modelling purposes, the complex real aircraft bodies are represented by simpler bodies enveloping the real bodies, e.g. rectangular blocks (shoeboxes) of dimensions $(\lambda_x, \lambda_y, \lambda_z)$ representing aircraft length, width and height, or standing (circular) cylinders (hockey pucks) with diameter λ_{xy} and height λ_z where λ_{xy} is commonly taken as the larger of aircraft length and width, see Figure 4.1. Aircraft dimensions are usually taken as those of a typical or average aircraft operating in the airspace under consideration as flight-hour weighted averages and aircraft collisions are modelled as collisions between two typical or average aircraft. The box model is more convenient for aircraft operating on parallel routes, at adjacent flight levels, or in trail on the same route whereas the cylinder model is more convenient for aircraft operating on intersecting routes. An important assumption about the aircraft box models is that their sides remain parallel to the original flight direction during an aircraft's deviation from the assigned route or flight level¹⁶. Similarly, it is assumed that a cylindrical aircraft model does not tilt during the aircraft's deviation from the original route or flight level.

In the lateral collision risk model originally developed by Reich (1966a) for the risk due to the loss of lateral separation on parallel routes in the NAT Region, the aircraft were represented by boxes. In the longitudinal collision risk model for aircraft on intersecting routes as documented e.g. in Appendix 1 to ICAO Doc 9689 (ICAO, 1998c), the aircraft were represented by cylinders.

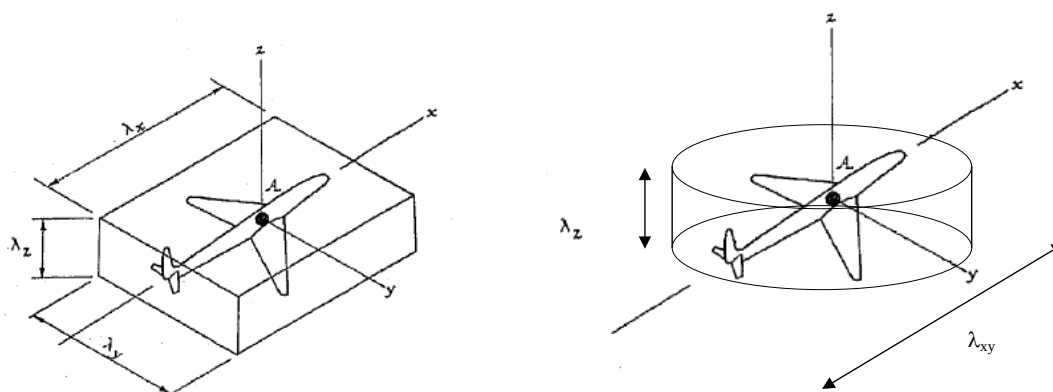


Figure 4.1: A box and cylinder enveloping a real aircraft

Thus, a collision between two aircraft is modelled as overlap between their boxes (or cylinders) at some point in time. A collision between two aircraft boxes can occur in three ways, namely the boxes colliding head-tail (or head-head dependent on the aircraft's flight directions), sideways, or from above/below. These three possibilities correspond to the aircraft entering into longitudinal overlap given that they are already in lateral and vertical overlap, the aircraft entering into lateral overlap given they are already in longitudinal and vertical overlap, and the aircraft entering into vertical overlap given they are already in longitudinal and lateral overlap (Flax, 2000; Reich, 1966a). Similarly, when the lateral and longitudinal dimensions are combined into a single horizontal dimension, a collision between two aircraft cylinders can occur in two ways,

¹⁶ To the best of the authors' knowledge, there is only one model that accounts for a change in aircraft attitude during a deviation. This concerns a model for vertical collision risk for an aircraft in rapid descent e.g. during pressurization failure. See model 2 in *Risk Assessment and System Monitoring for the Verification and Operation of a 300 m (1000 ft) Vertical Separation Minimum in the Minimum Navigation Performance Specifications Airspace of the North Atlantic Region*, Supplement to NAT Doc 002, Draft Version 2.0, 12th March 1996, prepared by the NAT SPG Mathematicians' Working Group. See Section 6.4.3.2.

namely sideways with the cylinder jackets colliding whilst the cylinders are already in vertical overlap and from above/below whilst the cylinders are already in horizontal overlap. For all cases, the modelling is greatly simplified by the assumption that the aircraft models keep their original orientation.

As will be seen in the subsequent chapters of this document, modelling of the mechanism described in the previous paragraph can be approached from different points of view but will result ultimately in the same model for the same operational scenario and set of modelling assumptions. Probabilities of overlap in one or more dimensions are generally defined in terms of proportions of flight time during which overlap in the dimension(s) concerned exists. The approach followed by Reich (1966a) is to start off from the three ways in which a collision can occur. Another approach would be to start off with the probability, over all aircraft operating in an airspace over a given period of time, of aircraft being in three-dimensional overlap and dividing this by the average duration of a three-dimensional overlap to obtain the number of three-dimensional overlaps, i.e. collisions, per flight hour.

A third approach, also utilized by Reich (1966a), is to utilize the mathematical equivalence of overlap between two boxes of dimensions $(\lambda_x, \lambda_y, \lambda_z)$ on the one hand and overlap between a point (or particle) and a box of doubled dimensions $(2\lambda_x, 2\lambda_y, 2\lambda_z)$ on the other, cf. Figure 4.2, 3D view, and Figure 4.3 for a 2D view. Considering the relative motion of one aircraft with reference to the other, the collision process may be looked at as the particle entering a particular face of the box with dimensions $(2\lambda_x, 2\lambda_y, 2\lambda_z)$. Similarly, the overlap of two cylinders of dimensions $(\lambda_{xy}, \lambda_z)$ is mathematically equivalent to the overlap between a point (or particle) and a cylinder with diameter $2\lambda_{xy}$ and height $2\lambda_z$ and the collision process may be looked at as the particle entering either the jacket or the top or bottom of the cylinder. This process is referred to in some papers as *incrossing* process and will be discussed in more detail in Chapters 8 and 9.

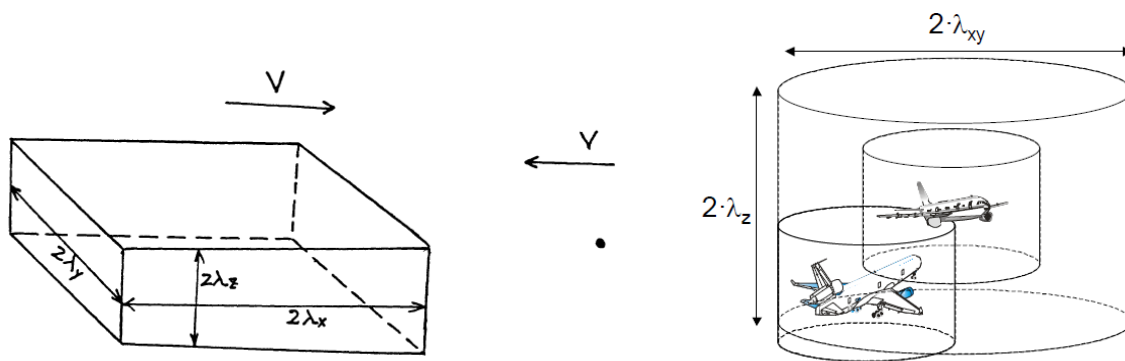


Figure 4.2: Overlap between boxes or cylinders versus overlap between a point (particle) and a double-sized box or cylinder – 3D view

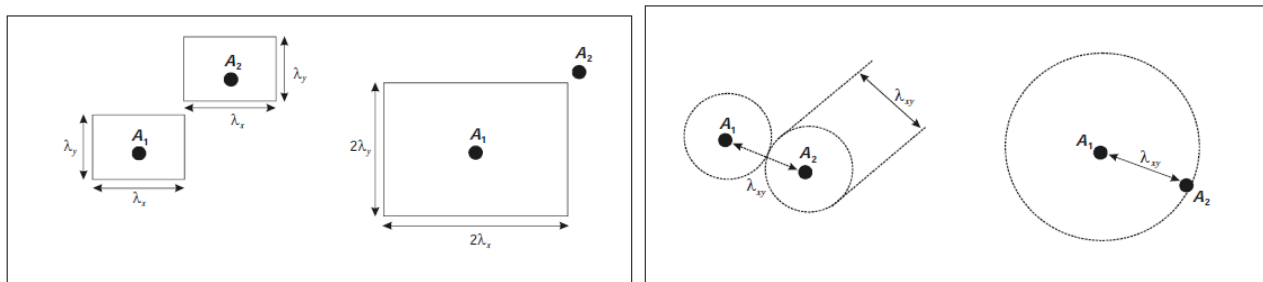


Figure 4-3: Overlap between two rectangles or circles versus overlap between a point (particle) and a double-sized square or circle – 2D view

The mathematical equivalence claimed in the previous paragraph can be demonstrated as follows, in combination with the relative motion between the aircraft. Let aircraft A and B have 3-dimensional positions $\mathbf{a}(t) \in \mathbb{R}^3$ and $\mathbf{b}(t) \in \mathbb{R}^3$ at time $t \in [t_0, t_1]$ respectively, where these positions represent the centres of the pertinent aircraft models (boxes or cylinders). Taking aircraft A as the reference aircraft, the distance between the two aircraft is given by $\mathbf{r}(t) = \mathbf{b}(t) - \mathbf{a}(t)$. When the aircraft are represented by boxes, the boxes are in overlap (and hence a collision occurs) if at some time $t^* \in [t_0, t_1]$ $|r_x(t^*)| \leq \lambda_x$, $|r_y(t^*)| \leq \lambda_y$, and $|r_z(t^*)| \leq \lambda_z$. When the aircraft are represented by cylinders, the cylinders are in overlap (and thus a collision occurs) if at some time $t^* \in [t_0, t_1]$.

It is not necessary to restrict the modelling of aircraft to boxes and cylinders. In fact any closed bounded convex volume of space can be used, either or not in combination with the assumption that the orientation of these representations remain unchanged.

When aircraft A and B are represented by (closed bounded convex) volumes V_A and V_B respectively and the aircraft positions are the centres of these volumes, a collision occurs as soon as the volumes V_A and V_B touch. The *collision surface* S_c is the surface centred at $\mathbf{a}(t)$ defined by all points of contact between the two volumes as a result of translating the centre of aircraft B, without any rotation, with respect to (the centre of) aircraft A. A two-dimensional illustration of the collision volume and surface is given in Figure 4.4 below with the first part of aircraft B's translation starting at the right upper corner of aircraft A's volume V_A ¹⁷. Since both aircraft are represented by the same model, the collision surface does not change if A and B are interchanged. The collision surface does not change either when the translation is started and ended at any point on any of the four sides of volume V_A . The collision volume V_c is the volume enclosed by the collision surface S_c , where the latter can be written symbolically as $S_c = \partial V_c$.

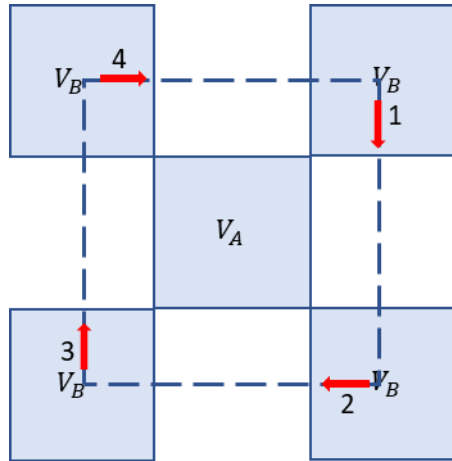


Figure 4.4: Illustration of the collision surface between V_A and V_B . In this diagram, four different positions of V_B relative to V_A are given marking the beginnings of the four sides defining the collision surface when V_B is translated (without rotation) around V_A whilst touching V_A . The collision surface is indicated by the dashed line

¹⁷ Strictly speaking, the collision surface becomes a collision boundary/curve and the collision volume becomes a collision surface for the 2-dimensional case.

If aircraft are represented by a box, then the collision volume is given by $V_c = \{(x, y, z) \in \mathbb{R}^3: |x| \leq \lambda_x, |y| \leq \lambda_y, |z| \leq \lambda_z\}$. For the cylinder representation, the collision volume is given by $V_c = \{(x, y, z) \in \mathbb{R}^3: x^2 + y^2 \leq \lambda_{xy}^2, |z| \leq \lambda_z\}$. Notice that the collision volume and surface do not depend on time $t \in [t_0, t_1]$.

Aircraft A and B collide if there is a time $t^* \in [t_0, t_1]$ such that $\mathbf{r}(t^*) \in V_c$ or equivalently there is a first moment $t^* \in [t_0, t_1]$ such that $\mathbf{r}(t^*) \in S_c$. Taking account of the relative motion between the two aircraft, this can be interpreted as a moving particle entering the stationary volume V_c .

Hence a collision is mathematically equivalent to a moving point (or particle) hitting a stationary box of dimensions $(2\lambda_x, 2\lambda_y, 2\lambda_z)$, see Figure 4.5.

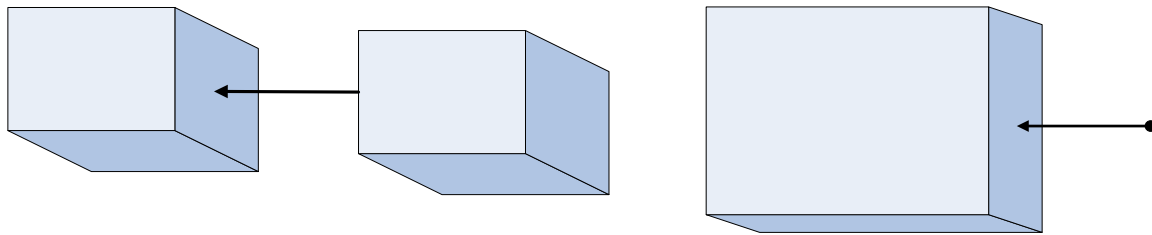


Figure 4.5: Illustration of a head-tail collision: left, collision between two boxes and, right, the mathematically equivalent collision between a particle and a double-sized box

It is finally noted that, for reasons of simplicity, it is assumed that the particle can pass through the collision volume once it has hit the collision surface. Each occurrence of this is considered to be a single collision. This is referred to as a transient boundary crossing. Bakker and Blom ((Bakker & Blom, 1993a, 1993b; Blom & Bakker, 2002) have investigated the relaxation of this assumption, leading to the notion of an absorbing boundary crossing. See Section 9.

4.4 Closest point of approach for straight-line aircraft motion

When two aircraft modelled as points pass each other on adjacent parallel routes and nominally follow their assigned routes, the minimum nominal separation between them equals the lateral separation standard/minimum. Similarly, when such aircraft pass each other at adjacent flight levels, following their assigned flight levels, the minimum nominal separation between them equals the vertical separation standard/minimum. For two point-model aircraft nominally following one of a pair of intersecting routes, the closest point of approach (CPA) during their passing of the intersection can be determined, i.e. the position at which the nominal separation between the aircraft reaches a minimum. For each of the three cases, the actual minimum separation will be affected by the probability distributions of the aircraft navigation and height-keeping errors, see Section 4.5.

One of the usage possibilities of the CPA concerns the calculation of the probability of horizontal overlap for aircraft at adjacent flight levels as a part of the vertical collision risk model. See Chapter 6.

The CPA can be determined as follows for two aircraft flying with a constant (aircraft dependent) speed along a pair of routes intersecting at an angle θ as sketched in Figure 4.6. Consider the aircraft locations as a function of time t , i.e. for the first aircraft $\mathbf{a}(t) = \mathbf{a}_0 + \mathbf{u}t$ and for the second aircraft $\mathbf{b}(t) = \mathbf{b}_0 + \mathbf{v}t$ where $\mathbf{a}_0$ and $\mathbf{b}_0$ are the positions of the respective aircraft at $t = 0$. So the distance between the two aircraft at time t is $d(t) = |\mathbf{b}(t) - \mathbf{a}(t)| = |\mathbf{w}(t)|$ with $\mathbf{w}(t) = \mathbf{w}_0 + (\mathbf{v} - \mathbf{u})t$ and $\mathbf{w}_0 = \mathbf{b}_0 - \mathbf{a}_0$.

Now, since $d(t)$ is a minimum when $D(t) = d(t)^2$ is a minimum, the latter is calculated without any square roots as :

$$D(t) = \mathbf{w}(t) \cdot \mathbf{w}(t) = (\mathbf{v} - \mathbf{u}) \cdot (\mathbf{v} - \mathbf{u})t^2 + 2\mathbf{w}_0(\mathbf{v} - \mathbf{u})t + \mathbf{w}_0 \cdot \mathbf{w}_0 \quad (4.7)$$

It takes a minimum value when

$$0 = \frac{d}{dt}D(t) = 2t[(\mathbf{v} - \mathbf{u}) \cdot (\mathbf{v} - \mathbf{u})] + 2\mathbf{w}_0 \cdot (\mathbf{v} - \mathbf{u}) \quad (4.8)$$

which can be solved for the time t_{CPA} of CPA as

$$t_{CPA} = -\frac{\mathbf{w}_0(\mathbf{v} - \mathbf{u})}{|\mathbf{v} - \mathbf{u}|^2} \quad (4.9)$$

Substitution of t_{CPA} into $d(t) = |\mathbf{b}(t) - \mathbf{a}(t)| = |\mathbf{w}(t)|$ gives the minimum distance at CPA as

$$d_{min} = d(t_{CPA}) = |\mathbf{w}(t_{CPA})| = \left| \mathbf{w}_0 - (\mathbf{v} - \mathbf{u}) \frac{\mathbf{w}_0(\mathbf{v} - \mathbf{u})}{|\mathbf{v} - \mathbf{u}|^2} \right| \quad (4.10)$$

Substitution of t_{CPA} into $\mathbf{a}(t) = \mathbf{a}_0 + \mathbf{u}t$ gives the closest point of approach as

$$\mathbf{a}_0 + \mathbf{u} \times t_{CPA} = \mathbf{a}_0 - \mathbf{u} \times \frac{\mathbf{w}_0(\mathbf{v} - \mathbf{u})}{|\mathbf{v} - \mathbf{u}|^2} \quad (4.11)$$

Finally, the relative speed between the aircraft is given by

$$V_{rel}(\theta) = \bar{V}\sqrt{2(1 - \cos\theta)} \quad (4.12)$$

Since the aircraft have been assumed to be flying at a constant speed, the relative speed between the aircraft is constant too.

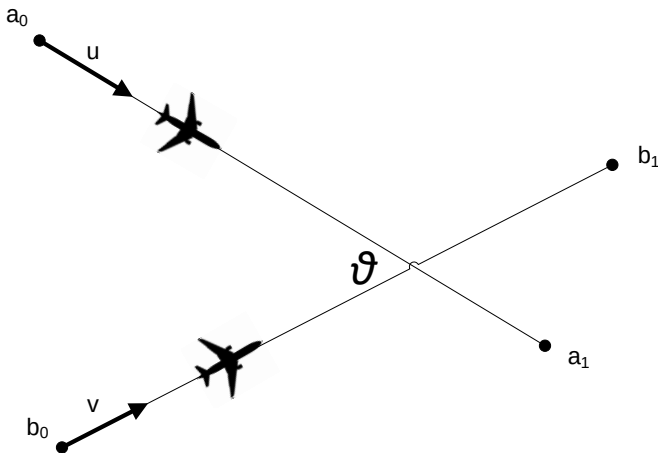


Figure 4.6: Geometry for the closest point of approach (CPA) computation of two aircraft on routes intersecting at an angle θ

4.5 Overlap probabilities and aircraft navigation and height-keeping deviations

As set out in Chapter 1, *Introduction*, aircraft collision risk modelling takes account of the communication, navigation, and surveillance means available in the airspace under consideration. The sources of aircraft collision risk are navigation and height-keeping deviations, i.e. deviations from an aircraft's intended flight path. These deviations are often subdivided into typical deviations and atypical deviations. Typical deviations are those resulting from the normal day-to-day technical performance of navigation systems. Atypical deviations are (relatively) rare deviations resulting from e.g. navigation or height-keeping system failure or degradation, or from operational error. Before considering possible choices for the probability distributions of the navigation and height-keeping deviations, an illustration of a typical overlap calculation will be given, viz. that of the probability of lateral overlap for aircraft operating on parallel routes spaced at the lateral separation standard/minimum S_y . Figure 4.7 shows the spacing between two parallel routes and the lateral deviations y_A and y_B from the assigned routes of aircraft A and B.

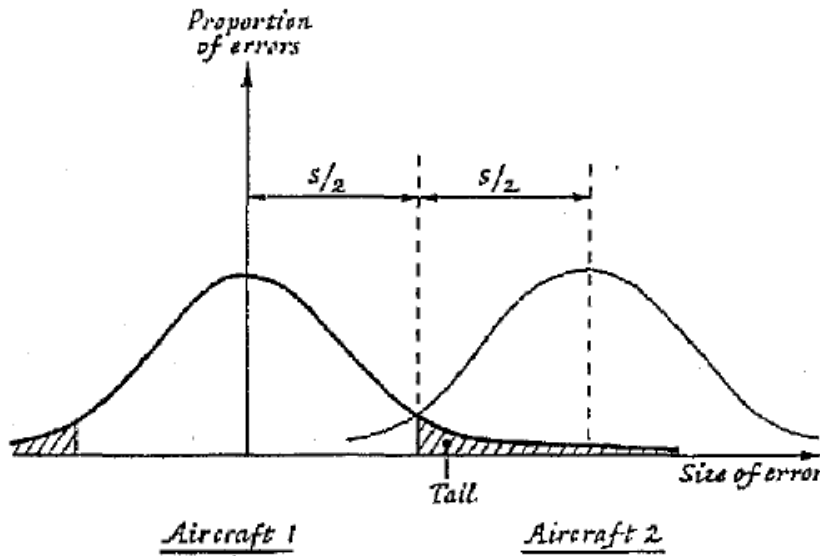


Figure 4.7: Lateral deviations from assigned parallel routes

Denote the probability density functions of the lateral deviations y_A and y_B as $f_A(y)$ and $f_B(y)$ respectively and define the lateral separation between the aircraft based on the separation standard/minimum and the lateral deviations of the aircraft as

$$d_y = S_y - y_A + y_B \quad (4.13)$$

The probability density function of d_y is then given by

$$f_{d_y}(d_y) = \int_{-\infty}^{\infty} f_A(y_A) f_B(y_A - S_y + d_y) dy_A \quad (4.14)$$

and the probability of lateral overlap $P_y(S_y)$ is given by

$$P_y(S_y) = \int_{-\lambda_y}^{\lambda_y} f_{dy}(d_y) dd_y = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f_A(y_A) f_B(y_A - S_y + d_y) dy_A dd_y \quad (4.15)$$

Dependent on the application, it may be possible to approximate eq. (4.15) by

$$P_y(S_y) \approx 2\lambda_y f_{dy}(0) = 2\lambda_y \int_{-\infty}^{\infty} f_A(y_A) f_B(y_A - S_y) dy_A \quad (4.16)$$

If the aircraft A and B operating on the respective routes comply with the same (performance-based) navigation specification, the lateral deviation probability densities $f_A(y)$ and $f_B(y)$ can be taken the same as $f(y)$ say, and the probability of lateral overlap $P_y(S_y)$ simplifies to

$$P_y(S_y) = \int_{-\lambda_y}^{\lambda_y} f_{dy}(d_y) dd_y = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f(y) f(y - S_y + d_y) dy dd_y \quad (4.17)$$

Equations (4.13) – (4.17) can easily be adapted for the probability of vertical overlap for aircraft at adjacent flight levels separated by the vertical separation standard/minimum S_z by replacing all subscripts “y” in these formulae by the subscript “z”, e.g.

$$P_z(S_z) = \int_{-\lambda_z}^{\lambda_z} f_{dz}(d_z) dd_z = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f_A(z_A) f_B(z_A - S_z + d_z) dz_A dd_z \quad (4.18)$$

It remains to specify the type and parameter values of the probability distributions of the navigation and height-keeping deviations. As will be seen in the following chapters, the double double exponential (DDE) distribution has been utilized a lot in the collision risk modelling work performed under the auspices of the ICAO RGCSF and SASP. A DDE probability distribution is a mixture of two double exponential (DE) probability distributions where one component is used to model typical navigation or height-keeping performance and the other to model atypical navigation or height-keeping performance. The component distributions are often referred to as the core distribution (typical performance) and the tail distribution (atypical performance) within the mixture. Accordingly, the scale parameter of the tail distribution will be (much) larger than that of the core distribution. An advantage of the double exponential distribution over the Gaussian or normal distribution is that it has a fatter tail, which is particularly important to account for uncertainty about the occurrence probability of rare but large deviations. See also Section 3. *Probability distribution of the flying errors* of Part II of Reich (1966b). In that section, under bullet (iii) in paragraph (f) *Alternative assumptions on tail shape*, reference is made to some observational data on path-keeping errors where the frequencies of the larger errors decayed at an exponential rate. In no cases a decay rate in the tails faster than exponential, such as would be given, for instance, by a Gaussian distribution, was observed. Paragraph (g) of the same section suggests that probabilities of overlap have been computed for a DDE probability distribution where the DE shape of the core distribution was based on experience with observational data.

A useful discussion of probability distribution models for navigational position errors is given by Hsu (Hsu, 1979b, 1979a, 1980, 1981). (Hsu, 1979b) references a number of papers documenting earlier work on this subject, including that by Burgerhout (Burgerhout, 1973) and then concentrates on the double exponential and Student's t distributions. (Hsu, 1979a) provides a summary of (Hsu, 1979b) and also suggests that the family of exponential power distributions holds promise for navigational position error modelling. This family of probability distributions is also known as the family of generalized Laplace distributions, the probability densities of which will be given below. (Hsu, 1980) examines a total of five probability distribution models, namely: double exponential, double double exponential, Student's t, double Student's t, and normal. Finally, (Hsu, 1981) proposes a collision risk model for aircraft on intersecting routes and uses both the normal and double double exponential models to illustrate the estimation of the model's key parameter, i.e. the overlap density function in the horizontal directions.

Double exponential distribution

The double exponential probability density with mean value μ and scale parameter a is given by

$$f_{DE}(x) = \frac{1}{2a} \exp\left(-\left|\frac{x-\mu}{a}\right|\right) \quad (4.19)$$

Normal (or Gaussian) distribution

The normal probability density with mean value μ and scale parameter a is given by

$$f_N(x) = \frac{1}{a\Gamma(1/2)} \exp\left(-\left(\frac{x-\mu}{a}\right)^2\right) \quad (4.20)$$

where

$$\Gamma(1/2) = \sqrt{\pi} \quad (4.21)$$

The two probability densities can also be expressed in terms of the standard deviation of the underlying random variable where it holds that

$$\text{Double exponential distribution : } a = \sigma/\sqrt{2} \quad (4.22)$$

$$\text{Normal distribution: } a = \sigma\sqrt{2} \quad (4.23)$$

and thus

$$f_{DE}(x) = \frac{1}{\sigma\sqrt{2}} \exp\left(-\left|\frac{(x-\mu)\sqrt{2}}{\sigma}\right|\right) \quad (4.24)$$

$$f_N(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right) \quad (4.25)$$

DDE mixture distribution

A DDE mixture distribution is a weighted sum of two double exponential distributions and can be expressed as:

$$f_{DDE}(x) = (1-\alpha) \frac{1}{2a_1} \exp\left(-\left|\frac{x-\mu}{a_1}\right|\right) + \alpha \frac{1}{2a_2} \exp\left(-\left|\frac{x-\mu}{a_2}\right|\right) \quad (4.26)$$

Generalized Laplace distributions

It is remarked that the double exponential or first Laplace probability distribution as well as the normal probability distribution are both members of the family of generalized Laplace (GL) distributions with the GL probability density function given by

$$f_{GL}(x) = \frac{1}{2ab\Gamma(b)} \exp\left(-\left|\frac{x-\mu}{a}\right|^{\frac{1}{b}}\right) \quad (4.27)$$

where the function $\Gamma(b)$ denotes the gamma function of the shape parameter b of the GL distribution,

$$\Gamma(b) = \int_0^{\infty} t^{b-1} e^{-t} dt \quad (4.28)$$

The generalised Laplace probability density reduces to a normal probability density when the shape parameter $b = \frac{1}{2}$, and it reduces to a double exponential probability density when the shape parameter $b = 1$. The shape parameter $b = 1$ of the double exponential probability density marks the boundary between exponential forms that are concave or convex on a logarithmic scale.

Generalized Laplace distributions have hardly been used in lateral collision risk modelling for parallel routes. They have been used extensively, however, by the European RMA, EUR RMA, for the modelling of altimetry system error (ASE) as a part of vertical collision risk modelling for RVSM airspace (EUROCONTROL, 2001).

Finally, the **generalized Laplace double exponential (GLDE)** mixture distribution with probability density

$$f_{GLDE}(z) = (1 - \alpha) \frac{1}{2a_1b_1\Gamma(b_1)} \exp\left(-\left|\frac{z-\mu}{a_1}\right|^{\frac{1}{b_1}}\right) + \alpha \frac{1}{2a_2} \exp\left(-\left|\frac{z-\mu}{a_2}\right|\right) \quad (4.29)$$

was used to model the ASE distribution.

Figure 4.8 shows a normal, a double exponential, and a double double exponential probability density on a linear scale. The standard deviation of the normal and double exponential probability densities was taken as $\sigma = 2.04$ NM and the mean as $\mu = 0$ NM. The specific parameter values used for the double double exponential density are an overall standard deviation of $\sigma = 2.09$ NM based on $\alpha = 0.001$, $\sigma_1 = 2.04$ NM and $\sigma_2 = 15$ NM. For a normal probability density, the parameter values chosen mean that 95% of the lateral deviations are less than 4 NM in magnitude. For the other two probability densities this percentage is somewhat lower. This corresponds with the fatter tails of these two probability densities compared to the normal probability density.

Figure 4.8 may seem to show only two probability densities, but this is misleading in the sense that for the parameter values chosen the double exponential and the double double exponential probability densities coincide on a linear scale. They become clearly distinguishable for larger deviations on the logarithmic scale of Figure 4.9. The latter figure shows that a normal probability density drops off very quickly (quadratically on a logarithmic scale). On the logarithmic scale of Figure 4.9, the double exponential density drops off linearly. For the particular parameter values chosen, the double double exponential density drops off initially in the same manner as the (single) double exponential density but ultimately drops off at a much slower (linear) rate with a transition in between.

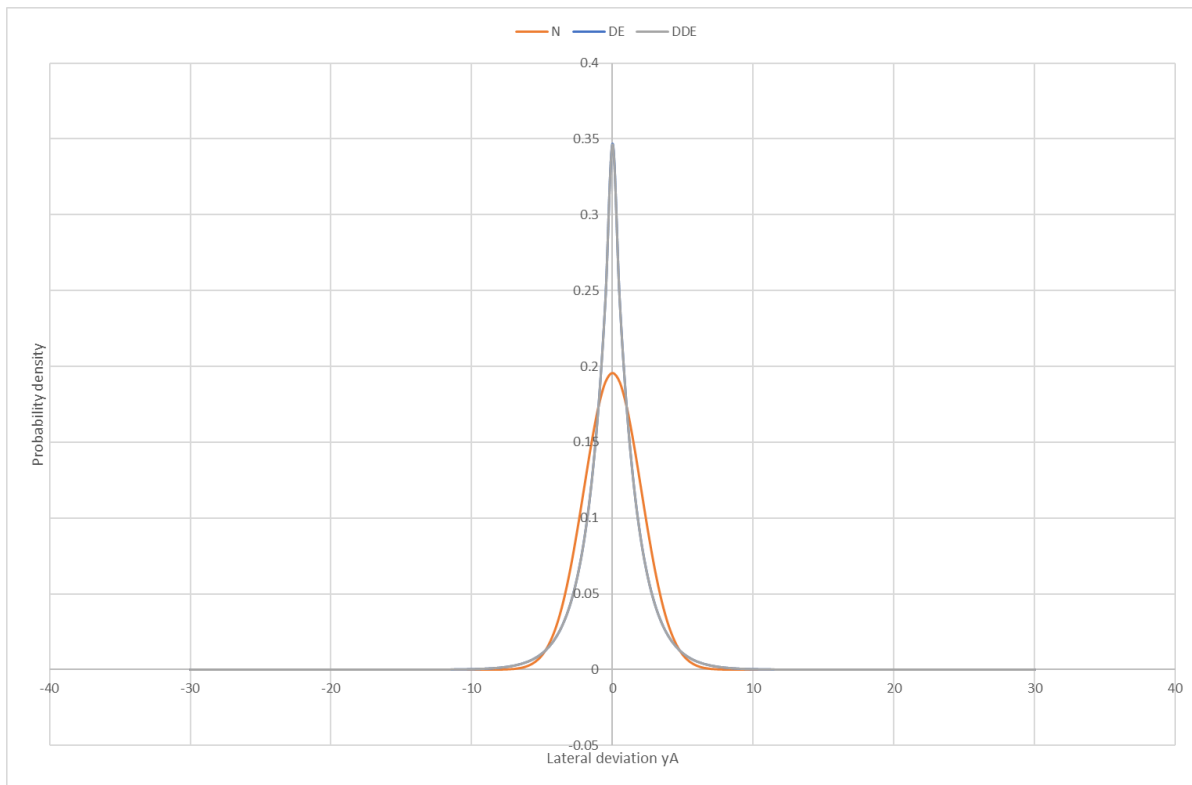


Figure 4.8: Illustration of a normal, a double exponential and a double double exponential probability density on a linear scale

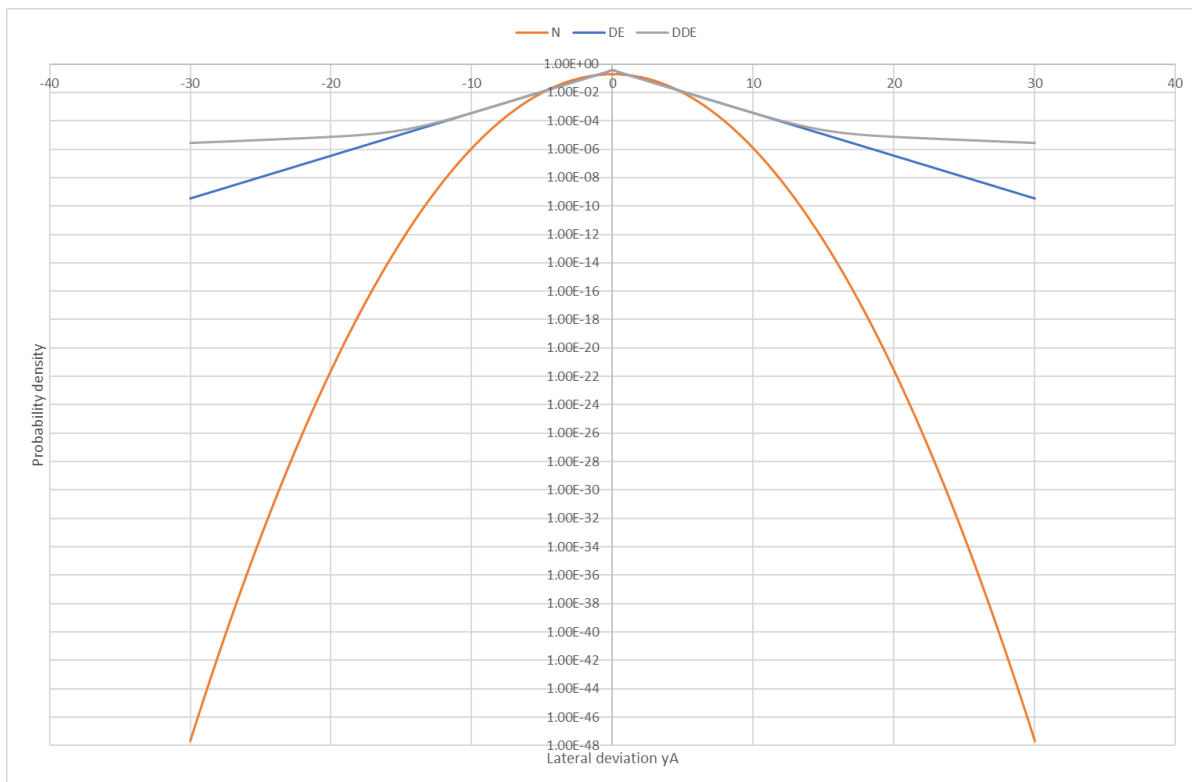


Figure 4.9: Illustration of a normal, a double exponential and a double double exponential probability density on a logarithmic scale

It is worthwhile to consider the integrand in the right side of the probability density $f_{dy}(d_y)$ defined in eq. (4.14) as a function of the lateral deviation y_A of aircraft A for the double exponential and normal distributions as well as for the double-double-exponential mixture-distribution, e.g. for a lateral separation between the aircraft of $d_y = 0$. This will show over the range of y_A the contribution of the lateral deviation y_A of aircraft A to the probability of lateral overlap as a result of the loss of lateral separation between the aircraft. Figures 4.10 – 4.12 are based on the same parameter values used in the previous three figures. In addition a lateral separation standard/minimum of $S_y = 30$ NM has been used.

Figure 4.10 shows the integrand for the normal and double exponential probability densities on a linear scale. The figure shows that for the double exponential probability density the contribution to the probability of lateral overlap as a function of the lateral deviation of aircraft A is constant between two parallel routes spaced at the lateral separation standard/minimum and drops off at both outward sides of the route system. The normal density appears to be constant over the full range, but this is misleading due to the linear scale as will become clear in Figure 4.12. What Figure 4.10 does show, however, is that, regardless of the precise shape of the curve for the normal density case, the contributions as a function of y_A to the probability of lateral overlap are much smaller for the normal probability density than for the double exponential density with the same standard deviation. This is in full agreement with the shapes of the probability densities shown in Figure 4.9 above.

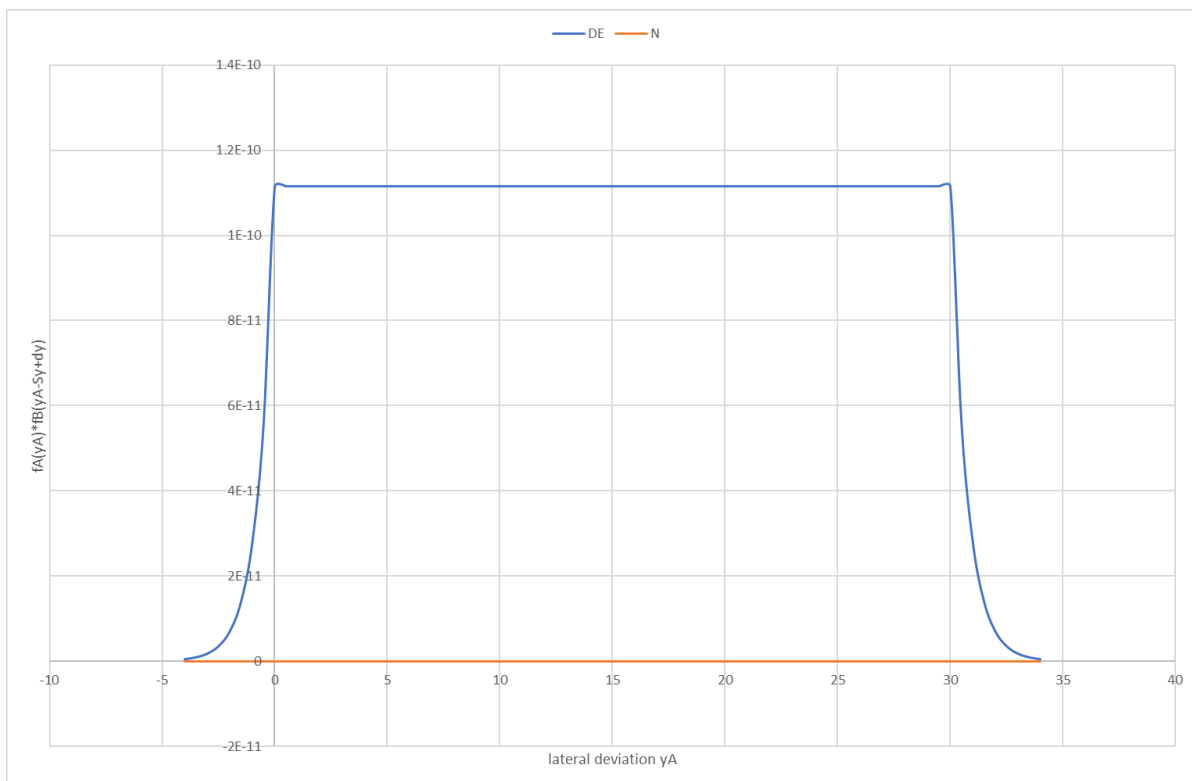


Figure 4.10: The integrand for the normal and double exponential probability densities on a linear scale

Consider now Figure 4.11. This figure, again on a linear scale, differs from Figure 4.10 in that the contributions for a double double exponential probability have been added. The figure shows two features, namely, firstly, that the contributions as a function of y_A to the probability of lateral overlap are much larger for the double double exponential probability density than for the double exponential and normal probability densities with

approximately the same standard deviation, and, secondly, that the contributions as a function of y_A are the largest around the two routes. This latter feature is often referred to as core-tail interaction providing the largest contribution to the probability of lateral overlap. A similar feature holds for a normal double exponential probability density, i.e. a mixture density with a normal core density and a double exponential tail density.

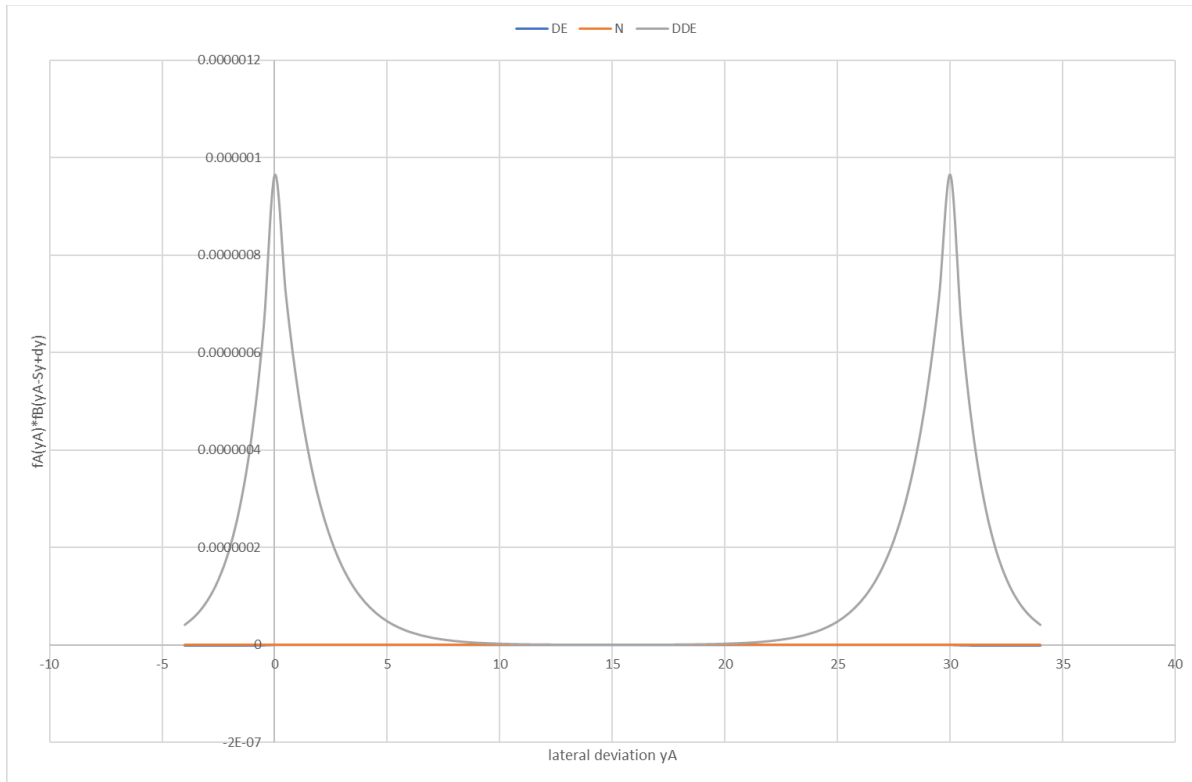


Figure 4.11: The integrand for the normal and double exponential probability densities on a linear scale where the contributions for a double double exponential probability have been added

Finally, consider Figure 4.12, which is on a logarithmic scale. The figure confirms the earlier noted order of the contributions to the probability of lateral overlap as a function of the lateral deviation y_A of aircraft A, with the contribution being the largest for the double double exponential density and the smallest for the normal probability density. It also confirms the shape of the curves representing the contributions for the double double exponential and double exponential densities in Figures 4.10 and 4.11. A new element concerns the shape of the contribution as a function of the lateral deviation y_A of aircraft A for the normal probability density. For the normal probability density, the maximum contribution is seen to be generated by deviations of aircraft A (and B) around half of the lateral separation standard/minimum.

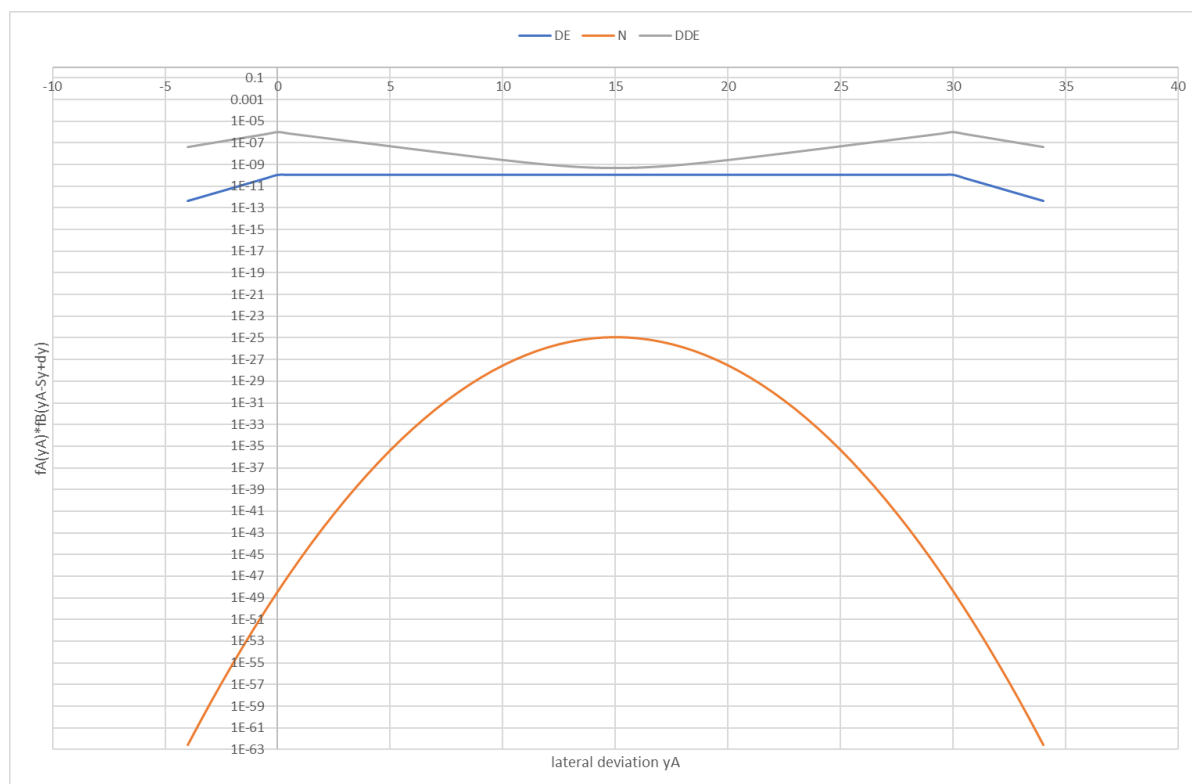


Figure 4.12: The integrand for the normal and double exponential probability densities on a logarithmic scale where the contributions for a double double exponential probability have been added

5 Lateral Collision Risk Modelling

5.1 Introduction

This chapter on lateral collision risk modelling begins in Section 5.2 with the model generally known as the Reich model for the safe spacing between parallel routes in procedural airspace. The Reich model was first applied to examine the feasibility of a safe reduction of the 120 NM lateral separation standard between parallel routes in North Atlantic (NAT) airspace in the mid-1960s (Marks, 1963; Reich, 1966a) and has since then been used in probably all work on the safe spacing of parallel routes in procedural airspace, including, approximately 20 years later, the development of the Minimum Navigation Performance Specification (MNPS) concept for the NAT Region and the subsequent reduction of the lateral separation standard (for aircraft at the same flight level) from 120 NM to 60 NM in NAT MNPS¹⁸ airspace (Brooker, 1979; ICAO, 1992a; White, 1979). This, and a number of other developments such as the use of 60 NM/1000 ft composite separation in the NAT, are described in Section 5.3. The originally regional lateral collision risk model for the NAT was presented to, and endorsed by, the ICAO Review of the General Concept of Separation Panel (RGCSP) for global application at its second meeting in 1973 (ICAO, 1976a, p. 1). Collision risk modelling for the lateral separation standards/minima subsequently developed by the RGCSP and the Separation and Airspace Safety Panel (SASP) will be reviewed in Section 5.4, thus supplementing section 2.5.1 of this document. By 2002, the model had been used as the basis for a number of regional applications other than the NAT, namely Europe, the Canaries, the North Pacific (NOPAC)¹⁹, and the Central East Pacific (CEP)²⁰. The type of model used in the different applications is the same, i.e. the Reich model, but with the parameter estimates being dependent on the characteristics of the airspace under consideration such as aircraft types, navigation performance, traffic flows, etc. All these applications concerned procedural airspace. Following the review of the RGCSP and SASP work for procedural airspace in Section 5.4, Section 5.5 considers route spacing studies based on the Reich model conducted under the auspices of EUROCONTROL and aimed (largely) at application to the safe spacing of parallel routes in Europe's radar-controlled airspace.

5.2 The Reich model for parallel routes in the NAT

According to Pool (1975), Machol (1975, 1995), and Burt (1999), it was Brian Marks of the United Kingdom's Royal Aircraft Establishment (RAE) who developed the first collision risk model in 1963 in the context of oceanic navigation (Marks, 1963). The model was based on computing the probability of proximity and the conditional probability of collision given proximity. Marks's approach was modified and enhanced by his co-worker Peter Reich and presented in several RAE internal memoranda which, after further development, were published as a series of three papers in the (refereed) *Journal of the Institute of Navigation (UK)* in 1966 (Reich, 1966a, 1966b, 1966c).

¹⁸ As of February 4th 2016, NAT MNPS airspace is called NAT High Level Airspace (HLA). This chapter uses the term MNPS airspace for all work prior to that date.

¹⁹ See section 3.1 of Hsu (1979b).

²⁰ See (Burt, 1993a; Busch et al., 1977; ICAO, 1994, 1998a, 2000; Olarte, 1999; Rawlings et al., 1997)

5.2.1 Part I of the Reich paper

A number of observations and assumptions made by Reich in Part I regarding his approach to estimating collision risk have been quoted in Appendix C and the reader is advised to refer to this section before proceeding. The model derived was in terms of a generic intended separation $[AB]$. Part II of the Reich paper deals with the application of the generic model to lateral separation between adjacent parallel routes and vertical separation between adjacent flight levels. The former separation is examined below and the latter one in Chapter 6 of this document.

Reich derived his model in terms of the intended separation $[AB]$ between the intended positions of two aircraft A and B , noting that because of the errors in keeping to speed, track, and height, the true positions of the aircraft are A' and B' and defining the collision risk as the expected number of times, in a given time interval, the actual separation vector $[A'B']$ shrinks to collision size. Both aircraft were given a notionally rectangular collision shape with λ_x , λ_y , and λ_z representing the length, span, and thickness of the aircraft respectively. Aircraft A was subsequently modelled as a double-sized rectangular collision shape, i.e. with dimensions $2\lambda_x$, $2\lambda_y$, and $2\lambda_z$, and aircraft B as a particle and the change in separation due to the combined flying errors of the two aircraft represented by $[BB'']$, with $[BB'']$ denoting the error in the relative position between the aircraft. Using the double-sized box model for aircraft A and the particle model for aircraft B , the collision rate was calculated as the sum of the expected number of times the particle B , with actual position B'' enters the aircraft A slab through the sides, the ends, and the top and bottom.

The frequency C_x with which the particle B'' enters the slab through either end is given by the probability P_{yz} that its y and z coordinates lie within the dimensions λ_y , λ_z of the end faces, multiplied by the frequency N_x with which its x coordinate becomes less than λ_x , i.e.

$$C_x = N_x P_{yz} = N_x P_y P_z \quad (5.1)$$

Notice that the probability of joint overlap in the y and z dimensions has been factored into the product of the probabilities of overlap in the individual dimensions. Similarly, the frequency C_z of entering through the top or bottom is given by

$$C_z = N_z P_{xy} = N_z P_x P_y \quad (5.2)$$

and through either side by

$$C_y = N_y P_{xz} = N_y P_x P_z \quad (5.3)$$

Thus, the collision rate C^{21} for the intended separation $[AB]$ may be written

$$C = N_x P_y P_z + N_y P_x P_z + N_z P_x P_y \quad (5.4)$$

The next, important, step is to re-express the frequencies N_x , N_y , and N_z as

$$N_{x/y/z} = \frac{\text{the proportion of flying time during which there is overlap in the } x/y/z \text{ dimension}}{\text{average duration of the intervals during which there is overlap in the } x/y/z \text{ dimension}} \quad (5.5)$$

In formula,

$$N_x = \frac{P_x}{t_x}, N_y = \frac{P_y}{t_y}, N_z = \frac{P_z}{t_z} \quad (5.6)$$

where

$$t_{x/y/z} = \text{average duration of the intervals during which there is overlap in the } x/y/z \text{ dimension} \quad (5.7)$$

Cf. bullet 21 in Appendix C.

Substitution of eq. (5.6) into eq. (5.4) results in the following equation for the collision rate C for the intended separation $[AB]$:

$$C = P_x P_y P_z \left(\frac{1}{t_x} + \frac{1}{t_y} + \frac{1}{t_z} \right) \quad (5.8)$$

Eq. (5.8) for the collision rate C corresponds with eq. (3) in Part I of the Reich paper (except that the right-hand side quantities in eq. (3) carry an additional subscript $[AB]$ to emphasize that the collision rate applies under the application of the intended separation $[AB]$).

The overlap probabilities P_x , P_y , and P_z have to be estimated from observation of the magnitudes of flying errors. It remains to calculate the average overlap durations t_x , t_y , and t_z , or, actually, the frequencies N_x , N_y , and N_z , featuring in the model of eq. (5.4). This is addressed implicitly only in Part I of the Reich paper under bullet 19 quoted in Appendix C. It is, however, explicitly addressed in Section 2. *Expressions for the collision rate of a pair of aircraft* of Part II of the Reich paper.

²¹ Denoted $C.R.$ in Part II of the Reich paper.

5.2.2 Part II of the Reich paper

Considering Part II of the Reich paper, it is noted in its introductory text that the separations under consideration are not monitored on the ground and that Part II is confined mainly to studying the collision risk to aircraft nominally separated, by a lateral or vertical standard, on parallel flight paths.

Using a subscript r to denote the separation of the aircraft pair in any one of the three dimensions x , y , or z , the following formula (eq. (2)) is provided in Part II of the Reich paper, based on Reich (1964):

$$N_r = 2 \int_0^\infty \dot{r} G(\lambda_r, \dot{r}) d\dot{r} \quad (5.9)$$

In eq. (5.9), $\dot{r}$ denotes the rate of change of r and $G(\lambda_r, \dot{r})$ denotes the joint probability density function $G(r, \dot{r})$ of r and $\dot{r}$ at $r = \lambda_r$. Assuming that $G(r, \dot{r})$ is likely to change only slightly over an interval of twice the collision size λ_r , eq. (5.9) can be approximated by

$$N_r \approx 2 \int_0^\infty \dot{r} G(0, \dot{r}) d\dot{r} \quad (5.10)$$

Part II of the Reich paper then notes that, in practice, it may sometimes be much more difficult to collect sufficient data to estimate the joint probability density function $G(r, \dot{r})$ than to estimate the density function $\phi(r)$, say, of r alone. On the assumption that r and $\dot{r}$ are statistically independent, eq. (5.10) simplifies to²²

$$N_r \approx \overline{|\dot{r}|} \times \phi(0) \quad (5.11)$$

where $\overline{|\dot{r}|}$ is the average value of $|\dot{r}|$. Making one more assumption, viz. that the probability density function $\phi(r)$ of the separation between the aircraft in the r -dimension is constant over an interval of $2\lambda_r$, gives the approximation

$$P_r \approx 2\lambda_r \times \phi(0) \quad (5.12)$$

i.e.

$$\phi(0) \approx \frac{P_r}{2\lambda_r} \quad (5.13)$$

and substitution of eq. (5.13) into eq. (5.11) gives the following relationship between N_r and P_r for each of the three dimensions represented by r ,

$$N_x \approx P_x \times \frac{\overline{|\dot{x}|}}{2\lambda_x} \quad (5.14)$$

$$N_y \approx P_y \times \frac{\overline{|\dot{y}|}}{2\lambda_y} \quad (5.15)$$

$$N_z \approx P_z \times \frac{\overline{|\dot{z}|}}{2\lambda_z} \quad (5.16)$$

²² The simplification, like eq. (5.10), assumes that the probability distribution of $\dot{r}$ is symmetric about 0.

(All derivations above in eqs. (5.9) – (5.16) are conditional on the intended separation [AB].)

Finally, substituting eqs. (5.14) – (5.16) into eq. (5.4) results in eq. (5.17) for the collision rate C for aircraft pair A and B (with intended separation [AB])

$$C = P_x P_y P_z \left(\frac{|\dot{x}|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right) \quad (5.17)$$

Eq. (5.17) depends on a number of approximations of which the one concerning the statistical independence of r and its rate of change $\dot{r}$ is the most critical. This is addressed by Reich in Part II by noting that although there may not be sufficient evidence to say that r and $\dot{r}$ are independent, it will usually be possible to set a plausible upper limit to $|\dot{r}|$ (i.e. to $|\dot{x}|$, $|\dot{y}|$, and $|\dot{z}|$) and hence to make safe use of eqs. (5.14) – (5.16). In this context, Reich also refers to the requirement quoted in Appendix C as requirement (ii).

Getting ahead of Section 4. *Getting practical measures of risk from the collision rate equations*, Section 2 of Part II of the Reich paper concludes with the following form of the model for the collision rate of pairs of aircraft assigned to the same flight level on parallel flight paths separated by the lateral separation standard (and a similar one for pairs of aircraft assigned to adjacent flight levels on the same track):

$$(C.R._y)_{[AB]} = (N_x)_{[AB]} P_y(\text{std}) P_z(0) + (P_x)_{[AB]} \{N_z(0) P_y(\text{std}) + N_y(\text{std}) P_z(0)\} \quad (5.18)$$

where

- $P_y(\text{std})$ is the probability that the across-track separation of a pair of aircraft, nominally spaced at the lateral standard, is less than λ_y ;
- $N_y(\text{std})$ is the expected frequency with which the across-track separation of a pair of aircraft, nominally spaced at the lateral standard, shrinks to less than λ_y ;
- $P_z(0)$ is the probability that the vertical separation of a pair of aircraft, assigned to the same flight level, is less than λ_z ;
- $N_z(0)$ is the expected frequency with which the vertical separation of a pair of aircraft, assigned to the same flight level, shrinks to less than λ_z .

In the right side of eq. (5.18), the suffix [AB] needs to be used only on the N_x and P_x terms, since the other terms are now treated as constants, determined by the lateral separation standard and by the probability distributions of the errors of track-keeping and height-keeping.

Section 3 of Part II of the Reich paper is entitled 3. *Probability distribution of the flying errors* and has been referenced in Section 4.5 of Chapter 4 of this document.

Section 4, 4. *Getting practical measures of risk from the collision rate*, deals with the final step to estimate the expected number of collisions in a traffic region during some (future) period, typically of a year or more and begins with recalling Requirement (iv) from Part I of the Reich paper, which was quoted as Requirement (iv) in Appendix C of this document, viz.

- (iv) The method of estimating should take account of the extent to which each of the three dimensions of space is used in separating aircraft.

The extent, i.e. the time, for which a proximate pair of aircraft is exposed at a given intended separation is termed proximity, see bullet 34 of Appendix C of this document. The reader is advised to take note of the bullets 35 and 36 too. Section 4 of Part II of the Reich paper then proceeds with the following text: *It is not feasible to predict the detailed behaviour of the separation vector $[AB]$ for each pair of aircraft which will become proximate during the period considered²³. However, it is both feasible and sufficient to study the aggregate behaviour of the traffic statistically. The ease with which this can be done depends very much on the configuration of flight paths which will prevail. It is straightforward when fixed numbers of parallel paths are to be used but tedious otherwise. It suffices here to give the theory for a system in which aircraft are assigned to a set of parallel tracks and flight levels, each separated by either the lateral or vertical separation standard. In this case there are three components of risk to take into account, associated with the usage of lateral vertical and (for aircraft on the same track and flight level) longitudinal separation standards. For simplicity, only the first two of these will be dealt with here.*

For this section of the current document, the lateral separation standard is progressed only. Figure 5.1 shows two routes spaced at the lateral separation standard/minimum $S_y(\text{std})$ and two sorts of proximate pairs, namely same direction and opposite direction.

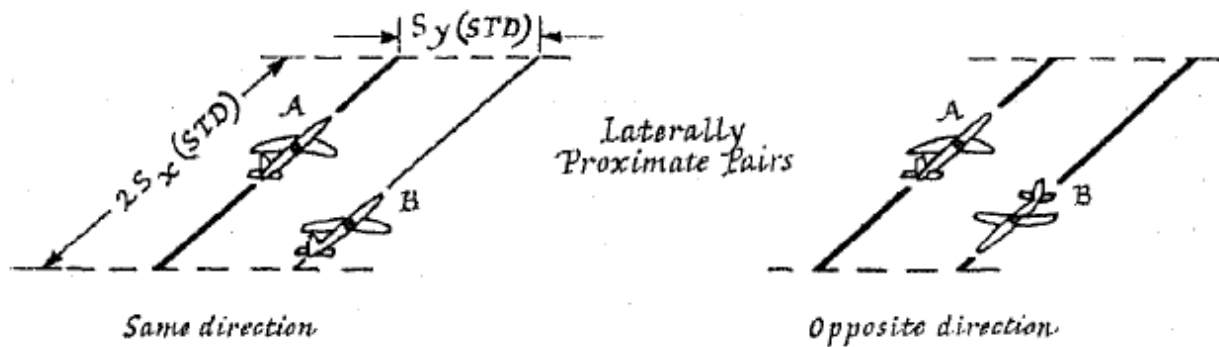


Figure 5-1: Two routes spaced at the lateral separation standard/minimum $S_y(\text{std})$ and two sorts of proximate pairs, namely same direction and opposite direction. (Source Reich (1966b))

The following two (additional) assumptions are then made:

- 1) The along-track positions of aircraft on adjacent flight-paths are independent of one another; and
- 2) The risk to aircraft nominally separated by two or more standard increments of separation is negligible²⁴.

The proximity criterion shown in Figure 5.1 is the longitudinal standard, i.e. a pair of aircraft is counted as proximate only when their nominal along-track separation is less than the longitudinal standard. Associated with Figure 5.1 are two sorts of proximity (i.e. times of exposure):

$$T_y(\text{same}) = \text{aggregate of times spent by all pairs in the configuration of Figure 5.1A} \quad (5.19)$$

$$T_y(\text{opp}) = \text{aggregate of times spent by all pairs in the configuration of Figure 5.1B} \quad (5.20)$$

²³ I.e. $(N_x)_{[AB]}$ and $(P_x)_{[AB]}$ in eq. (5.18).

²⁴ This assumption was dropped in some recent SASP work for the 30/23 NM lateral separation standard to be discussed in Section 5.4.

Before using eqs. (5.19) and (5.20) to calculate the expected number of collisions in a traffic region during some (future) period by means of the collision rate given by eq. (5.18), the statistically aggregate behaviour of the traffic referred to in the latest quote above from Part II of the Reich paper is used to calculate average values of the parameters $(N_x)_{[AB]}$ and $(P_x)_{[AB]}$ in eq. (5.18), viz.

$$\text{average of } (P_x)_{[AB]} = \overline{(P_x)_{[AB]}} \approx \frac{\lambda_x}{S_x(\text{std})} \quad (5.21)$$

$$\text{average of } (N_x)_{[AB]} = \overline{(N_x)_{[AB]}} \approx \frac{|\dot{x}|}{2S_x(\text{std})} \quad (5.22)$$

(cf. eq. (5.14)). Substitution of eqs. (5.21) and (5.22) into eq. (5.18) gives

$$\overline{C.R.y} = \frac{1}{S_x(\text{std})} \left[\frac{|\dot{x}|}{2} P_y(\text{std}) P_z(0) + \lambda_x P_y(\text{std}) N_z(0) + \lambda_x N_y(\text{std}) P_z(0) \right] \quad (5.23)$$

Eq. (5.23) does not yet account for the two different sorts of proximate pairs, i.e. same-direction and opposite-direction proximate pairs, for which the average of the absolute value of the relative along-track speed $|\dot{x}|$ takes two values, namely for opposite-direction traffic

$$|\dot{x}| = 2\bar{V} \quad (5.24)$$

where $\bar{V}$ is the average cruising speed and for same-direction traffic

$$|\dot{x}| = \Delta\bar{V} \quad (5.25)$$

where $\Delta\bar{V}$ represents the average difference of cruising speed in pairs of aircraft.

Multiplication of the average lateral collision rate of eq. (5.23) with the respective proximity times $T_y(\text{same})$ and $T_y(\text{opp})$ and using the corresponding $|\dot{x}|$ from eqs. (5.25) and (5.26) ultimately gives for the lateral collision risk in a traffic region during the period of interest

$$\text{Lateral risk (same)} = \frac{T_y(\text{same})}{S_x(\text{std})} \left[\frac{\Delta\bar{V}}{2} P_y(\text{std}) P_z(0) + \lambda_x P_y(\text{std}) N_z(0) + \lambda_x N_y(\text{std}) P_z(0) \right] \quad (5.26)$$

and

$$\text{Lateral risk (opp)} = \frac{T_y(\text{opp})}{S_x(\text{std})} \left[\bar{V} P_y(\text{std}) P_z(0) + \lambda_x P_y(\text{std}) N_z(0) + \lambda_x N_y(\text{std}) P_z(0) \right] \quad (5.27)$$

Part II of the Reich paper concludes with a method for the computation of the proximities $T_y(\text{same})$ and $T_y(\text{opp})$ in terms of flow rates for a statistically steady system made up of t tracks and f flight levels, or,

actually, dimensionless proximity rates²⁵ (time of exposure per unit time of operation). Cf. *Estimation of Occupancy Values and Variation of Risk with Occupancy* in Appendix C to Chapter 4, *Minimum Navigation Performance Specifications*, of Section 2, *Separation*, of Part II of the Air Traffic Services Planning Manual (ICAO, 1992a).

5.2.3 Part III of the Reich paper

Part III of the Reich paper deals with the application of the techniques developed in Parts I and II, including consideration of the requirements (vi) and (vii) formulated in Part I (and not previously addressed in Part II) and quoted in Appendix C of this document. It is recalled at the start of Part III that in the approach taken to estimating safe separation standards emphasis is laid on the observations of flying errors which occur in operational conditions and that dependence on theoretical assumptions is limited to the extent necessary to make usable ‘upper limit’ estimates of collision risk. Part III is subdivided into the following sections:

1. *Measures of collision risk and the need for a ‘guideline’.*
2. *Estimating the safety of a separation standard from observed navigation errors.*
3. *Specifying the conditions for a separation standard to be ‘safe’.*
4. *Effects of changing traffic control procedures.*
5. *Key assumptions.*

Two elements from Part III are worth discussing here.

Firstly, the ‘guideline’ utilized in Section 1 of Part III of the Reich paper was taken from an earlier UK working paper to the ICAO Special NAT RAN Meeting in 1965 (ICAO, 1965a) and reads as follows:

$$\text{‘guideline’ value of (loss rate)}_{x|y|z} = \frac{1}{3} \times \frac{1}{2} \times 10^{-7} \text{ per flight} \quad (5.28)$$

It should be noted that the loss rate is a fatal accident rate accounting for the loss of two aircraft as a result of a collision. The product $1/2 \times 10^{-7}$ represents the loss rate attributable to ATC which is divided equally over the separation standards in the three dimensions by the factor of $1/3$ up front in the right side of eq. (5.28).

Secondly, lateral collision risk estimates are provided for lateral separation standards of 60 NM and 90 NM based on 2470 observations on eastbound and westbound aircraft taken by radar at a point in mid-ocean and on eastbound traffic taken by coastal radar at landfall. For each standard, both an optimistic and a cautious risk estimate are given based on an exponentially decaying tail and a level (constant) tail respectively. Although important, the choice of tail is stated to be not hypercritical to the example under consideration. Table 5.1 gives the parameter values other than the probability of lateral overlap utilized in the collision risk computations at the time.

²⁵ Dividing the lateral risk estimates in eqs. (5.26) and (5.27) by the total time of operation allows the dimensionless proximity rates to be utilized.

Table 5.1: Parameter values used in Part III of the Reich paper for the lateral collision risk models of eqs. (5.26) and (5.27)

Parameter	Description	Default value
$S_y(\text{std})$	The lateral separation standard/minimum	60 NM, 90 NM
$S_x(\text{std})$	The longitudinal separation standard/minimum	120 NM (15 min)
$P_y(\text{std})$	The probability that the across-track separation of a pair of aircraft, nominally spaced at the lateral standard, is less than λ_y	
$N_y(\text{std})$	The expected frequency with which the across-track separation of a pair of aircraft, nominally spaced at the lateral standard, shrinks to less than λ_y	$\frac{52}{2 \times 0.025} \times P_y(\text{std})$
$P_z(0)$	The probability that the vertical separation of a pair of aircraft, assigned to the same flight level, is less than λ_z ;	0.26
$N_z(0)$	The expected frequency with which the vertical separation of a pair of aircraft, assigned to the same flight level, shrinks to less than λ_z .	40 per hour
λ_x	The length of the aircraft	0.025 NM (152 ft)
λ_y	The span of the aircraft	0.025 NM (152 ft)
$\Delta \bar{V}$	The average difference of cruising speed in pairs of aircraft	12 kts
$\bar{V}$	The average cruising speed	480 kts (2V)
$ \bar{y} $	The average cross-track velocity	52 kts
σ_y	The standard deviation in the lateral direction	12 NM
$T_y(\text{same})$	The aggregate of times spent by all pairs in the configuration of Figure 5.1A	2.46×10^5 hours
$T_y(\text{opp})$	The aggregate of times spent by all pairs in the configuration of Figure 5.1B	5.9×10^3 hours

It was concluded from the computations that if the ‘guideline’ were a firm criterion of safety, and assuming that the observations used are representative, neither standard could be taken to be ‘safe’. One would therefore call for an improvement in navigation before considering either a 60 NM or 90 NM standard. This problem is subsequently addressed in Section 3. *Specifying the conditions for a separation standard to be ‘safe’* of Part III but falls beyond the scope of this document. See, however, the discussion on Minimum Navigation Performance Specifications (MNPS) in section 5.3.

Part III concludes with recalling and commenting the more important assumptions made in the series of three papers:

- The blind-flying assumption;
- Assumption that path-keeping errors of an aircraft in three dimensions are independent;
- Assumption that the path-keeping errors of neighbouring aircraft in the same dimension are independent.

5.3 Further lateral separation developments in the NAT

This section describes a number of developments regarding lateral collision risk modelling for parallel routes in the NAT that occurred over time following the pioneering work by Reich, namely:

- Reduction of the lateral separation standard from 120 NM to 90 NM?;
- 60 NM/1000 ft composite separation;
- 60 NM lateral separation in NAT Minimum Navigation Performance Specification (MNPS) airspace;

- A review of the North Atlantic lateral collision risk model by (Davies & Sharpe, 1993);
- RLatSM, Reduced Lateral Separation Minimum;
- ASEPS, Advanced Separation Enhanced Procedural Separation; and
- Revised NAT Mathematicians Working Group (NAT/MWG) methodology for lateral collision risk assessment.

This is motivated by the fact that the NAT Region has the busiest oceanic airspace in the world and has continually been in the forefront of technological and operational developments. In addition, the Netherlands was actively involved in the MNPS development at the time.

5.3.1 Reduction of the lateral separation standard from 120 NM to 90 NM?

The example application of the Reich collision model discussed in Section 5.2.3 showed that, based on a sample of 2470 observations of lateral flying errors, a 90 NM lateral separation standard for the NAT OTS would not be 'safe'. Recall that the existing lateral separation standard was 120 NM at the time (Pool, 1983).

As set out in Pool (1983), work based on the Reich model was continued by the North Atlantic Systems Planning Group (NAT SPG), established by the Council of ICAO in 1965. In particular, the States participating in the NAT SPG organized a large data collection in the NAT area, which resulted in radar measurements on more than 14000 flights over the period between July 1967 and March 1968. The processed results indicated that a separation standard of 90 NM was not safe and that 120 NM was safe, (see fourth meeting of the NAT SPG (NAT SPG/4). The following nine paragraphs detail this development. See also Machol (1975).

An Explanatory Note at the beginning of the *Summary of Discussions of the Second Meeting of the NAT Systems Planning Group (NAT SPG/2, 1966)*²⁶ recalls that the Special NAT Meeting 1965 (ICAO, 1965b) recommended that for turbo-jet aircraft operating in six Flight Information Regions (FIRs) in the NAT the minimum lateral separation should be reduced from 120 NM to 90 NM and that this recommendation was subsequently approved by the Council of ICAO and became applicable on 13 January 1966. This separation standard had already been a subject of contention by Organizations representing some of the air-crew members, and, following its introduction, ultimately led to a temporarily suspension as a result of a decision by the provider States on 10 June 1966. The 2nd meeting of the NAT SPG (NAT SPG/2), amongst other things, then considered the *Method to be developed in assessing a safe separation standard* (Agenda Item 4) and the *Area for and Programme of data collection and analysis* (Agenda Items 3 and 6). The Group considered it essential to aim at setting a target level of safety from collision for the purpose of mathematical/statistical assessment of future separation standards over the North Atlantic and concluded that:

- 1) The overall target level of safety from collision over the North Atlantic would be to keep the fatal accident rate in the range from 1.1 to 0.44 per 10 million aircraft flying hours or lower;
- 2) The target level of safety for the lateral NAT separation standard should be to keep the fatal accident rate in the range from 0.366 to 0.146 per 10 million aircraft flying hours or lower.

²⁶ See Appendix E.4 for all *Summary of Discussions of the xth Meeting of the NAT Systems Planning Group*. These documents can be obtained from <https://www.icao.int/EURNAT/Pages/EURNAT-Meetings-NATSPG.aspx>.

The Group also accepted the Reich model as the basis for the risk calculations. The form of the model was precisely the same as given in eqs. (5.26) and (5.27) of section 5.2.2 of this document²⁷. (See eqs. (13) – (16) of Appendix B to the *Summary on Agenda Item 4: The method to be adopted in assessing a safe separation standard* in NAT SPG/2)

The Group agreed that the computed risk would depend on the parameter values used and that there was uncertainty about them. Thus, it was decided to treat the collision risk model parameters as random variables with certain probability distributions and to examine the uncertainty effect through a digital/Monte Carlo simulation method (DS method). The following model was used for the simulation:

$$N_a = 2P_y(\text{std}) \left\{ \frac{T_y(\text{same})}{S_x} \left[\frac{\Delta V}{2} P_z(0) + \gamma \Lambda_x N_z(0) + \frac{\Lambda_x |\bar{y}| P_z(0)}{2\lambda_y} \right] + \frac{T_y(\text{opp})}{S_x} \left[\bar{V} P_z(0) + \gamma \Lambda_x N_z(0) + \frac{\Lambda_x |\bar{y}| P_z(0)}{2\lambda_y} \right] \right\} \quad (5.29)$$

where N_a denotes the expected number of aircraft accidents occurring in a given period, due to failure of lateral separation and where a metallic collision is counted as two aircraft, but a fatal vortex penetration is counted as one only. Λ_x is the “effective” collision length of an aircraft after taking account of wing-tip vortices, and replaces λ_x , the metallic length of an aircraft. The coefficient γ allows alternative models of the effective collision shape to be simply represented in the equation as rectangular slabs of constant cross section $\lambda_y \lambda_z$, set by the metallic thickness and span of an aircraft.

γ is unlikely to be substantially greater than unity, the N_z terms are unlikely to make a major contribution to the total risk, and therefore little accuracy will be lost in treating γ as a constant. The quantities $P_z(0)$, S_x , λ_y , $\bar{V}$, and γ can be treated as known constants whereas the remaining eight quantities in eq. (5.29) have either to be estimated more or less imprecisely from limited numbers of observations, or depend to some extent on judgement.

Concerning subjects for further NAT SPG consideration, the Group agreed, amongst other things, that *Vertical separation above FL 290 in specified parts of the NAT Region*, should be placed on the agenda of the Group’s next meeting but that *Longitudinal separation in specified parts of the NAT Region* should be kept pending until a more opportune time.

The *Summary of Discussions of the Third Meeting of the NAT Systems Planning Group* (NAT SPG/3), amongst other things, provides a progress report on the data collection and analysis programme regarding navigational capability of aircraft in the NAT Region. Concerning the collision risk model and the target level of safety, a minor update to the latter is given for bullet 2) (of the conclusion of the 2nd meeting) only, viz. a rounded range from 0.4 to 0.15 per 10 million aircraft flight hours. As indicated in the previous paragraph, the subject of vertical separation applied to aircraft operating above FL 290 in the NAT was also dealt with by the meeting. Two items of the pertinent discussion are worth mentioning here. The first item concerns the possibility of increasing the capacity of the North Atlantic airspace by applying some sort of staggering to the flight paths of aircraft flying on adjacent tracks and/or flight levels and the second item concerns a vertical collision risk model. The form of the model used differs slightly from the vertical equivalent of eqs. (5.26) and (5.27) of section 5.2.2 of this document and reads

²⁷ It was agreed by the Group that the model should not give any credits to the possibility of visual collision avoidance and that the risk so evaluated should be described as “the blind flying collision risk”.

$$N_{az} = \frac{2 \times 10^7}{H} P_z(std) \left\{ \frac{T_z(same)}{S_x} \left[\frac{\Delta \bar{V}}{2} P_y(0) + \lambda_x N_y(0) + \frac{\lambda_x |\bar{z}| P_y(0)}{2 \lambda_z} \right] + \frac{T_z(opp)}{S_x} \left[\bar{V} P_y(0) + \lambda_x N_y(0) + \frac{\lambda_x |\bar{z}| P_y(0)}{2 \lambda_z} \right] \right\} \quad (5.30)$$

where N_{az} is the expected number of aircraft accidents per 10 million aircraft flying hours, due to failure of vertical separation and H is the total flying time (in aircraft hours) during the period, and in the region, considered. The two main items on the tentative agenda for the Group's fourth meeting were agreed to be *Review of the results of the data collection programme regarding navigational capability of aircraft in the NAT Region* and *Development of a method for the determination of longitudinal separation standards in the NAT Region*²⁸.

The *Summary of Discussions of the Fourth Meeting of the NAT Systems Planning Group* (NAT SPG/4, 1968) notes under its review of the data collection programme that it would be worthwhile, in the longer term, to endeavour to obtain international definition of the navigational performance requirements for Oceanic Regions. It was considered that the existing requirement for equipment carriage, related to the needs of the ATC system now set out in Annex 6, was not sufficiently precise. See for example Pool (1983) on the development of MNPS and further below under the MNPS heading.

The Group's review of various assumptions in the collision risk equation began with recalling the equation agreed during its second meeting as

$$N_{ay} = \frac{2 \times 10^7}{H} P_y(std) \left\{ \frac{T_y(same)}{S_x} \left[\frac{\Delta \bar{V}}{2} P_z(0) + \gamma \Lambda_x N_z(0) + \frac{\Lambda_x |\bar{y}| P_z(0)}{2 \lambda_y} \right] + \frac{T_y(opp)}{S_x} \left[\bar{V} P_z(0) + \gamma \Lambda_x N_z(0) + \frac{\Lambda_x |\bar{y}| P_z(0)}{2 \lambda_y} \right] \right\} \quad (5.31)$$

It is remarked that eq. (5.31) differs slightly from eq. (5.29) from the report of NAT SPG/2 (ICAO, 1966) concerning the left-hand side variable, N_{ay} , the expected number of aircraft accidents per 10 million aircraft flying hours. Eq. (5.31) was brought into a slightly different form at the 4th meeting, viz.

$$N_{ay} = 10^7 P_y(std) \left\{ \frac{E_y(same)}{S_x} \left[\frac{\Delta \bar{V}}{2} P_z(0) + \gamma \Lambda_x N_z(0) + \frac{\Lambda_x |\bar{y}| P_z(0)}{2 \lambda_y} \right] + \frac{E_y(opp)}{S_x} \left[\bar{V} P_z(0) + \gamma \Lambda_x N_z(0) + \frac{\Lambda_x |\bar{y}| P_z(0)}{2 \lambda_y} \right] \right\} \quad (5.32)$$

where the two "occupancy" variables $E_y(same)$ and $E_y(opp)$ were defined as

$$E_y(same) = \frac{2 T_y(same)}{H} \quad (5.33)$$

$$E_y(opp) = \frac{2 T_y(opp)}{H} \quad (5.34)$$

and represent the average number of aircraft occupying segments of length $2S_x$ of the tracks adjacent to the track and at the same flight level as the typical aircraft.

²⁸ The model proposed at the 4th and 5th meetings of the NAT SPG will be considered in Chapter 7, *Longitudinal collision risk modelling*.

The Group then considered how to precisely determine the collision risk estimates. It was noted that there were large differences in the percentages of deviations above 45 NM for the different stations. The Group decided that rather than using a weighted addition of the data, the correct procedure would be to divide the Ocean into a series of sub-areas and to compute for each sub-area the pertinent probability of lateral overlap, occupancies, flight hours, and expected number of accidents due to failure of lateral separation and to compute an estimate for the whole ocean as a weighted average of the expected numbers of accidents per sub-area. Due to limitations of time, it was necessary to assume during the meeting that the probability of lateral overlap was constant over the complete ocean supplemented with a correction factor to account for the underestimate this would cause. This method was referred to as the “NAT SPG-4 method”. Regarding confidence limits, it was agreed that a 90% upper confidence limit would be obtained by applying a factor of 1.62 to the central estimate and a factor of 0.5 to obtain a 10% lower confidence limit.

The results of the NAT SPG-4 method applied to the data available on all operators produced central estimates of 0.62 accidents per 10 million flying hours at a lateral separation standard of 90 NM and of 0.1 accidents per 10 million flying hours at a lateral separation standard of 120 NM. Figure 1.26 of NAT SPG/4 report refers. Cf. also Machol (1975). The results were interpreted as follows: It appears improbable that a 90 NM lateral separation standard applied uniformly over the North Atlantic Region would be safe as defined by the lateral target level of safety agreed at the 2nd meeting of the NAT/SPG. On the other hand, it appears probable that a 90 NM lateral separation standard would be safe if applied only to some appropriate subset of traffic. It was however noted that, in the mathematical/statistical sense, the standard of 120 NM was largely meeting the safety requirement used in the mathematical method upon which the work of the Group was based.

Concerning subjects for its next meeting, the Group agreed to put five principal items on the tentative agenda for its 5th meeting, including

- ii) Review of developments regarding the application of reduced vertical separation to aircraft operating above FL 290 in the NAT Region;*
- iii) Review of the possibility to apply “composite separation” to aircraft operating in the NAT Region²⁹; and*
- iv) Review of progress made in the assessment of longitudinal separation in certain parts of the Region, including the possible use of DME for the maintenance of such separation.*

Item *iii*) is briefly discussed below but consideration of items *ii*) and *iv*) is deferred to Section 6.4.2 and Chapter 7 respectively (although results on item *ii*) were utilized in the work on item *iii*) to be described below).

5.3.2 60 NM/1000 ft composite separation

Composite or staggered separation was on the agenda of the NAT SPG from the 5th to the 8th meeting inclusive and again at the 12th, 13th, and 15th meetings with the key work performed at the 5th and 6th meetings. The principle of composite separation is shown in Figure 3.1 in Chapter 3 (Pool, 1983) and also in e.g. Figure 7 of Machol (1975) and Figure 4 of Appendix 3 – A to NAT SPG/5 (ICAO, 1968a). The lateral separation between aircraft at the same flight level is 120 NM, the vertical separation between aircraft on

²⁹ A proposal to allow the application of composite separation was made and accepted at the Sixth Air Navigation Conference and was expected to be incorporated in Annex 11 with an applicability date of 4 February 1971 page 10-7 refers).

the same track is 2000 ft, but the separation between aircraft on adjacent tracks is 60 NM and 1000 ft. Providing the safety of the composite separation can be demonstrated, it can accommodate up to twice the number of aircraft in the same airspace as a non-composite system.

The model used to calculate the expected number N_{ayz} of accidents due to the loss of composite separation for same -direction traffic during the 5th meeting of the NAT SPG reads (NAT SPG/5) (ICAO, 1968a)

$$N_{ayz} = 10^7 P_z(1000) \frac{\lambda_x}{S_x} E_{yz}(same) P_y(60) \left\{ \frac{\Delta V}{2\lambda_x} + \frac{|\dot{y}(60)|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\} \quad (5.35)$$

where $E_{yz}(same)$ is the composite occupancy, i.e. the average number of same-direction aircraft occupying segments of length $2S_x$ of the four flight paths nearest to the flight path of a typical aircraft and the meaning of the other parameters should be clear. A difficulty that the Group had to deal with at its 5th meeting was that no agreed value of $P_z(1000)$ was as yet available. The difficulty was resolved by relating the composite risk N_{ayz} to the vertical collision risk for aircraft separated by 1000 ft, $N_{az}(1000)$, i.e. by considering eq. (2) in Appendix 3 – A to NAT SPG/5 (ICAO, 1968a),

$$\frac{N_{az}(1000)}{N_{ayz}} = \frac{E_z(same) P_y(0) \left\{ \frac{\Delta V}{2\lambda_x} + \frac{|\dot{y}(0)|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\}}{E_{yz}(same) P_y(60) \left\{ \frac{\Delta V}{2\lambda_x} + \frac{|\dot{y}(60)|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\}} \quad (5.36)$$

The occupancy ratio was eliminated from eq. (5.36) by using the slightly cautious approximation $E_{yz}(same) = 2E_z(same)$. Substitution of all the remaining, agreed, parameter values into eq. (5.36) resulted in

$$\frac{N_{az}(1000)}{N_{ayz}} = 31 \quad (5.37)$$

Eq. (5.37) states that a system with composite separation is 31 times safer than the corresponding system with a vertical separation of 1000 ft. Numerical results for the latter based on height-keeping performance without recalibration of the static system were then used to obtain central and 90% confidence level values for the composite system collision risk N_{ayz} . The calculations were subsequently extended by accounting for opposite-direction traffic and track changes and flight level changes. From the numbers obtained, the Group concluded that a system of tracks separated laterally by 60 NM whereby adjacent tracks are staggered by 1000 ft would be likely to afford an acceptable level of safety and that such a system may be practicable in the NAT oceanic area.

Discussion on the operational and collision risk aspects of 60 NM/1000 ft composite separation continued at the 6th meeting of the NAT/SPG (ICAO, 1969). With regard to the time scale for application of composite separation in the NAT Region, it was hoped that this type of separation could, in its initial form, be applied during 1970. Considerations of collision risk focused on a review of the main assumptions made at the 5th meeting and led to the conclusion that the assumptions made previously were valid. The Group recalled the target level of safety of 0.45 to 1.2 accidents per ten million flying hours for all dimensions agreed at its 3rd meeting and the equal subdivision between the vertical, lateral, and longitudinal dimensions agreed at its 2nd meeting. This subdivision had been made mainly because the initial work was done on lateral separation only and no estimates were available for the vertical and longitudinal separations. Composite separation added a fourth separation to be considered in combination with the other three. The Group felt that its work was

now advanced sufficiently to enable it to assign estimates for the risk due to each of the separations, although the risk figures for the vertical and longitudinal dimensions were not based on any detailed analysis but rather on cautious opinions of the Group on the basis of their overall experience with the matter. A list was drawn up of the “best estimate” (50% confidence limit) and “cautious estimate” (90% confidence limit) values of the number of accidents per flying hour for each of the four separations plus that due to flight level changes (Table 3.2 in the NAT SPG/6 report refers). This list has been reproduced below in Table 5.2.

Table 5.2 Best and cautious estimates produced at the 5th meeting of the NAT SPG for the organized track system in the NAT

Separation	Best estimate (accidents per 10 million flying hours)	Cautious estimate (accidents per 10 million flying hours)
Lateral separation (120 NM)	0.11	0.18
Vertical separation (2000 ft)	0.02	0.05
Diagonal separation 60 NM + 1000 ft	0.03	0.04
Longitudinal separation (15 min.)	0.05	0.15
Flight level changes	0.01	0.02
Total	0.22	0.44

Thus, the Group agreed that a composite system of separation using 60 NM and 1000 feet appears to meet the requirements of the target levels of safety even without segregation of opposite-direction traffic. However, it was agreed that the composite separation might not yield the same level of safety throughout future years, e.g. due to increases in opposite-direction and same-direction occupancy. As a final conclusion after considering all relevant factors the Group agreed to propose to the NAT V RAN meeting (ICAO, 1970) that it makes appropriate provisions to permit the application of a type of composite separation in the NAT Region consisting of 60 NM lateral separation combined with 1000 ft vertical separation, and this under specified conditions.

The proposal was followed up by Recommendation 10/4 – *Amendment of RAC SUPPS – Composite separation*, of the 5th North Atlantic Regional Air Navigation Meeting (ICAO, 1970).

The *Summary of Discussions of the 7th meeting of the NAT Systems Planning Group* states that the use of one composite track was planned to be used as of 1 April 1971. The need for progressive implementation of composite separation, commensurate with the experience gained in its use, both by controllers and pilots was stressed at the meeting. The *Summary of Discussions of the 8th meeting of the NAT Systems Planning Group* (February 1972) states that the Group agreed that, in the light of experience so far obtained, the application of composite separation in the NAT Region had given full satisfaction. It was also agreed that further extension of this type of separation within the organized track structure should be left to the discretion of the Oceanic Control Centers (OACs) directly concerned with its application based on appropriate coordination.

The *Summary of Discussions of the 12th meeting of the NAT Systems Planning Group* (31 May – 11 June, 1976) reports on possible extension of the use of composite separation. Canada informed the Group that they were engaged in studies aimed at the provision of one or more additional composite tracks through Labrador with a target date for provision of those tracks in November 1976. The United Kingdom informed the Group that the provision of additional composite tracks in the Northern part of the OTS was not expected to cause any difficulties to Shanwick OAC. As to the provision of a composite track in the Southern part of the organized track system, Canada could not give any indication of a possible implementation date due to certain transition problems. The Group also reflected on a proposal at the upcoming LIM NAT RAN Meeting (ICAO, 1976b) to reduce lateral separation between aircraft operating on the OTS³⁰. (See below under the next heading.) It was unanimous in its view that, should this proposal be accepted, it was not intended to discard the concept of composite separation within the OTS. This was confirmed by work reported at the 13th and 15th meetings of the NAT/SPG.

The *Summary of Discussions of the 13th meeting of the NAT Systems Planning Group* (12 – 22 September, 1977) states that it was reported that work on the introduction of additional composite tracks in the OTS south of those already being provided was underway but no specific date could be given for the conclusion of that work. The extension of the use of composite tracks to the north of the presently used tracks was expected to be possible some time in Spring 1978. Canada reported to be intending to extend the use of composite separation along tracks over Labrador and to implement this on 1 December 1977.

The *Summary of Discussions of the 15th meeting of the NAT Systems Planning Group* (19 – 28 February, 1979) deals with composite separation under Agenda item 3. *Review of the situation regarding the use of composite separation and determination of its priority use in relation to reduction in longitudinal separation.* Consideration of this item was sub-divided into three parts, namely:

- a) The general question of extending the use of composite separation versus a reduction of longitudinal separation;
- b) The possible intermediate use of reduced lateral separation and resultant use of composite separation should use of 60 NM lateral separation remain impracticable for a prolonged period; and
- c) Short-term measures for the increased use of composite separation under the present operational environment.

Concerning bullet a), the Group noted that, at the LIM NAT RAN meeting 1976 (ICAO, 1976b), the possibility had already been foreseen to introduce a composite separation, composed of 30 NM lateral separation and 1000 feet vertical separation once it had been found that this was feasible when 60 NM lateral separation was applied in the NAT Region. In conclusion, on this bullet, the Group felt that, even if feasible, the introduction of 30 NM lateral combined with 1000 feet vertical separation, could not be considered seriously for application in the MNPS airspace of the NAT Region before the end of 1980³¹. Concerning bullet b), a proposal was presented that, should it be found that the application of 60 NM lateral separation would, against expectations, not be feasible for a prolonged period, consideration should be given to the introduction of 90 NM lateral separation and the use of composite separation based on 45 NM lateral separation combined with 1000 feet vertical separation. The Group agreed to retain this proposal for consideration at such time when no other alternative was left to it regarding improvements of the operations in the NAT Region. Concerning bullet c), it was noted that some problems were being worked on and were expected to be resolved partly by mid-March and partly by mid-May 1979, but that extended use of

³⁰ 60 NM lateral separation in NAT MNPS airspace as of 5 October 1978.

³¹ The 30 NM/1000 ft composite separation returned to the NAT/SPG agenda at its 19th Meeting, 10 – 30 April 1982, and 20th Meeting, 14 – 25 March 1983.

composite separation in the NAT Region was essentially determined by conditions to be resolved in the transition areas between the NAT and domestic traffic flows.

Following the implementation of a 60 NM lateral separation standard in the NAT MNPS airspace as of 30 October 1980, see Section 5.3.3 below, the use of 60 NM/ 1000 ft composite separation in the NAT Region was discontinued as of that date.

5.3.3 60 NM lateral separation in NAT Minimum Navigation Performance Specification (MNPS) airspace

According to Machol (1995), after 60 NM/1000 ft composite separation was successfully introduced in the NAT in the early 1970s, the airlines immediately began petitioning for 60 NM lateral separation without composite, which, in combination with a number of developments, led to the development and implementation of the MNPS concept in the NAT region. These developments have been summarized very well by Pool in his Princeton lecture (Pool, 1983) reproduced in Chapter 3 of this document. The following paragraph, copied from Section 3.3 refers:

“The deviations from track of the aircraft coming off the North Atlantic Region have, since the data collection of 1967-68, been continually monitored by radar controllers in Ireland and Canada. If large deviations occur, the operators are asked for details about what has occurred. The reports on the monitoring results are submitted to the NAT/SPG. The first results showed that aircraft navigating on inertial navigation systems (INS) and, in the later years, OMEGA had markedly less large errors than those navigating on LORAN A/Doppler. The operators using this equipment wanted to earn economic advantages from its use. It proved, however, impossible to adapt the NAT route system to two classes of navigation performance. An opportunity to make use of the better performance possibilities came when the military authorities announced that they intended to stop the operation of LORAN A at the end of 1977. The operators which then used this navigation aid would have to re-equip their aircraft. It was decided that from that time onward all aircraft that flew above FL280 in the NAT Region would have to show a navigation performance that was at least as good as that achieved by INS-equipped aircraft at that time. The NAT SPG developed a Minimum Navigation Performance Specification (MNPS), which all aircraft flying in the NAT area are required to meet. This was not, as had been done in the past, a specification of the equipment that should be on board the aircraft, but a requirement about the actual navigation performance. The operators have to show that their aircraft and flight crew can meet this specification before they are certified to fly in the NAT area, and the actual performance is monitored by radars on both coasts of the ocean. The general principles of this new concept were discussed in and accepted by the ICAO Ninth Air Navigation Conference (1976) and the details were developed during the ICAO Limited NAT RAN Meeting in the same year (ICAO, 1976b). It was developed from the Reich model and the data which had been collected since 1967 by the monitoring process were used to define the range of shapes of the distributions of lateral deviations that were used in the derivation of the MNPS requirements and to estimate the occupancies. The MNPS was implemented in the NAT Region at the end of 1977 with the composite track system that was in use at that time, although it had been designed for operation with a “60 NM/2000 feet” rectangular system. During an “experimental” period of nearly 2 years the operators and controllers accustomed themselves to working under the new system, while all aircraft coming of the ocean

were closely monitored by radar. For every deviation from track larger than 25 NM the causes were closely investigated. From the experiences obtained during that period guidelines for using the MNPS were laid down by ICAO and IATA in a document (ICAO, 2020c) (Latest version 2020) that received a very wide distribution. Finally the track layout was changed to the rectangular 60 NM/2000 feet configuration near the end of 1980.”

The following paragraphs provide some details of the development sketched by Pool (Pool, 1983). Knowledge about the actual navigation performance of the aircraft population operating in the NAT obtained through monitoring played a key part in this respect. The *Summary of Discussions (and Conclusions)* of the first twenty NAT SPG meetings have been reviewed in two steps to identify the major milestones. In the first step, the agenda items were identified which seemed to be of importance, see Table 5.3. In the second step, the agenda items were studied in more detail. As will be seen below the table, not all of the agenda items initially selected pertained specifically to navigation performance in the sense of MNPS. The key meeting is NAT SPG/12 in May/June 1976.

Table 5.3: Review of navigation performance in the NAT at successive NAT SPG meetings

Meeting	Year	Agenda item	Description
NAT SPG/1	October, 1965	–	–
NAT SPG/2	December, 1966	5	Interim measures to improve navigational performance
NAT SPG/3	April, 1967	4	Exchange of views on criteria for the assessment of system performance
NAT SPG/4	June, 1968	1	Review of the results of the data collection programme regarding navigational capability of aircraft in the NAT Region and their application to lateral separation
NAT SPG/5	December, 1968	5	Review of the criteria for the assessment of system performance
NAT SPG/6	September, 1969	2	Establishment of methods for the assessment of system performance
NAT SPG/7	February, 1971	–	–
NAT SPG/8	February, 1972	–	–
NAT SPG/9	June, 1973	2	Review of the situation regarding the general navigation performance in the NAT Region resulting from the study conducted by Ireland and the Netherlands and assessment of its consequences on the overall navigation situation
		4	Review of the navigational performance of INS equipped aircraft in the NAT Region as presented by the study of the United Kingdom and assessment of its consequences on the NAT ATS route structure
NAT SPG/10	June, 1974	4	Development of proposals regarding action required in the field of navigation in the NAT Region, including the LORAN A situation, developments in the field of INS and OMEGA and minimum navigation performance specifications

Meeting	Year	Agenda item	Description
NAT SPG/11	May, 1975	6	Development of basic principles for minimum navigation capability specification for aircraft on oceanic and long-range flights
NAT SPG/12	June, 1976	2	Development of proposals for minimum navigation performance specifications in specified parts of the NAT Region preparatory to the LIM NAT RAN Meeting 1976
NAT SPG/13	September, 1977	1	Review of Situation and Measures required regarding the implementation of Minimum Navigation Performance Specifications (MNPS) in specified parts of the NAT Region
NAT SPG/14	April, 1978	1	Development of measures to permit the application of 60 NM lateral separation in the MNPS airspace of the NAT region as of 5 October 1978 in the light of data on aircraft performance obtained since 29 December 1977
NAT SPG/15	February, 1979	1	Continued work on measures required to permit the application of 60 NM lateral separation in the MNPS airspace of the NAT Region at the earliest feasible date
NAT SPG/16	October, 1979	1	Lateral separation in the NAT Region
NAT SPG/17	March, 1980	1	Proposed action on lateral separation in the MNPS airspace of the NAT Region.
NAT SPG/18	April, 1981	1	Review of the situation regarding lateral separation in the Region subsequent to the introduction of 60 NM lateral separation in MNPS airspace
NAT SPG/19	April, 1982	1	Review of the situation regarding lateral separation in the NAT Region including information on the 1981 survey on deviations from track in the 15 – 30 NM range
NATSPG 20	March, 1983	1	Review of navigation performance and application of separation standards in the NAT Region

NAT SPG/2 (21 November – 5 December, 1966)

One State explained that, as early as 1963, they had instituted a procedure whereby the operators concerned were notified on a monthly basis of any of their flights which by radar observation had been found to be more than 20 NM off track or which were in error longitudinally by more than 3 minutes. Another State stated that, at irregular intervals, they also provided summaries of navigational accuracy observed on radar to the operators.

NAT SPG/3 (17 – 28 April, 1967)

System performance at this meeting did not concern navigation performance but rather performance in terms of overall cost penalty from ATC deviations suffered by airlines.

NAT SPG/4 (17 – 28 June, 1968)

As set out in section 5.3.2 in the context of the safety assessment of a 90 NM lateral separation standard, the *Summary of Discussions of the Fourth Meeting of the NAT Systems Planning Group* (NAT SPG/4) noted under its review of the data collection programme that it would be worthwhile, in the longer term, to endeavour to obtain international definition of the navigational performance requirements for Oceanic Regions. It was considered that the existing requirement for equipment carriage, related to the needs of the ATC system

now set out in Annex 6, was not sufficiently precise. This refers essentially to the development of a notion such as MNPS.

NAT SPG/5 (4 – 18 December, 1968)

System performance in terms of overall cost penalty from ATC deviations suffered by airlines.

NAT SPG/6 (4 – 16 September, 1969)

Again, system performance in terms of overall cost penalty from ATC deviations suffered by airlines. However, it is worth mentioning a study carried out by the United Kingdom of navigational capability, in terms of accuracy (standard deviations) and reliability (MTBFs) which might be specified for airborne equipment in order to ensure that the requirements of particular ATC environments are met. A view was that the methods developed by the Group to determine the separation standards appropriate to the navigation capability measured in the data collection exercise, could be applied for future system planning. Thus if it were possible to express what would be a reasonable cost of deviation from the optimum flight path, the costing model would permit the approximate determination of the separation needed; in turn further development of the concept might permit the specification of navigation capability required to support such a separation standard in terms meaningful to system engineers, namely accuracy and reliability.

NAT SPG/9 (28 May – 6 June, 1973)

Agenda item 2: The Group noted that, in accordance with previous decisions, Provider States, and particularly Ireland and the United Kingdom, had maintained a continuous monitoring of the navigation performance in the NAT Region. It was also noted that this continuous survey of traffic had revealed a number of very practical problems which had immediate consequences on the operation of the Air Traffic Services in the NAT Region. This concerned primarily a question of gross errors and blunders. The traffic surveys revealed, in fact, that error and blunder distribution amongst operators was not proportional to the percentage of traffic their operations constituted of the overall traffic but that a limited number of operators seemed to be responsible for the bulk of errors and blunders. As a consequence, the United Kingdom, for each reported case, applied the reporting procedure for observed navigational errors in order to obtain necessary corrective action and improvement. The Group was informed that, while some operators had been very cooperative in following up of individual cases of gross errors or blunders, others had been less cooperative in that respect. Some of the errors observed in early 1973 with eastbound flights were of such magnitude and their frequency of occurrence was such that the United Kingdom had been forced to increase the lateral separation value between aircraft operating at the same flight level but in opposite directions to 180 NM in the area between 10°W and 40°W. While it was not possible to determine the exact causes for these errors with absolute certainty, three main reasons were identified. It was noted by the Group that the energetic follow-up action by the United Kingdom on all observed gross errors or blunders during 1972 and especially in early 1973 seemed to have resulted in a considerable improvement of the situation during the last few months so that the overall trend of navigational performance was once more in line with assumed values. In view of this situation, it was therefore not unreasonable to expect that the increase in lateral separation between aircraft at the same flight level but operating in opposite directions could be eliminated towards the end of 1973 if continued traffic surveys confirm the existing trend.

In a joint working paper, the Netherlands and the United Kingdom presented a calculation of the collision risk for 1976, on the basis of recently collected data (Pool & Simons, 1973). The main data used was collected by Shannon radar in the period from 1 October 1971 to 30 September 1972. When comparing the data with that collected at Kilkee in 1967, it was found that the percentage of deviations between 10 and 60 NM had

markedly decreased. This seems to indicate that the general standard of navigation has greatly improved since 1967. For deviations larger than 60 NM there is some improvement, but to a much lesser degree. A relatively small group of operators was identified as being responsible for these errors. A detailed analysis of the very large deviations, several of which by far exceeded 120 NM, showed that many of these had been caused by a more or less gradual deviation from the track over a relatively long period. It was realized that the model developed at earlier NAT SPG meetings based on the snapshot principle, i.e. lateral deviations from track measured at one point are (assumed to be) representative for the whole oceanic area, does not adequately cater for these cases and a new model was developed which treats these cases in a more realistic way.

The development of the new model for aircraft diverging at approximately constant angles from their nominal tracks during the whole flight started with the basic form of the Reich model, eq. (A.2) of Pool (Pool & Simons, 1973),

$$N_{ay} = 10^7 \times (N_x P_y P_z + N_y P_z P_x + N_z P_x P_y) \quad (5.38)$$

Although all individual parameters in eq. (5.38) are examined in Pool (Pool & Simons, 1973) and the final model is given in eqs. (A.13) and (A.14) of this reference for same- and opposite-direction traffic, no intermediate forms of the model are available. It has been attempted, therefore, to fill in the intermediate steps below.

Using eq. (5.14) for the relationship between N_x and P_x , eq. (5.38) can be expressed as

$$N_{ay} = 10^7 \times N_x \left\{ \left(P_z + N_z \frac{2\lambda_x}{|\dot{x}|} \right) P_y + P_z \frac{2\lambda_x}{|\dot{x}|} N_y \right\} \quad (5.39)$$

which, with the following parameter values in common with the snapshot-based collision risk model³², $N_z = 20$, $P_z = 0.25$, and $\lambda_x = 0.033$ NM, becomes

$$N_{ay} = 10^7 \times N_x \left\{ \left(0.25 + \frac{1.32}{|\dot{x}|} \right) \times P_y + \frac{0.0165}{|\dot{x}|} \times N_y \right\} \quad (5.40)$$

The ratio between the factors in front of P_y and N_y is given by

$$\frac{0.25 + \frac{1.32}{|\dot{x}|}}{\frac{0.0165}{|\dot{x}|}} = \frac{0.25|\dot{x}| + 1.32}{0.0165} \quad (5.41)$$

Eq. (5.40) may be further elaborated by distinguishing between same-direction and opposite-direction traffic with $|\dot{x}| = 13$ kts and $|\dot{x}| = 960$ kts respectively, i.e.

$$N_{ay}(\text{same}) = 10^7 \times N_x(\text{same}) \{ 0.351538 \times P_y + 0.00126923 \times N_y \} \quad (5.42)$$

$$N_{ay}(\text{opp}) = 10^7 \times N_x(\text{opp}) \{ 0.251375 \times P_y + 1.71875 \times 10^{-5} \times N_y \} \quad (5.43)$$

³² See eq. (5.61) under the NAT/SPG 12 (31 May – 11 June, 1976) caption.

The key step of the new model then concerns the computation of the probability P_y of lateral overlap due to an aircraft deviating from track at an approximately constant angle α during the whole flight of duration T . For such aircraft, the distance by which it has deviated from its track by the end of the oceanic crossing is

$$Y_m = T\bar{V} \sin \alpha \quad (5.44)$$

and the probability distribution of its deviation from track is taken as rectangular over the range $[0, Y_m]$. The probability of lateral overlap is then computed by means of the following version of eqs. (4.14) and (4.16),

$$P_y = \sum_{k=1}^{\infty} 2\lambda_y \int_0^{Y_m} \frac{1}{Y_m} f_{DE}(y - kS_y) dy \quad (5.45)$$

on the assumption that the probability distributions of the lateral deviations of aircraft following their assigned tracks spaced at distances kS_y from the assigned track of the diverging aircraft are double exponential.

Having calculated the probability of lateral overlap P_y , the number N_y of passings in the lateral dimension can be calculated by means of eq. (5.15),

$$N_y \approx P_y \times \frac{|\bar{y}|}{2\lambda_y} \quad (5.15)$$

The relative speed $|\bar{y}|$ is made up of a random component and a systematic component caused by the divergence from track. The latter component equals Y_m/T and the former was taken the same, resulting in

$$|\bar{y}| = 2 Y_m/T \quad (5.46)$$

and thus

$$N_y \approx P_y \times \frac{Y_m}{T\lambda_y} \quad (5.47)$$

The last step involves deriving a formula for the number N_x of passings between diverging and non-diverging aircraft per flight hour. The reader is referred to the report of Pool (Pool & Simons, 1973), for a derivation of this formula that reads

$$N_x = \frac{1}{480} \times \frac{M_c}{M} \times \frac{|\bar{x}|E_y}{T} \quad (5.48)$$

where M_c is the number of flights that must be handled by the new model out of a sample of M flights. Substitution of eq. (5.48) into eqs. (5.40) gives the final form of the new lateral collision risk model for aircraft diverging at an approximately constant angle α during the whole flight of duration T :

$$N_{ay} = 10^7 \times \frac{1}{480} \times \frac{M_c}{M} \times \frac{|\bar{x}|E_y}{T} \left\{ \left(0.25 + \frac{1.32}{|\bar{x}|} \right) \times P_y + \frac{0.0165}{|\bar{x}|} \times N_y \right\} \quad (5.49)$$

or

$$N_{ay} = 10^7 \times \frac{1}{480} \times \frac{M_c}{M} \times \frac{E_y}{T} \left\{ \left(0.25 \times |\bar{x}| + 1.32 \right) \times P_y + 0.0165 \times N_y \right\} \quad (5.50)$$

(It should be noted that the value of 480 in the denominator of the first quotient in the right-sides of eqs. (5.48) – (5.50) represents four times the proximity reference distance of 120 NM used in the definition of occupancy rather than the average aircraft speed.)

Like eq. (5.40), the model in eq. (5.50) can be elaborated further by distinguishing between same-direction and opposite-direction traffic with $|\bar{x}| = 13$ kts and $|\bar{x}| = 960$ kts, i.e.

$$N_{ay}(same) = 10^7 \times \frac{1}{480} \times \frac{M_c}{M} \times \frac{E_y(same)}{T} \{ (0.25 \times 13 + 1.32) \times P_y + 0.0165 \times N_y \} \quad (5.51)$$

$$N_{ay}(opp) = 10^7 \times \frac{1}{480} \times \frac{M_c}{M} \times \frac{E_y(opp)}{T} \{ (0.25 \times 960 + 1.32) \times P_y + 0.0165 \times N_y \} \quad (5.52)$$

or

$$N_{ay}(same) = 10^7 \times \frac{1}{480} \times \frac{M_c}{M} \times \frac{E_y(same)}{T} \{ 4.57 \times P_y + 0.0165 \times N_y \} \quad (5.53)$$

$$N_{ay}(opp) = 10^7 \times \frac{1}{480} \times \frac{M_c}{M} \times \frac{E_y(opp)}{T} \{ 241.32 \times P_y + 0.0165 \times N_y \} \quad (5.54)$$

The ultimate models in eqs. (A.13) and (A.14) of the report by Pool (Pool & Simons, 1973) are expressed in terms of M_c , the number of flights that must be handled by the new model (out of a sample of M flights), P_y , and N_y , viz.

$$N_{ay}(same) = M_c \{ 0.95 \times P_y + 0.0025 \times N_y \} \quad (A.13)$$

$$N_{ay}(opp) = M_c \{ 28. \times P_y + 0.0025 \times N_y \} \quad (A.14)$$

The last two equations are based on $T = 3.25$ hours and $M = 24050$ flights sampled, as well as values of the two occupancies $E_y(same)$ and $E_y(opp)$. Substitution of the values of T and M into eqs. (5.53) and (5.54) gives

$$N_{ay}(same) = M_c \times E_y(same) \times 0.266539 \times \{ 4.57 \times P_y + 0.0165 \times N_y \} \quad (5.55)$$

$$N_{ay}(opp) = M_c \times E_y(opp) \times 0.266539 \times \{ 241.32 \times P_y + 0.0165 \times N_y \} \quad (5.56)$$

The occupancy values are discussed in section 5.2.3 of the report by Pool (Pool & Simons, 1973), but do not appear to be explicitly specified. The first step is stated to be to determine the daily flow rate, which was taken to be 465 aircraft per day (with an uncertainty characterized by a level distribution between $\pm 20\%$ of this value). The text then suggests that this daily flow rate has been used in Figure 3 of the report by Pool (Pool & Simons, 1973) to read off the desired same-direction occupancy value. Following this procedure gives

$$E_y(same) \approx 0.84 \quad (5.57)$$

It has not been possible to infer a value for the opposite-direction occupancy $E_y(opp)$ because its computation in of the report by Pool (Pool & Simons, 1973) refers to a figure in reference 6 of the report by Pool (Pool & Simons, 1973), which is not available to the authors of the current document. Substitution of eq. (5.57) into eq. (5.55) gives

$$N_{ay}(same) = M_c \times 0.223893 \times \{4.57 \times P_y + 0.0165 \times N_y\} \quad (5.58)$$

or

$$N_{ay}(same) = M_c \times \{1.02319 \times P_y + 0.00369423 \times N_y\} \quad (5.59)$$

together with

$$N_{ay}(opp) = M_c \times E_y(opp) \times 0.266539 \times \{64.3211 \times P_y + 0.00439789 \times N_y\} \quad (5.60)$$

It is clear that eq. (5.59) derived here is not identical to eq. (A.13) of the report by Pool (Pool & Simons, 1973). In particular, the ratios between the respective factors in front of P_y and N_y are different, namely 276.97 as opposed to 380. As follows from eq. (5.39), this ratio depends on the values used for P_z , N_z , λ_x , and $|\bar{x}|$. Assuming that the values used for P_z , N_z , and λ_x are the same ones as used in the report by Pool (Pool & Simons, 1973), the difference between the ratios could be assigned to a difference in values for $|\bar{x}|$. A value of $|\bar{x}| = 19.8$ kts would yield the same ratio of 380 for the ratio between the factors in front of P_y and N_y in eq. (5.59).

The conclusions section of the *Summary of discussions of the ninth meeting of the NAT Systems Planning Group* comprises 14 items of which item k) has been reproduced for the benefit of this subsection of this document, viz.

- k) The Group confirmed its views that any possible reduction in the separation values applied depended primarily on the specification of an agreed navigation performance by all aircraft operating in the NAT.

Agenda item 4: The Group had before it two surveys conducted by Canada and the United Kingdom respectively, related to the navigation performance of INS equipped aircraft. The survey by Canada was with regard to longitudinal separation and the survey by the United Kingdom to lateral separation. The latter survey covered some 5000 flights by INS equipped aircraft in the NAT Region during the period from April to July 1971 which, taking into account the provision of either triple or at least dual INS installations onboard the aircraft concerned, amounted to some 15400 individual systems' flights in the NAT Region and some 12500 hours of system operation. The survey showed an apparent superior performance of INS equipped aircraft, both in terms of a 95% performance level and in terms of the occurrence of gross errors.

NAT SPG/10 (10 – 20 June, 1974)

After some discussion, the Group agreed that an item dealing with the development of minimum navigation performance specifications should be retained for inclusion in the Agenda of the next meeting of the NAT/SPG.

NAT SPG/11 (6 – 15 May, 1975)

The Group essentially dealt with administrative/organisational aspects of a minimum-navigation-performance-specification agenda item for the 9th Air Navigation Conference to be held in April/May 1976.

NAT SPG/12 (31 May – 11 June, 1976)

It was recalled that, based on work performed by a number of Working Groups of the NAT/SPG, proposals dealing with both the operational and mathematical aspects of the introduction of a minimum navigation performance specification were submitted to the 9th Air Navigation Conference in April/May 1976 for consideration. After extensive discussion, this Conference agreed to the application, on an interim basis, of the concept developed by the NAT SPG in the NAT Region pending further study of this matter on a world-wide basis. As a consequence, the Group at its 12th meeting developed specific proposals for action by the Limited NAT RAN 1976 Meeting (ICAO, 1976b) to be held in August/September 1976 and agreed that the material in Appendix A to the Summary of discussions and conclusions on Agenda Item 2 should be submitted for consideration under Agenda Item 1 of the latter meeting (NAT SPG/12) (ICAO, 1976c).

It was proposed to establish a Minimum Navigation Performance Specification for all aircraft using the NAT Organized Track System and to establish a monitoring programme in order to verify that the specification is being met. This new specification is designed for an Organized Track System with a planned lateral separation of 60 NM with a future capability to apply a 30 NM/1000ft composite separation.

The Group formulated five Recommendations for action by the Limited NAT RAN Meeting 1976 concerning:

- Amendment to Document 7030;
- Disposition of Guidance Material regarding Minimum Navigation Performance Specifications;
- Amendment of the statement of basic operational requirements and planning criteria for the NAT Region;
- Phased implementation of the revised NAT Regional Supplementary Procedures; and
- Further work for the NAT/SPG.

The proposed *Amendment to Document 7030* concerned amendment of two specific paragraphs, para 1 and para 3.5. Para 3.5 concerned Establishment and use of organized tracks and amendment of para 1 comprised four parts as follows:

- i) “1.1.1 Minimum lateral separation shall be:
 - a) 60 nautical miles between turbojet aircraft which meet the Minimum Navigation performance Specifications in accordance with para 1.5 below and which operate in the organized track system as established in accordance with para 3.5;
 - b) 90 nautical miles between aircraft operating
 - i) between the United States or Canada and Bermuda;
 - ii) between the United States, Canada or Bermuda and points in the CAR Region;
 - iii) between the Iberian Peninsula and the Azores Islands; and
 - iv) between Iceland and points in Scandinavia and in the United Kingdom;
 - c) 120 nautical miles between other aircraft.

except that the lower minima in 7.2 of Part II of the PANS-RAC may be applied, or further reduced in accordance with 9 of the same Part, where the conditions specified in the relevant PANS-RAC provisions are met.”

ii) “1.4 Composite separation

1.4.1 Between aircraft operating at or above FL290 and within the organized track system as established in accordance with para 3.5, composite separation, consisting of the combination of 30 nautical miles lateral and 300 metres (1 000 feet) vertical separation may be applied.

1.4.2 This type of separation may be applied between aircraft operating in the same or opposite directions.”

iii) “1.5 Minimum Navigation Performance Specifications

States having jurisdiction over operators intending to conduct flights within the Organized Track System established in accordance with para 3.5 shall ensure that aircraft, used for such operations have demonstrated navigation performance capability such that:

- a) The standard deviation of lateral track errors shall be less than 6.3 NM;
- b) The proportion of the total flight time spent by aircraft 30 NM or more off the cleared track shall be less than 5.2×10^{-4} ;
- c) The proportion of the total flight time spent by aircraft between 50 NM and 70 NM off the cleared track shall be less than 13×10^{-5} .”

iv) Renumber the existing para 1.5 as 1.6.

It is also worth reproducing the proposed *Phased implementation of the revised NAT Regional Supplementary Procedures* recommendation:

- a) The proposed NAT Regional SUPPs regarding adherence of aircraft operating in the Organized Track System to Minimum Navigation Performance Specifications should become applicable as of 29 December 1977;
- b) The provisions regarding the use of 60 NM lateral separation between aircraft operating on adjacent tracks in the Organized Track System should become applicable on 5 October 1978, unless another date was agreed in due time between States and Operators concerned; and
- c) The revised provisions regarding the use of composite separation within the Organized Track System should become applicable at some time after 5 October 1978 as agreed between States and operators concerned and notified in due time to ICAO.

Attachment 1 to Appendix A of the *Summary of discussions and conclusions on Agenda Item 2 of the 12th meeting of the NAT Systems Planning Group*³³ delineates the rationale and mathematical foundation for the proposed minimum navigation performance specification applicable in the North Atlantic. The material is also available in Appendix A to Chapter 4 – *Minimum navigation performance specifications* of Section 2. *Separation*, of the Air Traffic Services Planning Manual (ICAO, 1992a). This Manual provides two more Appendices related to the subject, namely Appendix B, *Collision Risk Model*, and Appendix C, *Estimation of Occupancy Values and Variation of Risk with Occupancy*. The Attachment is also available as Appendix A to the Report on Agenda item 1.2 – *Minimum navigation performance specifications* of the LIM NAT RAN Meeting 1976 (ICAO, 1976b). Appendix B to that report deals with and is entitled *Monitoring of Navigation Performance*.

³³ From here on referred to as “The Attachment”.

The derivation of the three MNPS requirements,

- The standard deviation of lateral track errors shall be less than 6.3 NM;
- The proportion of the total flight time spent by aircraft 30 NM or more off the cleared track shall be less than 5.2×10^{-4} ;
- The proportion of the total flight time spent by aircraft between 50 NM and 70 NM off the cleared track shall be less than 13×10^{-5} .

will now be reproduced below, starting with requirement c) and ending with requirement a).

As set out in the Attachment, the minimum navigation performance specification (MNPS) is established to provide a mechanism to assure that the risk of aircraft collision due to loss of lateral separation will be maintained at a satisfactory level, as defined by the target level of safety (TLS). It is assumed that the collision rate N_{ay} , i.e. the expected number of accidents per 10 million flight hours, is related to the probability of lateral overlap $P_y(S_y)$ by the agreed NAT SPG lateral collision risk model

$$N_{ay} = 10^7 P_y(S_y) P_z(0) \frac{\lambda_x}{S_x} \left[E_y(\text{same}) \left\{ \frac{|\Delta V|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right\} + E_y(\text{opp}) \left\{ \frac{2|\bar{V}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right\} \right] \quad (5.61)$$

with the following parameter values (cf. Table 5.1)

Table 5.4: Parameter values used in the derivation of the MNPS specification

Parameter	Description	Default value
S_y	The lateral separation distance/minimum	60 NM
$P_y(S_y)$	The lateral overlap probability	To be calculated
$P_z(0)$	The vertical overlap probability	0.25
λ_x	The length of an aircraft	0.033 NM (200 ft)
λ_y	The span of an aircraft	0.033 NM (200 ft)
λ_z	The height of an aircraft	0.0085 NM (50 ft)
S_x	The longitudinal separation distance/minimum	120 NM
$E_y(\text{same})$	The same-direction occupancy	0.5
$E_y(\text{opp})$	The opposite-direction occupancy	0.013
$\frac{ \Delta V }{2}$	The average difference of cruising speed in pairs of aircraft	13 kts
$\frac{ \bar{V} }{2}$	The average aircraft speed	480 kts (2V)
$ \bar{y} $	The lateral cross-track velocity	47 kts
$ \bar{z} $	The vertical velocity	1 kts

Notice that eq. (5.61) can be obtained from the form of the model in eq. (5.32) agreed at the 4th Meeting of the NAT SPG by using eq. (5.16), taking $\gamma = 1$ and $\Lambda_x = \lambda_x$, and rearranging the various terms and factors.

The objective of the MNPS specification was then stated in terms of the NAT SPG collision risk formula as:

- The level of navigation performance in the North Atlantic organized track system shall be such that the risk of collision due to loss of lateral separation does not exceed 0.2 fatal accidents in 10^7 flying hours.

Using the collision risk model in an inverse manner, i.e. taking $N_{ay} = 0.2$ and using the parameter values from Table 5.2, a maximum allowable value for the probability of lateral overlap $P_y(S_y)$ can be computed. Recall from Section 4.5, that the probability of lateral overlap is related to the probability density $f(y)$ of the lateral deviations from track through the double integral

$$P_y(S_y) = \int_{-\lambda_y}^{\lambda_y} f_{dy}(d_y) dd_y = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f(y) f(y - S_y + d_y) dy dd_y \quad (4.17)$$

which may be approximated by

$$P_y(S_y) \approx 2\lambda_y f_{dy}(0) = 2\lambda_y \int_{-\infty}^{\infty} f(y) f(y - S_y) dy \quad (5.62)$$

or, in the notation of the Attachment,

$$P_y(S_y) \approx 2\lambda_y C_y(S_y) \quad (5.63)$$

with

$$C_y(S_y) = \int_{-\infty}^{\infty} f(y) f(y - S_y) dy \quad (5.64)$$

Thus, eqs. (5.63) and (5.64) can be used to convert the maximum allowable value for the probability of lateral overlap $P_y(S_y)$ into a maximum allowable value for the convolution integral $C_y(S_y)$, which was found to be $C_y(S_y) = 6.45 \times 10^{-6} \text{ NM}^{-1}$.

Based on certain (regularity) assumptions on the lateral deviation probability density $f(y)$, it is then shown in the Attachment that the convolution integral $C_y(S_y)$ can be expressed in terms of the probability density $f(y)$ of the lateral deviations at the lateral separation standard $y = S_y$, viz.

$$C_y(S_y) \approx 2f(S_y) \quad (5.65)$$

Using the maximum allowable value for the convolution integral $C_y(S_y)$, a maximum allowable value for the probability density $f(S_y)$ at $y = S_y$ can be computed, i.e.

$$f(S_y) < 3.23 \times 10^{-6} \quad (5.66)$$

The probability density $f(S_y)$ at $y = S_y$ is a measurable function of the navigation performance of the aircraft and can be approximated by

$$f(S_y) \approx \frac{\int_{Y_1}^{Y_2} f(y) dy}{Y_2 - Y_1} \quad (5.67)$$

with $Y_2 - S_y = S_y - Y_1$.

It must be noted that $2 \times \int_{Y_1}^{Y_2} f(y) dy$ is the probability that aircraft will be between Y_1 and Y_2 from the centre line on either side of the track. Using the upper bound on $f(S_y)$ from eq. (5.66) and $S_y = 60 \text{ NM}$, $Y_1 = 50 \text{ NM}$, and $Y_2 = 70 \text{ NM}$, the following upper bound is obtained for this probability,

$$\varsigma = 2 \times \int_{Y_1}^{Y_2} f(y) dy \approx 2 \times 20 \times f(S_y) < 40 \times 3.23 \times 10^{-6} = 13 \times 10^{-5} \quad (5.68)$$

Eq. (5.68) defines requirement c) of the MNPS.

The next step in the derivation of the MNPS requirements was to put additional constraints on the standard deviation of nominal navigation performance and the probability of lateral deviations at least as large as half separation. The advantage of the full set of MNPS requirements is that navigation parameters which are more readily adaptable to design goals and performance measurements are included while the restriction on $f(S_y)$ is maintained. A parametric form of the lateral deviation distribution has been assumed, viz., based on past experience, a double double exponential distribution. The double double exponential probability density was parameterizes as follows (cf. eq. (4.26) in Chapter 4)

$$f(y) = \frac{(1 - \alpha)}{2\lambda_1} \exp\left(-\left|\frac{y}{\lambda_1}\right|\right) + \frac{\alpha}{2\lambda_2} \exp\left(-\left|\frac{y}{\lambda_2}\right|\right) \quad (5.69)$$

The standard deviation of the double double exponential probability density in eq. (5.69) is given by

$$\sigma^2 = 2\{(1 - \alpha)\lambda_1^2 + \alpha\lambda_2^2\} \quad (5.70)$$

and the probability of deviations by at least half standard is

$$\eta = \Pr(|Y| > S_y/2) = (1 - \alpha)e^{-S_y/2\lambda_1} + \alpha e^{-S_y/2\lambda_2} \quad (5.71)$$

The convolution integral $C_y(S_y)$ for the double double exponential probability density in eq. (5.69) can be evaluated analytically as ($\lambda_1 \neq \lambda_2$)

$$C_y(S_y) = (1 - \alpha)^2 \frac{\lambda_1 + S_y}{4\lambda_1^2} e^{-\frac{S_y}{\lambda_1}} + \alpha^2 \frac{\lambda_2 + S_y}{4\lambda_2^2} e^{-\frac{S_y}{\lambda_2}} + 2\alpha(1 - \alpha) \left\{ \frac{\lambda_1^2}{\lambda_1^2 - \lambda_2^2} \frac{1}{2\lambda_1} e^{-\frac{S_y}{\lambda_1}} - \frac{\lambda_2^2}{\lambda_1^2 - \lambda_2^2} \frac{1}{2\lambda_2} e^{-\frac{S_y}{\lambda_2}} \right\} \quad (5.72)$$

Combinations of values of λ_1 , λ_2 , and α were then determined for which $C_y(S_y)$ defined by eq. (5.72) was exactly equal to the maximum tolerable value of $6.45 \times 10^{-6} \text{ NM}^{-1}$ and for each such combination the value of the probability η of deviations by at least half standard was computed next as tabulated in Table 1 in the Attachment. The table shows that η has a minimum of 5.3×10^{-4} and this value was chosen as the maximum tolerable value for the probability of deviations by at least half standard, i.e. requirement b) of the MNPS.

Finally, it is stated in the Attachment that if the two requirements b) and c) are met, the collision risk is relatively independent of the standard deviation $\sigma_1 = \lambda_1 \times \sqrt{2}$ of the core density. Thus, based on previous experience, a maximum tolerable value of $\sigma = 6.3 \text{ NM}$ was chosen as a guide to designers of equipment and as a basis for certification tests, i.e. requirement a) of the MNPS.

Remarks:

1. It should be noted that the MNPS requirements are based on a single value for the target level of safety, viz. 0.2 fatal accidents per ten million flying hours. This single value differs from the target level of safety range of 0.15 to 0.4 accidents per ten million flying hours for the lateral dimension agreed at the 2nd and 3rd meetings of the NAT/SPG, cf. section 5.3.1, and still in use at NAT SPG/9 (Pool & Simons, 1973). As set out by Parker (Parker, 1996), the NAT SPG adopted this value based on the work performed by the ICAO RGCSF at its third meeting. See also section 7 of (ICAO, 1976a) and section 3 of (Brooker, 1979).
2. It follows from the derivation of the MNPS requirements that verification of these requirements, particularly requirements b) and c), based on a sample of large lateral deviations is equivalent to verification of the TLS being met. When the MNPS criteria are met by a certain margin, then the TLS is

also met by some (unknown) margin. Verification of the MNPS requirements can thus be considered as providing an implicit estimate of the lateral collision risk.

3. Verification of the MNPS requirements is based on monitoring of the aircraft when exiting oceanic airspace. Monitoring of the requirements b) and c) requires estimating the proportions of flying time spent by the aircraft over 30 NM from assigned track and between 50 to 70 NM from assigned track. In practice, the direct estimation of these proportions is not possible. As a substitute, the time proportions are estimated as proportions of flights that are observed at the oceanic exits to have deviations of 30 NM or more from assigned track and between 50 to 70 NM from assigned track. This approximation is based on the snapshot principle, which states that lateral deviations from track measured at one point are (assumed to be) representative for the whole oceanic area. Limitations of the snapshot principle were already noted in (Pool & Simons, 1973) and are discussed in more detail in (Pool, 1979b) and (Pool, 1979a). See also the next remark.
4. To address the limitations of the snapshot principle, weighting of the observed large lateral deviations based on the nature and magnitude of the deviations was proposed and discussed as of NAT SPG/15. This resulted in the so-called Model 1 and Model 2. See also section 5.3.4.
5. Assuming that the regularity assumptions on the probability distribution of the lateral deviations from track are valid, eqs. (5.63), (5.64), (5.67), and ς defined in (5.68) provide, in fact, a non-parametric estimator for the probability of lateral overlap $P_y(S_y)$:

$$P_y(S_y) \approx 2\lambda_y C_y(S_y) \approx 4\lambda_y f(S_y) \approx 4\lambda_y \frac{\varsigma}{40} = \lambda_y \frac{\varsigma}{10} \quad (5.73)$$

This estimator is used by (1993) as will be seen in section 5.3.4.

6. Assuming that the assumptions and parameter values used in the derivation of the MNPS requirements other than $P_y(S_y)$ are valid for a monitoring period under consideration, the lateral collision risk N_{ay} can be (explicitly) estimated with the model of eq. (5.61) and $P_y(S_y)$ estimated by eq. (5.73). The same can be done when any of the collision risk model parameters (other than the probability of lateral overlap), particularly occupancy, has changed significantly.
7. A number of graphical means have been used over time to visualize the lateral navigation performance with respect to the MNPS requirements b) and c), namely linear trend charts, sequential test charts ((Brooker, 1979), (Moek & Traas, 1979), and process control charts (12 months running estimate, MNPS limit and 1.5 times MNPS limit as an alarm limit).
8. The MNPS requirements were initially verified for the total MNPS airspace and the Organised Track system within MNPS airspace separately. Starting at NAT SPG/22, the MNPS requirements have been verified for the total MNPS airspace as well as its constituent parts, the OTS and Random airspace.
9. The MNPS requirements are conditional on the values of the collision risk model parameters other than the probability of lateral overlap $P_y(S_y)$, particularly occupancy. Increases in occupancy, if any, have been critically monitored as of NAT SPG/19. A review of all collision risk model parameters was performed at NAT SPG/25 resulting in a proposal for a more realistic set of parameter values.
10. See (Brooker, 1979) for a non-mathematical impression of the derivation of the MNPS specification.

NAT SPG/13 (12 – 22 September, 1977)

Concerning the Application of the MNPS as of 29 December 1977 and separation to be provided to aircraft outside the MNPS airspace after that date, the Group concluded that:

- a) There was no information available which would indicate that the application of the MNPS in specified parts of the NAT Region as of 29 December 1977 will lead to undue difficulties either to users or providers; and

- b) Lateral and longitudinal separation now applied in the NAT Region between aircraft operating outside the OTS to be continued to be applied between aircraft operating outside the MNPS airspace in the NAT Region after 29 December 1977, subject to continuing review.

The Group then agreed that the application of MNPS should be promulgated with an advance notice of two AIRAC cycles, i.e. on 3 November 1977. It was also agreed that this promulgation should be effected by Provider States by means of a commonly agreed text in the form of a NOTAM Class II.

NAT SPG/14 (17 – 28 April, 1977)

Comparatively little data on gross errors had become available during the short time since 29 December 1977. In addition, it had been found that at least part of them were due to the use of navigation equipment which was in the process of being replaced by more modern equipment, thus probably preventing the repetition of such errors by the operators concerned. In addition, the Group also realized that a purely mathematical-statistical application of gross errors to the mathematical model, upon which the MNPS concept was based, could not be accepted as the only basis for an operational decision as to whether safety in the MNPS was impaired or not. The Group was then unanimous in its views that there existed no valid reason which would militate against the retention of 5 October 1978 as the date at which it should become permissible to apply 60 NM lateral separation between MNPS equipped aircraft while operating in MNPS airspace.

In view of the expected trends noted in the previous paragraph, there was reason to expect that the overall navigation situation would steadily improve. Taking into account that it would be possible to increase significantly data on observed gross errors during the next few months, the Group felt it advisable to propose that the decision by provider States to actually apply 60 NM lateral separation on the date at which it became permissible should be delayed in the interest of gaining further supporting evidence for the correctness of such a decision. It was agreed that the decision by provider States could be made on a date not later than 11 August 1978. The Group agreed that a number of steps should be taken in order to arrive at a common decision whether 60 NM lateral separation should actually be applied in MNPS airspace as of 5 October 1978, including the provider States to hold, on the initiative of the United Kingdom, a meeting between 1 and 10 August 1978 to determine definitively whether to actually apply 60 NM lateral separation in MNPS airspace as of 5 October 1978, and to develop, as necessary, uniform procedures for application by ATC when using 60 NM lateral separation.

As to the collation and initial analysis of the data to be provided, the Group agreed that, further to the accepted mathematical-statistical method already accepted on previous occasions, the material contained in Appendix A to the *Summary of discussion and Conclusions on Agenda Item 1 of the 14th Meeting of the NAT Systems Planning Group* (NAT SPG/14 (ICAO, 1978)) should be taken into account. This material does not present any striking new elements but rather reviews (once more) the components of collision risk (navigational performance, traffic factors, aircraft parameters, the collision risk model), and of the planned reduction in lateral separation (gross errors, the standard deviation constraint).

NAT SPG/15 (19 – 28 February, 1979)

In the early August 1978 meeting held amongst provider States, latest data on observed gross errors up to the end of July 1978 was available. It was found that, contrary to expectations, the number and size of observed gross errors had not diminished to the point where the practical use of 60 NM lateral separation as of 5 October 1978 would be possible without any reservation. ICAO had been notified accordingly and been

informed that the next target date for the use of 60 NM lateral separation had tentatively been agreed as being 19 April 1979.

As to the proceedings of that Meeting, the Group noted that considerable discussion had arisen at that Meeting on the relative importance which should be attributed to different groups of gross errors when applying them to the mathematical-statistical model. A total of four categories had been distinguished. As a result, the Group agreed to a) review the mathematical-statistical model and its possible future refinement, b) review the gross errors in navigation observed in 1978, and c) to propose action regarding the application of 60 NM lateral separation in the NAT Region.

Concerning the review of the mathematical-statistical model, two papers submitted by IATA and the Member of the Netherlands respectively were discussed. The IATA paper raised four points, namely the assumption that errors of similar magnitude to those observed at the end points of the routes would occur anywhere else along the length of the route, the aircraft dimensions, the probability of vertical overlap (for aircraft at the same flight level), and the fact that no allowance was made in the model for avoidance action by pilots as a result of timely sighting of other aircraft. The Group did not support the points raised in this paper. The paper presented by the Netherlands (Pool, 1979b) dealt with the question of a mathematical model of “weighting” of the various gross errors observed and this not only with respect to their attribution to anyone of the four groups of errors distinguished, but also with respect to the size of the observed deviation. i.e. those of 30 NM deviation from track or more and those falling within the band from 50 to 70 NM off track. Although the Group was unable to accept the paper’s conclusion without reservation, it was however noted that the information provided seemed to indicate that a re-appraisal of the effect of large errors and of the requirement concerning errors of 30 NM and more appeared necessary and that, in addition, the application of weighted data to the statistical acceptance methodologies merited further investigation. Thus, an agreement was reached on further work on these two items as well as on the application of operational evaluation concerning gross errors for inclusion as input into the mathematical modelling.

Based on the review of gross errors in navigation observed during 1978, the Group agreed that a further observation period should be established, extending from 2 November 1978 to 31 August 1979 and that data on observed deviations from track should once more be collected and assessed. In addition, the Group agreed that the new target date for the practical application of 60 NM lateral separation in the MNPS airspace of the NAT Region should be established as 24 January 1980 at 1000 GMT.

Remark

1. See (Brooker, 1979) for a non-mathematical impression of the derivation of the MNPS specification and (White, 1979) for a sketch of the operational problems experienced during the first year of MNPS in the NAT Region, including a reference to the snapshot principle (i.e. the assumption that an error measured by the radars at exit from the Oceanic system is likely to have been replicated at other way-points not within radar cover) and the possibility of weighting of different types of large deviations.

NAT SPG/16 (1 – 10 October, 1979)

The Group had before it the result of the data collection mentioned in the previous paragraph, which showed a total of 37 gross errors, i.e. deviations from track of 30 NM or more out of some 62000 flights. One of the major difficulties in assessing the observed gross errors was to decide to what extent they could represent a trend for repetition in the future or to what extent they were non-repetitive because of improvements made

to the elements having caused them. For this reason, the errors were subdivided into five categories and the question of repetitiveness, or not, was addressed by category.

Further discussion on the introduction of 60 NM lateral separation in MNPS airspace took place at the hand of the following main subjects:

- Scrutiny of observed errors and their classification;
- Review of the mathematical-statistical methods;
- Corrective action regarding specific categories of errors;
- Proposed action regarding the application of 60 NM lateral separation

See NAT SPG/16 (ICAO, 1979b) for details on the first three bullets above and (Pool, 1979a) concerning weighting in the context of the review of the mathematical-statistical methods. Concerning the proposed action, after careful consideration of all relevant factors, the Group was forced to admit that, in the light of prevailing circumstances it did not find itself in a position to maintain the proposed new date of 24 January 1980 for application of 60 NM lateral separation in the MNPS airspace of the NAT Region, even though it was recognized that the pure navigation performance of aircraft in the NAT Region was satisfactory. In fact, it was believed that immediate action and consistent efforts were necessary to reduce, as much as possible, the ATC system loop errors and those caused by incorrect operation of airborne equipment.

Taking into account all other aspects, the Group defined a sequence of six events to offer the most appropriate way for resolving the difficult subject from then on, the two most important ones for this document being the following:

- e) Provider States should continue their routine data collection on observed gross errors whereby that part of it covering the period from 1 September 1979 to 31 July 1980 should include the determination of the causes of such errors in as much detail as possible;
- f) In early August 1980 provider States should organize a further meeting at which the situation will be reviewed, taking into account the data collection mentioned under e) above and assessing the potential collision risk in accordance with the measures developed at NAT SPG/17 and inform ICAO not later than 15 August 1980 of their views regarding the feasibility of introducing 60 NM lateral separation in MNPS airspace in the NAT Region, so that, if found acceptable, ICAO is in a position to take appropriate measures for the application of such separation by a target date of 27 November 1980.

NAT SPG/17 (10 – 21 March, 1980)

The Group had before it the result of data collection during the (sub)period from 1 September 1979 to 29 February 1980, viz. a total of 11 errors in navigation of 30 NM or more off track in a total of 31048 observed flight operations of which 4 fell in the band of 50-70 NM off track. A revised classification of errors was adopted by the Group on the understanding that this should not be changed in the future without pressing need. Using the MNPS criteria, it was calculated that the total number of flights observed would allow for 16.4 errors equal to or greater than 30 NM and for 4.03 observed errors in the 50-70 NM band. In view of this the Group concluded that, for the period considered, the criteria for the application of 60 NM have been met taking into account the cautiousness of the method of assessment used and the fact that the values from previous monitoring periods showed, in general, a decreasing trend in error rate, the Group agreed that 60 NM lateral separation could then be applied.

The Group then proceeded to the determination of the most suitable implementation date which it should propose to ICAO in this respect. Taking account of the target date of 27 November 1980 proposed at NAT

SPG/16, and after extensive discussion of all relevant aspects, the Group came to the conclusion that the most suitable date to be proposed to ICAO for implementation was the AIRAC date of 30 October 1980.

Tentative arrangements for the convening of a Provider States' coordination meeting regarding the application of 60 NM lateral separation in MNPS airspace in the NAT Region were agreed for 2-5 September 1980 in the ICAO Headquarters in Montreal.

Monitoring of navigation performance until 30 October 1980 and after 60 NM lateral separation is applied were then discussed. It was concluded that a central collecting agency for data on navigation performance in the NAT Region should be instituted as early as possible.

In addition to the results and conclusions described in the foregoing four paragraphs, the mathematical-statistical methodology was reviewed and updated for future application in an attempt to resolve a number of residual issues which had not been resolved to everybody's satisfaction in the past. A number of working papers presented at the meeting pertained to these issues. The issue of greatest dissatisfaction concerned the application of the "snapshot principle" of assessing lateral collision risk used up to NAT SPG/17 versus a more sophisticated method of assessment of the lateral collision risk which uses specific weighting for individual categories of errors based on their nature and possible consequences. The two methods were referred to as Model 1 and Model 2 respectively. Model 1 had been used so far. Concerning Model 2, recall the weighting proposed in a paper presented by the Member of the Netherlands at NAT SPG/15 (Pool, 1979b) and see also (Pool, 1979a). To resolve the differences of view, the Group agreed to apply the two models to the classes of errors observed and to attempt to draw conclusions from that application as regards the advantages and disadvantages of the two models. See NAT SPG/17 (ICAO, 1980b) for details of the comparison and also Section 5.3.4.

According to NAT SPG/17 (ICAO, 1980b), the prevailing view of the Group was that, while small samples of data treated by Model 2 might not produce more accurate answers than Model 1, Model 2 would give more realistic results as more data accumulated with time. The view was also expressed that it would remain to be seen whether the use of Model 2 with more data and different weighting of a multiple number of categories of errors would produce a more valid forecast of the likely collision risk. As a consequence of this, and since it had already been agreed that in the near future monitoring would have to be continued at least at the present rate, it was agreed that both Model 1 and Model 2 should be used for the time being and that the results obtained with the use of both models should be used to in formulating appropriate operational decisions until such time as the definite advantages obtained by either of the two models permitted the Group to make a definite choice. A brief description of Model 2 is given in Appendix B to the *Summary of Discussions and Conclusions on Agenda Item 1 of the 17th Meeting of the NAT Systems Planning Group* (ICAO, 1980b).

The Provider States' coordination meeting regarding the application of 60 NM lateral separation in MNPS airspace in the NAT Region took place from 2-3 September 1980 in the ICAO Headquarters in Montreal. Considering the results obtained from the assessment of observed errors during the period 1 September 1979 to 31 August 1980, the Group agreed unanimously that Conclusion 17/1 of the 17th Meeting of the NAT SPG proposing 30 October 1980 as the date of application of 60 NM lateral separation in the MNPS airspace of the NAT Region, as approved by the Council of ICAO on 18 June 1980, remained valid (ICAO, 1980c).

NAT SPG/18 (30 March – 10 April 1981)

Review of the use of 60 NM lateral separation led to the conclusion (Conclusion 18/1) that:

- a) Data presented to the Group at the Meeting had confirmed the continued validity of the use of 60 NM lateral separation in the NAT Region under conditions as now specified in the NAT RAC SUPPS;
- b) Future scrutiny work continue to use both Models 1 and 2 until such time as these can be replaced by a methodology developed in accordance with c) below; and
- c) The mathematical-statistical experts of the Group continue their work in this field with a view to developing proposals for a commonly acceptable methodology for the mathematical-statistical assessment of risk involved in the use of 60 NM lateral separation.

NAT SPG/19 (19 – 30 April 1982)

Review of the use of 60 NM lateral separation led to the conclusion (Conclusion 19/1) that:

- a) Data presented to the Group at the Meeting had confirmed the continued validity of the use of 60 NM lateral separation in the NAT Region under conditions as now specified in the NAT RAC SUPPS;
- b) Appropriate amendments be developed by the United States for inclusion in the ICAO NAT Guidance and Information Material to reflect the Group's considerations on the use of Omega in NAT MNPS airspace; and
- c) Monitoring procedures be expanded, control charts be introduced, and a consolidated description of the revised procedures be developed by the United Kingdom for inclusion in the ICAO NAT Guidance and Information Material.

NAT SPG/20 (14 – 25 March 1983)

Concerning validation of the continued use of 60 NM lateral separation in NAT MNPS airspace, the Group agreed that, on the basis of the achieved navigational performance in NAT MNPS airspace during the current scrutiny period, the use of 60 NM lateral separation continued to meet the target level of safety. This agreement was not formulated as a formal conclusion, indicating that the use of 60 NM lateral separation had essentially matured.

In connection with the above, the possible use of composite separation 30 NM/1000 ft in NAT MNPS airspace was on the Group's agenda under agenda item 2 with discussions on it leading to Conclusion 20/3:

That preparatory work required both in the operational and mathematical statistical fields regarding the use of composite separation within the Organized Track System of the NAT Region and between FL290 and FL390 be pursued with the objective that its practical application may become feasible by the end of 1985.

5.3.4 A review of the North Atlantic lateral collision risk model by Davies and Sharpe

The previous subsection outlined the developments which ultimately led to the implementation of 60 NM lateral separation in MNPS airspace of the NAT Region as of 30 October 1980, with a first major step taken at the 12th Meeting of the NAT Systems Planning Group (NAT SPG/12) in June 1976. As set out under the NAT SPG/17 and NAT SPG/18 headings in section 5.3.3, there remained differences of view concerning the application of the “snapshot principle” of assessing lateral collision risk used up to NAT SPG/17, Model 1,

versus a more sophisticated method of assessment of the lateral collision risk which uses specific weighting for individual categories of errors based on their nature and possible consequences, Model 2. See (Pool, 1979b) and (Pool, 1979a) concerning the snapshot principle and monitoring as part of MNPS in general and on weighting in Model 2. See also (Moek & Traas, 1979) on the application of sequential test charts to the two models to decide on the target level of safety being met or not (cf. Remark 7 under the *NAT SPG/12 (31 May – 11 June, 1976)* heading in section 5.3.3). To resolve the differences of view, it was agreed to apply the two models to the classes of errors observed and to continue to use both models until such time as these can be replaced by a commonly acceptable methodology for the mathematical-statistical assessment of risk involved in the use of 60 NM lateral separation.

The practice of using both Model 1 and Model 2 in assessing lateral collision risk continued from the 17th Meeting of the NAT SPG in March 1980 up to and including the 27th Meeting of the NAT SPG in June 1991, as can be inferred from the *Summary of Discussions and Conclusions* of the pertinent meetings. However, as set out in (Davies & Sharpe, 1993), in 1990, at the 26th Meeting of the NAT/SPG, a mathematicians' working group (MWG) was formed, one of whose purposes was to review the process of lateral risk assessment and recommend to NAT SPG the use of a single approach. As a consequence, a revised form of the Model 2 approach was adopted by NAT SPG at its 27th Meeting in 1991, and confirmed at its 28th Meeting in 1992, as the approved method of lateral risk estimation in the NAT Region. The revised form is termed the "Weighted Errors Model" and is described in (1993).

Thus, the key issue is to best estimate the proportion of flight time in MNPS requirement c), or, equivalently, the probability of lateral overlap from the data on large lateral deviations (magnitude and numbers) obtained from the system performance monitoring process

Davies and Sharpe (1993) begin with stating the lateral collision risk model for NAT MNPS airspace as

$$R = P_y(S_y)P_z(0)\frac{\lambda_x}{S_x}\left[E_y(\text{same})\left\{\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right\} + E_y(\text{opp})\left\{\frac{2|\overline{V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right\}\right] \quad (5.74)$$

where R denotes the expected number of fatal accidents per aircraft flying hour. The form of the collision risk model in eq. (5.74) is the same as that in eq. (5.61) utilized for the MNPS requirements derivation except that it expresses the risk per flight hour rather than per ten million flight hours, i.e. $R = N_{ay}/10^7$. The authors then give a formula for the probability of lateral overlap $P_y(S_y)$, viz.

$$P_y(S_y) = \lambda_y \frac{H}{10} \quad (5.75)$$

where H is the proportion of time spent by the aircraft within 10 NM of any incorrect track. Navigation errors contributing to H are called ς errors. Eq. (5.75) shows that in Model 1, errors observed outside the ς bands are not relevant to the estimation of H . Values of the model parameters other than $P_y(S_y)$ used by (1993) are shown in the third column of Table 5.5 and the original values used in the MNPS derivation are given in the table's last column.

Table 5.5: Parameter values used in the derivation of the weighted errors model and of the original MNPS specification

Parameter	Description	Value used in weighted Errors Model derivation	Value used in original MNPS derivation
S_y	The lateral separation distance/minimum		60 NM
$P_y(S_y)$	The lateral overlap probability	Estimated annually	To be calculated
$P_z(0)$	The vertical overlap probability	0.39	0.25
λ_x	The length of an aircraft	0.033 NM (200 ft)	0.033 NM (200 ft)
λ_y	The span of an aircraft	0.029 NM (176 ft)	0.033 NM (200 ft)
λ_z	The height of an aircraft	0.009 NM (55 ft)	0.0085 NM (50 ft)
S_x	The longitudinal separation distance/minimum	120 NM	120 NM
$E_y(\text{same})$	The same-direction occupancy	0.45	0.5
$E_y(\text{opp})$	The opposite-direction occupancy	0.0055	0.013
$ \Delta V $	The average difference of cruising speed in pairs of aircraft	13 kts	13 kts
$ \overline{V} $	The average aircraft speed	480 kts	480 kts
$ \dot{y} $	The lateral cross-track velocity	47 kts	47 kts
$ \dot{z} $	The vertical velocity	1.5 kts	1 kts

Based on the snapshot principle, i.e. the principle that navigation errors observed at the oceanic boundary are representative of errors occurring throughout NAT MNPS airspace, the Model 1 estimate for H say, H_1 , is expressed as

$$H_1 = \frac{\text{number of errors within 10 NM of any incorrect track at boundaries}}{\text{total number of flights}} \quad (5.76)$$

If the values of the collision risk model parameters other than $P_y(S_y)$ would be still the same as assumed in the derivation of the MNPS criteria, then the safety of the 60 NM lateral separation standard can be assessed by comparing the H_1 estimate with MNPS requirement c), i.e. it must hold that (see eq. (5.68))

$$H_1 < 13 \times 10^{-5} \quad (5.77)$$

If the current values of the collision risk model parameters other than $P_y(S_y)$ would no longer be the same as assumed in the derivation of the MNPS criteria, then this can be accounted for by substituting the value of H_1 for H in the right side of eq. (5.75) and substituting the resulting estimate of $P_y(S_y)$ into the collision risk model of eq. (5.74), together with the applicable values of the other collision risk model parameters. The safety of the 60 NM lateral separation standard requires that the estimate R_1 say, of the lateral collision risk R is less than the target level of safety of 0.2×10^{-7} fatal accidents per flight hour. Since the collision risk model parameter values, particularly occupancy, have increased considerably since the start of the MNPS operations, verification of the safety of the 60 NM lateral separation standard is performed by means of the collision risk model rather than MNPS requirement c).

Under the snapshot principle, the risk estimate R_1 can be written as a sum of equal risks $R_1(k)$, $k = 1, \dots, N$, for all ζ errors, i.e.

$$R_1 = R_1(1) + R_1(2) + \dots + R_1(N) \quad (5.78)$$

where N is the number of ς errors observed. As set out in (1993), due to the nature and cause of some of the ς errors, the snapshot principle leads to overestimation of the lateral overlap probability $P_y(S_y)$, which, in combination with the non-representativeness of the lateral cross-track velocity $|\dot{y}|$, results in an estimation of collision risk that is overly cautious. A possible solution would be to apply the model in eq. (5.74) to each of the ς errors individually, estimate the proportion of flight time within 10 NM of any incorrect track and the lateral cross-track velocity for each individual ς error, and to subsequently sum the individual risks to an estimate R_1 of the total risk R . Formally,

$$R_1 = R_1(1; H(1), |\dot{y}(1)|) + R_1(2; H(2), |\dot{y}(2)|) + \dots + R_1(N; H(N), |\dot{y}(N)|) \quad (5.79)$$

where $H(k)$ and $|\dot{y}(k)|$, $k = 1, \dots, N$, are the proportion of flight time within 10 NM of any incorrect track and the lateral cross-track velocity for ς error k respectively. This method, however, would be somewhat cumbersome and lengthy to apply in practice.

A simpler method of rectifying the Model 1 overestimation of lateral risk is then stated to be weighting the risk of each error under Model 1 with the weighting factors accounting for the magnitude and cause of each individual error. Formally,

$$R_2 = R_2(1) + R_2(2) + \dots + R_2(N) \quad (5.79)$$

where

$$R_2(k) = w_k(H(k), |\dot{y}(k)|) \times R_1(k), \quad k = 1, \dots, N \quad (5.80)$$

and thus

$$R_2 = w_1(H(1), |\dot{y}(1)|) \times R_1(1) + w_2(H(2), |\dot{y}(2)|) \times R_1(2) + \dots + w_N(H(N), |\dot{y}(N)|) \times R_1(N) \quad (5.81)$$

The quantities $H(k)$ and $|\dot{y}(k)|$ have been used as arguments of the weighting factors to represent the magnitude and cause of the k^{th} error to emphasize the difference between the two rectifications of Model 1. Since, by assumption of the snapshot principle, it holds that

$$R_1(1) = R_1(2) = \dots = R_1(N), \quad (5.82)$$

eq. (5.81) can also be written as

$$R_2 = \{w_1(H(1), |\dot{y}(1)|) + w_2(H(2), |\dot{y}(2)|) + \dots + w_N(H(N), |\dot{y}(N)|)\} \times R_1(1) \quad (5.83)$$

The main criticism of the weighting applied within Model 2 is that it was incomplete because not all types of errors were fully analyzed and so not all errors were appropriately weighted.

The weighted errors model, i.e. the revision of Model 2, is then described in Davies and Sharpe (1993) as follows. Define types of error e_{ij} where i denotes the error type's cause and j denotes its magnitude. The principle that underlies the weighting is that the weighting applied to each error should be proportional to

the *average* risk that an error of its type represents. The weighting, w_{ij} , appropriate to an error of cause i and magnitude j is calculated as the ratio

$$w_{ij} = \frac{R_t(i,j)}{R_1(i,j)} \quad (5.84)$$

where $R_1(i,j)$ is the risk due to such an error according to Model 1, and $R_t(i,j)$ is the risk calculated for that error using values of H and $|\dot{y}|$ appropriate for cause i and magnitude j .

With reference to eqs. (5.79) and (5.80), the weighted errors estimate of the lateral collision risk, R_2 , is then expressed as

$$R_2 = \sum_i \sum_j n_{ij} w_{ij} R_1(i,j) \quad (5.85)$$

where n_{ij} is the number of errors of cause i and magnitude j observed with $\sum_i \sum_j n_{ij} = N$. Since $R_1(i,j)$ is the same for all i and j as a result of the snapshot principle underlying Model 1, eq. (5.85) can be re-expressed as

$$R_2 = R_1(i,j) \sum_i \sum_j n_{ij} w_{ij} \quad (5.86)$$

and thus, for the same reason, as

$$R_2 = \frac{R_1}{\sum_i \sum_j n_{ij}} \sum_i \sum_j n_{ij} w_{ij} \quad (5.87)$$

with R_1 defined by eq. (5.78).

Numerically, the Model 1 risk, R_1 , is given by eq. (5.74) with the probability of lateral overlap $P_y(S_y)$ defined by (5.75) estimated by means of H_1 in eq. (5.76) and it follows that R_1 is proportional to H_1 ,

$$R_1 = c H_1 \quad (5.88)$$

where

$$c = \frac{\lambda_y}{10} P_z(0) \frac{\lambda_x}{S_x} \left[E_y(\text{same}) \left\{ \frac{|\Delta V|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\} + E_y(\text{opp}) \left\{ \frac{2|\dot{V}|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\} \right] \quad (5.89)$$

and, with reference to eq. (5.76),

$$H_1 = \frac{\sum_i \sum_j n_{ij}}{\text{total number of flights}} \quad (5.90)$$

The weighted errors model 2 can be written in the same form as eq. (5.88) for Model 1, viz.

$$R_2 = R_1 \frac{\sum_i \sum_j n_{ij} w_{ij}}{\sum_i \sum_j n_{ij}} = c H_1 \frac{\sum_i \sum_j n_{ij} w_{ij}}{\sum_i \sum_j n_{ij}} = c \frac{\sum_i \sum_j n_{ij}}{\text{total number of flights}} \frac{\sum_i \sum_j n_{ij} w_{ij}}{\sum_i \sum_j n_{ij}} = c \frac{\sum_i \sum_j n_{ij} w_{ij}}{\sum_i \sum_j n_{ij} \text{ total number of flights}} \quad (5.91)$$

or

$$R_2 = c H_2 \quad (5.92)$$

where

$$H_2 = \frac{\sum_i \sum_j n_{ij} w_{ij}}{\text{total number of flights}} \quad (5.93)$$

Table 5.6, reproduced from Davies and Sharpe (1993), summarizes the error weightings calculated for a total of 18 combinations of cause and deviation magnitude. It was found impossible to perform detailed calculations for the “Non-certified Users” category; therefore, the larger of the weightings for waypoint insertion/ATC system loop errors and equipment failure was taken for each deviation magnitude.

Table 5.6: Error Weightings

Deviation magnitude	Type of error Deviation		
	Waypoint insertion or ATC System Loop	Equipment Failure	Non-certified Users
1° (50 – 70 NM)	0.33	0.40	0.40
2° (70 – 130 NM)	0.58	0.55	0.58
3° (130 – 190 NM)	0.84	0.70	0.84
4° (190 – 250 NM)	1.09	0.85	1.09
5° (250 – 310 NM)	1.34	1.00	1.34
6° (310 – 370 NM)	1.59	1.1	1.59

The weightings in Table 5.6 are passed on the parameter values listed in Table 5.5, particularly occupancy. It is emphasized by Davies and Sharpe (1993) that a single permanent set of weightings should not be used because it could lead to inaccuracy if the annually estimated occupancies were to change significantly from the ones in Table 5.5.

Davies and Sharpe (1993) then discuss a number of questions that might be asked concerning the weighted errors model, namely

- What sizes of errors should be considered;
- Where should the errors be sampled;
- Which criteria should be used to define error magnitude (cf. the first column of Table 5.6); and
- Limitations of weighting set.

The reader is referred to Davies and Sharpe (1993) for details on these questions.

In conclusion, the lateral collision risk for the 60 NM lateral separation standard in NAT MNPS airspace is estimated annually using the weighted errors model in eqs. (5.92), (5.89), and (5.93). This is done for MNPS airspace as a whole as well as for the Organized track System and Random Airspace making up MNPS airspace.

Remarks

1. An update of the error weightings in Table 5.6 took place at NAT SPG/36, June 2000, for the lateral collision risk assessment for the 1999 monitoring year to account for significant changes in occupancy as a result of the (partial) implementation of RVSM in the NAT Region. The updated values are shown in Table 5.7 below. Notice that the weightings for waypoint insertion or ATC system loop errors have decreased and those for equipment failures have increased. The weights for non-certified users are the larger of the other weightings for the same deviation magnitude.

Table 5.7: Revised Error Weightings agreed at NAT SPG/36 (June 2000)

Deviation magnitude	Type of error Deviation		
	Waypoint insertion or ATC System Loop	Equipment Failure	Non-certified Users
1° (50 – 70 NM)	0.33	0.48	0.48
2° (70 – 130 NM)	0.55	0.62	0.62
3° (130 – 190 NM)	0.78	0.76	0.78
4° (190 – 250 NM)	1.00	0.91	1.00
5° (250 – 310 NM)	1.22	1.05	1.22
6° (310 – 370 NM)	1.44	1.19	1.44

2. Further review of the *Summary of discussions and conclusions of the 37th to 45th Meetings of the North Atlantic Systems Planning Group* indicates that no further revisions to the error weightings were made and that the model defined by eqs. (5.92), (5.89), and (5.93) had continued to be used for the safety assessment of the 60 NM lateral separation standard in NAT MNPS airspace.
3. The *Summary of discussions and conclusions of the 45th Meeting of the North Atlantic Systems Planning Group* refers, for the first time, to plans to reduce lateral separation in the NAT Region. This is further discussed in Section 5.3.5, *RLatSM*.
4. As of NAT SPG/46 (June 2010) the *Summary of discussions and conclusions of the 46th to 56th Meetings of the North Atlantic Systems Planning Group* does no longer provide any information on the annual safety assessment of the 60 NM lateral separation standard in NAT MNPS airspace.
5. As of June 2014, an Annual Safety Report has been published for the North Atlantic Region, the first one being the *North Atlantic Region 2013 Annual Safety Report*.
6. The *Summary of discussions and conclusions of the 52nd Meeting of the North Atlantic Systems Planning Group* (June 2016) states that the NAT SPG noted that the NAT SOG (Safety Overview Group) reviewed and agreed with the NAT MWG proposed modification to the current NAT MWG methodology for the treatment of lateral deviation and gross navigational error (GNE) reports in calculating the lateral collision risk estimates:
 - a) To eliminate the use of weight factors;
 - b) To account for risk due to time spent on an incorrect track as well as the number of un-cleared tracks crossed;

- c) To include risk bearing GNEs reported via ADS-C position data in addition to those identified within the current monitoring windows; and
- d) To revise the “buffer” surrounding the un-cleared track within which a deviating aircraft would be considered risk bearing.

This is further discussed in Section 5.3.7.

5.3.5 Reduced Lateral Separation Minimum (RLatSM)

RLatSM refers to a reduced 25 NM lateral separation minimum in the NAT Region as agreed in Conclusion 45/10 of the 45th Meeting of the NAT/SPG. In a similar manner as for the implementation of the 60 NM lateral separation standard in NAT MNPS airspace described in section 5.3.3, the material in this subsection is based on review of the *Summary of Discussions and Conclusions of the Forty-Fifth to Fifty-Fifth Meetings of the North Atlantic Systems Planning Group*. It should be noted that ICAO standards had not been established for 25 NM lateral separation (NAT SPG/46). Hence, a regional collision risk assessment based on the Reich model and a target level of safety of 5×10^{-9} fatal accidents per flight hour has been performed. Unfortunately, not any documentation on this assessment is publicly available and the text below focusses on a number of important steps towards implementation of the reduced 25 NM lateral separation minimum.

A phased implementation was followed, starting with a 2-phase operational trial with RLatSM Phase 1 starting on 15 December 2015. See below under the *NAT SPG/52 (June 2016)* heading. RLatSM Phase 2 was expected to begin no earlier than 1130Z on the 4th of January 2018 as set out under the *NAT SPG/54 (June 2018)* heading below. Appendix F to the *Summary of Discussions and Conclusions of the Forty-fourth Meeting of the North Atlantic Systems Planning Group* states that the implementation of Performance-Based Communications and Surveillance on 29 March 2018 moved RLatSM from the trial phase to the operational phase. See (ICAO, 2020c) for a brief description of PBCS operations in the ICAO NAT Region.

In summary, the developments concerning the regional lateral separation minimum of 25 NM have been able to benefit from the development of the global performance-based lateral separation minimum of 23 NM. Cf. the last entry, *16th Edition incorporating Amendments 1-7-A and 8 (applicability 8/11/2018)*, in Table 2.3 of Chapter 2.

NAT SPG/45 (June 2009)

It was agreed in Conclusion 45/10 of the 45th Meeting of the NAT/SPG (NAT SPG/45), that the:

a) following concept of operations be used to develop an implementation plan for reducing lateral separation to 25 NM:

- i) Phase 1 – 2012 – introduce 25 NM lateral separation by implementing ½ degree spacing between the two core tracks, FL350 to FL400 inclusive; only aircraft with the appropriate RNP approval, Automatic Dependent Surveillance-Contract (ADS-C) and Controller Pilot Data Link Communications (CPDLC) would be permitted to operate on the ½ degree spaced tracks.*
- ii) Phase 2 – 2013 – expand the introduction of 25 NM lateral separation by implementing ½ degree spacing through the entire NAT Organised Track System (OTS), FL350 to FL400 inclusive; only aircraft with the appropriate RNP approval, ADS-C and CPDLC would be permitted to operate on the ½ degree spaced tracks.*

iii) Phase 3 – 2015 – introduce 25 NM lateral separation throughout the entire NAT Region, including for converging and intersecting track situations, between FL350 to FL400 inclusive. The application of the reduced separation standard between targets of opportunity should be permissible in any part of the NAT Region outside the OTS (mixed mode operations).

b) NAT Implementation Management Group (NAT IMG) develop the following material to support implementation plan for reducing lateral separation to 25 NM:

i) a proposal for amendment to the NAT Regional Supplementary Procedures (Doc 7030); and

ii) safety material to so as to initiate the development of global provisions;

c) ICAO Regional Director, Europe and North Atlantic coordinate with ICAO Headquarters in order to initiate the development of global provisions; and

d) NAT IMG provide NAT SPG/46 with a progress report.

In order to obtain the full benefit of implementing the concept of operations outlined above, the Group agreed that it would be necessary to mandate the use of data link equipment required to support the stated reduction in separation. To facilitate the linkage between benefits and the encouragement for operators to equip, the Group agreed that the same geographic/vertical areas being proposed for the implementation of the concept of operations should apply to the areas where data link equipped aircraft would be given priority access. Non-equipped aircraft would be excluded from the airspace concerned. The Group agreed that the intent of the mandate was to require the use of CPDLC and ADS-C in the area concerned. However, the designated areas would not include airspace where ATS surveillance services (radar and ADS-B) were being provided.

NAT SPG/46 (June 2010)

A draft implementation plan for the trial application of RLatSM was provided in Appendix C to the *Summary of Discussions and Conclusions of the Forty-Sixth Meeting of the North Atlantic Systems Planning Group* (NAT SPG/46) of which the following elements have been extracted here in this document:

6. Identification of the Method of Safety Assessment

6.1 Risk has been estimated using the Reich collision risk model.

6.1.1 Calculations used in the safety assessment are sufficient to allow provisions for the application of SLOP where RLatSM is being applied.

7. Evaluation of the Risk;

7.1 The TLS for NAT MNPS airspace in the lateral dimension is currently 20×10^{-9} fatal accidents per flight hour (fapfh). For RLatSM the TLS will be 5×10^{-9} fapfh. Ongoing monitoring will determine whether the TLS in the vertical and longitudinal dimensions is affected by the introduction of RLatSM.

7.2 Hazard Identification and Risk Analyses (HIRA) to assess the impact of the proposed change on the current system shall be carried out. These will be made available to the appropriate regulatory authorities and planning bodies as they are completed.

In addition to the above quote, the following programme risks and issues have been reproduced from Appendix D to NAT SPG/46:

1. ICAO standards have not been established for 25 NM lateral separation. It is suggested that a Safety Assessment should assess 25 NM lateral, 5 minute longitudinal and 1000 feet vertical in NAT airspace in the long term (i.e., for the next 5-15 years).

2. Estimated vertical risk in NAT airspace currently exceeds the agreed Target Level of Safety by a significant amount.
3. The first target dates for implementation of the NAT initiatives are only 2-3 years away in 2012 and 2013 and the implementation plans for the RLatSM and Data Link mandate are not yet complete.
4. The lead time for operators to procure funding, schedule and install aircraft data link and GNSS systems does not appear to be adequate to meet the time schedule for the reduction of separation. The cost/benefit analysis that would serve to justify to operators the need to incur large aircraft equipage costs is not yet available and when, completed may show that operator benefits do not outweigh operator costs.
5. The preliminary estimate of operator costs to retrofit data link and GNSS systems would appear to make such installations cost prohibitive for many operators. In addition, inadequate lead time can force operators to pull aircraft out of service to complete aircraft GNSS and/or data link system installations thereby increasing operator costs. Data link retrofit packages are not yet available for some aircraft types.
6. It has not been established that the data link system will support the operation of a track system based on reduced separation standards which rely on data link equipage. The reliability and availability of the data link system remains in question.

NAT SPG/47 June 2011

The *Summary of Discussions and Conclusions of the Forty-Seventh Meeting of the North Atlantic Systems Planning Group* (NAT SPG/47) states that NAT SPG recalled that the NAT implementation plans for the trial application of RLongSM³⁴ and RLatSM included performance specifications for communications and surveillance. It was underlined that during the NAT RLongSM and RLatSM validation trials, a) the RCP 240, as defined in the GOLD (ICAO, 2013a), would be the guideline against which actual communication performance would be measured and b) the surveillance performance specification 180, as defined in the GOLD, would be the guideline against which actual surveillance performance would be measured. Concerning the performance specifications envisaged for the operational RLongSM and RLatSM implementations, the NAT SPG agreed to include a statement in the plan that RCP 240 and surveillance performance specification 180 were the candidate specifications to be prescribed. In this regard, the NAT SPG emphasized that the current separation standards/minima were not predicated on communications performance requirements, were strategic in nature and that no change to this status was envisaged. Meeting RCP and ADS-C surveillance performance specifications would therefore be applicable only to reduced separation and new separation standards. The NAT SPG agreed that when data link performance would be assessed for the current separation standards this would be done with reference to RCP 240 and surveillance specification (ICAO, 1976a).

Updates to the RLatSM concept of operations and draft implantation plan for the trial application were provided in Appendices E and F to the *Summary of Discussions and Conclusions of the Forty-Seventh Meeting of the North Atlantic Systems Planning Group* (NAT SPG/47) and the following has been reproduced from Appendix F:

4.5 Aircraft Equipage in Target Environment

- 4.5.1 The on-board equipment that provides the CPDLC and ADS-C capabilities required for the use of RLatSM is provided by FANS 1/A or equivalent. The State of Registry or the State of the Operator

³⁴ Longitudinal separation between in-trail aircraft using the Mach Number Technique is 10 minutes - a reduced longitudinal separation minimum (RLongSM) of 5 minutes between eligible aircraft pairs is to be trialled commencing 2010.

should verify that the equipment has been certified in accordance with the requirements specified in RTCA DO-258A/EUROCAE ED-100A and RTCA DO-306/ED 122 (see also paragraph 8.1.4) or equivalent.

- 4.5.2 The navigational accuracy component to support RLatSM will be provided by the RNP 4 navigation specification which explicitly requires GNSS.
- 4.5.3 The following performance values are valid for phase one of the RLatSM operational trial since the current CRM only supports same direction traffic.
 - a) Required navigation specification is RNP 4; and
 - b) due to the fact that all RNP 4 approved aircraft are GNSS equipped the standard deviation of lateral track errors is assumed to be less than 1.852 km (1 NM); and
 - c) the proportion of the total flight time spent by aircraft 27.8 km (15 NM) or more off the cleared track shall be less than 1.07×10^{-5} ; and
 - d) the proportion of the total flight time spent by aircraft between 46.3 and 64.8 km (25 and 35 NM) off the cleared track shall be less than 2.36×10^{-6} .
- 4.5.4 ADS-C position reports provide time-keeping accuracy of ± 1 second or better (Annex 2 paragraph 3.5.3 refers).

Collision risk modelling work conducted within the NAT region has determined that aircraft certified RNP 4, a navigation specification requiring navigation using GNSS, can be separated by 25 NM. The objectives of RLatSM implementation are to:

- Reduce lateral track spacing from one degree (nominal 60 NM with gentle slope rules) to one half degree (nominal 30 NM with gentle slope rules) from FL350 to FL400 between aircraft authorized RNP 4 and having ADS-C and CPDLC capability;
- increase the number of tracks available and therefore increase capacity at optimum flight levels;
- enhance the provision of fuel-efficient profiles and routes for NAT customers to reduce operating costs with minimal change to NAT operations;
- allow for reduction in fuel burn and a consequent reduction in greenhouse gas emissions through an increased likelihood of flights being able to operate at their optimum flight levels and routes.

In accordance with the outcome of NAT IMG/38, RLatSM will be implemented using the following phased approach:

- a) Phase 1 – 2014/2015 – introduce 25 NM lateral separation by implementing $\frac{1}{2}$ degree spacing between the two core tracks, within the vertical limits applicable to the airspace associated with the NAT Region Data Link Mandate; only aircraft with the appropriate RNP approval, ADS-C and CPDLC would be permitted to operate on the $\frac{1}{2}$ degree spaced tracks.
- b) Phase 2 – To Be Determined – introduce 25 NM lateral separation by implementing $\frac{1}{2}$ degree spacing through the entire NAT Organised Track System (OTS), within the vertical limits applicable to the airspace associated with the NAT Region Data Link Mandate; only aircraft with the appropriate RNP approval, ADS-C and CPDLC would be permitted to operate on the $\frac{1}{2}$ degree spaced tracks.
- c) Phase 3 – To Be Determined – introduce 25 NM lateral separation throughout the entire NAT Region, including for converging and intersecting track situations, within the vertical limits applicable to the airspace associated with the NAT Region Data Link Mandate. The application of the reduced separation standard between targets of opportunity should be permissible in any part of the NAT Region outside the OTS (mixed mode operations).

6. Identification of the Method of Safety Assessment

- 6.1 Collision risk for same direction traffic only has been estimated using the Reich model. This is considered to be applicable under phase 1 of the RLatSM operational trial.
 - 6.1.1 Calculations used in the safety assessment are sufficient to allow provisions for the application of SLOP where RLatSM is being applied.
 - 6.1.2 Additional collision risk modelling work will be necessary to consider opposite direction traffic for application in future phases of RLatSM implementation. It is not anticipated that this will have an effect on the core navigational component but may have some effect on the choice of the limit associated with maximum acceptable rate of large navigation errors.

7. Evaluation of the Risk

- 7.1 The TLS for NAT MNPS airspace in the lateral dimension is currently 20×10^{-9} fatal accidents per flight hour (fapfh). For RLatSM the TLS will be 5×10^{-9} fapfh. Ongoing monitoring will determine whether the TLS in the vertical and longitudinal dimensions is affected by the introduction of RLatSM.
- 7.2 Hazard Identification and Risk Analyses (HIRA) to assess the impact of the proposed change on the current system shall be carried out. These will be made available to the appropriate regulatory authorities and planning bodies as they are completed.

NAT SPG/48 (June 2012)

Updates to the RLatSM concept of operations and draft implementation plan for the trial application were provided in Appendices E and F to the *Summary of Discussions and Conclusions of the Forty-Eighth Meeting of the North Atlantic Systems Planning Group* (June 2012). There were no changes to the elements listed above under the NAT SPG/47 heading other than that the planned date for Phase 1 was given as 2015.

NAT SPG/49 (June 2013)

Updates to the RLatSM concept draft implementation plan for the trial application were provided in Appendix H to the *Summary of Discussions and Conclusions of the Forty-Ninth Meeting of the North Atlantic Systems Planning Group* (June 2013). There were no changes to the elements considered above for the previous NAT SPG meetings.

NAT SPG/50 (June 2014)

The upcoming RLatSM trial was set to begin November 2015.

NAT SPG/51 (June 2015)

NAT SPG Conclusion 51/05 – *Approval of the RLatSM Trial Implementation Phase 1 Commencement* stated that:

- a) the commencement of Phase 1 of the trial implementation of Reduced Lateral Separation Minima (RLatSM) in the ICAO NAT Region as of 12 November 2015 is approved;
- b) NAT IMG and NAT SOG:
 - i) monitor the trial to ensure that safety requirements were being met; and
 - ii) provide the NAT SPG with progress reports; and
- c) the ICAO Regional Director, Europe and North Atlantic, in the behalf of NAT SPG, notify the Provider, User States and International Organisations of the above decision.

The NAT SPG noted several updates to the Task List Supporting the Trial Implementation of RLatSM in the ICAO NAT Region (RLatSM Task List), e.g. concerning:

- b) Task 12 [*NAT Safety Assessment*]. It was noted that the updated Collision Risk Estimate (CRE) was of 4.60×10^{-9} fatal accidents per flight hour (fapfh) (less than the target level of safety (TLS) of 5×10^{-9} fapfh). This result included revised aircraft size estimates and a modified same direction lateral occupancy value to more closely reflect *anticipated* conditions on the core tracks of the NAT Organized Track System (OTS). This revised estimate completed the Task for Phase 1. The CRE was also presented to NAT SOG/12, and captured in Task 13 [*Coordination with NAT Safety Oversight Group*].

NAT SPG/52 (June 2016)

The *Summary of Discussions and Conclusions of the Fifty-Second Meeting of the North Atlantic Systems Planning Group* (June 2016) states that the first set of RLatSM tracks was published on 15th December 2015. The NAT SPG was provided with a table reflecting the success criteria for Phase 1 of the Trial Application of RLatSM in the NAT Region, which showed that all success criteria had been met so far and there was no indication that the trial was having any adverse safety impact on the operations.

The NAT SPG noted that a safety assessment of RLatSM Phase 2 related to Task 12 of the RLatSM Task List had been completed. The safety assessment included a detailed analysis of four years of lateral deviation data obtained from the NAT Deviations and Errors Monitoring Application (NAT DEMA). The safety analysis reviewed the parameters contained in the Reich lateral collision risk model, with a focus on the following three variables specific to RLatSM:

- a) an updated lateral overlap probability parameter, $P_v(25)$ derived based on an analysis of the most current four years of reported gross navigation errors (GNE) within the NAT, which considered the reduced lateral separation minima;
- b) the core tracks were typically the two busiest adjacent tracks on the NAT Organized Track System (OTS). Historical same direction lateral occupancy values were not available for the core tracks but were available for the OTS. The lateral occupancy values for the OTS were used to derive a more appropriate value for the core tracks. As well, a threshold analysis determined the maximum tolerable lateral occupancy; and
- c) an average aircraft size was computed for the core tracks based on 2014 NAT flight data.

The RLatSM Phase 2 safety assessment involved a comparison of the operational differences between Phase 1 and 2. In addition, the subsequent impact on the collision risk model parameter estimates and resulting collision risk assumed in Phase 1 was examined.

The NAT SPG noted that the revised collision risk estimate of Phase 1 increased slightly to 4.72×10^{-9} fatal accidents per flight hour (fapfh), but remained below the lateral Target Level of Safety (TLS) of 5×10^{-9} fapfh. In this respect, the NAT SPG commented that this increased estimate did not match with the definition of the SF1-3 success criteria set by the RLatSM Plan and that the lateral risk would not increase. It was agreed that the Project Team would need to further examine this discrepancy and report back. Furthermore, it was noted that a review of the collision risk parameters and lateral error rates used in the updated Phase 1 assessment indicated that they would also apply to Phase 2 and, therefore, the lateral collision risk estimate for Phase 2 was also expected to be below the lateral TLS.

In view of the above, the NAT SPG agreed that the commencement date of Phase 2 would be 10 November 2016, pending an expected positive outcome of the NAT MWG, NAT SG³⁵ and North Atlantic Procedures and

³⁵ SG: Scrutiny Group.

Operations Group (NAT POG) work based on further data to be collected by the RLatSM Phase 2 Transition Project Team in autumn 2016. Should the further reports indicate any adverse impact on the operations, the decision of the commencement date of Phase 2 would be revisited by correspondence in coordination with the NAT SPG, NAT IMG and North Atlantic Safety Oversight Group (NAT SOG).

NAT SPG/53 (June 2017)

Two subjects relevant to this Section, *5.3 Further lateral separation developments in the NAT*, of this document were dealt with at NAT SPG/53, namely RLatSM, this subsection, and ASEPS based on space-based ADS-B, Section 5.3.6.

The *Summary of Discussions and Conclusions of the Fifty-Third Meeting of the North Atlantic Systems Planning Group* (June 2017) states that the NAT SPG was presented with the outcomes of the NAT IMG and NAT SOG discussions related to the progress of the RLatSM programme and FANS 1/A data link problems resolutions. It was noted that the updated data in support of the success criteria for Phase 1 of the RLatSM trial was provided by Canada and the United Kingdom. The data indicated that the status of the success criteria SF1-6 (Monitor the failures to properly achieve FANS logon, or to maintain or transfer controller pilot data link communications (CPDLC) connection and automatic dependent surveillance – contract (ADS-C) contract resulting in ATC reverting to another form of separation) remained Pending.

The NAT SPG recalled that Phase 2 of the RLatSM trial as per NAT IMG Decision 48/01 would start only when the ATC workload associated with FANS 1/A connection issues was adequately mitigated. It was noted that the connection issues were being tracked and resolutions were being investigated and actioned by Canada and the United Kingdom in coordination the NAT Data Link Monitoring Agency (DLMA) and NAT Technology and Interoperability Group (NAT TIG) problem resolution activities in a bid to meet SF1-6 and transition to Phase 2 of the RLatSM trial. The group noted that updated data would be provided to September 2017 meetings of the NAT IMG contributory groups to demonstrate whether the implemented resolutions resulted in meeting SF1-6 success criterion. Provided that this objective proved to be attainable by September 2017, a planned transition to Phase 2 would take place in November 2017. In any case, the implementing ANSPs and States would make the updated data available to the NAT SPG by correspondence, in support of the trial success criteria, providing an agreed two (2) AIRAC (Aeronautical Information Regulation and Control) cycle notification prior to the implementation date.

Regarding space-based ADS-B, the NAT SPG was provided with an update on the NAT progress concerning the Space-based Automatic Dependent Surveillance – Broadcast (SB ADS-B) implementation. The Group noted that the outcome of the ICAO Separation and Airspace Safety Panel (SASP) work would need to be taken into account in further updates to the provisional version of the NAT SB ADS-B Concept of Operations (CONOPS). With regards to the NAT Safety Plan, the NAT SPG noted that the safety documentation in support of the SB ADS-B implementation would include the following:

- a) documentation produced by the ICAO SASP, including collision risk modelling (CRM) work and guidance to implementers describing all actions that would need to be completed; and
- b) safety management information produced by NAT air navigation service providers (ANSPs) implementing SB ADS-B.

Furthermore, the NAT SPG was presented with a proposal outlining a set of prerequisites for an operational trial for application of ASEPS based on SB ADS-B in the ICAO NAT Region. The NAT SPG recalled that a number of NAT ANSPs formalized, or were in the process of formalizing, arrangements with the SB ADS-B service

provider. Once it was confirmed that service provided would meet the performance requirements, this new capability could be made available to support new and improved ATS in the NAT Region, as outlined in the NAT SB ADS-B CONOPS. The NAT SPG noted that the collision risk modelling within the ICAO SASP to support ASEPS was nearing completion and that the joint Canada/United Kingdom concept of operations anticipated using the procedures developed by the SASP on a trial basis, pending publication of the minima in PANS-ATM (Doc 4444). The NAT SPG supported, in principle, the proposed operational trial for application of ASEPS based on SB ABS-B in the NAT Region and noted that such a trial would also provide valuable data and experience to support finalization of the global criteria. However, the completion of the work on the set of prerequisites would need to be reported and approved by the NAT SPG prior to the trial.

In this respect, IFALPA stated that while being supportive of the significant safety benefits derived from ASEPS implementation and their intention to participate proactively through various ICAO bodies in the development of operating procedures and standards, taking into account the significant remaining issues surrounding PBCS implementation and RLatSM Phase 2 expansion, consideration of “new” operational trials was premature. IFALPA believed that information on the forthcoming expansion of available satellites, further development of SB ADS-B CONOPS, data on current equipage levels, and feedback from various ICAO Groups (i.e. SASP) should be gathered and presented to the various NAT SPG contributory bodies to enable identifying specific proposed trial components that would form the basis for establishing an appropriate trial timeline.

In connection with the above, the NAT SPG recalled that the NAT Space Based ADS-B Project Team (SB ADS-B PT) was developing an implementation plan and a supporting task list for implementation of SB ADS-B in the NAT that would be reviewed by NAT IMG and NAT SOG and approved by NAT SPG. The NAT SPG was presented with an initial list of tasks that was agreed for insertion into the above-mentioned SB ADS-B PT work.

Based on the foregoing, it was agreed in *NAT SPG Conclusion 53/5 – Prerequisites for SB ADS-B Operational Trial*, that the following prerequisites are to be fulfilled in order to enable an operational trial to use Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B):

- a) the Separation and Airspace Safety Panel (SASP) has agreed minima and associated requirements for Advanced Surveillance-Enabled Procedural Separation (ASEPS);
- b) implementing Air Navigation Services Providers (ANSP) have:
 - i) completed ASEPS implementation plans aligned to the NAT SB ADS-B Concept of Operations (CONOPS) and the SASP output referred to in a) above;
 - ii) confirmed their SB ADS-B service meets identified performance requirements;
 - iii) completed safety management activities as required by their respective regulatory authorities; and
 - iv) confirmed that the Performance Based Communication and Surveillance (PBCS) performance is measured and reported in the same manner as other applications of reduced separation in the NAT;
- c) the plans and the outputs of the safety management activities referred to in b) above have been reviewed by the NAT Implementation Management Group (NAT IMG) and the NAT Safety Oversight Group (NAT SOG);
- d) the NAT IMG and NAT SOG identify success criteria and trial duration;
- e) neither the NAT IMG nor the NAT SOG identifies an issue that, in their opinion, requires resolution before an operational trial should commence;
- f) the NAT IMG has confirmed that implementing ANSPs have completed all required implementation activities; and

- g) NAT SPG has approved the implementation plan and supporting task list that would also include the above listed prerequisites to enable a trial for implementation of SB ADS-B in the NAT.

NAT SPG/54 (June 2018)

The *Summary of Discussions and Conclusions of the Fifty-fourth Meeting of the North Atlantic Systems Planning Group* (June 2018) suggests that RLatSM was only dealt with under Agenda Item 5. *NAT Documentation Updates*, specifically under 5.2 *NAT OPS BULLETINS RELATED TO RLATSM PHASE 2 AIC, RLATSM SPECIAL EMPHASIS ITEMS (SEI) AND NAT RLATSM TASK LIST V2017_2*.

NAT OPS Bulletin - RLatSM Phase 2 AIC (Serial no: 2017_003) states that RLatSM Phase 2 is expected to begin no earlier than 1130Z on the 4th of January 2018.

APPENDIX F — NORTH ATLANTIC ANNUAL SAFETY REPORT (NAT ASR) 2017 to the *Summary of Discussions and Conclusions of the Fifty-fourth Meeting of the North Atlantic Systems Planning Group* states that The RLatSM Phase 1 trial commenced November 12, 2015 in the Gander and Shanwick OCAs. The implementation of Performance-Based Communications and Surveillance on 29 March 2018 moved RLatSM from the trial phase to the operational phase. Half degree tracks will be published based on fleet equipage and demand.

NAT SPG/55 (June 2019)

RLatSM was referenced in the main body of the *Summary of Discussions and Conclusions of the Fifty-Fourth Meeting of the North Atlantic Systems Planning Group*, under Agenda Item 2.3, *Update to the NAT SPG Conclusion 49/05 (NAT PBCS Requirements)*. The NAT SPG was presented with a proposal to update the NAT SPG Conclusion 49/05 (RCP and RSP for RLatSM and RLongSM) that allowed the acceptance of the transaction time and surveillance data delivery time at a level of 99.0% rather than that at the specified 99.9% for RLatSM and RLongSM. It was agreed that Conclusion 49/5 should be repealed and anew one endorsed to take account of the completion of the trial and commencement of the operational implementation.

5.3.6 Advanced Surveillance-Enhanced Procedural Separation (ASEPS)

Advanced Surveillance-Enhanced Procedural Separation (ASEPS)³⁶ refers to oceanic separation where position surveillance reporting of order 2 – 60 seconds is available (ICAO, 2020a). Current technologies that may support ASEPS include space-based ADS-B. It concerns a lateral spacing of 19 NM between parallel or non-intersecting tracks. See also Table 2.3 of Chapter 2 and Section 5.4.

NAT SPG/53 (June 2017)

As set out above in section 5.3.5 under the *NAT SPG/53 (June 2017)* heading, the NAT SPG was provided with an update on the NAT progress concerning the Space-based Automatic Dependent Surveillance – Broadcast (SB ADS-B) implementation. The Group noted that the outcome of the ICAO Separation and Airspace Safety Panel (SASP) work would need to be taken into account in further updates to the provisional version of the NAT SB ADS-B Concept of Operations (CONOPS). With regards to the NAT Safety Plan, the NAT SPG noted that the safety documentation in support of the SB ADS-B implementation would include the following:

- a) documentation produced by the ICAO SASP, including collision risk modelling (CRM) work and guidance to implementers describing all actions that would need to be completed; and

³⁶ The ASEPS acronym originated at the 28th Meeting of the SASP Working Group, Reykjavik, Iceland, May 2016.

- b) safety management information produced by NAT air navigation service providers (ANSPs) implementing SB ADS-B.

Furthermore, the NAT SPG was presented with a proposal outlining a set of prerequisites for an operational trial for application of ASEPS based on SB ADS-B in the ICAO NAT Region. The NAT SPG recalled that a number of NAT ANSPs formalized, or were in the process of formalizing, arrangements with the SB ADS-B service provider. Once it was confirmed that service provided would meet the performance requirements, this new capability could be made available to support new and improved ATS in the NAT Region, as outlined in the NAT SB ADS-B CONOPS. The NAT SPG noted that the collision risk modelling within the ICAO SASP to support ASEPS was nearing completion and that the joint Canada/United Kingdom concept of operations anticipated using the procedures developed by the SASP on a trial basis, pending publication of the minima in PANS-ATM (Doc 4444). The NAT SPG supported, in principle, the proposed operational trial for application of ASEPS based on SB ADS-B in the NAT Region and noted that such a trial would also provide valuable data and experience to support finalization of the global criteria. However, the completion of the work on the set of prerequisites would need to be reported and approved by the NAT SPG prior to the trial.

In this respect, IFALPA stated that while being supportive of the significant safety benefits derived from ASEPS implementation and their intention to participate proactively through various ICAO bodies in the development of operating procedures and standards, taking into account the significant remaining issues surrounding PBCS implementation and RLatSM Phase 2 expansion, consideration of “new” operational trials was premature. IFALPA believed that information on the forthcoming expansion of available satellites, further development of SB ADS-B CONOPS, data on current equipage levels, and feedback from various ICAO Groups (i.e. SASP) should be gathered and presented to the various NAT SPG contributory bodies to enable identifying specific proposed trial components that would form the basis for establishing an appropriate trial timeline.

In connection with the above, the NAT SPG recalled that the NAT Space Based ADS-B Project Team (SB ADS-B PT) was developing an implementation plan and a supporting task list for implementation of SB ADS-B in the NAT that would be reviewed by NAT IMG and NAT SOG and approved by NAT SPG. The NAT SPG was presented with an initial list of tasks that was agreed for insertion into the above-mentioned SB ADS-B PT work.

Based on the foregoing, it was agreed in *NAT SPG Conclusion 53/5 – Prerequisites for SB ADS-B Operational Trial*, that the following prerequisites are to be fulfilled in order to enable an operational trial to use Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B):

- a) the Separation and Airspace Safety Panel (SASP) has agreed minima and associated requirements for Advanced Surveillance-Enabled Procedural Separation (ASEPS);
- b) implementing Air Navigation Services Providers (ANSP) have:
 - i) completed ASEPS implementation plans aligned to the NAT SB ADS-B Concept of Operations (CONOPS) and the SASP output referred to in a) above;
 - ii) confirmed their SB ADS-B service meets identified performance requirements;
 - iii) completed safety management activities as required by their respective regulatory authorities; and
 - iv) confirmed that the Performance Based Communication and Surveillance (PBCS) performance is measured and reported in the same manner as other applications of reduced separation in the NAT;

- c) the plans and the outputs of the safety management activities referred to in b) above have been reviewed by the NAT Implementation Management Group (NAT IMG) and the NAT Safety Oversight Group (NAT SOG);
- d) the NAT IMG and NAT SOG identify success criteria and trial duration;
- e) neither the NAT IMG nor the NAT SOG identifies an issue that, in their opinion, requires resolution before an operational trial should commence;
- f) the NAT IMG has confirmed that implementing ANSPs have completed all required implementation activities; and
- g) NAT SPG has approved the implementation plan and supporting task list that would also include the above listed prerequisites to enable a trial for implementation of SB ADS-B in the NAT.

NAT SPG/54 (June 2018)

It was noted that in general the implementation of PBCS on 29 March 2018 went smoother than anticipated, given the expectation that initial approval levels could have been very low. Increasing the collective approval rate of the NAT fleet from the 40-45% range into numbers more aligned to the FANS 1/A equipage numbers, typically over 90%, remained a concern, particularly since traffic would increase as the summer months approached.

The NAT SPG was presented with a status of implementations of actions agreed by NAT SPG Conclusion 53/5 (*Prerequisites for SB ADS-B Operational Trial* refers). With regards to a) of the foregoing conclusion, the NAT SPG was informed that the Second meeting of the ICAO Separation and Airspace Safety Panel (SASP/2) (Montreal, Canada, 7-18 May 2018) agreed on an Advanced Surveillance Enhanced Procedural Separation (ASEPS) Proposal for Amendment (PfA) to the *Procedures for Air Navigation Services — Air Traffic Management* (PANS-ATM, Doc 4444). The proposed changes to the PANS-ATM should become effective on 5 November 2020. The NAT SPG noted that the proposal for Doc 4444 amendment would be normally expected during the spring of 2019 and a State letter informing about the approval of the amendment would be circulated in the first half of 2020. Should any developments at these stages suggest that there might be any changes to the current SASP agreed wording, the Secretariat would take appropriate actions to inform the NAT SPG to discuss possible follow up actions with regards to the NAT trial.

Concerning sub-item g) of NAT SPG Conclusion 53/5, the NAT SPG was provided with the latest draft Implementation Plan and Task list (Appendix B³⁷ refers) in support of an operational trial of ASEPS using Space-based Automatic Dependent Surveillance-Broadcast (SB ADS-B). It was noted that the Implementation Plan and Task List were intended to cover both longitudinal and lateral separation applications, with the application of lateral separation proposed to commence no earlier than 6 (six) months after commencement of the longitudinal separation application. As per NAT SPG Conclusion 53/5, the Implementation Plan and Task List integrated and described in detail the prerequisites for the Operational Trial of ASEPS using SB ADS-B. In conjunction with this, the NAT SPG was also provided with the provisional version of the NAT SB ADS-B Concept of Operations (CONOPS) (Appendix C refers), developed by the SB ADSB Project Team, that would be further updated by the North Atlantic Procedures and Operations Group (NAT POG) taking the SASP outcomes into account.

This Implementation Plan (and associated Task List) supports a trial implementation period beginning in March 2019 and follows the guidelines provided in ICAO Doc 9689 (Manual on Airspace Planning Methodology for Determination of Minima). The NAT SPG agreed that the foregoing documents would be

³⁷ Appendix B to the *Summary of Discussions and Conclusions of the Fifty-fourth Meeting of the North Atlantic Systems Planning Group*.

further reviewed by the NAT IMG and NAT SOG contributory bodies culminating in the NAT IMG/53 and NAT SOG/19 meetings to ascertain whether all prerequisites of NAT SPG Conclusion 53/5 had been appropriately addressed so that the decision on the commencement of the NAT ASEPS trial using SB ADS-B could be taken.

Based on the above, the NAT SPG agreed to the following: *NAT SPG Conclusion 54/9 – Operational Trial of Advanced Surveillance Enhanced Procedural Separation (ASEPS) using Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B)* That:

- a) the Implementation Plan and Task List for an operational trial of Advanced Surveillance-Enhanced Procedural Separation (ASEPS) using Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B) be approved by the NAT IMG/53 and the NAT SOG/19 meetings, provided that the NAT IMG and NAT SOG have ascertained that all prerequisites of NAT SPG Conclusion 53/5 have been satisfied; and
- b) subject to the NAT IMG and NAT SOG approval, the operational trial be planned to:
 - i) commence on 28 March 2019 provided all prerequisites of NAT SPG Conclusion 53/5 have been satisfied; and
 - ii) continue until 5 November 2020 or the effective date of ASEPS provisions in the *procedures for Air Navigation Services - Air Traffic Management* (PANS-ATM, Doc 4444), whichever is later.

NAT SPG/55 (June 2019)

The NAT SPG was informed that in follow up to NAT SPG Conclusion 54/9, the NAT IMG/53 and NAT SOG/19 carried out an analysis of all the pre-requisites contained in NAT SPG Conclusion 53/5 and agreed that all of the pre-requisites had been met for the Operational Trial of ASEPS using SB ADS-B in the longitudinal dimension to start on 28 March 2019. Therefore, the conditions of the NAT SPG Conclusion 53/5 had been fulfilled and the trial could proceed as agreed on 28 March 2019.

Following the positive outcome from the NAT IMG/53 and NAT SOG/19 meetings, the NAT SPG Conclusion 55/1 was endorsed by correspondence and the following documents were published:

- a) *NAT OPS Bulletin – Trial Implementation of ASEPS using ADS-B* (Serial no: 2018_006);
- b) *NAT OPS Bulletin - Special Procedures for In-flight Contingencies* (Serial no: 2018_005); and
- c) amendment to the *North Atlantic Operations and Airspace Manual* (NAT Doc 007).

Therefore, the operational trial of ASEPS using ADS-B in the longitudinal dimension commenced in the NAT on 28 March 2019. Furthermore, the NAT SPG was presented with updates to the Implementation Plan for Operational Trial of ASEPS using ADS-B, and the draft NAT Operations (OPS) Bulletin addressing the expansion of the ASEPS Operational Trial to include lateral spacing of 19 NM between non-intersecting tracks. Concerning the safety cases, it was noted that NAT SOG/20 was presented with a draft Safety Case covering Shanwick and Gander Oceanic Control Areas (OCA) and identified no issues requiring resolution before an operational trial should commence for ASEPS lateral. The final safety cases would be submitted to the NAT SOG by correspondence and pending that submission, it was agreed that, all of the pre-requisites for NAT SPG Conclusion 54/9 had either been satisfied or a process had been put in place to ensure that they would be satisfied prior to the implementation date of the Operational Trial of ASEPS using SB ADS-B in the lateral dimension within Gander and Shanwick OCAs. Therefore, following the successful commencement of the ASEPS Longitudinal Separation Operational Trial on 28 March 2019, it was agreed that the date to commence the Lateral Separation Operational Trial would be 10 October 2019. The NAT OPS Bulletin would be published by 15 August 2019 together with State AICs which would allow for 2 AIRAC cycles notice.

5.3.7 Revised NAT/MWG methodology for lateral collision risk assessment

Paragraph 5.1.8 of agenda item 5. *SAFETY MONITORING* in the *Summary of Discussions and Conclusions of the Fifty-Second Meeting of the North Atlantic Systems Planning Group* (June 2016) states that the NAT SPG noted that the NAT SOG reviewed and agreed with the NAT MWG proposed modification to the current NAT MWG methodology for the treatment of lateral deviation and GNE reports in calculating the lateral collision risk estimates:

- a) To eliminate the use of weight factors;
- b) To account for risk due to time spent on an incorrect track as well as the number of un-cleared tracks crossed;
- c) To include risk bearing GNEs reported via ADS-C position data in addition to those identified within the current monitoring windows; and
- d) To revise the “buffer” surrounding the un-cleared track within which a deviating aircraft would be considered risk bearing.

Hence, the NAT SPG noted that the NAT SOG agreed to task NAT SG to capture the information on the time spent by the aircraft on an incorrect track.

Before proceeding, it is useful to define the meaning of the words risk bearing GNE. The North Atlantic 2017 Annual Safety report (European & office, 2018) defines a GNE as a deviation of 10 NM or greater. Davies and Sharpe (1993) in their work on the weighted errors model for the NAT Region use the term risk-bearing error for any error assessed to contribute to the risk. This covers all errors larger than 50 NM whereas some others may also be included dependent on the case. They also use the term ζ errors for those risk-bearing errors observed to be within the bands 50-70 NM, 110-130 NM, etc. Recall from Section that the key of the weighted errors lateral collision risk model is the estimation of the proportions of flying time spent within the bands 50-70 NM, 110-130 NM, etc. for all types of deviations based on the actual movement of the aircraft during a large deviation rather than the snapshot principle.

The revised NAT MWG methodology for lateral collision risk assessment is based on (ICAO?, 2016a) and (ICAO?, 2016b). As set out in (ICAO?, 2016a), the new methodology is predominantly driven by the availability of data on lateral deviations, cf. bullet c) above, and makes the lateral collision risk model more consistent with the vertical collision risk for operational risk due to aircraft flying at an un-cleared level or incorrectly crossing through another aircraft’s flight level (see Chapter 6).

The revised NAT MWG methodology estimates the probability of lateral overlap due to large lateral deviations (LLDs) explicitly as the proportion of flight time spent on wrong routes and/or proportion of flight time involved in deviating aircraft crossing through one or more routes (ICAO?, 2016a). In the methodology, the probability of lateral overlap for a deviating aircraft crossing through an adjacent or non-adjacent route is the same since the proportions of flight time associated with crossing each track are assumed to be the same (based on an assumed constant lateral speed of the deviating aircraft). Similarly, the probability of lateral overlap for aircraft flying on a wrong route is only dependent on the amount of time spent on wrong route and not on whether the route is adjacent or non-adjacent (though in the latter case on or more incorrect route crossings are to be accounted for also). It follows from the above that there are thus two estimates for the probability of lateral overlap, one for the time spent on un-cleared/incorrect route and another for the number of un-cleared/incorrect routes crossed.

The probability of lateral overlap $P_y(S_y)^{wrong\ route}$ for large lateral deviations resulting in time spent on uncleared/incorrect routes is given by (ICAO?, 2016a) and (ICAO?, 2016b):

$$P_y(S_y)^{wrong\ route} = \frac{T_r}{F} \times P_y(0) \quad (5.94)$$

where T_r represents the total amount of time spent on uncleared/incorrect routes in the airspace under consideration for a given period of calendar time and F denotes the total amount of flight time in the airspace over the period of calendar time. It is noted in (ICAO?, 2016a) that at the time of drafting that paper, it was not possible to determine the time spent by aircraft on incorrect routes directly from the information recorded in the NAT Deviations and Errors Monitoring Application (DEMA) database. It was thus assumed that each incorrect track joining event lasted for 13.5 minutes, based on the maximum intervention time in the traditional CPDLC/HF communications model. The remaining parameter, $P_y(0)$, on the right side of eq. (5.94) denotes the probability of lateral overlap for aircraft on the same route. It can be estimated from the probability distribution with probability density function $f(y)$, say, of the typical navigation performance of the target aircraft population operating on the parallel route system in the same way as the probability of lateral overlap $P_y(S_y)$ of eq. (4.17) of Chapter 4, viz.

$$P_y(0) = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f(y_1) f(y_1 - y) dy_1 dy \quad (5.95)$$

where λ_y denotes the average width of the aircraft.

The probability of lateral overlap $P_y(S_y)^{incorrect\ crossing}$ for large lateral deviations resulting in uncleared/incorrect routes crossed is given by (ICAO?, 2016a) and (ICAO?, 2016b):

$$P_y(S_y)^{incorrect\ crossing} = \frac{N_r}{F} \times \frac{2\lambda_y}{|\dot{y}(S_y)|} \quad (5.96)$$

where N_r represents the total number of crossings through uncleared/incorrect routes in the airspace under consideration for a given period of calendar time and F denotes again the total amount of flight time in the airspace over the period of calendar time. As in eq. (5.95), λ_y denotes the average width of the aircraft. The parameter $|\dot{y}(S_y)|$ in the denominator on the right side of eq. (B.7) denotes the average lateral cross-track speed for an aircraft deviating from its track. The number of crossings through uncleared/incorrect routes can be derived from the magnitude of the maximum deviation and the prevailing lateral separation standard. In practice, some buffers are incorporated into the computation.

As reported in (ICAO, 2019), the NAT MWG, noting PBCS implementation and application of the 23-NM lateral standard, agreed that, from 29 March 2018 forward, the buffer values used to classify lateral deviations as risk-bearing, should be:

- 17 NM if the aircraft is eligible for a 23-NM lateral separation OTS environment and, therefore, is RNP4 equipped (23NM – 4 NM [RNP4] – 2 NM [1 × SLOP]);
- 15 NM if the aircraft is eligible for a 23-NM lateral separation random environment and, therefore, is RNP4 equipped (23 NM – 4 NM [RNP4] – 4 NM [2 × SLOP to account for opposite direction traffic]);
- 36 NM if the aircraft is RNP10 (50 NM – 10 NM [RNP10] – 4 NM [2 × SLOP to account for opposite direction traffic]).

Buffer values for non-adjacent tracks can be derived from multiples of the separation standard minus the RNP value minus 1 or 2 times SLOP as applicable.

In principle, the probabilities of lateral overlap defined by eqs. (5.94) – (5.96) for time spent on wrong route and incorrect route crossings can be substituted into the lateral collision risk model of eq. (5.74) of Section 5.3.4, i.e. with $R = N_{ay}$ and $|\bar{y}| = |\bar{y}(S_y)|$,

$$N_{ay} = P_y(S_y)P_z(0)\frac{\lambda_x}{S_x}\left[E_y(\text{same})\left\{\frac{|\bar{\Delta V}|}{2\lambda_x} + \frac{|\bar{y}(S_y)|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right\} + E_y(\text{opp})\left\{\frac{2|\bar{V}|}{2\lambda_x} + \frac{|\bar{y}(S_y)|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right\}\right] \quad (5.97)$$

to estimate the lateral collision risk for each type of large lateral deviation and the two risk estimates summed to obtain an estimate of the total lateral risk. However, different values for $|\bar{y}(S_y)|$ are used for large lateral deviations involving time spent on wrong route and incorrect route crossing. For the latter, the usual definition and symbol $|\bar{y}(S_y)|$ (and values) are used whereas for the former the symbol $|\bar{y}(0)|$ is used for the average (absolute value of the) relative lateral speed between aircraft operating on the same route.

Thus, the lateral collision risk model based on the revised NAT MWG methodology is written as

$$N_{ay} = N_{ay}^{\text{wrong route}} + N_{ay}^{\text{incorrect crossing}} \quad (5.98)$$

with

$$N_{ay}^{\text{wrong route}} = P_y(S_y)^{\text{wrong route}}P_z(0)\frac{\lambda_x}{S_x}\left\{E_y(\text{same})\left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}(0)|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right] + E_y(\text{opp})\left[\frac{|\bar{V}|}{\lambda_x} + \frac{|\bar{y}(0)|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right]\right\} \quad (5.99)$$

and

$$N_{ay}^{\text{incorrect crossing}} = P_y(S_y)^{\text{incorrect crossing}}P_z(0)\frac{\lambda_x}{S_x}\left\{E_y(\text{same})\left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}(S_y)|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right] + E_y(\text{opp})\left[\frac{|\bar{V}|}{\lambda_x} + \frac{|\bar{y}(S_y)|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right]\right\} \quad (5.100)$$

In the conventional Reich collision risk model, each same- and opposite-direction aircraft pair is assumed to have the same probability of lateral overlap $P_y(S_y)$ (e.g. based on a GDE or DDE lateral deviation distribution) and the same assumption is reflected in the collision risk models of eqs. (5.99) and (5.100). However, dependent on the amount of information on a particular large lateral deviation and the flow direction on the wrong route(s) flown or crossed, it might be possible to compute probabilities of lateral overlap for time spent on wrong route or incorrect route crossings separately for same- and opposite-direction aircraft pairs.

5.4 Lateral separation standards/minima determined by the ICAO RGCSP and SASP

This section briefly describes the lateral collision risk models used in references (ICAO, 2010, 2014b, 2014a, 2014c, 2020a).

5.4.1 GNSS lateral separation minima based on VOR separation in ICAO Circular 322

Circular 322 (ICAO, 2014a) deals with the safety assessment for the extension of the traditional separation standards for VOR (and NDB) nav aids to aircraft using GNSS navigation. As set out in this reference, following the guidance from the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (ICAO, 1998c), SASP determined to conduct a safety analysis using the comparative safety assessment method, i.e. comparison of a proposed system (GNSS) with a reference system (VOR) that is (assumed to be) safe as opposed to an evaluation of system risk against a threshold. Since SASP was not seeking to determine new separation minima, but rather to demonstrate that a different technology could be used to allow the application of existing VOR-based separation minima, it determined that it would be reasonable to compare GNSS performance with the existing VOR/DME performance in terms of accuracy of position determination since GNSS cross-track accuracy is at least as good as VOR accuracy and GNSS along-track accuracy is at least as good as DME accuracy. The position determination accuracy of GNSS was therefore deemed to be better or at least no worse than for VOR/DME. The actual comparison was made at the hand of lateral collision risk for pairs of VOR and/or GNSS aircraft where the risk for VOR-VOR pairs was calculated first and used as a reference for pairs of GNSS aircraft or VOR-GNSS aircraft. The safety assessment was performed over three successive SASP meetings.

Collision risk for the different pairs of aircraft was calculated with the collision risk model based on reliability theory (Anderson, 2005). This model is presented in Chapter 7. of this document and the equations below have been taken from that chapter.

Consider a pair of aircraft with along-track and across-track navigation errors ε_1^A , ε_2^A , ε_1^C , and ε_2^C on routes intersecting at an angle of θ as in Figure 5.2.

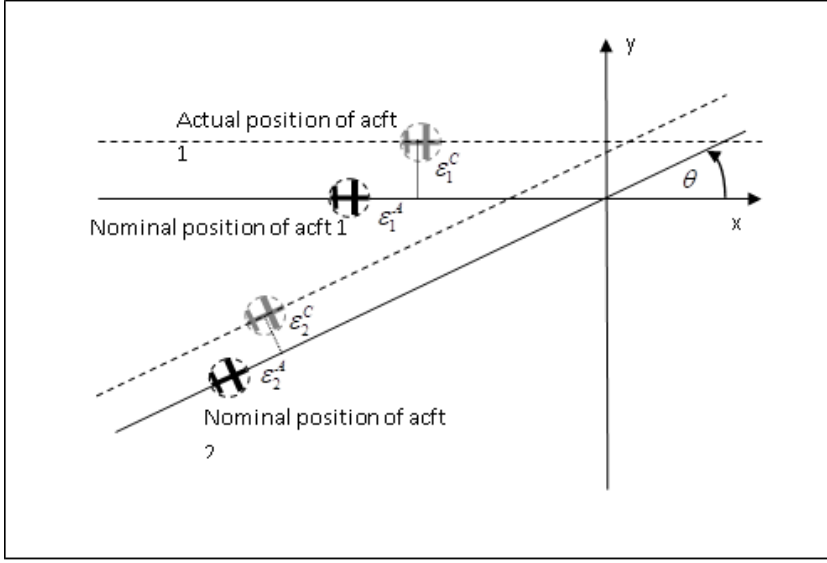


Figure 5.2: Illustration of the along-track errors and the across-track errors for a pair of aircraft on intersecting routes in the horizontal plane

Lateral collision risk for an aircraft pair over a time interval $[t_0, t_1]$ is given by ($m = 1$ in eq. (7.12))

$$N_a = 2\pi\lambda_{xy}^2 P_z \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) \left(1 + \frac{\pi\lambda_{xy}|\bar{z}|}{4\lambda_z v_{xy}} \right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (5.101)$$

where $f_i(v_i)$ is the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denotes the joint probability density of the relative position $r_x(t)$, $r_y(t)$ of two aircraft at time t for $r_x(t) = r_y(t) = 0$. The latter probability density is given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C$$

where ε_2^A and ε_2^C denote the along-track and across-track navigational errors of aircraft 2³⁸. $D_x(t)$ and $D_y(t)$ denote the nominal relative position between the aircraft.

In eq. (5.101), λ_{xy} and λ_z denote the diameter and height of the horizontal cylinder representing the aircraft respectively, v_{xy} denotes the relative horizontal speed between the aircraft, P_z denotes the pair's probability of vertical overlap, and $|\bar{z}|$ denotes the average of (the absolute value of the) relative vertical speed between the aircraft.

Anderson (Anderson, 2005) defines lateral separation of aircraft on intersecting tracks in terms of a defined area of conflict around the intersection. This area is a quadrilateral, see Figure 5.3, of which the corners are known as lateral separation points, defined as the points on a track where the perpendicular distance to the other track is equal to the lateral separation minimum for intersecting tracks. To avoid confusion with the lateral separation minimum S_y for parallel routes, the lateral separation minimum for intersecting routes is

³⁸ Both aircraft are assumed to have the same navigational error distributions and it is shown in Chapter 7 that $f_t(0,0)$ can be expressed in terms of either ε_2^A and ε_2^C or ε_1^A and ε_1^C .

denoted S_y^* . Lateral separation is achieved by the controller ensuring that two aircraft will not be simultaneously within the area of conflict at the same level. Figures 5.4 and 5.5 show the scenarios of both aircraft approaching the area of conflict and of one aircraft leaving the area of conflict as the other one enters respectively.

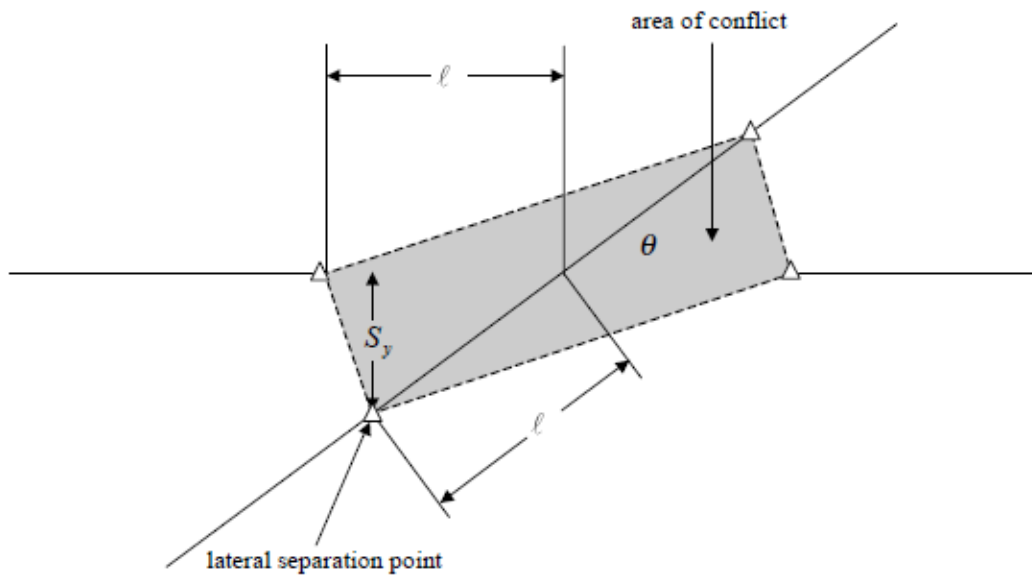


Figure 5.3: Lateral separation points and the area of conflict (Reproduced from (Anderson, 2005))

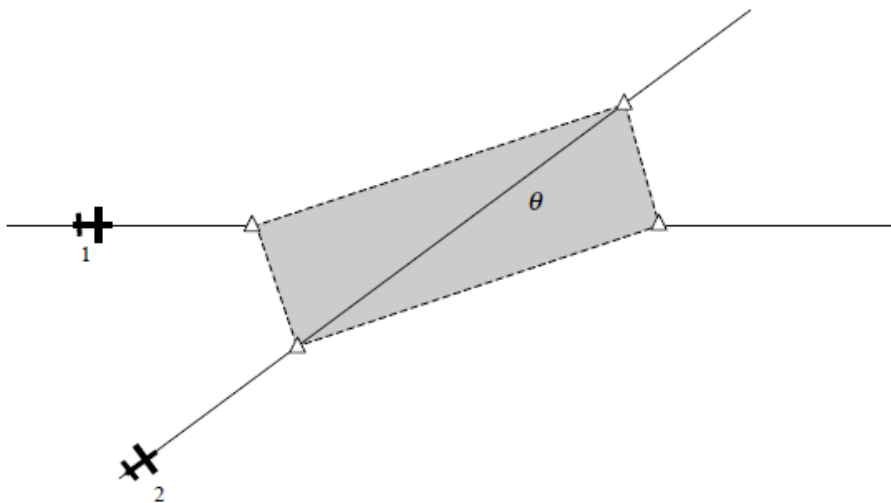


Figure 5.4: Both aircraft approaching the area of conflict (Reproduced from (Anderson, 2005))

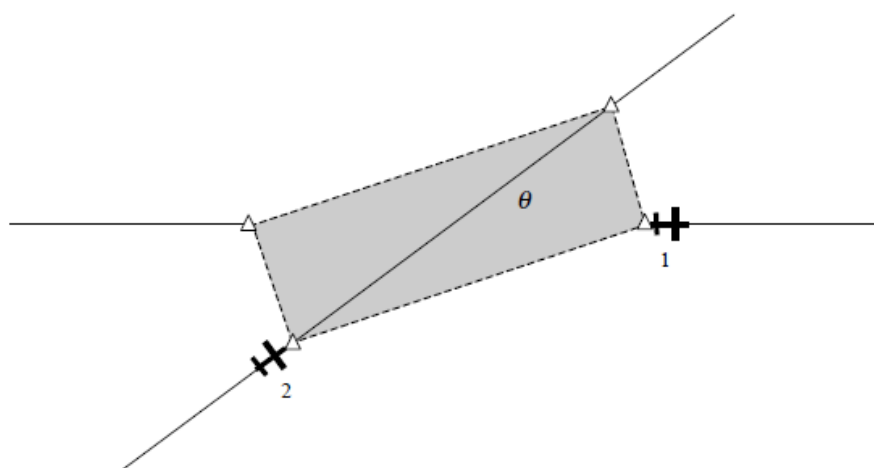


Figure 5.5: One aircraft leaving the area of conflict as the other one enters (Reproduced from (Anderson, 2005))

As described in (ICAO, 2014c), the strategy followed in the safety analysis was to choose an angle between radial tracks, a flight level, aircraft ground speeds and a combination of aircraft flight directions, towards or away from the VOR (at the intersection point). Calculations were done first for a VOR-VOR aircraft pair. The first aircraft was started at a trial lateral separation point, such as 15 NM from the VOR and a set of second aircraft were started at a range of distances from the VOR on the other radial track. The aircraft were then flown for 10 minutes, a collision risk for each pair was calculated using the collision risk model above, and an average collision risk over all the second aircraft starting positions was calculated. If the average risk was less than 4×10^{-10} , then the lateral separation point was decreased and the computations repeated until the collision risk was found to be just under 4×10^{-10} , which is the level of safety based on a target level of safety of 5×10^{-9} fatal accidents per flight hour converted to accidents for a 10 minute period. Taking the lateral separation point found from the VOR-VOR calculation, a GNSS aircraft was then substituted for either or both VOR aircraft and an average collision risk calculated for the new pairs. See (ICAO, 2014c) for the navigational accuracies used.

Tabular results were presented in a working paper (Ref. 1 of (ICAO, 2014c)) at the ninth meeting of the Working Group of the Whole of the SASP (SASP-WG/WHL/9) for a range of track intersection angles, flight levels, and combinations of ground speed and flight direction. To two decimal places, the results showed a lower or equal collision risk when a GNSS aircraft was substituted for a VOR aircraft on intersecting tracks at a VOR. It was also shown that the lateral separation points at angles higher than 15 degrees could be safely less than 15 NM.

A second working paper (Ref. 3 of (ICAO, 2014c)) presented at the tenth meeting of the Working Group of the Whole of the SASP (SASP-WG/WHL/10) extended the modelling to

- i) Have initial positions for the second aircraft every 0.1 NM rather than the previous 0.25 NM;
- ii) Include lower altitudes;
- iii) Include more aircraft ground speed combinations.

Very fast aircraft were not paired with very slow aircraft. Also, aircraft speeds greater than 300 kts were excluded below FL150 and speeds lower than 300 kts were excluded above FL150. Reference Levels of Safety (RLS) were calculated using both Gaussian and double exponential navigational-error distributions. These were the maximum collision risks obtained with the 15-degree – 15 NM VOR-VOR case, maximised over all the flight level/speed combinations for diverging, converging and passing cases. As in the first working paper, a GNSS aircraft was then substituted for either or both VOR aircraft and an average collision risk calculated for the new pairs until the maximum collision risks were either no more than 5% greater than the corresponding VOR-VOR value or negligible (less than 4×10^{-10}).

Based on four main recommendations made at SASP-WG/WHL/10, a third and final working paper (Ref. 4 of (ICAO, 2014c)) was presented at the eleventh meeting of the Working Group of the Whole of the SASP (SASP-WG/WHL/11). The recommendations concerned a refinement of the modelling of the tracking tolerance abeam a VOR (or NDB), constraining the reference levels of safety for VOR-VOR pairs only up to FL100, extending the risk calculations up to intersection angles of 135 degrees, and extending the calculations to NDB aircraft substituting for one or both aircraft. The final results gave theoretical minimum lateral separation values for all combinations of aircraft navigating by means VOR or NDB or GNSS. The values were obtained through a chain of comparisons against the collision risk for a 15 degree – 15 NM pair of aircraft navigating by means of VOR.

The new lateral separation minimum was incorporated into the PANS-ATM through Amendment 6 to its 15th Edition (with an applicability date of 13 November 2014). See the pertinent entry in Table 2.3 in Section 2.5.1.

5.4.2 Lateral separation minima in ICAO Circulars 334, 341, and 349

Circular 349 (ICAO, 2014b) deals with *Guidelines for the implementation of lateral separation minima* intended for the separation of aircraft approved for performance-based navigation (PBN) and/or global navigation satellite system (GNSS) operations. It supersedes two previous ICAO Circulars dealing with the subject of lateral separation minima, namely Circulars 334 (ICAO, 2014c) and 341 (ICAO, 2015b). The three Circulars cover the following cases:

- 50(/50) NM lateral separation of non-intersecting tracks – RNAV 10 (RNP 10), RNP 4 or RNP 2;
- 30 NM lateral separation of non-intersecting tracks – RNP 4
- 20/23 NM lateral separation of non-intersecting tracks – RNP 4 or RNP 2;
- 15 NM/Not Applicable lateral separation of non-intersecting tracks – RNP 2 or IFR GNSS;
- 7 NM/Not Applicable lateral separation while on climb or descent of an RNP 2 or GNSS aircraft through the flight level of another such aircraft;
- 20 NM lateral separation while on climb or descent of an RNP 2 or GNSS aircraft through the flight level of another such aircraft;
- Intersecting tracks: 15 NM – RNP 2/GNSS, 30 NM – RNP 4 and 50 NM -RNAV 10 (RNP 10);
- 9 NM/Not Applicable lateral separation while on climb or descent of an RNP 2 or GNSS aircraft through the flight level of another such aircraft; and
- Intersecting tracks: 15 NM – RNP 2/GNSS, 23 NM – RNP 4 and 50 NM -RNAV 10 (RNP 10);

The 50(/50) NM etc notation refers to a distinction between airspace where SLOP is not authorized, or is authorized only up to 0.5 NM, and airspace where SLOP up to 2 NM is authorized. Cf. the pertinent entries in Table 2.3 in Section 2.5.1. See also (ICAO, 2014d) for details of the incorporation of SLOP into the safety assessment of the lateral separation minima for parallel routes. Circulars 334, 341 and 349 document the safety assessments/collision risk assessments performed by SASP in support of the pertinent separation minima and present some implementation considerations as well. This subsection takes a quick look at the form of the collision risk models used for each of the eight cases.

5.4.2.1 50 NM lateral separation of non-intersecting tracks – RNAV 10 (RNP 10), RNP 4 or RNP 2

Eqs. (3.4.1) and (3.4.2) of Section 3.4 of Circular 334 (ICAO, 2014c) provide the following collision risk models, for same- and opposite-direction traffic on parallel routes,

$$N_{ay}(\text{same}) = P_y(S_y)P_z(0) \frac{\lambda_x}{S_x} E_y(\text{same}) \left\{ \frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} \quad (5.102)$$

$$N_{ay}(\text{opp}) = P_y(S_y)P_z(0) \frac{\lambda_x}{S_x} E_y(\text{opp}) \left\{ \frac{2|\overline{V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} \quad (5.103)$$

where the left-side variables $N_{ay}(\text{same})$ and $N_{ay}(\text{opp})$ denote the respective expected numbers of fatal accidents per flight hour. The models were used in conjunction with a target level of safety of 5×10^{-9} fatal accidents per flight hour. The two models are clearly of the Reich model type of eqs. (5.26) and (5.27) but use occupancy parameters rather than proximity times and different units for the collision risk. The two models may also be compared with the same- and opposite-direction components within the lateral collision risk models for parallel routes described in eq. (5.61) of section 5.3.3 (MNPS derivation), eq. (5.97) of section 5.3.4 (Davies and Sharpe (1993)), and eq. (5.97) of section 5.3.7 (revised NAT/MWG methodology). See textbox below.

$$\text{Lateral risk (same)} = \frac{T_y(\text{same})}{S_x(\text{std})} \left[\frac{\overline{\Delta V}}{2} P_y(\text{std})P_z(0) + \lambda_x P_y(\text{std})N_z(0) + \lambda_x N_y(\text{std})P_z(0) \right] \quad (5.26)$$

$$\text{Lateral risk (opp)} = \frac{T_y(\text{opp})}{S_x(\text{std})} \left[\overline{V} P_y(\text{std})P_z(0) + \lambda_x P_y(\text{std})N_z(0) + \lambda_x N_y(\text{std})P_z(0) \right] \quad (5.27)$$

$$N_{ay} = 10^7 P_y(S_y)P_z(0) \frac{\lambda_x}{S_x} \left[E_y(\text{same}) \left\{ \frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} + E_y(\text{opp}) \left\{ \frac{2|\overline{V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} \right] \quad (5.61)$$

$$R = P_y(S_y)P_z(0) \frac{\lambda_x}{S_x} \left[E_y(\text{same}) \left\{ \frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} + E_y(\text{opp}) \left\{ \frac{2|\overline{V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} \right] \quad (5.74)$$

$$N_{ay} = P_y(S_y)P_z(0) \frac{\lambda_x}{S_x} \left[E_y(\text{same}) \left\{ \frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y(S_y)}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} + E_y(\text{opp}) \left\{ \frac{2|\overline{V}|}{2\lambda_x} + \frac{|\overline{y(S_y)}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right\} \right] \quad (5.97)$$

The probability of lateral overlap $P_y(S_y)$ in eqs. (5.102) and (5.103) was calculated on the assumption of the probability distribution of the lateral deviations being double double exponential, i.e., c.f. eq. (5.69),

$$f(y) = \frac{(1-\alpha)}{2\lambda_1} \exp\left(-\left|\frac{y}{\lambda_1}\right|\right) + \frac{\alpha}{2\lambda_2} \exp\left(-\left|\frac{y}{\lambda_2}\right|\right) \quad (5.69)$$

with $P_y(S_y) \approx 2\lambda_y \times C_y(S_y)$ and the convolution integral $C_y(S_y)$ given by eq. (5.72),

$$C_y(S_y) = (1-\alpha)^2 \frac{\lambda_1 + S_y}{4\lambda_1^2} e^{-\frac{S_y}{\lambda_1}} + \alpha^2 \frac{\lambda_2 + S_y}{4\lambda_2^2} e^{-\frac{S_y}{\lambda_2}} + 2\alpha(1-\alpha) \left\{ \frac{\lambda_1^2}{\lambda_1^2 - \lambda_2^2} \frac{1}{2\lambda_1} e^{-\frac{S_y}{\lambda_1}} - \frac{\lambda_2^2}{\lambda_1^2 - \lambda_2^2} \frac{1}{2\lambda_2} e^{-\frac{S_y}{\lambda_2}} \right\} \quad (5.72)$$

Each of the two models was then used in a reverse manner to calculate a maximum tolerable value of $P_y(S_y)$ for $S_y = 50$ NM, as a function of occupancy with occupancies ranging from 0.1 to 2.0 in steps of 0.1, from a maximum tolerable risk of $N_{ay} = 5 \times 10^{-9}$ fapfh and suitable values for all the remaining collision risk model parameters other than occupancy and the probability of lateral overlap. Conservative values for the parameters α and λ_2 related to the probability distribution of atypical lateral deviations were determined from the maximum tolerable probabilities of lateral overlap as set out in Section 3.4 of Circular 334 (ICAO, 2014c). The next step was to determine a maximum tolerable value for the remaining scale parameter λ_1 of the probability distribution of typical lateral deviations by requiring the probability of lateral overlap due to typical deviations to be less than or equal to one per cent of the probability of lateral overlap due to atypical deviations.

The final step was to translate the maximum tolerable value of λ_1 into a navigation performance requirement using 95% containment for typical lateral deviations. This step found that at most levels of lateral occupancy, same-direction traffic would need to impose RNP 7 in order to meet the TLS, and opposite-direction traffic would need to impose RNP 6 in order to meet the TLS, where it should be noted that the safety assessment was actually performed before the development of PBN, i.e. with RNP defined in the Manual on RNP (ICAO, 1999b) as an RNP type based on a single navigation performance accuracy value that is expected to be achieved at least 95 per cent of the time by the population of aircraft operating within an airspace and not yet as a performance-based RNP navigation specification incorporating onboard performance monitoring and alerting (ICAO, 2013b). Cf. Section 2.4. However, both the RGCSP and its successor, the SASP, declined to consider the development of standards for either RNP 7 or RNP 6. An earlier RGCSP study, using a less stringent TLS of 2×10^{-8} fatal accidents per flight hour had derived a 95% containment distance of 8 NM for typical lateral errors. The 50 NM lateral separation standard ended up in the PANS-ATM for RNP 10 navigation performance in the pre-PBN era and, equivalently, for RNAV 10 (RNP 10) in the PBN era. Clearly, RNP 4 and RNP 2 in the PBN sense meet the 95% containment requirement of 6 NM or 7 NM.

The 50 NM lateral separation minimum was incorporated into the PANS-ATM through Amendment 3 to its 15th Edition (with an applicability date of 13 November 2014). See the pertinent entry in Table 2.3 in Section 2.5.1. Until then, the PANS-ATM included a means of providing lateral separation for *RNAV operations where RNP is specified on parallel tracks or ATS routes* based on non-overlapping protected airspace of the tracks or ATS routes with a reference to Guidance Material in Attachment B, *Method of Establishing ATS Routes for Use by RNAV-equipped Aircraft*, to ICAO Annex 11 (Moek, 2015b)).

SLOP was not considered in (EUROCONTROL, 1997) but has been addressed in an update in (ICAO, 2014b). See the pertinent entry in Table 2.3 in Section 2.5.1 for the 16th Edition of the PANS-ATM incorporating Amendment 8 with an applicability date of 8 November 2018.

5.4.2.2 30 NM lateral separation of non-intersecting tracks – RNP 4

Eqs. (3.5.1) and (3.5.2) of Section 3.5 of ICAO Circular 334 (ICAO, 2014c) provide the following collision risk models, for same- and opposite-direction traffic on parallel routes,

$$N_{ay}(same) = P_y(S_y)P_z(0)\frac{\lambda_x}{S_x}E_y(same)\left\{\frac{|\Delta V|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z}\right\} \quad (5.102)$$

$$N_{ay}(opp) = P_y(S_y)P_z(0)\frac{\lambda_x}{S_x}E_y(opp)\left\{\frac{2|\dot{V}|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z}\right\} \quad (5.103)$$

where the left-side variables $N_{ay}(same)$ and $N_{ay}(opp)$ denote the respective expected numbers of fatal accidents per flight hour. The models were used in conjunction with a target level of safety of 5×10^{-9} fatal accidents per flight hour. The form of the models is the same as for the 50 NM lateral separation minimum in the previous Section 5.4.2.1, but the values of the models' parameters are (partly) different, particularly those of the probabilities of lateral overlap $P_y(S_y)$.

It is noted in Section 3.5 of Circular 334 (ICAO, 2014c) that the model in eqs. (5.102) and (5.103) applies to a pair of co-altitude parallel flight paths separated by S_y . The exposure to the risk of collision due to the loss of planned lateral separation is represented by the occupancy parameter $E_y(\cdot)$. When a route system is made up of several parallel routes, with adjacent routes separated by S_y , the risk model needs to account for – and needs to combine – the rates of collision between aircraft assigned to co-altitude flight paths whose lateral separation is $2S_y, 3S_y, \dots$. The principle difficulties in doing so were the lack of a theoretical basis for computing the occupancies of path pairs having different separations and different aircraft flow rates, and the lack of formulas for “adding” the accident rates attributable to pairs of co-altitude paths in a route system. A solution to these difficulties is presented.

The probability of lateral overlap $P_y(S_y)$ in eqs. (5.102) and (5.103) was calculated on the assumption of the probability distribution of the lateral deviations being double double exponential, i.e., c.f. eq. (5.69),

$$f(y) = \frac{(1-\alpha)}{2\lambda_1} \exp\left(-\left|\frac{y}{\lambda_1}\right|\right) + \frac{\alpha}{2\lambda_2} \exp\left(-\left|\frac{y}{\lambda_2}\right|\right) \quad (5.69)$$

with $P_y(S_y) \approx 2\lambda_y \times C_y(S_y)$ and the convolution integral $C_y(S_y)$ given by eq. (5.72),

$$C_y(S_y) = (1-\alpha)^2 \frac{\lambda_1 + S_y}{4\lambda_1^2} e^{-\frac{S_y}{\lambda_1}} + \alpha^2 \frac{\lambda_2 + S_y}{4\lambda_2^2} e^{-\frac{S_y}{\lambda_2}} + 2\alpha(1-\alpha) \left\{ \frac{\lambda_1^2}{\lambda_1^2 - \lambda_2^2} \frac{1}{2\lambda_1} e^{-\frac{S_y}{\lambda_1}} - \frac{\lambda_2^2}{\lambda_1^2 - \lambda_2^2} \frac{1}{2\lambda_2} e^{-\frac{S_y}{\lambda_2}} \right\} \quad (5.72)$$

The lateral overlap probabilities $P_y(k \times S_y)$, $k = 1, 2, 3, \dots$, of aircraft assigned to parallel routes separated by $k \times S_y$ can be obtained from eq. (5.72) by substituting $k \times S_y$, $k = 1, 2, 3, \dots$, for S_y .

The principle of the approach followed is then described in section 3.5 of Circular 334 (ICAO, 2014c) for a single pair of routes carrying traffic in either the same or the opposite direction and it is stated that the reasoning can then be applied to systems made up of several parallel routes.

Thus, each of the two models was then used in a reverse manner to calculate a maximum tolerable value of $P_y(S_y)$ for $S_y = 30$ NM, as a function of occupancy with occupancies ranging from 0.1 to 2.0 in steps of 0.1, from a maximum tolerable risk of $N_{ay} = 5 \times 10^{-9}$ fapfh and suitable values for all the remaining collision risk model parameters other than occupancy and the probability of lateral overlap.

The next step was to determine values of the parameters λ_1 , λ_2 , and α of the double-double-exponential probability density of the lateral deviations. The parameter λ_1 was based on taking the 95% containment limit as 4 Nm, resulting in $\lambda_1 = 4/(-\ln 0.05) = 1.3354$ NM. The parameter λ_2 was conservatively taken as the spacing S_y between adjacent routes, i.e. $\lambda_2 = 30$ NM. Finally, a maximum tolerable value for the last parameter α was obtained by substituting the maximum tolerable values for the probability of lateral overlap into the equation $P_y(S_y) \approx 2\lambda_y \times C_y(S_y)$ with $C_y(S_y)$ given by eq. (5.72), substituting the value for λ_1 and λ_2 into $C_y(S_y)$ and solving for α . For the generalised case of lateral collision risk for adjacent as well as non-adjacent flight paths, the maximum tolerable value for α was obtained directly from the maximum tolerable risk (rather than the maximum tolerable probabilities of lateral overlap) since all probabilities of lateral overlap $P_y(k \times S_y)$ depend in the same way on α .

The 30 NM lateral separation minimum was incorporated into the PANS-ATM through Amendment 3 to its 15th Edition (with an applicability date of 13 November 2014). See the pertinent entry in Table 2.3 in Section 2.5.1.

SLOP was not considered for the 30 NM lateral separation minimum in (EUROCONTROL, 1997) and has not been addressed at a later stage because the 30 NM was overtaken by the 23 NM lateral separation minimum to be discussed in the next Section 5.4.2.3.

5.4.2.3 20/23 NM lateral separation of non-intersecting tracks – RNP 4 or RNP 2

The two collision risk models in eqs. (3.5.1) and (3.5.2) of Section 3.5 of Circular 334 (ICAO, 2014c) for same- and opposite-direction traffic on parallel routes quoted in the previous Section 5.4.2.2 for the 30 NM lateral separation standard for RNP 4 as eqs. (5.102) and (5.103), were also used for the safety assessment of this subsection's lateral separation minimum for RNP 4 (or RNP 2) approved aircraft, but with a slightly different notation for the lateral separation minimum, aircraft length, width, and height, namely S , l , w , and h , instead of the traditional symbols S_y , λ_x , λ_y , and λ_z . See (ICAO, 1998c) to Section 3.5 of Circular 341 (ICAO, 2015b). Thus,

$$N_{ay}(same) = P_y(S)P_z(0) \frac{l}{S_x} E_y(same) \left\{ \frac{|\Delta V|}{2l} + \frac{|\bar{y}|}{2w} + \frac{|\bar{z}|}{2h} \right\} \quad (5.104)$$

$$N_{ay}(opp) = P_y(S)P_z(0) \frac{l}{S_x} E_y(opp) \left\{ \frac{2|\bar{V}|}{2l} + \frac{|\bar{y}|}{2w} + \frac{|\bar{z}|}{2h} \right\} \quad (5.105)$$

As before, the left-side variables $N_{ay}(same)$ and $N_{ay}(opp)$ denote the respective expected numbers of fatal accidents per flight hour. The models were also used again in conjunction with a target level of safety of 5×10^{-9} fatal accidents per flight hour. The new symbols for the (average) aircraft dimensions have no special meaning but the use of a new symbol S instead of the traditional symbol S_y for the route spacing was

intentional to indicate that the lateral separation minimum was not specified in advance, but to be determined from the probability distribution of the lateral deviations of RNP 4 approved aircraft as a function of occupancy, given suitable values for the collision risk model parameters other than occupancy and probability of lateral overlap. Put differently, the lateral separation minimum S was to be determined as a fourth a parameter in addition to the three parameters characterizing the mixture distribution of the lateral deviations of RNP 4 approved aircraft and, thus, the probability of lateral overlap.

Unlike for the safety assessment of the 30 NM lateral separation minimum, the probability of lateral overlap $P_y(S)$ in eqs. (5.104) and (5.105) was calculated on the assumption of the probability distribution of the lateral deviations being normal double exponential, i.e.,

$$f(y) = \frac{(1-\alpha)}{\sigma\sqrt{2\pi}} \exp\left(-\frac{y^2}{2\sigma^2}\right) + \frac{\alpha}{2\lambda} \exp\left(-\frac{|y|}{\lambda}\right) \quad (5.106)$$

with $P_y(S) \approx 2w \times C_y(S)$ and the convolution integral $C_y(S)$ given by

$$C_y(S) = (1-\alpha)^2 \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{S}{\sigma}\right)^2} + \alpha(1-\alpha) \frac{1}{\lambda} e^{\frac{1}{2}\left(\frac{\sigma}{\lambda}\right)^2} \left\{ e^{-\frac{S}{\lambda}} \Phi\left(\frac{S}{\sigma} - \frac{\sigma}{\lambda}\right) + e^{\frac{S}{\lambda}} \Phi\left(-\frac{S}{\sigma} - \frac{\sigma}{\lambda}\right) \right\} + \alpha^2 \frac{\lambda+S}{4\lambda^2} e^{-\frac{S}{\lambda}} \quad (5.107)$$

The convolution integral $C_y(S)$ is seen to be made up of three terms, usually referred to as the core-core, core-tail, and tail-tail terms respectively. The change to the form of the probability distribution of the typical deviations of RNP 4 approved aircraft followed the convention adopted by the SASP in 2006 for aircraft approved to the PBN-based RNP 4 navigation specification in light of the onboard performance monitoring and alerting capability of such aircraft. The parameter σ of the core distribution of typical lateral deviations was taken to be the value that provides 95 per cent lateral containment within 4 NM of the intended flight path, i.e. $\sigma = 2.0408$ NM and the parameter λ of the tail distribution of atypical deviations was conservatively taken as the intended lateral separation standard/minimum S .

Having specified two (σ and λ) of the four unknown parameters, it remained to determine appropriate values for the proportion α of atypical lateral deviations and for the lateral separation minimum S given a maximum tolerable level of lateral collision risk (TLS) of 5×10^{-9} fatal accidents per flight hour. Expressions for α and S were obtained by approximating (and retrospectively verifying the validity of the approximation) the probability of lateral overlap $P_y(S)$ by $2w$ times the core-tail term of the convolution integral $C_y(S)$ of eq. (5.107) and by requiring that the core-core term to be a small fraction t of the core-tail term. This resulted in the maximum tolerable α and the smallest tolerable S given by

$$\alpha = \frac{P_y(S) \cdot e \cdot S}{2w} \quad (5.108)$$

$$S = 2\sigma \sqrt{-\ln\left(\frac{\sigma\sqrt{\pi t P_y(S)}}{w}\right)} \quad (5.109)$$

Both expressions depend on the probability of lateral overlap $P_y(S)$ and their derivation, as well as the specification of σ and λ , has not utilized the collision risk model yet. However, the collision risk model comes in through maximum tolerable values for $P_y(S)$ obtained by using the collision risk model (for same-direction

traffic as well as for opposite-direction traffic) in a reverse manner as a function of occupancy with occupancies ranging from 0.2 to 2.0 in steps of 0.2, for a maximum tolerable risk of $N_{ay} = 5 \times 10^{-9}$ fapfh and given suitable values for all the collision risk model parameters other than occupancy and the probability of lateral overlap.

For maximum occupancies of $E_y(\text{same}) = E_y(\text{opp}) = 2.0$, the minimum tolerable spacing S for pairs of same-direction aircraft on parallel RNP-4 routes was found to be 17.37 NM and that for pairs of opposite-direction aircraft on parallel RNP-4 routes was found to be 18.45 NM.

The calculations in (ICAO, 1998c) to Section 3.5 of Circular 341 (ICAO, 2015b) summarized above assumed that aircraft intend to follow the nominal cleared track. SLOP, however, allows the flight crew to follow a track up to 2 NM to the right of the nominal track. Thus, a “worst-case” application of SLOP for two opposite direction aircraft on adjacent tracks would reduce the nominal spacing between the tracks by 4 NM. Correcting the minimum tolerable spacing of $S = 18.45$ NM for pairs of opposite-direction aircraft on parallel RNP-4 routes for the use of SLOP gives $S = 22.45$ NM. Thus, a lateral separation minimum of $S_y = 23$ NM was adopted by the SASP for RNP 4 approved aircraft on parallel routes in procedural airspace where SLOP up to 2 NM is authorized.

The 23 NM lateral separation minimum was incorporated into the 16th Edition of the PANS-ATM with an applicability date of 10 November 2016. See the pertinent entry in Table 2.3 in Section 2.5.1.

The 20 NM lateral separation minimum for airspace where SLOP is not authorized, or is authorized only up to 0.5 NM, was incorporated into the 16th Edition of the PANS-ATM through Amendment 8 with an applicability date of 8 November 2018. See the pertinent entry in Table 2.3 in Section 2.5.1 and Circular 349 (ICAO, 2014b).

5.4.2.4 15 NM/Not Applicable lateral separation of non-intersecting tracks – RNP 2 or IFR GNSS

Eqs. (3.6.1) – (3.6.3) of Section 3.6 of Circular 334 (ICAO, 2014c) provide the following collision risk model used for the safety assessment of 15 NM spacing of parallel routes for IFR GNSS equipped aircraft:

$$N_{ac,same} = N_x(\text{same})P_y(S_y)P_z(0) \left\{ 1 + \frac{\lambda_x}{\lambda_y} \frac{|\bar{y}|}{2|\bar{V}|} + \frac{\lambda_x}{\lambda_z} \frac{|\bar{z}|}{2|\bar{V}|} \right\} \quad (5.110)$$

$$N_{ac,opp} = N_x(\text{opp})P_y(S_y)P_z(0) \left\{ 1 + \frac{\lambda_x}{\lambda_y} \frac{|\bar{y}|}{2|\bar{V}|} + \frac{\lambda_x}{\lambda_z} \frac{|\bar{z}|}{2|\bar{V}|} \right\} \quad (5.111)$$

$$N_{ac} = N_{ac,same} + N_{ac,opp} \quad (5.112)$$

where the left-side variables $N_{ac,same}$, $N_{ac,opp}$ denote the expected numbers of fatal accidents per flight hour for same- and opposite-direction traffic and N_{ac} denotes the expected total number of fatal accidents per flight hour. The model in eq. (5.112) was used in conjunction with a target level of safety of 5×10^{-9} fatal accidents per flight hour.

The two component models in eqs. (5.110) and (5.111) may be referred to as the passing frequency forms of the occupancy form of the Reich model given in eqs. (5.102) and (5.103) of section 5.4.2.1. The relationship between the passing frequency and occupancy parameters is given by

$$N_x(\text{same}) = E_y(\text{same}) \frac{\lambda_x \overline{|\Delta V|}}{S_x 2\lambda_x} \quad (5.113)$$

$$N_x(\text{opp}) = E_y(\text{opp}) \frac{\lambda_x \overline{|V|}}{S_x 2\lambda_x} \quad (5.114)$$

Since the combination of occupancy and the factor λ_x/S_x defines the probability of longitudinal overlap, eqs. (5.113) and (5.114) can also be written as

$$N_x(\text{same}) = P_x(\text{same}) \frac{\overline{|\Delta V|}}{2\lambda_x} \quad (5.115)$$

$$N_x(\text{opp}) = P_x(\text{opp}) \frac{\overline{|V|}}{2\lambda_x} \quad (5.116)$$

Cf. eq. (5.14) of Section 5.2.2, *Reich (1966) Part II*.

As explained in Section 3.6 of Circular 334 (ICAO, 2014c), the 15 NM lateral separation minimum was developed to exploit the advanced navigational capabilities of en-route GNSS-equipped aircraft in a VHF voice communications environment, but with no requirement for surveillance to be present. This “sensor-specific” focus did not mean that it was intended to exclude future navigation means. Rather, the restriction to GNSS enabled a clearer assessment of the sources of navigational error. The conclusions could be applied to any other navigation means with performance at least as good as GNSS and the navigational performance was later recognized to be similar to what could be expected of RNP 2 approved aircraft. As a consequence, the SASP decided to publish the separation minimum as applicable to both GNSS-equipped aircraft and RNP 2 approved aircraft.

Three sources of typical lateral navigation error were included in the modelling, namely GNSS navigational error, navigational error in the event of a RAIM outage, and flight technical error. Each source of error was assumed to have a normal distribution with standard deviation σ_i , $i = 1, 2, 3$. The combination of the first two error sources was taken as a mixture of two normal distributions and subsequently combined (convoluted) with the normal distribution of the third error source to give

$$f(y) = \frac{(1-\alpha)}{\sqrt{\sigma_1^2 + \sigma_3^2} \sqrt{2\pi}} \exp\left(-\frac{y^2}{2(\sigma_1^2 + \sigma_3^2)}\right) + \frac{\alpha}{\sqrt{\sigma_2^2 + \sigma_3^2} \sqrt{2\pi}} \exp\left(-\frac{y^2}{2(\sigma_2^2 + \sigma_3^2)}\right) \quad (5.117)$$

with $\sigma_1 = 0.538$ NM, $\sigma_2 = 2.94$ NM, $\sigma_3 = 1.28$ NM, and $\alpha = 1.9 \times 10^{-5}$. Typical aircraft passing frequencies of $N_x(\text{same}) = 1$ and $N_x(\text{opp}) = 3$ passings per flight hour were assumed and aircraft dimensions were conservatively set at Airbus A380 values. The probability of lateral overlap $P_y(S_y)$ for the normal mixture density in eq. (5.117) is given by

$$P_y(S_y) \approx 2\lambda_y \left\{ \frac{(1-\alpha)^2}{\sqrt{\sigma_1^2 + \sigma_3^2} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{S_y}{\sqrt{\sigma_1^2 + \sigma_3^2}} \right)^2} + 2\alpha(1-\alpha) \frac{(1-\alpha)^2}{\sqrt{\sigma_1^2 + \sigma_2^2 + 2\sigma_3^2} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{S_y}{\sqrt{\sigma_1^2 + \sigma_2^2 + 2\sigma_3^2}} \right)^2} + \alpha^2 \frac{(1-\alpha)^2}{\sqrt{\sigma_2^2 + \sigma_3^2} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{S_y}{\sqrt{\sigma_2^2 + \sigma_3^2}} \right)^2} \right\} \quad (5.118)$$

Substitution of all the collision risk model parameter values into the model given in eqs. (5.110) – (5.112) with $S_y = 15 \text{ NM}$ resulted in a risk estimate of $N_{ac} = 7.68 \times 10^{-10}$ fatal accidents per flight hour due to the loss of planned lateral separation and typical lateral navigation error, i.e. well below the target level of safety of 5×10^{-9} fatal accidents per flight hour. Atypical navigational errors were modelled by a double-exponential distribution and carried through the calculations. One example was given that led to a risk just under the TLS and it was concluded that it is therefore possible to have the collision risk under the TLS for RNP 2 approved aircraft on parallel routes spaced at 15 NM and operational error dominating the risk budget.

The 15 NM lateral separation minimum was incorporated into the PANS-ATM through Amendment 6 to its 15th Edition with an applicability date of 13 November 2014. See the pertinent entry in Table 2.3 in Section 2.5.1.

The lateral risk calculations summarized above did not account for SLOP. This was made explicit in the PANS-ATM through Amendment 8 to it with an applicability date of 8 November 2018. See the pertinent entry in Table 2.3 in Section 2.5.1 and Circular 349 (ICAO, 2014b).

5.4.2.5 7 NM or 20 NM, dependent on the type of communication, while one aircraft climbs/descends through the level of another aircraft for RNP 2 or GNSS equipage

Eq. (3.7.1) of Section 3.7 of Circular 334 (ICAO, 2014c) provides the following collision risk model used for the safety assessment of the climb or descent of an RNP 2 or GNSS aircraft through the flight level of another such aircraft when both are travelling in the same direction on parallel paths:

$$Prob\{\text{collision}\} = p_s \left(1 + \frac{k_s h}{cw} \right) \left(\frac{l}{m} + \frac{2\sigma}{cm\sqrt{2\pi}} \right) \quad (5.119)$$

Although this model is based on some of the principles of the Reich model, its result is not given as a rate of accidents but rather as the probability of collision in a typical execution of the procedure. The symbol p_s denotes the probability that, at a randomly chosen moment, aircraft whose assigned lateral separation is S NM, are actually in lateral overlap. The symbols l , w , and h denote the length, width, and height of a typical or average aircraft in nautical miles, cf. section 5.4.2.3. The symbol m (NM) denotes the minimum permitted longitudinal separation for aircraft assigned to the same route and flight level. The symbol σ (kt) denotes the standard deviation of the signed difference between the longitudinal speeds of the aircraft and the symbol c (kt) denotes the vertical speed of the climbing or descending aircraft. Finally, k_s (kt) denotes the average lateral passing speed of aircraft that lose their planned lateral separation of S NM. The model in eq. (5.119) was used in conjunction with a target level of safety defined as a maximum tolerable probability of a collision in a typical execution of the procedure with a numerical value 5×10^{-10} collisions per execution of the

procedure. See Section 3.7 of Circular 334 (ICAO, 2014c) for the rationale underlying the new measure of risk. It was applied for two different cases of communication as reflected in the subsection's heading and as will be detailed below.

As set out in section 3.7 of Circular 334 (ICAO, 2014c), the aircraft involved in the procedure are assumed to be flying on parallel paths with their longitudinal separation being less than the minimum distance-based longitudinal separation required of aircraft assigned to the same route and flight level. Since one aircraft passes through the flight level of the other, the pair can clearly not have any planned vertical separation. Thus, the only form of separation prescribed for the procedure is lateral separation.

The model in eq. (5.119) may be expressed in the more conventional notation using λ_x , $|\dot{z}|$, etc. as

$$Prob\{\text{collision}\} = p_s \left(1 + \frac{|\dot{y}|\lambda_z}{|\dot{z}|\lambda_y} \right) \left(\frac{\lambda_x}{S_x} + \frac{2\sigma}{|\dot{z}|S_x\sqrt{2\pi}} \right) \quad (5.120)$$

where S_x denotes the longitudinal separation minimum. This enters explicitly into the model because it assumes that the actual longitudinal separation at the start of the procedure is a random variable with a rectangular distribution over the interval $[0, S_x]$.

Returning to the notation used in Circular 334 (ICAO, 2014c), the probability of a nose-to-tail collision was estimated to be

$$Prob\{\text{nose-to-tail collision}\} = p_s \sigma (t_e - t_b) / (m\sqrt{2\pi}) \quad (5.121)$$

where t_b and t_e denote, respectively, the times at which the vertical overlap begins and ends. The probability of a top-to-bottom collision was estimated to be

$$Prob\{\text{top-to-bottom collision}\} = (lp_s)/m \quad (5.122)$$

and, finally, the probability of a side-to-side collision was estimated to be

$$Prob\{\text{side-to-side collision}\} = (2n_s h/c) (l/m + \sigma (t_e - t_b) / (m\sqrt{2\pi})) \quad (5.123)$$

with n_s denoting the average rate of entering into lateral overlap. Adding together the three component collision probabilities in eqs. (5.121) – (5.123) and simplifying the sum resulted into the model given by eq. (5.119).

Both aircraft involved in the procedure were assumed to be using GNSS to navigate with a normal-double-exponential mixture-distribution representing both typical and atypical performance. The pertinent probability density is given by

$$f(y) = \frac{(1-\alpha)}{\sigma_L\sqrt{2\pi}} \exp - \frac{1}{2} \left(\frac{y}{\sigma_L} \right)^2 + \frac{\alpha}{2\lambda} \exp \left(-\frac{|y|}{\lambda} \right) \quad (5.124)$$

(Section 3.7 of Circular 334 (ICAO, 2014c) uses the symbol $f(y; \alpha, \sigma_L, \lambda)$ instead of $f(y)$.)

The probability of lateral overlap p_S for a pair of aircraft separated by S NM and each having the same lateral deviation mixture density of eq. (5.124) is given by

$$p_S = (1 - \alpha)^2 \left[\Phi \left(\frac{w-S}{\sigma_L \sqrt{2}} \right) - \Phi \left(\frac{-w-S}{\sigma_L \sqrt{2}} \right) \right] + \alpha^2 \frac{e^{\frac{S}{\lambda}}}{2\lambda} \left[(S + 2\lambda) \sinh \left(\frac{w}{\lambda} \right) - w \cosh \left(\frac{w}{\lambda} \right) \right] + 2\alpha(1 - \alpha) \left\{ \Phi \left(\frac{w-S}{\sigma_L} \right) - \Phi \left(\frac{-w+S}{\sigma_L} \right) + \frac{1}{2} e^{\frac{1}{2} \left(\frac{\sigma_L}{\lambda} \right)^2} \left[e^{\frac{w-S}{\lambda}} \Phi \left(-\frac{w-S}{\sigma_L} - \frac{\sigma}{\lambda} \right) - e^{-\frac{w-S}{\lambda}} \Phi \left(\frac{w+S}{\sigma_L} - \frac{\sigma}{\lambda} \right) + e^{\frac{w+S}{\lambda}} \Phi \left(-\frac{S+w}{\sigma_L} - \frac{\sigma}{\lambda} \right) - e^{-\frac{S-w}{\lambda}} \Phi \left(-\frac{S-w}{\sigma_L} - \frac{\sigma}{\lambda} \right) \right] \right\},$$

$$w \leq S \quad (5.125)$$

Using eq. (5.125), the SASP computed tables of lateral overlap probability for two values of σ_L , for ranges of S , α , and λ , and for a single empirical estimate of the wingspan w . The values of S (in NM) were integers from 1 to 30. The values of α ranged from 10^{-5} to 10^{-3} , and, in the absence of relevant empirical data, λ was conservatively taken equal to S . The wingspan w estimate was 0.032 NM.

The two values of σ_L were based on two levels of performance-based navigation (PBN) thought by the SASP to exemplify terminal airspace and en-route airspace respectively. The first PBN level then required the standard deviation of typical lateral deviations to be no greater than $0.5/3$ NM = $1/6$ NM and the second PBN level required the standard deviation of typical lateral deviations to be no greater than $2.5/3$ NM = $5/6$ NM.

Using a longitudinal separation minimum m of 30 NM, empirically estimated values of l , w , and h , and conservative values of k_S , c , and σ , the product $\left(1 + \frac{k_S h}{c w}\right) \left(\frac{l}{m} + \frac{2\sigma}{c m \sqrt{2\pi}}\right)$ of the second and third factors on the right side of the collision risk model in eq. (5.119) was estimated to have the value 0.002083.

Multiplying each lateral overlap probability by 0.0020838 yielded two tables of collision probabilities in which each row corresponded to a hypothesized value of S and each column to a hypothesized value of α .

The final step in selecting a separation minimum for $\sigma_L = 1/6$ NM and $\sigma_L = 5/6$ NM was to specify suitable values of α , and to read from the tables the smallest value of S for which the collision probability was less than or equal to the TLS value of 5×10^{-10} . SASP chose values that it believed to be reasonably conservative, namely $\alpha = 6 \times 10^{-5}$ when direct controller-pilot communication (DCPC) is available, and $\alpha = 2 \times 10^{-4}$ when communication between controllers and pilots is accomplished through a third party. The corresponding smallest integer values for S for which the collision probabilities were less than the TLS of 5×10^{-10} were found to be $S = 7$ NM and $S = 20$ NM respectively.

The 7 NM and 20 NM lateral separation minima for the two types of communication were incorporated into the PANS-ATM through Amendment 6 to its 15th Edition with an applicability date of 13 November 2014. See the pertinent entry in Table 2.3 in Section 2.5.1.

The lateral risk calculations summarized above did not account for SLOP. This was made explicit for the 7 NM lateral separation minimum (for terminal airspace) in Amendment 8 to the PANS-ATM with an applicability date of 8 November 2018. See the pertinent entry in Table 2.3 in Section 2.5.1 and Circular 349 (ICAO, 2014b). SLOP has not been addressed for the 20 NM lateral separation minimum at a later stage because the 20 NM was overtaken by the 9 NM lateral separation minimum providing RCP 240 and RSP 180 performance-based

communication and surveillance performance, to be discussed in Section 5.4.2.3. See the pertinent entry in Table 2.3 in Section 2.5.1 and Circular 349 (ICAO, 2014b).

5.4.2.6 Intersecting tracks: 15 NM – RNP 2, 30 NM – RNP 4 and 50 NM – RNAV 10 (RNP 10)

Lateral separation minima for aircraft on intersecting tracks have traditionally been available for VOR, NDB, dead reckoning, and RNAV operations (where RNP is specified) in the PANS-ATM, see e.g. the first entry in Table 2.3 of Section 2.5.1 concerning the 14th Edition incorporating Amendments 1-4. As described in Section 5.4.1, the VOR separation minimum was extended to pairs of VOR and/or GNSS aircraft in Amendment 6 to the 15th Edition of the PANS-ATM. The minimum for RNAV operations (where RNP is specified) on intersecting tracks or ATS routes is based on a defined area of conflict around the intersection, where this area is defined as the area inside four lateral separation points, defined as points on a track where the distance to the other track is equal to the lateral separation minimum. Lateral separation is achieved by the controller ensuring that two aircraft will not be simultaneously within the area of conflict at the same level (Anderson, 2005).

The separation minima for which the collision risk modelling is to be discussed in this section of this document are based on an alternative method of applying lateral separation of which the SASP saw several operational advantages over the area of conflict method as set out in section 3.8 of Circular 334 (ICAO, 2014c). The new method is based on a “protected” region of the airspace either side of the track of a reference airspace (labelled aircraft 1). A second aircraft (labelled aircraft 2) flying on an intersecting track and which did not have longitudinal or vertical separation with the reference aircraft, would be required to change level before entering the protected region, and not to return to the original level until clear of the protected region. See Figure 5.3.

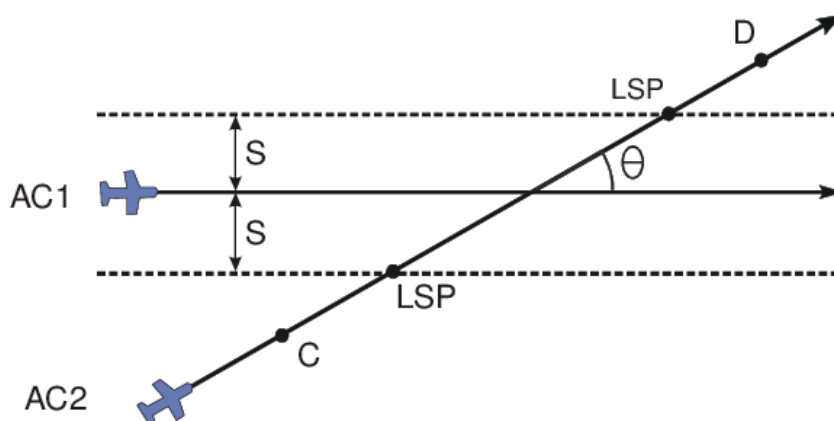


Figure 5.3: Two aircraft are at the same flight level on intersecting tracks. To assure separation, aircraft 2 will be required to climb/descend at C and reach another level by its first lateral separation point (LSP) (BLSP). Similarly, past the track of aircraft 1, aircraft 2 could descend/climb only after its second LSP is reached. Position D shows where aircraft 2 would regain its original flight level

Lateral collision risk for RNP 2/GNSS, RNP 4, and RNAV 10 (RNP 10) aircraft pairs over a time interval $[t_0, t_1]$ was calculated by means of the following form of the collision risk model based on reliability theory (Anderson, 2005) and described in Chapter 7 of this document (cf. eq. (7.12) of Chapter 7 and eq. (5.101) of Section 5.4.1)

$$N_a[t_0, t_1] = 2m\pi\lambda_{xy}^2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) P_z(h(t)) \left(\frac{2v_{xy}}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (5.126)$$

where $f_i(v_i)$ is the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denotes the joint probability density of the relative position $r_x(t)$, $r_y(t)$ of two aircraft at time t for $r_x(t) = r_y(t) = 0$. The latter probability density is given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C$$

where ε_2^A and ε_2^C denote the along-track and across-track navigational errors of aircraft 2³⁹. $D_x(t)$ and $D_y(t)$ denote the nominal relative position between the aircraft.

In eq. (5.126), λ_{xy} and λ_z denote the diameter and height of the horizontal cylinder representing the aircraft respectively, v_{xy} denotes the relative horizontal speed between the aircraft, $P_z(h(t))$ denotes the pair's probability of vertical overlap as a function of the height difference between the aircraft over the time interval $[t_0, t_1]$, and $|\bar{z}|$ denotes the average of (the absolute value of the) relative vertical speed between the aircraft. The time interval $[t_0, t_1]$ was defined by t_0 being the point in time at which aircraft 2 had a lead distance to C corresponding to 10 minutes and by t_1 being the point in time at which aircraft 2 had a distance beyond D corresponding to 10 minutes. For this scenario, the calculation of the collision risk over the time period $[t_0, t_1]$ actually splits into two parts, namely a period of time with the aircraft laterally separated from t_0 until aircraft 2 reaches its first lateral separation point, plus a period of time with the aircraft laterally separated starting with aircraft 2 reaching its second lateral separation point and ending at t_1 . The period of time with aircraft 2 flying from its first to its second lateral separation point does not contribute to the lateral risk because the two aircraft are then vertically separated. The risk was calculated with different starting positions for the reference aircraft at time t_0 , including both sides of the intersection. For each intersection angle, a **maximum** collision risk was found over all starting positions of the reference aircraft, and over all combinations of 300, 480, and 600 knots aircraft ground speeds. All calculations accounted for typical as well as atypical navigation performance. Five crossings per hour were assumed, i.e. $m = 5$ in eq. (5.122), with intersection angles ranging from 5 degrees to 175 degrees. The target level of safety utilized was 5×10^{-9} fatal accidents per flight hour.

The navigational error distributions for the three types of aircraft pairs/navigation specifications were chosen as follows.

Consider the 15 NM lateral separation minimum for the RNP 2/GNSS case first. In the same manner as for the 15 NM lateral separation minimum for GNSS aircraft on parallel or non-intersecting tracks in Section 5.4.2.4, three sources of typical lateral navigation error were included in the modelling, namely GNSS navigational error, navigational error in the event of a RAIM outage, and flight technical error, though the possibility of a RAIM outage during the short duration of the crossing was neglected. This simplified the mixture density defined by eq. (5.117) of Section 5.4.2.4 to a single normal probability density, viz.

$$f(y) = \frac{(1-\alpha)}{\sqrt{\sigma_1^2 + \sigma_3^2} \sqrt{2\pi}} \exp\left(-\frac{y^2}{2(\sigma_1^2 + \sigma_3^2)}\right) \quad (5.127)$$

³⁹ Both aircraft are assumed to have the same navigational error distributions and it is shown in Chapter 7 that $f_t(0,0)$ can be expressed in terms of either ε_2^A and ε_2^C or ε_1^A and ε_1^C .

with $\sigma_1 = 0.538$ NM and $\sigma_3 = 1.28$ NM. Typical aircraft passing frequencies of $N_x(\text{same}) = 1$ and $N_x(\text{opp}) = 3$ passings per flight hour were assumed and aircraft dimensions were conservatively set at Airbus A380 values. For the RNP 2 navigation specification, the calculations were actually based on RNAV 2 navigational error distributions, viz. double exponential distributions with scale parameters $\lambda_A = \lambda_C = -2/\ln 0.03 = 0.6676$ NM. As set out in Section 3.8 of Circular 334 (ICAO, 2014c), the most likely high-consequence operational error was identified as aircraft 2 failing to reach a vertically separated level by the edge of the protected area and continuing through the track of aircraft 1 at the same flight level. It was found that that this inferred a maximum tolerable rate of one operational error per 4 million executions of the procedure for the procedure to satisfy the TLS of 5×10^{-9} fatal accidents per flight hour.

For the RNP 4 navigation specification, typical navigational errors were modelled on the basis of the navigation specification and the separation minimum used in the calculations was 15 NM. Following the 2006 SASP agreement of normal navigational error distributions for RNP navigation specifications, the along-track and across-track navigational error distributions were taken as normal distributions. The standard deviations were based on the more stringent navigation requirement at twice the RNP value, resulting in $\sigma_A = \sigma_C = 8/4.46 = 1.7937$ NM. The most likely high-consequence operational error was again identified as aircraft 2 failing to reach a vertically separated level by the edge of the protected area and continuing through the track of aircraft 1 at the same flight level. It was found that that this inferred a maximum tolerable rate of one operational error per 2 million executions of the procedure for the procedure to satisfy the TLS of 5×10^{-9} fatal accidents per flight hour.

As suggested by this subsection's heading, the lateral separation minimum for RNP 4 approved aircraft on intersecting tracks provided for by the PANS-ATM amounts 30 NM rather than 15 NM. This is correct because SASP chose for a 30 NM lateral separation minimum rather than a smaller 15 NM minimum in order to achieve consistency with the 30 NM lateral separation minimum for parallel or non-intersecting tracks for RNP 4 approved aircraft (cf. Section 5.4.2.2).

For the RNAV 10 (RNP 10) navigation specification, typical navigational errors were modelled on the basis of the navigation specification. Following the 2006 SASP agreement of double-exponential navigational error distributions for RNAV navigation specifications, the along-track and across-track navigational error distributions were taken as double exponential distributions. The standard deviations were based on the 95% performance requirement, resulting in $\lambda_A = \lambda_C = -10/\ln 0.05 = 3.338$ NM. It was recognized that maximizing over all aircraft 1 starting positions was over-conservative and that there were many previous analyses which averaged over the possible starting positions of aircraft 1. It was agreed, therefore, that for 50 NM intersecting tracks lateral separation and RNAV 10 (RNP 10) aircraft, the lateral collision risk estimates would be averaged over the aircraft 1 starting positions rather than maximized. The most likely high-consequence operational error was again identified as aircraft 2 failing to reach a vertically separated level by the edge of the protected area and continuing through the track of aircraft 1 at the same flight level. It was found that that this inferred a maximum tolerable rate of one operational error per 1.4 million executions of the procedure for the procedure to satisfy the TLS of 5×10^{-9} fatal accidents per flight hour.

The 15 NM, 30 NM, and 50 NM intersecting-track lateral separation minima for the three types of navigation specifications were incorporated into the PANS-ATM through Amendment 6 to its 15th Edition with an applicability date of 13 November 2014. See the pertinent entry in Table 2.3 in Section 2.5.1. The lateral risk calculations summarized above did not account for SLOP. See also Circular 341 (ICAO, 2015b).

5.4.2.7 9 NM/Not Applicable lateral separation while on climb or descent of an RNP 2 or GNSS aircraft through the flight level of another such aircraft

This section will be completed as soon as ICAO Circular 349 is available.

5.4.2.8 Intersecting tracks: 15 NM – RNP 2, 23 NM – RNP 4 and 50 NM – RNAV 10 (RNP 10)

As set out in Section 5.4.2.6, the 15 NM, 30 NM, and 50 NM intersecting-track lateral separation minima for the respective RNP 2, RNP 4, and RNAV 10 (RNP 10) navigation specifications were incorporated into the PANS-ATM through Amendment 6 to its 15th Edition with an applicability date of 13 November 2014. The 30 NM minimum was adopted to achieve consistency between the lateral separation minima for RNP 4 approved aircraft on parallel or non-intersecting tracks and those for RNP 4 aircraft on intersecting tracks, though the assessment actually showed that a 15 NM lateral separation minimum satisfied the target level of safety.

A reduction of the 30 NM lateral separation minimum for RNP 4 approved aircraft on parallel or non-intersecting tracks was incorporated into the 16th Edition of the PANS-ATM with an applicability date of 10 November 2016 (cf. Section 5.4.2.3). At the same time, and again in order to maintain the consistency referenced in the previous paragraph, the 30 NM lateral separation minimum for RNP 4 approved aircraft on intersecting tracks was reduced to 23 NM. This required no further collision risk assessment because, as recalled above, the intersecting-tracks assessment described in Section 5.4.2.6 actually allowed a 15 NM lateral separation minimum.

5.4.3 Lateral separation of aircraft on published adjacent instrument procedures for arrivals and departures (ICAO Circular 324)

This subsection describes the collision risk assessment underlying the 7 NM lateral separation minimum between RNAV 1, Basic RNP 1, RNP APCH, and/or RNP AR APCH aircraft on published adjacent instrument flight procedures for arrivals and departures incorporated into the 15th Edition of the PANS-ATM through Amendment 3 with an applicability date of 18 November 2010 and subsequently refined through Amendment 6 to the 15th Edition of the PANS-ATM, applicable as of 13 November 2014, to 7 NM between any combination of RNAV 1 with RNAV 1, or RNP 1, RNP APCH or RNP AR APCH tracks and 5 NM between any combination of RNP 1, RNP APCH or RNP AR APCH tracks.

Figure 5.4 sketches the horizontal geometry of the published instrument flight procedure scenario described in (ICAO, 2010). The scenario assumes that an arriving aircraft, aircraft 2, makes a turn with a turn angle between 15 and 90 degrees to intercept the intermediate/final approach segment. The departing aircraft, aircraft 1, flies a certain distance beyond the end of the runway before turning and flying back parallel to the approach segment.

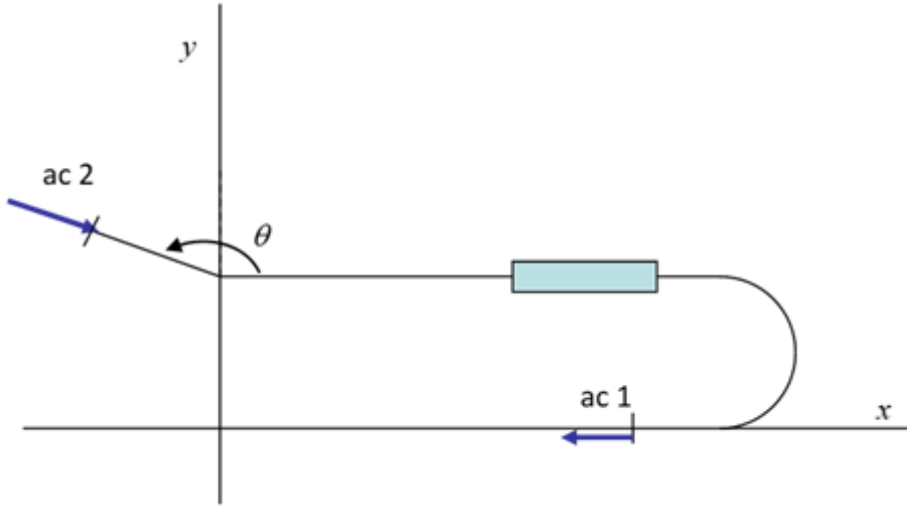


Figure 5.4: Horizontal view of the operational scenario

The collision risk assessment calculated the lateral collision risk, denoted $CR(t_0, t_1)$, expressed in collisions per arrival-departure pair, over a time interval $[t_0, t_1]$ where $t_0 = 0$ denotes the beginning of the approach and t_1 denotes the time of touchdown. Consistent with the risk measure of collisions per arrival-departure pair, the assessment utilized a target level of safety of 5×10^{-10} collisions per arrival-departure pair. See (ICAO, 2010) for the rationale behind this value. Lateral risk due to typical as well as atypical navigation performance was calculated by means of specialized versions of the collision risk model based on reliability theory (ICAO, 1998c) and described in Chapter 7 of this document (cf. eq. (7.12) of Chapter 7 as well as eq. (5.101) of Section 5.4.1 and eq. (5.122) of Section 5.4.2.6):

$$CR(t_0, t_1) = \pi \lambda_{xy}^2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) P_z(h(t)) \left(\frac{2v_{xy}}{\pi \lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (5.128)$$

where $f_i(v_i)$ is the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denotes the joint probability density of the relative position $r_x(t), r_y(t)$ of two aircraft at time t for $r_x(t) = r_y(t) = 0$. The latter probability density is given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C$$

where ε_2^A and ε_2^C denote the along-track and across-track navigational errors of aircraft 2⁴⁰. $D_x(t)$ and $D_y(t)$ denote the nominal relative position between the aircraft.

In eq. (5.128), λ_{xy} and λ_z denote again the diameter and height of the horizontal cylinder representing the aircraft respectively, v_{xy} denotes the relative horizontal speed between the aircraft, $P_z(h(t))$ denotes the pair's probability of vertical overlap as a function of the height difference between the aircraft at time t during the time interval $[t_0, t_1]$, and $|\bar{z}|$ denotes the average of (the absolute value of) the relative vertical speed between the aircraft.

⁴⁰ Both aircraft are assumed to have the same navigational error distributions and it is shown in Chapter 7 that $f_t(0,0)$ can be expressed in terms of either ε_2^A and ε_2^C or ε_1^A and ε_1^C .

Figure 5.5 details the horizontal view of the operational scenario of Figure 5.4 for the assessment of the lateral collision risk due to typical navigation performance. The approach path of aircraft 2 consists of an initial approach segment of length L_{2A} , an intermediate approach segment of length L_{2B} , a final approach segment of length L_{2C} , and a runway threshold to touch-down segment of length L_{2D} . The distance from touch-down to the end of the runway is L_{2E} . Table 5.8 shows the numerical values used. The departing aircraft 1 flies a distance L_{2F} beyond the end of the runway before turning and flying back parallel to the runway. In the region of interest, the nominal horizontal trajectory of the departing aircraft requires two parameters as listed in the last two rows of Table 5.8. It is remarked that the Table 5.8 values for the aircraft speeds $\hat{V}_1$ and $\hat{V}_2$ were developed during the initial modelling work and were supplemented subsequently with two more pairs of values, namely $\hat{V}_1 = 150$ kts and $\hat{V}_2 = 230$ kts, and $\hat{V}_1 = 215$ kts and $\hat{V}_2 = 230$.

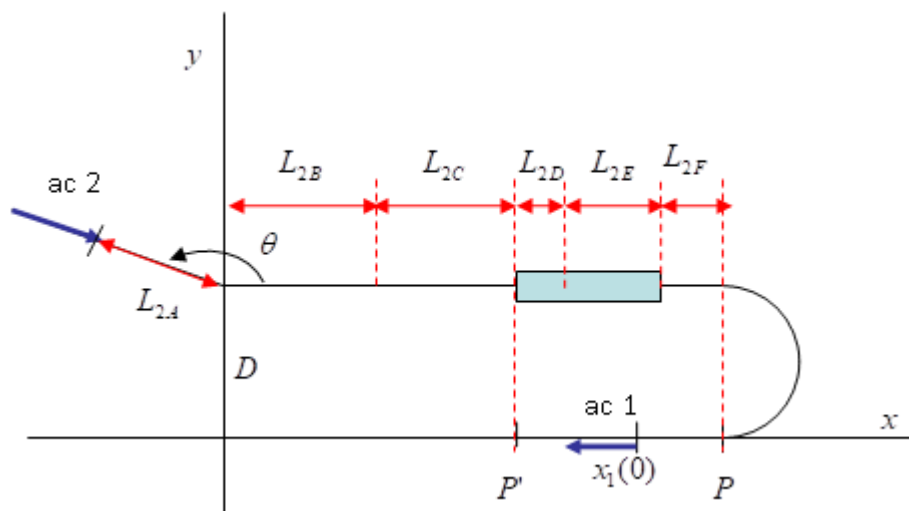


Figure 5.4: Detailed horizontal view of the operational scenario for the assessment of the risk due to typical navigation performance

Table 5.8: Numerical values related to the horizontal operational scenario of Figure 5.4

Parameter	Value
θ	90 – 165 degrees
L_{2A}	10 NM
L_{2B}	10 NM
L_{2C}	10 NM
L_{2D}	0.25 NM
$\hat{V}_2$	120 kts
$x_1(0)$	Variable (NM)
$\hat{V}_1$	150 kts

A simple model for the turn of the approaching aircraft was assumed, viz. an instantaneous turn at the intermediate approach fix. As a result, the time integral in the collision risk model of eq. (5.128) needs to be split up into two parts with different equations of motion for the approaching aircraft 2, the parts before and after the turn, leading to two sets of equations for $D_x(t)$ and $D_y(t)$. Let $\xi_2(0)$ denote the nominal distance of aircraft 2 to the intermediate approach fix or turning point and let $\hat{t}^*$ denote the nominal point in time at which aircraft reaches the turning point. This point in time is then given by $\hat{t}^* = \xi_2(0)/\hat{V}_2$. However, a turn duration was also modelled, viz. as a random variable τ with a rectangular distribution over the time interval

$[\tau_{min}, \tau_{max}]$ with $\tau_{min} = 10$ seconds and $\tau_{max} = 15$ seconds. The actual, random, point in time at which the instantaneous turn takes place is thus given by $\hat{t}^* = \xi_2(0)/\hat{V}_2 + \tau$.

It follows from reference 11 to (ICAO, 2010) that the respective pairs of nominal relative position components $D_x(t)$ and $D_y(t)$ are given by

$t_0 = 0 \leq t \leq \hat{t}^*$ (initial approach segment):

$$D_x(t) = x_1(0) - v_1 \times t - (\xi_2(0) - v_2 \times t) \cos \theta \quad (5.129)$$

$$D_y(t) = -(\xi_2(0) - v_2 \times t) \sin \theta - D \quad (5.130)$$

$\hat{t}^* \leq t \leq t_1$ (intermediate approach segment and beyond):

$$D_x(t) = x_1(0) - v_1 \times t - (\xi_2(0) - v_2 \times t) \cos \theta - v_2 \times (t - \hat{t}^*) \quad (5.131)$$

$$D_y(t) = -(\xi_2(0) - v_2 \times \hat{t}^*) \sin \theta - D \quad (5.132)$$

As regards the random navigational errors ε_2^A and ε_2^C (or ε_1^A and ε_1^C), both normal and double exponential probability distributions have been used where for RNAV aircraft the standard deviation was based on the RNAV 95% accuracy requirement and where for RNP aircraft the standard deviation was based on the RNP integrity or 2 times 95% accuracy requirement.

In addition to θ , $D_x(t)$, $D_y(t)$, and ε_2^A and ε_2^C that play a part in the joint probability density $f_t(0,0)$ of the relative position $r_x(t)$, $r_y(t)$ of the two aircraft at time t for $r_x(t) = r_y(t) = 0$, the probability $P_z(h(t))$ of vertical overlap between the aircraft at time t with a nominal height difference of $h(t)$ needs to be specified. The vertical profile of the approaching aircraft was characterized by a constant vertical descent speed where this speed was derived from an initial altitude and the duration of the descent,

$$h_2(0) = \frac{60 \times v_{2z}}{\hat{V}_2} (L_{2A} + L_{2B} + L_{2C} + L_{2D}) \quad (5.133)$$

In fact, three initial altitudes were utilized as listed in Table 5.9.

Table 5.9: Initial altitudes and vertical descent speeds for the approaching aircraft

Initial approach altitude $h_2(0)$ (ft)	Vertical descent speed v_{2z} (ft/min)
6000	396.694
5500	363.636
5000	330.579

The vertical profile of the approaching aircraft was thus described by

$$h_2(t) = h_2(0) - v_{2z} \times t, [t_0 \leq t \leq t_1] \quad (5.134)$$

The departing aircraft was assumed to have a constant 2.5% climb gradient starting from an initial altitude of $h_1(P)$ at the point P in Figure 5.4. See also Figure 5.5.

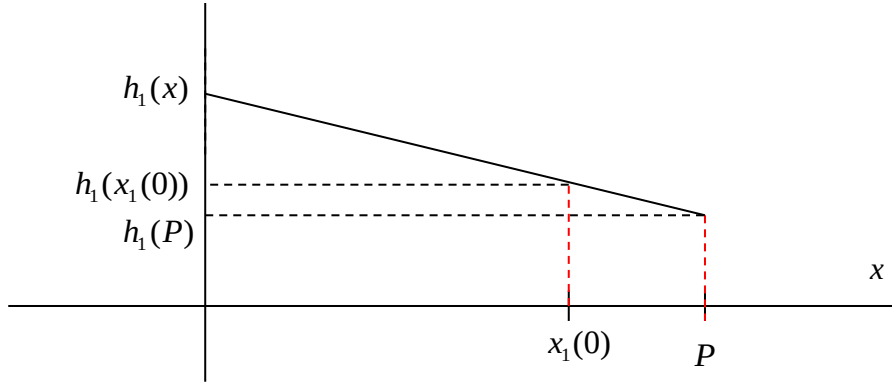


Figure 5.5: Altitude profile of departing aircraft

The initial altitude of the departing aircraft was set at $h_1(P) = 500$ ft and the vertical profile of the departing aircraft was thus modelled as

$$h_1(t) = 500 + 151.90 \times (x_P - x_1(0)) + v_{1z} \times t \text{ (ft)}, [t_0 \leq t \leq t_1] \quad (5.135)$$

with $v_{1z} = 380$ ft/min. Combining eqs. (5.130) and (5.131) results in

$$h(t) = h_2(t) - h_1(t) = h_2(0) - v_{2z} \times t - (500 + 151.90 \times (x_P - x_1(0)) + v_{1z} \times t) \quad (5.136)$$

or

$$h(t) = h_2(t) - h_1(t) = h_2(0) - (500 + 151.90 \times (x_P - x_1(0))) - (v_{2z} + v_{1z}) \times t \quad (5.137)$$

Given the nominal altitude difference $h(t)$, the probability of vertical overlap $P_z(h(t))$ can be calculated as set out in (Anderson, 2005).

As follows from the above, the calculated collision risk estimates are dependent on the initial position and altitude of the departing aircraft at time $t_0 = 0$. This dependence was accounted for by comparing the maximum risk, as a function of the departing aircraft's initial position and altitude, with the target level of safety.

It is to be remarked that the numerical values of the vertical speeds v_{1z} and v_{2z} specified above, were developed during the initial modelling work and were supplemented subsequently with three more pairs of values, namely $v_{1z} = 1250$ ft/min and $v_{2z} = 1250$ ft/min, $v_{1z} = 1700$ ft/min and $v_{2z} = 1250$ ft/min, and

$v_{1z} = 2250$ ft/min and $v_{2z} = 1250$ ft/min. Results obtained for these vertical speed combinations confirmed the results for the initially specified vertical speed combinations. See reference 16 to (ICAO, 2010).

Regarding the lateral collision risk for the instrument flight procedure due to atypical navigation performance, a single type of operational error or blunder was examined, viz. the arriving aircraft missing the turn from the initial approach segment to the intermediate approach segment, continuing flying along its original heading, and crossing through the departure path. Figure 5.6 details the horizontal view of the operational scenario of Figure 5.4 for the assessment of the lateral collision risk due to atypical navigation performance or blunder error. As explained in paragraph 3.39 ff. of (ICAO, 2010), collision risk for the blunder scenario was estimated in two different ways, where each way estimated the collision risk given that a blunder had occurred. Multiplication by the probability of a blunder occurring then gives an estimate of the collision risk due to atypical performance or blunder. Both ways of modelling were found to provide similar results under similar circumstances. See the referenced paragraphs for further details of the two ways of blunder modelling and the calculation of maximum tolerable rates of blunders as a function of various parameter sets.

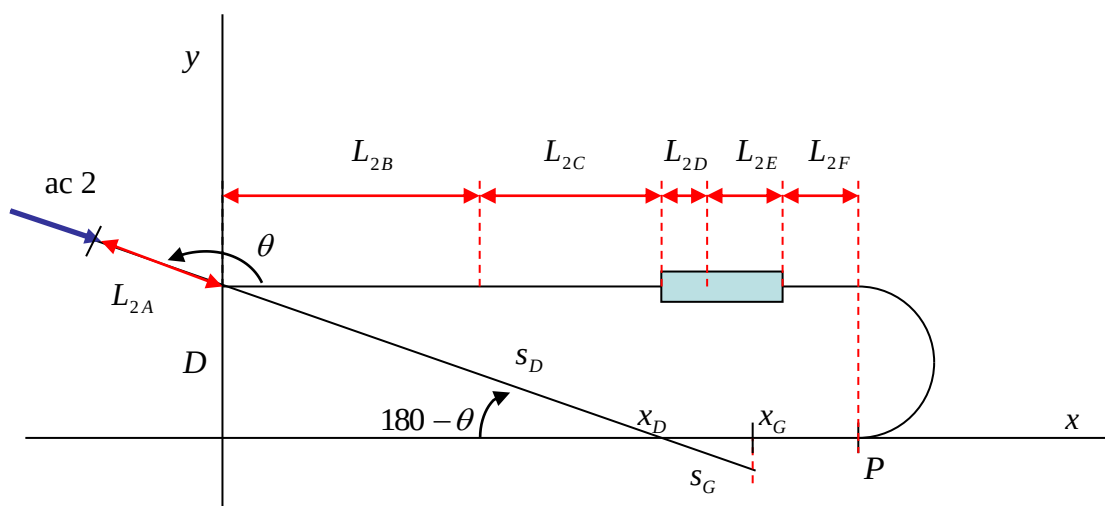


Figure 5.6: Detailed horizontal view of the operational scenario for the assessment of the risk due to atypical navigation performance or blunder error

5.4.4 ASEPS lateral separation minima

ICAO Doc 10116 (ICAO, NN) deals with Advanced Surveillance Enhanced Procedural Separation, ASEPS. See Section 7.3.8 for some background information on the origin of SASP's work on ASEPS (longitudinal ASEPS work started before lateral ASEPS work). Appendices D and E to the reference deal with the lateral collision risk modelling for parallel and intersecting routes respectively. It is assumed that all aircraft operating in airspace where ASEPS lateral separation minima apply meet the performance-based communication and surveillance standards RCP 240 and RSP 180, where the numbers in these acronyms denote maximum tolerable times for communication and position reporting in minutes. Consider the parallel routes case first.

5.4.4.1 Parallel routes

Figure 5.7 sketches an aircraft, aircraft 1, with speed V_1 deviating from its nominal path at a random angle θ towards the adjacent route. Notice that the spacing between the parallel routes is denoted S rather than the lateral separation standard S_y . The reason for this is to be able to account more easily for SLOP and/or a deviation alerting distance at a later stage of the analysis. Regular position reports are assumed to be obtained from space-based ADS-B. A key difference between the traditional Reich modelling for parallel routes and the ASEPS modelling is that the latter calculates the probability of reaching the adjacent route as a function of the deviation angle θ and a probability distribution of the deviation angle θ . Let $f_\theta(\theta)$ denote the probability density function of the deviation angle θ . In the past, it was not possible to determine this probability density in a traditional procedural environment.

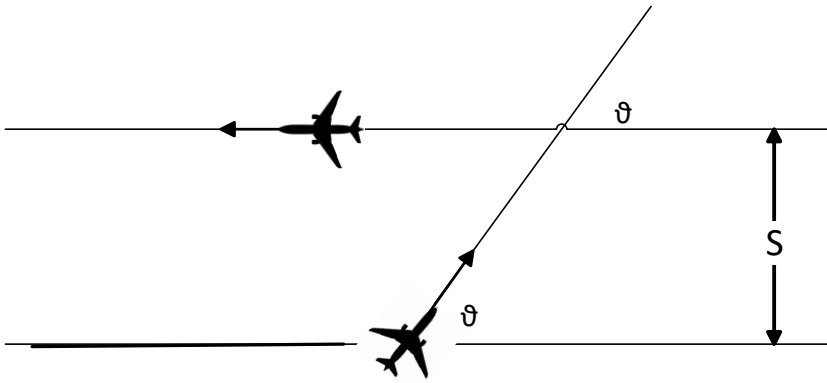


Figure 5.7: An aircraft deviating from its nominal path to an adjacent route under an angle θ under the ASEPS scenario.

Without intervention, a deviating aircraft will reach the adjacent route at time $t(\theta)$ given by

$$t(\theta) \times V_1 \sin \theta = S \quad (5.138)$$

Let T_a denote the, random, action time, that is the time needed to detect a deviation from the nominal path of an aircraft and to successfully intervene such that no further risk of collision exists due to the deviation. The action time T_a defines a critical angle θ^* , say, through

$$T_a \times V_1 \sin \theta^* = S \quad (5.139)$$

from which θ^* may be solved as

$$\theta^* = \theta^*(T_a, V_1) = \sin^{-1} \left[\frac{S}{T_a \times V_1} \right]_1 \quad (5.140)$$

provided that $S/(T_a \times V_1) \leq 1$. The latter is expressed by the $[S/(T_a \times V_1) \leq 1]_1$ notation in eq. (5.140). The condition will not be met when T_a and/or V_1 are small compared to S , i.e. when a deviation is detected and successfully resolved very quickly or the deviation increases so slowly that it will be detected and successfully resolved regardless of the value of the action time. Hence, the risk of collision is zero when the condition $S/(T_a \times V_1) \leq 1$ is not satisfied.

The risk of collision is also zero when the time needed to detect and resolve the deviation is less than the time needed to reach the adjacent route given the deviation angle, i.e. when

$$T_a < t(\theta) \quad (5.141)$$

or

$$\frac{s}{V_1 \sin \theta^*} < \frac{s}{V_1 \sin \theta} \quad (5.142)$$

and thus

$$\theta < \theta^* = \theta^*(T_a, V_1) \quad (5.143)$$

Reversely, there is a risk of collision with an aircraft on the other route due to the deviating aircraft reaching the other route if

$$T_a \geq t(\theta) \quad (5.144)$$

or, in terms of the deviation angle θ , if

$$\theta \geq \theta^*(T_a, V_1) \quad (5.145)$$

Thus, the conditional probability of the deviating aircraft 1 reaching the other route given a value of the action time T_a is given by

$$\Pr\{\text{ac 1 reaches route 2} | T_a\} = \int_{\theta^*(T_a, V_1)}^{\pi/2} f_{\theta}(\theta) d\theta \quad (5.146)$$

where the dependence of the critical angle θ^* on the action time T_a has been made explicit through the notation $\theta^*(T_a)$. The unconditional probability of the deviating aircraft 1 reaching the other route is given by

$$\Pr\{\text{ac 1 reaches route 2}\} = \int_{T_{a,\min}}^{T_{a,\max}} \int_{\theta^*(T_a, V_1)}^{\pi/2} f_{\theta}(\theta) d\theta f_{T_a}(T_a) dT_a \quad (5.147)$$

The model development in ICAO Doc 10116 (ICAO, NN) then proceeds with considering a single aircraft deviating from route 1 towards the adjacent route 2 at a given angle θ with all other parameters, T_a , V_1 , V_2 , fixed. The deviating aircraft will collide with an aircraft on route 2 if it reaches that route and is simultaneously in vertical and longitudinal overlap with an aircraft on route 2. The conditional probability of a collision given aircraft 1 is deviating is given by

$$\Pr(\text{collision} | \text{ac 1 on route 1 deviates towards route 2}) = \frac{2\lambda_x}{\delta_2} \left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta}\right) \left(1 + \frac{\pi \lambda_x |\bar{z}|}{2 V_r 2\lambda_z}\right) P_z(0) \Pr(\text{ac 1 reaches route 2}) \quad (5.148)$$

where

$$V_r = \sqrt{V_1^2 + V_2^2 - 2V_1 V_2 \cos \theta} \quad (5.149)$$

In eq. (5.148), δ_2 is the local average longitudinal spacing between aircraft on route 2 when aircraft 1 from route 1 deviates. Eq. (5.144) is approximated by

$$\Pr(\text{collision} | \text{ac1 on route1 deviates towards route2}) = \frac{2\lambda_x}{\delta_2} \left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) P_z(0) \Pr(\text{ac 1 reaches route 2}) \quad (5.150)$$

A similar expression can be derived for an aircraft 2 on route 2 deviating at a given angle θ towards route 1, viz.

$$\Pr(\text{collision} | \text{ac2 on route2 deviates towards route1}) = \frac{2\lambda_x}{\delta_1} \left(1 + \frac{|V_2 \cos \theta - V_1|}{V_2 \sin \theta} \right) P_z(0) \Pr(\text{ac2 reaches route1}) \quad (5.151)$$

An unconditional probability of a collision due to an aircraft deviating from its assigned route at an angle θ is then given by

$$\begin{aligned} \Pr(\text{collision}) = & \Pr(\text{deviation}) \times \frac{2\lambda_x}{\delta_2} \left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) P_z(0) \Pr(\text{ac 1 reaches route 2}) \Pr(\text{ac 1 is the aircraft that deviates}) + \\ & \Pr(\text{deviation}) \times \frac{2\lambda_x}{\delta_1} \left(1 + \frac{|V_2 \cos \theta - V_1|}{V_2 \sin \theta} \right) P_z(0) \Pr(\text{ac 2 reaches route 1}) \Pr(\text{ac 2 is the aircraft that deviates}) \end{aligned} \quad (5.152)$$

where it remains to determine the probabilities that aircraft 1 or aircraft 2 are the aircraft that are deviating. Taking account of the local average longitudinal spacings $\frac{\delta_1}{\delta_2}$ between aircraft on route 1/2 when aircraft 2/1 from route 2/1 deviates, ICAO Doc 10116 (ICAO, NN) provides the following expressions

$$\Pr(\text{ac 1 is the aircraft that deviates}) = \frac{\delta_2}{\delta_1 + \delta_2} \quad (5.153)$$

$$\Pr(\text{ac 2 is the aircraft that deviates}) = \frac{\delta_1}{\delta_1 + \delta_2} \quad (5.154)$$

Since the average number of aircraft on a route is inversely proportional to the average longitudinal spacing between the aircraft on the route, a larger value of e.g. δ_2 compared to δ_1 implies fewer aircraft on route 2 than on route 1 and thus a higher probability that it is an aircraft from route 1 that is deviating. Substitution of eqs. (5.153) and (5.154) into eq. (5.152) gives

$$\Pr(\text{collision}) = \Pr(\text{deviation}) \times \frac{2\lambda_x}{\delta_1 + \delta_2} P_z(0) \left[\left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) \Pr(\text{ac 1 reaches route 2}) + \left(1 + \frac{|V_2 \cos \theta - V_1|}{V_2 \sin \theta} \right) \Pr(\text{ac 2 reaches route 1}) \right] \quad (5.155)$$

ICAO Doc 10116 (ICAO, NN) then derives the following expression for the occupancy of a pair of routes in terms of δ_1 , δ_2 , and the proximity distance, denoted d_x , on the assumption that $V_1 \approx V_2$,

$$E = \frac{4d_x}{\delta_1 + \delta_2} \quad (5.156)$$

Eq. (5.152) can be shown to be equivalent to the usual expression for occupancy in terms of flow rates for a steady state system made up of two parallel routes (ICAO, 1992a). Traffic flows of m_1 and m_2 per hour give time spacings of $1/m_1$ and $1/m_2$ per hour for the routes and distance spacings of $\delta_1 = V_1/m_1$ and $\delta_2 = V_2/m_2$ respectively with $\delta_1 + \delta_2 = (m_2 V_1 + m_1 V_2)/(m_1 m_2)$ and thus, assuming equal aircraft speeds,

$$E = \frac{4d_x m_1 m_2}{V(m_1 + m_2)} \quad (5.157)$$

Eq. (5.156) allows eliminating $1/(\delta_1 + \delta_2)$ from the model in the right side of eq. (5.151) to obtain

$$P(\text{collision}) = P(\text{deviation}) \times \frac{2\lambda_x}{4d_x} E \times P_z(0) \left[\left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) P(\text{ac 1 reaches route 2}) + \left(1 + \frac{|V_2 \cos \theta - V_1|}{V_2 \sin \theta} \right) P(\text{ac 2 reaches route 1}) \right] \quad (5.158)$$

or

$$\Pr(\text{collision}) = \Pr(\text{deviation}) \times \frac{\lambda_x E}{d_x} \times P_z(0) \left[\left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) \Pr(\text{ac 1 reaches route 2}) + \left(1 + \frac{|V_2 \cos \theta - V_1|}{V_2 \sin \theta} \right) \Pr(\text{ac 2 reaches route 1}) \right] \quad (5.159)$$

As follows from eqs. (5.140) and (5.147), in eq. (5.159), the probabilities $\Pr(\text{ac 1 reaches route 2})$ and $\Pr(\text{ac 2 reaches route 1})$ depend on the respective aircraft speeds V_1 and V_2 . These aircraft speeds are modelled as random variables. Assuming that the two aircraft speeds have the same probability distribution, eq. (5.155) may be further simplified to

$$\Pr(\text{collision}) = \Pr(\text{deviation}) \times \frac{\lambda_x}{d_x} E \times P_z(0) \left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) \Pr(\text{ac 1 reaches route 2}) \quad (5.160)$$

or, equivalently,

$$\Pr(\text{collision}) = \Pr(\text{deviation}) \times \frac{\lambda_x}{d_x} E \times P_z(0) \left(1 + \frac{|V_2 \cos \theta - V_1|}{V_2 \sin \theta} \right) \Pr(\text{ac 2 reaches route 1}) \quad (5.161)$$

where $\Pr(\text{ac 1 reaches route 2})$ and $\Pr(\text{ac 2 reaches route 1})$ depend on V_1 and V_2 respectively.

Let the probability of a deviation $\Pr(\text{deviation})$ be expressed as the number of deviations per flight hour Ω and the number of accidents per flight hour as N_m . The latter then follows from integrating eq. (5.156) over the probability distributions of the random variables V_1 , V_2 , θ , and T_a . Thus,

$$N_m = 2\Omega \frac{\lambda_x}{d_x} E \times P_z(0) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{T_{a,\min}}^{T_{a,\max}} \left(1 + \frac{|V_1 \cos \theta - V_2|}{V_1 \sin \theta} \right) \int_{\theta^*(T_a, V_1)}^{\pi/2} f_{\theta}(\theta) d\theta f_{T_a}(T_a) dT_a f_1(V_1) f_2(V_2) dV_1 dV_2 \quad (5.162)$$

It should be noted that the form of the collision risk model in eq. (5.158) depends on the assumption that the critical angle θ^* in the pertinent lower integration limit is a function of two random variables T_a and V_1 and a constant route spacing S , cf. eq. (5.140). Dependent on the operational environment, the route spacing S is a function of the lateral separation minimum S_y , a deviation detection threshold d_a , SLOP, and or multiple tracks. If applicable, the last two variables can be accounted for by appropriate weighted summations. The route spacing S could also be made dependent on the (typical) lateral deviations of the non-deviating aircraft given its RNP performance value and probability distribution.

Lateral ASEPS collision risk has been computed in Appendix D to ICAO Doc 10116 (ICAO, NN) for a variety of parallel-route scenarios, resulting in a lateral separation minimum for parallel routes of 19 NM or 15 NM with additional constraints on occupancy E and the lateral deviation rate Ω . These minima have been incorporated into the 16th Edition of the PANS-ATM through Amendment 9 with an applicability date of November 2020.

5.4.4.2 Intersecting routes

Appendix E to ICAO Doc 10116 (ICAO, NN) deals with the ASEPS lateral collision risk modelling for intersecting routes. It states that this has been addressed by the area of conflict method using the standard collision risk model based on reliability theory in Section 5.3 of (Anderson, 2005) and described in Chapter 7 of this document. The geometry of the operational context is similar to that considered in Section 5.4.1 dealing with *GNSS lateral separation minima based on VOR separation in ICAO Circular 322*. For ease of reference, Figures 5.3 – 5.5 have been reproduced from Section 5.4.1. Lateral separation is achieved by the controller ensuring that two aircraft will not be simultaneously within the area of conflict at the same level.

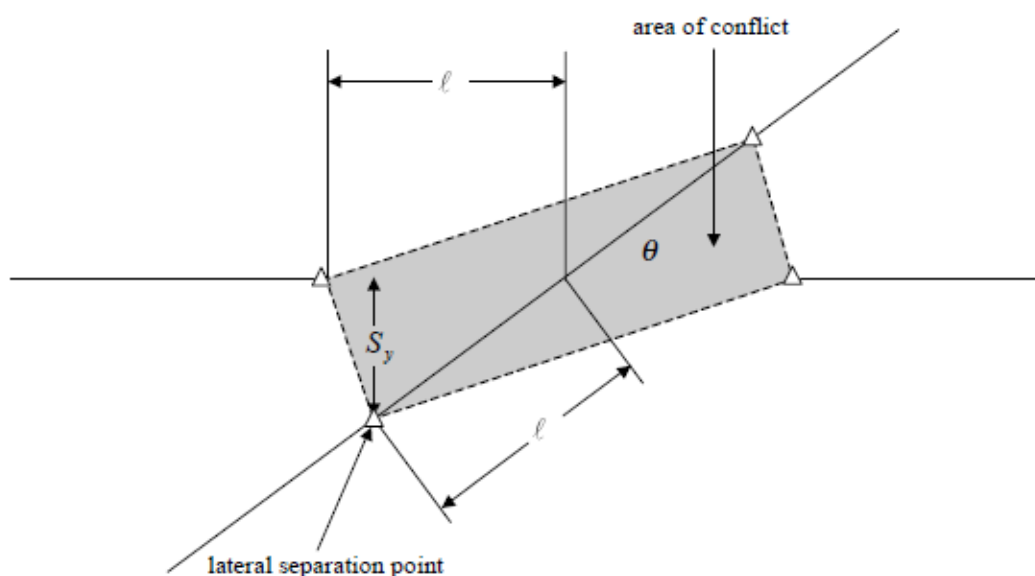


Figure 5.3: Lateral separation points and the area of conflict

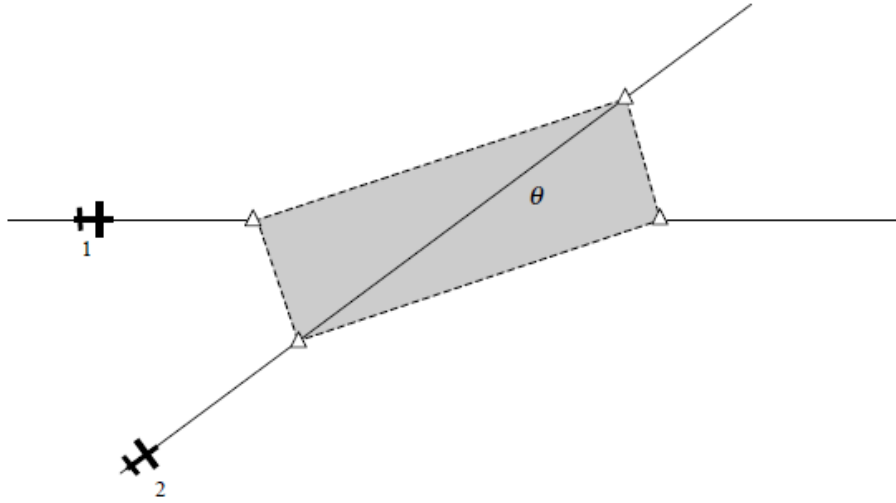


Figure 5.4: Both aircraft approaching the area of conflict

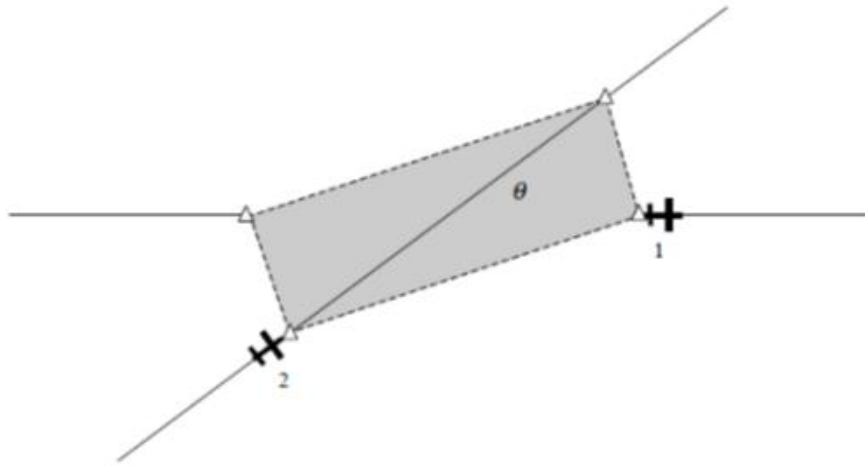


Figure 5.5: One aircraft leaving the area of conflict as the other one enters

For the scenario of Figure 5.3, aircraft 2 is given the instruction to climb before the lateral separation point it is approaching. Usually, this instruction is given as a distance to the intersection point/ waypoint. The collision risk is to account for the navigational errors as illustrated in Figure 5.2. Collision risk exist over a period of time prior to aircraft 2 reaching vertical separation at its lateral separation point. The collision risk model given in Eq. (E.1.3) of Appendix E to ICAO Doc 10116 (ICAO, NN) reads as follows, where the notation of Chapter 7 of this document has been used:

$$N_a[t_0, t_1] = 2m\pi\lambda_{xy}^2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) P_z(h(t)) \left(\frac{2v_{xy}}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right) f_1(v_1)f_2(v_2) dt dv_1 dv_2 \quad (5.163)$$

with $f_i(v_i)$ denoting the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denoting the joint probability density of the relative position $r_x(t)$, $r_y(t)$ between the two aircraft at time t for $r_x(t) = r_y(t) = 0$ and being given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C \dots$$

The risk calculations started at $t_0 = 0$ with the aircraft being at nominal distances to the intersection being given by

$$d_1 = l + v_1(t_c + T_r) \quad (5.164)$$

$$d_2 = l + v_2(t_c + T_r) \quad (5.165)$$

with t_c denoting the time needed to achieve vertical separation, T_r denoting the position reporting time interval and l being given as a function of the intersecting angle θ and the lateral separation minimum for intersecting routes S_y^* by

$$l = \frac{S_y^*}{\sin \theta} \quad (5.166)$$

The initial distances d_1 and d_2 to the intersection are used to compute the initial relative position components $D_x(t)$ and $D_y(t)$ at time $t_0 = 0$ after which these components evolve as described by eqs. (5.164) and (5.165). The end time t_1 is specified as $t_1 = t_c + T_r$. The integrand $f_t(0,0)$ is given by a relatively simple analytical formula when the navigational error distributions are normal but requires extensive computer software for the case of double-exponential probability distributions.

So far, nothing specific to ASEPS has been used. The ASEPS element is discussed in paragraph E.1.8 of Appendix D to ICAO Doc 10116 (ICAO, NN). It is first stated that use of double exponential distributions for the along-track and across-track navigational error ε_2^A and ε_2^C would be intended to conservatively model long-tailed aircraft positioning errors. If normal distributions were used, insufficient aircraft with large deviations from track would be accounted for, which would then need to be modelled separately as aircraft deviating at an angle in much the same way as for the parallel routes case of Section 5.4.4.1. However, separate work within SASP showed that the use of double exponential distributions for position errors gave a higher risk than assuming normal distributions with a separate term for aircraft deviating at an angle. Thus, the ASEPS lateral separation minimum for intersecting routes is actually a conventional procedural lateral separation minimum for intersecting routes.

The last parameter to be discussed is the number of aircraft pairs passing the intersection per flying hour, i.e. m in eq. (5.163). Two values have been used in Appendix D to ICAO Doc 10116 (ICAO, NN), namely $m = 0.5$ and $m = 0.1$. As stated, the former value was used in the original modelling for the 30 NM intersecting-route lateral separation minimum with indications that this would be conservative by a factor of 25 based on available data for this new minimum. Crossing rates for aircraft at adjacent flight levels published by regional monitoring agencies at international cooperation meetings are consistent with the factor of 25 and show values of m less than 0.1.

For the scenario of Figure 5.4 with one aircraft entering the area of conflict and the other leaving it, aircraft 2 is given the instruction to not arrive at the separation point it is approaching before a given point in time. The collision risk model for this scenario is that given by eqs. (5.163), (7.XX), and (5.166) with modified versions of eqs. (5.164) and (5.166) for the distances d_1 and d_2 of the aircraft to the intersection point at time $t_0 = 0$ and the time interval $[t_0, t_1]$ over which the risk is calculated. To maximize the risk over all possible reporting times, the modelling assumed that the aircraft report when aircraft 2 is a reporting time interval T_r before the intersection and the risk was calculated over two reporting periods, i.e. the time interval $[t_0, t_1] = [0, 2T_r]$. The initial distances d_1 and d_2 are then given by

$$d_1 = v_1 T_r \quad (5.167)$$

$$d_2 = v_2 T_r + l \times \left(1 + \frac{v_2}{v_1}\right) \quad (5.168)$$

Lateral ASEPS collision risk has been computed for RNP 2 and RNP 4 approved aircraft in Appendix E to ICAO Doc 10116 (ICAO, NN) for a variety of intersecting-route scenarios. It was concluded that the lateral separation minimum that meets the target level of safety for intersecting tracks is less than the equivalent lateral separation minimum for parallel tracks/routes. Hence the lateral separation minimum for intersecting tracks is the same as the parallel-track minimum. Recall from section 5.4.4.1 that the latter was equal to 15 NM or 19 NM dependent on additional constraints on occupancy E and the lateral deviation rate Ω . Since occupancy is not a parameter of the lateral collision risk model for intersecting routes, and since the deviation rate Ω was implicitly modelled by the double-exponential navigational error distributions, the resulting lateral separation minimum for intersecting routes was taken as of 19 NM. This minimum has been incorporated into the 16th Edition of the PANS-ATM through Amendment 9 with an applicability date of November 2020.

5.5 Lateral collision risk modelling for parallel routes by EUROCONTROL

5.5.1 Introduction

This section will distinguish four stages of collision risk modelling for parallel routes in European airspace performed under the auspices of EUROCONTROL, namely:

- For ATS routes defined by VOR or VOR/DME;
- For RNAV routes conducted by Dr L. Burt;
- For RNAV routes conducted by Dr E. Smith; and
- For PBN routes conducted by Dr G. Moek.

For all cases, emphasis is on the form of the collision risk model(s) used rather than the separation minima calculated.

5.5.2 ATS routes defined by VOR or VOR/DME

As stated in the *Foreword* to ICAO Circular 120 (ICAO, 1976a), the ICAO RGCSP at its second meeting in October 1973 (RGCSP/2) considered a comprehensive study on determination of separation minima for the spacing of parallel tracks in ATS route structures in a defined air traffic services environment. The defined air traffic services environment concerned selected ATS route segments in France, defined by VOR or VOR/DME and with lengths between 30 NM and 170 NM⁴¹. The meeting agreed that the data collected on the navigational performance of the aircraft population flying along the route segments concerned were reasonably representative of the environment but noted a number of aspects which impaired the confidence that could be attached to the results. This data, its collection, processing, and initial analysis are documented in Section 3 of ICAO Circular 120 (ICAO, 1976a). The data were subsequently reprocessed and analysed as set out in Sections 4 and 5 of ICAO Circular 120 (ICAO, 1976a) for consideration by the RGCSP at its third meeting in the second half of 1975 (RGCSP/3). The collision risk model described in Section 2 of ICAO Circular 120 (ICAO, 1976a) was used in conjunction with the results of both the initial and reprocessed analysis of the navigation performance data, albeit with a slightly revised value for the probability of joint longitudinal and vertical overlap (P_{xz}). See also (Brooker & Ingham, 1978). Other collision risk model parameters such as aircraft dimensions and relative speeds between aircraft were given the same values in both cases. A preliminary target level of safety value of 0.16 – 0.08 fatal accidents per 10 million flying hours was chosen as a working tool for assessing the minimum spacing required between parallel tracks on the basis of the collision risk calculated by the mathematical model at RGCSP/2. However, a single value of 0.2 fatal accidents per 10 million flying hours was suggested as a reasonable basis for assessment of the lateral spacing required at RGCSP/3.

The collision risk model developed in ICAO Circular 120 (ICAO, 1976a), based on the Reich collision risk model utilized by the NAT SPG, see Sections 5.2 and 5.3 of this document, is summarized below. It should be emphasized that the collision risk model assumed that the airspace was a non-radar environment although the data had been collected in a radar environment. However, every attempt had been made, through careful scrutiny of the data, to remove any ATC input into the data from it. It is concluded in Section 8 of ICAO Circular 120 (ICAO, 1976a) that the required spacing in case of opposite-direction traffic at the same flight levels on both tracks was 19.3 NM if the total data sample was used. For a subsample of about 75% of the total data⁴² on segments with lengths between 29 NM and 143 NM the value of 18 NM was derived. For same-direction traffic the required spacing was found to be about 1.5 NM less than for opposite-direction traffic.

In view of the doubts still existing regarding the validity and application of the data used in arriving at the 18 NM and 16.5 NM required spacings for opposite-direction and same-direction traffic respectively on parallel routes in procedural airspace, the RGCSP at its third meeting decided that it was premature to propose a uniform value for world-wide application. However, the Panel was of the opinion that its work relating to lateral separation between parallel tracks could be used to provide guidance to States and developed draft guidance material which was proposed for inclusion in an attachment to Annex 11.

As set out in Section 2 of ICAO Circular 120 (ICAO, 1976a), the collision risk model developed for parallel ATS routes defined by VOR or VOR/DME was derived from the model developed by the NAT SPG in (ICAO, 1966, 1967, 1968b, 1968a) based on the Reich model. This is the model given by eqs. (5.32) – (5.34), covering both

⁴¹ The data collection is often referred to as the 1972 EUROCONTROL data collection.

⁴² The remaining 25% of the total data sample (the “Midhurst” sample) included the longest routes where the VOR radial for one of the two routes showed considerable curvature and was outside the limits set by ICAO.

same-direction and opposite-direction traffic. See Section 5.3.1. However, the section actually starts off with the more basic form of the Reich model, viz.

$$N_{ay} = 10^7 \times (N_x P_y P_z + N_y P_z P_x + N_z P_x P_y) \quad (5.38)$$

Cf. eq. (5.4) in Section 5.2.1 for the collision rate C in number of collisions per flight hour. The model was then expressed as

$$N_{ay} = 10^7 \times P_x P_z \left\{ P_y \left(\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{z}|}{2\lambda_z} \right) + N_y \right\} = 10^7 \times P_x P_z \left\{ \frac{1}{2\lambda_y} \times P_y \left(|\bar{\dot{x}}| \frac{\lambda_y}{\lambda_x} + |\bar{\dot{z}}| \frac{\lambda_y}{\lambda_z} \right) + N_y \right\} \quad (5.169)$$

to account for two characteristics of ATS routes defined by VOR or VOR/DME, namely that the probability distributions of the lateral deviations by the aircraft vary with the distances of the aircraft to the VOR or VOR/DME beacons being used and similarly for the lateral speeds of the aircraft and thus for the relative lateral speed between the aircraft. The development also assumed that the aircraft lateral speeds were dependent on the size of the aircraft's lateral deviations. See the discussion on this assumption at the beginning of Section 5.2.2.

Thus, the (average) probability of lateral overlap was defined as (cf. eqs. (4.16) and (4.17))⁴³

$$P_y = 2\lambda_y \times \frac{1}{X_0} \int_0^{X_0} \int_{-\infty}^{\infty} f(y; X) f(y - S_y; X) dy dX \quad (5.170)$$

where $f(y; X)$ denotes the probability density of the lateral deviations of the aircraft as a function of the distance X to the start of a route segment and X_0 denotes the length of the route segment. Notice that the form of eq. (5.170) assumes that the lateral deviation distributions of the aircraft are the same and that the aircraft are flying in the same direction along the route segment. Opposite-direction traffic should formally utilize an inner integrand of the form $f(y; X) f(y - S_y; X_0 - X)$. As a function of the along-track location X , the inner integral is assumed to have a rectangular distribution over the range $[0, X_0]$, which may be interpreted as the aircraft flying at constant speeds.

The number N_y of lateral overlaps per flight hour was defined in a similar manner as the probability of lateral overlap, viz.

$$N_y = \frac{1}{X_0} \int_0^{X_0} \int_{-\infty}^{\infty} f(y; X) f(y - S_y; X) |\bar{y}|(y; X) dy dX = \quad (5.171)$$

where $|\bar{y}|(y; X)$ denotes the average or expectation of the absolute value the relative lateral speed between the aircraft dependent on their lateral separation y and longitudinal location X . The product of the probability density functions, $f(y; X) f(y - S_y; X)$, denotes the probability density function of the lateral distance between the aircraft at a lateral distance equal to zero given the longitudinal location X of the two aircraft.

Ignoring the longitudinal dimension, eq. (5.171) may be compared with eqs. (5.9) – (5.11) specified by Reich (1966) based on Reich (1964) in Section 5.2.2 for the separation r in any of the three dimensions x , y , or z ,

⁴³ The notation in eqs. (5.170) – (5.171) was slightly adapted from that used in the original text in Section 2 of Reich.

$$N_r = 2 \int_0^\infty \dot{r} G(\lambda_r, \dot{r}) d\dot{r} \quad (5.9)$$

$$N_r \approx 2 \int_0^\infty \dot{r} G(0, \dot{r}) d\dot{r} \quad (5.10)$$

$$\overline{\dot{r}} \approx \overline{|\dot{r}|} \times \phi(0) \quad (5.11)$$

where $\dot{r}$ denotes the rate of change of r , $G(\lambda_r, \dot{r})$ denotes the joint probability density function $G(r, \dot{r})$ of r and $\dot{r}$ at $r = \lambda_r$, and $\phi(r)$ denotes the probability density function of the separation r . Eq. (5.10) is based on the assumption that $G(r, \dot{r})$ is likely to change only slightly over an interval of twice the collision size λ_r , and eq. (5.11) is based on the assumption that r and $\dot{r}$ are statistically independent. Eq. (5.171) seems to treat $\dot{y}$ and thus $\overline{|\dot{y}|}$ as a function of the random lateral deviation y rather than as a separate random variable.

Substitution of eqs. (5.170) and (5.171) into the model in eq. (5.169) gives

$$N_{ay} = 10^7 \times P_x P_y \frac{1}{X_0} \int_0^{X_0} \int_{-\infty}^{\infty} f(y; X) f(y - S_y; X) \left\{ \overline{|\dot{y}|}(y; X) + \left(\overline{|\dot{x}|} \frac{\lambda_y}{\lambda_x} + \overline{|\dot{z}|} \frac{\lambda_y}{\lambda_z} \right) \right\} dy dX \quad (5.172)$$

where the terms in the relative along-track and vertical speeds $\overline{|\dot{x}|}$ and $\overline{|\dot{z}|}$ do not depend on the longitudinal location X but the relative across-track-speed term $\overline{|\dot{y}|}(y; X)$ does. It remains to specify this last term. Eq. (1.7) of Reich (1966) states this was done as

$$\overline{|\dot{y}|}(y; X) = \int_{-\infty}^{\infty} |\dot{y}|(y; X) g(\dot{y}, y; X) d\dot{y} \quad (5.173)$$

where $g(\dot{y}, y; X)$ denotes the probability density function of the relative lateral speed $\dot{y}$ between the aircraft as a function of the lateral deviation y of one of the aircraft and given the aircraft pair has zero lateral separation and longitudinal location X . This density is given by

$$g(\dot{y}, y; X) = \int_{-\infty}^{\infty} f_{\dot{y}_1}(\dot{y}_1, y|X) f_{\dot{y}_2}(\dot{y} - \dot{y}_1, y - S_y|X) d\dot{y}_1 \quad (5.174)$$

Eq. (1.7) in ICAO Circular 120 (ICAO, 1976a) seems to contain a minor editorial error in that it uses the differential $d\dot{y}_1$ rather than $d\dot{y}_1$, or, in the original notation of ICAO Circular 120 (ICAO, 1976a), dY instead of $d\dot{Y}$.

See also Appendix C of this document for a list of assumptions underlying the lateral collision risk model developed.

5.5.3 RNAV routes Part I

This subsection describes a series of papers on collision risk modelling for RNAV drafted by Dr L. Burt for *The Navigation and Separation Studies Sub-Group* (NSG, later NSSG) of the EUROCONTROL *Navigation and Separation Panel* (NAVSEP) (later *Airspace and Navigation Team* (ANT)) during the years 1993 – 1995 (Burt, 1993a, 1993b, 1993c, 1994, 1995a, 1995b, 1995d, 1995c). Given the time period during which the work was performed, RNAV as defined in the *Manual on RNAV Operations* (ICAO, 1991) and RNP as defined in the First Edition of the *Manual on Required Navigation Performance (RNP)* (ICAO, 1999b) are of relevance. Appendix A to

(Burt, 1993b) describes the underlying EUROCONTROL Separation Studies work programme. The lateral component of that work programme only will be dealt with here.

(Burt, 1993a) begins with noting that the wider availability of RNAV in the (then) present aircraft population should allow more efficient use of airspace and that further improvements should come from the introduction of precision RNAV (PRNAV) to replace the basic RNAV (BRNAV). It continues noting that States aim to introduce in continental airspace routes specified in terms of RNAV characteristics – BRAV/RNP 4 by 1995 and PRNAV/RNP 1 by 1998 and refers to the earlier work on the safe spacing between ATS routes defined by VOR or VOR/DME of ICAO Circular 120 (ICAO, 1976a), see the previous Subsection 5.5.2, based on the EUROCONTROL 1972 data collection. Since many of the factors, including the characteristics of navigation equipment, the traffic levels, and the provision of ATC have changed since that time, there is a need to revise the findings of ICAO Circular 120 (ICAO, 1976a). Specifically, the minimum track spacing for PRNAV/RNP 1, with a 95% lateral navigation performance constraint of 1 NM and for mixtures of PRNAV/RNP 1 and BRNAV/RNP 4 (with a 95% lateral navigation performance constraint of 4 NM) is analysed, where for the mixture case it is assumed that the routes are segregated, i.e. the PRNAV/RNP 1 approved aircraft are flying one route and the BRNAV/RNP 4 approved aircraft are flying the other route.

The first collision risk model presented in (Burt, 1993a) is the following

$$N_{ay} = P_x P_y P_z \left(\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \quad (5.175)$$

This is of the same form as eq. (5.4) in Section 5.2.1 for the collision rate C in number of collisions per flight hour as derived by Reich (1966). The left-hand side variable N_{ay} denotes the expected number of accidents due to the loss of lateral separation per flight hour. Cf. also eq. (5.38) of Section 5.5.2. The target level of safety used is 0.2×10^{-7} fatal accidents per flight hour.

Probabilities of lateral overlap, P_y , were calculated for several RNP values on the assumption of a double exponential distribution of the lateral navigational errors with the standard deviation calculated from the pertinent 95% containment values.

To facilitate comparison with the results obtained in ICAO Circular 120 (ICAO, 1976a), that reference's parameter values, other than P_y , were used, including an un-factored probability of joint longitudinal and vertical overlap, P_{xz} , to account for a mixture of level flights and climbs and descents, and the collision risk model expressed as

$$N_{ay} = P_{xz} P_y \left(\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \quad (5.176)$$

The probability of lateral overlap P_y was calculated on the assumption of RNP 4 performance for early nineteen seventies navigation performance. Based on ICAO Circular 120 (ICAO, 1976a), the value of $|\bar{y}|$ was taken as a linear function of the route spacing S , viz.

$$|\bar{y}| = 29.3 + 1.833 \times S \quad (5.177)$$

Next, calculations were performed for procedural lateral collision risk for RNP 1 and/or RNP 4 approved aircraft on (segregated) parallel routes in continental airspace in the mid nineteen nineties. To that end, the collision risk model in eq. (5.175) was re-expressed as

$$N_{ay} = N_x P_y P_z \left(1 + \frac{\lambda_x \overline{|\dot{y}|}}{\lambda_y \overline{|\dot{x}|}} + \frac{\lambda_x \overline{|\dot{z}|}}{\lambda_z \overline{|\dot{x}|}} \right) \quad (5.178)$$

by combining the probability of longitudinal overlap, P_x , with the inverse of the duration of a longitudinal overlap, $\overline{|\dot{x}|}/(2\lambda_x)$, into the passing-frequency parameter N_x and subsequently split up into a same-direction part and an opposite-direction part,

$$N_{ay} = N_x(opp) P_y P_z \left(1 + \frac{\lambda_x \overline{|\dot{y}|}}{\lambda_y \overline{|\Delta V|}} + \frac{\lambda_x \overline{|\dot{z}|}}{\lambda_z \overline{|\Delta V|}} \right) + N_x(same) P_y P_z \left(1 + \frac{\lambda_x \overline{|\dot{y}|}}{\lambda_y \overline{2|V|}} + \frac{\lambda_x \overline{|\dot{z}|}}{\lambda_z \overline{2|V|}} \right) \quad (5.179)$$

See (Burt, 1993a) for the values of the remaining collision risk model parameters, i.e. average aircraft dimensions, average aircraft speeds and relative speeds.

Finally, calculations were performed for the North Atlantic, with the collision risk model stated in occupancy form, i.e.

$$N_{ay} = P_y(S_y) P_z(0) \frac{\lambda_x}{S_x} \left[E_y(same) \left\{ \frac{\overline{|\Delta V|}}{2\lambda_x} + \frac{\overline{|\dot{y}|}}{2\lambda_y} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right\} + E_y(opp) \left\{ \frac{2\overline{|V|}}{2\lambda_x} + \frac{\overline{|\dot{y}|}}{2\lambda_y} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right\} \right] \quad (5.180)$$

Eq. (5.180) may be compared with the collision risk model agreed at NAT SPG/4 (1968), i.e. eq. (5.32) from Section 5.3.1 with $\gamma = 1$ and $\Lambda_x = \lambda_x$, the one utilized for the development of the MNPS specification (Attachment 1 to Appendix A to the report of NAT SPG/12 (1976)), eq. (5.61) of Section 5.3.3, or the one stated in Davies and Sharpe's review of the North Atlantic Lateral Collision Risk Model (1993), eq. (5.74) of Section 5.3.4.

(Burt, 1993a) concludes with a need for further work on the lateral error distributions, covering both the core distribution of navigation system errors and gross navigation errors.

(Burt, 1994, 1995b, 1995c) deal with the calculation of ATC intervention rates for aircraft on dual tracks in connection with the determination of safe route spacing in radar controlled airspace. As set out in these references, in an airspace using procedural control, the minimum lateral spacing between parallel tracks is governed by the distribution of aircraft lateral errors, and must be such that the chance of a collision arising from the loss of lateral separation is acceptably small. In a region where radar is available, however, the safe track spacing can be reduced due to reliance on ATC intervention; lateral errors are monitored by the ground controller, and aircraft are re-directed to avoid potential conflicts. The improvements in lateral navigation accuracy brought about by new technology such as PRNAV should enable further reduction in parallel track spacing provided that the intervention rate is shown to lead to an acceptable ATC workload. The two references then deal with the estimation of the intervention rate as a function of the track spacing and the other parameters and functions involved, such as traffic flow rates and speeds, sector length, and the probability density functions and time histories of lateral and – where appropriate – vertical errors. The papers deal with two methods of intervention, namely the deviation mode and the conflict mode. In the deviation mode, any aircraft deviating from its track by more than a given lateral distance is redirected, while

in the conflict mode action is only taken when a potential conflict arises. (Burt, 1995c) appears to be the concluding paper on the subject and will be summarized at the end of this subsection.

(Burt, 1995a) returns to the calculation of procedural lateral collision risk for aircraft on dual tracks with collision risk estimated for RNP 1, RNP 4, and RNP 5 approved aircraft. The collision risk model used is that of eq. (5.178) with a slightly refined notation, viz.

$$N_{ay} = N_x P_y(S) P_z(0) \left(1 + \frac{\lambda_x \overline{|y|}}{\lambda_y \overline{|x|}} + \frac{\lambda_x \overline{|z|}}{\lambda_z \overline{|x|}} \right) \quad (5.181)$$

The passing frequency is given by the following formula,

$$N_x = \frac{2f_1 f_2}{V_1 f_1 + V_2 f_2} |\dot{x}| \sum_{i=1}^{i=n} r_{1,i} r_{2,i} \quad (5.182)$$

with V_1 and V_2 the mean aircraft speeds and f_1 and f_2 the flow rates on tracks 1 and 2 respectively. These flow rates are assumed to be distributed over n flight levels with $r_{1,i}$ and $r_{2,i}$ the relative flow rates on track 1 and track 2 at flight level i . Eq. (5.182) simplifies for a single pair of flight levels to

$$N_x = \frac{2f_1 f_2}{V_1 f_1 + V_2 f_2} |\dot{x}| \quad (5.183)$$

which may be converted to the probability of longitudinal overlap P_x by means of $N_x = P_x \times \overline{|\dot{x}|} / (2\lambda_x)$, i.e.

$$P_x = 2\lambda_x \frac{2f_1 f_2}{V_1 f_1 + V_2 f_2} = \lambda_x \frac{4f_1 f_2}{V_1 f_1 + V_2 f_2} = \frac{\lambda_x}{S_x} \frac{4S_x f_1 f_2}{V_1 f_1 + V_2 f_2} \quad (5.184)$$

where S_x denotes the proximity criterion used in the definition of occupancy. Approximating the aircraft speeds V_1 and V_2 in the right most side of eq. (5.184) by their average value gives

$$P_x \approx \frac{\lambda_x}{S_x} \frac{4S_x f_1 f_2}{V(f_1 + f_2)} \quad (5.185)$$

The second factor on the right side of eq. (5.185) should be recognized as the occupancy parameter of a steady-state system made up of a pair of parallel routes. Cf. eq. (5.157) from Section 5.4.4.1,

$$E = \frac{4d_x m_1 m_2}{V(m_1 + m_2)} \quad (5.157)$$

Flow rates f_1 and f_2 of 25 aircraft entering each track per hour were used in the (Burt, 1995a) lateral collision risk calculations with a typical flow rate distribution factor of

$$r = \sum_{i=1}^{i=n} r_{1,i} r_{2,i} \approx 0.2 \quad (5.186)$$

Two types of mixture distributions were used to calculate the probability-of-lateral-overlap parameter $P_y(S)$ of the collision risk model, namely a normal-double-exponential distribution and a double-double-exponential distribution. The respective probability density functions are (see sections 5.4.2.3 and 5.3.3)

$$f(y) = \frac{(1-\alpha)}{\sigma\sqrt{2\pi}} \exp\left(-\frac{y^2}{2\sigma^2}\right) + \frac{\alpha}{2\lambda} \exp\left(-\frac{|y|}{\lambda}\right) \quad (5.106)$$

$$f(y) = \frac{(1-\alpha)}{2\lambda_1} \exp\left(-\left|\frac{y}{\lambda_1}\right|\right) + \frac{\alpha}{2\lambda_2} \exp\left(-\left|\frac{y}{\lambda_2}\right|\right) \quad (5.69)$$

As before for mixture densities, the core densities represent normal navigation performance whereas the tail densities represent abnormal performance, such as blunder or equipment failure. For the calculations, the tail density parameters λ and λ_2 were taken equal to the lateral separation minimum S to be evaluated. This can be shown to be conservative. The weighting factor α was given the following values: $\alpha = 0, 10^{-6}, 10^{-5}, 10^{-4}$, and 10^{-3} . Three cases were considered for the core density of the lateral errors of RNP 1 approved aircraft. Firstly, the core density was taken as a normal density with the standard deviation σ based on either 99.999% containment or 95% containment. The core density was also taken as double exponential with the scale parameter λ_1 based on 95% containment. For RNP 4 and RNP 5 approved aircraft, the core densities were taken as double exponential with the scale parameter λ_1 based on 95% containment.

See (Burt, 1995a) for the values of the remaining collision risk model parameters, i.e. average aircraft dimensions, average aircraft speeds and relative speeds.

(Burt, 1995a) concludes with a paragraph on the effect of ATC intervention. If ATC intervention can resolve on average $\eta\%$ of the conflicts, the accident rate at a given track separation S is

$$N_I(S) = N_{ay}(S)(1 - \eta/100) \quad (5.187)$$

since any conflict could lead to a collision, but no collision can occur without a preceding conflict.

(Burt, 1995d) used a collision risk model specified by eqs. (5.181), (5.183), and (5.187) in combination with the normal-double-exponential lateral deviation probability density of eq. (5.106) to calculate both collision risk and ATC intervention rates for RNP 1, RNP 4, and RNP 5 approved aircraft. The ATC intervention rates were derived from the formulae developed in (Burt, 1995c). See (Burt, 1995d) for the particular collision risk model parameter values used.

This subsection concludes with a summary of the intervention rate formulae from (Burt, 1995c). Consider a pair of parallel tracks of length L and lateral spacing S within an ATC sector of interest. Let y_D be the deviation intervention threshold and let $h(y)$ be the probability density of the lateral deviations from track. The deviation intervention rate for the deviation mode is then given by

$$N_D = \frac{1}{2} L \left(\frac{f_1}{V_1} + \frac{f_2}{V_2} \right) v_y h(y_D) \quad (5.188)$$

In the above equation, V_1 and V_2 are the mean aircraft speeds and f_1 and f_2 are the flow rates on tracks 1 and 2 respectively, and v_y is the absolute mean of the lateral speed of a deviating aircraft. The intervention rate is identical for same- and opposite-direction traffic.

For the conflict mode, let M_x , M_y , and M_z the minimum allowable relative separation in the longitudinal, lateral, and vertical dimensions respectively. In addition, let f_x , f_y , and f_z denote the probability density

functions of the relative motion in the respective directions, and v_x , v_y , and v_z the absolute means of the speed components of a deviating aircraft in the three directions. The intervention rate for the conflict mode and a cuboid hazard space is then given by (using symbols Q_x , Q_y , and Q_z rather than the reference symbols P_x , P_y , and P_z)

$$r_c = Q_x Q_y n_z + Q_y Q_z n_x + Q_z Q_x n_y \quad (5.189)$$

with

$$Q_x = \int_{-M_x}^{M_x} f_x(x) dx \quad (5.190)$$

$$Q_y = \int_{-M_y}^{M_y} f_y(y) dy \quad (5.191)$$

$$Q_z = \int_{-M_z}^{M_z} f_z(z) dz \quad (5.192)$$

$$n_x = \frac{1}{2} v_x [f_x(M_x) + f_x(-M_x)] \quad (5.193)$$

$$n_y = \frac{1}{2} v_y [f_y(M_y) + f_y(-M_y)] \quad (5.194)$$

$$n_z = \frac{1}{2} v_z [f_z(M_z) + f_z(-M_z)] \quad (5.195)$$

It is shown in (Burt, 1995c) that the Reich model is a special case of eq. (5.189) for the intervention rate of the conflict mode.

(Burt, 1995c) derived formulae for the conflict mode and a cylindrical hazard space too.

5.5.4 RNAV routes Part II

This subsection describes a series of papers on lateral collision risk modelling for P-RNAV, B-RNAV, RNP 1 RNAV, and A-RNP approved aircraft on parallel routes in radar airspace (Clarke & David, 1988; EUROCONTROL, 1992; Smith, 1996, 2003, 2004, 2005, 2011, 2012; Vernon & Izquierdo, 2004), drafted by Dr E. Smith under contract to EUROCONTROL during three periods of time, namely during the years 1994 – 1996, 2001 – 2005, and 2011 – 2012. A key part of the work performed concerned modelling of controller intervention in radar airspace. A second key part of the work performed concerned modelling of lateral deviation data. Two primary data sources utilized are documented in (Clarke & David, 1988) and (EUROCONTROL, 1992). (Clarke & David, 1988) concerns a large scale data collection to assess the lateral navigation performance of aircraft equipped with advanced navigation systems (P-RNAV) at the Karlsruhe and Maastricht Upper Area Control Centres between March 1982 and May 1984. (EUROCONTROL, 1992) concerns the RNAV performance in the Zurich TMA. Different ways of modelling blunder errors have been explored in (Smith, 1996, 2003, 2004, 2005, 2011, 2012; Vernon & Izquierdo, 2004). Apart from the A-RNP study, the studies pertain to the pre-PBN era with RNAV as defined in the *Manual on RNAV Operations* (ICAO, 1991) and RNP as defined in the First Edition of the *Manual on Required Navigation Performance (RNP)* (ICAO, 1999b) being of relevance.

P-RNAV (hazard analysis)

Based on ICAO Circular 120 (ICAO, 1976a), (Smith, 1996) specifies the Reich collision risk model in the following form

$$N_{ay} = P_x P_z P_y(S) \left(\frac{V_x}{2a} + \frac{V_y}{2b} + \frac{V_z}{2c} \right) \quad (5.196)$$

where V_x , V_y , and V_z are described as relative velocities in the x-plane (longitudinal), y-plane (lateral), and z-plane (vertical) respectively and a , b , and c are, respectively, dimensions of aircraft in x-direction, y-direction, and z-direction. This model applies for procedural separation, N_{ay} (no ATC), and was supplemented with the following model accounting for ATC intervention in radar airspace, N_{ay} (with ATC):

$$N_{ay}(\text{with ATC}) = \text{Deviation frequency} \times \text{Prob of ATC failure} \times N_{ay}(\text{no ATC}) \quad (5.197)$$

The left-hand side variable is called overall risk.

Overall risk was calculated for opposite- and same-direction routes for five failure scenarios, viz.

- Scenario 1 – Gradual drift;
- Scenario 2 – Sharp turn on straight line;
- Scenario 3 – After planned deviation in heading (HDG) mode;
- Scenario 4 – Sharp turn at waypoint; and
- Scenario 5 – Join wrong route.

These scenarios resulted from hazard identification using structured hazard identification sessions, HAZOPS, and search of incident databases and relevant literature. The occurrence frequency of each of the five lateral deviation scenarios was estimated (see Table 7.1.2 of (Smith, 1996)) and the consequences analysed in terms of:

- The speed and probability of a deviation being detected;
- The speed and probability of a deviation being recovered; and
- The probability of an imminent conflict being resolved.

The consequence analysis was subsequently combined with event trees to estimate probabilities of successful/failed ATC intervention as a function of route spacing ranging from 7-16 NM. A common, sharp-deviation-from-track, success/failure probability (as a function of route spacing) was determined for the Scenarios 2 – 4. It is noted in (Smith, 1996) that the credible range of detection and recovery probabilities derived led to a significant uncertainty range in the predictions for the ATC failure probabilities.

The probability of lateral overlap $P_y(S)$ was calculated for each scenario as the product of two factors, namely the probability of the scenario occurring and the probability of a deviating aircraft being in lateral overlap with a non-deviating aircraft on the other route

(Smith, 1996) concluded that it had been demonstrated that the method developed was capable of producing collision risk estimates that take account of ATC intervention. However, before one could be confident that lateral separation minima for parallel routes carrying P-RNAV approved aircraft could be reduced, further work would be required to;

- Improve quantification of the speed and probability of success of ATC intervention, with special emphasis on sharp turns;
- Improve quantification of the speed and probability of pilot reactions to ATC intervention; and
- Better define the frequency of blunder errors, if feasible.

P-RNAV route spacing

(Smith, 2003) deals with lateral collision risk modelling for parallel P-RNAV routes in en-route and terminal airspace with radar surveillance. It states that its collision risk model is based on the Reich model and quotes the following model from ICAO Circular 120 (ICAO, 1976a):

$$N_{ay} = P_{xz}P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.198)$$

The effect of controller intervention is not included in this model. Although no explicit model equation for the collision risk in radar airspace is given in (Smith, 2003), it can be inferred from the text and the numerical values of the lateral overlap probabilities $P_y(S)$ and the controller intervention failure probabilities as a function of the route spacing S , $P_{ATC}(S)$, that the model used for radar airspace is given by,

$$N_{ay} = P_{xz}P_{ATC}(S)P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.199)$$

In fact, (Vernon & Izquierdo, 2004) presents this same model whilst referring to (Smith, 2003). Cf. also eq. (5.197) above.

The work presented in (Smith, 2003) differs from that in (Smith, 1996) as summarized above in two important ways, namely, firstly, with regard to the modelling of the lateral deviation distribution and the calculation of the lateral overlap probability $P_y(S)$, and, secondly, with regard to the estimation of the ATC intervention failure probability $P_{ATC}(S)$. Different lateral deviation data sets were used for en-route airspace (Clarke & David, 1988) and terminal airspace (EUROCONTROL, 1992). Both data sets were modelled by double double exponential distributions with probability densities $f(y)$,

$$f(y) = \frac{(1-\alpha)}{2\lambda_1} \exp\left(-\left|\frac{y}{\lambda_1}\right|\right) + \frac{\alpha}{2\lambda_2} \exp\left(-\left|\frac{y}{\lambda_2}\right|\right) \quad (5.69)$$

and it was concluded that the same set of parameter values could be used for both data sets. It was also assumed that this model was representative of the aggregate of the five scenarios distinguished in (Smith, 1996). The parameter of the double exponential tail density within the mixture was estimated in two ways, resulting in a best estimate and a pessimistic or conservative estimate. The latter estimate was obtained by setting the parameter equal to the route spacing, i.e. $\lambda_2 = S$. See Section 2.2.2 of (Smith, 1996) for how the other parameter values were chosen.

An important part of the P-RNAV route-spacing study of (Smith, 2003) concerned the estimation of controller intervention. As set out in (Smith, 2003), this was based on real-time ATC simulations conducted in October 2002 for en-route as well as terminal airspace. Based on previous experience and the limited amount of simulation runs, “average” ATC failure probabilities covering sharp as well as shallow deviation angles were estimated for each route spacing. The word average does not refer to a formal averaging, but rather to the fact that the data was collected over a variety of conditions, e.g. deviation angle, controller performance, and direction of traffic. The baseline ATC intervention failure estimates were obtained for a 7 NM parallel route spacing and a method was developed with which these estimates were extrapolated to a range from 5 NM to 10 NM. Best estimates as well as pessimistic/conservative ATC intervention failure probabilities were derived. These estimates are presented in a graphical rather than numerical form in (Smith, 2003). Numerical

values have been reconstructed in Section 2.2.1 of (Moek, 2015b). Some discussion of the limitations of real time simulations is included in (Smith, 2003).

(Smith, 2003) also provides some analysis of the performance of P-RNAV aircraft during turns on the basis of three data sets. It was concluded that for turn angles larger than 20° the 95% containment was significantly larger than 1 NM.

In addition to the bulk of the material in the P-RNAV study dealing with the spacing of parallel routes, (Smith, 2003) also includes a section dealing with diverging aircraft separation. Three approaches to this subject are presented namely geometrical, equivalence, and collision risk modelling where the last approach was taken as the preferred one. The model used was an adapted version of the collision risk model for vertical separation of aircraft on crossing routes and, as noted in the (Smith, 2003), the appropriateness of the model used was still under review by the EUROCONTROL Mathematics Drafting Group at the time of drafting of the P-RNAV study report.

Best-estimate lateral collision risk estimates were compared with a target level of safety of 5×10^{-9} fatal accidents per flight hour. Together with sensitivity analysis, this suggested the following route spacings for P-RNAV routes in radar airspace:

- En-route: 7 – 8 NM for same-direction traffic and 10 NM for opposite-direction traffic; and
- Terminal airspace: 7 – 8 NM for same-direction traffic and 8-9 NM for opposite-direction traffic.

B-RNAV route spacing

(Smith, 2004) deals with lateral collision risk modelling for the spacing of parallel B-RNAV routes in en-route radar airspace. The collision risk model of eqs. (5.198) and (5.199) developed under the P-RNAV study was used with all parameters adjusted to a B-RNAV environment. As set out in Section 3 of (Smith, 2004), although the mandated minimum navigation performance criterion for B-RNAV is RNP 5, i.e. 95% containment within 5 NM from the cleared route, it was considered unrealistic to model all aircraft on European B-RNAV routes as RNP 5. In practice, a large proportion of aircraft are navigating much more accurately. It was therefore proposed to model the traffic on European B-RNAV routes as a mixture of RNP 5 and RNP 1 where the mixing factor was assumed to be 30% RNP 5 and 70% RNP 1.

Thus, the probability density of the lateral deviations in a European B-RNAV environment was taken as

$$f(y) = 0.3 \times f_{RNP\ 5}(y) + 0.7 \times f_{RNP\ 1}(y) \quad (5.200)$$

The probability density of lateral deviations of RNP 1 approved aircraft was taken as the double double exponential density for P-RNAV approved aircraft and the probability density of RNP 5 approved aircraft was taken as normal double exponential, i.e.

$$f_{RNP\ 1}(y) = \frac{(1-\alpha)}{2\lambda_1} \exp\left(-\left|\frac{y}{\lambda_1}\right|\right) + \frac{\alpha}{2\lambda_2} \exp\left(-\left|\frac{y}{\lambda_2}\right|\right) \quad (5.201)$$

$$f_{RNP\ 5}(y) = \frac{(1-\beta)}{\sigma\sqrt{2\pi}} \exp\left(-\frac{y^2}{2\sigma^2}\right) + \frac{\beta}{2\lambda} \exp\left(-\frac{|y|}{\lambda}\right) \quad (5.202)$$

A set of best-estimate parameter values and a set of pessimistic-estimate parameter values were specified for $f_{RNP\ 1}(y)$ and $f_{RNP\ 5}(y)$. See (Smith, 2004) for details.

Estimation of controller intervention was also an important part of the B-RNAV route-spacing study. This was based on a combination of two real-time simulations, namely the October 2002 one referenced above for the P-RNAV study and a second one conducted in June 2003 for en-route airspace only. See Section 6 of (Smith, 2004) and/or Section 2.2.2 of (Moek, 2015b) for the numerical estimates obtained.

The B-RNAV study concluded that its indicative results showed that the then adopted route spacings of 16.5 NM for same-direction and 18 NM for opposite-direction traffic on ATS routes defined by VOR or VOR/DME (cf. Section 5.5.2) both met the target level of safety of 5×10^{-9} fatal accidents per flight hour, even after the adoption of the most pessimistic estimates for the tail of the lateral navigation performance distribution of non RNP 1 capable aircraft, the proportion of such aircraft, and the efficacy of ATC in preventing collisions when these assumptions were made independently.

RNP 1 RNAV route spacing

The procedural collision risk model utilized in (Smith, 2005) is based on the Reich model and is given in the same form as for the RNP 1 route-spacing study, viz.

$$N_{ay} = P_{xz}P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.198)$$

The effect of controller intervention is not included in this model. Although no explicit model equation for the collision risk in radar airspace is given in (Smith, 2005), it can be concluded that the model used for radar airspace is also the same as for the P-RNAV route-spacing study, i.e.

$$N_{ay} = P_{xz}P_{ATC}(S)P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.199)$$

The key elements of the RNP 1 RNAV route-spacing study were again the modelling of the probability distribution of the lateral deviations from track and controller intervention.

Controller intervention was again modelled on the basis of real time simulations, i.e. the October 2002 and June 2003 ones, and potentially supplemented with two more real-time simulations performed in August 2003 for terminal airspace and in April 2004. Unfortunately, the results of the August 2003 real-time simulation were not yet available at the time of the RNP 1 RNAV route-spacing study and the April 2004 real-time simulation did not produce any deviations that were not detected/resolved. Unfortunately, it is not possible to calculate best (point) estimates of controller intervention failure for zero observed events. Thus, the real-time simulation data actually utilized for the RNP 1 RNAV study are the combined data from the October 2002 and June 2003 real-time simulations. See Section 5 of (Smith, 2005) and/or Section 2.2.3 of (Moek, 2015b) for further details.

As regards the lateral deviation distribution, the main data source used was (Clarke & David, 1988) concerning P-RNAV performance in 1982-1984. It was realized that the main limitations of this data were their age and the fact that they did not relate specifically to RNP 1 RNAV certified aircraft. To overcome these limitations, questionnaires were distributed to FMS/RNAV equipment experts asking them about the relative likelihood (modern RNP RNAV systems /environment versus 1980s equipment/environment) of the failure causes seen in 1982-1984. See Section 3.2 of (Smith, 2005) for the modifications made to the tails of the 1982-1984 data. The modified tails were subsequently modelled with probability distributions based on extreme value theory.

Best-estimate lateral collision risk estimates were compared with a target level of safety of 5×10^{-9} fatal accidents per flight hour. This suggested the following route spacings for RNP 1 RNAV routes in radar airspace:

- En-route: 7 NM; and
- Terminal airspace: 6 NM for same-direction traffic and 7 NM for opposite-direction traffic.

Three different pessimistic-estimate lateral collision risk estimates were also compared with the target level of safety of 5×10^{-9} fatal accidents per flight hour, suggesting the following route spacings for RNP 1 RNAV routes in radar airspace:

- En-route: 7 – 9 NM, dependent on the pessimistic estimate used; and
- Terminal airspace: 6 – 7 NM for same-direction traffic and 8 – 9 NM for opposite-direction traffic, dependent on the pessimistic estimate used.

Advanced RNP

As stated in (Smith, 2012), Advanced RNP (A-RNP) is a performance-based navigation specification (ICAO, 2013b) that is designed to provide a single specification capable of being used in all phases of flight. For most en-route applications its performance is expected to be the same as defined by RNP 1.

The procedural collision risk model utilized in (Smith, 2011) is based on the Reich model and is given in the same form as for the P-RNAV and RNP 1 RNAV route-spacing studies, viz.

$$N_{ay} = P_{xz}P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.198)$$

The effect of controller intervention is not included in this model. Also, although no explicit model equation for the collision risk in radar airspace is given in (Smith, 2012), it can be concluded that the model used for radar airspace is also the same as for the P-RNAV and RNP 1 RNAV route-spacing studies, i.e.

$$N_{ay} = P_{xz}P_{ATC}(S)P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.199)$$

The key elements of the A-RNP route-spacing study were again the modelling of the probability distribution of the lateral deviations from track and controller intervention. The A-RNP study utilized the same best estimates of the ATC intervention failure probability as the RNP 1 RNAV study. See Section 8 of (Smith, 2012) and/or Section 2.2.4 of (Moek, 2015b) for further details.

As regards the lateral deviation distribution, (Smith, 2012) used six different data sets, including those from (Clarke & David, 1988) and (EUROCONTROL, 1992), supplemented with expert judgement. See section 3 of (Smith, 2012). Based on analysis of the data and the expert judgement, different lateral A-RNP distributions are proposed in Section 5 of (Smith, 2012) for A-RNP 1, A-RNP 0.3, and A-RNP 0.5.

It is concluded in (Smith, 2012) that for busy, same-direction traffic, a spacing of 6 NM has been derived for A-RNP 1 in both en-route and terminal airspace and that enhancing the navigational accuracy to A-RNP 0.5 or 0.3 does not reduce this predicted minimum route spacing. A series of sensitivity tests concerning the tails of the lateral deviation distributions, ATC intervention capability, other collision risk model parameters, target level of safety, and scenario specifics resulted in route spacing ranges of 5 – 8 NM for A-RNP 1 in en-route and terminal airspace.

Another important conclusion of (Smith, 2012) is that there is an urgent need for more track keeping data to better support the A-RNP and future route-spacing studies.

Such data have been collected and processed under the auspices of the EUROCONTROL Enhanced Route Spacing Task Force (ERS TF) over the period June 2014 – January 2016 and used for lateral collision risk modelling and estimation for a number of PBN application scenarios as described below in Section 5.5.5.

5.5.5 PBN routes

5.5.5.1 Introduction

Each of the route-spacing studies reviewed in the previous subsection (Section 5.5.4) was limited to a single navigation specification and parallel routes. References (Moek, 2015b), (Moek, 2014) and (Moek, 2015a, 2016, 2017) document work performed by Dr G. Moek under contract to EUROCONTROL on two main extensions, namely:

1. Different combinations of five PBN navigation specifications; and
2. Different application scenarios.

The work was supported by recent performance-based navigation data made available to the ERS TF by three European Air Navigation Service Providers, namely DSNA (Direction des Services de la Navigation Aérienne) from France, LVNL (LuchtVerkeersLeiding Nederland) from the Netherlands, and NATS (National Air Traffic Services) from the UK.

As explained in (Moek, 2015b), the impact of the first extension on the collision risk methodology is limited. Given a probability distribution for the navigation deviations under the individual PBN navigation specifications, an overall distribution can be constructed by weighting the individual distributions by the flight time of the proportion of the aircraft population utilizing each individual navigation specification. The overall probability distribution can then be used to compute the probability of lateral overlap for parallel routes or as a part of the computation of the probability of horizontal overlap for non-parallel routes.

The impact of the second extension on the collision risk methodology is much wider. At the highest level, three cases of different application scenarios have been considered, some of which were further subdivided as follows:

1. Minimum spacing between parallel routes requiring different performance requirements for each route;
2. Minimum spacing between non-parallel routes with same or different navigation performance requirements for each route;
 - 2.1. Spacing between non-parallel routes that are initially parallel or converge and then diverge – the same PBN navigation specification on each route;
 - 2.2. Spacing between non-parallel routes that are initially parallel or converge and then diverge – different varieties of PBN navigation specifications on each route;
 - 2.3. Spacing between PBN routes and Temporary Reserved Airspaces/Temporary Segregated Airspaces (TRAs/TSAs where the activity in the TRA or TSA is clearly defined);
 - 2.4. Spacing between PBN routes and holding areas;
3. Crossing tracks using same or different navigation specifications;

- 3.1. Operational requirement 3A; and
- 3.2. Operational requirement 3B.

Collision risk models for each application scenario in radar airspace have been developed in two steps similar to eqs (5.198) and (5.199) in Section 5.5.4, i.e. as collision risk models for procedural airspace supplemented with a controller intervention failure probability appropriate to the scenario. The sub-scenarios of the scenarios 2 and 3 require a different type of collision risk model than the parallel route scenario, because the lateral component of the relative position between two aircraft varies over time for the scenarios 2 and 3 instead of being (modelled as) constant for scenario 1. Their collision risk models are based on the general collision risk model based on reliability theory (Anderson, 2005).

At the time, it was foreseen that empirical lateral navigational error distributions would be(come) available that would show a clear relationship with the PBN navigation specification required for each route. Two developments have affected that expectation. Firstly, it has been suggested in the (recent) past, e.g. at the ICAO SASP, that empirical or observed PBN performance is much better than specified PBN performance. This suggestion has, in fact, been confirmed by the results of the ERS TF data collection as described in Chapter 2 of (Moek, 2015a) through lateral navigational error standard deviation values of 0.037 NM to 0.059 NM for straight route segments. The ranges for the standard deviations of the three turn-data types distinguished in Section 2.3 of (Moek, 2015a), pre-turn, mid-turn, post turn, are 0.027 – 0.046 NM (pre-turn data), 0.047 – 0.110 NM (mid-turn data), and 0.056 – 0.103 NM (post-turn data). Secondly, the data have been collected for given aircraft samples/populations rather than by navigation specification. As a result, the lateral collision risk computed in (Moek, 2015a) and (Moek, 2016) with the collision risk models developed in this subsection pertain to mixed aircraft samples/populations rather than specific PBN navigation specifications. The aircraft samples/populations may be taken as representing samples/populations made up of Advanced RNP 1, RNAV 1, and RNP 1 capable aircraft. Dependent on the type of navigation sensor being used by RNP 2 aircraft, the risk computations may also be representative of aircraft samples/populations including RNP 2 aircraft. Alternatively, a hypothetical (empirical) RNP 2 navigational error distribution may be constructed by scaling the available empirical distributions up by a factor of two (2) on the assumption that the typical accuracy of RNP 2 aircraft is a factor of two worse than that of RNP 1 aircraft.

All straight-segment and turn-segment data sets under the ERS TF data collection have been modelled by double double exponential probability distributions, implying a considerable simplification of the horizontal overlap probability formulae from the subsections to follow.

Sections 5.5.5.2 – 5.5.5.8 focus on the form of the collision risk models developed and Section 5.5.5.9 presents the results of the modelling of the performance-based navigation data made available to the ERS TF and utilized in references (Moek, 2015a) and (Moek, 2016).

5.5.5.2 Minimum spacing between parallel routes requiring different performance requirements for each route

The procedural collision risk model utilized in (Moek, 2015b) for this scenario is the same as that used for parallel routes in Section 5.5.4, but with S_y rather than S denoting the route spacing, i.e.

$$N_{ay} = P_{xz}P_y(S_y) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.198)$$

and similarly for the collision risk model for radar airspace, i.e., with S_y instead of S ,

$$N_{ay} = P_{xz}P_{ATC}(S_y)P_y(S) \left(\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z} \right) \quad (5.199)$$

The key elements of the collision risk modelling were again the modelling of the probability distribution of the lateral deviations from track and controller intervention. As regards the latter, (Moek, 2015b) used the same best estimates of the ATC intervention failure probabilities as the A-RNP study of (Smith, 2012). See Section 6.2 of (Moek, 2015b) for further details.

Consider now the probability of lateral overlap parameter of the collision risk model, $P_y(S_y)$, under extension 1, different combinations of five PBN navigation specifications. Assume that the aircraft population on a route is made up of the following PBN navigation specifications, indexed from 1 -5:

1	A-RNP
2	RNP 1
3	RNP 2
4	RNAV 1
5	B-RNAV

(5.203)

The route's overall lateral navigation distribution can then be represented by the following probability density

$$f(y) = \alpha_1 f_1(y) + \alpha_2 f_2(y) + \alpha_3 f_3(y) + \alpha_4 f_4(y) + \alpha_5 f_5(y) \quad (5.204)$$

where α_i , $i = 1, \dots, 5$, represents the proportion of flight time generated by aircraft with the i -th PBN navigation specification and

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 = 1 \quad (5.205)$$

Assume also that each component lateral navigation probability density $f_i(y)$, $i = 1, \dots, 5$, is a mixture distribution made up of n_i terms, i.e.

$$f_i(y) = \beta_{i1}f_{i1}(y) + \beta_{i2}f_{i2}(y) + \beta_{i3}f_{i3}(y) + \beta_{i4}f_{i4}(y) + \beta_{i5}f_{i5}(y), \quad i = 1, \dots, 5, \quad (5.206)$$

The formulation in eq. (5.206) uses an arbitrary number of terms n_i ($n_i \leq 5$) for each value of i , $i = 1, \dots, 5$, but in practice the number of terms is expected to be no larger than two. (The exception may be the B-RNAV sub-population, whose lateral navigation error probability density was modelled in (Smith, 2004) as a weighted combination of a VOR mixture probability density and a P-RNAV mixture probability density. Cf. eqs. (5.200) – (5.202)) Two terms are usually interpreted as representing a combination of typical and atypical performance for the i -th, $i = 1, \dots, 5$, PBN navigation specification.

Substitution of eq. (5.206) into eq. (5.204) gives for the overall lateral navigation distribution the following probability density:

$$f(y) = \sum_{i=1}^5 \alpha_i \left(\sum_{j=1}^{n_i} \beta_{ij} f_{ij}(y) \right) \quad (5.207)$$

which may also be written as

$$f(y) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i \beta_{ij} f_{ij}(y) \quad (5.208)$$

Eq. (5.208) can now be used for the aircraft on each flight level of each of the two routes. However, since the routes may carry different proportions of aircraft certified to the different navigation specifications, the notation is refined as follows:

$$\text{Route 1: } f^1(y) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^1 \beta_{ij} f_{ij}(y) \quad (5.209)$$

$$\text{Route 2: } f^2(y) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^2 \beta_{ij} f_{ij}(y) \quad (5.210)$$

Notice that only the flight-time proportions α_i , $i = 1, \dots, 5$, have been made route dependent through an additional superscript.

Before proceeding, recall from Section 4.5 that the lateral distance d_y between a pair of aircraft on parallel routes separated by the lateral separation minimum S_y is given by

$$d_y = S_y - y_A + y_B \quad (4.13)$$

where y_A and y_B denote the aircraft's lateral deviations. Denoting the probability density functions of the lateral deviations y_A and y_B as $f_A(y)$ and $f_B(y)$ respectively, the probability density function of d_y is then given by

$$f_{dy}(d_y) = \int_{-\infty}^{\infty} f_A(y_A) f_B(y_A - S_y + d_y) dy_A \quad (4.14)$$

and the probability of lateral overlap $P_y(S_y)$ is given by

$$P_y(S_y) = \int_{-\lambda_y}^{\lambda_y} f_{dy}(d_y) dd_y = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f_A(y_A) f_B(y_A - S_y + d_y) dy_A dd_y \quad (4.15)$$

Dependent on the application, it may be possible to approximate eq. (4.15) by

$$P_y(S_y) \approx 2\lambda_y \times f_{dy}(0) = 2\lambda_y \times \int_{-\infty}^{\infty} f_A(y_A) f_B(y_A - S_y) dy_A \quad (4.16)$$

Substitution of $f^1(y)$ for $f_A(y_A)$ and of $f^2(y - S_y)$ for $f_B(y_A - S_y)$ in eq. (4.16) gives for the probability of lateral overlap

$$P_y(S_y) \approx 2\lambda_y \int_{-\infty}^{\infty} \left(\sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^1 \beta_{ij} f_{ij}(y) \right) \left(\sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_k^2 \beta_{kl} f_{kl}(y - S_y) \right) dy \quad (5.211)$$

or

$$P_y(S_y) \approx \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_i^1 \beta_{ij} \alpha_k^2 \beta_{kl} 2\lambda_y \int_{-\infty}^{\infty} f_{ij}(y) f_{kl}(y - S_y) dy \quad (5.212)$$

i.e.

$$P_y(S_y) \approx \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_i^1 \beta_{ij} \alpha_k^2 \beta_{kl} P_y(S_y)_{ijkl} \quad (5.213)$$

Where

$$P_y(S_y)_{ijkl} \approx 2\lambda_y \int_{-\infty}^{\infty} f_{ij}(y) f_{kl}(y - S_y) dy \quad (5.214)$$

The integrals in the right-hand side of eq. (5.214) may be evaluated analytically or numerically, dependent on the type of probability densities $f_{ij}(y)$ and $f_{kl}(y)$. The formulae provided in Appendix A to (Moek, 2015b) can be used to evaluate the lateral overlap probabilities of eq. (5.214) for navigation distributions made up of normal and/or double exponential densities.

The collision risk model specified by eqs. (5.198), (5.199), (5.213), and (5.214) was derived in (Moek, 2015b) for straight route segments. Section 3.3 of (Moek, 2015b) provides an extensive discussion on the impact of controlled turns using RF (Radius to Fix) and/or FRT (Fixed Radius Turn) when a route requiring an RNP specification is to be spaced from a route requiring an RNAV specification.

5.5.5.3 Spacing between non-parallel routes that are initially parallel or converge and then diverge – the same PBN navigation specification on each route

The key difference between parallel routes and non-parallel routes is that for non-parallel routes, the nominal (lateral) distance between the aircraft varies over time simply as a result of the geometry of the routes. This time-dependence can be handled by the general collision risk model based on reliability theory (Anderson, 2005) in a similar manner as set out in Sections 5.4.1, 5.4.2.6, 5.4.2.8, and 5.4.3. Recall that the (Anderson, 2005) collision risk model is treated in Chapter 7 of this document.

A general geometry for converging and diverging routes has been reproduced from (Moek, 2015b) below. It is characterised by four track angles $\psi_1, \dots, \psi_4$, a connection angle ψ_{AB} , and a distance D_{AB} . All angles are measured positive counter-clock-wise with regard to the pertinent dashed lines. It is convenient to choose the dashed lines such that $180^\circ \leq \psi_1 < 270^\circ$. A special case of the general geometry is given by the symmetrical geometry of Figure 5.9, which is characterised by $\psi_4 = \psi$, $\psi_1 = 180 + \psi$, $\psi_2 = 180 - \psi$, $\psi_3 = 360 - \psi$, and the connection angle ψ_{AB} being equal to 90 degrees. Other special cases can also be defined, e.g. the four track angles as above but the connection angle ψ_{AB} unequal to 90 degrees.

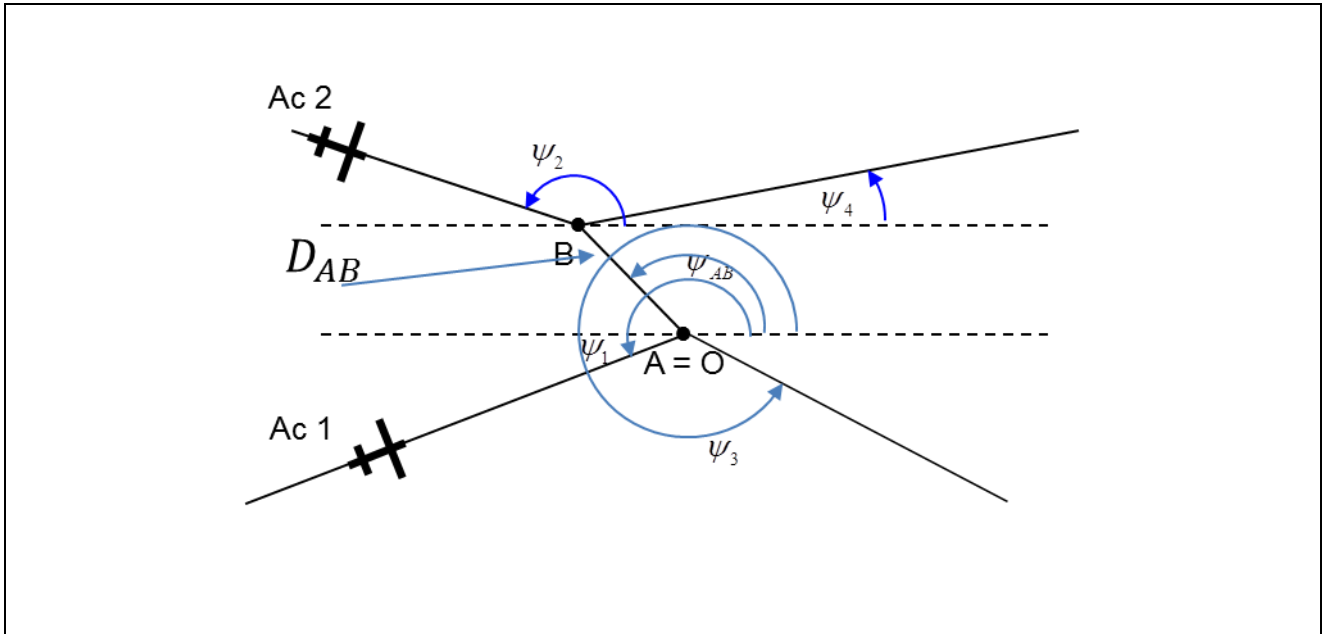


Figure 5.8: General geometry for converging and diverging routes

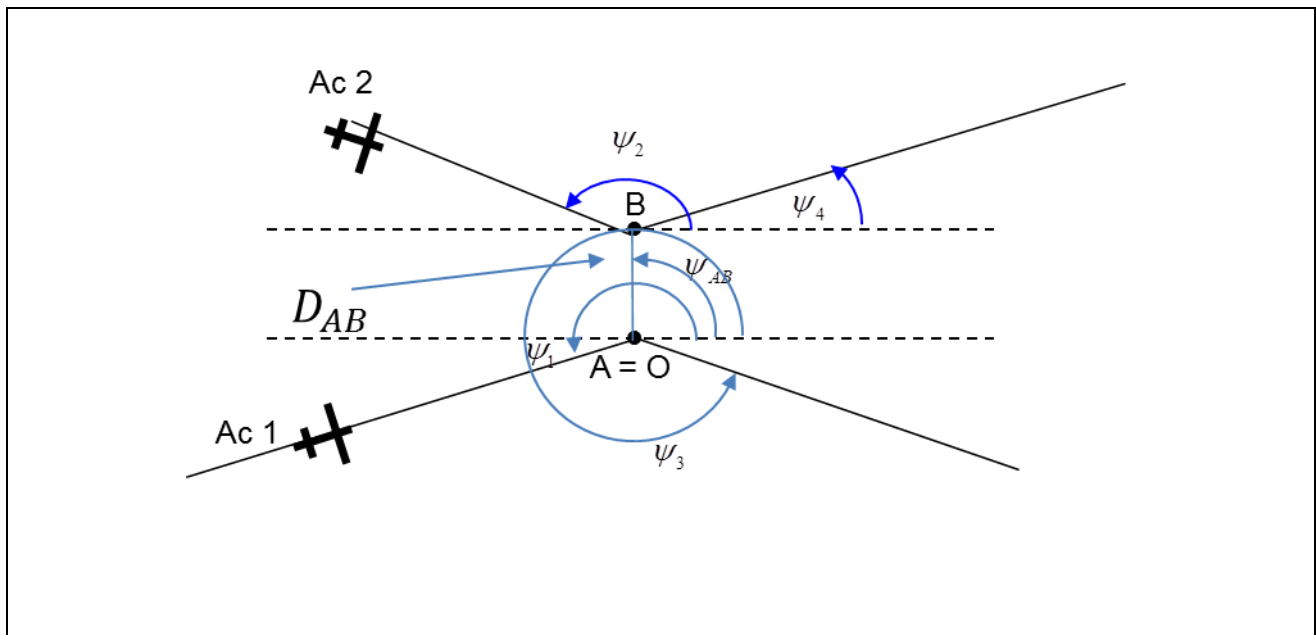


Figure 5.9: Symmetrical geometry for converging and diverging routes

Given values for the four track angles and the connection angle, the spacing between the converging and diverging routes is said to be defined by the distance D_{AB} between the two waypoints A and B. The collision risk model is to be used to determine the minimum value of D_{AB} that is consistent with the applicable Target Level of Safety. The turns at the waypoints A and B can be fly-by or fixed radius turns, but turn modelling has not been included in the non-parallel route collision risk model here. For the modelling, it is assumed that the turns take place instantaneously at the waypoints A and B. It follows from the geometry that this assumption leads to a conservative risk estimate because the defined paths followed by aircraft 1 and aircraft 2 will lie below waypoint A and above waypoint B respectively. Rather than representing the real aircraft by rectangular blocks as for the parallel route case, the aircraft are represented by standing cylinders with height

λ_z and diameter λ_{xy} . This simplifies the calculation of the probability of horizontal overlap and has been used in most or all of the SASP collision risk modelling work for aircraft on intersecting routes. The modelling further assumes that each aircraft has (constant) random navigation errors in both the along-track and across-track directions. It is also assumed that each aircraft has a random speed about some nominal value.

To be able to apply the collision risk model based on reliability theory (Anderson, 2005) to the general geometry of Figure 5.8, a suitable coordinate system needs to be specified. There are many possibilities to locate the origin of such a co-ordinate frame for the converging route case. In (Moek, 2015b), waypoint A was chosen as the origin and the positive x -axis in the flight direction of aircraft 1 prior to its passing of waypoint A. See Figure 5.10. The diagram also shows the along-track and across-track navigation errors of aircraft 1 and aircraft 2, i.e. ε_1^A , ε_2^A , ε_1^C , and ε_2^C where a superscript “A” refers to “along track” and a superscript “C” refers to “cross track”. Along-track deviations are taken positive in the direction of flight and across-track deviations are taken positive when they are to the left with respect to the direction of flight.

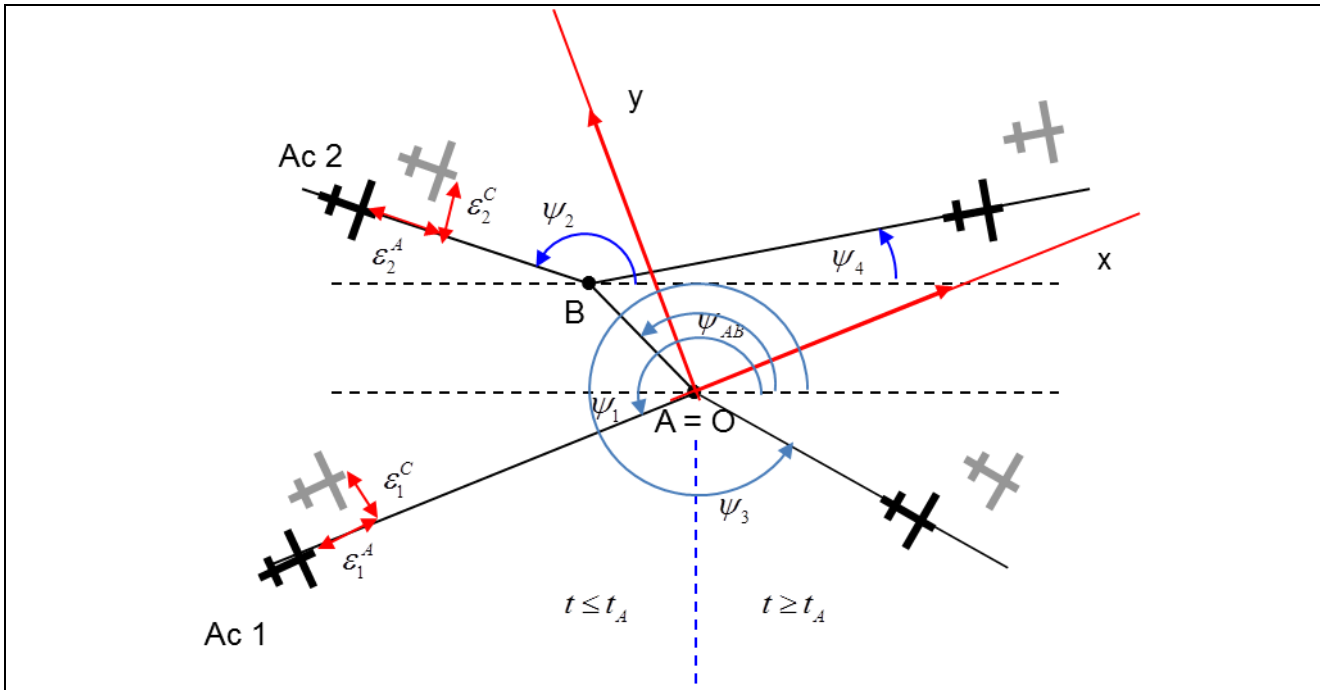


Figure 5.10: Coordinate system used for the general converging and diverging route geometry and the along-track and across-track navigation errors of aircraft 1 and aircraft 2

The collision risk model requires the random relative position differences $\Delta x(t)$ and $\Delta y(t)$ in the true x - and y -coordinates between aircraft 1 and 2 on converging/diverging routes at time t to be expressed into their differences at time $t = t_0 = 0$, their along-track and across-track navigational errors and the other parameters characterizing the scenario/geometry. To that end, assume that the nominal distances of the aircraft to their respective waypoints A and B at time $t_0 = 0$ are given by $\hat{d}_1^0$ and $\hat{d}_2^0$. Assume also that the aircraft pass their respective waypoints at nominal points in time $\hat{t}_A$ and $\hat{t}_B$. The formulae to be developed split into three parts. The first part covers the time period up to the first waypoint passing. This may be either aircraft 1 or aircraft 2. The second part covers the time period between the first waypoint passing and the passing of the other waypoint and the third part covers the time period following the second waypoint's passing. The form of the formulae for the second part depends on whether aircraft 1 or aircraft 2 passes its waypoint first, i.e. whether $\hat{t}_A < \hat{t}_B$ or $\hat{t}_A > \hat{t}_B$. The second part of the formulae can be ignored when $\hat{t}_A = \hat{t}_B$.

Thus, for procedural airspace and using the notation of (Moek, 2015b), the general collision risk model of eq. (7.13) was split up as

$$\begin{aligned}
 CR(t_0, t_1) = & 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{\min(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) dt dV_1 dV_2 \\
 & + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\min(\hat{t}_A, \hat{t}_B)}^{\max(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) dt dV_1 dV_2 \\
 & + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\max(\hat{t}_A, \hat{t}_B)}^{\infty} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) dt dV_1 dV_2
 \end{aligned} \tag{5.215}$$

where (Moek, 2015b) lists the following expressions for the three probabilities of horizontal overlap given the aircraft speeds and the relative speeds between the aircraft:

- **First time period, $t_0 \leq t \leq \min(\hat{t}_A, \hat{t}_B)$**

$$\begin{aligned}
 HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} \approx \pi\lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_1^A \left(-D_x^F(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \right. \\
 \left. \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_2^A(\varepsilon_2^A) f_1^C \left(-D_y^F(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_2^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A
 \end{aligned} \tag{5.216}$$

$$V_{rel} = \sqrt{V_1^2 - 2V_1V_2\cos(\psi_2 - \psi_1) + V_2^2} \tag{5.217}$$

- **Second time period, aircraft 1 passes its waypoint first: $t_0 < \hat{t}_A \leq t < \hat{t}_B$**

$$\begin{aligned}
 HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} \approx \pi\lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_1^A \left(-D_x^{S1}(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \right. \\
 \left. \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_2^A(\varepsilon_2^A) f_1^C \left(-D_y^{S1}(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_2^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A
 \end{aligned} \tag{5.218}$$

$$V_{rel} = \sqrt{V_1^2 + 2V_1V_2\cos(\psi_2 - \psi_3) + V_2^2} \tag{5.219}$$

- **Second time period, aircraft 2 passes its waypoint first: $t_0 < \hat{t}_B \leq t < \hat{t}_A$**

$$\begin{aligned}
 HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} \approx \pi\lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_1^A \left(-D_x^{S2}(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \right. \\
 \left. \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_2^A(\varepsilon_2^A) f_1^C \left(-D_y^{S2}(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_2^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A
 \end{aligned} \tag{5.220}$$

$$V_{rel} = \sqrt{V_1^2 + 2V_1V_2\cos(\psi_1 - \psi_4) + V_2^2} \tag{5.221}$$

- **Third time period, $\max(\hat{t}_A, \hat{t}_B) \leq t \leq t_1$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} \approx \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_1^A}^{\varepsilon_1^C} f_1^A \left(-D_x^T(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_2^A(\varepsilon_2^A) f_1^C \left(-D_y^T(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_2^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.222)$$

$$V_{rel} = \sqrt{V_1^2 - 2V_1V_2\cos(\psi_3 - \psi_4) + V_2^2} \quad (5.223)$$

In eqs. (5.216) – (5.223), $D_x^F(t)$, $D_y^F(t)$, $D_x^{S1}(t)$, $D_y^{S1}(t)$, $D_x^{S2}(t)$, $D_x^T(t)$, and $D_y^T(t)$ denote the nominal relative position between the aircraft during the first, second, and third period of time respectively where the superscript $S1$ refers to aircraft 1 passing its intersection first and $S2$ refers to aircraft 2 passing its intersection first. See Section 4.2 of (Moek, 2015b) for the precise formulae for the nominal relative positions. Notice that, compared to eq. (7.##) in Sections 7.# and 5.4.1, the role of the intersection angle θ has been taken over by the angular difference $\psi_2 - \psi_1$ between the extended inbound routes. The other three angles, ψ_3 , ψ_4 , and ψ_{AB} feature in the nominal relative positions $D_x^F(t)$, $D_y^F(t)$, ..., $D_y^T(t)$ and all four track angles ψ_1 , ..., ψ_4 feature in one or more of the formulae for the relative speed between the aircraft.

The last step in the evaluation of the probability of horizontal overlap is to specify the type of the navigation error probability density functions $f_1^A(\varepsilon)$, $f_1^C(\varepsilon)$, $f_2^A(\varepsilon)$, and $f_2^C(\varepsilon)$.

Having described the collision risk model for procedural airspace for non-parallel routes that are initially parallel or converge and then diverge, its counterpart for radar airspace is given in (Moek, 2015b) as

$$CR(t_0, t_1) = P_{ATC}(\psi_{AB}, D_{AB}) \left[2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{\min(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \right. \\ + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\min(\hat{t}_A, \hat{t}_B)}^{\max(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\ \left. + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\max(\hat{t}_A, \hat{t}_B)}^{t_1} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \right] \quad (5.224)$$

where $P_{ATC}(\psi_{AB}, D_{AB})$ denotes the probability of ATC intervention failure as a function of the connection angle ψ_{AB} and the (defined) separation minimum D_{AB} . As set out in (Moek, 2015b), the ATC intervention failure probabilities available from the A-RNP study of (Smith, 2012) apply to parallel routes (only) and are not directly applicable to the non-parallel routes converging/diverging scenario. A number of suggestions are presented in (Moek, 2015b) as to how the parallel-route ATC-intervention-failure probabilities might be used for the current scenario. As regards the last, (Moek, 2015b) used the same best estimates of the ATC intervention failure probabilities as the A-RNP study of (Smith, 2012). See Section 6.2 of (Moek, 2015b) for further details.

5.5.5.4 Spacing between non-parallel routes that are initially parallel or converge and then diverge – different varieties of PBN navigation specifications on each route

The collision risk models specified by eqs (5.215) and (5.224) of the previous subsection are generic in that they do not depend on any specific assumptions concerning the navigation error probability densities $f_1^A(\epsilon_1^A)$, $f_1^C(\epsilon_1^C)$, $f_2^A(\epsilon_2^A)$, and $f_2^C(\epsilon_2^C)$. The specifics of these probability densities play a part only in the ultimate computation of $HOP(t|V_1, V_2)$ in eqs. (5.216), (5.218), (5.220), and (5.222). Thus, the collision risk model for procedural airspace is again given by

$$\begin{aligned}
 CR(t_0, t_1) = & 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{\min(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\
 & + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\min(\hat{t}_A, \hat{t}_B)}^{\max(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\
 & + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\max(\hat{t}_A, \hat{t}_B)}^{\infty} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2
 \end{aligned} \tag{5.215}$$

and that for radar airspace by

$$\begin{aligned}
 CR(t_0, t_1) = & P_{ATC}(\psi_{AB}, D_{AB}) \left[2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{\min(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \right. \\
 & + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\min(\hat{t}_A, \hat{t}_B)}^{\max(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\
 & \left. + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\max(\hat{t}_A, \hat{t}_B)}^{\infty} HOP(t|V_1, V_2) \times P_z(0) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \right]
 \end{aligned} \tag{5.224}$$

The extension to the case of the routes carrying different varieties of PBN navigation specifications proceeds in the same manner as in section 5.5.5.2. Thus, assuming that the aircraft population on each of the routes is made up of the following PBN navigation specifications, indexed from 1 -5,

1	A-RNP	
2	RNP 1	
3	RNP 2	(5.203)
4	RNAV 1	
5	B-RNAV	

each route's overall lateral navigation distribution can again be represented by a probability density

$$f(\epsilon) = \alpha_1 f_1(\epsilon) + \alpha_2 f_2(\epsilon) + \alpha_3 f_3(\epsilon) + \alpha_4 f_4(\epsilon) + \alpha_5 f_5(\epsilon) \tag{5.225}$$

where α_i , $i = 1, \dots, 5$, represents the proportion of flight time generated by aircraft with the i -th PBN navigation specification and

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 = 1 \quad (5.205)$$

Formally, each component navigation error probability density $f_i(\varepsilon)$, $i = 1, \dots, 5$, is again represented by a mixture distribution made up of n_i ($n_i \leq 5$) terms, i.e.

$$f_i(\varepsilon) = \beta_{i1}f_{i1}(\varepsilon) + \beta_{i2}f_{i2}(\varepsilon) + \beta_{i3}f_{i3}(\varepsilon) + \beta_{i4}f_{i4}(\varepsilon) + \beta_{i5}f_{i5}(\varepsilon), \quad i = 1, \dots, 5, \quad (5.226)$$

As explained before in Section 5.5.5.2, the formulation above uses an arbitrary number of terms n_i ($n_i \leq 5$) for each value of i , $i = 1, \dots, 5$, but in practice the number of terms is expected to be no larger than two, where two terms are often interpreted as representing a combination of typical and atypical performance for the i -th, $i = 1, \dots, 5$, PBN navigation specification. Substitution of eq. (5.226) into eq. (5.225) gives

$$f(\varepsilon) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i \beta_{ij} f_{ij}(\varepsilon) \quad (5.227)$$

where eq. (5.227) is to be used for both the along-track and across-track navigation errors of the aircraft following the non-parallel routes defined by the waypoints A and B (cf. Figure 5.10), where different navigation specifications may apply to the two routes. Thus, eq. (5.227) gives

$$f_1^A(\varepsilon_1^A) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^1 \beta_{ij}^A f_{ij}^A(\varepsilon_1^A) \quad (5.228)$$

$$f_1^C(\varepsilon_1^C) = \sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_k^1 \beta_{kl}^C f_{kl}^C(\varepsilon_1^C) \quad (5.229)$$

$$f_2^A(\varepsilon_2^A) = \sum_{u=1}^5 \sum_{v=1}^{n_u} \alpha_u^2 \beta_{uv}^A f_{uv}^A(\varepsilon_2^A) \quad (5.230)$$

$$f_2^C(\varepsilon_2^C) = \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_x^2 \beta_{xy}^C f_{xy}^C(\varepsilon_2^C) \quad (5.231)$$

Notice that only the flight-time proportions α_i^1 , α_k^1 , α_x^2 , and α_u^2 , $i, k, x, u = 1, \dots, 5$ have been made route dependent through an additional subscript. Since the flight time proportions α_i^1 and α_k^1 pertain to the aircraft 1 population following the inbound and outbound routes through waypoint A, it must hold that these flight time proportions for the along-track and across-track errors are the same, i.e.

$$\alpha_i^1 = \alpha_k^1, \quad i, k = 1, \dots, 5, \quad i = k \quad (5.232)$$

Similarly, it must hold that

$$\alpha_u^2 = \alpha_x^2, \quad x = 1, \dots, 5, \quad u = x \quad (5.233)$$

Eqs. (5.228) – (5.231) can be substituted into eqs. (5.216), (5.218), (5.220), and (5.222) for $HOP(t|V_1, V_2)$, resulting in the following formulae for the routes carrying different varieties of PBN navigation specifications:

- **First time period, $t_0 \leq t \leq \min(\hat{t}_A, \hat{t}_B)$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^1 \beta_{ij}^A \alpha_k^1 \beta_{kl}^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{ijkluvxy} \quad (5.234)$$

$$HOP(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_{ij}^A \left(-D_x^F(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_{kl}^C \left(-D_y^F(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.235)$$

- **Second time period, aircraft 2 passes its waypoint first: $t_0 < \hat{t}_B \leq t < \hat{t}_A$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^1 \beta_{ij}^A \alpha_k^1 \beta_{kl}^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{ijkluvxy} \quad (5.236)$$

$$HOP(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_{ij}^A \left(-D_x^{S1}(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_{kl}^C \left(-D_y^{S1}(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.237)$$

- **Second time period, aircraft 2 passes its waypoint first: $t_0 < \hat{t}_B \leq t < \hat{t}_A$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^1 \beta_{ij}^A \alpha_k^1 \beta_{kl}^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{ijkluvxy} \quad (5.238)$$

$$HOP(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_{ij}^A \left(-D_x^{S2}(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_{kl}^C \left(-D_y^{S2}(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.239)$$

- **Third time period, $\max(\hat{t}_A, \hat{t}_B) \leq t \leq t_1$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^1 \beta_{ij}^A \alpha_k^1 \beta_{kl}^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{ijkluvxy} \quad (5.240)$$

$$HOP(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_2^C}^{\varepsilon_2^A} f_{ij}^A \left(-D_x^T(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_{kl}^C \left(-D_y^T(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.241)$$

As for eqs. (5.216) – (5.223), in eqs. (5.234) – (5.241), $D_x^F(t)$, $D_y^F(t)$, $D_x^{S1}(t)$, $D_y^{S1}(t)$, $D_x^{S2}(t)$, $D_y^{S2}(t)$, $D_x^T(t)$, and $D_y^T(t)$ denote again the nominal relative position components between the aircraft during the first, second, and third period of time respectively where the superscript S1 refers to aircraft 1 passing its intersection first and S2 refers to aircraft 2 passing its intersection first. See Section 4.3 of (Moek, 2015b) for the precise formulae for the nominal relative positions. Compared to eq. (7.XX) in Sections 7.X and 5.4.1, not surprisingly, the role of the intersection angle θ has again been taken over by the angular difference $\psi_2 - \psi_1$ between the extended inbound routes and the other three angles, ψ_3 , ψ_4 , and ψ_{AB} feature in the nominal relative positions $D_x^F(t)$, $D_y^F(t)$, ..., $D_y^T(t)$. Similarly, all four track angles ψ_1 , ..., ψ_4 feature in one or more of the

formulae for the relative speed between the aircraft where the relative aircraft speeds continue to be given by eqs. (5.217), (5.219), (5.221), and (5.223).

The last step in the evaluation of the probability of horizontal overlap is to specify the type of the navigation error probability density functions $f_{ij}^A(\varepsilon_1^A)$, $f_{kl}^C(\varepsilon_1^C)$, $f_{uv}^A(\varepsilon_2^A)$, and $f_{xy}^C(\varepsilon_2^C)$

5.5.5.5 Spacing between PBN routes and Temporary Reserved Airspaces/Temporary Segregated Airspaces (TRAs/TSAs) where the activity in the TRA or TSA is clearly defined

Section 4.4 of (Moek, 2015b) specified a collision risk model for this subsection's scenario. The section noted that collision risk modelling for parallel routes takes advantage of the fact that the spacing between the routes (and hence the nominal lateral separation between aircraft on those routes) is constant over time. The general collision risk model based on reliability theory (Anderson, 2005) can, in principle, be applied to any route configuration where the nominal (lateral/horizontal) separation between the aircraft varies over time. Sections 5.5.5.3 and 5.5.5.4 of this document dealt with the application of the general collision risk model to the case of non-parallel routes that are initially parallel or converge and then diverge. The material presented was based on Sections 4.2 and 4.3 of (Moek, 2015b). Some other applications for fairly complicated geometries treated by the ICAO SASP MSG are referenced in section 4.4 of (Moek, 2015b). It was thus concluded in (Moek, 2015b) that if the activity in a TRA or TSA can be described in terms of some route structure, a suitable version of the general collision risk model based on reliability theory (Anderson, 2005) should be able to be developed. The specific form would depend on the characteristics of the route structure as well as of the aircraft involved.

Activities that may be conducted in a TRA/TSA include air combat, missile firing, parachuting, etc., where air combat can be considered to be the most dynamic. Let ∂A denote the boundary of a TRA/TSA and assume that the nominal path of an activity must stay within or up to this boundary. This would allow an aircraft to fly along the boundary for some time and to turn into the TRA/TSA at some point in time as sketched in Figure 5.11. From a modelling perspective, the turning point may be considered a waypoint. Another scenario would be a combat aircraft flying towards the boundary at a (very) high speed and making a (sharp) turn at the boundary, i.e. as if there were a waypoint on the TRA/TSA boundary as in Figure 5.12.

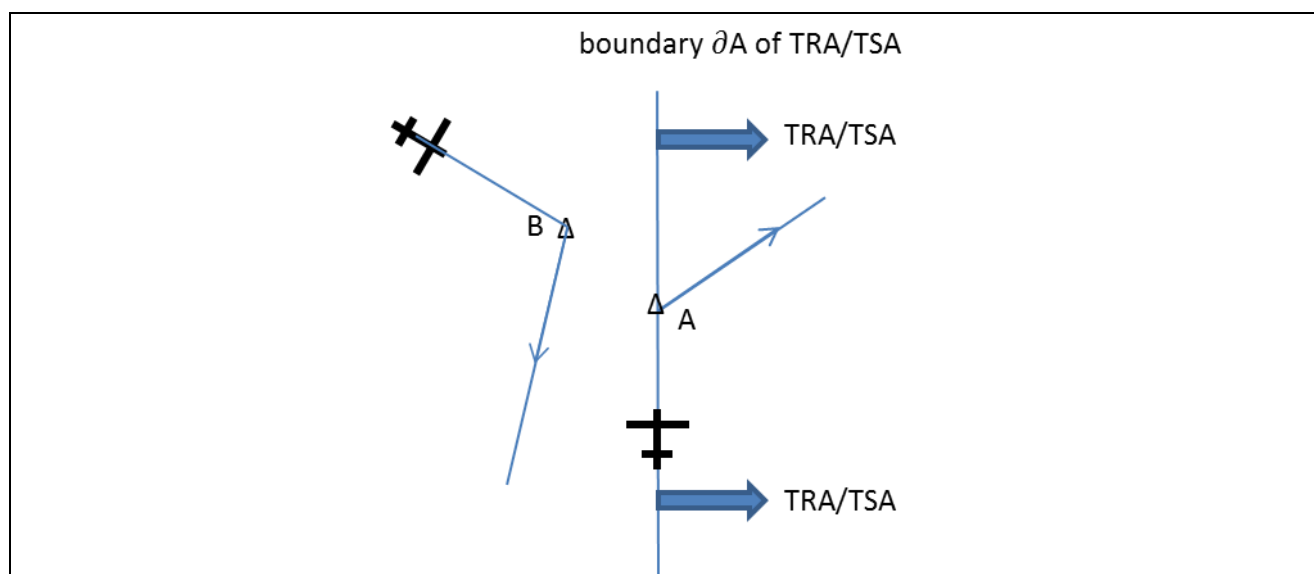


Figure 5.11: Aircraft on a PBN route adjacent to a TRA/TSA with an aircraft flying initially along the TRA/TSA boundary and subsequently turning into the TRA/TSA

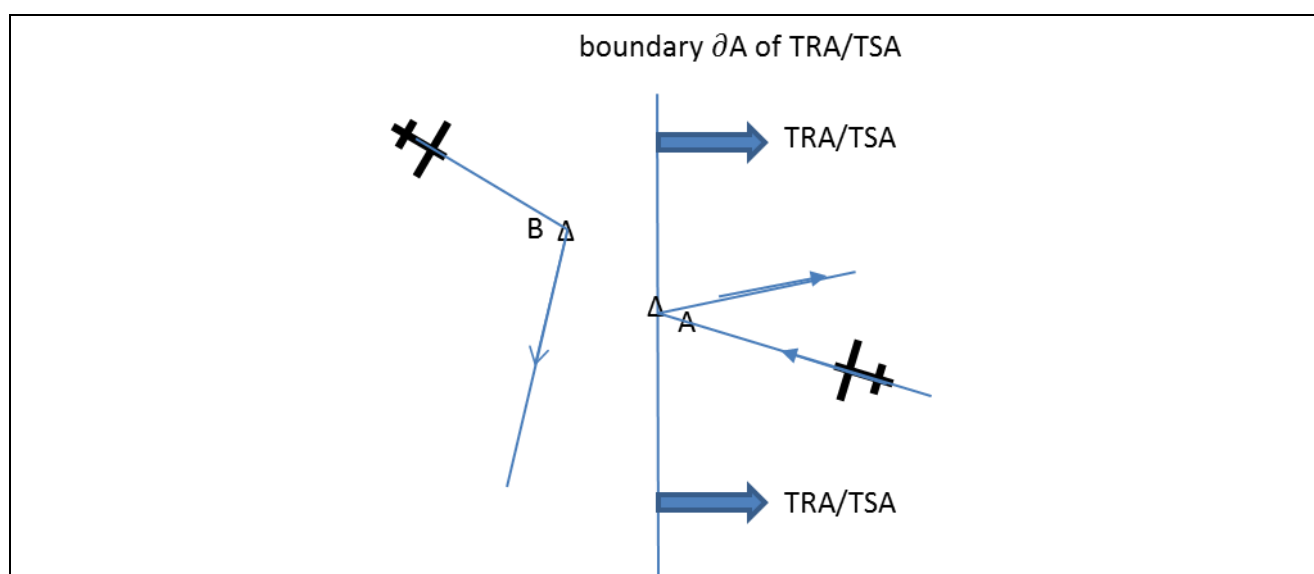


Figure 5.12: Aircraft on a PBN route adjacent to a TRA/TSA with an aircraft flying initially towards the TRA/TSA boundary and subsequently making a sharp turn into the TRA/TSA

From a collision risk modelling perspective, Figures 5.11 and 5.12 fall within the general class of initially (parallel or) converging and then diverging routes evaluated in Sections 5.5.5.3 and 5.5.5.4. The only prerequisite for the application of a suitable version of the general collision risk model based on reliability theory (Anderson, 2005) is that the actual path associated with the activity in the TRA/TSA can be described in terms of a nominal path and deviations from the nominal path in three-dimensional space over time. Thus, the following collision risk model for procedural airspace could be used to determine the spacing between a PBN route and a TRA/TSA,

$$\begin{aligned}
CR(t_0, t_1) = & 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{\min(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\
& + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\min(\hat{t}_A, \hat{t}_B)}^{\max(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\
& + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\max(\hat{t}_A, \hat{t}_B)}^{\infty} HOP(t|V_1, V_2) \times P_z(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2
\end{aligned} \tag{5.242}$$

supplemented with

$$\begin{aligned}
CR(t_0, t_1) = & P_{ATC} \left[2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{\min(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \right. \\
& + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\min(\hat{t}_A, \hat{t}_B)}^{\max(\hat{t}_A, \hat{t}_B)} HOP(t|V_1, V_2) \times P_z(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \\
& \left. + 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\max(\hat{t}_A, \hat{t}_B)}^{\infty} HOP(t|V_1, V_2) \times P_z(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2) dt dV_1 dV_2 \right]
\end{aligned} \tag{5.243}$$

for radar airspace, where P_{ATC} denotes the probability of ATC intervention failure for the scenario under consideration. Since the modelling is based on the converging/diverging route scenario, the ATC intervention failure probability P_{ATC} may be expressed as a function of a connection angle ψ_{AB} and a separation minimum D_{AB} (cf. Figure 5.10) and be based in some manner on the ATC intervention failure probabilities available from the A-RNP study of (Smith, 2012). However, as set out in (Moek, 2015b), the ATC intervention failure probabilities available from the A-RNP study of (Smith, 2012) apply to parallel routes (only) and cannot be used in a straightforward manner for the current scenario. Thus, one of the 13 options listed in Section 6.3.1 of (Moek, 2015b) might be used.

It should be noted that the two collision risk models above show a minor difference with respect to the models used in Sections 5.5.5.3 and 5.5.5.4 in that the constant vertical overlap probability $P_z(0)$ for aircraft in level flight has been replaced by a potentially time-variable vertical overlap probability $P_z(h_z(t))$ for aircraft with a nominal vertical distance (separation) $h_z(t)$ at point in time t . Apart from that, the collision risk models defined by eqs. (5.215) and (5.224) and the subsequent equations in Section 5.5.5.4 might be used for the TRA/TSA scenario. However, there is a minor simplification in that the aircraft in the TRA/TSA was assumed to have a single specification only.

The aircraft may be labelled arbitrarily as aircraft 1 and 2, but it is convenient to label the aircraft (or more generally the object/subject) that resides in the TRA/TSA as aircraft 1 and the aircraft on the PBN route as aircraft 2. The x, y -coordinate frame has not yet been defined but it is convenient to take its origin at (way)point A on the boundary of the TRA/TSA with the x -axis pointing into the direction of motion of aircraft 1 and the y -axis pointing to the left. The nominal trajectories of aircraft 1 and 2 can then be defined in the same manner as in Section 5.5.5.4.

Thus, assuming that the aircraft 2 population on the PBN route is made up of the following PBN navigation specifications, indexed from 1 – 5,

- 1 A-RNP
 - 2 RNP 1
 - 3 RNP2
 - 4 RNAV 1
 - 5 B-RNAV
- (5.203)

the overall navigation error distributions in both the along-track and across-track directions for aircraft on the PBN route are described by the following probability density

$$f(\varepsilon) = \alpha_1 f_1(\varepsilon) + \alpha_2 f_2(\varepsilon) + \alpha_3 f_3(\varepsilon) + \alpha_4 f_4(\varepsilon) + \alpha_5 f_5(\varepsilon) \quad (5.225)$$

where α_i , $i = 1, \dots, 5$, represents the proportion of flight time generated by aircraft with the i -th PBN navigation specification and

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 = 1 \quad (5.205)$$

Formally, each component navigation error probability density $f_i(\varepsilon)$, $i = 1, \dots, 5$, can be represented by a mixture distribution made up of n_i ($n_i \leq 5$) terms, i.e.

$$f_i(\varepsilon) = \beta_{i1} f_{i1}(\varepsilon) + \beta_{i2} f_{i2}(\varepsilon) + \beta_{i3} f_{i3}(\varepsilon) + \beta_{i4} f_{i4}(\varepsilon) + \beta_{i5} f_{i5}(\varepsilon), \quad i = 1, \dots, 5, \quad (5.226)$$

(As explained before in Section 5.5.5.2, the formulation above uses an arbitrary number of terms n_i ($n_i \leq 5$) for each value of i , $i = 1, \dots, 5$, but in practice the number of terms is expected to be no larger than two, where two terms are often interpreted as representing a combination of typical and atypical performance for the i -th, $i = 1, \dots, 5$, PBN navigation specification.) Substitution of eq. (5.226) into eq. (5.225) gives

$$f(\varepsilon) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i \beta_{ij} f_{ij}(\varepsilon) \quad (5.227)$$

Eq. (5.227) is to be used for both the along-track and across-track navigation errors of the aircraft 2 population on the PBN route. Thus, eq. (5.227) gives (using indices u and v , and x and y for aircraft2)

$$f_2^A(\varepsilon_2^A) = \sum_{u=1}^5 \sum_{v=1}^{n_u} \alpha_u^2 \beta_{uv}^A f_{uv}^A(\varepsilon_2^A) \quad (5.230)$$

$$f_2^C(\varepsilon_2^C) = \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_x^2 \beta_{xy}^C f_{xy}^C(\varepsilon_2^C) \quad (5.231)$$

Since the flight time proportions α_u^2 and α_x^2 pertain to the aircraft 2 population following the route through waypoint B, it must hold that these flight time proportions for the along-track and across-track errors are the same, i.e.

$$\alpha_u^2 = \alpha_x^2, \quad x = 1, \dots, 5, \quad u = x \quad (5.233)$$

Only a single navigation specification is assumed for the aircraft, aircraft 1, operating in the TRA/TSA, which may or may not be a PBN navigation specification. Assume that the pertinent navigation specification's along-track and across-track errors are also given by a model of the form of eq. (5.227), i.e.

$$f_1^A(\varepsilon_1^A) = \sum_{j=1}^{n_A} \beta_j^A f_j^A(\varepsilon_1^A) \quad (5.242)$$

$$f_1^C(\varepsilon_1^C) = \sum_{l=1}^{n_C} \beta_l^C f_l^C(\varepsilon_1^C) \quad (5.243)$$

Recalling that the TRA/TSA scenario falls within the general class of initially (parallel or) converging and then diverging routes, eqs. (5.230) – (5.231) and (5.242) – (5.243) can be substituted into eqs. (5.216), (5.218), (5.220) and (5.222) for $HOP(t|V_1, V_2)$ to obtain the following expressions for the probabilities of horizontal overlap for the TRA/TSA scenario:

- **First time period, $t_0 \leq t \leq \min(\hat{t}_A, \hat{t}_B)$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{j=1}^{n_A} \sum_{l=1}^{n_C} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \beta_j^A \beta_l^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{jluvxxy} \quad (5.244)$$

$$HOP(t|V_1, V_2)_{jluvxxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_j^A \left(-D_x^F(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_l^C \left(-D_y^F(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.245)$$

- **Second time period, aircraft 2 passes its waypoint first: $t_0 < \hat{t}_B \leq t < \hat{t}_A$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{j=1}^{n_A} \sum_{l=1}^{n_C} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \beta_j^A \beta_l^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{jluvxxy} \quad (5.246)$$

$$HOP(t|V_1, V_2)_{jluvxxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_j^A \left(-D_x^{S1}(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_l^C \left(-D_y^{S1}(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.247)$$

- **Second time period, aircraft 2 passes its waypoint first: $t_0 < \hat{t}_B \leq t < \hat{t}_A$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{j=1}^{n_A} \sum_{l=1}^{n_C} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \beta_j^A \beta_l^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{jluvxxy} \quad (5.248)$$

$$HOP(t|V_1, V_2)_{jluvxxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_j^A \left(-D_x^{S2}(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_l^C \left(-D_y^{S2}(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.249)$$

- **Third time period, $\max(\hat{t}_A, \hat{t}_B) \leq t \leq t_1$**

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{j=1}^{n_A} \sum_{l=1}^{n_C} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \beta_j^A \beta_l^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{jluvxxy} \quad (5.250)$$

$$HOP(t|V_1, V_2)_{jluvxxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_j^A \left(-D_x^T(t) + \varepsilon_2^A \cos(\psi_2 - \psi_1) - \varepsilon_2^C \sin(\psi_2 - \psi_1) \right) f_{uv}^A(\varepsilon_2^A) f_l^C \left(-D_y^T(t) + \varepsilon_2^A \sin(\psi_2 - \psi_1) + \varepsilon_2^C \cos(\psi_2 - \psi_1) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.251)$$

As before, $D_x^F(t)$, $D_y^F(t)$, $D_x^{S1}(t)$, $D_y^{S1}(t)$, $D_x^{S2}(t)$, $D_y^{S2}(t)$, and $D_x^T(t)$, and $D_y^T(t)$ denote again the nominal relative position components between the aircraft during the first, second, and third period of time respectively where the superscript $S1$ refers to aircraft 1 passing its intersection first and $S2$ refers to aircraft 2 passing its intersection first. See Section 4.4 of (Moek & Aldis, 2008) for the precise formulae for the nominal relative positions. The relative aircraft speeds continue to be given by eqs. (5.217), (5.219), (5.221), and (5.223).

The last step in the evaluation of the probability of horizontal overlap is to specify the type of the navigation error probability density functions $f_j^A(\varepsilon)$, $f_l^C(\varepsilon)$, $f_{uv}^A(\varepsilon)$, and $f_{xy}^C(\varepsilon)$. For the PBN aircraft on the route this can be done in the same manner as for PBN aircraft under the scenarios discussed in the previous subsections, e.g. by means of exponential probability densities. (Cf. Section 5.5.5.9.) If a PBN navigation specification is applicable to the aircraft operating in the TRA/TSA, then the same approach can be followed for that aircraft as well. Otherwise the probability distribution of this aircraft's navigation errors needs to be taken from an additional source.

5.5.5.6 Spacing between PBN routes and holding areas

Section 4.5 of (Moek, 2015b) specified a collision risk model for the spacing between PBN routes and holding areas. It was required that the holding pattern be based on the holding criteria described in Chapter 1 of PANS-OPS Volume II Part II Section 4. Figure 5.13 sketches the nominal holding pattern and an adjacent PBN route. It is assumed that the outbound leg is flown based upon time where the outbound timing is denoted t_{outb} . Similarly, the timing of the inbound leg is denoted t_{inb} . The other parameter describing the nominal holding pattern is the turn radius. Appendix C to Chapter 3 of PANS-OPS Volume II Part I Section 4 deals with the construction of obstacle clearance areas for reversal and holding procedures. The protection area of a holding procedure consists of an area (the basic area) and a buffer area.

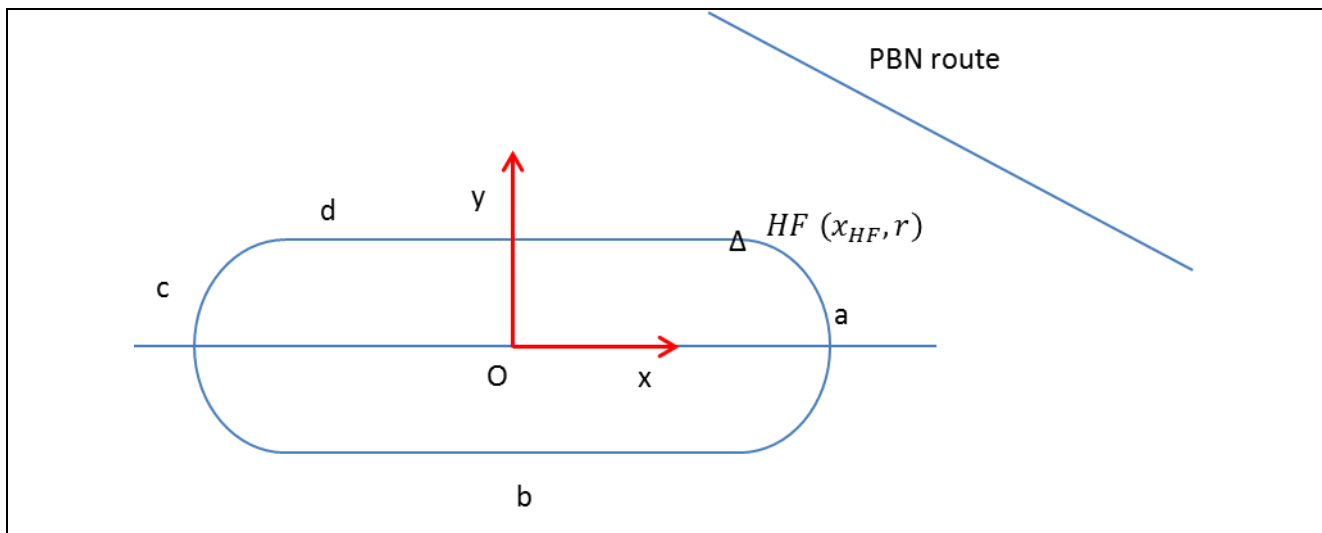


Figure 5.13: Nominal holding pattern and an adjacent PBN route for the study of route spacing between PBN routes and holding areas

The construction of the basic area of a holding procedure is made in two steps. The first step is to construct a template for the appropriate time, speed, and altitude. This template caters for all factors which can cause an aircraft to deviate from the nominal pattern, except those due to the fix tolerance area. The second step

is to draw the basic area of the procedure by moving the template origin around the fix tolerance area. Finally, a 5 NM buffer area is added around the basic area. The calculations for the basic area are indicated in Table I-4-3 App C-4. In the first step, the nominal pattern is based on a specified outbound timing and a radius of turn in still air, i.e. based on true airspeed. The template then accounts for the flight technical tolerance (fix tolerance and outbound leg tolerance) and the ± 5 degree heading tolerance. The fix tolerance and outbound leg tolerance are plotted in Diagram I-4-3 App C-6 as simple translations. The heading tolerances are plotted in Diagram I-4-3 App C-6 as dashed lines splaying about the nominal outbound leg. Before the template can be drawn, the influence of wind is accounted for in the template, namely for the outbound turn and the inbound turn. This can be done by means of the wind spiral method. The wind effect is calculated for each point along the turn by multiplying the wind speed with the flying time to the point, i.e. $W_\theta = (\theta/R) \times w/3600$ NM where θ is the angle of turn, R the turn rate and w the wind speed. For each point on the nominal still air turn the wind effect is added to the turn radius in radial direction. The process is applied to both the outer and the inner turns of the holding, where for the inner turn the fix, outbound leg, and heading tolerances are taken into account. The second step consists of the construction of the basic area and includes accounting for the fix tolerance area.

The question, then, was how to account for the above mentioned factors in the model for the aircraft collision risk between the holding aircraft and a non-holding aircraft instead of an obstacle. The influence of the fix tolerance area was accounted for through the along-track and across-track navigation errors ε_1^A and ε_1^C . The flight technical tolerances, i.e. fix tolerance and outbound leg tolerance, were modelled as two random delay variables τ_1 and τ_2 with uniform distributions over the ranges $[5, 11]$ seconds and $[-5, 15]$ seconds. Following the splaying dashed lines for the heading tolerances in Diagram I-4-3 App C-6 referred to above, the heading tolerance was modelled for the aircraft collision risk model as another random variable with a uniform distribution over the range ± 5 degrees. Collision risk was then calculated conditional on the heading with the PBN navigation errors measured with reference to the given heading and subsequently integrated over the heading-tolerance range.

The remaining modelling element for the aircraft collision risk model concerns the influence of the wind. Given the wind spiral method as used for the construction of obstacle clearance areas for holding procedures, the wind effect was modelled as a zero-mean across-track random variable W_1^C with standard deviation σ_w where the subscript 1 refers to the holding aircraft and the superscript 'C' refers to the cross-track direction. Like the wind effect W_θ described above, the standard deviation was varied with the point along a turn, i.e. $\sigma_w^C = \sigma_w^C(\theta)$, or, equivalently, $\sigma_w^C = \sigma_w^C(t)$ with t denoting the time needed to achieve a heading change of θ degrees. Assuming the wind effect to describe a 95% containment value and assuming a normal distribution, this resulted in a standard deviation

$$\sigma_w^C(\theta) = \sigma_w^C(t) = w * t / 1.96 \quad (5.252)$$

with

$$w = \min(2h + 47, 120) \text{ kts} \quad (5.253)$$

and with h the holding aircraft altitude in thousands of feet. This standard deviation was used all along the outbound turn, the outbound leg, and the inbound turn. In addition, with regard to the wind effect modelling along the inbound leg, it was assumed that the standard deviation $\sigma_w^C(t)$ decreased linearly from its value at the end of the inbound turn to zero at the holding fix.

A specialized version of the general collision risk model based on reliability theory (Anderson, 2005) was developed in Section 4.5 of (Moek, 2015b), viz.

$$CR(t_0, t_1) = 2 \times NP \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \times \left[\frac{2V_{rel}^2}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) f_{\tau_1}(\tau_1) f_{\tau_2}(\tau_2) f(\varphi_{head}) dt dV_1 dV_2 d\varphi_{head} d\tau_2 d\tau_1 \quad (5.254)$$

The right-hand side of the collision risk model in eq. (5.254) has three additional integrals representing the conditioning of the risk on, and subsequent integration over, the fix tolerances τ_1 and τ_2 and the heading tolerance φ_{head} . The probability densities of these three variables are denoted $f_{\tau_1}(\tau_1)$, $f_{\tau_2}(\tau_2)$, and $f(\varphi_{head})$. Notice that this conditioning has been made explicit in the probability of horizontal overlap parameter $HOP(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)$ of the collision risk model, in addition to the conditioning on the aircraft speeds.

The time interval $[t_0, t_1]$ was split up into four parts, corresponding with the outbound turn a , the outbound leg b , the inbound turn c , and the inbound leg d . It was assumed that the holding aircraft is at the holding fix at time $t_0 = 0$. Accordingly, the procedural collision risk model specified in (Moek, 2015b) for the spacing between PBN routes and holding areas splits up into four parts⁴⁴:

$$\begin{aligned} CR(t_0, t_1) = & 2 \times NP \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^a}^{\hat{t}_2^a} HOP^a(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^a}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) f_{\tau_1}(\tau_1) f_{\tau_2}(\tau_2) f(\varphi_{head}) dt dV_1 dV_2 d\varphi_{head} d\tau_2 d\tau_1 \\ & + 2 \\ & \times NP \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^b}^{\hat{t}_2^b} HOP^b(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^b}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) f_{\tau_1}(\tau_1) f_{\tau_2}(\tau_2) f(\varphi_{head}) dt dV_1 dV_2 d\varphi_{head} d\tau_2 d\tau_1 \\ & + 2 \\ & \times NP \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^c}^{\hat{t}_2^c} HOP^c(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^c}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) f_{\tau_1}(\tau_1) f_{\tau_2}(\tau_2) f(\varphi_{head}) dt dV_1 dV_2 d\varphi_{head} d\tau_2 d\tau_1 \\ & + 2 \\ & \times NP \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^d}^{\hat{t}_2^d} HOP^d(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^d}{\pi\lambda_{xy}} + \frac{|\dot{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) f_{\tau_1}(\tau_1) f_{\tau_2}(\tau_2) f(\varphi_{head}) dt dV_1 dV_2 d\varphi_{head} d\tau_2 d\tau_1 \end{aligned} \quad (5.255)$$

⁴⁴ Actually, there is a (very) short fifth initial part for the time interval $[t_0 = 0, \tau_1]$ corresponding with the fix tolerance τ_1 during which the holding aircraft flies in the direction of the x-axis in Figure 5.13. Though this is not shown in the collision risk model in eqs. (5.254) and (5.255), it has been included in the software for the actual computations.

The lower and upper integration limits $\hat{t}_1^a$ and $\hat{t}_2^a$ denote the nominal times at which the holding aircraft enters and exits the outbound turn segment a with $\hat{t}_1^a = \tau_1$ and $\hat{t}_2^a$ based on the duration of the turn of the holding aircraft and likewise for the other segments of the holding track. See Appendix F to (Moek, 2015b) for the precise definitions of these points in time. It should be noted that the collision risk model in eq. (5.255) does not (yet) account for the wind effect on the holding aircraft. It will be discussed later on how this can be taken into account.

The collision risk model for the spacing between PBN routes and holding areas in radar airspace is given by eq. (5.255) with an additional ATC intervention failure probability P_{ATC} , i.e.

$$\begin{aligned}
 CR(t_0, t_1) = & P_{ATC} \times 2 \times \left[\begin{aligned} & \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^a}^{\hat{t}_2^a} HOP^a(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^a}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2)f_{\tau_1}(\tau_1)f_{\tau_2}(\tau_2)f(\varphi_{head})dtdV_1dV_2d\varphi_{head}d\tau_2d\tau_1 \\ & + 2 \times \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^b}^{\hat{t}_2^b} HOP^b(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^b}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2)f_{\tau_1}(\tau_1)f_{\tau_2}(\tau_2)f(\varphi_{head})dtdV_1dV_2d\varphi_{head}d\tau_2d\tau_1 \\ & + 2 \times \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^c}^{\hat{t}_2^c} HOP^c(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^c}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2)f_{\tau_1}(\tau_1)f_{\tau_2}(\tau_2)f(\varphi_{head})dtdV_1dV_2d\varphi_{head}d\tau_2d\tau_1 \\ & + 2 \times \int_{\tau_{1min}}^{\tau_{1max}} \int_{\tau_{2min}}^{\tau_{2max}} \int_{\varphi_{head\_min}}^{\varphi_{head\_max}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\hat{t}_1^d}^{\hat{t}_2^d} HOP^d(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) \times P_z(h_z) \\ & \times \left[\frac{2V_{rel}^d}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right] f_1(V_1)f_2(V_2)f_{\tau_1}(\tau_1)f_{\tau_2}(\tau_2)f(\varphi_{head})dtdV_1dV_2d\varphi_{head}d\tau_2d\tau_1 \end{aligned} \right] \quad (5.256)
 \end{aligned}$$

As in the previous subsections, ATC intervention failure probability P_{ATC} was to be based on the A-RNP study of (Smith, 2012), pertaining to parallel routes (only) and could not be used in a straightforward manner for the current scenario. Therefore, the following approach was followed. For the holding area versus PBN route spacing scenario, collision risk is calculated as a function of the heading and the waypoint used to define the route. The characteristics of the PBN route allow calculating the minimum distance between the route and the holding pattern. This can be done by calculating for any point on the route the distance to the holding

pattern along the hypotenuse on the route through the point and by subsequently taking the minimum over all points on the route. This minimum distance can then be used as a substitute for S_y in the ATC failure probabilities $P_{ATC}(S_y)$ in Section 2.2.4 of (Moek, 2015b).

The geometry of the holding scenario defined was then translated into the successive probabilities of horizontal overlap $HOP^a(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) = Prob\{\Delta x^a(t)^2 + \Delta y^a(t)^2 \leq \lambda_{xy}^2\}$ up to $HOP^d(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) = Prob\{\Delta x^d(t)^2 + \Delta y^d(t)^2 \leq \lambda_{xy}^2\}$ of the collision risk model. It was assumed that both the holding and the PBN route carried different varieties of PBN navigation specifications with the following probability densities for the along-track and across-track navigation error distributions:

$$f_1^A(\varepsilon_1^A)^H = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^{1H} \beta_{ij}^A f_{ij}^A(\varepsilon_1^A) \quad (5.257)$$

$$f_1^C(\varepsilon_1^C)^H = \sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_k^{1H} \beta_{kl}^C f_{kl}^C(\varepsilon_1^C) \quad (5.258)$$

$$f_2^A(\varepsilon_2^A)^H = \sum_{u=1}^5 \sum_{v=1}^{n_u} \alpha_u^{2H} \beta_{uv}^A f_{uv}^A(\varepsilon_2^A) \quad (5.259)$$

$$f_2^C(\varepsilon_2^C)^H = \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_x^{2H} \beta_{xy}^C f_{xy}^C(\varepsilon_2^C) \quad (5.260)$$

where the flight time proportions for the along-track and across-track errors are constrained by

$$\alpha_i^{1H} = \alpha_k^{1H}, i, k = 1, \dots, 5, i = k \quad (5.261)$$

Similarly, it must hold that

$$\alpha_u^{2H} = \alpha_x^{2H}, u, x = 1, \dots, 5, u = x \quad (5.262)$$

The above equations differ only with those introduced in Sections 5.5.5.2 and 5.5.5.3 in that a superscript “H”, Holding, has been added to the flight-time proportions and the probability densities. The current flight-time proportions will numerically differ from those in Sections 5.5.5.2 and 5.5.5.3 and hence the probability densities. The superscript “H” refers to the holding scenario rather than the holding aircraft. The distinction between the holding and non-holding aircraft is made through subscripts (or superscripts) 1 and 2 where the holding aircraft is labelled 1 and the aircraft following the PBN route is labelled 2.

(Moek, 2015b) lists the following expressions for the four probabilities of horizontal overlap in eqs. (5.255) and (5.256) given the five conditioning random variables and the relative aircraft speeds:

- **Segment a , $\hat{t}_1^a \leq t \leq \hat{t}_2^a$**

$$\begin{aligned} HOP^a(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) &= Prob\{\Delta x^a(t)^2 + \Delta y^a(t)^2 \leq \lambda_{xy}^2\} \\ &= \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^{1H} \beta_{ij}^A \alpha_k^{1H} \beta_{kl}^C \alpha_u^{2H} \beta_{uv}^A \alpha_x^{2H} \beta_{xy}^C HOP^a(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} \end{aligned} \quad (5.263)$$

$$HOP^a(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_{ij}^A \left(-DD_x^a(t) + \varepsilon_2^A \cos(\theta^a) - \varepsilon_2^C \sin(\theta^a) \right)^H f_{uv}^A (\varepsilon_2^A)^H f_{kl}^C \left(-DD_y^a(t) + \varepsilon_2^A \sin(\theta^a) + \varepsilon_2^C \cos(\theta^a) \right)^H f_{xy}^C (\varepsilon_2^C)^H d\varepsilon_2^C d\varepsilon_2^A \quad (5.264)$$

$$V_{rel}^a = \sqrt{V_1^2 - 2V_1V_2 \cos\left(\frac{V_1}{R}(t - \hat{t}_1^a) + \psi_2\right) + V_2^2} \quad (5.265)$$

- **Segment b**, $\hat{t}_1^b \leq t \leq \hat{t}_2^b$

$$\begin{aligned} HOP^b(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) &= Prob\{\Delta x^b(t)^2 + \Delta y^b(t)^2 \leq \lambda_{xy}^2\} \\ &= \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^{1H} \beta_{ij}^A \alpha_k^{1H} \beta_{kl}^C \alpha_u^{2H} \beta_{uv}^A \alpha_x^{2H} \beta_{xy}^C HOP^b(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} \end{aligned} \quad (5.266)$$

$$HOP^b(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_{ij}^A \left(-DD_x^b(t) + \varepsilon_2^A \cos(\theta^b) - \varepsilon_2^C \sin(\theta^b) \right)^H f_{uv}^A (\varepsilon_2^A)^H f_{kl}^C \left(-DD_y^b(t) + \varepsilon_2^A \sin(\theta^b) + \varepsilon_2^C \cos(\theta^b) \right)^H f_{xy}^C (\varepsilon_2^C)^H d\varepsilon_2^C d\varepsilon_2^A \quad (5.267)$$

$$V_{rel}^b(t) = \sqrt{V_1^2 + 2V_1V_2 \cos(\varphi_{head} - \psi_2) + V_2^2} \quad (5.268)$$

- **Segment c**, $\hat{t}_1^c \leq t \leq \hat{t}_2^c$

$$\begin{aligned} HOP^c(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) &= Prob\{\Delta x^c(t)^2 + \Delta y^c(t)^2 \leq \lambda_{xy}^2\} \\ &= \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^{1H} \beta_{ij}^A \alpha_k^{1H} \beta_{kl}^C \alpha_u^{2H} \beta_{uv}^A \alpha_x^{2H} \beta_{xy}^C HOP^c(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} \end{aligned} \quad (5.269)$$

$$HOP(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_{ij}^A \left(-DD_x^c(t) + \varepsilon_2^A \cos(\theta^c) - \varepsilon_2^C \sin(\theta^c) \right)^H f_{uv}^A (\varepsilon_2^A)^H f_{kl}^C \left(-DD_y^c(t) + \varepsilon_2^A \sin(\theta^c) + \varepsilon_2^C \cos(\theta^c) \right)^H f_{xy}^C (\varepsilon_2^C)^H d\varepsilon_2^C d\varepsilon_2^A \quad (5.270)$$

$$V_{rel}^c = \sqrt{V_1^2 - 2V_1V_2 \sin(\varphi^c(t) - \psi_2) + V_2^2} \quad (5.271)$$

- **Segment d**, $\hat{t}_1^d \leq t \leq \hat{t}_2^d$

$$\begin{aligned} HOP^d(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1) &= Prob\{\Delta x^d(t)^2 + \Delta y^d(t)^2 \leq \lambda_{xy}^2\} \\ &= \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^{1H} \beta_{ij}^A \alpha_k^{1H} \beta_{kl}^C \alpha_u^{2H} \beta_{uv}^A \alpha_x^{2H} \beta_{xy}^C HOP^d(t|V_1, V_2, \varphi_{head}, \tau_2, \tau_1)_{ijkluvxy} \end{aligned} \quad (5.272)$$

$$HOP^d(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\square} \int_{\varepsilon_2^C}^{\square} f_{ij}^A \left(-DD_x^d(t) + \varepsilon_2^A \cos(\theta^d) - \varepsilon_2^C \sin(\theta^d) \right)^H f_{uv}^A (\varepsilon_2^A)^H f_{kl}^C \left(-DD_y^d(t) + \varepsilon_2^A \sin(\theta^d) + \varepsilon_2^C \cos(\theta^d) \right)^H f_{xy}^C (\varepsilon_2^C)^H d\varepsilon_2^C d\varepsilon_2^A \quad (5.273)$$

$$V_{rel}^d(t) = \sqrt{V_1^2 - 2V_1V_2 \cos(\psi_2) + V_2^2} \quad (5.274)$$

The quantities $DD_x^a(t)$, $DD_y^a(t)$, $DD_x^b(t)$, $DD_y^b(t)$, $DD_x^c(t)$, $DD_y^c(t)$, $DD_x^d(t)$ and $DD_y^d(t)$ denote the nominal relative position components between the aircraft during the four parts of the holding trajectory. See section 4.5 of (Moek, 2015b) for the precise formulae. In the same manner as in the previous subsections, eqs. (5.264), (5.267), (5.270), and (5.273) for the scenario of spacing between PBN routes and holding areas, differ only with regard to the terms $DD_x^a(t)$, $DD_y^a(t)$, ..., $DD_y^d(t)$ (and the angles θ^a , θ^b , ..., θ^d) in the arguments of the probability densities $f_{ij}^A(\varepsilon)$ and $f_{kl}^C(\varepsilon)$.

It was remarked after eq. (5.255) for the collision risk model in procedural airspace, that its derivation did not (yet) account for the wind effect on the holding aircraft and that this would be discussed later on. As set out in the description of the holding procedure, the wind effect was to be modelled as a zero-mean across-track random variable W_1^C with standard deviation σ_{w1}^C , where the value of the standard deviation was specified in eqs. (5.252) and (5.253). As a result, there are two (independent) random variables working on the holding aircraft in the across-track direction all along the holding pattern, i.e.

$$\varepsilon_1'^C = \varepsilon_1^C + W_1^C \quad (5.275)$$

The standard deviation of the resulting across-track position uncertainty for the holding aircraft is simply

$$\sigma_{\varepsilon_1'}^C = \sqrt{(\sigma_{\varepsilon_1}^C)^2 + (\sigma_{w1}^C)^2} \quad (5.276)$$

Eq. (5.275) implies that eqs. (5.263) – (5.274) remain valid when the original across-track-error random variable ε_1^C is replaced by the new random variable $\varepsilon_1'^C$, which, based on eq. (5.276), has a time-dependent standard deviation rather than a constant standard deviation over time. The substitution affects eqs. (5.264), (5.267), (5.270), and (5.273) through the probability density functions $f_{ij}^A(\dots)$. The only assumption that is made is that the type of probability distribution of the new across-track error $\varepsilon_1'^C$ is the same as that of the original across-track error ε_1^C . This assumption is automatically satisfied when the probability distributions of the across-track errors ε_1^C and W_1^C are both normal. Strictly speaking, the assumption is not true when the probability distributions of ε_1^C and W_1^C are, e.g., both double exponential. However, the assumption is believed to provide a reasonable approximation within the scope of the overall wind modelling.

The last step in the evaluation of the probability of horizontal overlap is to specify the type of the navigation error probability density functions $f_{ij}^A(\varepsilon_1^A)$, $f_{kl}^C(\varepsilon_1^C)$, $f_{uv}^A(\varepsilon_2^A)$, and $f_{xy}^C(\varepsilon_2^C)$.

5.5.5.7 Crossing tracks using same or different navigation specifications – Operational requirement 3A

Section 5.4.2.6 described a lateral collision risk model for aircraft on intersecting tracks based on a “protected” region of airspace either side of the track of a reference aircraft (aircraft 1). See Figure 5.14. The size of the protected airspace either side of an aircraft’s nominal track is S_y . A second aircraft flying on an intersecting track and which does not have longitudinal or vertical separation with the reference aircraft, would be required to change level before entering the reference aircraft’s protected region, and not to return to the original level until clear of the protected region. The points at which the first level change needs to be completed and at which the second level change may start were called lateral separation points (LSPs). The model was based on the general collision risk model based on reliability theory (Anderson, 2005).

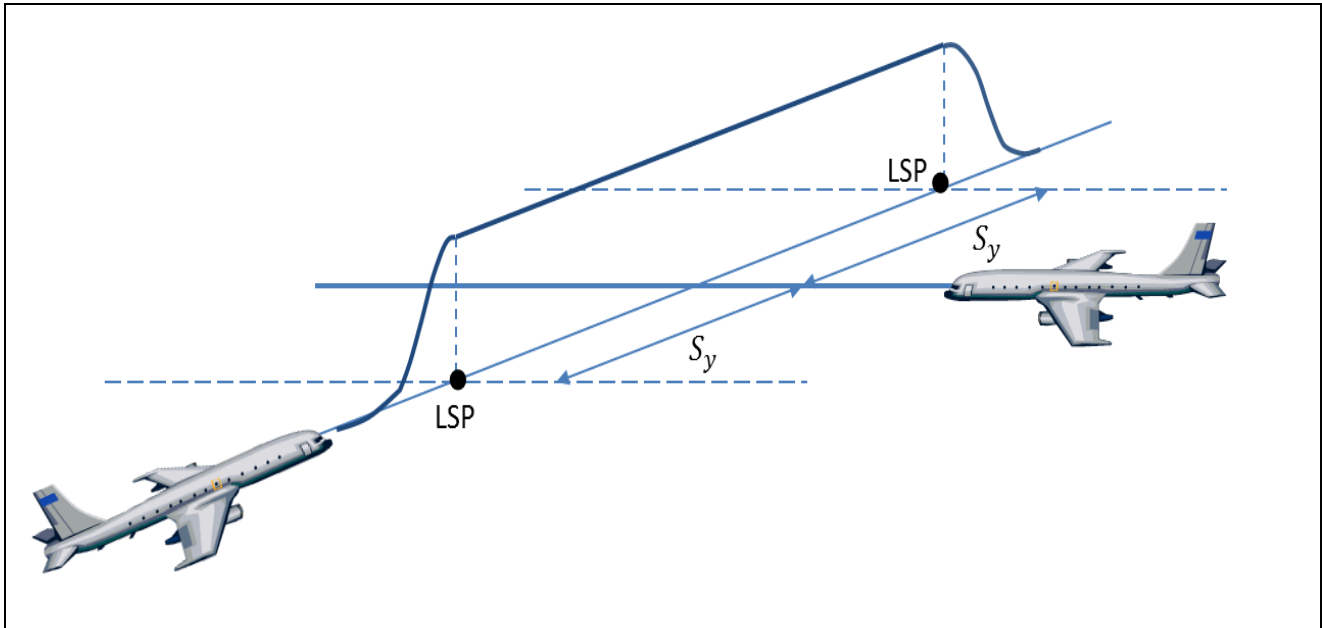


Figure 5.14: Two aircraft at the same flight level on intersecting tracks. To assure separation, the left aircraft will be required to climb (or descend) and reach another level by the left boundary of the right aircraft's protected airspace and could descend (or climb) back to its original flight level only after the right boundary of the right aircraft's protected airspace

For the above scenario, the calculation of the collision risk over the time period $[t_0, t_1]$ splits into two parts, namely a period of time with the aircraft laterally separated from t_0 until aircraft 2 reaches its first lateral separation point, plus a period of time with the aircraft laterally separated starting with aircraft 2 reaching its second lateral separation point and ending at t_1 . See Circular 334 (ICAO, 2014c), where each of the two time intervals was taken as 10 minutes. The period of time with aircraft 2 flying from its first to its second lateral separation point does not contribute to the lateral risk because the two aircraft are then vertically separated.

This subsection summarizes the collision risk model derived in Section 5.2 of (Moek, 2015b), which utilized Anderson's general collision risk model based on reliability theory (Anderson, 2005) and Circular 334 (ICAO, 2014c) for intersecting track lateral separation for the benefit of EUROCONTROL's Operational Requirement (OR) 3A. OR 3A concerns a STAR crossing above a SID as sketched in Figure 5.15 (reproduced from reference 69 to (Moek, 2015b)). The supplementary scenario of a SID crossing above a STAR, OR 3B, is summarized in Section 5.5.5.8.

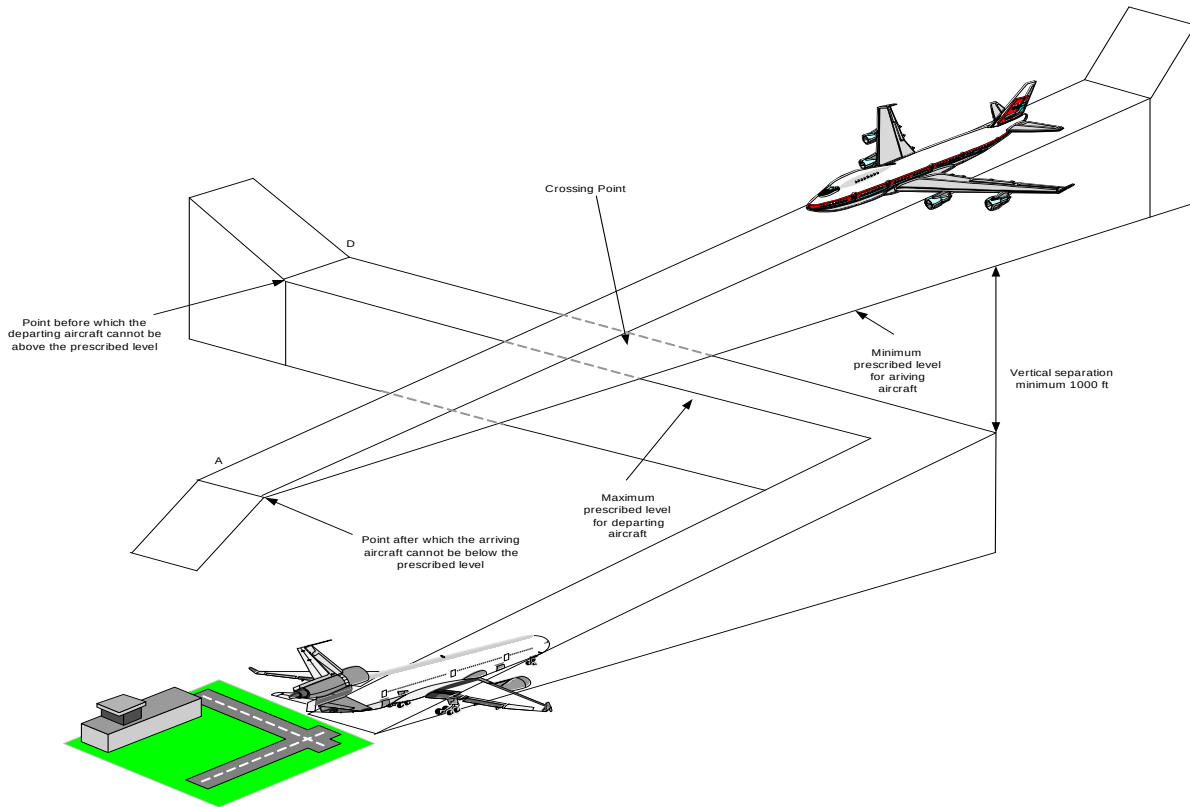


Figure 5.15: ⁴⁵ Operational requirement 3A with an arriving aircraft crossing above a departing aircraft

The objective of the lateral risk calculations for OR 3A was to determine the earliest point after crossing at which both aircraft can continue their climb/descent. These points are referred to as point A for the arriving aircraft and point D for the departing aircraft and the distances of these points to the crossing are denoted d_A and d_D respectively. A minimum value was to be determined for d_A . Determination of point A for OR 3A through collision risk modelling is comparable to determining the size of the protected airspace S_y in Figure 5.14, i.e. determination of the lateral separation point where vertical separation can be ended. Cf. also the methodology used for the determination of GNSS lateral separation minima based on VOR separation minima in Section 5.4.1. of (ICAO, 2014a).

With the arriving aircraft crossing above the departing aircraft under OR 3A, the two aircraft have vertical separation until at least the intersection point. With the departing aircraft still in level flight at the intersection, vertical separation gets lost when the arriving aircraft descends through its minimum prescribed level at, say, point in time t_A at the distance d_A beyond the intersection point. From this time/distance onwards, horizontal/lateral separation needs to be provided. Thus, the point in time t_A can be taken as the starting point t_0 for the lateral collision risk calculation. The risk depends, through the probability of horizontal overlap, on the location of the departing aircraft at time $t_0 = t_A$ and this dependence needs to be accounted for. The dependence of the calculated risk on the location of the second aircraft was extensively examined by the SASP MSG in its work on VOR/GNSS lateral separation minima, the spacing of proximate instrument flight procedures, and lateral separation minima for intersecting tracks (ICAO, 2010, 2014a,

⁴⁵ The correct text referring to point A should read: Point before which the arriving aircraft cannot be below the prescribed level

2015b). The lateral collision risk will also depend on the point in time t_D at which the departing aircraft starts leaving its maximum prescribed level (or its distance d_D to the intersection at that point in time). Taking t_A as the starting time for the calculation implies that t_D must not be smaller than t_A because otherwise vertical separation might be lost prior to the start of lateral separation at t_A . The distances of the departing aircraft to the intersection at t_A and t_D are related by $d_D(t_D) = d_D(t_A) + V_D(t_D - t_A)$. The lateral risk calculation can stop at point in time t_1 when either the arriving aircraft has landed or the aircraft have achieved vertical separation again at time t^+ following passing through a common level at point in time t^0 . See Figure 5.16.

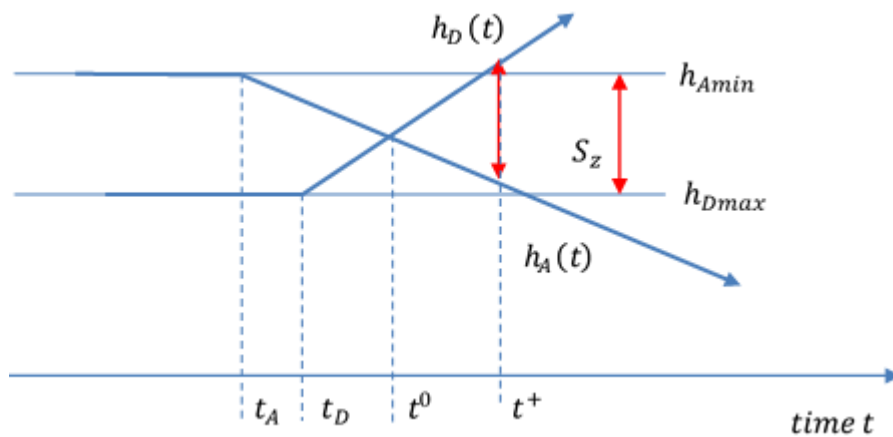


Figure 5.16: Height profiles of the arriving and departing aircraft as a function of time

In summary, the lateral collision risk was to be calculated for a given value of the distance $d_A = d_A(t_A)$ of the arriving aircraft to the intersection when passing through its minimum prescribed level as a function of the distance $d_D(t_A)$ of the departing aircraft to the intersection at point in time t_A . The dependence of the lateral collision risk on the latter distance was treated by a suitable form of either averaging or conservative bounding. A minimum value of d_A was calculated since the lateral risk increases with decreasing distance d_A . Determining the distance $d_A = d_A(t_A)$ at which the vertical separation can be ended is similar to determining the outbound lateral separation point for the intersecting track scenario of Figure 5.14 (ICAO, 2014c) or the outbound case for VOR/GNSS lateral separation minima (ICAO, 2014a).

Figure 5.17 sketches the geometry of OR 3A in the horizontal plane where the departing aircraft is denoted aircraft 1 and the arriving aircraft denoted aircraft 2. The origin of an x, y, z -coordinate frame was taken at the intersection point of the departure and arrival tracks with the X -axis in the direction opposite to that of the departing aircraft. The inbound track of the arriving aircraft makes an angle θ with that of the departing aircraft, where $45^\circ \leq \theta \leq 135^\circ$. Notice that the turn in the departing aircraft's track is not included in Figure 5.17. The reason is that for OR 3A, the risk calculation starts at time $t_0 = t_A$ with both aircraft having passed the intersection point. For both aircraft, their true and nominal locations at this point in time $t_0 = t_A$ play a part. However, this implies that the trajectories of the two aircraft prior to $t_0 = t_A$ do not play any part in the calculation, particularly that the turn in the departing aircraft's trajectory before the intersection point does not need to be modelled for OR 3A.

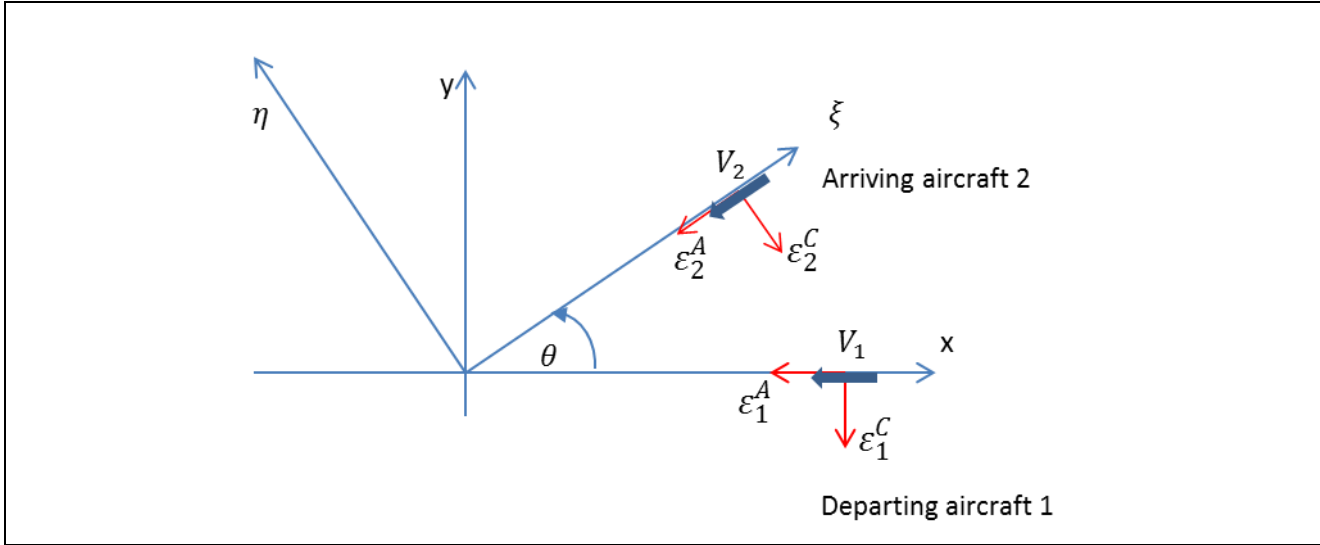


Figure 5.17: Coordinate system used for OR 3A (and OR 3B), including the along-track and across-track errors of the arriving and departing aircraft as well as their speed vectors

With careful attention for the signs of the various variables shown in Figure 5.17, the generalized collision risk model based on reliability theory by Dalm (1987) is directly applicable, i.e. for procedural airspace

$$CR(t_0, t_1; S_z = VSM) = 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) \times P_z^{3A}(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|z|}{2\lambda_z} \right] f_1(V_1)f_2(V_2)dt dV_1 dV_2 \quad (5.277)$$

with

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} \approx \pi\lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_1^C}^{\varepsilon_1^A} f_1^A(-D_x^{\square}(t) + \varepsilon_2^A \cos\theta - \varepsilon_2^C \sin\theta) f_2^A(\varepsilon_2^A) f_1^C(-D_y^{\square}(t) + \varepsilon_2^A \sin\theta + \varepsilon_2^C \cos\theta) f_2^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.278)$$

and

$$V_{rel} = \sqrt{V_1^2 - 2V_1V_2\cos\theta + V_2^2} \quad (5.279)$$

See section 5.2 of (Moek, 2015b) for the calculation of the probability of vertical overlap $P_z^{3A}(h_z(t))$ over time specific to OR 3A. The quantities $D_x^{\square}(t)$ and $D_y^{\square}(t)$ denote the nominal relative position components between the aircraft during the time interval $[t_0, t_1]$ over which lateral collision risk exists. See section 5.2 of (Moek, 2015b) for the precise formulae. Notice that a conditioning variable $S_z = VSM$ with VSM denoting the applicable Vertical Separation Minimum has been added to the lateral collision risk variable $CR(t_0, t_1)$ in the left-hand side of the model in eq. (5.277). The reason for this addition is explained in the next four paragraphs.

The navigational-error probability-densities $f_1^A(\cdot)$, $f_1^C(\cdot)$, $f_2^A(\cdot)$, and $f_2^C(\cdot)$ have not yet been detailed.

Given a PBN navigation specification, modelling of the navigational errors under the specification was done in the previous subsections through a mixture of up to five probability densities, cf. eqs. (5.206), (5.226), or (5.227). It was noted that, in practice, mixtures of two probability densities are often used, where one density represents typical performance and the other atypical performance, including operational error/blunder,

technical degradation or failure. However, some atypical errors can be better modelled in the form of a constant or varying offset rather than as an increased spread of a random variable (without offset). The modelling developed in (Moek, 2015b) was based on a hazard identification and analysis performed previously by EUROCONTROL (EUROCONTROL, 2008).

An FHA workshop conducted as a part of the safety assessment conducted in (EUROCONTROL, 2008) indicated that there were two main failure modes or hazards associated specifically with routes in close proximity, involving positional error in the lateral or vertical dimension as follows:

- Hazard 1: aircraft at wrong level; and
- Hazard 2: Aircraft in wrong horizontal position.

Both hazards were considered category 3 (major incident) events according to the ESARR4 classification as the worst credible case was a large reduction in separation with the aircrew able to recover from the situation. Since a maximum tolerable probability of a category 3 event was not available at the time of the workshop, a value was derived for the benefit of the safety assessment by assuming that the probability would decrease by an order of magnitude for each category below category 1, thus resulting in a maximum tolerable probability of failure for OR 3A/3B of 1.55×10^{-6} .

Using an event tree with two risk mitigations, namely ATC hazard detection and ATC successful hazard intervention, the maximum failure probability of 1.55×10^{-6} was converted into a so-called hazard TLS in (EUROCONTROL, 2008). The conversion resulted in a TLS for each initiating hazard in the form of a maximum tolerable failure probability of 5.2×10^{-4} . See (EUROCONTROL, 2008) or Section 5.5.5.7 of (Moek, 2015b) for further details. A fault tree was then developed for hazard 1 and the hazard TLS was used to derive nine safety integrity requirements on lower level events such that the TLS would be met if all the safety integrity requirements would be jointly met. The hazards associated with the lateral error, hazard 2, were considered to be equivalent to those analysed in the P-RNAV safety assessment (Smith, 2003).

It follows from the above that atypical positional errors in both the vertical and horizontal dimensions need to be considered. Consider the vertical dimension first. Some atypical vertical error in the form of increased spread about the aircraft's nominal heights is included in the TVE probability distribution used to calculate the probability of vertical overlap parameter $P_z^{3A}(h_z(t))$ of the collision risk model in eq. (5.277). The vertical separation minimum for OR 3A plays a part through the variables $h_A(t_A)$ and $h_D(t_D)$ in Figure 5.16. The difference between these two aircraft heights would normally be 1000 ft, but the model is equally applicable for any multiple of 1000 ft. In addition, the model is applicable also for zero foot vertical separation, which is precisely the scenario for hazard 1. Thus, the collision risk model of eq. (5.277) can be used in a straightforward manner to calculate the OR 3A risk given that hazard 1 has occurred. This risk is denoted $CR(t_0, t_1; S_z = 0)$ and the OR 3A risk in the absence of hazard 1 is denoted $CR(t_0, t_1; S_z = VSM)$ where VSM denotes the vertical separation minimum under consideration.

Consider now atypical error in the horizontal dimension, i.e. Hazard 2. (EUROCONTROL, 2008) noted that either the arrival or departing aircraft being in the wrong lateral position can infringe vertical separation when the crossing aircraft climbs/descends through the conflicting aircraft's level. Random lateral and longitudinal navigation errors are an intrinsic part of the collision risk model of eq. (5.277) where both typical and atypical errors can be included in the types of navigation error distributions. These distributions do not include any systematic offsets in the horizontal dimension. However, such offsets can easily be incorporated into the equations for the initial locations of the two aircraft at time $t_0 = t_A$. (See eqs. (5.37) – (5.40) of (Moek, 2015b).) When the offsets for aircraft 1 and 2 are denoted as x_1^{off}, y_1^{off} and $\xi_2^{off}, \eta_2^{off}$ respectively,

the only resulting change to the probability of horizontal overlap $HOP(t|V_1, V_2)$ in eq. (5.278) concerns the nominal relative position components $D_x(t)$ and $D_y(t)$, which may thus be denoted $D_x^{off}(t)$ and $D_y^{off}(t)$ as shown in eqs. (5.41) and (5.42) of (Moek, 2015b).

Thus, denoting the OR 3A risk given that hazard 2 has occurred as $CR(t_0, t_1; x_1^{off}, y_1^{off}, \xi_2^{off}, \eta_2^{off})$ and denoting the OR 3A risk in the absence of both hazard 1 and hazard 2 as before as $CR(t_0, t_1; S_z = VSM)$, the overall OR 3A lateral collision risk in procedural airspace can be expressed as

$$CR(t_0, t_1) = (1 - p_{hazard\ 1} - p_{hazard\ 2}) \times CR(t_0, t_1; S_z = VSM) + p_{hazard\ 1} \times CR(t_0, t_1; S_z = 0) + p_{hazard\ 2} \times CR(t_0, t_1; x_1^{off}, y_1^{off}, \xi_2^{off}, \eta_2^{off}) \quad (5.280)$$

supplemented with

$$CR(t_0, t_1) = P_{ATC} [(1 - p_{hazard\ 1} - p_{hazard\ 2}) \times CR(t_0, t_1; S_z = VSM) + p_{hazard\ 1} \times CR(t_0, t_1; S_z = 0) + p_{hazard\ 2} \times CR(t_0, t_1; x_1^{off}, y_1^{off}, \xi_2^{off}, \eta_2^{off})] \quad (5.281)$$

for radar airspace where P_{ATC} denotes the probability of ATC intervention failure for the OR 3A scenario.

The numerical values used for the parameters $p_{hazard\ 1}$, $p_{hazard\ 2}$, and P_{ATC} of the two collision risk models in eqs. (5.280) and (5.281) were taken as follows. For the weighting factor $p_{hazard\ 1}$, its maximum tolerable value was used, i.e. the hazard TLS of 5.2×10^{-4} and similarly for $p_{hazard\ 2}$.

The value of the ATC intervention failure probability for OR 3A was based on (EUROCONTROL, 2008). This reference includes some discussion on the magnitude of the vertical separation minimum to be used for OR 3A and 3B. It stated that a 2000 ft minimum was very well received by controllers who participated in the real time simulations as a part of the assessment of OR 3A and 3B. It also stated that it was important to note that in the 1000 ft case controllers were often able to detect and correct deviations from assigned level in time. When traffic was increased, however, this resulted in significantly higher controller workload than a similar increase in traffic with 2000 ft vertical separation. Reference was already made above to two risk mitigations considered at the FHA workshop for OR 3A and 3B, namely ATC detects aircraft at wrong level and ATC intervenes successfully. It was perceived at the workshop that the probability of ATC not detecting the error was an “error of omission where the actions are embedded in a well-rehearsed procedure”. Using human error probabilities as defined in UK Defence Standard 00-56 (Part 2)/2 (Ref. 72 to (EUROCONTROL, 2008)), this resulted in a failure probability of 3×10^{-3} . The probability of ATC not intervening successfully given detection was likened to a “general decision error during high stress”, resulting in a (conditional) failure probability of 0.2 – 0.3. The overall ATC intervention failure probability for OR 3A thus becomes $3 \times 10^{-3} + 3 \times 10^{-3} \times 0.25 = 3.75 \times 10^{-3}$. The same value was obtained in (EUROCONTROL, 2008) for Hazard 2, aircraft in wrong horizontal position. It has been assumed in (Moek, 2015b) that this value is also applicable to the general situation of a collision due to typical and/or atypical random navigation errors in the vertical and horizontal dimensions. Thus, $P_{ATC} = 3.75 \times 10^{-3}$ was used in the collision risk model of eq. (5.281) for OR 3A in radar airspace. This value was to be considered as a best estimate. Unfortunately, no further information or data was available from which optimistic and pessimistic bounds for P_{ATC} could be inferred.

The last step modelling step concerns the specification of the type of the navigation error probability density functions $f_1^A(\cdot)$, $f_1^C(\cdot)$, $f_2^A(\cdot)$, and $f_2^C(\cdot)$ for the probability of horizontal overlap $HOP(t|V_1, V_2)$ in eq. (5.278).

The simplest application of the collision risk model would be to a single aircraft pair where the navigation error distributions of the aircraft would be only single, normal or double exponential, distributions. The most general application would be to streams of approaching and departing aircraft with different combinations of five PBN navigation specifications with each along-track and across-track mixture probability density made up of up to five terms as set out in Section 5.5.5.4, i.e.

$$f_1^A(\varepsilon_1^A) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^1 \beta_{ij}^A f_{ij}^A(\varepsilon_1^A) \quad (5.228)$$

$$f_1^C(\varepsilon_1^C) = \sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_k^1 \beta_{kl}^C f_{kl}^C(\varepsilon_1^C) \quad (5.229)$$

$$f_2^A(\varepsilon_2^A) = \sum_{u=1}^5 \sum_{v=1}^{n_u} \alpha_u^2 \beta_{uv}^A f_{uv}^A(\varepsilon_2^A) \quad (5.230)$$

$$f_2^C(\varepsilon_2^C) = \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_x^2 \beta_{xy}^C f_{xy}^C(\varepsilon_2^C) \quad (5.231)$$

For the latter application, the probability of horizontal overlap would become

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^1 \beta_{ij}^A \alpha_k^1 \beta_{kl}^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{ijkluvxy} \quad (5.282)$$

with

$$HOP(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\infty} \int_{\varepsilon_2^C}^{\infty} f_{ij}^A \left(-D_x(t) + \varepsilon_2^A \cos(\theta) - \varepsilon_2^C \sin(\theta) \right) f_{uv}^A(\varepsilon_2^A) f_{kl}^C \left(-D_y(t)(t) + \varepsilon_2^A \sin(\theta) + \varepsilon_2^C \cos(\theta) \right) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.283)$$

5.5.5.8 Crossing tracks using same or different navigation specifications – Operational requirement 3B

This subsection summarizes the collision risk model derived in Section 5.3 of (Moek, 2015b), which again utilized Anderson's general collision risk model based on reliability theory (Anderson, 2005) and Circular 334 (ICAO, 2014c) for intersecting track lateral separation for the benefit of EUROCONTROL's Operational Requirement 3B. OR 3B concerns a SID crossing above a STAR as sketched in Figure 5.18 (reproduced from reference 69 to (Moek, 2015b)).

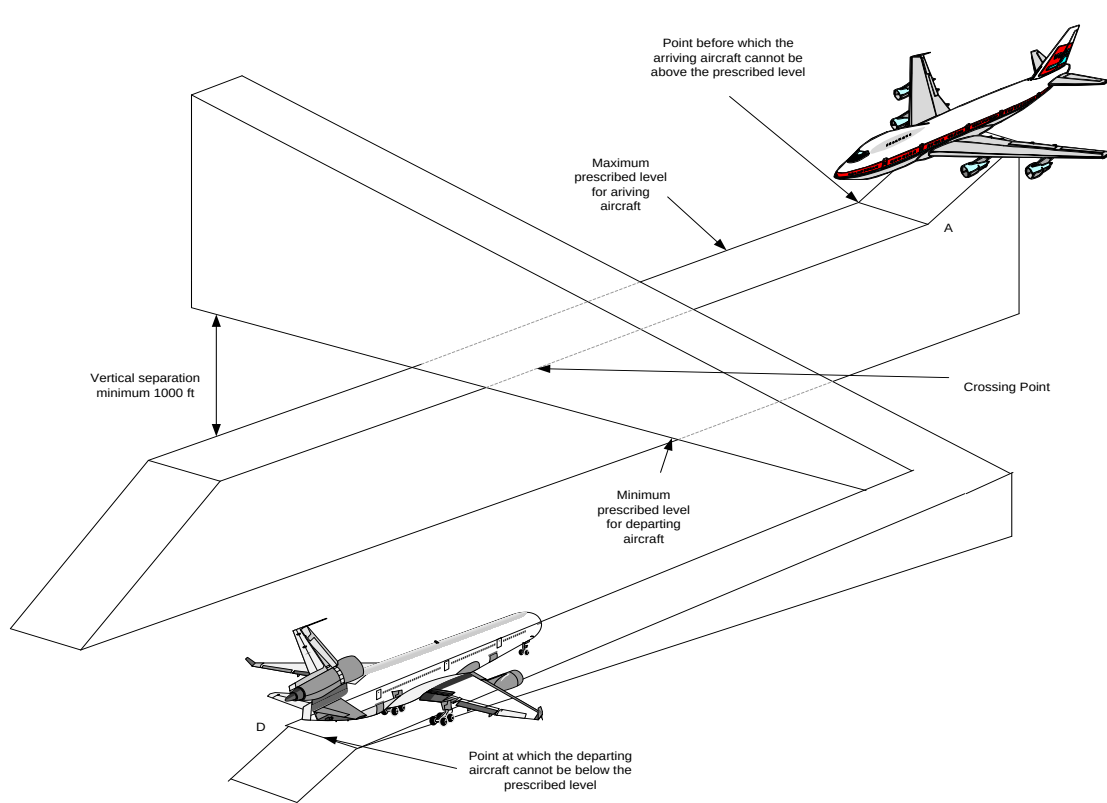


Figure 5.18:⁴⁶ Operational requirement 3B with a departing aircraft crossing above an arriving aircraft

The objective of the lateral risk calculations for OR 3B was to determine the latest point before crossing at which both aircraft must reach their level. These points are referred to as point A for the arriving aircraft and point D for the departing aircraft and the distances of these points to the crossing are denoted d_A and d_D respectively. A minimum value was to be determined for d_D . Determination of point D for OR 3B through collision risk modelling is comparable to determining the size of the protected airspace S_y in Figure 5.14, i.e. determination of the lateral separation point where vertical separation needs to be achieved. Cf. also the methodology used for the determination of GNSS lateral separation minima based on VOR separation minima in Section 5.4.1. or (ICAO, 2014a).

Lateral collision risk was again calculated over a time interval $[t_0, t_1]$ by means of a suitable version of the general collision risk model based on reliability theory (Anderson, 2005), adapted to the OR 3B scenario. Due to the nature of OR 3B, the determination of the time interval $[t_0, t_1]$ is more complicated than for OR 3A. With the arriving aircraft crossing underneath the departing aircraft under OR 3B, the two aircraft have to have achieved vertical separation at, say, point in time t_A at a distance d_A before the intersection point for the arriving aircraft. Prior to this time/distance, horizontal/lateral separation is to be provided. Thus, the lateral risk calculation for OR3B can stop at point in time $t_1 = t_A$. This is an upper bound for the limit case of the departing aircraft in level flight at its minimum prescribed level. See Figure 5.19. Vertical separation $\Delta h(t) = h_A(t) - h_D(t)$ equals zero foot at time t^0 and equals S_z ft at time $t^- = t_A - 2S_z/v_{zA}$. Thus,

$$t_0 = t^- = t_A - 2S_z/v_{zA} \quad (5.284)$$

⁴⁶ The correct text referring to point A should read: Point after which the arriving aircraft cannot be below the prescribed level

could be used as the starting point for the lateral risk calculation for the limit case with the departing aircraft in level flight at its minimum prescribed level. If the departing aircraft would be in level flight at a height $\Delta h_D > 0$ above its minimum prescribed level, the time interval over which $|\Delta h(t)| \leq S_z$ would shift backward over $\Delta h_D / v_{zA}$. This could be used to adjust the starting time t_0 of the lateral risk calculation. The end time $t_1 = t_A$, however, should not be adjusted to cover the limit case of the departing aircraft at its minimum prescribed level.

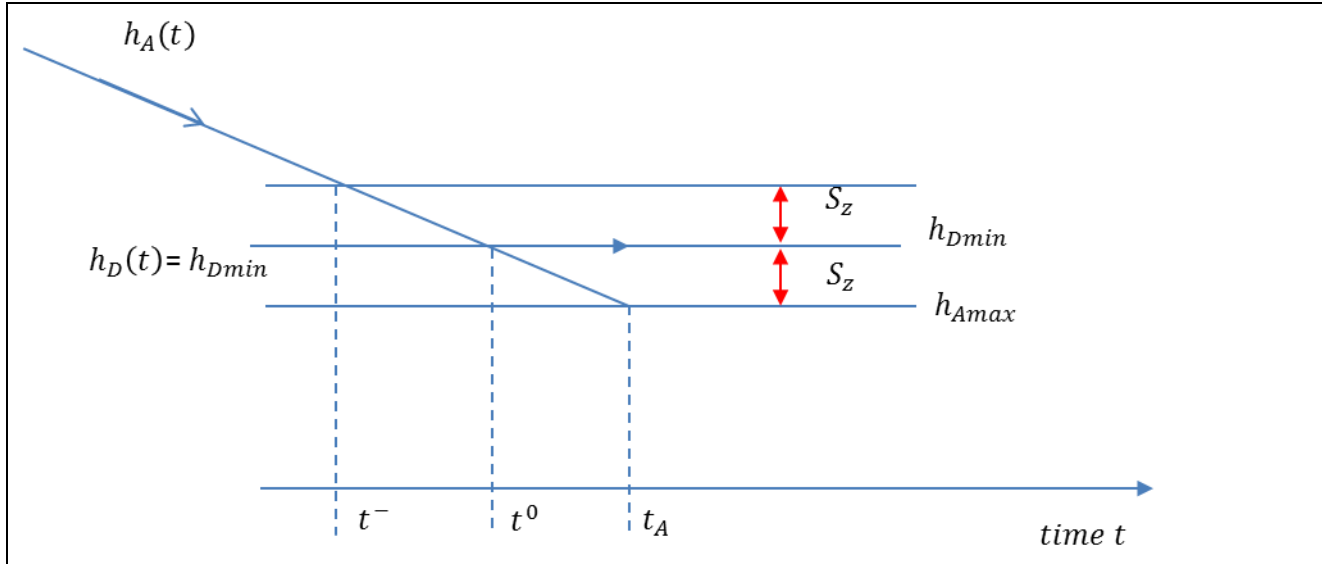


Figure 5.19: Limit case of the departing aircraft in level flight at its minimum prescribed level

Figures 5.20 – 5.22 show the general case of the departing aircraft climbing. Figure 5.20 shows the case where the two aircraft are at the same height above the departing aircraft's minimum prescribed level, whereas Figure 5.21 shows the case where the aircraft are at the same height at precisely the departing aircraft's minimum prescribed level. Finally, Figure 5.22 shows the departing and arriving aircraft at the same height in between of the respective maximum and minimum prescribed levels. In fact, this figure shows three possibilities with regard to the departing aircraft's height at point in time t_A , namely $h_D(t_A) > h_{Dmin}$, $h_D(t_A) = h_{Dmin}$, and $(h_{Amax} <) h_D(t_A) < h_{Dmin}$. The last possibility is shown as an orange line and is not possible in practice because it would violate the basic assumption of the aircraft being vertically separated after point in time t_A .

In all the diagrams, t^- and t^+ mark the points in time at which the (positive) vertical separation reduces to the vertical separation minimum S_z and the (negative) vertical separation increases again in absolute value beyond S_z .

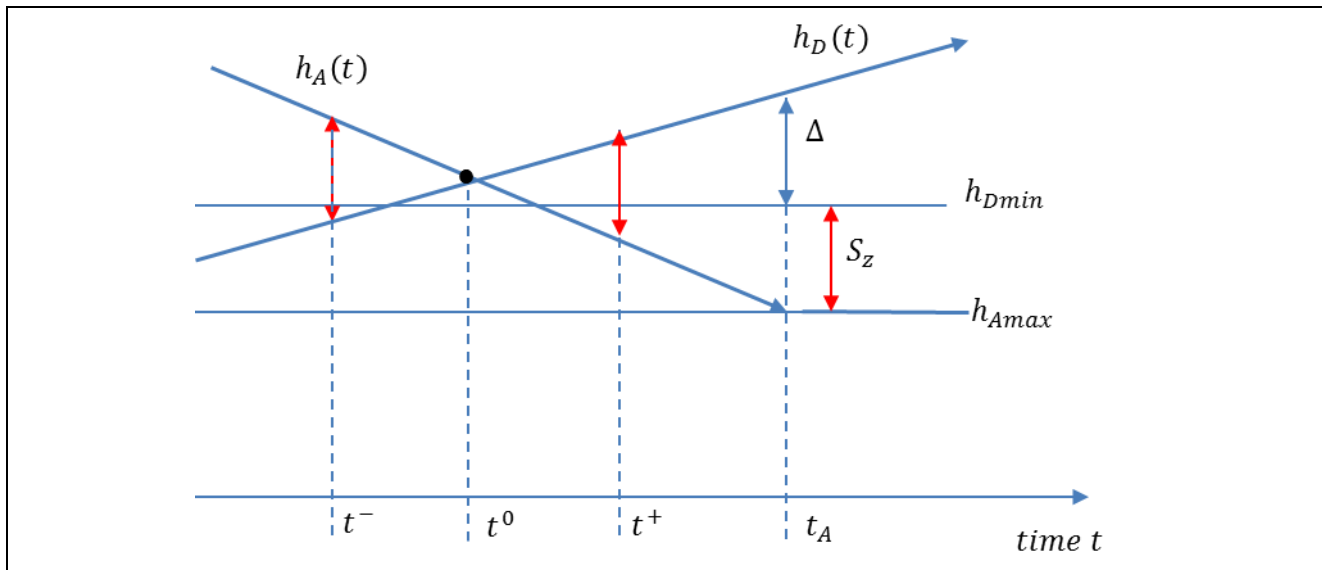


Figure 5.20: Height profiles of the arriving and departing aircraft as a function of time for OR 3B, showing in particular the aircraft at the same height above the departing aircraft's minimum prescribed level at point in time t^0 and the aircraft losing and re-gaining vertical separation at points in time t^- and t^+ respectively

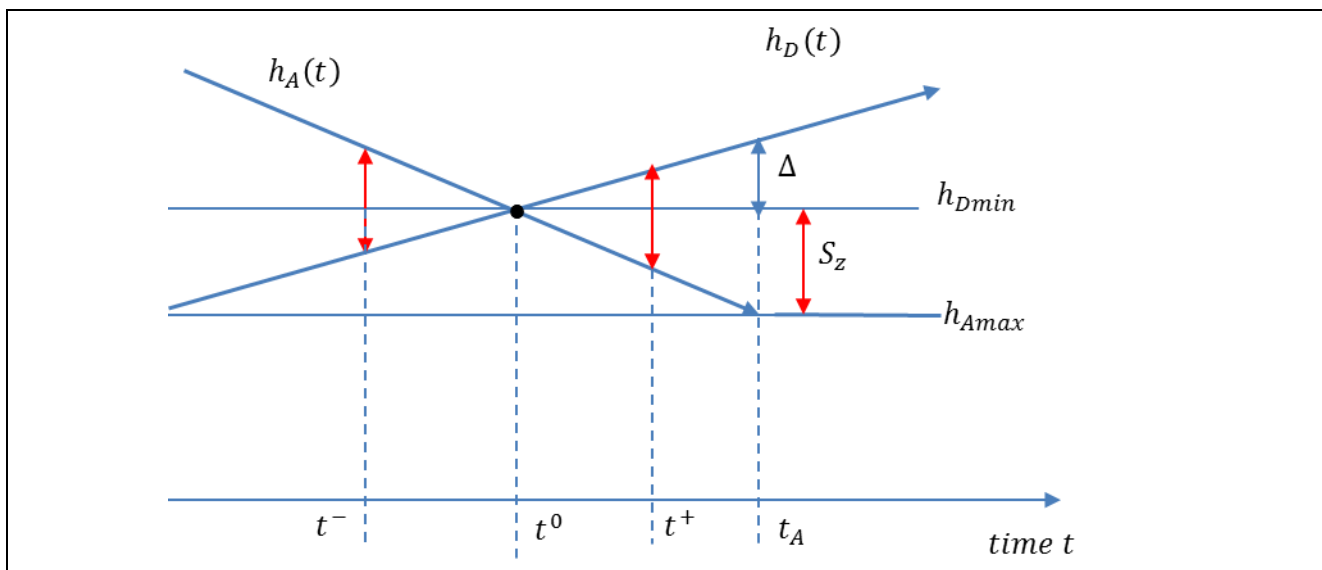


Figure 5.21: Height profiles of the arriving and departing aircraft as a function of time for OR 3B, showing in particular the aircraft at the same height at the departing aircraft's minimum prescribed level at point in time t^0 and the aircraft losing and re-gaining vertical separation at points in time t^- and t^+ respectively

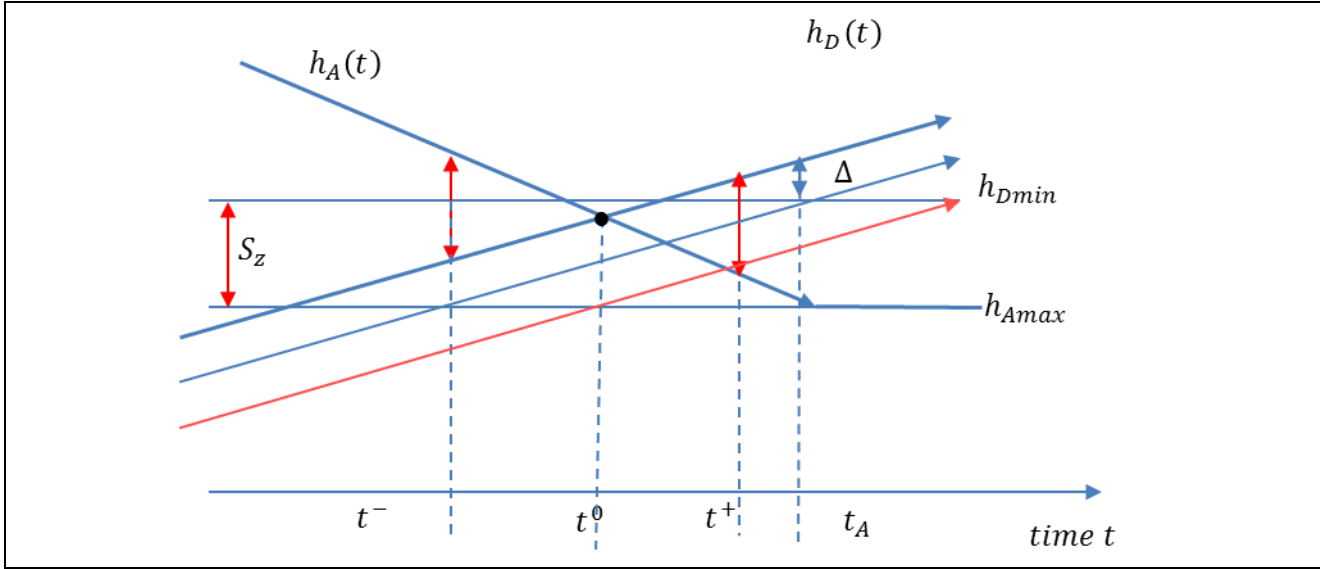


Figure 5.22: Height profiles of the arriving and departing aircraft as a function of time for OR 3B, showing in particular the aircraft at the same height below the departing aircraft's minimum prescribed level at point in time t^0 and the aircraft losing and re-gaining vertical separation at points in time t^- and t^+ respectively

It is shown in Section 5.3 of (Moek, 2015b) that the starting time t_0 for the lateral risk calculation is given by

$$t_0 = \min \left\{ t_A - \frac{2S_z}{v_{zA}}, t_A - \frac{2S_z + \Delta}{v_{zA} + v_{zD}} \right\} \quad (5.285)$$

The minimum of the two variables in the right-hand side of eq. (5.285) is $t_A - 2S_z/v_{zA}$ when

$$\Delta < \frac{v_{zD}}{v_{zA}} 2S_z \quad (5.286)$$

As indicated before, the end time t_1 of the lateral risk calculation should not be replaced by t^+ but be kept as $t_1 = t_A$ to cover all cases up to the limit case of a departing aircraft in level flight at its minimum prescribed level.

Having specified the time interval $[t_0, t_1]$ for the lateral collision risk calculation, this risk was to be calculated for a given value of the distance $d_A = d_A(t_A)$ of the arriving aircraft to the intersection where it has to have levelled off at its maximum prescribed level as a function of the distance $d_D(t_A)$ of the departing aircraft to the intersection at point in time t_A at which it has to have passed its minimum prescribed level. The dependence of the lateral collision risk on the latter distance was to be treated by a suitable form of either averaging or conservative bounding. A minimum value of d_A was calculated since the lateral risk increases with decreasing distance d_A . Determining the distance $d_A = d_A(t_A)$ at which vertical separation has to be achieved may be compared to determining the inbound lateral separation point for the intersecting track scenario of Figure 5.14 (cf. Circular 334 (ICAO, 2014c)) or the inbound case for VOR/GNSS lateral separation minima (ICAO, 2014a). The determination of the required time interval $[t_0, t_1]$ for OR 3B is, however, more complicated due to both aircraft being in vertical motion at the start of the time period over which the lateral collision risk is to be calculated.

It follows from the geometry in Figures 5.15 and 5.18 that the movement of the two aircraft in the horizontal plane is exactly the same for OR 3A and OR 3B. Consequently, eq. (5.278) for the probability of horizontal

overlap $HOP(t|V_1, V_2)$ derived in Section 5.5.5.7 for OR 3A is also valid for OR 3B and the same is true for the discussion on the types of navigation error distributions. However, the specific expressions for the nominal relative position components $D_x^{\square}(t)$ and $D_y^{\square}(t)$ between the aircraft do not cover the turn in the departing aircraft's trajectory. Since for OR 3B the risk calculation covers a time period with both aircraft not yet having passed the intersection point, this time period may need to include the departing aircraft's fixed-radius turn. Appendix G to Moek (2015) derived an extension to the model for the case with a turn in the departing aircraft's track.

Ignoring the turn in the departing aircraft's track, it follows that the collision risk model for procedural airspace in the absence of both hazard 1 and hazard 2 is given by

$$CR(t_0, t_1; S_z = VSM) = 2 \times NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) \times P_z^{3B}(h_z(t)) \times \left[\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right] f_1(V_1) f_2(V_2) dt dV_1 dV_2 \quad (5.287)$$

with

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} \approx \pi\lambda_{xy}^2 \int_{\varepsilon_2^A}^{\varepsilon_2^C} \int_{\varepsilon_1^A}^{\varepsilon_1^C} f_1^A(-D_x^{\square}(t) + \varepsilon_2^A \cos\theta - \varepsilon_2^C \sin\theta) f_2^A(\varepsilon_2^A) f_1^C(-D_y^{\square}(t) + \varepsilon_2^A \sin\theta + \varepsilon_2^C \cos\theta) f_2^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.278)$$

and

$$V_{rel} = \sqrt{V_1^2 - 2V_1V_2\cos\theta + V_2^2} \quad (5.279)$$

The quantities $D_x^{\square}(t)$ and $D_y^{\square}(t)$ denote again the nominal relative position components between the aircraft during the time interval $[t_0, t_1]$ over which lateral collision risk exists and their formulae are the same as for OR 3A. See section 5.2 of (Moek, 2015b) for the precise formulae. Apart from the specific formulae for t_0 and t_1 , the collision risk model for OR 3B in eq. (5.287) differs from that for OR 3A in eq. (5.277) only with regard to the probability of vertical overlap $P_z^{3B}(h_z(t))$ as opposed to $P_z^{3A}(h_z(t))$ as a result of the different altitude profiles of the aircraft during the time interval $[t_0, t_1]$ over which the risk is calculated. Notice that, in the same manner as for OR 3A, a conditioning variable $S_z = VSM$ with VSM denoting the applicable Vertical Separation Minimum has been added to the lateral collision risk variable $CR(t_0, t_1)$ in the left-hand side of the model in eq. (5.287).

As set out in Chapter 5 of (Moek, 2015b), the hazard identification and analysis performed in (EUROCONTROL, 2008) applied equally well to both OR 3A and OR 3B.

Thus, the overall OR 3B lateral collision risk in procedural airspace can be expressed as

$$CR(t_0, t_1) = (1 - p_{hazard\ 1} - p_{hazard\ 2}) \times CR(t_0, t_1; S_z = VSM) + p_{hazard\ 1} \times CR(t_0, t_1; S_z = 0) + p_{hazard\ 2} \times CR(t_0, t_1; x_1^{off}, y_1^{off}, \xi_2^{off}, \eta_2^{off}) \quad (5.288)$$

with $CR(t_0, t_1; S_z = VSM)$ given by eq. (5.287) and $CR(t_0, t_1; S_z = 0)$ and $CR(t_0, t_1; x_1^{off}, y_1^{off}, \xi_2^{off}, \eta_2^{off})$ based on eq. (5.287), supplemented with

$$CR(t_0, t_1) = P_{ATC} \left[(1 - p_{hazard\ 1} - p_{hazard\ 2}) \times CR(t_0, t_1; S_z = VSM) + p_{hazard\ 1} \times CR(t_0, t_1; S_z = 0) + p_{hazard\ 2} \times CR(t_0, t_1; x_1^{off}, y_1^{off}, \xi_2^{off}, \eta_2^{off}) \right] \quad (5.289)$$

for radar airspace and P_{ATC} denoting the probability of ATC intervention failure for the OR 3B scenario.

The OR 3A values of the parameters $p_{hazard\ 1}$, $p_{hazard\ 2}$, and P_{ATC} apply also to OR 3B, i.e. $p_{hazard\ 1} = 5.2 \times 10^{-4}$, $p_{hazard\ 2} = 5.2 \times 10^{-4}$, and $P_{ATC} = 3.75 \times 10^{-3}$.

The OR 3A discussion in the previous subsection on the last modelling step concerning the specification of the type of the navigation error probability density functions $f_1^A(\cdot)$, $f_1^C(\cdot)$, $f_2^A(\cdot)$, and $f_2^C(\cdot)$ for the calculation of the probability of horizontal overlap $HOP(t|V_1, V_2)$ in eq. (5.278) is equally applicable to

OR 3B, i.e. the simplest application of the collision risk model of eq. (5.287) would be to a single aircraft pair where the navigation error distributions of the aircraft would be only single, normal or double exponential, distributions and the most general application would be to streams of approaching and departing aircraft with different combinations of five PBN navigation specifications with each along-track and across-track mixture probability density made up of up to five terms as set out in Section 5.5.5.4, i.e.

$$f_1^A(\varepsilon_1^A) = \sum_{i=1}^5 \sum_{j=1}^{n_i} \alpha_i^1 \beta_{ij}^A f_{ij}^A(\varepsilon_1^A) \quad (5.228)$$

$$f_1^C(\varepsilon_1^C) = \sum_{k=1}^5 \sum_{l=1}^{n_k} \alpha_k^1 \beta_{kl}^C f_{kl}^C(\varepsilon_1^C) \quad (5.229)$$

$$f_2^A(\varepsilon_2^A) = \sum_{u=1}^5 \sum_{v=1}^{n_u} \alpha_u^2 \beta_{uv}^A f_{uv}^A(\varepsilon_2^A) \quad (5.230)$$

$$f_2^C(\varepsilon_2^C) = \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_x^2 \beta_{xy}^C f_{xy}^C(\varepsilon_2^C) \quad (5.231)$$

For the latter application, the probability of horizontal overlap would become

$$HOP(t|V_1, V_2) = Prob\{\Delta x(t)^2 + \Delta y(t)^2 \leq \lambda_{xy}^2\} = \sum_{i=1}^5 \sum_{j=1}^{n_i} \sum_{k=1}^5 \sum_{l=1}^{n_k} \sum_{u=1}^5 \sum_{v=1}^{n_u} \sum_{x=1}^5 \sum_{y=1}^{n_x} \alpha_i^1 \beta_{ij}^A \alpha_k^1 \beta_{kl}^C \alpha_u^2 \beta_{uv}^A \alpha_x^2 \beta_{xy}^C HOP(t|V_1, V_2)_{ijkluvxy} \quad (5.282)$$

With

$$HOP(t|V_1, V_2)_{ijkluvxy} = \pi \lambda_{xy}^2 \int_{\varepsilon_2^A}^{\infty} \int_{\varepsilon_2^C}^{\infty} f_{ij}^A(-D_x(t) + \varepsilon_2^A \cos(\theta) - \varepsilon_2^C \sin(\theta)) f_{uv}^A(\varepsilon_2^A) f_{kl}^C(-D_y(t) + \varepsilon_2^A \sin(\theta) + \varepsilon_2^C \cos(\theta)) f_{xy}^C(\varepsilon_2^C) d\varepsilon_2^C d\varepsilon_2^A \quad (5.283)$$

5.5.5.9 Summary of the ERS TF lateral deviation data modelling and sample route spacings

As explained in Section 5.5.5.1, recent performance-based navigation data was made available to the EUROCONTROL ERS TF by three European Air Navigation Service Providers, namely DSNA (Direction des Services de la Navigation Aérienne) from France, LVNL (LuchtVerkeersLeiding Nederland) from the Netherlands, and NATS (National Air Traffic Services) from the UK for the benefit of the PBN route-spacing study for which the collision risk models in Sections 5.5.5.2 – 5.5.5.8 have been developed. The data pertain to the lateral dimension only and were found to be representative of a mixture of Advanced RNP 1, RNAV 1,

and RNP 1 capable aircraft. The data collected pertain to straight route segments as well as turns and have been subdivided into

- Non-speed-dependent lateral deviations (Moek, 2016);
- High-speed lateral deviations (Moek, 2017); and
- Low-speed lateral deviations (Moek, 2017).

The boundary between high-speed and low-speed deviations was set at 350 kts (Moek, 2017). The turn data were subdivided into

- pre-turn, mid-turn, and post-turn data (non-speed-dependent and non-turn-angle-dependent) (Moek, 2016);
- shallow, moderate, and sharp-extended turn-angle data (non-speed-dependent) (Moek, 2016); and
- 45 and 90 degree speed-dependent mid-turn data (Moek, 2017).

Section 2.4.1 of SASP-WG/WHL/14-WP/42 (Moek, 2008) defines the three categories of turn angles as follows:

Type of turn	Range for turn angle α (degrees)
Shallow	$0 < \alpha < 25$
Moderate	$25 \leq \alpha \leq 55$
Sharp-extended	$55 < \alpha \leq 180$

The 45 degree speed-dependent mid-turn data set was obtained by pooling all of the speed-dependent deviation data for turn angles between 30 and 60 degrees inclusive. The 90 degree high-speed mid-turn data set was obtained by pooling all of the high-speed deviation data for turn angles between 77.7 and 103.6 degrees inclusive and the 90 degree low-speed data set was obtained by pooling of all of the low-speed deviation data for turn angles from 90.7 up to and including 91.1 degrees as available in the data.

Analysis of the data suggested that each data set could best be modelled by means of a double double exponential (mixture) probability distribution. Extensive sensitivity analysis was performed to avoid underestimation of the probability of lateral overlap to the maximum extent credible. See (Moek, 2016). The double double exponential densities were parameterized as follows:

$$f_{DDE}(y) = (1 - \alpha) \frac{1}{\sigma_1 \sqrt{2}} e^{-\frac{|y|\sqrt{2}}{\sigma_1}} + \alpha \frac{1}{\sigma_2 \sqrt{2}} e^{-\frac{|y|\sqrt{2}}{\sigma_2}} \quad (5.284)$$

The following five tables shows the results of the modelling of the lateral-deviation data for the combined DSNA, LVNL, and NATS data sets, i.e. model parameter best-estimates and best-estimates of the probability of lateral overlap $P_y(S_y)$ for parallel route segments, straight segments as well as turns, spaced at S_y NM. See references (Moek, 2016) and (Moek, 2017) for full details of the analysis and modelling performed.

Table 5.10: Parameter values of best-estimate DDE model for combined LVNL, NATS, and DSNA **straight-segment** data and corresponding probabilities of lateral overlap $P_y(S_y)$ as a function of parallel route spacing S_y (Refs. (Moek, 2016) and (Moek, 2017))

Parameters			Probability of lateral overlap $P_y(S_y)$					
Non-speed-dependent straight-segment lateral deviations								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.025	0.215	0.050	4.34E-11	6.44E-14	9.53E-17	1.40E-19	2.06E-22	3.02E-25
High-speed straight-segment lateral deviations								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.03	0.22	0.09	1.35E-10	2.41E-13	4.27E-16	7.49E-19	1.31E-21	2.27E-24
Low-speed straight-segment lateral deviations								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.025	0.22	0.018	2.12E-11	3.52E-14	5.84E-17	9.67E-20	1.60E-22	2.65E-25

Table 5.11: Parameter values of best-estimate DDE model for combined LVNL, NATS, and DSNA **non-speed-dependent** and **non-turn-angle-dependent turn-segment** data and corresponding probabilities of lateral overlap $P_y(S_y)$ as a function of parallel route spacing S_y (ICAO, 2014a)

Parameters			Probability of lateral overlap $P_y(S_y)$					
Pre-turn lateral deviations								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.025	0.380	0.006	1.29E-08	3.13E-10	7.62E-12	1.85E-13	4.51E-15	1.10E-16
Mid-turn lateral deviations								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.075	0.320	0.050	1.83E-08	2.30E-10	2.90E-12	3.64E-14	4.56E-16	5.71E-18
Post-turn lateral deviations								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.035	0.322	0.090	3.72E-08	4.97E-10	6.61E-12	8.74E-14	1.15E-15	1.51E-17

Table 5.12: Parameter values of best-estimate DDE model for combined LVNL, NATS, and DSNA **non-speed-dependent shallow, moderate and sharp-extended turn** data and corresponding probabilities of lateral overlap $P_y(S_y)$ as a function of parallel route spacing S_y (ICAO, 2014a) Moek

Turn type	data	Parameters		Probability of lateral overlap $P_y(S_y)$					
Shallow turn angles									
	σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
pre-turn	0.025	0.220	0.0 22	2.64E-11	4.39E-14	7.32E-17	1.22E-19	2.02E-22	3.36E-25
mid-turn	0.050	0.245	0.0 70	6.31E-10	2.12E-12	7.07E-15	2.35E-17	7.77E-20	2.56E-22
post-turn	0.035	0.26	0.1 30	3.36E-09	1.64E-11	7.89E-14	3.76E-16	1.78E-18	8.36E-21
post-turn	0.035	0.28	0.1 30	9.74E-09	6.96E-11	4.92E-13	3.45E-15	2.4E-17	1.66E-19
Moderate turn angles									
	σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
pre-turn	0.025	0.360	0.0 15	1.86E-08	3.72E-10	7.42E-12	1.48E-13	2.95E-15	5.89E-17
mid-turn	0.060	0.390	0.0 30	8.89E-08	2.43E-09	6.62E-11	1.80E-12	4.91E-14	1.34E-15
post-turn	0.050	0.450	0.0 30	3.22E-07	1.42E-08	6.26E-10	2.76E-11	1.22E-12	5.36E-14
Sharp-extended turn angles									
	σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
pre-turn	0.023	0.190	0.0 27	1.85E-12	1.13E-15	6.91E-19	4.21E-22	2.56E-25	1.55E-28
mid-turn	0.085	0.260	0.1 80	5.45E-09	2.71E-11	1.33E-13	6.40E-16	3.06E-18	1.45E-20
post-turn	0.065	0.280	0.1 20	9.02E-09	6.40E-11	4.49E-13	3.13E-15	2.17E-17	1.49E-19

Table 5.13: Parameter values of best-estimate DDE model for combined LVNL, NATS, and DSNA **speed-dependent 45 degree mid-turn-angle** data and corresponding probabilities of lateral overlap $P_y(S_y)$ as a function of parallel route spacing S_y (Moek & Aldis, 2009)

Parameters			Probability of lateral overlap $P_y(S_y)$					
High-speed 45 degree mid-turn angle								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.08	0.35	0.14	1.68E-07	3.27E-09	6.29E-11	1.20E-12	2.28E-14	4.30E-16

Parameters			Probability of lateral overlap $P_y(S_y)$					
Low-speed 45 degree mid-turn angle								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.55	0.37	0.01	1.67E-08	3.69E-10	8.15E-12	1.80E-13	3.97E-15	8.77E-17

Table 5.14: Parameter values of best-estimate DDE model for combined LVNL, NATS, and DSNA **speed-dependent 90 degree mid-turn angle** data and corresponding probabilities of lateral overlap $P_y(S_y)$ as a function of parallel route spacing S_y (Moek & Aldis, 2009)

Parameters			Probability of lateral overlap $P_y(S_y)$					
High-speed 90 degree mid-turn angle								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.150	0.520	0.125	4.83E-06	3.40E-07	2.38E-08	1.67E-09	1.16E-10	8.06E-12
Low-speed 90 degree mid-turn angle								
σ_1 (NM)	σ_2 (NM)	α	$S_y = 3$ (NM)	$S_y = 4$ (NM)	$S_y = 5$ (NM)	$S_y = 6$ (NM)	$S_y = 7$ (NM)	$S_y = 8$ (NM)
0.125	0.280	0.030	2.13E-09	1.40E-11	9.21E-14	6.06E-16	3.98E-18	2.62E-20

(Moek, 2017) presents sample route spacings for a number of route configurations, comprising parallel routes, merging routes, converging routes, as well as crossing routes. Sample route spacings ranging from 3 – 6 NM have been obtained for the parallel-, merging-, and converging-route configurations. For the crossing-route Operational Requirement 3A configuration, sample earliest points after crossing at which the arriving and departing aircraft can continue descent/climb to ensure vertical separation ranged from 1 NM to 2 NM, depending on the crossing angle. For the crossing-route Operational Requirement 3B configuration, sample latest points at which the arriving and departing aircraft must reach their level to ensure vertical separation ranged from 1 NM to 3 NM, depending on the crossing angle. The sample spacings have been documented in a table in Annex 1 to the ERS-TF deliverable (EUROCONTROL, 2016), accompanied by a triple of KEY POINTS concerning the practical application of the sample route spacings derived by collision risk modelling.

6 Vertical Collision Risk Modelling

6.1 Introduction

For the aircraft collision risk modelling by Reich, a number of assumptions were made. Appendix C presented lists of aircraft collision risk modelling assumptions made in a number of studies, in particular the assumptions made by Reich (1966a). It also listed seven *Basic requirements when estimating collision risk* formulated by Reich, the first one of which read *All possible directions from which one aircraft can come into collision with another should be accounted for*. These directions are the same for aircraft flying at adjacent flight levels (of the same route) as for aircraft flying on adjacent parallel routes (at the same altitude), although the values of the relative speeds in the vertical and lateral dimensions will obviously be different when vertical separation is lost or lateral separation is lost.

As set out in Section 5.2.1, Part I of the Reich paper derived an aircraft collision risk model in terms of a generic intended separation $[AB]$ whereas Part II dealt with the application of the generic model to lateral separation between adjacent parallel routes and vertical separation between adjacent flight levels. The lateral separation part only was examined in Section 5.2.2 and concluded with lateral collision risk models for same-direction and opposite-direction traffic on adjacent parallel routes given by eqs. (5.26) and (5.27), representing eqs. (13) and (14) of Part II of the Reich paper. Eqs. (6.1) and (6.2) below present the vertical collision risk models given by Reich in his eqs. (15) and (16), namely

$$\text{Vertical risk (same)} = \frac{T_z(\text{same})}{S_x(\text{std})} \left[\frac{\overline{\Delta V}}{2} P_y(0)P_z(\text{std}) + \lambda_x N_y(0)P_z(\text{std}) + \lambda_x P_y(0)N_z(\text{std}) \right] \quad (6.1)$$

and

$$\text{Vertical risk (opp)} = \frac{T_z(\text{opp})}{S_x(\text{std})} \left[\overline{V} P_y(0)P_z(\text{std}) + \lambda_x N_y(0)P_z(\text{std}) + \lambda_x P_y(0)N_z(\text{std}) \right] \quad (6.2)$$

Notice that the two models are expressed in terms of vertical proximities $T_z(\text{same})$ and $T_z(\text{opp})$, where $T_z(\text{same})$ equals the aggregate of times spent by all aircraft pairs in the configuration of Figure 6.1(a) and $T_z(\text{opp})$ equals the aggregate of times spent by all aircraft pairs in the configuration of Figure 6.1(b).

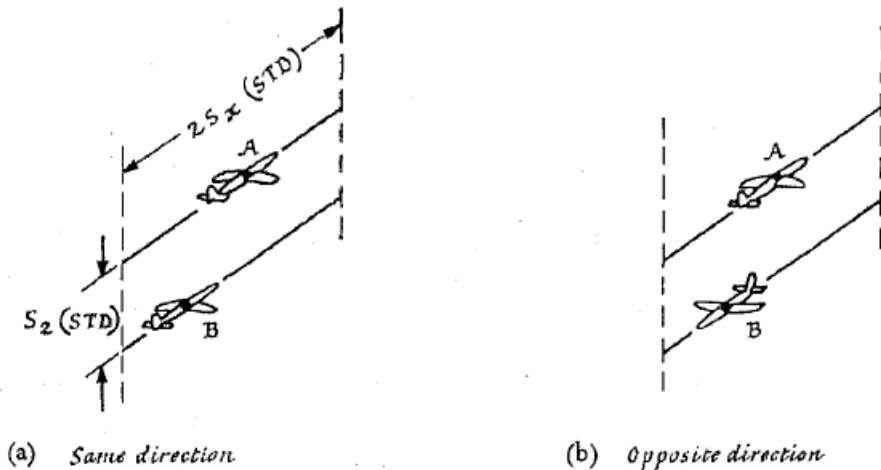


Figure 6.1: Proximate aircraft pairs at adjacent flight levels of the same route in same direction (a) and opposite direction (b)

The concept of lateral proximity was replaced by the North Atlantic Systems Planning Group (NAT SPG) at its 4th meeting (NAT SPG/4, 1968) by lateral occupancy as described in Section 5.3.1 by eqs. (5.33) and (5.34). The same can be done for the vertical collision risk model, i.e.

$$E_z(\text{same}) = \frac{2T_z(\text{same})}{H} \quad (6.3)$$

$$E_z(\text{opp}) = \frac{2T_z(\text{opp})}{H} \quad (6.4)$$

where $E_z(\text{same})$ and $E_z(\text{opp})$ denote same-direction and opposite-direction vertical occupancy respectively and H is the total flying time (in aircraft hours) during the period of time over which the vertical collision risk is to be estimated and the vertical collision risk models in eqs. (6.1) and (6.2) can be expressed as

$$N_{az}(\text{same}) = \frac{E_z(\text{same})}{S_x(\text{std})} \left[\frac{\overline{\Delta V}}{2} P_y(0) P_z(\text{std}) + \lambda_x N_y(0) P_z(\text{std}) + \lambda_x P_y(0) N_z(\text{std}) \right] \quad (6.5)$$

and

$$N_{az}(\text{opp}) = \frac{E_z(\text{opp})}{S_x(\text{std})} \left[\overline{V} P_y(0) P_z(\text{std}) + \lambda_x N_y(0) P_z(\text{std}) + \lambda_x P_y(0) N_z(\text{std}) \right] \quad (6.6)$$

Notice a simultaneous change to the left-hand side variables from expected numbers of collisions during the period of time of interest to expected numbers of accidents per flight hour, where each collision is counted as two accidents through the factor of 2 in the numerators of the two occupancy parameters.

Using eqs. (5.14) – (5.16) for the relationships between the numbers of times an aircraft pair enters into overlap in each dimension and the probability of overlap in that dimension,

$$N_x \approx P_x \times \frac{\overline{|\dot{x}|}}{2\lambda_x} \quad (5.14)$$

$$N_y \approx P_y \times \frac{\overline{|\dot{y}|}}{2\lambda_y} \quad (5.15)$$

$$N_z \approx P_z \times \frac{\overline{|\dot{z}|}}{2\lambda_z} \quad (5.16)$$

with $\overline{|\dot{x}|} = \overline{\Delta V}/2$ for same-direction traffic and $\overline{|\dot{x}|} = 2\overline{V}$ for opposite-direction traffic, the two vertical collision risk models can be expressed as

$$N_{az}(\text{same}) = E_z(\text{same}) \frac{\lambda_x}{S_x(\text{std})} P_y(0) P_z(\text{std}) \left[\frac{\overline{\Delta V}}{2\lambda_x} + \frac{\overline{|\dot{y}|}}{2\lambda_y} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right] \quad (6.7)$$

and

$$N_{az}(\text{opp}) = E_z(\text{opp}) \frac{\lambda_x}{S_x(\text{std})} P_y(0) P_z(\text{std}) \left[\frac{2\overline{V}}{2\lambda_x} + \frac{\overline{|\dot{y}|}}{2\lambda_y} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right] \quad (6.8)$$

The key parameter of the two vertical collision risk models above is the probability of vertical overlap, $P_z(std)$, resulting from the loss of vertical separation due to technical height-keeping deviations of two aircraft in a pair. Technical height deviations of aircraft are usually denoted Total Vertical Error (TVE) where TVE is made up of two components, Flight Technical Error (FTE) and Altimetry System Error (ASE) and FTE is often approximated by Assigned Altitude Deviation (AAD). See Section 6.5.2.2.1 for the precise definitions of TVE, FTE, ASE, and AAD.

Following the presentation of the Reich/ NAT SPG lateral collision risk model in Chapter 5, Chapter 5 then proceeded with the presentation of collision risk models for a variety of lateral separation standards/minima dependent on different communication, navigation, and surveillance performance requirements because different airspaces may have different performance requirements. Vertical separation, however, is different in that there are only two vertical separation minima/standards, namely 1000 ft and 2000 ft. The split is related to the accuracy of aircraft height-keeping equipment based on a single, world-wide technology, viz. barometric pressure levels.

As explained in the *Manual on Implementation of a 300 m (1 000 ft) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive* (ICAO, 2012b)⁴⁷, it was recognized in the late 1950s that, as a result of the reduction in pressure-sensing accuracy of barometric altimeters with increasing altitude, there was a need above a certain flight level (FL) to increase the prescribed vertical separation minimum (VSM) of 300 m (1000 ft). In 1960, an increased VSM of 600 m (2000 ft) was established for use between aircraft operating above FL290 except where, on the basis of regional air navigation agreement, a lower flight level was prescribed for the increase. The selection of FL290 as the vertical limit for the 300 m (1000 ft) VSM was not so much an empirically-based decision but rather a function of the operational ceiling of the aircraft at that time. In 1966, this changeover level was established at FL290 on a global basis. At the same time, it was considered that the application of a reduced VSM above FL290, on a regional basis and in carefully prescribed circumstances, was a distinct possibility in the not too distant future. Accordingly, ICAO provisions stated that such a reduced VSM could be applied under specified conditions within designated portions of airspace on the basis of regional air navigation agreement.

The reduced vertical separation minimum of 1000 ft between FL290 and FL410 inclusive subsequently developed has become known as RVSM and any airspace where this minimum is utilized is referred to as RVSM airspace. Figure 6.2 illustrates the increase in the number of flight levels available on a bi-directional route in RVSM airspace.

⁴⁷ From here on referred to as the RVSM Manual.

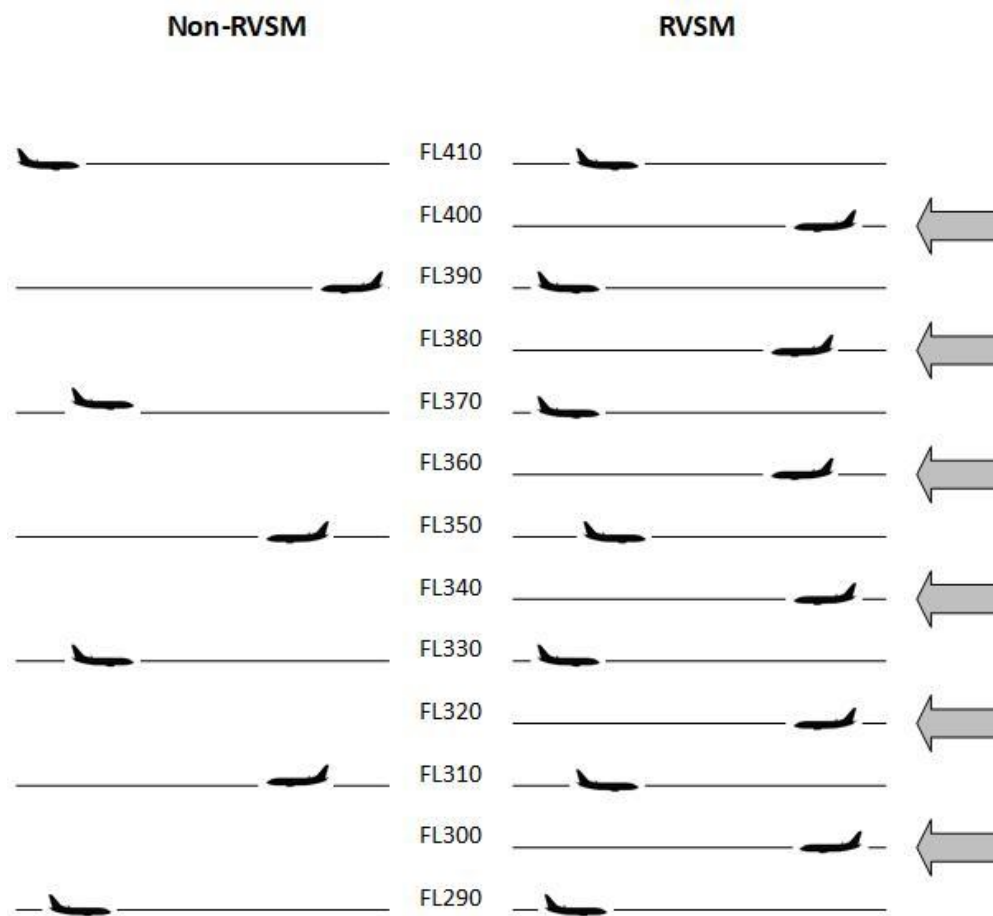


Figure 6.2: Additional flight levels available on a bi-directional route under RVSM

Section 6.2 provides background information on the development of RVSM by the ICAO Review of the General Concept of Separation Panel (RGCSP) over the period of time from 1982 up to the Panel's sixth meeting in 1988 (RGCSP/6) (ICAO, 1988b). The above mentioned RVSM Manual was subsequently developed by the RGCSP with the basic purpose of providing Regional Planning Groups (RPGs) with a basis for the development of documents, procedures and programmes to enable the introduction of RVSM within their regions in accordance with the criteria and requirements developed by ICAO. The RVSM Manual also provides guidance to State aviation authorities on those measures necessary to ensure that the criteria and requirements are met within their area of responsibility, provides background information for operators to assist in the development of operating manuals and flight crew procedures, and a basic reference document from which the MASPS⁴⁸ for operations in RVSM airspace can be developed. Three editions of the RVSM Manual have been published over time, namely in 1992, 2002, and 2012, where the later editions took account of the knowledge and experience gained with the implementation, Region by Region, and the subsequent continued use of RVSM to date.

Before considering the modelling of vertical collision risk in RVSM airspace for a number of ICAO Regions in support of their implementation and continued safe use of RVSM, the Strategic Lateral Offset Procedure (SLOP) developed by the ICAO Separation and Airspace Safety Panel (SASP) will be briefly discussed in Section 6.3.

⁴⁸ Minimum Aircraft System Performance Specification.

SLOP was developed to counteract the adverse effect of very accurate lateral navigation on the vertical collision risk due to loss of vertical separation.

The first ICAO Region to implement RVSM was the North Atlantic (NAT) Region and Section 6.4 reviews the history of vertical separation and collision risk modelling in this region where the prospect of reducing the vertical separation standard of 2000 ft above FL290 was considered a number of times before the global effort coordinated by the RGCSP commenced. Collision risk models for operational risk in RVSM airspace were first developed by the North Atlantic Mathematicians Working Group (NAT MWG) (NAT, 1996).

Section 6.5 provides details of vertical collision risk modelling for the annual RVSM safety assessments for the Africa and Indian Ocean (AFI) Region of ICAO that the authors of this document have conducted from the pre-implementation safety assessment phase up to the latest post-implementation safety assessment based on data on RVSM operations in the region for 2019 (Moek & Smeltink, 2005; Smeltink et al., 2021). Unlike Chapter 5 and Sections 6.2 - 6.4, which are focused on the form of the pertinent collision risk models rather than the estimation of the models' parameters, Section 6.5 will also provide details of the estimation of all the collision risk model parameters, particularly the two main parameters of the vertical collision risk model(s) for the AFI Region, namely the probability of vertical overlap and vertical passing frequency (occupancy) for aircraft at adjacent flight levels.

Finally, Section 6.6 discusses some vertical collision risk models utilized in ICAO Regions other than the NAT and AFI that the authors know about.

6.2 Development of RVSM by the ICAO RGCSP

6.2.1 Background and implementation history

The background information in the following nine paragraphs has been taken from the Second Edition of the RVSM Manual (ICAO, 2012b)⁴⁹.

It has long been recognized that any decision concerning the feasibility of reducing the vertical separation minima above FL290 could not be based upon operational judgement alone, but would need to be supported by a rigorous assessment of the risk associated with such a reduction of separation. The lack of a clear-cut method of achieving such an assessment was the primary cause of the failure of various attempts to determine the feasibility of a reduced VSM.

In the mid-1970s, the series of world fuel shortages and the resultant rapid escalation of fuel costs, allied to the growing demand for a more efficient use of the available airspace, emphasized the need for a detailed appraisal of the proposal to reduce the vertical separation minima above FL290. Thus, at its fourth meeting (in 1980), the ICAO Review of the General Concept of Separation Panel (RGCSP) concluded that, despite the cost and time involved, the potential benefits of reducing the vertical separation minima above FL290 to 300 m (1000 ft) were so great that States should be encouraged to conduct the necessary major evaluations.

⁴⁹ This text is identical to that in the Third Edition and differs slightly from that in the First Edition of the RVSM Manual in the eighth and ninth paragraphs.

In 1982, coordinated by the RGCSP, States initiated programmes to study comprehensively the question of reducing the vertical separation minima above FL290. Studies were carried out by Canada, Japan, Member States of EUROCONTROL (France, Federal Republic of Germany, Kingdom of the Netherlands, and United Kingdom), Union of Soviet Socialist Republics, and United States, and in December 1988 the results were considered by the RGCSP at its sixth meeting (RGCSP/6).

These studies employed quantitative methods of risk assessment to support operational decisions concerning the feasibility of reducing the vertical separation minima. The risk assessment consisted of two elements: first, risk estimation, which concerns the development and use of methods and techniques with which the actual level of risk of an activity can be estimated; and second, risk evaluation, which concerns the level of risk considered to be the maximum tolerable value for a safe system. The level of risk that is deemed acceptable was termed the target level of safety (TLS).

The process for estimating risk in the vertical plane using the collision risk model (CRM) assumed that collisions result solely from vertical navigation errors of aircraft to which procedural separation had been correctly applied. The TLS was derived to apply to this source of collision risk alone; it does not address risk from other sources, such as height deviations due to turbulence, responses to airborne collision avoidance system alerts, emergency descents and operational errors in the issuance of, or compliance with, air traffic control (ATC) instructions.

The recognition of several sources of risk in addition to vertical navigation errors played a role in the choice of TLS values made by various States during their studies. Several approaches were followed in order to establish an appropriate range of values, including all en-route mid-air collisions and the implicit period between collisions, and adjusting the TLS until the period of time became acceptable. Nevertheless, the primary approach, and the traditional manner, was to use historical data from global sources, predicted forward to approximately the year 2000 to provide safety improvement and to apportion resultant risk budgets to derive the vertical collision risk element.

The derived values for the TLS ranged between 1×10^{-8} and 1×10^{-9} fatal accidents per aircraft flight hour. On the basis of these figures, it was agreed that an assessment TLS of 2.5×10^{-9} fatal accidents per aircraft flight hour would be used to assess the technical feasibility of a 300 m (1000 ft) vertical separation minimum above FL290 and also to develop aircraft height-keeping capability requirements for operating in a 300 m (1000 ft) vertical separation minimum.

Using the assessment TLS of 2.5×10^{-9} fatal accidents per aircraft flight hour, RGCSP/6 concluded that a 300 m (1000 ft) VSM above FL290 was technically feasible. This technical feasibility refers to the fundamental capability of aircraft height-keeping systems, which could be built, maintained and operated in such a manner that the expected, or typical, performance is consistent with safe implementation and use of a 300 m (1 000 ft) vertical separation minimum above FL290. In reaching this conclusion on technical feasibility, the panel found it necessary to establish:

- a) airworthiness performance requirements embodied in a comprehensive minimum aircraft system performance specification (MASPS) for all aircraft utilizing the reduced separation;
- b) new operational procedures; and
- c) a comprehensive means of monitoring the safe operation of the system.⁵⁰

⁵⁰ The First Edition of the RVSM Manual contained an additional paragraph following bullets a) – c): For the shorter term, the reduced VSM was considered to be feasible for implementation, on a regional basis, during the interim period leading to an agreed date on which the global standards could be introduced. This interim regional application should be based on a TLS of not more than 5×10^{-9} fatal accidents per aircraft flight hour.

It is important to emphasize that the assessment TLS did not address all causes of risk of collision in the vertical plane. In the first edition of this guidance material, regional planning authorities were advised of the necessity to institute measures to ensure that the risks associated with operational errors and emergency actions did not increase in the 300 m (1 000 ft) vertical separation minimum environment. In the North Atlantic (NAT) Region, which on 27 March 1997 became the first ICAO region to implement the reduced vertical separation minimum (RVSM), it was agreed that a more formal approach was necessary to assessing all causes of risk in the vertical plane. On the basis of the experience gained in the monitoring and analysis of the causes of operational errors in NAT minimum navigation performance specification (MNPS) airspace, the NAT Systems Planning Group (NAT SPG) agreed that limiting the risk of collision due to the loss of planned vertical separation as a consequence of such events should receive attention at least equal to that devoted to limiting the effects of technical errors (errors of aircraft height-keeping systems). Therefore, in addition to the TLS for technical errors, i.e. 2.5×10^{-9} fatal accidents per aircraft flight hour, an overall TLS of 5×10^{-9} fatal accidents per aircraft flight hour resulting from a loss of vertical separation due to any cause was adopted.

Figure 6.3 shows the history of the implementation of RVSM worldwide.⁵¹ The NAT Region was selected for initial implementation because of the relatively uniform flow of traffic on basically an east-west orientation with few altitude changes by aircraft being flown in the airspace (Flight Safety Foundation, 2004). This implementation was conducted in three phases, namely Phase I for FL330 to FL370 starting on 27 March 1997, Phase II for FL310 to FL390 starting on 8 October 1998, and Phase III for FL290 to FL410 starting on 24 January 2002. RVSM was also implemented on this last date in the airspace of 41 States in Europe under the lead of EUROCONTROL and in the Europe/South America (EUR/SAM) Corridor.

Following Phase II of the NAT RVSM implementation, implementation of RVSM over most of the Pacific Region took place in February 2000. It is noted in (Flight Safety Foundation, 2004) that unlike other ICAO Regions, non-RVSM-approved aircraft were permitted to be flown at FL410 in the Pacific Region. A 2-phase implementation of RVSM was followed for the West Atlantic Route System (WATRS) with Phase I starting in October 2000 and Phase II starting on 1 November 2001. Australia implemented domestic RVSM in November 2001. Implementation in the Western Pacific Region and over the South China Sea took place in February 2002.

Further implementation of RVSM took place as follows:

- North Canada – April 2002;
- Middle East – November 2003;
- Asia/Europe (South of Himalayas) – November 2003;
- South of Canada – January 2005;
- Domestic US – January 2005;
- Caribbean/ South American (CAR/SAM) Regions – January 2005;
- Africa and Indian Ocean (AFI) Region – September 2008.

The Russian Federation was the last to implement RVSM on 17 November 2011. The People's Republic of China implemented *metric* RVSM on 21 November 2007.

⁵¹ Obtained from the FAA website: https://www.faa.gov/air_traffic/separation_standards/rvsm

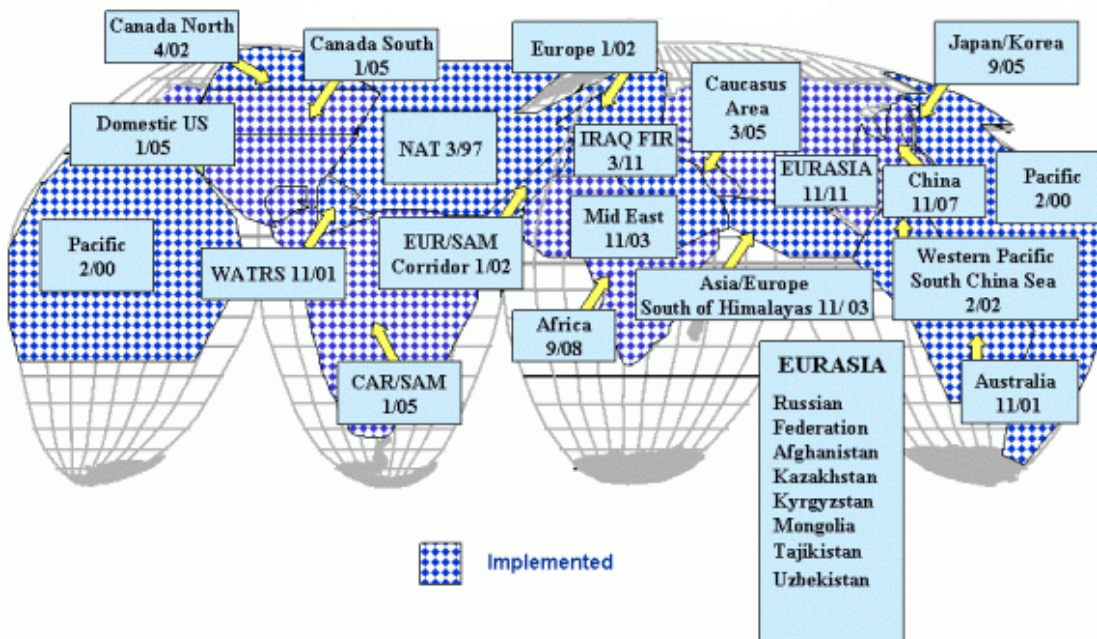


Figure 6.3: RVSM implementation dates per region. (Reproduced from the FAA website: https://www.faa.gov/air_traffic/separation_standards/rvsm)

6.2.2 RVSM collision risk modelling presented at RGCSF/6

As described in the previous subsection, the RGCSF, using the assessment TLS of 2.5×10^{-9} fatal accidents per aircraft flight hour, concluded at its 6th meeting, RGCSF/6, that a 300 m (1000 ft) VSM above FL290 was technically feasible (ICAO, 1988b). This technical feasibility refers to the fundamental capability of aircraft height-keeping systems, which could be built, maintained and operated in such a manner that the expected, or typical, performance is consistent with safe implementation and use of a 300 m (1000 ft) VSM above FL290. The report of RGCSF/6 comprises two volumes with Volume 1 containing the history and report of the meeting on all of its agenda items, except for Annexes A to E to the Report on the feasibility of RVSM and Volume 2 containing those Annexes. The Annexes provide detailed information concerning studies on vertical separation above FL290 conducted by four EUROCONTROL Member States (France, Federal republic of Germany, Kingdom of the Netherlands, and the United Kingdom), Canada, Japan, Union of Soviet Socialist Republics, and the United States.

This subsection lists the vertical collision risk models used in the Annexes in support of RGCSF's assessment of the technical feasibility of RVSM based on data of the height-keeping performance of the aircraft populations operating in the airspaces examined in the respective Annexes. As before, emphasis is laid on the form of the pertinent collision risk models rather than on the assignment or estimation of the values of the collision risk model parameters. For the latter, as well as for the data utilized, the reader is referred to Volume 2 of the RGCSF/6 report. It should be emphasized that technical vertical collision risk was modelled only. Models for operational/total vertical collision risk will be presented in Sections 6.4.3.2 and 6.5.3.

Annex A

Annex A in Volume 2 of RGCSF/6 report documents the European studies of RVSM and gives vertical collision risk models for two airway structures in its Chapter 5, namely for a single airway and for two crossing airways. For both airway structures, two equivalent formulations of the collision risk model are given where the

difference between the formulations concerns the way in which certain parameters (relating to occupancy or aircraft passing frequency) are grouped. The passing frequency formulation is more convenient as a description of continental European airspace and the occupancy formulation is more convenient for North Atlantic airspace. It was noted in the Annex that for more complicated airway structures comprised of several parallel and crossing airways, a new model may be constructed using the models for the two basic airway structures.

Collision risk model for a single airway, occupancy formulation

$$N_{az} = P_z(\text{std})P_y(0)\frac{\lambda_x}{S_x}\left[E_z(\text{same})\left(\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right) + E_z(\text{opp})\left(\frac{\overline{v}}{\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right)\right] \quad (6.9)$$

Collision risk model for a single airway, passing frequency formulation

$$N_{az} = P_z(\text{std})P_y(0)\left[N_x(\text{same})\left(1 + \frac{2\lambda_x}{|\overline{\Delta V}|}\left(\frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right)\right) + N_x(\text{opp})\left(1 + \frac{\lambda_x}{\overline{v}}\left(\frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right)\right)\right] \quad (6.10)$$

Collision risk model for two crossing airways, occupancy formulation

$$N_{az} = P_z(\text{std})E_z(\text{cross})\left(\frac{2V_{rel}}{\pi\lambda_{xy}} + \frac{|\overline{z}|}{2\lambda_z}\right) \quad (6.11)$$

Collision risk model for two crossing airways, passing frequency formulation

$$N_{az} = P_z(\text{std})N_{xy}(\text{cross})\left(1 + \frac{\pi\lambda_{xy}}{2\lambda_z}\frac{|\overline{z}|}{2V_{rel}}\right) \quad (6.12)$$

Notice that for the single-airway case, the collision risk models for same-direction and opposite-direction traffic have been combined into a single overall model. Notice also that for the single-airway occupancy formulation the formulae for the two component models are exactly those for the vertical Reich model (in occupancy form) in eqs. (6.7) and (6.8).

Table 6.1 lists the parameters featuring in eqs. (6.9) – (6.12) and their definitions.

Table 6.1: Definition of parameters of the vertical collision risk models of eqs. (6.9) – (6.12)

Parameter	Definition
N_{az}	expected number of aircraft accidents per aircraft flight hour in the system due to failure of vertical separation
std	vertical separation minimum/standard (1000 ft)
$P_z(\text{std})$	probability of vertical overlap
$P_y(0)$	probability of lateral overlap
$ \overline{\Delta V} $	mean absolute relative velocity between aircraft on same direction routes
$\overline{v}$	mean velocity
$ \overline{y} $	mean absolute relative lateral velocity between aircraft on the same route
$ \overline{z} $	mean absolute relative vertical velocity between aircraft on either the same or crossing routes
λ_x	mean length of aircraft

Parameter	Definition
λ_y	mean width of aircraft
λ_z	mean height of aircraft
$E_z(\text{same})$	same-direction occupancy
$E_z(\text{opp})$	opposite-direction occupancy
$E_z(\text{cross})$	probability of plan overlap of circles representing horizontal cross sections of aircraft on crossing airways
S_x	along-track criterion of proximity
$N_x(\text{same})$	expected number of longitudinal overlaps (passing events) experienced by an average aircraft per aircraft flight hour, for same direction traffic on adjacent flight levels
$N_x(\text{opp})$	expected number of longitudinal overlaps (passing events) experienced by an average aircraft per aircraft flight hour, for opposite direction traffic on adjacent flight levels
$N_{xy}(\text{cross})$	The expected number of plan overlaps at crossings experienced by an average aircraft per aircraft flight hour

It follows from eqs. (6.9) – (6.12) that the relationships between the occupancy and passing frequency parameters are given by

$$N_x(\text{same}) = \frac{\lambda_x}{S_x} E_z(\text{same}) \frac{|\Delta V|}{2\lambda_x} \quad (6.13)$$

$$N_x(\text{opp}) = \frac{\lambda_x}{S_x} E_z(\text{opp}) \frac{2V}{2\lambda_x} \quad (6.14)$$

$$N_{xy}(\text{cross}) = E_z(\text{cross}) \frac{2V_{rel}}{\pi\lambda_{xy}} = E_z(\text{cross}) \frac{2V_{rel}}{(\pi/2)\lambda_{xy}} \quad (6.15)$$

Eqs. (6.13) and (6.14) are, apart from the factor of 2 in $E_z(\text{same})$ and $E_z(\text{opp})$, specific cases of eq. (5.14), for same-direction and opposite-direction traffic respectively, for the relationship between the number of times per flight hour that aircraft enter into longitudinal overlap and the probability of longitudinal overlap since occupancy (being twice the probability of the centres of two aircraft being within the proximity distance S_x) scaled by λ_x/S_x equals twice the probability of the centres of two aircraft being within a distance of the aircraft length λ_x , i.e. the aircraft being in longitudinal overlap. The factor λ_x/S_x is missing in eq. (6.15) because both the crossing-airway occupancy $E_z(\text{cross})$ and the crossing-airway passing frequency $N_{xy}(\text{cross})$ were defined in Table 6.1 in terms of plan overlap. In practice, the estimation of crossing-airway occupancy $E_z(\text{cross})$ would also use a proximity distance S_x and a scale factor λ_x/S_x to obtain the probability of horizontal overlap $P_{xy}(\text{cross})$ and hence the number of horizontal overlaps per flight hour $N_{xy}(\text{cross})$.

The main, common, parameter of the four vertical collision risk models above is the probability of vertical overlap $P_z(\text{std})$ with $\text{std} = 1000$ ft. It was estimated for two samples of aircraft height keeping data, referred to as the *All sites* sample and the *North Atlantic* sample respectively. The data modelled comprised single-aircraft as well as paired-aircraft⁵² total vertical error (TVE) data. The *All sites* height-keeping data sample

⁵² Paired aircraft data were used to eliminate the effect of biases, if any, in the estimates of the heights of the aircraft's assigned flight levels. Pairing individual aircraft measurements taken at different points in time and locations puts, in principle, constraints on the maximum differences in time and position of the measurements to be paired.

was modelled by a generalized Laplace double exponential (GLDE) mixture distribution with probability density

$$f_{GLDE}(z) = (1 - \alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)} \exp\left(-\left|\frac{z-\mu}{a_1}\right|^{\frac{1}{b_1}}\right) + \alpha \frac{1}{2a_2} \exp\left(-\left|\frac{z-\mu}{a_2}\right|\right) \quad (6.16)$$

resulting in an estimate of the probability of vertical overlap of $P_z(std) = 2.03 \times 10^{-6}$. The *North Atlantic* height-keeping data sample was modelled by a normal double exponential mixture distribution with probability density

$$f(z) = \frac{(1-\alpha)}{\sigma\sqrt{2\pi}} \exp\left(-\frac{z^2}{2\sigma^2}\right) + \frac{\alpha}{2\lambda} \exp\left(-\frac{|z|}{\lambda}\right) \quad (6.17)$$

which resulted in an estimate of the probability of vertical overlap of $P_z(std) = 3.22 \times 10^{-7}$. The smaller estimate for the *North Atlantic* sample was believed to be caused by its aircraft population meeting specially certificated performance requirements and carrying a higher than average level of altimetry equipment. See Annex A in Volume 2 of the RGCSP/6 report (ICAO, 1988b) for further details of the height-keeping data and their modelling.

Chapter 7 of Annex A in Volume 2 of the RGCSP/6 report deals with the development of system performance requirements for RVSM as referred to in Section 6.2.1. The process of deriving such requirements started-off with deriving a maximum permissible value for the probability of vertical overlap by using the vertical collision risk model, in combination with the target level of safety, in a reverse manner. See Section 6.2.3 for further details.

Annex B

Annex B in Volume 2 of the RGCSP/6 report documents the United States studies on RVSM and refers to vertical collision risk on one or more single routes as well as on crossing routes. However, the vertical collision model for the continental United States applied to a system structure of single routes only and was given in Chapter 5 of Annex B by

$$N_{az} = 10^9 P_z(1,000) P_y(0) \left[N_x(\text{same}) \left(1 + \frac{\lambda_x \overline{|y|}}{\lambda_y \overline{|\Delta V|}} + \frac{\lambda_x \overline{|z|}}{\lambda_y \overline{|\Delta V|}} \right) + N_x(\text{opp}) \left(1 + \frac{\lambda_x \overline{|y|}}{\lambda_y \overline{2V}} + \frac{\lambda_x \overline{|z|}}{\lambda_z \overline{2V}} \right) \right] \quad (6.18)$$

Table 6.2 lists the parameters featuring in eq. (6.18) and their definitions. Apart from a 1-billion-flying-hour factor up front of the right side of eq. (6.18), and hence a different definition of the left-side variable N_{az} , eq. (6.18) is the same as the single airway passing frequency formulation of the vertical collision risk model in eq. (6.10) used in the European study of RVSM in Annex A of Volume 2 of the RGCSP/6 report.

Table 6.2: Definition of parameters of the vertical collision risk models of eq. (6.18)

Parameter	Definition
N_{az}	expected number of aircraft collisions/accidents ⁵³ per 1 billion flying hours due to failure of vertical separation

⁵³ Eq. (6.18) has been copied from Equation 5-8 in Annex B in Volume 2 of 2 of the RGCSP/6 report (ICAO, 1988b). It is stated in the sentence preceding Equation 5-8 that this equation for the collision risk N_{az} was obtained from Equation 5-7 for the collision rate CR_{az} by multiplying that equation by 1 billion flying hours and substituting passing frequency terms for the two probabilities of longitudinal overlap for same-direction and opposite-direction traffic. It is not clear whether the conversion from collisions to accidents, i.e. multiplication by a factor of 2, was carried out, although the unit specified for N_{az} in Table 5-9 of Annex B in Volume 2 of 2 of the RGCSP/6 report (ICAO, 1988b) is accidents/billion hours.

Parameter	Definition
$P_z(1,000)$	proportion of time that a typical aircraft pair, with 1,000-foot VSM, spends in vertical overlap
$P_y(0)$	proportion of time that a pair of aircraft assigned to the same route at adjacent flight levels with nominal 1,000-foot vertical spacing are within cross-route distance of $2\lambda_y$ nautical miles (overlap laterally)
$ \overline{\Delta V} $	average relative along-route speed of a pair of aircraft assigned to the same route at adjacent flight levels spaced nominally by 1,000-feet travelling in the same direction as they overlap longitudinally
$\overline{V}$	average along-route speed of aircraft in the system
$ \overline{y} $	average relative cross-route speed of a pair of aircraft assigned to the same route at adjacent flight levels spaced nominally by 1,000-feet as they overlap laterally
$ \overline{z} $	average relative vertical speed of a pair of aircraft assigned to the same route at adjacent flight levels spaced nominally by 1,000-feet as they overlap vertically
λ_x	metallic length of a typical aircraft
λ_y	wingspan of a typical aircraft
λ_z	height of simplified aircraft shape
$N_x(\text{same})$	the number of aircraft in longitudinal overlap while on the same route traveling in the same direction at adjacent flight levels divided by the total number of aircraft hours on the route
$N_x(\text{opp})$	the number of aircraft in longitudinal overlap while on the same route traveling in opposite directions at adjacent flight levels divided by the total number of aircraft hours on the route

The main parameter of the vertical collision risk model of eq. (6.18) is again the probability of vertical overlap $P_z(1,000)$. For the reasons explained in Annex B of Volume 2 of the RGCSP/6 report (ICAO, 1988b), this was estimated by the *components approach*, see Section 6.5.2.2.1, i.e. single aircraft Assigned Altitude Deviation (AAD) and Altimetry System Error (ASE) data were separately modelled by analytical probability distributions and the resulting component distributions convoluted to obtain a single aircraft TVE distribution. This TVE distribution with probability density $f_{TVE}(z)$, say, was then used to obtain an estimate of $P_z(1,000)$ by means of self-convolution, i.e. eq. (4.18) with $f_A(z) = f_B(z) = f_{TVE}(z)$.

The AAD and ASE data were both modelled by means of mixture power-exponential probability densities given by

$$f(z) = \sum_{i=1}^N \alpha_i f_i(\Phi_i, \beta_i, \mu_i, z), \quad -\infty < z < \infty \quad (6.19)$$

where

$$f(\Phi, \beta, \mu, z) = \frac{1}{\Phi \Gamma(\delta) 2^\delta} \exp\left(-\frac{1}{2} \left(\frac{|z-\mu|}{\Phi}\right)^{2/(1+\beta)}\right) \quad (6.20)$$

With $\delta = 1 + \frac{1+\beta}{2}$ and $\Gamma(\delta)$ is the gamma function defined by (cf. eq. (4.28))

$$\Gamma(\delta) = \int_0^\infty t^{\delta-1} e^{-t} dt \quad (6.21)$$

In eq. (6.19), the α_i , $0 \leq \alpha_i \leq 1$, are mixture parameters summing to 1; Φ_i , $0 < \Phi_i < \infty$, are spread parameters; β_i , $-1 < \beta_i \leq 1.5$ are shape parameters; and μ_i , $-\infty < \mu_i < \infty$ are location parameters. Notice that the variable δ is not an independent parameter but just a function of the β parameter. The argument of the exponential function on the right side of eq. (6.20) can be slightly rearranged to obtain the following form for the power-exponential probability density $f(\Phi, \beta, \mu, z)$,

$$f(\Phi, \beta, \mu, z) = \frac{1}{\Phi \Gamma(\delta) 2^\delta} \exp \left(- \left(\frac{|z - \mu|}{2^{(1+\beta)/2} \Phi} \right)^{2/(1+\beta)} \right) \quad (6.22)$$

Eq. (6.22) for the power-exponential probability density may be compared with the generalized Laplace probability density defined by eq. (4.27), i.e.

$$f(x) = \frac{1}{2ab\Gamma(b)} \exp \left(- \left| \frac{x - \mu}{a} \right|^{\frac{1}{b}} \right) \quad (4.27)$$

It can be seen that power-exponential and generalized Laplace probability distributions constitute the same family of probability distributions with different parameterizations, related to each other by

$$b = \frac{1+\beta}{2} \quad (6.23)$$

and

$$a = 2^{(1+\beta)/2} \Phi \quad (6.24)$$

Using the properties of the gamma function, it follows that the normalizing factors are equal, as required, i.e.

$$2ab\Gamma(b) = \Phi \Gamma(\delta) 2^\delta \quad (6.25)$$

The AAD data sample was modelled by a mixture of a power-exponential core density and a double exponential tail density (Equation 5-10 of Annex B of Volume 2 of), i.e.

$$f_{AAD}(z) = (1 - \alpha) \frac{1}{\Phi_1 \Gamma(\delta_1) 2^{\delta_1}} \exp \left(- \frac{1}{2} \left(\frac{|z|}{\Phi_1} \right)^{2/(1+\beta_1)} \right) + \alpha \frac{1}{2\Phi_2} \exp \left(- \frac{1}{2} \left| \frac{z}{\Phi_2} \right| \right) \quad (6.27)$$

The ASE data sample was modelled by a mixture of 100 individual normal densities for 100 aircraft types or series-types and 3 mixed normal densities (with two terms each) for 3 more aircraft types or series-types. The AAD and ASE component densities were numerically convoluted to obtain a (numerical) TVE probability density, which was subsequently used to obtain an estimate of the probability of vertical overlap of $P_z(1,000) = 3.6 \times 10^{-6}$.

Chapter 6 of Annex B in Volume 2 of the RGCSP/6 report (ICAO, 1988b) deals with the development of system performance requirements for RVSM as referred to in Section 6.2.1. The process of deriving such requirements started off with deriving a maximum permissible value for the probability of vertical overlap by using the vertical collision risk model, in combination with the target level of safety, in a reverse manner. See Section 6.2.3 for further details.

Annex C

Annex C in Volume 2 of the RGCSP/6 report (ICAO, 1988b) documents the Japanese studies on RVSM and presents the following vertical collision risk model (slightly edited compared to eqs. (2-1) – (2-3) of Annex C in Volume 2 of the RGCSP/6 report (ICAO, 1988b))

$$N_{az} = P_y(0)P_z(S_z) \frac{L_x}{S_x} [E_z(s)K_s + E_z(o)K_o] \quad (6.28)$$

where

$$K_s = \frac{|\overline{\Delta V}|}{2L_x} + \frac{|\overline{y}|}{2L_y} + \frac{|\overline{z}|}{2L_z} \quad (6.29)$$

$$K_o = \frac{2\overline{V}}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \quad (6.30)$$

Substitution of eqs. (6.29) and (6.30) into eq. (6.28) gives

$$N_{az} = P_y(0)P_z(S_z) \frac{L_x}{S_x} \left[E_z(s) \left(\frac{|\overline{\Delta V}|}{2L_x} + \frac{|\overline{y}|}{2L_y} + \frac{|\overline{z}|}{2L_z} \right) + E_z(o) \left(\frac{2\overline{V}}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z} \right) \right] \quad (6.31)$$

which is exactly the same as the single-airway occupancy model of eq. (6.9) from Annex A of Volume 2 of the RGCSP/6 report (ICAO, 1988b) utilized in the European studies of RVSM. Table 6.3 lists the parameters featuring in eq. (6.31) and their definitions.

Table 6.3: Definition of parameters of the vertical collision risk models of eqs. (6.28)

Parameter	Definition
N_{az}	expected number of fatal accidents in flying hour due to the loss of vertical separation
S_z	vertical separation standard
S_x	a parameter used for calculating occupancies
$P_z(S_z)$	the probability of vertical overlap
L_x	the length of a typical aircraft
L_y	the width of a typical aircraft
L_z	the height of a typical aircraft
$E_z(o)$	the opposite direction occupancy
$E_z(s)$	the same direction occupancy
$\overline{V}$	the average ground speed
$ \overline{\Delta V} $	the average relative along track speed
$ \overline{y} $	the average relative cross track speed
$ \overline{z} $	the average relative vertical speed
$P_y(0)$	the probability of lateral overlap

Paired aircraft TVE data were used to obtain a sample of relative vertical distances between aircraft in a pair from which the main parameter $P_z(S_z)$ of the vertical collision risk model was estimated. The relative vertical distance between two aircraft in a pair was defined as

$$z_{12} = TVE_1 + v_1 - (TVE_2 + v_2) = TVE_1 - TVE_2 + v_1 - v_2 \quad (6.32)$$

where v_1 and v_2 denote measurement/processing errors in the TVE of the aircraft making up a measurement pair. Two approaches were followed to model the probability distribution of the relative vertical distance z_{12} . The first approach consisted of assuming probability distributions for the total vertical errors TVE_1 and TVE_2 as well as for the measurement errors v_1 and v_2 and to compute the probability distribution of z_{12} by convolution. The resulting z_{12} was then fitted to the sample of relative vertical distances between aircraft. A zero-mean normal distribution with a certain standard deviation was assumed for the measurement errors and both a double exponential and a double double exponential distribution were assumed for the total vertical errors. The two resulting z_{12} models were denoted RVD(DE-N) and RVD(DDE-N) respectively. The second approach consisted of assuming a probability distribution model directly for the sample of relative vertical distance data, thus avoiding the convolutions of the first approach. Three candidate distributions were considered, namely normal (N), double exponential (DE), and a normal double exponential mixture distribution (DE-N Mixed). The DE-N Mixed and RVD(DE-N) models were found to fit the empirical data well with the former being more conservative and producing an estimate of the probability of vertical overlap of $P_z(1,000) = 4.4 \times 10^{-6}$.

Annex D

Annex D in Volume 2 of the RGCSP/6 report (ICAO, 1988b) documents the Canadian Mode C data collection in support of the technical feasibility of RVSM. It does not deal with vertical collision risk modelling.

Annex E

Annex E in Volume 2 of the RGCSP/6 report (ICAO, 1988b) documents the USSR studies on RVSM and presents the following vertical collision risk model

$$N_{az} = P_z P_y(0) N_x \left(1 + \frac{\lambda_x}{V} \left(\frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \right) \quad (6.33)$$

with its parameters defined in Table 6.4. Eq. (6.33) is seen to correspond to the opposite-direction-traffic part of the vertical collision risk model of eq. (6.18). Notice that N_{az} is defined as a number of collisions rather than accidents.

Table 6.4: Definition of parameters of the vertical collision risk models of eqs. (6.33)

Parameter	Definition
N_{az}	the number of collisions per hour of aircraft flying towards each other on adjacent flight levels
P_z	the probability of vertical overlap
$P_y(0)$	the probability of lateral overlap
V	the average aircraft speed
$ \bar{y} $	the average relative lateral speed
$ \bar{z} $	the average relative vertical speed
λ_x	the average length
λ_y	the average width
λ_z	the average height
N_x	the number of encounters on an adjacent level per flying hour

The probability of vertical overlap of a pair of aircraft flying at adjacent flight levels was determined using the following correlation

$$P_z = P_c \cdot P_z(S) + (1 - P_c)P_z(0) \quad (6.34)$$

where

- P_c : the probability that the ATC service controller has assigned the adjacent flight level correctly
- $1 - P_c$: the probability of the erroneous assignment of an opposite direction flight level

Annex E in Volume 2 of the RGCSP/6 report (ICAO, 1988b) then presented a list of factors influencing aircraft height-keeping performance together with statistics derived from checks on altimeters during scheduled maintenance work and from the difference in altimeter readings under flight conditions at the same altitude. Based on that, it was concluded that:

- The core of the altimeter error distribution can, with sufficient accuracy, be described by a normal law;
- The probability of large deviations should, from the safety point of view, be described by an equal probability distribution law;
- The monitoring system used in operational maintenance do not exclude the use in flight of altimeters with errors exceeding the tolerance in a minor way.

Statistics on the pressure sensing system error derived from flight testing and on the accuracy of acquiring and keeping of assigned altitude were also presented.

The probability of vertical overlap P_z was not estimated but the collision risk model was used in a reverse manner to obtain a maximum permissible level, $P_{z \text{ perm.}}$, consistent with three different values of a vertical TLS, as a function of three values of the opposite-direction passing frequency N_x and representative single values of the remaining collision risk model parameters for the benefit of the development of system performance requirements for RVSM. Cf. the similar use of the vertical collision risk model reported for the Annexes A and B. See the next subsection for further details of the development of system performance requirements.

6.2.3 Minimum Aircraft System Performance Specification (MASPS)

This subsection outlines the guidance material developed by the RGCSP concerning the RVSM MASPS and concludes with a paragraph in which reference is made to an appendix in ICAO Annex 6 where the ultimate altimetry system performance requirements for operations in RVSM airspace developed by specialist groups can be found.

As set out earlier in the *Background and implementation history* Subsection 6.2.1, one of the pre-requisites underlying the RGCSP's conclusion on the technical feasibility of RVSM was the necessity to establish airworthiness performance requirements embodied in a comprehensive minimum aircraft system performance specification (MASPS) for all aircraft utilizing the reduced separation. To this end, the RGCSP started off with the development of a global system performance specification. This is a statement of the parameters that form the basis for defining the integrated set of requirements for aircraft height-keeping,

aircraft systems, aircraft operating procedures, ATC procedures, and monitoring practices as described in Sections 2.2 – 2.6 of the First Edition (published in 1992) of the RVSM Manual (ICAO, 2012b). The global system performance specification defines the height-keeping performance necessary to meet the system safety goal of 2.5×10^{-9} fatal accidents per flight hour for the risk of collision associated with vertical navigation performance, termed *height-keeping performance*. (This TLS does not address the risk arising from either errors in ATC instructions or loss of vertical separation associated with in-flight emergencies.) Obviously, this level of height-keeping performance depends on specific values of important airspace parameters affecting the risk of collision should vertical separation be lost. The height-keeping performance requirement of the global system performance specification is expressed as the maximum value for the probability that aircraft will lose vertical separation equal to the RVSM value, $P_z(1000)$. The important airspace parameters are the frequency with which aircraft pass while having procedural vertical separation equal to the RVSM and no nominal horizontal separation, and the standard deviation of the error with which aircraft maintain assigned track in the lateral dimension.

The height-keeping performance requirement of the global system performance specification was derived from the following inverse use of the vertical collision risk model,

$$2.5 \times 10^{-9} = N_{az} = P_z(1000)P_y(0)N_x(\text{opp}) \left(1 + \frac{\lambda_x |\bar{y}|}{\lambda_y 2\bar{V}} + \frac{\lambda_x |\bar{z}|}{\lambda_z 2\bar{V}} \right) \quad (6.35)$$

by substituting values for all the parameters of the model other than $P_z(1000)$. See Table 1 in the Appendix to the First Edition of RVSM Manual (ICAO, 2012b) for the specific parameter values used. The quantitative statement of the global system performance specification consists of maximum values for the probability of vertical overlap $P_z(1000)$ and the two important airspace parameters passing frequency and standard deviation of lateral-path keeping error and reads as follows⁵⁴:

- a) a passing frequency equal to 2.5 opposite-direction passings per aircraft flight hour;
- b) a standard deviation of lateral path-keeping error equal to 0.3 NM; and
- c) a probability that two aircraft will lose procedural vertical separation of the RVSM value, $P_z(1000)$, equal to 1.7×10^{-8} .

The value of 0.3 NM for the standard deviation of lateral path-keeping error in requirement b) was based on the accuracy of VOR navigation in the late nineteen-eighties and resulted in a value of 0.058 for the probability of lateral overlap parameter, $P_y(0)$, of the vertical collision risk model.

It is important to note that the values for passing frequency and the standard deviation of lateral path-keeping error were chosen to forecast future global airspace conditions, reflecting the intention to ensure that the TLS will continue to be met even with anticipated increases in global air traffic volume and expected technological improvements in navigation. As a consequence, satisfaction of the global system performance specification should ensure safe operation of RVSM airspace at least through the year 2005. One technological development that evolved faster than anticipated at the time concerns that of satellite navigation and its very accurate path keeping. As will be seen in Section 6.3, a Strategic Lateral Offset Procedure (SLOP) has been developed to counteract the adverse effect of very accurate lateral path keeping on the risk of collision due to the loss of vertical separation.

⁵⁴ The Second Edition of the RVSM Manual introduces the concept of combining the maximum values of the passing frequency and the standard deviation of lateral path-keeping error, the latter in the form of the probability of lateral overlap $P_y(0)$, into a single maximum value of 0.145 for the frequency of opposite-direction passing events involving lateral overlap and allowing, if so desired, a trade-off between passing frequency and probability of lateral overlap, provided their product is smaller than 0.145.

The second step taken by the RGCSP concerned the development of a global height-keeping performance specification so that, if met, the required $P_z(1000)$ value of the global system performance specification will be met. The global height-keeping performance specification applies to the aggregate of height-keeping errors of individual aircraft and simultaneously satisfies of the following four requirements:

- a) the proportion of height-keeping errors beyond 90 m (300 ft) in magnitude is less than 2.0×10^{-3} ;
- b) the proportion of height-keeping errors beyond 150 m (500 ft) in magnitude is less than 3.5×10^{-6} ;
- c) the proportion of height-keeping errors beyond 200 m (650 ft) in magnitude is less than 1.6×10^{-7} ; and
- d) the proportion of height-keeping errors between 290 m and 320 m (950 ft and 1050 ft) in magnitude is less than 1.7×10^{-8} .

The third step was to provide guidance to the specialist groups who must translate the global height-keeping performance specification above into detailed specifications and procedures controlling the height-keeping standards of aircraft operating in RVSM airspace. These detailed specifications and procedures must be developed for use by designers, manufacturers, operators, and approval authorities, and must be applicable to airworthiness approval of groups of aircraft as well as to individual aircraft. When taken together, they will form a MASPS, Minimum Aircraft System Performance Specification, comprising three sets of controls, type approval, production release, and continued airworthiness.

The following characteristics were developed in accordance with the conclusions of RGCSP/6 (ICAO, 1988b):

- a) the mean altimetry system error (ASE) of the group shall not exceed ± 25 m (± 80 ft);
- b) the sum of the absolute value of the mean ASE for the group and three standard deviations of ASE within the group shall not exceed 75 m (245 ft); and
- c) errors in altitude keeping shall be symmetric about a mean of 0 m (0 ft), shall have a standard deviation not greater than 13 m (43 ft) and be such that the error frequency decreases with increasing error magnitude at a rate which is at least exponential.

The fourth step was to recommend, on the basis of the studies reported in Volume 2 of the report on RGCSP/6 (ICAO, 1988b), that the required margin between the operational performance specified in the previous paragraph and design capability should be achieved by ensuring that the type approval part of the MASPS is developed to fulfil the following requirements, where the narrower tolerance in item b) is specifically to allow for some degradation with increasing age:

- a) the mean uncorrected residual position error (static source error) of the group shall not exceed ± 25 m (± 80 ft);
- b) the sum of the absolute value of the mean ASE for the group, and three standard deviations of ASE within the group, shall not exceed 60 m (200 ft);
- c) each individual aircraft in the group shall be built to have ASE contained within ± 60 m (± 200 ft); and
- d) an automatic altitude-keeping device shall be required and will be capable of controlling altitude within a tolerance band of ± 15 m (± 50 ft) about commanded altitude when operated in the altitude-hold mode in straight and level flight under non-turbulent, non-gust conditions .

The Second Edition of the RVSM Manual published in 2002 was restructured compared to the First Edition published in 1992 to improve the presentation and to take into account new material resulting from RVSM-related developments since the publication of the First Edition. Of particular relevance to this section of this document is an updated chapter, Chapter 4, on *Aircraft Requirements and Approval*. That chapter contains two references to the RVSM MASPS developed by technical bodies dealing with airworthiness standards and RVSM as anticipated by the RGCSP in its First Edition of the RVSM Manual. The first reference is *Joint Aviation*

Authority (JAA) Temporary Leaflet (TGL) No. 6, Approved Final Draft – April 24 1998 (Joint Aviation Authority (JAA), 1998). This document replaced *JAA Information Leaflet No. 23* published in October 1994 (Joint Aviation Authority (JAA), 1994). A revision, Revision 1, of *JAA TGL No. 6* was issued in October 1999 (Joint Aviation Authority (JAA), 1999). Since 2013, guidance on airborne RVSM equipment and performance requirements has been available in (EASA, 2013) accompanied by a website on where provides useful guidance as to where to find this information⁵⁵ in (EASA, 2013). The second reference is Federal Aviation Administration (FAA) Document 91-RVSM (Federal Aviation Administration (FAA), 1994). Two later versions are references (Federal Aviation Administration (FAA), 1993) and (Federal Aviation Administration (FAA), 2004), whereas the latest version is (FAA, 2019).

The title and sequence of material in the Third Edition of the RVSM Manual published in 2012 reflect amended content and presentation that focus on continuing RVSM operations, in contrast to the first two editions that focused on implementation. The changes were made on the basis that RVSM had been successfully implemented globally, cf. Section 6.2.1.

Two specialist groups that were involved in the development of the RVSM MASPS are the European Organisation for Civil Aviation Electronics (EUROCAE) Working Group 30 and the Radio Technical Committee for Aeronautics (RTCA) Special Committee SC 150.

A review of the RVSM MASPS is well beyond the scope of this document, but the following is needed in connection with system performance monitoring to be discussed in the next subsection. The MASPS, for the purposes of RVSM approval, make a distinction between aircraft to be considered as members of a group and aircraft not to be considered as members of a group, i.e. so-called non-group aircraft. For aircraft to be considered as members of a group for purposes of RVSM approval, they should satisfy all of the following conditions (Federal Aviation Administration (FAA), 1993):

- (i) Aircraft should have been manufactured to a nominally identical design and be approved by the same Type Certificate (TC), TC amendment, or supplemental TC, as applicable.
- (ii) The Pitot/Static system of each aircraft should be installed in a nominal identical manner and position. The same SSE corrections should be incorporated in all aircraft of the group.
- (iii) The avionics units installed on each aircraft to meet the RVSM equipment requirements of paragraph 8a (of (Federal Aviation Administration (FAA), 1993)) should be manufactured to the manufacturer's same specification and have the same part number.
- (iv) The RVSM data package should have been produced or provided by the airframe manufacturer or an approved design organization.

If an airframe does not meet the conditions of paragraphs (i), (ii), (iii), and (iv) to qualify as a member of a group or is presented as an individual airframe for approval, then it must be considered as a non-group aircraft for the purposes of RVSM approval.

The altimetry system performance requirements for operations in RVSM airspace derived by the specialist groups on the basis of the requirements a) – d) formulated by the RGCSP can be found in Appendix 4 to Part I of ICAO Annex 6 (ICAO, 2016a). They were incorporated into Annex 6 through Amendment 29 to the Eighth Edition of Annex 6 and became applicable in 2005. The altimetry system performance requirements consist of two parts, with the first part pertaining to groups of aeroplanes that are nominally of identical design and build with respect to all details that could influence the accuracy of height-keeping performance (i.e. criteria

⁵⁵ See <https://www.eurocontrol.int/publication/guidance-where-find-information-related-airborne-rvsm-equipment-and-performance> (Accessed September 2025)

(i) – (iv) above) and the second part referring to aeroplanes for which the characteristics of the airframe and altimetry system fit are unique and so cannot be classified as belonging to a group of aircraft encompassed by the first part.

Verification of the height-keeping requirements being met takes place through system performance monitoring as outlined in the next subsection. A group of aircraft as defined above is therefore generally referred to as a monitoring group. Monitoring groups also play a key part in the modelling of the TVE probability distribution for the benefit of the estimation of the probability of vertical overlap $P_z(1000)$ and subsequently the estimation of the technical vertical collision risk N_{az} as will be shown in Section 6.5.2.2.1.

6.2.4 System performance monitoring

This subsection begins with an outline of the guidance material developed by the RGSCP and subsequently the SASP concerning RVSM system performance monitoring, particularly aircraft height-keeping monitoring requirements, and concludes with a brief description of how height-keeping monitoring data on TVE, AAD, and ASE of RVSM approved aircraft can be obtained.

A second pre-requisite formulated by the RGSCP concerning the technical feasibility of RVSM was the necessity to establish a comprehensive means of monitoring the safe operation of the system (cf. Section 6.2.1.). Guidance on monitoring of compliance with the global system performance and global height-keeping performance specifications and examination of other safety measures is addressed in Section 2.6 of the First Edition of the RVSM Manual (ICAO, 2012b). The guidance on monitoring is subdivided into the monitoring of the probability of vertical overlap $P_z(1000)$, aircraft passing frequencies, lateral overlap probability, and the other collision risk model parameters. Quantitative aspects of system performance monitoring are provided in an Appendix to the RVSM Manual. Responsibilities of the authorities are also addressed, namely at three levels: Regional Planning Group (RPG), Regional Monitoring Agency (RMA), and Air Traffic Control (ATC). The establishment of an RMA for each region in which RVSM is introduced is stated to be essential and a list of nine typical RMA duties is presented. See (ICAO, 2011) for further details on RMAs.

The importance of system performance monitoring was re-iterated in Chapter 6 of the Second Edition of the RVSM Manual (ICAO, 2012b), and, for practical purposes, a distinction was made about the monitoring process in the context of:

- a) the risk associated with the aircraft technical height-keeping performance (technical risk); and
- b) the overall risk, i.e. due to all causes.

For a), the monitoring process should aim to achieve the following:

- a) provide confidence that the technical TLS of 2.5×10^{-9} fatal accidents per aircraft flight hour will be met when RVSM is implemented and will continue to be met thereafter;
- b) provide guidance on the efficacy of the RVSM MASPS and on the effectiveness of altimetry system modifications; and
- c) provide evidence of ASE stability.

For b) (the first one above), the monitoring process should take into account the additional risk associated with operational errors and in-flight contingencies. Appendix A to the Second Edition of the RVSM Manual provides an expanded version of the Appendix to the First Edition, the expansion largely concerning the

assessment and evaluation of operational errors and in-flight contingencies conducted in the NAT and EUR Regions. This material will be taken into account in Sections 6.4 and 6.5. The text on system performance monitoring in the Third Edition of the RVSM Manual is the same as in the second Edition

A provision requiring height-keeping performance monitoring in RVSM airspace was incorporated in paragraph 3.3.4.1 of 13th edition ICAO Annex 11 with effect of 24 November 2005 (ICAO, 2018a) stating that:

For all airspace where a vertical separation minimum of 300 m (1000 ft) is applied above FL 290, a program shall be instituted, on a regional basis, for monitoring the height-keeping performance of aircraft operating at and above FL 290, in order to ensure that the implementation and continued application of this vertical separation minimum meets the safety objectives.

The provision is currently in paragraph 3.3.5.1 of the 15th edition of Annex 11. It is referenced in paragraph 7.2.8 of Part I of Annex 6, following paragraphs 7.2.6 and 7.2.7 which, inter alia, require an aircraft operating in RVSM airspace to demonstrate a vertical navigation performance in accordance with Appendix 4 to Part I of Annex 6. Paragraph 7.2.9 of Part I of Annex 6 requires that:

The State of the Operator that has issued an RVSM approval to the operator shall establish a requirement which ensures that a minimum of two aeroplanes of each aircraft type grouping of the operator have their height-keeping performance monitored, at least once every two years or within intervals of 1 000 flight hours per aeroplane, whichever period is longer. If the operator aircraft type grouping consists of a single aeroplane, monitoring of that aeroplane shall be accomplished within the specified period.

As explained in (ICAO, 2005), the Annex 6 Part I paragraph 7.2.9 requirement resulted from concerns and examination of the stability of ASE over time. It is usually referred to as long-term monitoring requirements. The requirement was incorporated into the 8th Edition of Annex 6 by Amendment 29 in 2005 and was updated through Amendment 34 (9th Edition) in 2010.

In practice, States/RMAs determine the precise number of aircraft of each type grouping of an operator to be monitored by means of the Minimum Monitoring Requirements table (Colamosca & Beritsky, 2019). This table is reviewed annually by NAARMO and EUR RMA prior to the annual RMA Coordination Group (RMACG) meeting and submitted to the RMACG meeting for approval by all RMAs. The table distinguishes three categories of aircraft groups as follows:

- Category 1 – Group Approved: data indicates compliance with RVSM MASPS;
- Category 2 – Group Approved: insufficient data on approved aircraft; and
- Category 3 – Non-group.

See e.g. Appendix F to (ICAO, 2011) for a description of the review process conducted by the EUR RMA.

Having reviewed the aircraft height-keeping monitoring requirements, this subsection proceeds with how aircraft height-keeping errors can be measured as a part of the system performance monitoring process in connection with the technical vertical risk. The total vertical error (TVE) of an aircraft is defined as the difference between the aircraft's geometric height at a given time and the contemporaneous and collocated geometric height of the flight level to which it is assigned. An aircraft height monitoring system should therefore consist of an integrated set of measurement and processing systems and procedures for:

- a) Measuring TVE;
- b) Measuring AAD through Mode C or Mode S coverage; and
- c) Producing a companion ASE estimate for each TVE measure.

Traditionally, height monitoring data has been collected by ground-based Height Monitoring Units (HMUs), Aircraft Geometric Height Monitoring Elements (AGHMEs), or by independent on-board portable GPS Monitoring Units (GMUs). HMUs and AGHMEs can provide lots of data for the modelling of ASE of large numbers of aircraft whereas GMUs are more suitable to collect ASE data on a limited number of aircraft that are unable to overfly an HMU or AGME. In addition, the Australian Airspace Monitoring Agency (AAMA) has pioneered the use of ADS-B data for the benefit of ASE modelling as presented to the SASP in May 2012 (Barry et al., 2012).

At EUROCONTROL, the Regional Monitoring Agency for the European region (EUR RMA) operates three HMUs located in Central Europe at Nattenheim (Germany), Linz (Austria), and Geneva (Switzerland)⁵⁶. See Figure 6.4. An HMU is a ground-based system consisting of two main components, a Height Monitoring element (HME) and a Total vertical error Monitoring Unit (TMU). The HME captures transponder signals from aircraft replying to interrogations from a Master and four Slave radar stations. The signals contain the information from Mode S, C, and A transmissions. The HME determines the geometric height and position of an aircraft by comparing the time of reception of the SSR transponder signals at the different receiver locations. This information is transmitted to the TMU as one plot per second. The data is collated by the TMU to create a track history of the aircraft passing through the area of coverage. The track information is then combined with meteorological data to evaluate the overall value for the TVE of an aircraft. When completed, the monitoring process produces TVE, AAD, and ASE readings for each aircraft measured. The height monitoring results are automatically transmitted to the EUR RMA.

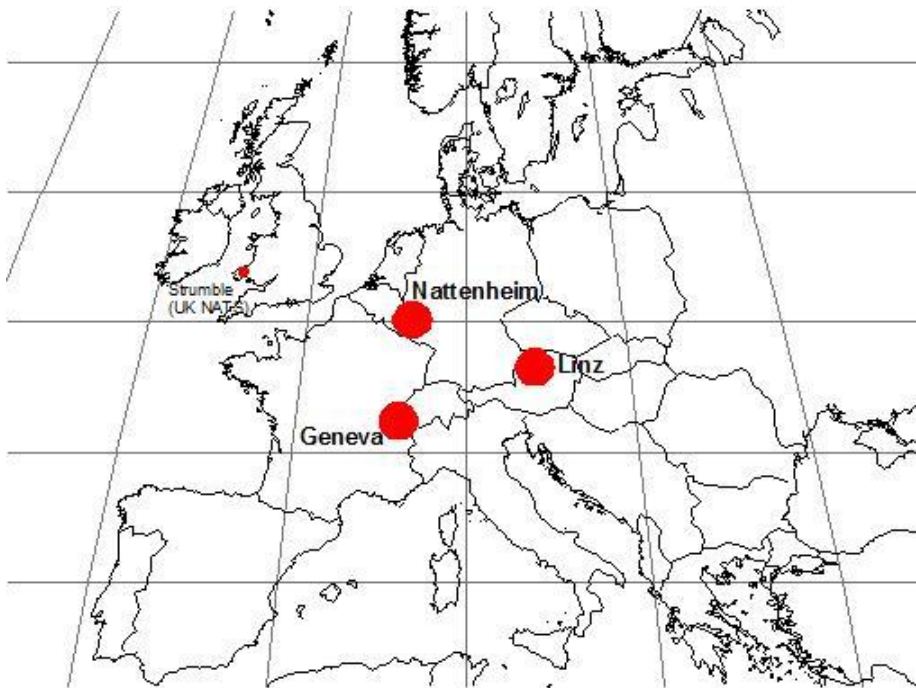


Figure 6.4: Location of three continental European HMUs (reproduced from [https://www.skybrary.aero/index.php/Height_Monitoring_Units_\(HMU\)](https://www.skybrary.aero/index.php/Height_Monitoring_Units_(HMU)))

At the FAA Technical Center, the North American Approvals Registration and Monitoring Organization (NAARMO) as the Regional Monitoring Agency for the North American Region, supports implementation and continued safe use of the North American RVSM. For the benefit of aircraft height-keeping monitoring, the

⁵⁶ See Skybrary website: <https://skybrary.aero/articles/height-monitoring-units-hmu> (Accessed September 2025)

FAA Technical Center has developed the ground-based Aircraft Geometric Height Measurement Element (AGHME) system as the principal means of ensuring that the height-keeping performance in RVSM airspace as a whole complies with system requirements supporting continued safe use of the North American RVSM⁵⁷. Three AGHME systems are positioned at fixed locations in the United States and Canada, namely Atlantic City, New Jersey, United States, Ottawa, Ottawa, Canada, and Lethbridge, Alberta, Canada⁵⁸. The FAA Technical Center has also developed the GPS-based Monitoring Unit (GMU). The GMU is a special-purpose system carried aboard an aircraft for one flight, during which the unit collects Global Positioning System pseudo-ranges. Post-flight processing of these data ensures estimates of aircraft geometric height which are of sufficient accuracy to permit estimation of relevant height-keeping performance parameters. In parallel, the current-generation FAA GMU also collects secondary surveillance radar Mode C data, which also contributes to parameter estimation. The GMU has been in use since 1996 and GMU height monitoring service is provided by ARINC and CSSI Inc. Following the development of the first generation GMU, an Enhanced GMU (EGMU) and an Enhanced2 GMU (E²GMU) have also been developed.

ADS-B height monitoring systems (AHMS) use ADS-B receivers to obtain geometric height data from ADS-B equipped aircraft. To use this method requires the aircraft to be ADS equipped and for the aircraft to fly in a region where ADS-B is performed. According to the website of the NAT Central Monitoring Agency (NATCMA)⁵⁹, the following RMAs have ADS-B Height Monitoring Systems: AAMA, China RMA, and MAAR (Monitoring Agency for Asia Region). In addition, the NAARMO website⁶⁰ states that aircraft equipped with qualified ADS-B out systems are now continually height-monitored during normal operations at RVSM altitudes when operating in airspace where sufficient ADS-B data is available to the FAA to determine RVSM performance (p 4-2 of (FAA, 2019) refers).

6.3 Strategic Lateral Offset Procedure (SLOP)

As set out in Section 4.3, a collision between two aircraft requires their bodies to overlap in three dimensions simultaneously at some point in time. In the vertical collision risk model, the dependence of the vertical risk on the accuracy of the lateral navigation of the aircraft is expressed by the model parameter $P_y(0)$, the probability of lateral overlap for aircraft at adjacent flight levels of the same route/track⁶¹. The vertical performance requirements underlying the derivation of the RVSM MASPS were based on a $P_y(0)$ value of 0.058, calculated on the assumption of a standard deviation of lateral path-keeping error of $\sigma_y = 0.3$ NM, representing VOR aircraft navigation performance in the late nineteen-eighties, cf. Section 6.2.3. When the uptake of global satellite navigation system (GNSS) based navigation with extremely high accurate lateral navigation became clear in the nineteen-nineties, it was realized that this dramatically increased the probability of a collision, through a much higher value of $P_y(0)$, once vertical separation would be lost under RVSM⁶². Mitigation of this effect resulted in the development of the Strategic Lateral Offset Procedure (SLOP) by the ICAO RGCSP and SASP. Guidance on the implementation of SLOP is provided in ICAO Circulars 331 and 354 (ICAO, 2014d).

⁵⁷ See FAA website: https://www.faa.gov/air_traffic/separation_standards/naarmo/monitoring_methods (Accessed September 2025)

⁵⁸ See <https://natcma.com/height-monitoring-2/how-to-have-an-aircraft-height-monitored/> (Accessed September 2025)

⁵⁹ See <https://natcma.com/> (Accessed September 2025)

⁶⁰ See https://www.faa.gov/air_traffic/separation_standards/naarmo (Accessed September 2025)

⁶¹ For aircraft at adjacent flight levels on intersecting tracks, aircraft lateral navigation performance plays a part in the calculation of the probability of horizontal overlap.

⁶² This is sometimes referred to as the navigation paradox, i.e. improved navigation performance in one dimension may have an adverse effect on the risk of collision due to the loss of separation in a different dimension.

SLOP allows aircraft to fly on a track parallel to the right of the centre line relative to the direction of flight to mitigate the lateral overlap probability due to increased navigation accuracy, and wake turbulence encounters as specified currently in section 16.5 of the Sixteenth Edition of the PANS-ATM incorporating Amendments 1 – 9 (ICAO, 2016c), of which paragraph 16.5.2 has been quoted below:

“16.5.2 Strategic lateral offsets shall be authorized only in en-route airspace as follows:

- a) where the lateral separation minima or spacing between route centre lines is 28 km (15 NM) or more, offsets to the right of the centre line relative to the direction of flight in tenths of a nautical mile up to a maximum of 3.7 km (2 NM); and
- b) where the lateral separation minima or spacing between route centre lines is 19 km (10 NM) or more and less than 28 km (15 NM), while one aircraft climbs/descends through the level of another aircraft, offsets to the right of the centre line relative to the direction of flight in tenths of a nautical mile up to a maximum of 3.7 km (2 NM); and
- c) where the lateral separation minima or spacing between route centre lines is 11.1 km (6 NM) or more and less than 28 km (15 NM), offsets to the right of the centre line relative to the direction of flight in tenths of a nautical mile up to a maximum of 0.9 km (0.5 NM).”

The possible effect of the use of lateral offsets on the probability of lateral overlap $P_y(0)$ will now be illustrated by means of an example. Consider the situation of Figure 6.5, showing opposite-direction traffic at a pair of adjacent flight levels of a route. Let the proportions of aircraft at flight level 1 utilizing lateral offsets of 0, 1, and 2 NM be p_{10} , p_{11} , and p_{12} respectively and let the corresponding proportions of aircraft at flight level 2 be p_{20} , p_{21} , and p_{22} , with $p_{10} + p_{11} + p_{12} = 1$ and $p_{20} + p_{21} + p_{22} = 1$.

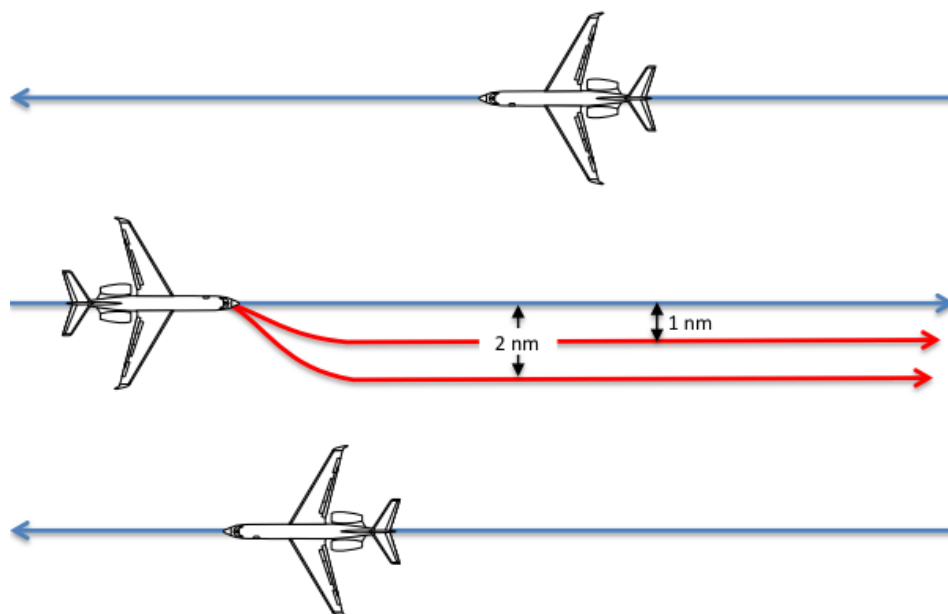


Figure 6.5: 0, 1, and 2 NM lateral offsets allowed for opposite-direction traffic at adjacent flight levels of a route.
(Source: <https://code7700.com/slop.htm>)

Instead of all aircraft pairs at adjacent flight levels having the same lateral separation of 0 NM, different proportions β_i , $i = 0, 1, \dots, 4$, of aircraft pairs will then have lateral separations of i NM, $i = 0, 1, \dots, 4$, where

$$\beta_0 = p_{20}p_{20} \quad (6.36)$$

$$\beta_1 = p_{21}p_{10} + p_{20}p_{11} \quad (6.37)$$

$$\beta_2 = p_{22}p_{10} + p_{21}p_{11} + p_{20}p_{12} \quad (6.38)$$

$$\beta_3 = p_{22}p_{11} + p_{21}p_{12} \quad (6.39)$$

$$\beta_4 = p_{22}p_{12} \quad (6.40)$$

As a result, the probability of lateral overlap $P_y(0)$ generalizes to $P_y(0, 1, \dots, 4)$, say, given by

$$P_y(0, 1, \dots, 4) = \beta_0 P_y(0) + \beta_1 P_y(1) + \beta_2 P_y(2) + \beta_3 P_y(3) + \beta_4 P_y(4) \quad (6.41)$$

where each of the probabilities of lateral overlap $P_y(i)$, $i = 0, 1, \dots, 4$, on the right side of eq. (6.41) can be calculated by means of eq. (4.17), i.e.

$$P_y(i) = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f(y)f(y - i + d_y)dy dd_y, \quad i = 0, 1, \dots, 4, \quad (6.42)$$

once the probability density $f(y)$ of the lateral deviations from track is known. However, the calculation of the resulting probability of lateral overlap $P_y(0, 1, \dots, 4)$ also requires the proportions $\beta_0, \beta_1, \dots, \beta_4$ to be known, i.e. the proportions of aircraft p_{10}, p_{11}, p_{12} and p_{20}, p_{21}, p_{22} offsetting by 0, 1, or 2 NM at flight level 1 and flight level 2 respectively.

A possible model for the probability density $f(y)$ of the lateral deviations from track is a mixture distribution made up of two component normal probability densities with one component density representing GNSS-based lateral navigation performance and the other component density representing VOR/DME-based lateral navigation performance. Such a model is in use for the annual RVSM collision risk assessment for the AFI Region of ICAO where the proportion of aircraft utilizing GNSS-based navigation is reviewed annually. See eq. (6.111) ff. in Section 6.5.2.2.3. This model has been used for the example calculation on the assumption that 85% of the aircraft population is utilizing GNSS-based navigation. The example calculation has also assumed that equal proportions of aircraft are offsetting by 1 and 2 NM respectively, i.e. $p_{11} = p_{12} = p_{21} = p_{22} = p$ and $p_{10} = p_{20} = 1 - 2p$.

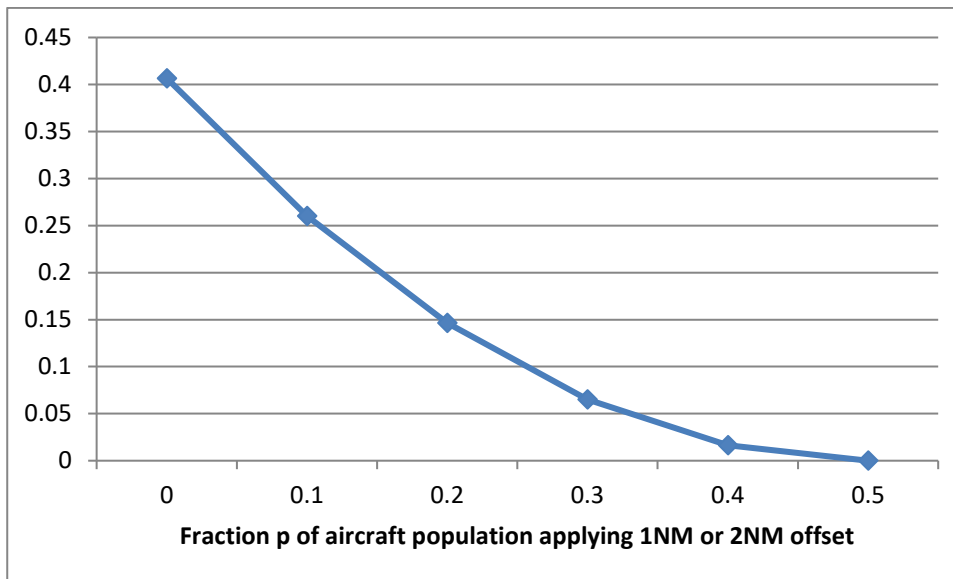


Figure 6.6: The probability of lateral overlap $P_y(0, 1, \dots, 4)$ under SLOP as a function of the proportion p of aircraft offsetting by either 1 NM or 2 NM to the right of centre line relative to the direction of flight

An “ideal” application of SLOP would involve an equal use of the three options, i.e. $p = 1/3$. Figure 6.6 then yields $P_y(0, 1, \dots, 4) = 0.0452$, i.e. a reduction in the probability of lateral overlap by a factor of approximately 10 relative to the aircraft population not using any offset but just flying route centre line.

With the NAT being the first ICAO Region to implement RVSM, the concept of lateral offsets was discussed as early as at the twenty-eighth meeting of the NAT SPG (NAT SPG/28) in 1992 (ICAO, 1992b). It was assumed that only aircraft with automatic offset capability would be required to fly offsets. The Group concluded that even with small proportions of aircraft flying offset, there would be reductions in collision risk. These reductions could be considerable if the lateral navigation accuracy of aircraft in the region were to improve. The Group was informed that improvements in lateral navigation accuracy in the future could eventually make the use of lateral offsets in the NAT Region essential in order to meet the vertical TLS. Thus, the Group agreed that offsets would be required in the future in an RVSM environment in order to achieve the vertical TLS. Based on available lateral navigational performance data, it was felt that it would not be necessary to mandate offset capability for the existing aircraft fleet. However, this should be considered for new aircraft. This decision could change if future data indicated that there was a substantial proportion of traffic with highly accurate navigation equipment but without offset capability.

Formally, flight crew have had the discretion to fly right-hand offsets of 1 NM or 2 NM in NAT RVSM airspace since 2004. The use of 1 or 2 NM offsets in NAT MNPS airspace became a requirement rather than a (very strong) recommendation as of January 2017. So called micro-offsets in tenths of a nautical mile have been allowed by ICAO for global application since 2014 but only the NAT has adopted that as of 7 August 2019. A fairly recent note⁶³ suggests that only the Boeing Business Jet (BBJ), B737 (NG, MAX), B777X (when it enters service), and B787 are currently capable of offsetting in tenths of a nautical mile. The same reference states that Airbus is planning enhancement across their product offerings in the 2022* timeframe.

⁶³ See <https://aviation.stackexchange.com/questions/67993/which-commercial-aircraft-can-fly-micro-slop-procedures> (Accessed September 2025)

It is not known to the authors to what extent SLOP has been authorized by the appropriate ATS authorities in airspaces other than NAT RVSM airspace. It must be stressed that before the beneficial effect of SLOP can be accounted for in an airspace's RVSM collision risk assessment, the use of SLOP must be authorized and the extent of its actual usage must be known, i.e. the proportions p_{10} , p_{11} , p_{12} and p_{20} , p_{21} , p_{22} of aircraft offsetting by 0, 1, or 2 NM respectively when integer offsets are in use and, more generally, all proportions of aircraft using tenths-of-a-nautical-mile offsets when those are in use.

6.4 Vertical separation in the NAT

6.4.1 Introduction

As set out in Section 6.2.1, the NAT Region was the first ICAO region that implemented RVSM with NAT RVSM Phase I starting on 27 March 1997 and covering the flight level band from FL310 to FL370. The NAT region has performed very significant work on e.g. aircraft height-keeping monitoring, stability of ASE, and modelling of vertical risk due to operational errors and in-flight contingencies in NAT RVSM airspace. Before considering that modelling work in Section 6.4.3, earlier work on vertical separation in the NAT region by the NAT SPG will be reviewed as a matter of historical interest in Section 6.4.2. This will cover the period of time from 1965 (NAT SPG/1) to 1996 (NAT SPG/32) based on the *Summary of Discussions (and Conclusions) of the NAT SPG's annual meetings*⁶⁴. Recall that the technical feasibility of RVSM was established in late 1988 at the sixth meeting of the RGSCP (RGSCP/6). As a result, it was agreed at the 26th meeting of the NAT SPG in 1990 that a Vertical Studies Group (NAT VSG) be established to address a list of issues for the benefit of the implementation of RVSM in the whole or part of the NAT MNPS airspace (NAT SPG/26, 1990).

6.4.2 Vertical separation in the NAT: the years 1965 – 1996

Table 6.5 lists a number of NAT SPG meetings at which vertical separation was on the Group's agenda for the period of time under consideration in this subsection. Following work on vertical separation at the first five meetings of the NAT SPG, the possible introduction of reduced vertical separation above FL290 in the NAT Region was included as one of the tasks of the NAT SPG's future work programme at NAT SPG/19 in 1982. It featured on the work programme as such up to NAT SPG/26 when it also became an agenda item on its own again. A brief discussion of the work reported under the pertinent agenda items is provided by meeting below the table. Vertical separation has also played a part in composite separation. Two different types of composite separation have been considered over time, namely 60 NM/1000 ft and 30 NM/1000 ft. The former type was amply considered in Section 5.3.2 of Chapter 5 and the latter will be covered in this subsection.

⁶⁴ See Appendix E.4 for *Summary of Discussions of the xth Meeting of the NAT Systems Planning Group*. These documents can be obtained from <https://www.icao.int/EURNAT/Pages/EURNAT-Meetings-NATSPG.aspx>

Table 6.5: NAT SPG meetings at which vertical separation was on the meetings' agenda

Year	Meeting	Agenda item
1965	NAT SPG/1	2: Review of the general task allocated to the Group, selection of those matters requiring early attention and proposed manner of dealing with them 2.3.6 Separation minima
1966	NAT SPG/2	7: Review of subjects for future NAT SPG consideration
1967	NAT SPG/3	2: Vertical separation applied to aircraft operating above FL290 in the NAT region 5: Any other Business 5.2.1 Review of the work programme of the Group x) Vertical separation above FL290 in specified parts of the NAT Region
1968	NAT SPG/4	-
1968	NAT SPG/5	2: Review of developments regarding the application of reduced vertical separation to aircraft operating above FL290 in the NAT Region 3: Review of the possibility to apply "composite separation" (i.e. a form of separation composed of the <u>simultaneous</u> application of reduced lateral and vertical separation to aircraft operating above FL290 in the NAT Region
1969	NAT SPG/6	3: Review of progress of studies towards the application of composite separation
1971	NAT SPG/7	2: Review of the situation with regard to the use of composite separation
1972	NAT SPG/8	2: Review of the situation with regard to a) the use of composite separation in the NAT Region and those problems in the adjacent transition areas resulting therefrom
1973	NAT SPG/9	–
1974	NAT SPG/10	–
1975	NAT SPG/11	7: Operational problems of current interest a) Developments regarding vertical separation in the EUR Region and possible effects on NAT operations
1976	NAT SPG/12	6: Possible extension of the use of composite separation, including a problem raised in Recommendation 10/3 of the NAT/V RAN Meeting
1977	NAT SPG/13	4: Extension of the area of use of <u>current</u> composite separation
1978	NAT SPG/14	10: Any other Business 10.4 Use of composite separation by Canada
1979	NAT SPG/15	3: Review of the situation regarding the use of composite separation and determination of its priority use in relation to reduction of longitudinal separation
1979	NAT SPG/16	–
1980	NAT SPG/17	–
1981	NAT SPG/18	5: Initial assessment of the feasibility of using <u>composite</u> separation (30 NM/1000 feet) in MNPS airspace of the Region 11: Updating of the work programme of the NAT/SPG during the next two years 11.1 Future work programme

Year	Meeting	Agenda item
		c) Further review of relevant aspects regarding the use of composite separation in MNPS airspace in the NAT Region
1982	NAT SPG/19	3: Review of progress of studies regarding the possible future use introduction of composite separation (30 NM/1000 feet) in the NAT Organized Track structure 11: Updating of the work programme of the NAT SPG 11.2 Reduction of vertical separation criteria 11.3 Further work programme c) Further efforts regarding the possible use of 30 NM/1000 ft composite separation in MNPS airspace of the NAT Region o) i) procedures required for possible implementation of reduced vertical separation in the NAT Region
1983	NAT SPG/20	2: Possible use of composite separation 30 NM/1000 ft in NAT MNPS airspace 16: Updating of the work programme of the NAT SPG 16.2.1 System safety performance review a) iii) vertical performance 16.2.4 Planning b) Further efforts regarding the possible use of 30 NM/1000 ft composite separation in MNPS airspace of the NAT Region c) Consideration of the possible introduction of reduced vertical separation above FL290 in the NAT region
1984	NAT SPG/21	? (incomplete report available only)
1985	NAT SPG/22	6: Updating of the work programme of the NAT SPG 6.2.1 System safety performance review a) iii) vertical performance 6.2.4 Planning b) Further efforts towards the introduction of 30 NM/1000 ft composite separation in the NAT MNPS airspace and its implications in the oceanic/domestic interface areas c) Consideration of the possible introduction of reduced vertical separation above FL290 in the NAT region
1986	NAT SPG/23	? (incomplete report available only)
1987	NAT SPG/24	1: NAT air navigation system safety performance review 1.2 Mathematical-statistical aspects of risk assessment methodology Composite system risk estimates 6: Updating of the work programme of the NAT SPG 6.1.1 Part 1 – Air Navigation System Safety Performance Review 1) c) vertical performance 6.1.1 Part 4 – Planning 3) Use of 30 NM/1000 ft composite separation in the NAT MNPS airspace and its implications in the oceanic/domestic interface areas 4) Possible introduction of reduced vertical separation above FL290 in the NAT region
1988	NAT SPG/25	4: Planning in the NAT Region

Year	Meeting	Agenda item
		4.0.1 c) further efforts towards the introduction of 30 NM/1000ft composite separation in the NAT MNPS airspace and its implications in the oceanic/domestic interface areas 4.0.1. d) possible introduction of reduced vertical separation above FL290 in the NAT Region 6: Updating of the work programme of the NAT SPG 6.1.1 Part VI – Planning 3. Possible introduction of reduced vertical separation above FL290 in the NAT region
1990	NAT SPG/26	1: NAT Air Navigation System safety performance review 1.2.7 Reduced vertical separation minimum and its effects on other collision risk estimates 4: Planning in the NAT 4.3 Possible introduction of reduced vertical separation above FL290 in the NAT Region 6: Updating of the work programme of the NAT SPG 6.1.1 Part I – Air Navigation System Safety Performance Review 1. c) vertical performance 4. Mathematical-statistical issues relating to vertical and longitudinal collision risk 6.1.1 Part IV – Planning 3. Introduction of reduced vertical separation above FL290 in the NAT region (VSG, RGCSP)
1991	NAT SPG/27	4: Planning in the NAT Region 4.3 Introduction of reduced vertical separation above FL290 in the NAT Region 6: Updating of the work programme of the NAT SPG 6.1.1 Part I – Air Navigation System Safety Performance Review 1. c) vertical performance 5. Mathematical-statistical issues relating to vertical and longitudinal collision risk 6.1.1 Part IV – Planning and implementation in the NAT Region 2.d) report of the VSI group
1992	NAT SPG/28	1: Air Navigation System Safety Performance Review 1.2.4 RVSM operations in the NAT Region 4: Planning and implementation in the NAT Region 4.0.1 b) iv) report of the VSI group 4.2.4 Report of the Vertical Separation Implementation group
1993	NAT SPG/29	1: Air Navigation System Safety Performance Review 1.7 Aspects of the Future NAT System Vertical occupancy and risk 1.8 Mathematicians Work Programme for 1993/94 4: Planning and implementation in the NAT Region 4.3 Reports of the implementation sub-groups

Year	Meeting	Agenda item
		Report of the NAT Vertical Separation Implementation Group
1994	NAT SPG/30	2: Planning and Implementation 2.5 Report of the Reduced Separation Standards Implementation Group 3: Air Navigation System Review 3.2 Review of system safety performance RVSM topics Vertical occupancy and risk Proposed Mathematicians Work Programme for 1994/95
1995	NAT SPG/31	2: Planning and Implementation 2.3 Report of the NAT Implementation Management Group Reduced Vertical separation Minimum 2.5 Other issues Extension of the Brest transition area RVSM interface area between Iceland, Norway and the United Kingdom Allocation of levels in an RVSM environment 3: Air Navigation System Review 3.2 Review of system safety performance Scrutiny matters Monitoring of height deviations RVSM topics Vertical occupancy and risk Aircraft dimension parameters Aircraft contingency events Deviations due to meteorological conditions TCAS RVSM implementation Preparation for RVSM verification Mathematicians Work Programme and actions for 1995/96
1996	NAT SPG/32	2: Planning and Implementation 2.3 Report of the NAT Implementation Management Group RVSM institutional arrangements RVSM information and implementation programmes Preliminary safety assessment for RVSM 2.4 Implementation planning Change of the vertical dimensions of MNPS airspace 3: Air Navigation System Review 3.2 Review of system safety performance Scrutiny matters Monitoring of height deviations

NAT SPG/1 (1965)

The agenda for the first meeting of the NAT SPG comprised an introduction and two items, namely:

- Agenda Item 2: Review of the general task allocated to the Group, selection of those matters requiring early attention and proposed manner of dealing with them; and
- Agenda item 3: determination of the working methods of the group during and between meetings.

One of the “significant” tasks considered under Agenda Item 2 was *Separation minima*. It was noted that with regard to vertical separation, the US was developing a report on its domestic programme for reduced vertical separation which would be made available to interested members. The Group received information that the time scale of the programme for assessing the feasibility of introducing reduced vertical separation above FL290 had been altered⁶⁵. It was therefore unlikely that reduced vertical separation (if endorsed by the next Limited NAT RAN Meeting) could be applied during the 1966 peak traffic season.

NAT SPG/2 (1966)

Vertical separation was addressed only under Agenda Item 7 of NAT SPG/2: *Review of subjects for future NAT SPG consideration* (ICAO, 1966). Vertical separation above FL290 in specified parts of the NAT region was one of the subjects to be retained on the Group’s work programme.

NAT SPG/3 (1967)

The Group agreed that many of the basic principles concerning assessing separation standards discussed and agreed at NAT SPG/2 with a view to assessing the safety of the lateral separation standard in the NAT Region, cf. Section 5.3.1, were valid for assessing vertical separation standards, including the target level of safety. On the assumption that the effects of wing-tips vortices were negligible and counting a collision as two aircraft accidents, the following vertical collision risk model was adopted at the meeting (ICAO, 1967)

$$N_{az} = \frac{2 \times 10^7}{H} P_z(std) \left\{ \frac{T_z(same)}{S_x} \left[\frac{\Delta \bar{V}}{2} P_y(0) + \lambda_x N_y(0) + \frac{\lambda_x |\bar{z}| P_y(0)}{2\lambda_z} \right] + \frac{T_z(opp)}{S_x} \left[\bar{V} P_y(0) + \lambda_x N_y(0) + \frac{\lambda_x |\bar{z}| P_y(0)}{2\lambda_z} \right] \right\} \quad (6.43)$$

where N_{az} denotes the number of aircraft accidents per 10 million flying hours. This model, in fact, was already referenced in Section 5.3.1 as eq. (5.30) as a spin-off of the review of the NAT SPG’s work on the lateral collision risk model. Notice that the model can also be obtained by combining eqs. (6.1) and (6.2) for the Vertical risk (*same*) and Vertical risk (*opp*) collision risks during a period of interest, converting collisions into accidents, dividing by the number of flying hours H during the period of interest, and multiplying by 10 million flying hours.

The Group noted that there were considerable difficulties in obtaining a sufficiently large and representative data sample by measurements of vertical separation which lead directly to estimates of $P_z(1000)$ and that, moreover, direct measurements would not in themselves give understanding of the mechanism of significant errors in height separation. A total of six components of the total height-separation was then discussed, including data already being available or being collected, but it was concluded that insufficient measurements were available to arrive at a definitive conclusion.

A different approach was then discussed, viz. one that concentrated on the possibility of persistent uncorrected large static pressure error. The principle of this approach was to use the available data on flight technical and random altimetry errors to find the margin left for a permissible static calibration error corresponding to the acceptable levels of risk at 1000 ft vertical separation. These margins were represented by probability distribution functions specified by tail areas and of a form likely to be associated with cautious estimates of the probability of vertical overlap $P_z(1000)$. It should then be possible to give a pessimistic estimate of how often each aircraft’s static pressure system should be re-checked if the frequency of large

⁶⁵ See (ICAO, 1965b).

changes in pressure calibration error were to be brought down to a level compatible with an acceptable vertical collision risk. Further work was concluded to be necessary before it could be shown that a vertical separation of 1000 ft would be safe for operation over the North Atlantic.

As referenced before in Section 5.3.1, the concept of applying some form of staggering to the flight paths of aircraft flying on adjacent tracks and/or flight levels was also discussed and a recommendation was adopted to discuss this subject in detail at the Group's next meeting.

Finally, two methods for executing static pressure error calibrations were discussed under agenda item 2 of the NAT SPG/2 meeting, namely: the trailing cone method and the performance-check method. The interested reader is referred to (ICAO, 1967) for further details since this subject is well beyond the scope of this document.

NAT SPG/4 (1967)

Vertical separation above FL290 in specified parts of the NAT Region was not on the agenda for the 4th meeting but was discussed under the *Review of the future work programme of the Group*. It was subsequently included in the tentative agenda for the 5th meeting.

NAT SPG/5 (1968)

As indicated in Table 6.5 above, vertical separation by itself as well as a part of composite separation was discussed at the 5th Meeting of the NAT/SPG. Consider the former first.

The following equivalent of the lateral collision risk model of eq. (5.32) with $\gamma = 1$ and $\Lambda_x = \lambda_x$ was accepted by the Group although there were differences of opinion within the Group on the values which should be accorded to some of the model parameters (ICAO, 1968a):

$$N_{az} = 10^7 P_y(0) P_z(std) \frac{\lambda_x}{s_x} \left[E_z(\text{same}) \left(\frac{|\Delta V|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) + E_z(\text{opp}) \left(\frac{\bar{v}}{\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \right] \quad (6.44)$$

Attention was concentrated on a system in which the 1000 feet standard would be applied only to same-direction aircraft; aircraft flying in opposite direction were still required to be separated by 2000 feet. The parameters of the model on which there were differences of opinion concerning their values were $P_z(1000)$, $P_y(0)$, $|\bar{y}|$, and independence of occupancy E_z . The Group decided that it could not at the (then) present time estimate a value of $P_y(0)$ which would be representative of future track-keeping accuracy. It was also concluded that no conclusion could be reached on the independence of occupancy E_z without detailed, analytical and operational, study. (ICAO, 1968a) presents a detailed discussion on issues concerning the estimation of $P_z(1000)$. These, together with the issues concerning $P_y(0)$ and the independence of occupancy E_z led to the following: "The Group concluded that there was at the present time insufficient evidence for showing that a 1000 feet vertical separation standard would be safe for application on the present track system over the North Atlantic". Concerning the vertical dimension, two areas for action on static pressure error were identified and States should be encouraged to make measurements of total altitude error as discussed at the meeting.

Returning to the form of the vertical collision risk model, it is remarked that eq. (6.44) was derived in the introductory Section 6.1 of this chapter from the vertical Reich model and the occupancy concept agreed at NAT SPG/4, which for the vertical dimension was given in eqs. (6.3) and (6.4),

$$E_z(\text{same}) = \frac{2T_z(\text{same})}{H} \quad (6.3)$$

$$E_z(\text{opp}) = \frac{2T_z(\text{opp})}{H} \quad (6.4)$$

Eq. (6.44) is also the same as the single-airway occupancy formulation of the vertical collision risk model utilized in Annex A of Volume 2 of the RGCSF/6 report (ICAO, 1988b) concerning the European studies of RVSM presented at RGCSF/6 in 1988.

Consider now vertical separation as a part of composite separation. As set out in Section 5.3.2, *60 NM/1000 ft composite separation*, composite or staggered separation was on the agenda of the NAT SPG from the 5th to the 8th meeting inclusive and again at the 12th, 13th, and 15th meetings with the key work performed at the 5th and 6th meetings. The principle of composite separation was shown in Figure 3.1 in Chapter 3 (Pool, 1983) and also in e.g. Figure 7 of Machol (1975) and Figure 4 of Appendix 3 – A to NAT SPG/5 (ICAO, 1968a). For completeness, some of the text from Section 5.3.2 has been repeated below.

The collision risk model used to calculate the expected number N_{ayz} of accidents due to the loss of composite separation for same-direction traffic during the 5th meeting of the NAT SPG as presented in Section 5.3.2 reads

$$N_{ayz} = 10^7 P_z(1000) \frac{\lambda_x}{S_x} E_{yz}(\text{same}) P_y(60) \left\{ \frac{\Delta V}{2\lambda_x} + \frac{|\dot{y}(60)|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\} \quad (5.35)$$

where $E_{yz}(\text{same})$ is the composite occupancy, i.e. the average number of same-direction aircraft occupying segments of length $2S_x$ of the four flight paths nearest to the flight path of a typical aircraft and the meaning of the other parameters should be clear. As follows from the discussion above on 1000 ft vertical separation by itself, a difficulty that the Group had to deal with at its 5th meeting was that no agreed value of $P_z(1000)$ was as yet available. The difficulty was resolved by relating the composite risk N_{ayz} to the vertical collision risk for aircraft separated by 1000 ft, $N_{az}(1000)$, i.e. by considering eq. (2) in Appendix 3 – A to NAT SPG/5 (ICAO, 1968a),

$$\frac{N_{az}(1000)}{N_{ayz}} = \frac{E_z(\text{same}) P_y(0) \left\{ \frac{\Delta V}{2\lambda_x} + \frac{|\dot{y}(0)|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\}}{E_{yz}(\text{same}) P_y(60) \left\{ \frac{\Delta V}{2\lambda_x} + \frac{|\dot{y}(60)|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right\}} \quad (5.36)$$

The occupancy ratio was eliminated from eq. (5.36) by using the slightly cautious approximation $E_{yz}(\text{same}) = 2E_z(\text{same})$. Substitution of all the remaining, agreed, parameter values into eq. (5.36) resulted in

$$\frac{N_{az}(1000)}{N_{ayz}} = 31 \quad (5.37)$$

Eq. (5.37) states that a system with composite separation is 31 times safer than the corresponding system with a vertical separation of 1000 ft. Numerical results for the latter based on height-keeping performance without recalibration of the static system were then used to obtain central and 90% confidence level values for the composite system collision risk N_{ayz} . The calculations were subsequently extended by accounting for opposite-direction traffic and track changes and flight level changes. From the numbers obtained, the Group

concluded that a system of tracks separated laterally by 60 NM whereby adjacent tracks are staggered by 1000 ft would be likely to afford an acceptable level of safety and that such a system may be practicable in the NAT oceanic area.

NAT SPG/6 (1969)

As summarized in Section 5.3.2, discussion on the operational and collision risk aspects of 60 NM/1000 ft composite separation continued at the 6th meeting of the NAT/SPG. With regard to the time scale for application of composite separation in the NAT Region, it was hoped that this type of separation could, in its initial form, be applied during 1970. Considerations of collision risk focused on a review of the main assumptions made at the 5th meeting and led to the conclusion that the assumptions made previously were valid. The Group recalled the target level of safety of 0.45 to 1.2 accidents per ten million flying hours for all dimensions agreed at its 3rd meeting and the equal subdivision between the vertical, lateral, and longitudinal dimensions agreed at its 2nd meeting. This subdivision had been made mainly because the initial work was done on lateral separation only and no estimates were available for the vertical and longitudinal separations. Composite separation added a fourth separation to be considered in combination with the other three. The Group felt that its work was now advanced sufficiently to enable it to assign estimates for the risk due to each of the separations, although the risk figures for the vertical and longitudinal dimensions were not based on any detailed analysis but rather on cautious opinions of the Group on the basis of their overall experience with the matter. A list was drawn up of the “best estimate” (50% confidence limit) and “cautious estimate” (90% confidence limit) values of the number of accidents per flying hour for each of the four separations plus that due to flight level changes (Table 3.2 in NAT SPG/6 (1969) (ICAO, 1969) refers). This list has been reproduced in Table 5.2 of Section 5.3.2.

Thus, the Group agreed that a composite system of separation using 60 NM and 1000 feet appears to meet the requirements of the target levels of safety even without segregation of opposite-direction traffic. However, it was agreed that the composite separation might not yield the same level of safety throughout future years, e.g. due to increases in opposite-direction and same-direction occupancy. As a final conclusion after considering all relevant factors the Group agreed to propose to the NAT V RAN meeting (ICAO, 1970) that it makes appropriate provisions to permit the application of a type of composite separation in the NAT Region consisting of 60 NM lateral separation combined with 1000 ft vertical separation, and this under specified conditions.

The proposal was followed up by Recommendation 10/4 – *Amendment of RAC SUPPS – Composite separation*, of the 5th North Atlantic Regional Air Navigation Meeting (ICAO, 1970).

NAT SPG/7 (1971) and NAT SPG/8 (1972)

The *Summary of Discussions of the 7th meeting of the NAT Systems Planning Group* states that the use of one composite track (60 NM/1000 ft) was planned to be used as of **1 April 1971**. The need for progressive implementation of composite separation, commensurate with the experience gained in its use, both by controllers and pilots was stressed at the meeting. The *Summary of Discussions of the 8th meeting of the NAT Systems Planning Group* (February 1972) states that the Group agreed that, in the light of experience so far obtained, the application of composite separation in the NAT Region had given full satisfaction. It was also agreed that further extension of this type of separation within the organized track structure should be left to the discretion of the Oceanic Control Centers (OACs) directly concerned with its application based on appropriate coordination.

NAT SPG/11 (1975)

The Group was informed that the European Air Navigation Planning Group (EANPG) had requested ICAO to instruct its Panel conducting a General Review of the Concept of Separation (RGCSP) to undertake, as a matter of priority, work on the feasibility of reducing the vertical separation minima above FL290 in the EUR Region or specified parts thereof. It was likely that, should the separation be changed, this would have immediate consequences on the handling of air traffic in the transition area between the EUR and NAT Regions. However, it became apparent that, based on existing conditions, there was very little likelihood that the separation minima applied in the EUR Region above FL290 could be changed safely in the near future. It was thus concluded that there was no immediate need to consider the effects of a reduction in vertical separation above FL290 in the EUR Region on NAT operations.

NAT SPG/12 (1976) – NAT SPG/15 (1979)

No further collision risk modelling work was presented or discussed at these meetings. See Section 5.3.2 for some discussion on operational aspects of the use of composite separation in the NAT Region and recall from Section 5.3.3 that, following the implementation of a 60 NM lateral separation standard in the NAT MNPS airspace as of 30 October 1980, the use of 60 NM/1000 ft composite separation was discontinued as of that date.

NAT SPG/18 (1981) – NAT SPG/20 (1983)

Following the implementation of the 60 NM lateral separation standard in the NAT MNPS airspace as of 30 October 1980, the question of the feasibility of 30 NM/1000 ft composite separation was addressed at NAT SPG/18 to NAT SPG/20 inclusive, cf. the pertinent agenda items in Table 6.5. The subject was discussed at each of these meetings under the following aspects:

- a) Mathematical statistical considerations;
- b) Cost-effectiveness considerations;
- c) Practical operational questions related to the implementation of this type of separation.

The Group agreed at NAT SPG/18 that preparatory work was required both in the operational and mathematical statistical fields regarding the use of 30 NM/1000 ft composite separation. The Group agreed at NAT SPG/19 not to pursue the question of the introduction of composite separation in the NAT MNPS airspace with any particular urgency at the time of the meeting, but to nevertheless retain the subject on its work programme and to consider the matter on future occasions as required. Extensive discussion of the three aspects listed above took again place at NAT SPG/20 leading to agreement by the Group that considerable further discussion was required and that these studies should continue within national administrations concerned, particularly with respect to the establishment of new MNPS criteria and monitoring procedures. It was thus concluded that preparatory work required both in the operational and mathematical statistical fields be pursued with the objective that its practical application may become feasible by the end of 1985.

Agenda item 11 of the *Summary of Discussions and Conclusions of the Nineteenth Meeting of the NAT Systems Planning Group* reads *Updating of the Work Programme of the NAT SPG*. Given that lateral and longitudinal separation standards had been reduced within the NAT MNPS airspace and efforts were in hand to increase system flexibility, it appeared that, for the time being, further work should concentrate on essential improvements within the current framework of the system. Reduction of vertical separation criteria above FL290 was one of the fields in which activities would particularly entail. It was pointed out at the meeting that significant efforts were being made on a world-wide level by the RGCSP of ICAO. Since it was conceivable that, under certain conditions, a reduction of vertical separation criteria could be introduced in NAT MNPS airspace before the world-wide introduction of related provisions, it was agreed that the Group's attention

should focus, among other matters, also on this subject, with a view to achieve progress as soon as possible and the subject was included (as item o) i)) in the list of tasks of the Group.

Updating of the Work Programme of the NAT SPG constituted Agenda item 16 of the *Summary of Discussions and Conclusions of the Twentieth Meeting of the NAT Systems Planning Group*. It was found useful to group the various tasks to be performed under broader subject headings. *Consideration of the possible introduction of reduced vertical separation above FL290 in the NAT Region* was one of the tasks included under the *Planning* heading of the Group's future work programme.

NAT SPG/21 (1984) – NAT SPG/25 (1988)

As reflected in Table 6.5, the subjects of the use of 30 NM/1000 ft composite separation in NAT MNPS airspace and the possible reduction of vertical separation in the NAT Region were not on the NAT SPG's agenda (as high level items) at the NAT SPG/21 (1984) meeting. Nonetheless, the meeting report's list of conclusions shows a Conclusion 21/13 concerning the former subject. Unfortunately, the meeting report available is incomplete and the contents of the conclusion are unknown.

The subjects of the use of 30 NM/1000 ft composite separation in NAT MNPS airspace and the possible reduction of vertical separation in the NAT Region were neither listed as high level agenda items nor as conclusions at the NAT SPG/22 (1985) – NAT SPG/25 (1988) Meetings. The complete report of the NAT SPG/22 (1985) Meeting refers to both subjects only under anywhere Agenda Item 6.2.4, *Planning*. The report of the NAT SPG/23 (1986) Meeting was incomplete and it is unknown to what extent the subjects were addressed.

The report of the NAT SPG/24 (1987) Meeting states in paragraph 1.2.14 under the *Composite system risk estimates* heading that four working papers relating to the mathematical-statistical aspects of the subject were presented at the meeting dealing with the risk associated with step-climbs and the risk from contingencies. No further details on the four papers were available. However, additional discussion on the still-open safety and operational aspects of the subject took place under *Planning* Agenda Item 4.3. A small working party was established to identify contentious points and to make proposals for the manner in which they could be possibly be resolved. The working party identified six points which appeared to require resolution. Some further work mentioned therein was agreed to be carried out and the Group agreed that the start of use of 30 NM/1000 ft composite separation should be aimed for some time in 1989/90. Pending completion of the RGCSP's work on RVSM (Cf. Section 6.2), some preliminary mathematical-statistical work on the reduction of vertical separation to 1000 ft between aircraft on crossing tracks was agreed to be conducted under *Planning* Agenda Item 4.4.

The report of the NAT SPG/25 (1988) Meeting dealt with *Composite separation and associated contingency risk* in paragraphs 1.2.24 ff. Simulation of traffic patterns in a composite separation organized track system and composite separation contingency risk were considered but no details of the collision risk models used were included. Additional discussion took place under *Planning in the NAT Region* Agenda Item 4.3. The Group was informed by the Member from the United Kingdom that because of the problems of congestion in continental European airspace, an application of 30 NM/1000 ft composite separation could not be envisaged in the foreseeable future. Furthermore, it was the consensus of the meeting that very little economic benefit could be derived from the application of this form of composite separation. The Group considered the upcoming completion of the RGCSP's work on RVSM later in the year under *Planning in the*

NAT Region Agenda Item 4.4 and shared the opinion that relevant action could be envisaged for inclusion of provisions allowing the use of 1000 ft vertical separation in the NAT Region.

NAT SPG/26 (1990)

The Group noted that the RGCSP had concluded at its 6th meeting in late 1988 that the application of a 1000 ft vertical separation minimum was technically feasible and that the Air Navigation Commission had endorsed this conclusion. In view of the major benefits which the implantation of a 1000 ft vertical separation minimum in the NAT MNPS airspace could offer in terms of increased capacity and cost savings, it was agreed that a Vertical Studies Group (NAT VSG)⁶⁶ be established with a list of issues to be addressed by the NAT VSG as laid down in Attachment B to the report on agenda item 4 (NAT SPG/26, 1990).

NAT SPG/27 (1991)

The VSG reported on the statistical/mathematical studies it had performed concerning the implementation of RVSM in the whole or part of MNPS airspace. This covered the RGCSP collision risk model parameters, assessment of risk employing current and future traffic levels and height-keeping performance of NAT aircraft, recommendation of TLS, monitoring requirements, and risk associated with in-flight contingencies in the reduced vertical separation minimum airspace. No details of the collision risk calculations are included in the NAT SPG/27 Meeting report⁶⁷. The discussion on Agenda Item 4.3, *Introduction of reduced vertical separation above FL290 in the NAT Region*, resulted in Conclusion 27/26 concerning *Implementation Planning for the Introduction of RVSM*, two elements of which are worth quoting here:

“That:

- a) the NAT Vertical Studies Group
- b) , established pursuant to NAT SPG/26 Conclusion 26/19, be disbanded;
- c) a NAT Vertical Studies Implementation Group (VSIG) be established in accordance with the terms of reference and work programme set out in Attachment A⁶⁸ to the Report on Agenda Item 6;
- d)

The VSIG comprised three sub-groups, ATC, OPS/AIR, and Airspace. The terms of reference of the VSIG comprised three tasks, including to report to NAT SPG/28 an expanded implementation strategy for reduced vertical separation of 1000 ft between FL290 and FL410.

NAT SPG/28 (1992)

It was reported under Agenda Item 1.2.4, *RVSM operations in the NAT Region*, that two methods of RVSM safety assessment were under development, namely one method based on sequential sampling and the other method based on direct risk assessment. It was intended that both methods be developed in time for NAT SPG/29 (1993). Several lateral offset scenarios were discussed (cf. Section 6.3). Twelve main areas of work which needed to be progressed over the next year were identified, including review of mathematical documentation for NAT RVSM operations. A report of the VSIG was also provided under Agenda Item 4.2.4 of Agenda Item 4, *Planning and Implementation in the NAT Region*, but without direct relevance to this document.

⁶⁶ Ad hoc sub-groups established at and for the duration of meetings have been utilized by the NAT SPG from its first meeting onwards. The VSG was one of the first sub-groups operating between NAT SPG meetings. A NAT SPG Task Force (TF) established at NAT SPG/25 preceded the VSG as a longer-lasting sub-group.

⁶⁷ A consequence of the establishment of sub-groups operating independently between NAT SPG meetings is that less detailed information is available in the NAT SPG Meeting reports.

⁶⁸ The correct reference should read Attachment D.

NAT SPG/29 (1993)

Vertical occupancy estimates for 1992/1993 were reported under Agenda Item 1.7, *Aspects of the Future NAT System – Vertical Occupancy and Risk*. An interim classification scheme for large height deviations was agreed. The scheme was based on a two-part code and, where necessary a weather indicator. The first part of the code consisted of a number (1 – 3) which identified the region of airspace in which the final flight level was located, with the codes being as follows:

- 1 Final level within MNPS airspace
- 2 Final level above MNPS airspace
- 3 Final level below MNPS airspace

The second part of the code was a letter (A – I or O) which identified the type of event that caused the deviation. The codes were as follows:

- A Contingency action due to engine fault
- B Contingency action due to pressurisation failure
- C Contingency action due to other cause
- D Failure to climb/descent as cleared
- E Climb/descent without ATC clearance
- F Entry to MNPS airspace at an incorrect level
- G ATC FL re-clearance resulting in loss of lateral or longitudinal separation
- H Deviation due to TCAS
- I Aircraft unable to maintain level
- O other

Finally, the weather modifier, W, was to be included in brackets if the cause of the event was due to weather conditions (particularly turbulence).

A total of fifteen work items were identified under Agenda Item 1.8, *Mathematicians work programme for 1993/94*, of which the following ones should be mentioned here in connection with vertical separation:

- 8. **United Kingdom** to develop documentation for direct vertical risk estimation technique (By February 1994).
- 9. **United States** to develop documentation for sequential sampling approach (By February 1994).
- 10. **All** to produce a vertical risk assessment guidance document by NAT SPG/30.
- 11. **All** to examine the proposed methodology for assessment of risk from contingency manoeuvres and operational errors (By November 1993).
- 12. **Canada and United Kingdom** to examine data for HMU sites in Canada and in the United Kingdom (By November 1993).
- 13. **All** to consider proposals for a height monitoring programme.

See Section 6.4.3 concerning work item 10. from the above list.

Various elements of the NAT VSIG's work programme were reported under Agenda Item 4.3, *Reports of the implementation sub-groups*, namely, requirements for system monitoring, matters related to airspace monitoring, amendment to the NAT Regional Supplementary Procedures, airplane/operator approval, cost/benefit analysis, updates to the guidance material, effects of turbulence on collision risk, non-approved aircraft climbing or descending through MNPS airspace, future role of the VSIG and work programme, height monitoring units – cost sharing, and cost recovery.

Concerning the future role of the VSIG and work programme, the question of expanding the terms of reference of the VSIG to include reductions in horizontal separation minima was discussed. It was agreed that the VSIG be replaced by another working group called the Reduced Separation Standards Implementation Group (RSSIG) and that it be constituted along the same lime lines as the VSIG, that is, a main coordinating group assisted by specialized sub-groups.

NAT SPG/30 (1994)

Various elements of the NAT RSSIG's work programme were reported under Agenda Item 2.5, *Report of the Reduced Separation Standards Implementation Group*, namely, Operations/Airworthiness, Airspace Monitoring, Use of RVSM by the military, Real time alerts, Update the RVSM Guidance Material, Further amendments to the NAT Regional Supplementary Procedures, Reduced horizontal separation minima, Preparation of RVSM presentation package and Aeronautical Information Circular, Preparation for the RVSM seminar, Turbulence data collection, Cost/benefit studies and decision making tools, Arrangement on the joint financing of the NAT Height Monitoring System.

Vertical occupancy estimates for the 1993/1994 monitoring year were reported under Agenda Item 3.2, *Review of system safety performance – RVSM Topics – Vertical Occupancy and Risk*. Computer simulation results of lateral and vertical occupancies for three main scenarios were also considered.

A total of thirteen work items were identified under Agenda Item 3.2, *Review of system safety performance – Proposed Mathematicians' Work Programme for 1994/95*, of which the following ones are related to RVSM:

1. **United Kingdom** to review the CRM parameters for use with RVSM.
2. **United Kingdom** and **United States** to determine a common core set of data from the HMU and GMS monitoring programmes for the height monitoring database by July 1994.
3. **United Kingdom** to provide an assessment of airframes likely to be observed by the HMU system.
4. **United Kingdom** and **United States** to develop proposals for ASE/TVE action trigger levels for use during the height monitoring programme.
12. **All** to continue to develop mathematical guidance material for RVSM implementation.

See Section 6.4.3 concerning work item 12. from the above list.

NAT SPG/31 (1995)

It was noted under Agenda Item 2.3, *Report of the NAT Implementation Management Group*, that the programme for reducing the vertical separation minimum from 2000 ft to 1000 ft between FL290 and FL410 was ongoing and that the NAT IMG was focusing on two major areas, namely delays in the development and implementation of the monitoring system threatening the target date of 2 January 1997 for the commencement of an operational trial, and matters related to Service Bulletins. Some transition area issues and the allocation of RVSM flight levels were briefly reported under Agenda Item 2.5, *Other Issues*.

Vertical occupancy estimates for the 1994/1995 monitoring year were reported under Agenda Item 3.2, *Review of system safety performance – RVSM Topics – Vertical Occupancy and Risk*. Same-direction, opposite-direction, and equivalent⁶⁹ opposite-direction vertical occupancies were presented based on data provided by Canada and the United Kingdom. Both the Canadian and United Kingdom data showed that over the last few years the vertical occupancy for the organized track system had been increasing whilst that for random

⁶⁹ Equivalent opposite-direction occupancy is the sum of opposite-direction occupancy and same-direction occupancy converted in terms of opposite-direction occupancy. See Sections 6.4.3.2 and 6.5.2.1.

traffic had been in decline. An estimate of the operational vertical risk under RVSM solely due to large height deviations reported to the Central Monitoring Agency (CMA) during the 1994/95 monitoring year of 1.1×10^{-9} fatal accidents per flight hour due to loss of vertical separation was determined. This risk component estimate was based on up-to-date estimates of average aircraft dimensions provided by the United Kingdom. The estimate assumed an initial decrease of 60% in vertical occupancy under RVSM, but did not take into account the effect of increases in traffic or the possible bunching of traffic towards a core track. It was noted that this estimated risk component had to be supplemented with estimates of the technical vertical collision risk due to height-keeping performance and the risks associated with contingency events and turbulence. The importance of full quantitative data on the last two causes of vertical collision risk was stressed.

The importance of a trial risk assessment including both the direct assessment and the sequential sampling technique was recognized under Agenda Item 3.2, *Review of system safety performance – RVSM Topics – Preparation for RVSM verification*. This assessment would make use of whatever prototype HMU and GMU data were available. The first true preliminary assessment of vertical collision risk under RVSM in NAT MNPS airspace was planned for the Spring of 1996 subject to the availability of sufficient data. On that point, concern was expressed at the slippage in the MASPS approval process, meeting the minimum monitoring requirements, and delays, if any, in HMU production.

Two actions out of a total of 17 ones agreed under Agenda Item 3.2, *Review of system safety performance – Mathematicians' Work Programme and actions for 1995/96*, were *Prepare for RVSM verification* and *Produce next version of Supplement to NAT Doc 002*. The latter action is a continuation of action 12 of the work programme defined at the previous NAT SPG/30 Meeting. This Supplement will be utilized in Section 6.4.3 to present the modelling of total/operational vertical collision risk developed by the MWG for NAT MNPS RVSM airspace.

NAT SPG/32 (1996)

The Group noted a preliminary safety assessment concerning the implementation of RVSM under Agenda Item 2.3, *Report of the NAT Implementation Management Group – Preliminary safety assessment for RVSM*. The assessment was based on height monitoring data collected from December 1995 to July 1996 and on large height deviations between January 1995 and June 1996 that had been reported to the CMA. It was noted that the next update to the assessment would include an examination of all height monitoring data accumulated up to the end of October 1996. The estimates of risk based on airworthiness approved aircraft seen so far were very encouraging but given the small amount of data seen (210 airframes), they remained inconclusive. It was anticipated, however, that when a representative sample of monitoring results of airworthiness approved aircraft from the Phase I RVSM population became available, it would result in a technical risk value well within the safety constraint.

One of the twenty-seven actions listed in Appendix E, *Actions and proposed Mathematicians' Work Programme for 1996/976*, was to *Produce next version of Supplement to NAT Doc 002* by NAT SPG/33. As indicated before, this supplement will be utilized in the next sub-section to present the two safety assessment methods developed by the MWG for NAT MNPS RVSM airspace, i.e. *The direct assessment of system risk*, and *Sequential sampling risk assessment*. A key element of the former method is the modelling of the operational vertical collision risk due to large height deviations of a non-technical nature as a part of the total vertical collision risk. The second method focusses on the technical vertical collision risk, i.e. the risk due to normal height deviations of RVSM approved aircraft.

6.4.3 Safety assessment for NAT RVSM

6.4.3.1 Introduction

In the previous subsection, it was reported under the *NAT SGP/28 (1992)* heading that two methods of safety assessment were under development, namely one method based on sequential sampling and the other method based on direct risk assessment. Development of these methods continued as tasks on the mathematicians work programme for the subsequent years, ultimately as a task to develop mathematical guidance material for RVSM implementation.

The “Supplement to NAT Doc 002” (NAT, 1996) provides Draft version 2.0 of that mathematical guidance material. Sections 1 – 3 of it discuss the background to RVSM and the system safety and global performance requirements similar to Section 6.2 of this document. Section 4 of the supplement summarizes the proposed RVSM implementation programme. Section 5 of the supplement consists of two parts, Part A, *The direct assessment of system risk*, and Part B, *Compliance with the TLS*. A sub-section of part B is entitled *Sequential sampling risk assessment*. A similar document has been developed by the EUROCONTROL Mathematics Drafting Group (MDG) for the benefit of the implementation of RVSM in the European Region (EUROCONTROL, 2001).

Section 6.4.3.2 provides a summary of Part A, *The direct assessment of system risk*, of (Joint Aviation Authority (JAA), 1999). It recalls the form of the vertical collision risk model used and then focusses on new work performed by the NAT MWG on the modelling of the vertical collision risk due to large height deviation with a non-technical cause, i.e. operational vertical collision risk. Section 6.4.3.3 provides a summary of Part B, *Compliance with the TLS*, of the Supplement to NAT Doc 002 (NAT, 1996).

6.4.3.2 Direct assessment of system risk

Vertical collision risk does not only depend on typical height-keeping performance but also, critically, on the incidence of large height deviations (LHDs). The method used to evaluate the collision risk of the NAT system was to be the same as that was used in the original determination of RVSM feasibility, i.e. the Reich collision risk model. The statement of the Reich model for the vertical dimension given by eq. (1) of (NAT, 1996) is

$$N_{az} = P_z(S_z)P_y(0)^{\frac{\lambda_x}{\hat{S}_x}} \left[E_z(\text{same}) \left(\frac{|\Delta V|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) + E_z(\text{opp}) \left(\frac{2\bar{V}}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \right] \quad (6.45)$$

This is essentially the occupancy formulation of the collision risk model for a single airway given by eq. (6.9) as utilized in Annex A of Volume 2 of the RGCSP/6 report (ICAO, 1988b). Two minor differences between eq. (6.45) and eq. (6.9) are the use of the symbol $P_z(S_z)$ for the probability of vertical overlap rather than $P_z(std)$ and the use of the symbol $\hat{S}_x$ for the proximity distance used in the occupancy definition instead of the symbol S_x (which is also used to denote the longitudinal separation standard). Recall Table 6.1 for the definitions of the various collision risk model parameters.

The collision risk model of eq. (6.45) is also expressed in terms of same and opposite-direction passing frequencies $N_x(\text{same})$ and $N_x(\text{opp})$ as defined by eqs. (6.13) and (6.14) and in the current notation

$$N_x(\text{same}) = \frac{\lambda_x}{\hat{s}_x} E_z(\text{same}) \frac{|\overline{\Delta V}|}{2\lambda_x} \quad (6.46)$$

$$N_x(\text{opp}) = \frac{\lambda_x}{\hat{s}_x} E_z(\text{opp}) \frac{\overline{2V}}{2\lambda_x} \quad (6.47)$$

Taking account of eqs. (6.46) and (6.47), eq. (6.45) can be rearranged as

$$N_{az} = P_z(S_z)P_y(0) \left[\frac{\lambda_x}{\hat{s}_x} E_z(\text{same}) \frac{|\overline{\Delta V}|}{2\lambda_x} \left(1 + \frac{\lambda_x}{\lambda_y} \frac{|\overline{y}|}{|\overline{\Delta V}|} + \frac{\lambda_x}{\lambda_z} \frac{|\overline{z}|}{|\overline{\Delta V}|} \right) + \frac{\lambda_x}{\hat{s}_x} E_z(\text{opp}) \frac{\overline{2V}}{2\lambda_x} \left(1 + \frac{\lambda_x}{\lambda_y} \frac{|\overline{y}|}{\overline{V}} + \frac{\lambda_x}{\lambda_z} \frac{|\overline{z}|}{\overline{V}} \right) \right] \quad (6.48)$$

and thus

$$N_{az} = P_z(S_z)P_y(0) \left[N_x(\text{same}) \left(1 + \frac{\lambda_x}{\lambda_y} \frac{|\overline{y}|}{|\overline{\Delta V}|} + \frac{\lambda_x}{\lambda_z} \frac{|\overline{z}|}{|\overline{\Delta V}|} \right) + N_x(\text{opp}) \left(1 + \frac{\lambda_x}{\lambda_y} \frac{|\overline{y}|}{\overline{V}} + \frac{\lambda_x}{\lambda_z} \frac{|\overline{z}|}{\overline{V}} \right) \right] \quad (6.49)$$

or

$$N_{az} = P_z(S_z)P_y(0) [N_x(\text{same})c_1 + N_x(\text{opp})c_2] \quad (6.50)$$

with

$$c_1 = \left(1 + \frac{\lambda_x}{\lambda_y} \frac{|\overline{y}|}{|\overline{\Delta V}|} + \frac{\lambda_x}{\lambda_z} \frac{|\overline{z}|}{|\overline{\Delta V}|} \right) \quad (6.51)$$

and

$$c_2 = \left(1 + \frac{\lambda_x}{\lambda_y} \frac{|\overline{y}|}{\overline{V}} + \frac{\lambda_x}{\lambda_z} \frac{|\overline{z}|}{\overline{V}} \right) \quad (6.52)$$

Rewriting eq. (6.50) as

$$N_{az} = P_z(S_z)P_y(0)c_2 \left[N_x(\text{same}) \frac{c_1}{c_2} + N_x(\text{opp}) \right] \quad (6.53)$$

and defining

$$N_x(\text{equivalent}) = N_x(\text{same}) \frac{c_1}{c_2} + N_x(\text{opp}) \quad (6.54)$$

ultimately gives for the passing frequency of the vertical collision risk model of (NAT, 1996)

$$N_{az} = P_z(S_z)P_y(0)c_2 N_x(\text{equivalent}) \quad (6.55)$$

See Supplement to NAT Doc 002 (NAT, 1996) for how the collision risk model parameters other than the probability of vertical overlap $P_z(S_z)$ for $S_z = 1000$ ft were estimated for the implementation of RVSM in the NAT region.

Various causes, both technical and operational, contribute to the probability of vertical overlap $P_z(1000)$. As stated in Supplement to NAT Doc 002, technical errors are continuously distributed in general and the process of determining their contribution to $P_z(1000)$ is well documented, viz. in the RVSM manual (ICAO, 2012b) and the RGCSP/6 report (ICAO, 1988b). Although Section 5.4 of (ICAO, NN) summarizes the estimation of this component of the probability of vertical for the implementation of RVSM in the NAT Region, it will not be dealt with further here because it will be treated in full detail in Subsection 6.5.2.1 of Section 6.5, *RVSM collision risk assessment for the AFI Region of ICAO*.

Section 5.5 of Supplement to NAT Doc 002 deals with the estimation of the contribution of large height deviations (LHDs) other than technical height deviations to the collision risk and the models developed in that section were developed from basic principles by the NAT MWG for the first time. The section begins with a subdivision of the large height deviations collected by the NAT CMA into four main types:

- (1) ATC-pilot loop errors and incorrect clearances;
- (2) Aircraft contingency events;
- (3) Deviations due to meteorological effects; and
- (4) Deviations due to TCAS.

See also the preliminary classification listed under the *NAT SPG/29 (1993)* heading in Section 6.4.2.

ATC-pilot loop errors and incorrect clearances are likely to result in aircraft flying at integral multiples of the separation minimum from their correct level. Contingency procedures are designed to minimize the risk in case of a contingency event by turning away from the assigned track and descending and resuming flight at a level which differs from the normally used levels by 500 ft. However, it is possible that due to the nature of the event, an aircraft may be forced to descend through one or more levels before being able to leave the assigned track. The number of levels transited before leaving the assigned track then determines the contribution of contingency events to the vertical collision risk. The deviations-due-to-meteorological-effects category of large height deviations includes large height deviations caused by aircraft being unable to maintain their assigned level due bad weather conditions, e.g. turbulence. At the time of the start of RVSM Phase I in the NAT Region on 27 March 1997, a large percentage of aircraft was equipped with TCAS version 6.04 which assumed a 2000 ft environment above FL290 and Version 7 which included changes to the TCAS logic to cope with RVSM was not due to be in widespread use until 1998. As a result, it was conceived that TCAS might give a large number of Traffic Advisories (TAs) and a smaller number of Resolution Advisories (RAs) until Version 7 would be widely available. If the extent of the height deviation is significant, then the event leading to a TCAS RA needs to be included in the collision risk estimation process. For NAT RVSM, TCAS events were subdivided in genuine TCAS RAs and nuisance RAs with the latter mostly requesting the pilot to return to the originally assigned flight level.

Following the subdivision of large height deviations into four categories, a classification for risk assessment purposes is described in Section 5.5 of (NAT, 1996). The following table shows the classification and, where applicable, the type of data needed to estimate the vertical collision risk with each type of large height deviation.

Table 6.6: NAT MWG classification of large height deviations for risk assessment purposes

Risk bearing deviations		Non-risk bearing deviations
Involving whole numbers of flight levels	Not involving whole numbers of flight levels	
(i) The number of flight levels crossed without clearance, if any (ii) The rate of ascent/descent (iii) The time spent in level flight at uncleared flight levels, if any	- Magnitude of (maximum) deviation - Duration of deviation	- Occurred wholly outside MNPS airspace - Explicit statement of correct contingency procedures followed and aircraft turned off track prior to any level change

In principle, quantitative information on risk-bearing large height deviations should be obtained from the pertinent event reports. It was recognised, however, that this information is not always included in practice and a kind of “default” values for ascent/descent rates and time spent at incorrect level have been determined by the NAT MWG for different causes of large height deviations.

The last step of *The direct assessment of system risk* method was then to specify how the above can be used to estimate the probability of vertical overlap $P_z(1000)$ due to large height deviations of an operational-error nature. It follows from Table 6.6 that the vertical collision risk due to large height deviations involving whole numbers of flight levels is made up of two parts, namely the risk due to time spent at incorrect levels and that due to levels crossed without a clearance. Using a notation similar to that introduced in Section 5.3.7 for the probability of lateral overlap due to time spent at wrong parallel routes, the probability of vertical overlap due to large height deviations resulting in time spent at uncleared/incorrect flight levels given by eq. (23) of (NAT, 1996) can be written as

$$P_z(S_z)^{\text{wrong level}} = \frac{T_l}{F} \times P_z(0) \quad (6.56)$$

where T_l represents the total amount of time spent at uncleared/incorrect flight levels in the airspace under consideration for a given period of calendar time and F denotes the total amount of flight time in the airspace over the period of calendar time. The total amount of time T_l spent at uncleared/incorrect flight levels needs to be estimated on the basis of information in the event reports on large height deviations. The total amount of flight time F was estimated as the product of the number of movements in the NAT and an average flight duration of 3.5 hours. The remaining parameter, $P_z(0)$, on the right side of eq. (6.56) denotes the probability of vertical overlap due to normal technical height deviations of RVSM approved aircraft at the same flight level. It can be estimated from the probability distribution with probability density function $f(z)$, say, of those height deviations in the same way as the probability of vertical overlap $P_z(S_z)$, viz.

$$P_z(0) = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f(z_1) f(z_1 - z) dz_1 dz \quad (6.57)$$

where λ_z denotes the average height of the aircraft. Cf. eq. (6.98) of Section 6.5.2.2.1 for $P_z(S_z)$. As set out in Section 5.3.7, eq. (6.56) and eq. (6.58) below were the basis for the revised NAT MWG methodology for the assessment of lateral collision risk on parallel routes.

Two models have been developed by the NAT MWG for the risk due to levels crossed without clearance, dependent on the climb/descent rate as that affects the angle at which the transitioning aircraft crosses each flight level. Model 1 was employed for climb/descent rates less than or equal to 4000 ft/min (approximately 40 knots) while Model 2 was used for pressurization failures which can result in descent rates of 4000 ft/min to 6000 ft/min (approximately 40 to 60 knots).

For model 1, the usual assumption is made that the sides of the box representing a climbing/descending aircraft remain parallel to the original level flight path during the large height deviation. The Reich model is then re-derived for Model 1 in eqs. (24) – (32) of (NAT, 1996) for a single flight level crossing and it is noted that this needs to be multiplied by the number of levels crossed during the period of time under consideration. It then follows that the probability of vertical overlap $P_z(S_z)^{wrong_{cl}^d}$ for large height deviations resulting in uncleared/incorrect levels crossed can be expressed as

$$P_z(S_z)^{wrong_{cl}^d} = \frac{N_l}{F} \times \frac{2\lambda_z}{|\dot{z}(S_z)|} \quad (6.58)$$

where N_l represents the total number of crossings through uncleared/incorrect flight levels in the airspace under consideration for a given period of calendar time and F denotes again the total amount of flight time in the airspace over the period of calendar time. As in eq. (6.57), λ_z denotes the average height of the aircraft. The parameter $|\dot{z}(S_z)|$ in the denominator on the right side of eq. (6.58) denotes the average absolute relative vertical speed between an incorrectly climbing/descending aircraft and an aircraft in level flight when the vertical separation minimum is S_z feet. The number of crossings through uncleared/incorrect levels needs to be estimated on the basis of information in the event reports on large height deviations.

Model 2 accounts for the crenelating of a very rapidly descending aircraft. This can be done by considering the relative motion between a descending aircraft and an aircraft in level flight in a lateral dimension and a combined longitudinal and vertical dimension. This is similar, to combining the lateral and longitudinal dimensions for aircraft on intersecting tracks, see e.g. Sections 5.4.2.6 and 6.5.2.1. A paper was referenced in which Model 2 was derived and eq. (33) of (Burt, 1999) presents the model for a single uncleared/incorrect flight level crossing per flight hour. Accounting for N_l uncleared/incorrect flight level crossings per flight hour, Model 2 can be expressed as

$$N_{az} = P_z(S_z)^{wrong_{cl}^d} P_y(0) \frac{\lambda_x}{S_x} \left[E_z(\text{same}) \left(\frac{|\bar{y}|}{2\lambda_y} + \frac{\sqrt{|\Delta V|^2 + |\dot{z}|^2}}{2\lambda_{xz}(\text{same})} \right) + E_z(\text{opp}) \left(\frac{|\bar{y}|}{2\lambda_y} + \frac{\sqrt{(2\bar{V})^2 + |\dot{z}|^2}}{2\lambda_{xz}(\text{opp})} \right) \right] \quad (6.59)$$

with

$$P_z(S_z)^{wrong_{cl}^d} = \frac{N_l}{F} \times \frac{\lambda_x(1+\pi/4)+2\lambda_y}{4|\dot{z}(S_z)|} \quad (6.60)$$

The collision risk model in eq. (6.59) contains two new parameters, $\lambda_{xz}(\text{same})$ and $\lambda_{xz}(\text{opp})$ which are the average lengths of the paths followed by the descending aircraft's centre as it passes through the lozenge surrounding a same-direction or opposite-direction aircraft in level flight respectively. Notice that the aircraft height plays a role in these two parameters but not in the probability of vertical overlap given by eq. (6.60).

In conclusion, the estimate of $P_z(1000)$ due to technical height-deviations of RVSM approved aircraft can be substituted in one of the collision risk models in eqs. (6.45) or (6.55) to obtain an estimate of the technical vertical collision risk. This estimate is to be compared with the technical vertical target level of safety of 2.5×10^{-9} fatal accidents per flight hour. Similarly the sum of the probabilities of vertical overlap due to technical height deviations and risk-bearing large height-deviations of an operational error can be substituted in one of the collision risk models in eqs. (6.45) or (6.55) for Model 1 (and similarly for Model 2) to obtain an estimate of the total vertical collision risk. The latter estimate is to be compared with the total vertical target level of safety of 5×10^{-9} fatal accidents per flight hour. The resulting risk estimates are best estimates or point estimates and may, in principle, be supplemented with interval estimates or confidence intervals. This applies in particular to the estimate of the technical vertical collision risk because of the continuous probability distribution of the technical height deviations. A related perspective is presented in the next sub-section, *Compliance with the TLS*.

6.4.3.3 Compliance with the TLS

As stated at the beginning of the introduction of Part B, *Compliance with the TLS*, of (NAT, 1996), the purpose of Part B is to describe a set of complementary procedures that can determine when it can be forecast with confidence that the TLS will be met under RVSM or that the TLS is being met once RVSM is in place. At the heart of this process is the sequential sampling risk assessment method which equates the actual operational errors and flight technical errors seen, against the allowed or expected number given a system meeting the TLS. An application of this technique in the lateral dimension can be found in (Moek & Traas, 1979). The assessment is based on the assumptions that the MASPS are working and the risks due to altimetry system error for RVSM approved aircraft and due to contingency events are negligible. As regards altimetry system error, a section on the assessment of ASE using (non- sequential) statistical hypothesis testing in combination with the MASPS's requirements precedes the section dealing with the sequential sampling risk assessment method in (NAT, 1996).

The *Compliance with the TLS* method is described for completeness although it deals with the use of statistical methods rather than collision risk modelling proper. The collision risk model is only used in a reverse manner to obtain constraints on

- the probability of vertical overlap due to technical height deviations; and
- the probability of vertical overlap due to the total of all causes, i.e. technical, operational, turbulence, contingencies and other, if any,

that are consistent with the technical and total vertical target levels of safety for MNPS airspace in the NAT region respectively. The derivation of the constraints and the use of a sequential statistical hypothesis testing method proceed fairly easily. A complicating factor, however, concerns the question of ensuring that the samples obtained through the height monitoring process are independent for time-dependent (large) height deviations. The sample data constitute the input to the hypothesis test.

The *Sequential sampling risk assessment method* section of (NAT, 1996) is stated to summarize the following:

- (a) A method to relate the frequency of occurrence for different types of vertical errors from individual aircraft to the probability of vertical overlap;

- (b) A procedure to simultaneously test that the sum of frequencies from different types of vertical errors are at or below values consistent with a TLS at a specified high level of confidence. It includes operational errors which usually occur at one or more separation standards;
- (c) A procedure to estimate the average number of samples required for the test to successfully terminate;
- (d) A spreadsheet program to automatically configure different tests for 500 ft, 650 ft, and 950-1050 ft frequencies based on vertical occupancies and lateral standard deviation.

(a) A method to relate the frequency of occurrence for different types of vertical errors from individual aircraft to the probability of vertical overlap

Bullet (a) is then translated into the need to establish four connections concerning the development of individual aircraft maximum error frequencies required to meet the TLS, namely concerning:

- (1) The chosen TLS and $P_z(1000)$;
- (2) $P_z(1000)$ and the probability that an error of a given magnitude occurs from an individual aircraft;
- (3) The probability that the error occurs and the error frequency in a given time interval; and
- (4) The sum of frequencies from one or more error types in a given time interval and $P_z(1000)$.

Consider the **first** step of the translation of bullet (a), i.e. the establishment of a connection between the applicable target level of safety and the probability of vertical overlap $P_z(1000)$. This connection can be obtained from the collision risk model, e.g. the one given by eq. (6.45). The model is then used in what is often called a reverse manner, i.e. by substituting the value of the TLS for N_{az} , choosing representative values for all the collision risk model parameters other than $P_z(1000)$, particularly for occupancy and the probability of lateral overlap, and solving for $P_z(1000)$. This is the same process as described in Section 6.2.3 for the height-keeping performance requirement of the global system performance specification for RVSM.

The **second** step of the translation of bullet (a) consists of establishing a connection between $P_z(1000)$ and individual aircraft error probability. This needs to be addressed differently for aircraft height-keeping errors and operational vertical errors. For height-keeping errors, it can be done in the same way as was done to derive the global height-keeping performance specification. It can be shown that, under certain regularity conditions, the following relationship exists between $P_z(1000)$ and the probability of height-keeping errors z between 950 and 1050 feet,

$$P(950 \leq |z| \leq 1050) \approx \frac{100}{2\lambda_z} \times P_z(1000) \quad (6.61)$$

with λ_z in feet, say, approximately 50 ft. Cf eqs. (5.63) – (5.67) of Section 5.3.3. Taking the value of $P_z(1000)$ as derived under the first step as an upper bound for it, the approximation in eq. (6.61) may be used as an inequality, i.e.

$P(950 \leq z \leq 1050) \leq \frac{100}{2\lambda_z} \times P_z(1000) \quad (6.62)$

In addition, the RGCSP recommended that height-keeping performance values for errors z greater than or equal to 650 feet and 500 feet should be no more than a factor of 10 and 100, respectively, than the corresponding value of $P_z(1000)$ (ICAO, 1988b). Thus, it should hold additionally that

$$P(|z| \geq 650) \leq 10 \times P_z(1000) \quad (6.63)$$

$$P(|z| \geq 500) \leq 100 \times P_z(1000) \quad (6.64)$$

Eqs. (6.63) and (6.64), when satisfied, provide early indications of the target level of safety being met.

For large height deviations involving flying at a wrong level as a result of operational error, the connection between the probability of error, p_{OE} say, and $P_z(1000)$ was given above by eq (6.56) with

$$p_{OE} = \frac{T_l}{F} \quad (6.65)$$

Taking $P_z(1000)$ in eq. (6.56) again as an upper bound for it, eq. (6.56) may be used as a constraint on p_{OE} ,

$$p_{OE} \leq \frac{P_z(1000)}{P_z(0)} \quad (6.66)$$

The parameter T_l^{70} in the right side of eq. (6.65) denotes the total time of flying at a wrong level and may be expressed as the product of the number, n_l , and average duration, $\bar{T}_l$, of such errors, i.e.

$$T_l = n_l \times \bar{T}_l \quad (6.67)$$

To be precise, n_l is the number of errors involving flying at a wrong level during F flight hours. Substitution of eq. (6.67) into eq. (6.65) gives after some rearrangement

$$\frac{n_l}{F} = \frac{p_{OE}}{\bar{T}_l} \quad (6.68)$$

For given values of F , the total amount of flight time for a given period of calendar time, and $\bar{T}_l$, the average duration of a wrong-level flying event in the given period of calendar time, the upper bound in eq. (6.66) on p_{OE} translates into an upper bound on the number of wrong-level-flying events n_l , i.e.

$$n_l = \frac{F}{\bar{T}_l} p_{OE} \leq \frac{F}{\bar{T}_l} \frac{P_z(1000)}{P_z(0)} \quad (6.69)$$

The **third** step of the translation of bullet (a) concerns the connection between the probability that an error occurs and its error frequency in a given time interval. This connection addresses the question of obtaining independent samples of time-varying height-keeping errors. It is illustrated for the probability p_{OE} of an operational error involving flying at a wrong flight level. The ratio on the left side of eq. (6.68) is denoted α in eq. (51) of (NAT, 1996) and the equation is expressed as

⁷⁰ The subscript l (level) on T_l rather than OE is used to maintain consistency in notation with the probability of lateral overlap due to time spent at wrong parallel routes in Section 5.3.7.

$$\alpha = \frac{p_{OE}}{\bar{T}_l} \quad (6.70)$$

Both sides of eq. (6.68) are then multiplied by an error-type-dependent fixed-time interval t , which is the length of time required for independent samples, resulting in the error-frequency or the number of errors f_t in a fixed-time interval, i.e.

$$f_t = \alpha \cdot t = \frac{t}{\bar{T}_l} \cdot p_{OE} \quad (6.71)$$

where $t \geq \bar{T}_l$. The error-frequency f_t in a fixed-time interval can also be expressed in terms of the number of wrong-level—flying errors, viz.

$$f_t = \frac{t}{F} \cdot n_l \quad (6.72)$$

The upper bound on n_l in eq. (6.69) can now be translated into an upper bound on the error-frequency f_t in a fixed-time interval. Making the pertinent symbols dependent on the type of height-keeping error, here large height deviations due to operational error (OE), it follows that

$$f_{t;OE} \leq \frac{t_{OE}}{\bar{T}_l} \cdot \frac{P_z(1000)}{P_z(0)} \quad (6.73)$$

Upper bounds similar to eq. (6.73) can be derived from the constraints on the probabilities of height-keeping errors z between 950 and 1050 feet, $P(950 \leq |z| \leq 1050)$, greater than or equal to 650 feet, $P(|z| \geq 650)$, and greater than or equal to 500 feet, $P(|z| \geq 500)$ in eqs. (6.62) – (6.64). This was done for FTE height-keeping errors in (NAT, 1996) (on the assumption that the risk due to ASE is negligible), resulting in

$$f_{t;FTE950} \leq \frac{t_{FTE950}}{\bar{T}_{FTE950}} \cdot \frac{100}{2\lambda_z} \cdot P_z(1000) \quad (\lambda_z \text{ in feet}) \quad (6.74)$$

$$f_{t;FTE650} \leq \frac{t_{FTE650}}{\bar{T}_{FTE650}} \cdot 10 \cdot P_z(1000) \quad (6.75)$$

$$f_{t;FTE500} \leq \frac{t_{FTE500}}{\bar{T}_{FTE500}} \cdot 100 \cdot P_z(1000) \quad (6.76)$$

In eqs. (6.74) – (6.76), $\bar{T}_{FTE950}$, $\bar{T}_{FTE650}$, and $\bar{T}_{FTE500}$ denote the average durations of an FTE error between 950 and 1050 feet, greater than or equal to 650 feet, and greater than or equal to 500 feet, respectively.

The scaling by means of the factors $t_{OE}/\bar{T}_l$ etc. in eqs (6.73) – (6.76) is necessary in the context of obtaining independent samples. It should be noted that the numerators of the (first) ratios in these equations are required to be larger than or equal to their corresponding denominators.

In order to be able to apply the upper bounds in eqs. (6.73) – (6.76) to the equations' left-side variables, the average event durations and the error-type-dependent fixed-time intervals $t_{...}$ had to be estimated. The second and third columns in Table 6.7 below show the estimates provided in Table 13 of (NAT, 1996), which reference should be consulted for details of the estimations. The average duration of FTE errors was based on data of FTEs of 500 feet or greater and that of operational errors OE on the average time between

waypoint reports. The fixed-time interval for independent samples of operational errors OE was taken as the average duration of a NAT crossing.

The last column of Table 6.7 shows the upper bounds on the error-frequencies f_t computed by the current authors by means of eqs. (6.73) – (6.76) for the current NAT airspace scenario in (NAT, 1996). Not surprisingly, the computed values agree with those in Tables 14 and 15 of (NAT, 1996) for the same scenario. Apart from additional operations on the values of the error-frequencies f_t in the last column of Table 6.7, the values will serve as the “success” probability (of an error occurring) in a Bernoulli trial for a sample of n trials defining the probability distribution for the sequential hypothesis test to be described further on (under bullet (b) following the description of the fourth step under bullet (a)).

Table 6.7: Average time durations and fixed-intervals lengths for FTE and OE types of large height deviations (from (NAT, 1996)) and resulting maximum error frequencies (own computation)

Error type	Average duration $\bar{T}_{...}$ (minutes)	Fixed-time interval $t_{...}$ (minutes)	Ratio $r_{...} = t_{...}/\bar{T}_{...}$	Error-frequency $f_{...}$
$950 \leq FTE \leq 1050$	10	30	3.0	3.09E-06
$ FTE \geq 650$	10	30	3.0	3.09E-05
$ FTE \geq 500$	10	30	3.0	3.09E-04
OE	50	210	4.2	2.70E-05

The **fourth** step of the translation of bullet (a) concerns the connection between individual aircraft frequencies and the combined sum of FTE and OE frequencies necessary to meet the total vertical TLS. This connection is needed because there is not a separate TLS for the vertical collision risk due to large height deviations caused by operational error. On the assumption that the risk due to height deviations as a result of turbulence, TCAS, contingencies, etc. is negligible, the resulting risk is the sum of the risks due to technical height deviations, here FTE, and operational error OE that needs to be compared with the total vertical TLS of 5×10^{-9} fatal accidents per flight hour. Combining eqs. (6.71) and (6.72) gives

$$f_{t;FTE950} + f_{t;OE} \leq \left(\frac{t_{FTE950}}{\bar{T}_{FTE950}} \cdot \frac{100}{2\lambda_z} + \frac{t_{OE}}{\bar{T}_l} \frac{1}{P_z(0)} \right) \cdot P_z(1000) \quad (6.77)$$

On the other hand, eq (54) of (NAT, 1996) reads

$$f_{t;FTE950} + f_{t;OE} \leq r \cdot P_z(1000) \quad (6.78)$$

with

$$r = \max \left(r_{FTE}, \frac{r_{OE}}{P_z(0)} \right) \quad (6.79)$$

and $r_{FTE} = t_{FTE950}/\bar{T}_{FTE950}$ and $r_{OE} = t_{OE}/\bar{T}_l$. Since λ_z was taken as 49.96 feet, the ratio $100/(2\lambda_z)$ in eq. (6.77) can be ignored. With $r_{FTE} = 3.0$, $r_{OE} = 4.2$ (cf. Table 6.7) and $P_z(0) = 0.32$, it follows that $r = \max(3.0, 13.125) = 13.125$. Use of this value of r in eq. (6.78) would, compared with eq. (6.77) be “exact” if $r_{FTE} = t_{FTE950}/\bar{T}_{FTE950}$ would increase from its Table 6.7 value of 3.0 to a value of 13.125, i.e. would increase by a factor 4.378. This increase was applied in (NAT, 1996) to the fixed-time interval t_{FTE950} for sampling FTE, making it increase from 30 minutes to $30 \times 4.378 = 131.34$ minutes or 2.189 hours.

Table 16 of (NAT, 1996) presents the resulting maximum frequencies computed based on eq. (6.78) with $r = 13.125$. The results for the (NAT, 1996) NAT airspace scenario have been reproduced in the second column of Table 6.8 below. The last three values for FTE based on an FTE fixed-interval length of 2.2 hours are a factor of 4.367 larger than their counterparts in the last column of Table 6.7 based on an FTE fixed-interval length of 30 minutes. The difference with the factor of 4.378 is believed to be caused by rounding errors. Unfortunately, however, it is not clear why the value of 2.70×10^{-5} for $f(950 \leq |FTE| \leq 1050) + f_{OE}(1000)$ in Table 6.8 is the same as that for $f_{t;OE}$ alone in Table 6.7.

Table 6.8: Required frequencies for current NAT airspace over a fixed-time intervals of 2.2 hours for FTE and 3.5 hours for OE (NAT, 1996)

Required error frequency	Value
$f_{t;FTE950} + f_{t;OE}$	2.70E-05
$f_{t;FTE950}$	1.35E-05
$f_{t;FTE650}$	1.35E-04
$f_{t;FTE5000}$	1.35E-03

As stated in (NAT, 1996), the above table completes the four connections necessary to construct a statistical test for the sum of FTEs and OEs and the NAT TLS. All the computations outlined under the four connections are performed in the spreadsheet to be discussed below under bullet (d).

(b) A procedure to simultaneously test that the sum of frequencies from different types of vertical errors are at or below values consistent with a TLS at a specified high level of confidence. It includes operational errors which usually occur at one or more separation standards

Assessing whether an observed frequency of errors is consistent with a specified occurrence frequency can be done by means of a statistical hypothesis test. The statistical hypothesis test actually used is not explicitly specified. However, the text in paragraph 5.10.9 of (NAT, 1996) under the *Description of Central Portion of Spreadsheet Output Page* heading states that:

“5.10.9 The chart in the central portion of the spreadsheet output can be used in the same manner as the table to its left. The abscissa (x-axis) corresponds to the number of samples. The ordinate (y-axis) corresponds to the number of errors observed. The portion of the chart to the right of the lower line is the accept region of the chart. The rectangles on the lower line correspond to the values in the accept column of the table. The portion of the chart to the left of the upper line is the non-acceptable region. The asterisks on the lower line correspond to the reject column in the table. The area of the chart between the two lines corresponds to when there are not enough samples to terminate the test.”

It can be inferred from the above that the test is a sequential test on the number of errors observed in a sample of increasing size n , say. This type of test was utilized to verify the safety of a lateral separation standard and is described in e.g. Sections 3.10 – 3.12 of (Lehman, 1966). The test is based on the sequential probability ratio for a sample under the alternative hypothesis H_1 and the null hypothesis H_0 and assuming, for the (NAT, 1996) application, either a binomial or Poisson probability distribution for the number of observed large height deviations, FTE, operational, or both, in a sample of increasing size n .

(c) A procedure to estimate the average number of samples required for the test to successfully terminate

Having specified the probabilities α and β for any statistical hypothesis test's type I and type II errors, the sample size necessary to control the type II error can be calculated from the value of β and the values of the probability distribution's parameter under H_0 and H_1 . The details of the calculation depend on the type of probability distribution under consideration.

Sample size estimates have been calculated in Part B of (NAT, 1996) for the benefit of the implementation of RVSM in NAT MNPS airspace for $\alpha = \beta = 0.05$ and a total NAT RVSM TLS of 5×10^{-9} fatal accidents per flight hour under H_0 and a vertical TLS of 2×10^{-8} under H_1 . The latter value was the then existing pre-RVSM vertical target level of safety. It has been successfully attempted to reconstruct the calculated sample sizes in Figure 4 of (NAT, 1996).

(d) A spreadsheet program to automatically configure different tests for 500 ft, 650 ft, and 950-1050 ft frequencies based on vertical occupancies and lateral standard deviation.

This last part of the *Sequential sampling risk assessment method* cannot be described since the figures showing the spreadsheet-output pages were not included in the available copy of (NAT, 1996).

6.5 RVSM collision risk assessment for the AFI region

6.5.1 Introduction

Based on its experience with RVSM safety/collision risk assessment at the RGCSP, the EUR/SAM Corridor, and the EUR Region (EUROCONTROL, 2001; Harrison & Moek, 1992; Moek et al., 2001), NLR was invited to give a presentation on RVSM collision risk assessment at the 1st RVSM Symposium for the Africa and Indian Ocean (AFI) Region of ICAO hosted by the Eastern and Southern African (ESAF) Regional Office in Nairobi in April 2004⁷¹. Following that, a consortium of Altran France and NLR submitted a successful bid for the development of an AFI RVSM pre-implementation case. The work performed on this was reported in (ALTRAN, 2006) and the hazard assessment part, completed in May 2005, was reported in (ALTRAN, 2005). Following three pre-implementation collision risk assessments, RVSM was implemented in the Africa and Indian Ocean (AFI) Region of ICAO on 25 September 2008. In compliance with ICAO guidelines, annual post-implementation RVSM collision risk assessments (CRAs) has been conducted by the authors based on, in particular, the following two safety objectives of the AFI RVSM Safety Policy (Office (ARPO), 2004):

- (iv) In accordance with ICAO Guidance Material the management of vertical collision risk within RVSM airspace shall meet the Target Level of Safety of 5×10^{-9} fatal accidents per flight hour;
- (v) In accordance with ICAO Guidance Material, the risk of mid-air collision in the vertical dimension within RVSM airspace, due to technical height keeping performance, shall meet a Target Level of Safety of 2.5×10^{-9} fatal accidents per flight hour.

The collision risk models utilized for the annual assessment of the technical and total vertical collision risk are presented in the next two subsections. The models utilized will be seen to be consistent with those described in the previous subsections of this chapter. In particular, the model(s) utilized for the vertical

⁷¹

collision risk due to large height deviations resulting from operational error are based on the model(s) developed by the NAT MWG, see eqs. (6.56) – (6.58) of Section 6.4.3.2. Unlike for the collision risk models presented in Chapter 5 and in this chapter so far, details of the estimation of various collision risk model parameters and an overall computation scheme for the technical vertical risk will also be provided based on data on RVSM operations in AFI RVSM airspace provided by the AFI Regional Monitoring Agency (ARMA) on an annual basis.

The data made available by ARMA consist of several parts. Firstly, it comprises data to be provided by States participating in AFI RVSM to ARMA on a monthly basis in what are called ARMA Form 1, ARMA Form 2, ARMA Form 3, and ARMA Form 4. ARMA Form 1 is to be used for the reporting of all height deviations of 300 ft or more. Full details of the large height deviation event are to be reported, particularly the nature of the deviation, the total height deviation, and the total time of the deviation. These data is used for the assessment of the total vertical risk, see Section 6.5.3. ARMA Form 2 provides a summary of the monthly movements in a State's RVSM airspace, i.e. number of movements in level flight as well as in climb or descent, together with the average time per movement for the two modes of flight. This information is used in support of the calculation of the annual number of flight hours in AFI RVSM airspace in addition to the data to be provided in ARMA Form 4. ARMA Form 3 is used for the reporting of "other operational considerations" that may be of relevance to the safety of the AFI RVSM operations. Although the form contains fields for four specific operating conditions, it should also be used in case of any other operational circumstances that might have an impact upon the safety of RVSM operations in the AFI Region. The four specific conditions concern coordination failures, communication failures, turbulence, and ACAS events. Like the ARMA Form 1 data, the ARMA Form 3 data are used for the assessment of the total vertical risk. In practice, events that should, strictly speaking, be reported in ARMA Form 1 are reported sometimes only in ARMA Form 3 and sometimes duplicated in ARMA Form 3. ARMA Form 4 concerns a State/FIR/UIR's monthly air traffic flow data, i.e. for each flight some administrative data, date, route, flight number, aircraft type, navigation equipment, origin, and destination, plus, for all a flight's waypoints, the waypoint identification, time of waypoint passing, and the corresponding flight level. The primary use of these data concerns the estimation of the passing frequency parameter of the collision risk model. In addition, these data are used to characterize the aircraft population, e.g. aircraft types (and thus aircraft dimensions) and the proportion of flight time contributed by each aircraft type (and ultimately by monitoring group).

The second part of the data consists of data on large height deviations in the form of Unsatisfactory Condition Reports (UCRs) filed by mainly aircrew and made available for the collision risk assessment by ARMA and the AFI Tactical Action Group (TAG). This data is also reviewed on an annual basis by the IATA Airprox Incident Analysis Group (AIAG) with a view to identifying causes of large height deviations and proposing measures to prevent their re-occurrence in the future. The UCR data is the main source of data for the estimation of the vertical collision risk due to operational error as a component of the total vertical collision risk in AFI RVSM airspace. Some events reported in ARMA Form 1 or ARMA Form 3 are occasionally duplicated in the UCR data.

The third part of the data concerns height monitoring data on the technical height-keeping performance of the AFI RVSM aircraft population. This data is needed for the assessment of the technical vertical collision risk, but is not directly available for the AFI Region. It will be set out in Section 6.5.2.2 how this problem can be resolved. Finally, data is needed on the lateral navigation performance in AFI RVSM airspace and, if possible, on the use of SLOP.

6.5.2 Technical Vertical Collision Risk

6.5.2.1 Technical vertical risk model

The model for technical vertical collision risk for RVSM approved aircraft at adjacent flight levels of the same route, flying in either the same or the opposite direction is given by

$$N_{az} = 2P_z(S_z)P_y(0) \left[n_x(\text{same}) \left\{ 1 + \frac{2\lambda_x}{2\lambda_y} \frac{|\bar{y}|}{|\Delta V|} + \frac{2\lambda_x}{2\lambda_z} \frac{|\bar{z}|}{|\Delta V|} \right\} + n_x(\text{opp}) \left\{ 1 + \frac{2\lambda_x}{2\lambda_y} \frac{|\bar{y}|}{2\bar{V}} + \frac{2\lambda_x}{2\lambda_z} \frac{|\bar{z}|}{2\bar{V}} \right\} \right] \quad (6.80)$$

The left-hand side variable N_{az} represents the expected number of aircraft accidents per flight hour due to normal or typical technical-height-deviations of RVSM approved aircraft for the given same- and opposite-direction traffic geometry. The factor of two (2) up front on the right side of eq. (6.73) accounts for the conversion of collisions into accidents where one collision is counted as two aircraft accidents. The model in eq. (6.80) may be compared with the model of eq. (6.49) used by the NAT MWG for technical vertical collision risk in NAT RVSM airspace. The two models are equal when

$$2n_x(\text{same}) = N_x(\text{same}) \quad (6.81)$$

$$2n_x(\text{opp}) = N_x(\text{opp}) \quad (6.82)$$

Eqs. (6.81) and (6.82) are true, because the factor of two in the equations' left sides is included in $N_x(\text{same})$ and $N_x(\text{opp})$ in eqs. (6.46) and (6.47) through the occupancies $E_z(\text{same})$ and $E_z(\text{opp})$ where the latter are defined in eqs. (6.3) and (6.4). All parameters in the model of eq. (6.80) are defined in Table 6.9.

The most important parameter is the probability of vertical overlap $P_z(S_z)$ with the vertical separation minimum S_z here being 1000 ft. The longitudinal overlap frequency parameters $n_x(\text{same})$ and $n_x(\text{opp})$, together with the kinematic factors in accolades (as functions of the relative speeds and aircraft dimensions), and the probability of lateral overlap $P_y(0)$ represent the different levels of exposure to the risk of the loss of vertical separation for the two traffic geometries covered by the collision risk model of eq. (6.80).

Table 6.9: Definition of parameters of the vertical collision risk model of eq. (6.80)

Parameter	Definition
N_{az}	The expected number of fatal aircraft accidents per flight hour due to the loss of vertical separation
S_z	The vertical separation minimum
$P_z(S_z)$	The probability of vertical overlap for aircraft nominally flying at adjacent flight levels
$P_y(0)$	The probability of lateral overlap for aircraft nominally flying on the same route

Parameter	Definition
$n_x(\text{same})$	The frequency with which same-direction aircraft at adjacent flight levels of the same route enter into longitudinal overlap
$n_x(\text{opp})$	The frequency with which opposite-direction aircraft at adjacent flight levels of the same route enter into longitudinal overlap
$\overline{ \Delta V }$	The average of the absolute value of the relative along-track speed between two same-direction aircraft flying at adjacent flight levels of the same route
$\bar{V}$	The average ground speed of a typical aircraft
$\overline{ \dot{y} }$	The average of the absolute value of the relative cross-track speed between two typical aircraft flying at adjacent flight levels of the same route
$\overline{ \dot{z} }$	The average of the absolute value of the relative vertical speed between two typical aircraft which have lost S_z feet of vertical separation
λ_x	The average length of a typical aircraft
λ_y	The average width of a typical aircraft
λ_z	The average height of a typical aircraft

Each of the terms inside the accolades in eq. (6.80) represents one of the three ways in which a collision can originate, i.e. head/tail, sideways, or top/bottom for same-direction traffic and similarly for opposite-direction traffic. (Each term in fact equals the inverse of the ratio of the duration of an overlap in the pertinent dimension to the duration of a longitudinal overlap.)

The model for technical vertical collision risk for aircraft at adjacent flight levels of two routes intersecting at an angle θ and cylindrical aircraft models is given as

$$N_{az} = 2P_z(S_z)n_{xy}(\theta) \left\{ 1 + \frac{\pi\lambda_{xy}}{2\lambda_z} \frac{\overline{|\dot{z}|}}{V_{rel}(\theta)} \right\} \quad (6.83)$$

where the average relative speed $V_{rel}(\theta)$ is defined by

$$V_{rel}(\theta) = \bar{V}\sqrt{2(1 - \cos\theta)} \quad (6.84)$$

The model in eq. (6.83) may be compared with the model of eq. (6.11) used for vertical collision risk between aircraft flying at adjacent flight levels of crossing routes in Annex B of Volume 2 of the RGCSP/6 report (ICAO, 1988b) at the time with

$$2n_{xy}(\theta) = N_x(\text{cross}) \quad (6.85)$$

and the factor of two on the equation's left side included in $N_{xy}(\text{cross})$ in eq. (6.15) through the occupancy $E_z(\text{cross})$.

The new model parameters are defined in Table 6.10. Notice that for intersecting routes the lateral overlap probability $P_y(0)$ no longer appears explicitly in the model as it is effectively included within the intersecting-route frequency of horizontal overlap $n_{xy}(\theta)$. Indeed, for intersecting routes, it is more convenient to

combine the head/tail and sideways collision directions into a combined horizontal direction. In line with this, the quantity $\frac{\pi}{2}\lambda_{xy}$ in eq. (6.83) represents the average length of a horizontal overlap between two typical aircraft on intersecting routes as represented by (standing) cylinders with diameter λ_{xy} .

Table 6.10: Definition of additional parameters for vertical collision risk model of eq. (6.83)

Parameter	Definition
θ	The angle of intersection between two routes
λ_{xy}	The average diameter of a standing cylinder representing a typical aircraft
$n_{xy}(\theta)$	The frequency with which aircraft on adjacent flight levels of two routes intersecting at an angle of θ enter into horizontal overlap
$V_{rel}(\theta)$	The average relative horizontal speed between aircraft flying at adjacent flight levels of two routes intersecting at an angle θ

For the case of n pairs of routes intersecting at different angles $\theta_i, i = 1, \dots, n$, the collision risk model of eq. (6.83) can be extended to

$$N_{az} = 2P_z(S_z) \sum_{i=1}^n n_{xy}(\theta_i) \left\{ 1 + \frac{\frac{\pi}{2}\lambda_{xy}}{2\lambda_z} \frac{|\bar{z}|}{V_{rel}(\theta_i)} \right\} \quad (6.86)$$

Combining the models in eqs. (6.80) and (6.86) gives the full technical vertical collision risk model:

$$N_{az} = 2P_z(S_z)P_y(0) \left[n_x(\text{same}) \left\{ 1 + \frac{2\lambda_{xy}}{2\lambda_{xy}} \frac{|\bar{y}|}{|\Delta V|} + \frac{2\lambda_{xy}}{2\lambda_z} \frac{|\bar{z}|}{|\Delta V|} \right\} + n_x(\text{opp}) \left\{ 1 + \frac{2\lambda_{xy}}{2\lambda_{xy}} \frac{|\bar{y}|}{2\bar{V}} + \frac{2\lambda_{xy}}{2\lambda_z} \frac{|\bar{z}|}{2\bar{V}} \right\} + 2P_z(S_z) \sum_{i=1}^n n_{xy}(\theta_i) \left\{ 1 + \frac{\frac{\pi}{2}\lambda_{xy}}{2\lambda_z} \frac{|\bar{z}|}{V_{rel}(\theta_i)} \right\} \right] \quad (6.87)$$

Notice that for the same- and opposite-direction components the original aircraft length and width λ_x and λ_y have been replaced by a diameter λ_{xy} . The lateral overlap probability parameter $P_y(0)$ may be combined with the same-direction and opposite-direction longitudinal overlap frequencies $n_x(\text{same})$ and $n_x(\text{opp})$, respectively, to give frequencies of horizontal overlap for these two traffic types (comparable to the horizontal overlap frequency $n_{xy}(\theta_i)$ for traffic on intersecting routes).

Aside from $P_z(S_z)$, the impact of any opposite-direction passing on the vertical collision risk is determined by the probability of lateral overlap $P_y(0)$ and the kinematic factor $\left\{ 1 + |\bar{y}|/2\bar{V} + \lambda_{yx}/\lambda_z \times |\bar{z}|/2\bar{V} \right\}$. Thus, any same-direction passing event included in $n_x(\text{same})$ and any intersecting-route traffic passing included in $n_{xy}(\theta_i)$ may be translated into an equivalent opposite-direction passing by means of these two factors, i.e.

$$\begin{aligned}
N_{az} = & 2P_z(S_z)P_y(0)n_x(\text{opp}) \left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\} \\
& + 2P_z(S_z)P_y(0)n_x(\text{same}) \frac{\left\{ 1 + \frac{|\bar{y}|}{|\Delta V|} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z |\Delta V|} \right\}}{\left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}} \left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\} \\
& + 2P_z(S_z)P_y(0) \frac{1}{P_y(0)} \sum_{i=1}^n n_{xy}(\theta_i) \left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\} \left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}
\end{aligned} \tag{6.88}$$

or

$$\begin{aligned}
N_{az} = & 2P_z(S_z)P_y(0) \left\{ n_x(\text{opp}) + n_x(\text{same}) \frac{\left\{ 1 + \frac{|\bar{y}|}{|\Delta V|} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z |\Delta V|} \right\}}{\left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}} \right. \\
& \left. + \frac{1}{P_y(0)} \sum_{i=1}^n n_{xy}(\theta_i) \frac{\left\{ 1 + \frac{\pi \lambda_{xy} |\bar{z}|}{2 \lambda_z V_{rel}(\theta_i)} \right\}}{\left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}} \right\} \left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}
\end{aligned} \tag{6.89}$$

Defining

$$n_x(\text{equiv}) = n_x(\text{opp}) + n_x(\text{same}) \frac{\left\{ 1 + \frac{|\bar{y}|}{|\Delta V|} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z |\Delta V|} \right\}}{\left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}} + \frac{1}{P_y(0)} \sum_{i=1}^n n_{xy}(\theta_i) \frac{\left\{ 1 + \frac{\pi \lambda_{xy} |\bar{z}|}{2 \lambda_z V_{rel}(\theta_i)} \right\}}{\left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\}} \tag{6.90}$$

eq. (6.89) can be written in the so-called equivalent opposite-direction passing frequency form as

$$N_{az} = 2P_z(S_z)P_y(0)n_x(\text{equiv}) \left\{ 1 + \frac{|\bar{y}|}{2V} + \frac{\lambda_{xy} |\bar{z}|}{\lambda_z 2V} \right\} \tag{6.91}$$

The last expression is precisely of the opposite-direction traffic form, whereas numerically it takes account of all the different types of traffic geometries through the equivalent opposite-direction passing frequency $n_x(\text{equiv})$. Ignoring the crossing-route component of $n_x(\text{equiv})$ it holds that, similar to eqs. (6.81) – (6.83)

$$2n_x(\text{equiv}) = N_x(\text{equivalent}) \tag{6.92}$$

where $N_x(\text{equivalent})$ for the NAT MWG collision risk model in eq. (6.53) for same-direction and opposite-direction traffic is defined by eq. (6.54).

6.5.2.2 Parameter estimation

This section provides details of the estimation of the parameters of the technical vertical collision risk model and deals with the probability of vertical overlap, passing frequency, probability of lateral overlap, and aircraft dimensions and relative speeds respectively.

6.5.2.2.1 Probability of vertical overlap

The probability of vertical overlap $P_z(S_z)$ for aircraft flying at adjacent flight levels (separated by S_z) of the same route or intersecting routes is calculated from the probability distribution of normal, or typical, height deviations of RVSM approved aircraft. These aircraft height deviations are usually defined in terms of Total Vertical Error (TVE) (in geometric feet) with:

$$TVE = \{\text{actual pressure altitude flown by an aircraft}\} - \{\text{assigned altitude}\} \quad (6.93)$$

The components approach is used to express TVE as the (statistically independent) sum of Altimetry System Error (ASE) and Flight Technical Error (FTE) or Assigned Altitude Deviation (AAD), as illustrated in Figure 6.7 below, i.e.

$$TVE = ASE + FTE \quad (6.94)$$

$$TVE \approx ASE + AAD \quad (6.95)$$

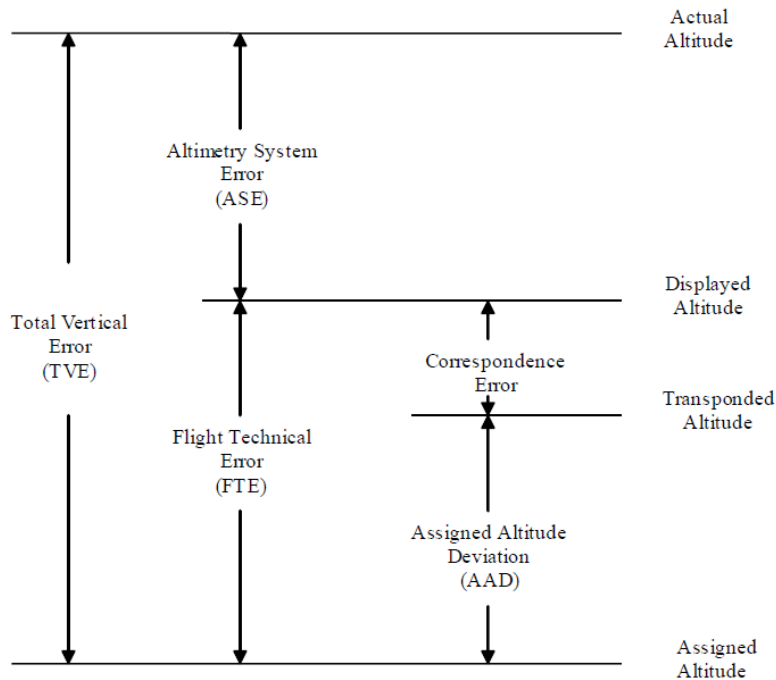


Figure 6.7: Illustration of the different components of the Total Vertical Error (TVE)

The error components ASE, FTE, and AAD are defined by

$$ASE = \{\text{actual pressure altitude flown by an aircraft}\} - \{\text{displayed altitude}\} \quad (6.96)$$

$$FTE = \{\text{displayed altitude}\} - \{\text{assigned altitude}\} \quad (6.97)$$

and

$$AAD = \{\text{transponded altitude}\} - \{\text{assigned altitude}\} \quad (6.98)$$

Within the components approach, the TVE probability density follows from the ASE and AAD probability densities by means of the convolution integral

$$f^{TVE}(z) = \int_{-\infty}^{\infty} f^{ASE}(a) f^{AAD}(z - a) da \quad (6.99)$$

and the probability of vertical overlap for aircraft at adjacent flight levels separated by S_z is calculated by means of the expression

$$P_z(S_z) = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{TVE}(z_1) f^{TVE}(S_z + z_1 - z) dz_1 dz \quad (6.100)$$

where $f^{TVE}(z)$ denotes the TVE probability density of an aircraft given by eq. (6.99) and the inner integral represents the probability density of the vertical distance between two aircraft at adjacent flight levels. For RVSM the vertical separation standard is 1000 ft, i.e. $S_z = 1000$ ft. Notice that eq. (6.100) assumes that the aircraft at the adjacent flight levels have the same TVE probability densities. (Cf. eq. (4.17) for the probability of lateral overlap, $P_y(S_y)$, for aircraft on adjacent parallel routes spaced at a lateral separation standard S_y). The more general case of the aircraft having different TVE probability densities was given in eq. (4.18) of Chapter 4, but is rarely used in practice.

The key part of the calculation of $f^{TVE}(z)$, and hence of the probability of vertical overlap $P_z(S_z)$, is formed by the overall ASE probability density $f^{ASE}(a)$ of the RVSM approved aircraft population operating in AFI RVSM airspace. Assuming that this population is made up of n_{MG} aircraft monitoring groups (recall Section 6.2.3, last paragraph, and Section 6.2.4) with ASE probability densities $f_i^{ASE}(a)$, $i = 1, \dots, n_{MG}$, the overall ASE probability density can be written as a weighted mixture of the ASE densities by monitoring group, i.e.

$$f^{ASE}(a) = \sum_{i=1}^{n_{MG}} \beta_i f_i^{ASE}(a) \quad (6.101)$$

where the weighting factors β_i , $i = 1, \dots, n_{MG}$, are the proportions of flight time contributed by monitoring group i .

Height monitoring data is required to determine the individual monitoring groups' ASE probability densities $f_i^{ASE}(a)$ whereas the flight time proportions β_i can, in principle, be derived from traffic flow data reported

in ARMA Form 4. Traditionally, height monitoring data has been collected by ground-based Height Monitoring Units (HMUs), Aircraft Geometric Height Monitoring Elements (AGHMEs), or by independent on-board portable GPS Monitoring Units (GMUs). Height monitoring systems are operated by the RMAs. HMUs and AGHMEs can provide lots of data for the modelling of the monitoring groups' ASE whereas GMUs are more suitable to collect ASE data on a limited number of aircraft that are unable to overfly an HMU or AGME. As explained in Section 6.2.4, a number of RMAs now have ADS-B Height Monitoring Systems (HMSs). Ground-based HMUs, AGHMEs, or ADS-B HMSs are not available in the AFI Region. However, since the normal height-keeping of RVSM approved aircraft is not dependent on the region of operation, ASE probability densities $f_i^{ASE}(a)$, $i = 1, \dots, n_{MG}$, based on European height monitoring data collected and processed by the EUR RMA are used for the annual AFI RVSM collision risk assessments.

Each monitoring group's ASE probability density, $f_i^{ASE}(a)$, is the result of both within and between airframe ASE variability of all the airframes making up the group. Within-airframe variability refers to the variation of the ASE of each individual airframe within a monitoring group about an airframe-dependent mean μ_{ij} , $j = 1, \dots, n_i$, where the variability about the airframes' means is assumed to be characterized by one or more airframe-independent parameters, e.g. a standard deviation σ_i . The aircraft's within-airframe ASE probability density can thus be denoted $f_{a|\mu_{ij}}(a|\mu_{ij}; \sigma_i)$, $j = 1, \dots, n_i$.

Between airframe variability refers to the variability in the mean ASEs of the individual airframes belonging to a monitoring group. This is characterized by a monitoring group ASE mean μ_{Gi} and variability of the individual airframe ASE means about the group mean, where the variability about the group's mean is assumed to be characterized by one or more group-dependent parameters, e.g. a standard deviation σ_{Gi} . The monitoring group's between-airframe ASE probability density can thus be denoted $f_i(\mu_{ij}|\mu_{Gi}, \sigma_{Gi})$, $i = 1, \dots, n_{MG}$.

Given the above, the joint probability density of ASE a and within airframe ASE mean μ_{ij} is given by the product of the two probability densities $f_{a|\mu_{ij}}(a|\mu_{ij}; \sigma_i)$ and $f_i(\mu_{ij}|\mu_{Gi}, \sigma_{Gi})$ and a monitoring group's ASE probability density is obtained by integration over μ_{ij} , i.e.

$$f_i^{ASE}(a) = \int_{-\infty}^{\infty} f_{a|\mu_{ij}}(a|\mu_{ij}; \sigma_i) f_i(\mu_{ij}|\mu_{Gi}, \sigma_{Gi}) d\mu_{ij} \quad (6.102)$$

Dependent on the form of the within-airframe and between airframe probability densities, the integration in eq. (6.102) may be able to be performed analytically and needs to be performed numerically otherwise. The integration can be performed analytically when the two component probability densities are both normal probability densities. It can then be shown that the resulting ASE probability density $f_i^{ASE}(a)$ is normal too, i.e.

$$f_i^{ASE}(a) = \frac{1}{A_i \sqrt{2\pi}} \exp -\frac{1}{2} \left(\frac{a - \mu_{Gi}}{A_i} \right)^2 \quad (6.103)$$

with

$$A_i = \sqrt{\sigma_i^2 + \sigma_{Gi}^2} \quad (6.104)$$

The within-airframe and between-airframe probability density models used by the EUR RMA are mixtures of up to five generalized Laplace probability densities, i.e.

$$f_{a|\mu_{ij}}(a|\mu_{ij}; \dots) = \sum_{k=1}^{n_i} \alpha_k \frac{1}{2a_{ik}b_{ik}\Gamma(b_{ik})} \exp\left(-\left|\frac{a - \mu_{ij}}{a_{ik}}\right|^{\frac{1}{b_{ik}}}\right) \quad (6.105)$$

with $\dots = a_{i1}, b_{i1}, \dots, a_{in_i}, b_{in_i}$ and

$$\sum_{k=1}^{n_i} \alpha_k = 1, \quad n_i \leq 5 \quad (6.106)$$

$$f_i(\mu_{ij}|\mu_{Gi}, \dots) = \sum_{k=1}^{n_{Gi}} \alpha_{Gk} \frac{1}{2a_{Gik}b_{Gik}\Gamma(b_{Gik})} \exp\left(-\left|\frac{a - \mu_{Gi}}{a_{Gik}}\right|^{\frac{1}{b_{Gik}}}\right) \quad (6.107)$$

with $\dots = a_{Gi1}, b_{Gi1}, \dots, a_{in_{Gi}}, b_{in_{Gi}}$ and

$$\sum_{k=1}^{n_{Gi}} \alpha_{Gk} = 1, \quad n_{Gi} \leq 5 \quad (6.108)$$

Notice the generalized notation used in eqs. (6.105) – (6.108). Recall from Section 4.5 that the parameters $a_{\dots}$ are usually referred to as scale parameters and the parameters $b_{\dots}$ as shape parameters and that $\Gamma(b_{\dots})$ denotes the gamma function defined by eq. (4.28). Recall also that the family of generalized Laplace probability distributions includes the normal ($b_{\dots} = 0.5$) and double exponential $b_{\dots} = 1.0$ probability distributions.

Deciding on the number of terms to be included in the within-airframe and between-airframe ASE probability densities and estimating the densities' parameters based on a sample of aircraft height-monitoring data is a complicated process requiring advanced statistical and (numerical) mathematical methods and software. This process is conducted by the EUR RMA for the benefit of the annual EUR RVSM collision risk assessments. Once this has been completed, the overall ASE probability density $f^{ASE}(a)$ can be determined for the aircraft population under consideration by means of eq. (6.101).

Having determined the overall ASE probability density $f^{ASE}(a)$, the assigned altitude deviation (AAD) probability density $f^{AAD}(a)$ also needs to be determined. It is assumed that the AAD probability density is the same for all aircraft of all monitoring groups. The AAD probability density $f^{AAD}(a)$ is also determined by the EUR RMA on the basis of AAD data collected as a part of the aircraft height-keeping monitoring process. Experience has shown that the AAD data can generally be modelled well by a double exponential probability distribution with a standard deviation σ_{AAD} of approximately 32 ft.

An agreement is in place between the EUR RMA and ARMA that provides for two things for the benefit of the annual AFI RVSM collision risk assessments. Firstly, on behalf of the ARMA, an ASE parameter file and an AAD data file are made available to NLR by the EUR RMA. The ASE parameter file lists for each aircraft monitoring group processed by the EUR RMA the set of ASE probability density parameters $\mu_{Gi}, a_{i1}, b_{i1}, \dots, a_{in_i}, b_{in_i}, a_{Gi1}, b_{Gi1}, \dots, a_{in_{Gi}}, b_{in_{Gi}}, i = 1, \dots, n_{MG}$. NLR selects the aircraft monitoring groups relevant to the latest AFI

RVSM collision risk assessment and may add parameters from previous years for one or more monitoring groups no longer being monitored in Europe.

Table 6.11 gives an example for the top ten monitoring groups of the latest AFI RVSM collision risk assessment as measured by proportion of flight time. The first column shows the aircraft monitoring groups, whilst the second column shows the flight time proportion of the groups. The third column shows the combination of the groups' within-airframe and between-airframe probability distributions (in that order) separated by the underline symbol. The different terms making up the respective distributions are separated by a hyphen and the symbols used stand for normal, G, double exponential, DE, and generalized Laplace, GL.⁷² The subsequent triples of columns show the parameters in generalized Laplace form for the successive component densities corresponding to the designator in the table's third column. The flight time proportions are calculated by the NLR based on the traffic flow data provided in ARMA Form 4. This calculation includes assigning the flight time proportions by aircraft type resulting from the ARMA Form 4 processing to the monitoring group(s) an aircraft type belongs to.

Table 6.11: Example of an ASE parameter file

Aircraft type	Proportion FT	Type of PDF	μ (ft)	a_1	b_1	α_1	a_2	b_2	α_2	a_3	b_3	α_3	a_4	b_4	α_4	a_5	b_5	α_5	a_6	b_6	α_6
A124	1.194E-4	G_G-DE	27,960	44,617	0,5	1	41,019	0,5	0,81	48,269	1	0,19									
A310-GE	3.190E-2	G_G-DE	-61,669	41,102	0,5	1	33,479	0,5	0,75	29,000	1	0,25									
A310-PW	1.030E-2	G_G-DE	3,698	38,233	0,5	1	24,244	0,5	0,68	31,512	1	0,32									
A318	2.687E-4	DE_G-DE	30,803	26,912	1	1	22,263	0,5	0,80	30,365	1	0,20									
A320	4.650E-2	G-DE_GL-GL-GL	27,210	39,542	0,5	0,74	34,268	1	0,26	55,188	0,54	0,18	31,272	0,55	0,82	200,362	0,15	0,00			
A330	2.828E-1	DE_G-G-DE	40,477	29,209	1	1	18,588	0,5	0,5	28,017	0,5	0,39	34,548	1	0,12						
A340	1.314E-1	G-DE_G-G-DE	-2,170	32,927	0,5	0,65	45,275	1	0,35	17,112	0,5	0,59	31,062	0,5	0,37	47,674	1	0,04			

Secondly, the agreement licenses NLR to use the EUR RVSM toolset software to

- Calculate the overall ASE probability density $f^{ASE}(a)$ of eq. (6.101);
- Model/calculate the AAD probability density $f^{AAD}(a)$ based on the AAD data provided;
- Calculate the TVE probability density $f^{TVE}(z)$ of eq. (6.99); and
- Calculate the probability of vertical overlap $P_z(S_z)$ due to technical height deviations of RVSM approved aircraft for $S_z = 1000$ ft, eq. (6.100).⁷³

6.5.2.2.2 Passing frequency

As set out in the introductory Section 6.5.1, ARMA Form 4 provides a State/FIR/UIR's monthly air traffic flow data as input for the estimation of the vertical passing frequency in the pertinent part of AFI RVSM airspace. The data to be provided for each flight comprise some administrative data, date, route, flight number, aircraft type, navigation equipment, origin, and destination, plus, for **all** a flight's waypoints, the waypoint identification, time of waypoint passing, and the corresponding flight level. The waypoint data is critical to the passing frequency estimation. Before detailing the calculation of a State/FIR/UIR's passing frequency for a full calendar year, it is necessary to note that the passing frequency parameter of the vertical collision risk model represents an annual average value for all of AFI RVSM airspace. Since passing frequency can vary considerably from one FIR/UIR to the other, the RVSM Manual (ICAO, 2012b) prescribes how the averaging is performed.

⁷² Although the normal and double exponential probability distributions are members of the family of generalized Laplace distributions, they are explicitly labelled G and DE when they have been determined to provide the best model, whilst their parameters are given in generalized Laplace form.

⁷³ The EUR RVSM toolset can also be used to compute $P_z(S_z)$ for values of S_z other than 1000 ft, e.g. $S_z = 0$ ft. For example, $P_z(0)$ plays a part in the probability of vertical overlap for aircraft flying at a wrong flight level as a result of an operational error. See Section 6.5.3.4.

Based on the global system performance specification for RVSM, paragraph 5.2.12 of Chapter 5, *System Performance Monitoring*, of the Third Edition⁷⁴ of RVSM Manual (ICAO, 2012b) requires an assessment of the annual average passing frequency over the whole airspace of three adjacent area control centres (ACCs) covering the region's busiest traffic flows or highest passing frequency. The use of these adjacent ACCs covering the highest passing frequency is to address the problem of high traffic flows where higher-than-average collision risk may pertain.

For the AFI Region, the averaging is done over the region's busiest triple of FIR/UIRs rather than ACCs, although a few States provide the ARMA Form 4 traffic flow data by ACC. Thus, the first step of the passing frequency calculation concerns estimating the annual passing frequency for each State/FIR/UIR's RVSM airspace and the second step consists of identifying the three busiest adjacent FIR/UIRs and performing the averaging. Depending on the quality of the traffic flow data provided, some pre-processing may need to be performed.

The collision risk model used for the technical vertical collision risk assessment was given in eq. (6.91) with the passing frequency parameter expressed as equivalent opposite direction passing frequency, $n_x(\text{equiv})$, with

$$n_x(\text{equiv}) = n_x(\text{opp}) + n_x(\text{same}) \frac{\left\{1 + \frac{|\dot{y}|}{|\Delta V|} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{|\Delta V|}\right\}}{\left\{1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2V}\right\}} + \frac{1}{P_y(0)} \sum_{i=1}^n n_{xy}(\theta_i) \frac{\left\{1 + \frac{\frac{\pi}{2} \lambda_{xy}}{V_{\text{rel}}(\theta_i)} \frac{|\dot{z}|}{2\lambda_z}\right\}}{\left\{1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2V}\right\}} \quad (6.90)$$

It follows from eq. (6.90) that the calculation of $n_x(\text{equiv})$ needs, in the first place, the same-direction and opposite-direction passing frequencies $n_x(\text{same})$ and $n_x(\text{opp})$ together with the intersecting-track passing frequencies $n_{xy}(\theta_i)$ for each intersection angle θ_i , and, secondly, the additional quantities $P_y(0)$ and the three types of kinematic factors $\left\{1 + \frac{|\dot{y}|}{|\Delta V|} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{|\Delta V|}\right\}$, $\left\{1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2V}\right\}$, and $\left\{1 + \frac{\frac{\pi}{2} \lambda_{xy}}{V_{\text{rel}}(\theta_i)} \frac{|\dot{z}|}{2\lambda_z}\right\}$. The calculation of the probability of lateral overlap for aircraft at adjacent flight levels of the same route will be described in Section 6.5.2.2.3 and the calculation of the kinematic factors in Section 6.5.2.2.4. Each component passing frequency is calculated as the quotient of the number of aircraft passings of the type concerned per annum and the annual number of flight hours where both factors are computed from the traffic flow data to be provided in ARMA Form 4.

Passing frequency, as well as occupancy, can be calculated in different ways. The method used for AFI RVSM is based on computing the closest point of approach (CPA) for a pair of aircraft flying at adjacent flight levels along a pair of route segments. To this end, each flight recorded in ARMA Form 4 is broken down into route segments based on the flight's waypoints provided in the ARMA Form 4 data file. The passing frequency calculation will be outlined below for a pair of aircraft flying at adjacent flight levels on intersecting route segments and it will be shown subsequently how the method simplifies for same-direction and opposite-direction traffic at adjacent flight levels of the same route.

Section 4.4 dealt with the calculation of the minimum distance at the closest point of approach, CPA, for two aircraft A and B, represented by points, flying with constant speeds along two route segments defined by waypoints A_0 and A_1 , and B_0 and B_1 , respectively. On the assumption that the aircraft are flying along these

⁷⁴ The same requirement is listed in the earlier editions of the RVSM Manual, but in different paragraphs of different chapters.

route segments for some common period of time, this calculation can be used for the calculation of the passing frequency for aircraft at adjacent flight levels of the same or intersecting routes. For the same-route-segment case, a passing takes place when the CPA sits on the route segment and the minimum distance is thus less than or equal to the horizontal dimension, λ_{xy} , of the aircraft. For the intersecting-route-segment case, the CPA will generally not sit on either of the route segments and the likelihood of observing a minimum distance at CPA less than or equal to the horizontal dimension λ_{xy} of an aircraft will be very small. Therefore, the number of passings at route intersections within a larger intersecting-route proximity distance R , e.g. $R = 5$ NM, is computed in practice and subsequently scaled by a factor of λ_{xy}/R .

The passing frequency calculation outlined below does not use the flight levels at which the aircraft are flying other than that they are adjacent. Given the semi-circular cruising level system, one of the aircraft in a pair will be flying eastbound with a heading φ_{east} , say, and the other westbound with a heading φ_{west} with $\varphi_{west} > \varphi_{east}$. The intersection angle θ is then given by $\theta = \varphi_{west} - \varphi_{east}$ degrees when $\varphi_{west} - \varphi_{east} \leq 180^\circ$ and by $\theta = 360 - (\varphi_{west} - \varphi_{east})$ degrees when $\varphi_{west} - \varphi_{east} > 180^\circ$.

Recall from Section 4.4 that the straight-line motion of two aircraft A and B in a horizontal plane can be represented by vectors $\mathbf{a}(t) = \mathbf{a}_0 + \mathbf{u}t$ and $\mathbf{b}(t) = \mathbf{b}_0 + \mathbf{v}t$ respectively, where $\mathbf{a}_0$ and $\mathbf{b}_0$ are the positions of the aircraft at time⁷⁵ $t = 0$ and $\mathbf{u} = \mathbf{a}_1 - \mathbf{a}_0$ and $\mathbf{v} = \mathbf{b}_1 - \mathbf{b}_0$ denote the constant aircraft speeds. Consequently, the distance between the two aircraft at time t is $d(t) = |\mathbf{b}(t) - \mathbf{a}(t)| = |\mathbf{w}(t)|$ with $\mathbf{w}(t) = \mathbf{w}_0 + (\mathbf{v} - \mathbf{u})t$ and $\mathbf{w}_0 = \mathbf{b}_0 - \mathbf{a}_0$. For the case of Figure 4.6, reproduced here as Figure 6.8, the vectors $\mathbf{a}_0$, $\mathbf{a}_1$, $\mathbf{b}_0$, and $\mathbf{b}_1$ are computed from the latitude and longitude of the waypoints defining the route segments. The route segments must have at least one common point.

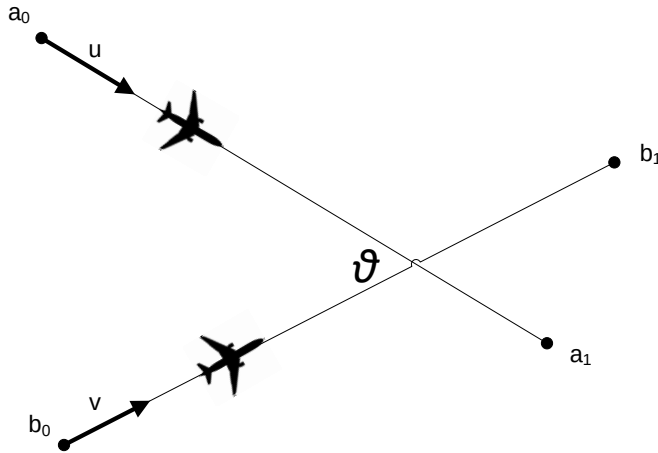


Figure 6.8: Geometry for the closest point of approach (CPA) computation of two aircraft on routes intersecting at an angle

The time t_{CPA} of the aircraft being at CPA was given by

$$t_{CPA} = -\frac{w_0(v - u)}{|v - u|^2} \quad (4.9)$$

⁷⁵ A common point in time $t = 0$ for the aircraft being at A_0 and B_0 is assumed here for simplicity of the formulae. The software used for the passing frequency calculations takes account of the fact that the aircraft will not necessarily be entering their respective route segments at the same point in time.

and the minimum distance d_{min} at CPA was given by

$$d_{min} = d(t_{CPA}) = \dots \quad (4.10)$$

In addition, the vector defining the CPA was given by

$$CPA = \mathbf{a}_0 + \mathbf{u} \times t_{CPA} = \dots \quad (4.11)$$

Having determined the pair's minimum distance d_{min} , it needs to be determined next whether the aircraft pair qualifies as a same-direction, opposite-direction, or intersecting-route aircraft pair. This is done through the angle of intersection θ , which follows from

$$\cos \theta = \frac{(\mathbf{u}, \mathbf{v})}{|\mathbf{u}| |\mathbf{v}|}, \quad 0 \leq \theta \leq 180 \text{ degrees} \quad (6.109)$$

Strictly speaking, an opposite-direction aircraft pair is characterized by $\theta = 180$ degrees and a same-direction aircraft pair by $\theta = 0$ degrees. In practice, it is convenient to widen these definitions slightly as defined in Table 6.12.

Table 6.12: Definition of same-direction, opposite-direction, and intersecting-route aircraft pairs

Intersection Angle (θ)	Type of passing
0° - 5°	Same direction passing
5° - 175°	Crossing
175° - 180°	Opposite direction passing

Having determined an aircraft pair's minimum distance d_{min} , angle θ , and traffic type (as a function of θ), the final step is to determine whether the pair counts as a passing aircraft pair. A passing occurs if the minimum distance between the aircraft at CPA is smaller than or equal to λ_{xy} . This is the only criterion used for same-direction and opposite direction aircraft pairs at adjacent flight levels of a route. For an opposite-direction passing with θ equal to precisely 180 degrees, the passing takes place on the common route segment with the minimum distance being zero. For a same-direction passing with θ equal to precisely 0 degrees, the passing takes place on the common route segment also, but the minimum distance will be zero only when the (centre of the) trailing aircraft catches up on the (centre of the) leading aircraft.

For a pair of aircraft at adjacent flight levels of intersecting routes, the minimum distance can be equal to zero only when the passing (of the aircraft centres) takes place precisely at the intersection point. Since the likelihood of this happening is extremely small, the aircraft will generally be on different route segments at the time of minimum distance. Also, the likelihood of such a pair passing within a distance of less than or equal to λ_{xy} is very small. Therefore, in order to obtain a more stable estimate of the number of passing events for intersecting routes, it is verified whether the minimum distance is less than the intersecting-route proximity distance R and, if so, the pair counted as an intersecting route passing. Finally, for each intersection angle θ_i , $i = 1, \dots, n$, the resulting overall count of intersecting route proximity events is corrected by a factor of $\frac{\lambda_{xy}}{R}$ to obtain the intersecting route passing frequency $n_{xy}(\theta_i)$.

For an intersecting-route passing, the intersection-angle-dependent kinematic factor $\left\{1 + \frac{\pi \lambda_{xy}}{V_{rel}(\theta_i)} \frac{|\bar{z}|}{2\lambda_z}\right\}$ is also needed for the calculation of the equivalent opposite-direction passing frequency $n_x(\text{equiv})$ in eq. (6.83), where $V_{rel}(\theta_i)$ is given by

$$V_{rel}(\theta) = \bar{V} \sqrt{2(1 - \cos\theta)} \quad (4.12)$$

For same-direction and opposite-directing passings, the “constant” kinematic factors $\left\{1 + \frac{|\bar{y}|}{|\Delta V|} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\bar{z}|}{|\Delta V|}\right\}$ and $\left\{1 + \frac{|\bar{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\bar{z}|}{2\bar{V}}\right\}$ are needed. See Section 6.5.2.2.4 for details of the relative aircraft speeds and the aircraft dimensions.

It is useful to consider a number of cases regarding Figure 6.8. In the figure, the intersection point itself is not a waypoint and the minimum distance can occur with

- Both aircraft approaching the intersection point;
- Both aircraft flying away from the intersection point; or
- Either of the aircraft approaching/flying away from the intersection.

6.5.2.2.3 Probability of lateral overlap

Lateral navigation accuracy has an essential influence on the likelihood of a collision between two aircraft once vertical separation has been lost. This influence is expressed as the probability of lateral overlap for aircraft nominally flying at (adjacent flight levels of) the same route, $P_y(0)$, and is defined by the following equivalent of $P_z(0)$ defined by eq. (6.57) (cf. also eq. (4.17) for $P_y(S_y)$ or eq. (6.100) for $P_z(S_z)$)

$$P_y(0) = \int_{-\lambda_y}^{\lambda_y} \int_{-\infty}^{\infty} f_Y(y_1) f_Y(y_1 - y) dy_1 dy \quad (6.110)$$

where λ_y denotes the average width of the aircraft (cf. Table 6.9) and $f_Y(y)$ denotes the probability density of the lateral deviations from route centre line. The probability density $f_Y(y)$ is dependent on the type of navigation equipment being used in the airspace under consideration.

The approach followed has been to assume that a proportion α , $0 \leq \alpha \leq 1$, of the airspace users is using GNSS navigation and that the remaining proportion $1 - \alpha$ is using VOR/DME navigation. Recall from Section 6.2.3 that the latter type of navigation with a standard deviation of 0.3 NM was assumed in the derivation of the global system performance specification for RVSM. The following mixture of two Gaussian probability densities was then specified:

$$f_Y(y) = (1 - \alpha) \frac{1}{\sigma_{VOR/DME} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{y}{\sigma_{VOR/DME}} \right)^2} + \alpha \frac{1}{\sigma_{GNSS} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{y}{\sigma_{GNSS}} \right)^2} \quad (6.111)$$

Given that the probability density is a mixture of two Gaussian probability densities, $P_y(0)$ can now be calculated as follows

$$P_y(0) = \int_{-\lambda_y}^{\lambda_y} f_{Y12}(y) dy \quad (6.112)$$

with

$$\begin{aligned}
 f_{Y12}(y) = & (1 - \alpha)^2 \frac{1}{\sigma_{\text{VOR/DME}} \sqrt{2} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{y}{\sigma_{\text{VOR/DME}} \sqrt{2}} \right)^2} \\
 & + 2\alpha(1 - \alpha) \frac{1}{\sqrt{\sigma_{\text{VOR/DME}}^2 + \sigma_{\text{GNSS}}^2} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{y}{\sqrt{\sigma_{\text{VOR/DME}}^2 + \sigma_{\text{GNSS}}^2}} \right)^2} \\
 & + \alpha^2 \frac{1}{\sigma_{\text{GNSS}} \sqrt{2} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{y}{\sigma_{\text{GNSS}} \sqrt{2}} \right)^2}
 \end{aligned} \tag{6.113}$$

and $\sigma_{\text{VOR/DME}} = 0.3$ NM and $\sigma_{\text{GNSS}} = 0.02551$ NM. The latter standard deviation was taken from (Aldis & Barry, 2014a).

The model specified by eqs. (6.105) – (6.106) and $\sigma_{\text{VOR/DME}} = 0.3$ NM and $\sigma_{\text{GNSS}} = 0.02551$ NM has been used to calculate the probability of lateral overlap as a function of the proportion α of the airspace users using GNSS navigation and an average aircraft width of $\lambda_y = 154.92$ ft (Smeltink et al., 2021) as shown in Table 6.13.

Table 6.13: The probability of lateral overlap, $P_y(0)$, as a function of the proportion α of GNSS flying time (based on $\lambda_y = 154.92$ ft)

Proportion α of GNSS flying time	$P_y(0)$	Proportion α of GNSS flying time	$P_y(0)$
0	0.0479	0.65	0.2564
0.05	0.0510	0.7	0.2876
0.1	0.0562	0.75	0.3210
0.2	0.0731	0.8	0.3565
0.25	0.0848	0.85	0.3942
0.5	0.1758	0.9	0.4340
0.55	0.2005	0.95	0.4761
0.6	0.2274	1.00	0.5203

The next step is to specify the proportion α of GNSS flying time. This proportion is specified by ARMA on an annual basis. The first six CRAs all used a value of $\alpha = 0.50$ for the proportion of GNSS flying time, as was believed to be correct at the time. Recognizing an ever increasing usage of GNSS-based navigation, an upward revision to $\alpha = 0.60$ was used for CRA 7 2012 and another one to $\alpha = 0.65$ for CRA 8 2013. The question of an appropriate GNSS usage proportion was subsequently revisited for CRA 9 2014. Based on a then recent traffic/equipment review, it was decided to further increase the GNSS usage proportion to $\alpha = 0.85$. The same proportion was used for CRA 10 based on some related ADS-B and RMACG discussions that ARMA was involved in. As advised by ARMA, the same GNSS usage proportion of $\alpha = 0.85$ has also been adopted for CRA 13 2018 and CRA 14 2019. Taking an aircraft width of 154.92 ft, Table 6.13 gives a value for $P_y(0)$ using $\alpha = 0.85$ of $P_y(0) = 0.3942$. This value is considerably greater than the value of 0.058 assumed in the derivation of the global system performance specification for RVSM (cf. Section 6.2.3) and illustrates the adverse effect of improved lateral navigation on the risk of collision due to the loss of vertical separation.

As set out in Section 6.3, a means to reduce the increase in the probability of lateral overlap $P_y(0)$ due to very accurate GNSS-based navigation is the use of the Strategic Lateral Offset Procedure (SLOP) under certain conditions specified in section 16.5 of the PANS-ATM (ICAO, 2016c). To be able to take the risk mitigating effect of lateral offsets on $P_y(0)$ into account, it needs to be known to what extent the offsets are actually used in practice. Since this knowledge is currently unavailable, the beneficial effects of lateral offsets have not yet been able to be taken into account in the annual AFI RVSM collision risk assessments.

6.5.2.2.4 Aircraft dimensions and speeds

The technical vertical collision risk model in eqs. (6.90) and (6.91) contains three aircraft dimensions, λ_x , λ_y and λ_z , and five (or more, dependent on the number of different intersection angles) relative speeds, $2|\overline{V}|$, $|\overline{\Delta V}|$, $|\overline{\dot{y}}|$, $|\overline{\dot{z}}|$, and $V_{\text{rel}}(\theta_i)$, $i = 1, \dots, n$. The aircraft dimensions are flight-time weighted averages of the dimensions by aircraft type, calculated from the ICAO aircraft type data entry in ARMA Form 4 and a table of aircraft dimensions by aircraft type.

$2|\overline{V}|$ denotes the average (of the absolute value of the) relative longitudinal speed between opposite-direction traffic at adjacent flight levels of the same route, i.e. twice the average speed of such aircraft. $|\overline{V}|$ is also calculated as a flight-time weighted average of the aircraft speed by aircraft type, where, per flight, the pertinent aircraft speed is calculated from the passing times at the first and last waypoint and the distance between those two waypoints. $|\overline{\Delta V}|$ denotes the average (of the absolute value of the) relative longitudinal (along-track) speed between same-direction traffic at adjacent flight levels of the same route. In principle, $|\overline{\Delta V}|$ can be determined from the ARMA Form 4 traffic flow data on same-direction aircraft pairs at adjacent flight levels of the same route. However, since there is very little same-direction traffic at adjacent flight level in AFI RVSM airspace, a default value of $|\overline{\Delta V}| = 20$ kts is used in practice (ICAO Doc 9574, Third Edition, 2012, (ICAO, 2012b)). Having determined $|\overline{V}|$ and knowing the intersection angle θ_i , $i = 1, \dots, n$, the relative horizontal speed $V_{\text{rel}}(\theta_i)$ between aircraft at adjacent flight levels of intersecting routes can be calculated by means of eq. (4.12).

$|\overline{\dot{y}}|$ and $|\overline{\dot{z}}|$ denote the averages (of the absolute value of the) relative lateral (across-track) and vertical speeds respectively between aircraft at adjacent flight levels flying in the same-direction or opposite-direction of the same route or at adjacent flight levels of intersecting routes, where, in particular, $|\overline{\dot{z}}|$ pertains to an aircraft pair that has lost vertical separation. These relative speed parameters cannot be determined from the ARMA Form 4 traffic flow data since no direct data on them is available in these forms. A default value of $|\overline{\dot{z}}| = 1.5$ kts is used based on (EUROCONTROL, 2001; NAT, 1996). Based on the same references, a default value of $|\overline{\dot{y}}| = 20$ kts is used.

Recall from eqs. (6.90) and (6.91) for the technical vertical collision risk model that the average aircraft dimensions and relative speeds are used to evaluate the kinematic factors for the three traffic types, same-direction and opposite-direction on the same route, and intersecting routes, where each kinematic factor describes the effect of the three or two ways in which two aircraft can collide as the result of the loss of vertical separation.

6.5.2.2.5 Computation scheme

This subsection summarizes the calculation of the technical vertical collision risk N_{az} in the form of a process flow chart, based on the collision risk model in eqs. (6.90) and (6.91),

$$N_{az} = 2P_z(1000)P_y(0)n_x(\text{equiv}) \left\{ 1 + \frac{|\dot{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2\bar{V}} \right\} \quad (6.91)$$

$$n_x(\text{equiv}) = n_x(\text{opp}) + n_x(\text{same}) \frac{\left\{ 1 + \frac{|\dot{y}|}{|\Delta V|} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{|\Delta V|} \right\}}{\left\{ 1 + \frac{|\dot{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2\bar{V}} \right\}} + \frac{1}{P_y(0)} \sum_{i=1}^n n_{xy}(\theta_i) \frac{\left\{ 1 + \frac{\pi}{2} \frac{\lambda_{xy}}{V_{\text{rel}}(\theta_i)} \frac{|\dot{z}|}{2\lambda_z} \right\}}{\left\{ 1 + \frac{|\dot{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2\bar{V}} \right\}} \quad (6.90)$$

Formula (6.91) can be evaluated by determining the following factors:

- $P_z(1000)$, the probability of vertical overlap for aircraft at adjacent flight levels (i.e. 1000ft);
- $P_y(0)$, the probability of lateral overlap for aircraft on the same track/route;
- $n_x(\text{equiv})$, the equivalent opposite-direction passing frequency and
- $K(\text{opp}) = \left\{ 1 + \frac{|\dot{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2\bar{V}} \right\}$, the kinematic factor for opposite-direction traffic.

Figure 6.12 below presents the flow chart for the computation of the four factors above. As discussed in Sections 6.5.2.2.1, 6.5.2.2.2, and 6.5.2.2.4, the ARMA Form 4 traffic flow data provides a critical input for the computation of $P_z(1000)$, $n_x(\text{equiv})$, and the kinematic factor $K(\text{opp})$ for opposite-direction traffic. In addition, as set out in Section 6.5.2.2.3, the proportions of aircraft utilizing GNSS and VOR/DME navigation and the standard deviation of GNSS navigation performance play an important part. Moreover, the technical vertical collision risk computation utilizes four additional fixed tables:

- Waypoint coordinates, containing the latitude-longitude coordinates for each waypoint;
- Aircraft dimensions, containing for each ICAO aircraft type the length, width, height, and typical cruising speed;
- Monitoring Groups (MGs), containing a mapping of the ICAO aircraft types into the monitoring groups⁷⁶;
- Vertical performance per Monitoring Group, a parameter file representing the vertical performance for each monitoring group (Section 6.5.2.2.1).

⁷⁶ For the mapping the version used in the EUR region is applied. See <https://www.eurocontrol.int/sites/default/files/2025-04/mmr-final-2024.pdf> (Accessed September 2025)

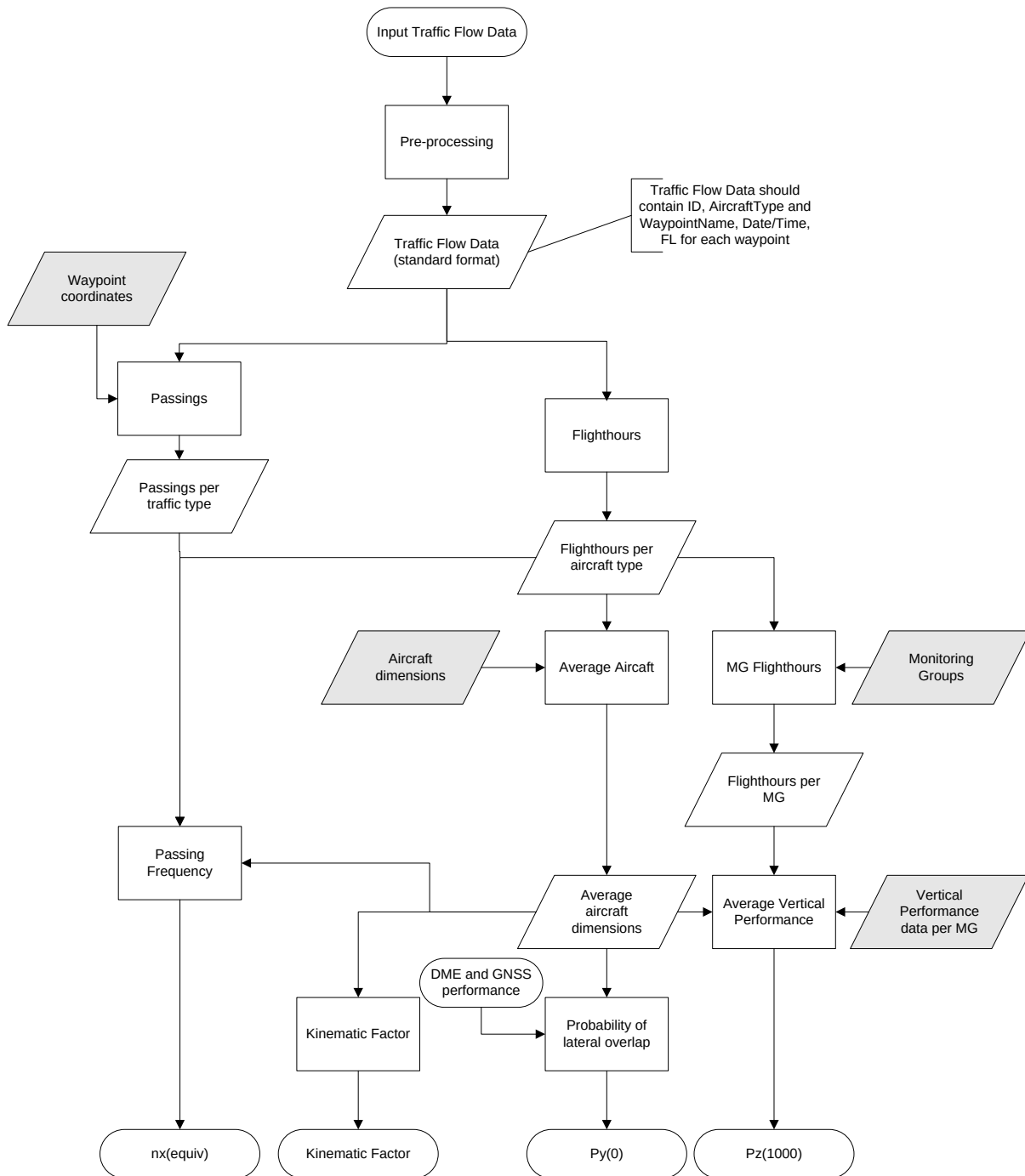


Figure 6.12: Flow chart of the technical vertical collision risk computation

6.5.3 Total Vertical Collision Risk Modelling

6.5.3.1 Introduction

As set out at a number of places in this chapter, total vertical collision risk is the sum of vertical collision risk due to normal technical height deviations of RVSM approved aircraft and vertical collision risk due to all other possible causes, and as set out in Section 6.5.1 of this chapter, the total vertical collision risk in AFI RVSM airspace is to be assessed against a total vertical target level of safety of 5×10^{-9} fatal accidents per flight hour. As set out in that section as well, event data from the ARMA Forms 1 and 3, supplemented with event data from Unsatisfactory Condition Reports (UCRs) filed by mainly aircrew and made available by ARMA and the AFI Tactical Action Group (TAG) are used to estimate the vertical collision risk due to non-technical causes.

The following broad categories of potential causes of total vertical collision risk have been distinguished in the successive assessments of the total vertical collision risk for AFI RVSM airspace (Moek & Smeltink, 2005; Smeltink et al., 2021):

- ATC error;
- Pilot error;
- ACAS events;
- Non-RVSM approved aircraft;
- Equipment failure;
- Turbulence/weather;
- Unknown civil aircraft;
- Unknown military aircraft operating outside designated military areas; and
- Aircraft contingency events.

ATC error and pilot error are also referred to as operational error. Each category may be subdivided further dependent on the specific nature of the error or problem as required. From a collision risk assessment point of view, the importance of these causes is that they may lead to large or atypical height deviations of, say, 300 ft or more and it is essentially the vertical risk due to this type of height deviations that is to be modelled for their contribution to the comparison with the total vertical TLS.

The broad categories above may be compared with the subdivision of the large height deviations collected by the NAT CMA into four main types (NAT, 1996) as listed in Section 6.4.3.2:

- (1) ATC-pilot loop errors and incorrect clearances;
- (2) Aircraft contingency events;
- (3) Deviations due to meteorological effects; and
- (4) Deviations due to TCAS.

where ATC pilot-loop errors refer to errors where aircraft fail to climb or descend as required (CMA Code D) or where aircraft climb or descend without ATC clearance (CMA Code E). The CMA Codes in brackets in the previous sentence were introduced under the *NAT SPG/33* heading in Section 6.4.2 and have been reproduced below:

A	Contingency action due to engine fault
B	Contingency action due to pressurisation failure
C	Contingency action due to other cause
D	Failure to climb/descent as cleared
E	Climb/descent without ATC clearance

- F Entry to MNPS airspace at an incorrect level
- G ATC FL re-clearance resulting in loss of lateral or longitudinal separation
- H Deviation due to TCAS
- I Aircraft unable to maintain level
- O other

Following the subdivision of large height deviations into four categories, a classification for risk assessment purposes was developed by the NAT MWG in Section 5.5 of (NAT, 1996) and has been reproduced in Table 6.6 of Section 6.4.3.2 of this document. The (latter) classification made a distinction between risk-bearing deviations and non-risk-bearing deviations, where the risk-bearing deviations were further classified into

- large height deviations involving whole numbers of flight levels; and
- large height deviations not involving whole numbers of flight levels.

This classification for risk assessment purposes has been used in all AFI RVSM total vertical collision risk assessments to date.

For example, an ATC error in issuing a clearance may lead to an aircraft levelling off at a wrong flight level, leading to two types of risk. Firstly, it may lead to a risk for any aircraft that may already correctly be flying at that level. Secondly, on its way towards the wrong flight level, the pertinent aircraft may have traversed through one or more intermediate flight levels. As another example, ATC misjudging the climb rate of an aircraft may lead to the aircraft passing through another aircraft's flight level too early or too late. From a risk point of view, this is very similar to passing through a level without a proper clearance.

A pilot error in following a correct ATC clearance may also lead to a large height deviation of the whole number of flight levels type. On the other hand, a level bust is an example of a pilot error not involving a whole number of flight levels. It involves an overshoot over a certain short period of time after which the aircraft levels off correctly at the intended flight level.

Height deviations due to ACAS do not normally involve whole numbers of flight levels but may be much larger than an aircraft's typical height deviations. Height deviations of non-RVSM approved aircraft will generally not involve whole numbers of flight levels either but may be expected to have a larger probability of relatively large height deviations, larger than, say, 300 ft. Height deviations due to equipment failure, turbulence or other adverse weather conditions will also generally lead to large height deviations not involving whole numbers of flight levels.

Unknown civil or military aircraft operating at an RVSM flight level involve by definition height deviations of the whole number of flight levels type as such aircraft should simply not be flying where they are. When they also happen to be non-RVSM approved, they may also cause the other type of large height deviation. Aircraft contingency procedures should be designed in such a way that they do not involve any significant risk when executed properly. Due to the nature of the situation, however, it may occasionally not be possible to fully comply with the procedure as a result of which one or more flight levels may be crossed without a proper clearance before levelling off at a new level.

The following subsections will present total vertical collision risk models for the following cases:

- Large height deviations not involving whole numbers of flight levels $N_{az}^{non-whl}$;
- Aircraft climbing or descending through a flight level $N_{az}^{cl/d}$; and
- Aircraft levelling off at a wrong level N_{az}^{wl} .

The last two cases obviously concern large height deviations involving whole numbers of flight levels. See Figure 6.13.

Having described the three total vertical collision risk component models, the full total vertical collision risk for AFI RVSM airspace is then given by

$$N_{az}^{total} = N_{az}^{non-whl} + N_{az}^{cl/d} + N_{az}^{wl} + N_{az} \quad (6.114)$$

where the technical vertical collision risk component N_{az} is given by eqs. (6.90) and (6.91).

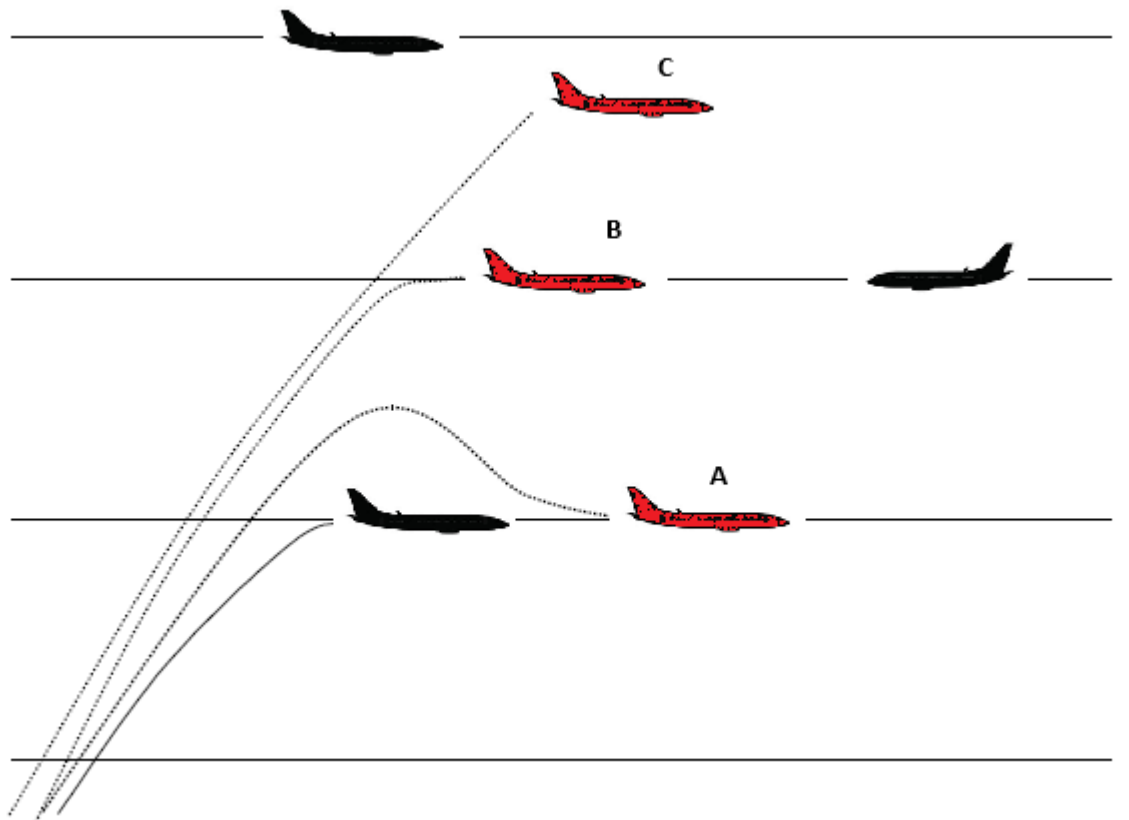


Figure 6.13: Illustration of the three basic error categories: A: Large height deviations not involving whole numbers of flight levels; B: Aircraft having levelled off at a wrong (opposite-direction) flight level; and C: Aircraft climbing (or descending) through a flight level

6.5.3.2 Large height-deviations not involving whole numbers of flight levels

The vertical collision risk due to large height deviations not involving whole numbers of flight levels can be modelled in the same way as the technical vertical collision risk, i.e.

$$N_{az}^{non-whl} = 2P_z(S_z)^{non-whl} P_y(0) n_x(\text{equiv}) \left\{ 1 + \frac{|\dot{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2\bar{V}} \right\} \quad (6.115)$$

A superscript “non-whl” is used to distinguish this type of vertical collision risk from the technical vertical collision risk. See Figure 6.13 above. The basic method to estimate the probability of vertical overlap $P_z(S_z)^{\text{non-whl}}$ due to large height deviations not involving whole numbers of flight levels is to model assigned altitude deviation (AAD) by means of an appropriate probability distribution explicitly accounting for the large height deviations within the components approach described in Section 6.5.2.2.1. Recall from that section that experience has shown that typical assigned altitude deviation can be satisfactorily modelled by a zero-mean double exponential probability distribution with a standard deviation of approximately 32 ft. This approach requires large height deviation data observed over a fairly broad range and would use an appropriate type of probability distribution with a mean of zero and a standard deviation (much) larger than 32 ft. It fails when the data available is heavily concentrated at one (or a few) value(s). Therefore, an alternative method to estimate $P_z(S_z)^{\text{non-whl}}$ has been developed as follows.

Recall from Section 6.5.2.2.1 that for the technical vertical collision risk assessment the TVE of a typical RVSM approved aircraft is modelled as the sum of typical ASE and typical AAD. Both error components were assumed to be random variables with the ASE probability density of a typical aircraft given by eq. (6.101) of Section 6.5.2.2.1 and the probability density of typical AAD being double exponential with a mean of zero and a standard deviation of approximately 32 ft.

A large height deviation over a relatively long period of time is modelled by taking the mean of the AAD as a (large) constant value. Thus, the TVE of any aircraft involved in a large height deviation of the non-whole numbers of flight levels type will be modelled as

$$TVE_{LHD} = AAD_{LHD} + ASE \quad (6.116)$$

where AAD_{LHD} is now a double-exponentially-distributed random variable with a large constant mean value and ASE continues to be random with probability density given by eq. (6.101).

The probability of vertical overlap between a typical RVSM approved aircraft and an RVSM approved aircraft involved in a large height deviation of the non-whole numbers of flight levels type is then calculated by the following variant of eq. (6.100),

$$P_z(S_z)_{LHD} = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{TVE}(z_1) f^{TVE_{LHD}}(S_z + z_1 - z) dz_1 dz \quad (6.117)$$

or

$$P_z(S_z)_{LHD} = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{TVE}(z_1) f^{TVE}(S_z - \overline{AAD}_{LHD} + z_1 - z) dz_1 dz \quad (6.118)$$

The inner integral represents the probability density of the vertical distance between the two aircraft where the aircraft are nominally separated by S_z and where one of the aircraft is assumed to have a large mean AAD of magnitude $\overline{AAD}_{LHD}$. This large mean AAD effectively reduces the nominal separation S_z by an amount equal to $\overline{AAD}_{LHD}$. In addition to the large mean AAD, the pertinent aircraft is assumed to have a normal random ASE.

Suppose now that there are n_{LHD} large height deviations of the non-whole numbers of flight levels type with magnitudes $\overline{AAD}_{LHD,i}$ and duration $t_{LHD,i}$, $i = 1, \dots, n_{LHD}$, during a period of time of T flight hours, where information on the number, magnitude, and duration of the large height deviations is to be obtained from the event reports. The probability of vertical overlap due to these deviations is then estimated by

$$P_z(S_z)^{non-whole} = \sum_{i=1}^{n_{LHD}} \frac{t_{LHD,i}}{T} P_z(S_z)_{LHD,i} \quad (6.119)$$

Eq. (6.119) may be compared with eq. (6.56) of Section 6.4.3.2 for the probability of vertical overlap due to large height deviations resulting in time spent at uncleared/incorrect flight levels developed by the NAT MWG in (NAT, 1996), i.e.

$$P_z(S_z)^{wrong\ level} = \frac{T_l}{F} \times P_z(0) \quad (6.56)$$

where T_l represents the total amount of time spent at uncleared/incorrect flight levels in the airspace under consideration for a given period of calendar time and F denotes the total amount of flight time during that calendar period. In eq. (6.56), T_l is also a sum of event durations, but since each event results in a pair of aircraft of which one is flying at a wrong level, the probability of vertical overlap is the same for each event and no explicit summation as in eq. (6.119) is needed.

It is finally noted that large height deviations not involving a whole number of flight levels are generally towards the next adjacent flight level, which in the case of the AFI Region predominantly carries opposite-direction traffic. Applying the probability of vertical overlap $P_z(S_z)^{non-whl}$ in the collision risk model of eq. (6.115) in combination with the equivalent opposite-direction passing frequency n_x (equiv) covering all the three traffic types, opposite-direction on the same route, same-direction on the same route, and intersecting routes, therefore, is slightly conservative. As will be seen in the next two subsections, it is more appropriate to model the probability of joint vertical and longitudinal overlap (or joint vertical and horizontal overlap for intersecting routes) for large height deviations involving whole numbers of flight levels by individual traffic type.

6.5.3.3 Large height-deviations involving aircraft climbing or descending through a flight level

Consider Figure 6.14, recalled below, for an aircraft climbing through a flight level and assume that the sides of the box representing the climbing aircraft remain parallel to the original level flight path during the large height deviation. Following the NAT MWG modelling for this type of large height deviation referenced in Section 6.4.3.2 (cf. eq. (6.58)), the probability of vertical overlap due to an aircraft climbing (or descending (cl/d)) through a single flight level is given by

$$P_z(S_z)_{FL}^{cl/d} = \frac{\frac{2\lambda_z}{|\dot{z}_c|}}{T} \quad (6.120)$$

and the probability of vertical overlap due to climbing or descending through $n^{\frac{cl}{d}}$ flight levels by

$$P_z(S_z)^{cl/d} = n^{\frac{cl}{d}} \frac{\frac{2\lambda_z}{|\dot{z}_c|}}{T} \quad (6.121)$$

where λ_z denotes the average aircraft height, $\overline{|\dot{z}_c|}$ is the average relative vertical speed between the aircraft and T the total flight time. See Table 6.14 further below. The formulae for the probabilities of vertical overlap in eqs. (6.120) and (6.121) are the same for an aircraft climbing (or descending) through an opposite- or same-direction flight level and also for a flight level on an intersecting route, but the actual numbers of same-direction and opposite-direction flight levels crossed may be different.

When an aircraft climbs or descends through a number of flight levels of a bidirectional route, the numbers of same- and opposite-direction flight levels crossed, say, $n_{same}^{\frac{cl}{d}}$ and $n_{opp}^{\frac{cl}{d}}$, need to be determined as well as the probability of the subject aircraft being in longitudinal overlap at each same- and opposite-direction flight level crossed. With opposite-direction traffic at adjacent flight levels, it is assumed that the probability of longitudinal overlap is the same for each opposite-direction flight level crossed. Similarly, it is assumed that the probability of longitudinal overlap is the same for each same-direction flight level crossed. The probability of joint vertical and longitudinal overlap between two aircraft due to one aircraft climbing or descending through a flight level is taken as the product of the probability of vertical overlap and the probability of longitudinal overlap defined by the flight level direction.

When the climb or descent of an aircraft on a route without proper clearance takes place in the vicinity of the route's intersection with another route, there is also an intersecting route vertical collision risk concerning the other route due to the loss of vertical separation and the probability of the subject aircraft being in horizontal overlap at the intersection with aircraft on the other route is needed. Dependent on the aircraft climbing or descending through an opposite- or same-direction flight level at/near the intersection, the probability of horizontal overlap is given by the probability of horizontal overlap for aircraft at adjacent flight levels of intersecting routes or by the probability of horizontal overlap for aircraft at flight levels separated by twice the vertical separation minimum S_z on intersecting routes. See Figure 6.16.

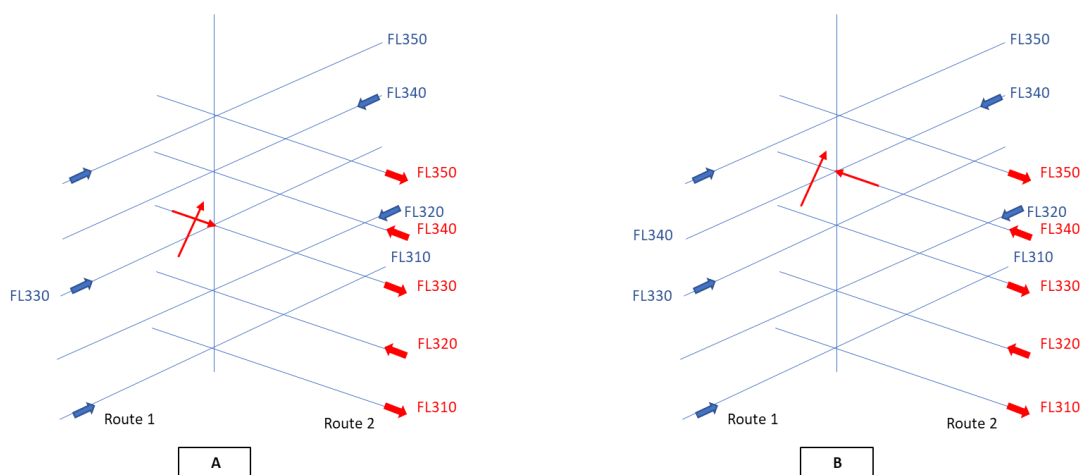


Figure 6.16: Abnormal situation at a route intersection point as a result of an improper climb/descent operational error (aircraft shown inbound to the intersection)

Figure 6.16A sketches the (abnormal) situation where the eastbound aircraft on route 1 climbs through the eastbound flight level FL330 of aircraft on route 2 near the intersection point of the two routes. Apart from the resulting vertical risk at FL330 of route 1, there is additional vertical risk at the intersection concerning aircraft flying eastbound at FL330 on route 2. Figure 6.16B sketches the (abnormal) situation where the

eastbound aircraft on route 1 climbs through the westbound flight level FL340 of aircraft on route 2 near the intersection point of the two routes. Apart from the resulting vertical risk at FL340 of route 1, there is additional vertical risk at the intersection concerning aircraft flying westbound at FL340 on route 2.

Thus, the vertical collision risk model for aircraft climbing or descending through a flight level without (proper) clearance is given by:

$$\begin{aligned}
 N_{az}^{cl/d} = & 2P_z(S_z)_{opp}^{cl/d} P_y(0) n_x(opp) \left\{ 1 + \frac{|\dot{y}|}{2V} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}|}{2V} \right\} \\
 & + 2P_z(S_z)_{same}^{cl/d} P_y(0) n_x^*(same) \left\{ 1 + \frac{|\dot{y}|}{\Delta V} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\dot{z}_c|}{\Delta V} \right\} \\
 & + 2 \sum_i^n P_z(S_z)_{\theta_i}^{cl/d} n_{xy}(\theta_i) \left\{ 1 + \frac{\frac{\pi}{2} \lambda_{xy} |\dot{z}_c|}{V_{rel}(\theta_i) 2\lambda_z} \right\} \\
 & + 2 \sum_i^n P_z(S_z)_{\pi-\theta_i}^{cl/d} n_{xy}^*(\theta_i) \left\{ 1 + \frac{\frac{\pi}{2} \lambda_{xy} |\dot{z}_c|}{V_{rel}(\pi - \theta_i) 2\lambda_z} \right\}
 \end{aligned} \tag{6.122}$$

where the superscript “cl/d” refers to an aircraft climbing or descending through a flight level without a proper clearance and the various probabilities of vertical overlap are given by

$$P_z(S_z)_{opp}^{cl/d} = n_{opp}^{cl/d} \frac{\frac{2\lambda_z}{|\dot{z}_c|}}{T} \tag{6.123}$$

$$P_z(S_z)_{same}^{cl/d} = n_{same}^{cl/d} \frac{\frac{2\lambda_z}{|\dot{z}_c|}}{T} \tag{6.124}$$

$$P_z(S_z)_{\theta_i}^{cl/d} = n_{\theta_i}^{cl/d} \frac{\frac{2\lambda_z}{|\dot{z}_c|}}{T} \tag{6.125}$$

$$P_z(S_z)_{\pi-\theta_i}^{cl/d} = n_{\pi-\theta_i}^{cl/d} \frac{\frac{2\lambda_z}{|\dot{z}_c|}}{T} \tag{6.126}$$

The new parameters of the collision risk model of eqs. (6.122) – (6.126) are defined in Table 6.14. (See Table 6.9 and Table 6.10 for the previously defined parameters.) Notice that opposite- and same-direction flight levels of a single route constitute special cases of routes intersecting at angles of $\theta = 180^\circ$ and $\theta = 0^\circ$ respectively (with supplementary angles $\pi - \theta = 0^\circ$ and $\pi - \theta = 180^\circ$). Notice also that an additional superscript “*” is used on $n_x^*(same)$ and $n_{xy}^*(\theta_i)$ to emphasize that these passing frequencies concern longitudinal/horizontal passings between aircraft at flight levels separated by twice the vertical separation minimum S_z . All passing frequencies can be calculated as set out in Section 6.5.2.2.2 by appropriately defining the aircraft pairs to be processed on the basis of the adjacent opposite-direction and next-adjacent same-direction flight levels.

Table 6.14: Definition of additional parameters of the vertical collision risk model of eqs. (6.122) - (6.126)

$N_{az}^{cl/d}$	Expected number of fatal aircraft accidents per flight hour due to aircraft climbing or descending through a flight level without a proper clearance
$P_z(S_z)_{opp}^{cl/d}$	Probability of vertical overlap due to aircraft climbing or descending through an opposite direction flight level without a proper clearance
$P_z(S_z)_{same}^{cl/d}$	Probability of vertical overlap due to aircraft climbing or descending through a same direction flight level without a proper clearance
$P_z(S_z)_{\theta_i}^{cl/d}$	Probability of vertical overlap due to eastbound/westbound aircraft climbing or descending without a proper clearance through a westbound/eastbound flight level for flights' intersection angle θ_i
$P_z(S_z)_{\pi-\theta_i}^{cl/d}$	Probability of vertical overlap due to eastbound/westbound aircraft aircraft climbing or descending without a proper clearance through an eastbound/westbound flight level for flights' intersection angle θ_i
$n_{opp}^{cl/d}$	Number of aircraft climbing or descending through an opposite-direction flight level without a proper clearance during a period of time with T flying hours
$n_{same}^{cl/d}$	Number of aircraft climbing or descending through a same-direction flight level without a proper clearance during a period of time with T flying hours
$n_{\theta_i}^{cl/d}$	Number of eastbound/westbound aircraft climbing or descending without a proper clearance through a westbound/eastbound flight level for flights' intersection angle θ_i (at or near the intersection point)
$n_{\pi-\theta_i}^{cl/d}$	Number of eastbound/westbound aircraft climbing or descending without a proper clearance through an eastbound/westbound flight level for flights' intersection angle θ_i (at or near the intersection point)
$n_x^*(same)$	Same direction passing frequency for same direction aircraft nominally separated by twice the vertical separation minimum S_z
$n_{xy}^*(\theta_i)$	Passing frequency for aircraft nominally separated by twice the vertical separation minimum S_z for flights' intersection angle θ_i
$ \dot{z}_c $	Average climb or descent rate for aircraft climbing or descending through a flight level without a proper clearance
T	Amount of flying time during the period of time the incident data were collected

Information on the number of incorrect flight level crossings and the pertinent vertical speeds is to be obtained from the event reports. Although the likelihood of an aircraft climbing or descending through a flight level without a proper clearance at, or near, the intersection point of two routes is very small, this type of event has occasionally been found to occur in AFI RVSM airspace. When no information on the vertical speed is included in a particular report, a default value will have to be used. Default values for a number of cases are given in (NAT, 1996) and (EUROCONTROL, 2001), for example, 20 kts and 15 kts respectively for a normal climb/descent. Both references specify a value of 50 kts in case of pressurisation failure, and 2 – 5 kts for engine failures. Since the probabilities of vertical overlap are inversely proportional to the vertical speed, a value of 15 kts is used for normal climb/descents when specific information is missing in the event report. The common references (NAT, 1996) and (EUROCONTROL, 2001) values will be used for the other cases, where the distinction between 2 kts and 5 kts depends on the aircraft being triple (or more) engined or twin-engined.

6.5.3.4 Large height-deviations involving aircraft levelled off at a wrong flight level

Consider Figure 6.13, recalled below, showing an aircraft flying at a wrong (opposite-direction) flight level of a route as a result of a 1000 ft large height deviation due to operational error. Following the NAT MWG modelling for this type of large height deviation referenced in Section 6.4.3.2 (cf. eq. (6.49)), the probability of vertical overlap due to a single aircraft levelling off at a wrong (same-direction or opposite-direction) flight level can be given by

$$P_z(S_z)_{\text{FL}}^{\text{wl}} = \frac{t^{\text{wl}} P_z(0)}{T} \quad (6.127)$$

and the probability of vertical overlap due to n^{wl} aircraft having levelled off at a wrong flight level by

$$P_z(S_z)_{\text{FL}}^{\text{wl}} = n^{\text{wl}} \frac{t^{\text{wl}} P_z(0)}{T} \quad (6.128)$$

where the new parameters t^{wl} and $\bar{t}^{\text{wl}}$ denote the sojourn time of a single aircraft and the average sojourn time of aircraft at a wrong flight level respectively and $P_z(0)$ denotes the probability of vertical overlap for aircraft at the same flight level. See Table 6.15 further below. The formulae for the vertical overlap probabilities in eqs. (6.127) and (6.128) are the same for an aircraft levelling off at a same- or opposite-direction flight level but the actual numbers of aircraft flying at wrong same-direction and opposite-direction flight levels may be different in applications. The formulae are also valid for the case of aircraft levelling off at a wrong flight level and the aircraft's route(s) intersecting another route.

When an aircraft levels off at a wrong flight level, the sojourn time at the wrong level needs to be determined as well as the probability of the subject aircraft being in longitudinal overlap at the wrong flight level, which may be either same or opposite direction, of the assigned route. When the aircraft levels off at an opposite-direction flight level, it is assumed that the probability of longitudinal overlap is the same as that for opposite-direction traffic at adjacent flight levels. Similarly, when the aircraft levels off at a same-direction flight level, it is assumed that the probability of longitudinal overlap is the same as that for same-direction traffic at flight levels separated by twice the vertical separation minimum S_z on the same route.

When the route on which the aircraft levelled off at a wrong flight level intersects another route, there is also an intersecting route vertical collision risk due to the loss of vertical separation and the probability of the subject aircraft being in horizontal overlap at the intersection at the wrong flight level is needed. Dependent on the aircraft having levelled off at an opposite- or same-direction flight level, the probability of horizontal overlap is given by the probability of horizontal overlap for aircraft at adjacent flight levels of intersecting routes or by the probability of horizontal overlap for aircraft at flight levels separated by twice the vertical separation minimum S_z on intersecting routes. See Figure 6.17.

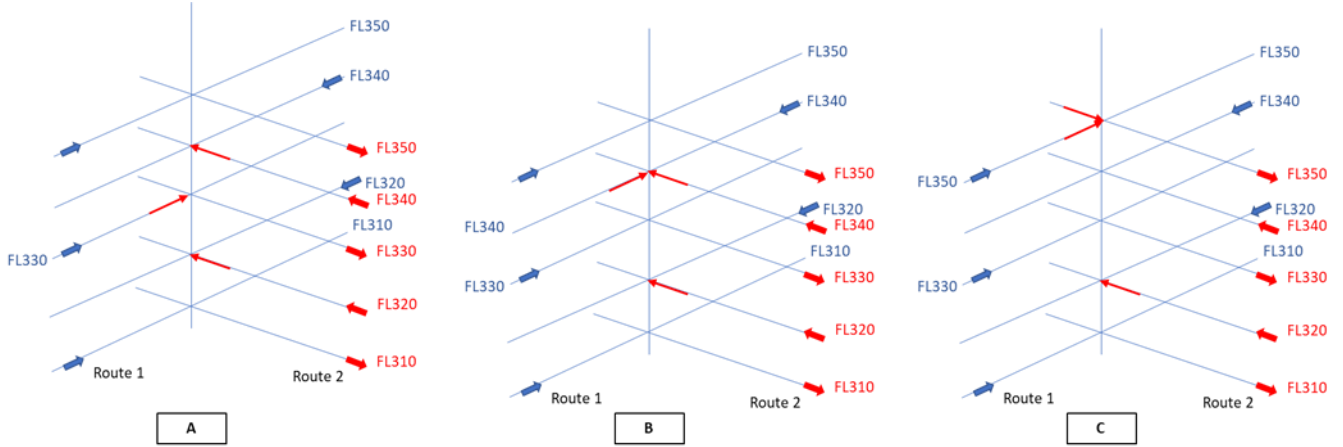


Figure 6.17: Normal and abnormal situation at a route intersection point as a result of a wrong-level-flying operational error (aircraft shown inbound to the intersection)

Figure 6.17A sketches the normal situation of an aircraft flying eastbound at FL330 of route 1. At the intersection, it is vertically separated from aircraft flying westbound at FL320 or FL340 on route 2. Figure 6.17B sketches the abnormal situation where the aircraft cleared to FL330 is actually flying eastbound at the wrong opposite-direction FL340. Apart from the resulting vertical risk at FL340 of route 1, there is additional vertical risk at the intersection concerning aircraft flying westbound on route 2. Figure 6.17C sketches the abnormal situation where the aircraft cleared to FL330 is actually flying eastbound at the wrong same-direction FL350. Apart from the resulting vertical risk at FL350 of route 1, there is additional vertical risk at the intersection concerning aircraft flying eastbound on route 2.

In all cases, the probability of joint vertical and longitudinal, or horizontal, overlap between two aircraft due to one aircraft levelling off at a wrong flight level is taken as the product of the probability of vertical overlap and the probability of longitudinal, or horizontal, overlap defined by the flight level direction.

Thus, the vertical collision risk model for aircraft levelling off at a wrong flight level is given by:

$$\begin{aligned}
 N_{az}^{wl} = & 2P_z(S_z)_{opp}^{wl}P_y(0)n_x(opp)\left\{1 + \frac{|\bar{y}|}{2\bar{V}} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\bar{z}|}{2\bar{V}}\right\} \\
 & + 2P_z(S_z)_{same}^{wl}P_y(0)n_x^*(same)\left\{1 + \frac{|\bar{y}|}{\Delta V} + \frac{\lambda_{xy}}{\lambda_z} \frac{|\bar{z}_c|}{\Delta V}\right\} \\
 & + 2\sum_i^n P_z(S_z)_{opp,\theta_i}^{wl}n_{xy}(\theta_i)\left\{1 + \frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)} \frac{|\bar{z}_c|}{2\lambda_z}\right\} \\
 & + 2\sum_i^n P_z(S_z)_{same,\theta_i}^{wl}n_{xy}^*(\theta_i)\left\{1 + \frac{\frac{\pi}{2}\lambda_{xy}}{V_{rel}(\theta_i)} \frac{|\bar{z}_c|}{2\lambda_z}\right\}
 \end{aligned} \tag{6.129}$$

where the superscript “wl” refers to an aircraft levelling off at a wrong flight level and the various probabilities of vertical overlap are given by

$$P_z(S_z)_{opp}^{wl} = n_{opp}^{wl} \frac{\bar{t}_{opp}^{wl} P_z(0)}{T} \tag{6.130}$$

$$P_z(S_z)_{same}^{wl} = n_{same}^{wl} \frac{\bar{t}_{same}^{wl} P_z(0)}{T} \quad (6.131)$$

$$P_z(S_z)_{same}^{wl} = n_{same}^{wl} \frac{\bar{t}_{same}^{wl} P_z(0)}{T} \quad (6.132)$$

$$P_z(S_z)_{opp,\theta_i}^{wl} = n_{opp,\theta_i}^{wl} \frac{\bar{t}_{opp,\theta_i}^{wl} P_z(0)}{T} \quad (6.133)$$

$$P_z(S_z)_{same,\theta_i}^{wl} = n_{same,\theta_i}^{wl} \frac{\bar{t}_{same,\theta_i}^{wl} P_z(0)}{T} \quad (6.134)$$

The new parameters of the collision risk model in eqs. (6.129) – (6.134) are defined in Table 6.15. (See Table 6.9, Table 6.10, and Table 6.14 for the parameters defined previously.)

Table 6.15: Definition of additional parameters of the vertical collision risk model of eqs. (6.129) - (6.134)

N_{az}^{wl}	Expected number of fatal aircraft accidents per flight hour due to aircraft levelling off at a wrong flight level
$P_z(0)$	Probability of vertical overlap for aircraft nominally flying at the same flight level
$P_z(S_z)_{opp}^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong, opposite direction, flight level
$P_z(S_z)_{same}^{wl}$	Probability of vertical overlap due to aircraft levelling off at a wrong, same direction, flight level
$P_z(S_z)_{opp,\theta_i}^{wl}$	Probability of vertical overlap due to eastbound/westbound aircraft levelling off at a wrong, opposite direction, westbound/eastbound flight level for flights' intersection angle θ_i
$P_z(S_z)_{same,\theta_i}^{wl}$	Probability of vertical overlap due to eastbound/westbound aircraft levelling off at a wrong, same direction, eastbound/westbound flight level for flights' intersection angle θ_i
n_{opp}^{wl}	Number of aircraft levelling off at a wrong, opposite direction, flight level during a period of time with T flying hours
n_{same}^{wl}	Number of aircraft levelling off at a wrong, same direction, flight level during a period of time with T flying hours
n_{opp,θ_i}^{wl}	Number of eastbound/westbound aircraft levelling off at a wrong, opposite direction, westbound/eastbound flight level for flights' intersection angle θ_i
n_{same,θ_i}^{wl}	Number of eastbound/westbound aircraft levelling off at a wrong, same direction, eastbound/westbound flight level for flights' intersection angle θ_i
$\bar{t}_{opp}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong, opposite direction, flight level after incorrectly levelling off
$\bar{t}_{same}^{wl}$	Average sojourn time (hours) of an aircraft at a wrong, same direction, flight level after incorrectly levelling off
$\bar{t}_{opp,\theta_i}^{wl}$	Average sojourn time (hours) of an eastbound/westbound aircraft at a wrong, opposite direction, westbound/eastbound for flights' intersection angle θ_i after incorrectly levelling off
$\bar{t}_{same,\theta_i}^{wl}$	Average sojourn time (hours) of an eastbound/westbound aircraft at a wrong, same direction, eastbound/westbound flight level for flights' intersection angle θ_i after incorrectly levelling off

Not surprisingly, the number of times aircraft level off at a wrong level and the average duration of their stay at the wrong level are a part of the probability of vertical overlap for this particular type of event. Information on these two parameters is to be obtained from the event reports. The probability of vertical overlap $P_z(0)$ accounts for the normal technical height deviations of aircraft that, in this case, are flying at the same flight level after the incorrect levelling off. $P_z(0)$ can be calculated in a similar manner as the probability of vertical overlap $P_z(S_z)$ due to normal technical height deviations by putting $S_z = 0$ in eq. (6.100) (see eq. (6.57)).

6.5.3.5 Total vertical collision risk

Having described the three total vertical collision risk component models $N_{az}^{non-whl}$, $N_{az}^{cl/d}$, and N_{az}^{wl} , in the previous three subsections of Section 6.5.3, and the technical vertical collision risk component N_{az} in Section 6.5.2.1, the full total vertical collision risk model for AFI RVSM airspace is then given by

$$N_{az}^{total} = N_{az}^{non-whl} + N_{az}^{cl/d} + N_{az}^{wl} + N_{az} \quad (6.114)$$

(This summary equation was already given in the introductory Section 6.5.3.1.)

Each of the component collision risk models in the overall model in eq. (6.114) might, in principle, be extended with some intervention factor. This has not been done as AFI RVSM airspace is essentially procedurally controlled airspace and the risk mitigating effect of ACAS (and IFBP) as a safety net is not allowed to be accounted for in collision risk assessment.

6.6 Vertical collision risk models for other ICAO Regions

6.6.1 Introduction

There are thirteen RMAs world wide⁷⁷:

- North Atlantic Central Monitoring Agency (NAT CMA)
- Australian Airspace Monitoring Agency (AAMA)
- Africa and Indian Ocean (AFI) Regional Monitoring Agency (ARMA)
- Monitoring Agency For Asia Region (MAAR)
- China Regional Monitoring Agency (China RMA)
- Regional Monitoring Agency EURASIA
- European Regional Monitoring Agency (EUR RMA)
- Japan Airspace Safety Monitoring Agency (JASMA)
- Middle East Regional Monitoring Agency (MIDRMA)
- North American Approvals Registry and Monitoring Organization (NAARMO)
- Pacific Approvals Registry and Monitoring Organization (PARMO)
- Caribbean and South American Monitoring Agency (CARSAMMA)
- South Atlantic Monitoring Agency (SATMA)

⁷⁷ The website of the North Atlantic Central Monitoring Agency (NAT CMA) provides links to the following other RMAs:

The websites of all the thirteen RMAs have been visited in search for publicly available documentation on the type of collision risk models utilized by the RMAs for the annual RVSM safety assessments under their jurisdiction. No such documentation was found for ten of the RMAs. The website of the China RMA states that “China RMA applies the Reich collision risk model recommended by ICAO to perform safety assessment”. See Section 6.4.3 for the RVSM safety assessment approach utilized by the NAT MWG in conjunction with the NAT CMA and see (EUROCONTROL, 2001) for the methodology utilized by the EUR RMA.

The website of the RMA EURASIA contains a link to a safety report in Russian that seems to be dated 31.07.2014. The safety report contains a number of references in English, including references (Moek & Smeltink, 2005), (NAT, 1996), (Moek et al., 2001), and (EUROCONTROL, 2001) to this document. Eq. (2.1) of the safety report presents a collision risk model which, apart from a missing factor of two (2) and a minor change in notation, is the same as the technical vertical collision risk model of eq. (6.87) utilized for the annual RVSM safety assessment for the AFI Region described in Section 6.5. Eq. (2.12) of the safety report gives an expression for the probability of vertical overlap $P_z(S_z)^{cl/d}$ due to improper climbing or descending through other flight levels. Apart from an additional factor of two (2), eq. (2.12) is the same as eq. (6.121) of this document. Eq. (2.12) is then used in eq. (2.13) for this type of vertical risk on crossing routes. Eq. (2.14) provides a collision risk model for the vertical collision risk due to wrong-level-flying on crossing routes with a probability of vertical overlap $P_z(S_z)^{wl}$ as defined in eq. (6.128) of this document, but also with an additional factor of two (2). It might be speculated that the additional factors of two incorporated into the safety report’s probabilities of vertical overlap are to correct for the missing factor of two in the report’s first collision model in eq. (2.1).

The remainder of this subsection will subsequently discuss vertical collision risk models utilized by SATMA, NAARMO, and AAMA.

6.6.2 South Atlantic Monitoring Agency - SATMA

The SATMA website provides extensive documentation on the safety assessments of RVSM and RNP 10 operations in the EUR/SAM Corridor connecting south-western Europe to north-eastern South America. It lists the pre-implementation collision risk assessment of RVSM and RNP10 in the EUR/SAM Corridor published in August 2001 (Moek et al., 2001) and *LHD Monitoring Reports* and *EUR/SAM Corridor RVSM/RNP10 20XX Safety Assessments* for the years 2012 to 2019 inclusive.

The *EUR/SAM Corridor RVSM/RNP10 2019 Safety Assessment* (ENAIRe, 2020) presented the following model for the technical vertical collision risk (Equation 3), where the original notation has been slightly adapted to the notation used in this document:

$$N_{az} = P_z(S_z)P_y(0)\frac{\lambda_x}{s_x}\left\{E_z(\text{same})\left(\frac{|\overline{\Delta V}|}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right) + E_z(\text{opp})\left(\frac{2\overline{V}}{2\lambda_x} + \frac{|\overline{y}|}{2\lambda_y} + \frac{|\overline{z}|}{2\lambda_z}\right)\right\} + P_z(S_z)\sum_{i=1}^n P_h(\theta_i) E_z(\theta_i) \left\{\frac{V_{rel}(\theta_i)}{\frac{\pi}{2}\lambda_h} + \frac{|\overline{z}|}{2\lambda_z}\right\} \quad (6.135)$$

In eq (6.135), $P_h(\theta_i)$ denotes the probability of horizontal overlap for pairs of aircraft on routes intersecting at angle θ_i . The same-direction and opposite-direction components of the above model are the same as the

same-direction and opposite-direction components in eq. (6.45) of the occupancy form of the technical vertical collision risk model described in Section 6.4.3.2 for the North Atlantic Region. The last component in eq. (6.135) describes the vertical collision risk for aircraft at adjacent flight levels of n pairs intersecting at angles θ_i , $i = 1, \dots, n$. This component does not feature in the vertical collision risk model for the NAT due to the traffic flows in the North Atlantic predominantly being east-west and west-east. Two airspaces that contain a significant amount of crossing traffic are the Western Atlantic Route System and U.S. domestic airspace (NAARMO, 2015). The intersecting-route component of the vertical collision risk model seems to be based on equation (3a) of (NAARMO, 2015). The occupancy form of the technical vertical collision risk model in eq. (6.135) may also be compared with the technical vertical collision risk model in passing frequency form in eq. (6.87) as described for the AFI Region in Section 6.5.2. It is remarked that the explicit factor of two (2) upfront in the passing frequency form of eq. (6.87), is included in the three occupancy parameters of the vertical collision risk model of eq. (6.135).

Equation 5 of Section 4.2.2, *Total vertical collision risk*, of (ENAIRe, 2020) provides the following overall formula for this risk in the EUR/SAM Corridor RVSM airspace, in original notation,

$$N_{az}^{total} = N_{az}^{tech} + N_{az}^{wl} + N_{az}^{cl/d} + N_{az}^* \quad (6.136)$$

where N_{az}^{tech} denotes the technical vertical collision risk (i.e. eq. (6.135)), N_{az}^{wl} the vertical collision risk due to wrong-level-flying, $N_{az}^{cl/d}$ the vertical collision risk due to improper flight level crossings, and N_{az}^* denotes the vertical collision risk due to large height deviations of the non-whole-number-of-flight levels type. Not surprisingly, eq. (6.136) is the same as eq. (6.114) of Section 6.5.3.5 utilized for the annual RVSM collision risk assessments for the AFI Region of ICAO. Formulae for the three risk components other than the technical vertical collision risk component are missing in (ENAIRe, 2020). This is probably caused by the fact that (ENAIRe, 2020) refers to it using a methodology published in June 2018 ([Ref. 34] to (ENAIRe, 2020)). However, the *EUR/SAM Corridor RVSM/RNP10 2014 Safety Assessment* up to and including the *EUR/SAM Corridor RVSM/RNP10 2016 Safety Assessment* reports do include formulae for the vertical collision risk components N_{az}^{wl} , $N_{az}^{cl/d}$, and N_{az}^* . The following formulae have been reproduced from the latter (ENAIRe, 2017) (Equation 51. – Equation 56.):

$$N_{az}^{wl} = P_y(0) \frac{\lambda_x}{\bar{s}_x} \left\{ P_z^{wl}(S_z)_{same} E_z(same) \left(\frac{|\Delta V|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) + P_z^{wl}(S_z)_{opp} E_z(opp) \left(\frac{2\bar{V}}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \right\} + \frac{P_z(0) \times t_{same}^{wl}}{T} \sum_{i=1}^n P_h(\theta_i) E_z(\theta_i) \left\{ \frac{V_{rel}(\theta_i)}{\frac{\pi}{2}\lambda_h} + \frac{|\bar{z}|}{2\lambda_z} \right\} \quad (6.137)$$

$$P_z^{wl}(S_z)_{same} = \frac{P_z(0) \times t_{same}^{wl}}{T} \quad P_z^{wl}(S_z)_{opp} = \frac{P_z(0) \times t_{opp}^{wl}}{T} \quad (6.138)$$

$$N_{az}^{cl/d} = P_y(0) \frac{\lambda_x}{\bar{s}_x} \left\{ P_z^{cl/d}(S_z)_{same} E_z(same) \left(\frac{|\Delta V|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) + P_z^{cl/d}(S_z)_{opp} E_z(opp) \left(\frac{2\bar{V}}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right) \right\} + P_z^{cl/d} \sum_{i=1}^n P_h(\theta_i) E_z(\theta_i) \left\{ \frac{V_{rel}(\theta_i)}{\frac{\pi}{2}\lambda_h} + \frac{|\bar{z}|}{2\lambda_z} \right\} \quad (6.139)$$

$$t_z = \frac{2\lambda_z}{|\bar{z}_c|} \quad (6.140)$$

$$P_z^{cl/d} = \frac{N \times t_z}{T} = \frac{N \times 2\lambda_z / |\dot{z}_c|}{T} \quad (6.141)$$

$$N_{az}^* = P_y(0) \frac{\lambda_x}{\bar{s}_x} \left\{ P_z^*(S_z)_{same} E_z(same) \left(\frac{|\Delta V|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right) + P_z^*(S_z)_{opp} E_z(opp) \left(\frac{2\bar{V}}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right) \right\} + P_z^* \sum_{i=1}^n P_h(\theta_i) E_z(\theta_i) \left\{ \frac{V_{rel}(\theta_i)}{\frac{\pi}{2}\lambda_h} + \frac{|\dot{z}|}{2\lambda_z} \right\} \quad (6.142)$$

Eq. (6.137) and (6.138) with eq. (6.137) in occupancy form correspond with eqs. (6.129) – (6.134) of the passing frequency form of the wrong-level-flying total vertical collision risk model for AFI RVSM airspace presented in Section 6.5.3.4 when t_{same}^{wl} , the total time spent at wrong same-direction flight levels, and t_{opp}^{wl} , the total time spent at wrong opposite-direction flight levels, are interpreted as $t_{same}^{wl} = n_{same}^{wl} \times \bar{t}_{same}^{wl}$ and $t_{opp}^{wl} = n_{opp}^{wl} \times \bar{t}_{opp}^{wl}$ with the overbar-ed quantities denoting average times spent at a wrong flight level per event. Notice that the model in (6.137) uses a total time of flying at wrong intersecting-route flight levels aggregated over the various intersecting angles.

Eq. (6.139) and (6.141) with eq. (6.139) in occupancy form correspond with eqs. (6.122) – (6.126) of the passing frequency form of the wrong-level-flying total vertical collision risk model for AFI RVSM airspace presented in Section 6.5.3.3. Notice that the model in (6.139) uses a total time of flying at wrong intersecting-route flight levels aggregated over the various intersecting angles and that $P_z^{cl/d}(S_z)_{same}$ and $P_z^{cl/d}(S_z)_{opp}$ were not explicitly defined in (ENAIRe, 2017). Their definition, however, is straightforward.

Finally, Eq. (6.142) in occupancy form corresponds with eqs. (6.115) for the passing frequency form of the vertical collision risk model for the risk due to large height deviations not involving whole numbers of flight levels for AFI RVSM airspace presented in Section 6.5.3.2. Notice that the model in (6.142) was not supplemented with formulae for $P_z^*(S_z)_{same}$, $P_z^*(S_z)_{opp}$, or P_z^* in (ENAIRe, 2017). P_z^* is stated to be able to be calculated in the same way as the probability of vertical overlap $P_z(S_z)$ with $S_z = 1000$ ft due to normal typical height deviations of RVSM approved aircraft of the technical vertical collision risk model of eq. (6.135). Cf. Section 6.5.3.2.

It was suggested above that the intersecting-route component of the vertical collision risk model of eq. (6.135) reproduced from Annex 11 (ICAO, 2018a) seemed to be based on equation (3a) of (NAARMO, 2015). Section 4.2.4, *Probability of horizontal overlap* $P_h(\theta)$, and Section 4.2.7, *Vertical occupancy*, of (ENAIRe, 2017) support this claim.

6.6.3 North American Approvals Registry and Monitoring Organization – NAARMO

Having referred to (NAARMO, 2015) in the context of the annual RVSM safety assessment for the EUR/SAM corridor, this subsection proceeds with a more detailed look at (NAARMO, 2015). This reference provides a detailed description of the crossing track risk model used in the vertical risk estimates for North American and the Western Atlantic Route System (WATRS) Plus airspace. The model was originally developed for the implementation of RVSM in South China Sea airspace in February 2002. The South China Sea was the first procedural airspace with significant crossing tracks considered for the RVSM.

(NAARMO, 2015) begins with the two ways by which a pair of proximate aircraft at adjacent flight levels on intersecting tracks that has lost vertical separation can enter into collision, i.e. in the horizontal plane and vertically, giving a collision rate

$$CR_z = N_h(\theta)P_z(S_z) + N_zP_h(\theta) \quad (6.143)$$

Proximity of a pair of aircraft at adjacent flight levels on intersecting tracks is defined in Table 1 of Section 1 of the reference as the aircraft being within a pre-determined horizontal distance S_h during their passing of the intersection. In equation (6.143), $P_z(S_z)$ and $P_h(\theta)$ denote the probabilities of vertical and horizontal overlap for the intersecting route scenario, where, more precisely, $P_h(\theta)$ is the conditional probability of horizontal overlap given proximity. The respective frequencies $N_h(\theta)$ and N_z of entering into horizontal overlap given proximity and of entering into vertical overlap are then eliminated by means of the well-known relationships between frequencies of overlap and probabilities of overlap, cf. eqs. (5.14) – (5.16), resulting in (eq. (1b) of (NAARMO, 2015))

$$CR_z = P_h(\theta)P_z(S_z) \left(\frac{1}{t_h(\theta)} + \frac{1}{t_z} \right) + \quad (6.144)$$

where $t_h(\theta)$ and t_z denote the average duration of a horizontal overlap and of a vertical overlap respectively. The average overlap durations are then eliminated in favour of average aircraft dimensions and relative speeds, i.e. (eq. (1c) of (NAARMO, 2015))

$$CR_z = P_h(\theta)P_z(S_z) \left(\frac{2\overline{|\dot{h}(\theta)|}}{\pi\lambda_h} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right) \quad (6.145)$$

where $\overline{|\dot{h}(\theta)|}$ denotes the average value of the magnitude of the relative horizontal speed between the aircraft in a pair and $\overline{|\dot{z}|}$ denotes the average value of the magnitude of their relative vertical speed.

The collision rate defined by eq. (6.145) pertains to a pair of proximate aircraft, which means that the time dimension is proximity time. Multiplication by total proximity time and division by total flight time converts the collision rate per proximity hour into collision rate per flight hour, and multiplication by a factor of two (2) converts the latter collision rate into accident rate per flight hour. The model thus becomes (eq. (3a) of (NAARMO, 2015))

$$N_{az} = P_h(\theta)P_z(S_z)E_z(\theta) \left(\frac{2\overline{|\dot{h}(\theta)|}}{\pi\lambda_h} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right) \quad (6.146)$$

where $E_z(\theta)$ denotes intersecting-track occupancy as a function of the intersection angle θ , i.e.

$$E_z(\theta) = 2 \frac{T_h(\theta)}{H}, \quad (6.147)$$

and $T_h(\theta)$ and H denote the proximity time for aircraft pairs on tracks intersecting at angle θ and the total flight time during a given observation period. It is emphasized in (NAARMO, 2015) that the conversion of the collision rate CR_z per proximity hour in eq. (6.145) into the accident rate N_{az} per flight hour in eq. (6.146) assumes that the probabilities of horizontal overlap and vertical overlap are constant during proximity and

that this puts an extremely strict constraint on the probability of horizontal overlap in that the horizontal overlap probability (given proximity) will be set at its maximum value for the entire proximity duration $T_h(\theta)$.

The intersecting-track collision risk model of eq. (6.146) may be compared with the occupancy form of the vertical collision risk model for same-direction or opposite-direction traffic on the same route, e.g. eq. (6.45) of Section 6.4.3.2 or eq. (6.135) of this section (Section 6.6). In the latter models, the conditional probability of longitudinal overlap given proximity is given by the ratio λ_x/S_x where S_x denotes the longitudinal proximity distance for aircraft at adjacent flight levels on the same track.

(NAARMO, 2015) then proceeds with one more transformation of the collision risk model by re-expressing the intersecting-track occupancy $E_z(\theta)$. To this end, total proximity time $T_h(\theta)$ is expressed as the product of number of the proximities $K(\theta)$, say, and the average duration of a proximity, t_{S_h} , where the latter duration is calculated from a specified proximity distance S_h and the average relative horizontal speed $|\dot{h}(\theta)|$. Similarly, total flight time H is expressed as the product of the number of flights, N , and the average flight duration, t_F , say. Thus, intersecting-track occupancy $E_z(\theta)$ can be expressed as

$$E_z(\theta) = 2 \frac{K(\theta) t_{S_h}}{N t_F} \quad (6.148)$$

This expression may be compared with the result of the *Direct Estimation from Time at Waypoint Passing* occupancy estimation method for same-direction traffic occupancy in Appendix C to Chapter 4 of Section 2 in Part II of (ICAO, 1992a), i.e.

$$E_z(\theta) = 2 \frac{\text{number of proximate pairs}}{\text{number of flights}} \quad (6.149)$$

where the quantities on the right side of eq. (6.149) are counts obtained at a representative reference point on the route. Notice that eq. (6.149) (conservatively) takes the ratio of the average duration of a same-direction proximity and the average duration of a flight equal to one. Substitution of eq. (6.148) into eq. (6.146) then gives the following form of the vertical collision risk model for aircraft at adjacent flight levels of intersecting tracks (eq. (5) of (NAARMO, 2015)):

$$N_{az} = P_h(\theta) P_z(S_z) \frac{\pi S_h}{2|\dot{h}(\theta)|} \frac{1}{t_F} \frac{2K(\theta)}{N} \left(\frac{2|\dot{h}(\theta)|}{\pi \lambda_h} + \frac{|\dot{z}|}{2\lambda_z} \right) \quad (6.150)$$

The first ratio on the right-hand side of eq. (6.150) denotes the average duration t_{S_h} of a proximity. (NAARMO, 2015) uses eq. (6.150) when the average duration t_{S_h} of a proximity is less than the average flight duration t_F and uses

$$N_{az} = P_h(\theta) P_z(S_z) \frac{2K(\theta)}{N} \left(\frac{2|\dot{h}(\theta)|}{\pi \lambda_h} + \frac{|\dot{z}|}{2\lambda_z} \right) \quad (6.151)$$

when the average duration t_{S_h} of a proximity is greater than or equal to the average flight duration t_F . Eqs. (6.150) and (6.151) are finally extended to the case of n different intersection angles θ_i , $i = 1, \dots, n$ by summation of $N_{az}(\theta_i)$, $i = 1, \dots, n$, over $i = 1$.

The intersecting-track occupancy form of the technical vertical collision risk model of eq. (6.150) (and 6.151)) developed by NAARMO, originally for the South China Sea and subsequently for North American domestic and WATRS Plus oceanic airspace maybe compared with the intersecting-track passing frequency form of the vertical collision risk of eq. (6.83) utilized for the AFI Region of ICAO.

To this end, eq. (6.150) is first re-written as

$$N_{az} = 2P_h(\theta)P_z(S_z) \frac{\text{total proximity time}}{\text{total flight time}} \left(\frac{2|\overline{h(\theta)}|}{\pi\lambda_h} + \frac{|\overline{z}|}{2\lambda_z} \right) \quad (6.152)$$

after which the first term terms in brackets on the right side of eq. (6.152) is divided out to obtain

$$N_{az} = 2P_h(\theta)P_z(S_z) \frac{\text{total proximity time}}{\text{total flight time}} \frac{|\overline{h(\theta)}|}{\frac{\pi}{2}\lambda_h} \left(1 + \frac{\frac{\pi}{2}\lambda_h}{2\lambda_z} \frac{|\overline{z}|}{|\overline{h(\theta)}|} \right) \quad (6.153)$$

and

$$N_{az} = 2P_h(\theta)P_z(S_z) \frac{\text{number of proximities}}{\text{total flight time}} \left(1 + \frac{\frac{\pi}{2}\lambda_h}{2\lambda_z} \frac{|\overline{z}|}{|\overline{h(\theta)}|} \right) \quad (6.154)$$

since $|\overline{h(\theta)}|/\left(\frac{\pi}{2}\lambda_h\right)$ is the average duration t_{sh} of a proximity. Since $P_h(\theta)$ denotes the probability of horizontal overlap given proximity, eq. (6.154) can be written as

$$N_{az} = 2P_z(S_z) \frac{\text{number of horizontal overlaps}}{\text{total flight time}} \left(1 + \frac{\frac{\pi}{2}\lambda_h}{2\lambda_z} \frac{|\overline{z}|}{|\overline{h(\theta)}|} \right) \quad (6.155)$$

Eq. (6.155) is precisely eq. (6.83) for the AFI Region with

$$n_{xy}(\theta) = \frac{\text{number of horizontal overlaps}}{\text{total flight time}} \quad (6.156)$$

and $V_{rel}(\theta) = |\overline{h(\theta)}|$.

Thus, NAARMO and the AFI Region thus use different parameterizations of the same intersecting-track vertical collision risk model. As set out in Section 6.5.2.2.2, the minimum horizontal distance between each pair of aircraft at adjacent flight levels on intersecting tracks is explicitly computed in the case of the AFI Region, whereas, as will be explained below, NAARMO computes the time difference between the passing times at the intersection of the aircraft in a pair.

(NAARMO, 2015) then proceeds with two more important steps, namely

- deriving a conservative estimate of the probability of horizontal overlap $P_h(\theta)$, valid for the full range of intersection angles under consideration as referenced above; and
- deriving an estimator for the number of proximities in terms of the difference between the times at which a pair of proximate aircraft pass the intersection rather than in terms of their distance.

The conservative estimate derived for the (conditional) probability of horizontal overlap $P_h(\theta)$ is conservative for the following reasons:

- The time-dependence of the probability of horizontal is conservatively approximated by taking the maximum over the time period during which the aircraft are proximate at the intersection;
- The maximum is taken for both aircraft nominally at the intersection at the same point in time;
- The along-track positions of the aircraft about the intersection point are assumed to have a uniform distribution over twice the proximity distance interval centred at the intersection point. This distribution is subsequently conservatively approximated by a normal distribution with standard deviation equal to that of the uniform distribution;
- The across-track positions of the aircraft about the intersection point are defined by (zero mean) normal distributions where the standard deviations are based on producing a probability of lateral overlap as least as large as that obtained for the latest assessment of $P_y(0)$ for the parallel route model.

The expression derived (eq. (6) of (NAARMO, 2015)) reads as follows

$$P_h(\theta) = \frac{h(0,0)\pi\lambda_h^2}{\int_{-S_h}^{S_h} \int_{-\sqrt{S_h^2-x^2}}^{\sqrt{S_h^2-x^2}} h(x,y) dy dx} \quad (6.157)$$

This equation is quoted in (ENAI, 2017) for the EUR/SAM Corridor. Eq. (6.157) was then evaluated in (NAARMO, 2015) for two example crossing angles, namely $\theta = 0$ degrees and $\theta = 90$ degrees. The result for the first value was then compared to the probability of horizontal overlap given proximity for the same-direction Reich model. It was found to produce a conservative estimate indeed. The result for the second value was approximately two orders of magnitude smaller. Results were subsequently computed for $\theta = 0$ degrees to $\theta = 90$ degrees in 5 degree increments. $P_h(\theta)$ was found to decrease rapidly as a function of the intersection angle θ over the range from zero to ninety degrees, with the decay being more gradual for angles larger than 60 degrees. The probability of horizontal overlap $P_h(0)$ was then taken as the conservative upper bound for $P_h(\theta)$ for all crossing angles between 0 and 90 degrees with a numerical value of 4.568×10^{-5} for an intersecting-track horizontal proximity distance of $S_h = 80$ NM and 3.046×10^{-5} for $S_h = 120$ NM.

The second step referenced above was addressed in Section 6 of (NAARMO, 2015). Recall that proximity was defined as the aircraft being within a pre-determined horizontal distance S_h . The number of proximate aircraft pairs $K(\theta)$ plays a part in the numerator of the crossing-track occupancy. For same-direction and opposite-direction vertical and lateral occupancy, a representative reference point is chosen and an aircraft pair is counted as proximate when both aircraft pass the reference point within a time interval that is equivalent to the proximity distance, where the former is derived from the latter by means of the average aircraft speed. See the *Direct Estimation from Time at Waypoint Passing* occupancy estimation method in Appendix C to Chapter 4 of Section 2 in Part II of (ICAO, 1992a). (NAARMO, 2015) then wants to be able to count the number of proximate pairs at adjacent flight levels of intersecting tracks in the same manner, i.e. to count crossing-track proximate aircraft also in terms of a time difference, particularly the time difference between the passing times at the intersection of the aircraft in a pair, rather than in terms of a proximity distance.

To that end, the distance between a pair of aircraft on intersecting tracks was calculated on the assumption of constant-speed straight-line aircraft motion with aircraft A passing the intersection at time $t = 0$ and aircraft B passing the intersection at time Δt , $\Delta t > 0$. Equating the squared distance to the square of the

proximity distance S_h produced a quadratic equation for the times t_S at which proximity begins and ends, the solution of which is given by

$$t_S = \frac{-v_B \Delta t (v_A \cos \theta - v_B) \pm \sqrt{v_A^2 v_B^2 \Delta t^2 (\cos^2 \theta - 1) + (v_A^2 + v_B^2 - 2 v_A v_B \cos \theta) S_h^2}}{v_A^2 + v_B^2 - 2 v_A v_B \cos \theta} \quad (6.158)$$

Real values for t_S can only be obtained if the expression under the square-root sign is positive, which is easily seen to put an upper bound on Δt , viz.

$$\Delta t_{max} = \pm \sqrt{\frac{(v_A^2 + v_B^2 - 2 v_A v_B \cos \theta) S_h^2}{v_A^2 v_B^2 \sin^2 \theta}} \quad (6.159)$$

It is intuitively clear that when Δt is too large, the aircraft cannot become proximate during their passing of the intersection. The dependence of the maximum time difference Δt_{max} on the intersection angle θ was illustrated for two pairs of aircraft speeds, namely $V_A = V_B = 480$ kts and $V_A = 520$ kts and $V_B = 440$ kts, two proximity distances $S_h = 80$ NM and $S_h = 120$ NM, and the intersection angle ranging from 45 to 135 degrees. The maximum time difference increased with the intersection angle and showed little change with different aircraft speeds, the unequal speeds case giving slightly larger maximum time differences.

Figure 3 of (NAARMO, 2015) for the unequal aircraft speed case has been reconstructed as Figure 6.18 below. The lower curve of each pair of curves in the figure shows the exact values of Δt_{max} as computed from eq. (6.159) whereas the upper curve of each pair of curves shows the Δt_{max} values after upward rounding. Table 6.16 shows the results in tabular form. The respective resulting maximum time differences are larger than their counterparts of 10 and 15 minutes for same-direction traffic at adjacent flight levels at an average aircraft speed of 480 kts and longitudinal proximity distances of $S_h = 80$ NM and $S_h = 120$ NM. Thus, the table demonstrates that using a time difference of 10 or 15 minutes for intersecting-track occupancy based on horizontal proximity distances $S_h = 80$ NM or $S_h = 120$ NM may lead to some proximities being missed and thus to under-estimation of the vertical collision risk for aircraft at adjacent flight levels on intersecting tracks. The number of proximities that may be missed increases with the angle of intersection. On the other hand, the table shows that when the correct maximum time difference is taken as a function of the intersection angle, intersecting-track vertical proximities can be determined in the same manner as vertical proximities for same-direction traffic at adjacent flight levels of a route.

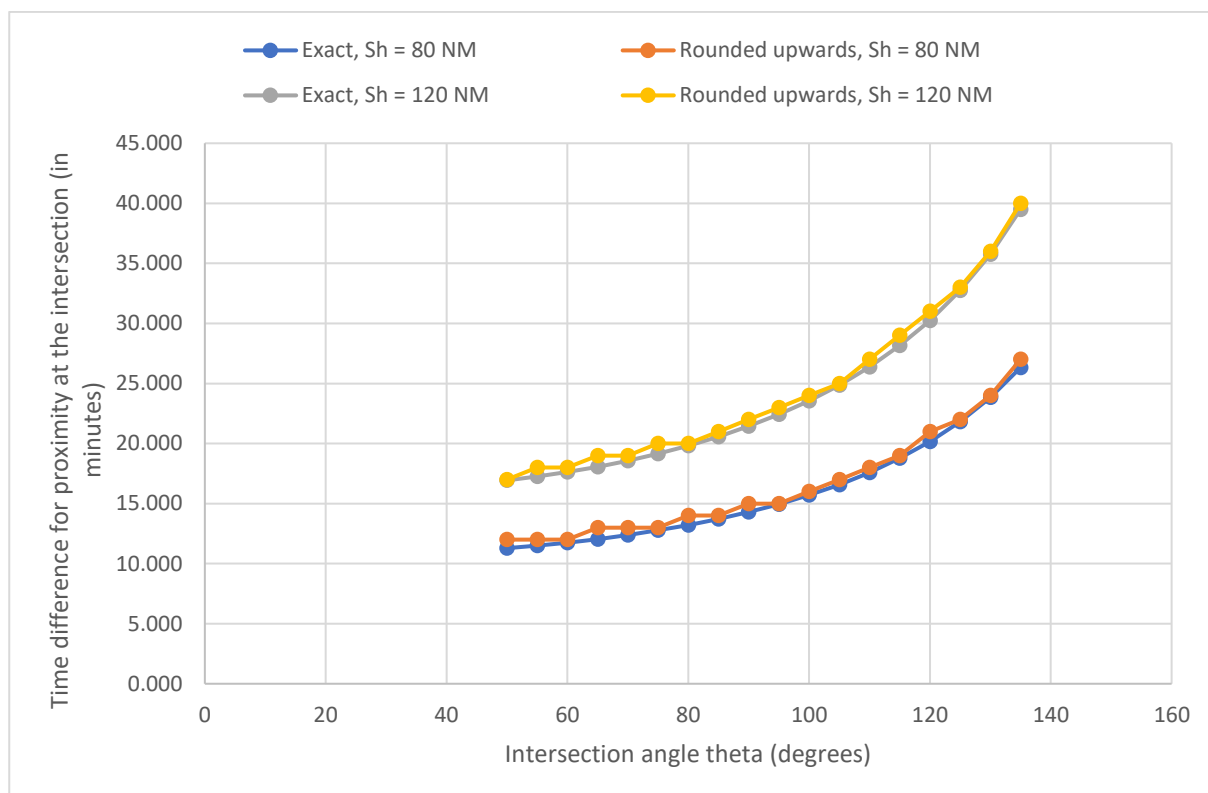


Figure 6.18: Maximum time differences that two aircraft within horizontal proximity distances $S_h = 80$ NM and $S_h = 120$ NM

Table 6.16: Maximum time difference, Δt_{max} , for intersecting route angle θ and horizontal proximity distance $S_h = 80$ NM

Intersection angle θ (degrees)	Δt_{max} (minutes)			
	$S_h = 80$ NM		$S_h = 120$ NM	
	Exact	Rounded upwards	Exact	Rounded upwards
45 – 50	11.287	12	16.930	17
50 – 55	11.497	12	17.246	18
55 – 60	11.748	12	17.622	18
60 – 65	12.042	13	18.062	19
65 – 70	12.380	13	18.570	19
70 – 75	12.768	13	19.151	20
75 – 80	13.210	14	19.815	20
80 – 85	13.715	14	20.572	21
85 – 90	14.290	15	21.436	22
90 – 95	14.949	15	22.423	23
95 – 100	15.704	16	23.556	24
100 – 105	16.575	17	24.863	25
105 – 110	17.586	18	26.379	27
110 – 115	18.768	19	28.152	29
115 – 120	20.163	21	30.245	31

Intersection angle θ (degrees)	Δt_{max} (minutes)			
	$S_h = 80$ NM		$S_h = 120$ NM	
	Exact	Rounded upwards	Exact	Rounded upwards
120 – 125	21.829	22	32.743	33
125 – 130	23.845	24	35.768	36
130 – 135	26.330	27	39.495	40

As recalled in the introduction of (NAARMO, 2015), presented by NAARMO at the tenth meeting of the RMACG as RMACG/10-WP/181, the presentation of Working Paper RMACG/9-WP/132, *Crossing track risk in the RVSM safety assessment* (Aldis & Barry, 2014b), by AAMA at the ninth meeting of the RMACG had called for a comparison of crossing track models amongst RMAs with the goal to standardize the global assessment of crossing-track vertical collision risk. Thus, this section concludes with a discussion of the crossing-track vertical collision risk model of (Aldis & Barry, 2014b).

6.6.4 Australian Airspace Monitoring Agency – AAMA

(Aldis & Barry, 2014b) begins with the following model for the technical vertical collision risk in an airspace with same-direction and opposite-direction traffic on one-way or two-way routes plus traffic on intersecting routes,

$$\begin{aligned}
 N_{az,tech} &= N_{az,tech,same} + N_{az,tech,opp} + N_{az,tech,cross} \\
 &= P_z(S_z)P_y(0) \frac{\lambda_x}{S_x} E_z(\text{same}) \left[\frac{|\Delta V|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] + P_z(S_z)P_y(0) \frac{\lambda_x}{S_x} E_z(\text{opp}) \left[\frac{2\bar{V}}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] + P_z(S_z)P_h \left(\frac{V_h}{\lambda_h} + \frac{|\bar{z}|}{2\lambda_z} \right)
 \end{aligned}
 \tag{6.160}$$

The first two components on the right-most side of eq. (6.160) appear to be the same as those in eq. (6.135) for the model used by SATMA for the EUR/SAM Corridor. There is, however, a difference concerning the use of the qualifiers “same”, “opposite”, and “crossing” as explained in the next paragraph. Throughout Chapters 5 and 6 of this document, up and including eq. (6.159), the term “same-direction” has been used for same identical-track, the term “opposite-direction” for opposite identical-track, and the term “crossing/intersecting” for the remaining geometries, although the passing frequency estimation method used for the AFI Region (cf. Section 6.5.2.2.2), allowed small angular deviations up to ± 5 degrees for same-direction and opposite-direction tracks to account for minor numerical inaccuracies. (Aldis & Barry, 2014b), however, used the three qualifiers in the sense of Paragraph 5.4.2.1.5 of Section 5.4.2, *Longitudinal separation*, of the PANS-ATM (ICAO, 2016c), i.e. in terms of ranges of intersection angles. This affects the choice of a proper relative horizontal speed between a pair of aircraft for each of the three risk components as also explained in the next paragraph. Finally, the third component has a different form than that of SATMA’s eq. (6.135) (apart from an (explicit) summation in the latter), although both components use a parameter P_h . In fact, clarifying the meaning of the P_h parameter was a main objective of (Aldis & Barry, 2014b). Regardless of the clarification, it holds that P_h in AAMA’s eq. (6.160) is an unconditional probability of horizontal overlap whereas $P_h(\theta_i)$ in SATMA’s eq. (6.135) and $P_h(\theta)$ in NAARMO’s eq. (6.146) are conditional probabilities of horizontal overlap given proximity at the intersection.

(Aldis & Barry, 2014b) thus proceeds with a discussion on the average relative horizontal speed V_{rel} for same-direction, opposite-direction, and crossing routes with these three cases defined as in Paragraph 5.4.2.1.5 of Section 5.4.2 of the PANS-ATM (ICAO, 2016c), i.e. for intersection angles θ , with $|\theta| \leq 45^\circ$, $|\theta - \pi| \leq 45^\circ$, and $45^\circ \leq |\theta| \leq 135^\circ$ respectively. It is shown in (Aldis & Barry, 2014b) that $\overline{|\Delta V|}$ for $\theta = 0^\circ$ and $2\overline{|V|}$ for $\theta = 180^\circ$ are risk conservative, i.e. maximize the risk components in eq. (6.160)) for the ranges of intersection angles specifying the same-direction and opposite-direction cases in the PANS-ATM. On the assumption of equal aircraft speeds on a pair of intersecting routes, the intersection angle which maximizes the vertical collision risk for the range of intersection angles defining crossing routes in the PANS-ATM sense turns out to be $\theta = 135^\circ$ with an associated relative horizontal speed of $V_{rel} = V_h = \sqrt{2 + \sqrt{2}}\overline{|V|}$. This relative horizontal speed is recommended for the crossing route case in the model of eq. (6.160).

Consider now the third component in the vertical collision risk model of eq. (6.160) pertaining to crossing routes as defined in the PANS-ATM for intersection angles between 45 and 135 degrees. After recalling a previous definition of P_h as “the probability that two aircraft on adjacent levels on crossing tracks are in horizontal overlap” (Aldis et al., 2013), (Aldis & Barry, 2014b) concludes that, by comparison with the other components in eq. (6.160), P_h involves a combination of a horizontal overlap probability and some crossing occupancy $E_z(cross)^{78}$. This is precisely the case for the crossing-track components of SATMA’s model of eq. (6.135) and NAARMO’s model of eq. (6.146). (Aldis & Barry, 2014b) then recalls the following crossing-track vertical collision risk model from its reference [3],

$$N_{az,tech,cross} = P_z(S_z)N_{xy}(cross) \left(1 + \frac{|\vec{z}|}{2\lambda_z} \frac{\pi\lambda_h}{2V_h} \right) = P_z(S_z)N_{xy}(cross) \frac{\pi\lambda_h}{2V_h} \left(\frac{2V_h}{\pi\lambda_h} + \frac{|\vec{z}|}{2\lambda_z} \right) \quad (6.161)$$

where $N_{xy}(cross)$ is described as the crossing track passing frequency and defined as “the expected number of plan overlaps per aircraft flight hour” and a plan overlap refers to “an overlap which occurs with a crossing track angle in the interval $\pi/4 < \theta < 3\pi/4$ ”. Some other equations and two definitions are also recalled from reference [3], where the crossing track occupancy $E_z(cross)$ is defined as “the expected number of aircraft within $\pm W$ hours of a typical aircraft on any crossing track and at either adjacent flight level” and “two aircraft will be in overlap at an intersection if their crossing times differ by less than t_0 hours”. It is then concluded that

$$P_h = \frac{\sqrt{2}\pi\lambda_h^2}{S_x|\overline{V}|} E_z(cross) \quad (6.162)$$

where S_x is the distance equivalent of the time window W , i.e. $S_x = W|\overline{V}|$ and that a preferred definition of P_h is “the probability that two aircraft are in crossing-angle horizontal overlap at adjacent flight levels”. Unfortunately, reference [3] to (Aldis & Barry, 2014b) is not available to the authors and it has not been possible to verify the ratio preceding $E_z(cross)$ on the right side of eq. (6.162). It should be noted, however, that the ratio should be dimensionless, which does appear to be the case.

Nonetheless, substitution of eq. (6.162) into the crossing-track component of eq. (6.160) gives for AAMA’s crossing-track risk model

$$N_{az,tech,cross} = P_z(S_z) \frac{\sqrt{2}\pi\lambda_h^2}{S_x|\overline{V}|} E_z(cross) \left(\frac{V_h}{\pi\lambda_h} + \frac{|\vec{z}|}{2\lambda_z} \right) \quad (6.163)$$

⁷⁸ This horizontal overlap probability must thus be a conditional one, viz. conditional on proximity.

which may be compared with NAARMO's model of eq. (6.146) (with N_{az} denoting intersecting-track vertical collision risk),

$$N_{az} = P_h(0)P_z(S_z)E_z(\theta) \left(\frac{2|\dot{h}(\theta)|}{\pi\lambda_h} + \frac{|\dot{z}|}{2\lambda_z} \right) \quad (6.146)$$

and SATMA's intersecting track model from eq. (6.135),

$$N_{az}(cross) = P_z(S_z)P_h(0) \sum_{i=1}^n E_z(\theta_i) \left\{ \frac{V_{rel}(\theta_i)}{\frac{\pi}{2}\lambda_h} + \frac{|\dot{z}|}{2\lambda_z} \right\} \quad (6.135)$$

Recall that $P_h(0)$ in eqs. (6.146) and (6.135) is the conservative upper bound for $P_h(\theta)$ and $P_h(\theta_i)$, $i = 1, \dots, n$, as a function of the intersection angles θ and θ_i derived in (NAARMO, 2015) with numerical values of 4.568×10^{-5} for an intersecting-track horizontal proximity distance of $S_h = 80$ NM and 3.046×10^{-5} for $S_h = 120$ NM. Taking $\lambda_h = 0.0081$ NM (Aldis & Barry, 2014b), the ratio $(\sqrt{2}\pi\lambda_h^2)/(S_x|\overline{V}|)$ becomes

$$\frac{\sqrt{2}\pi\lambda_h^2}{S_x|\overline{V}|} = \frac{0.000291}{S_x|\overline{V}|} \quad (6.136)$$

and with an average value of $|\overline{V}| = 480$ kts,

$$\frac{\sqrt{2}\pi\lambda_h^2}{S_x|\overline{V}|} = \frac{6.073 \times 10^{-7}}{S_x} \quad (6.137)$$

The numerator of the ratio on the right side of eq. (6.137) is two orders of magnitude smaller than either value of $P_h(0)$ and dividing this by $S_x > 1.0$ makes the left-side quantity even smaller. Compared to the values of $P_h(0)$ it needs to be recalled that $P_h(0)$ was deliberately chosen as a conservative upper bound in (NAARMO, 2015). Table 5 of (NAARMO, 2015), together with the relationship $P_h(90^\circ + \theta) = P_h(90^\circ - \theta)$, indicates that $P_h(\theta)$ is of the order of 10^{-7} for intersection angles between 45 degrees and 135 degrees. Taking $S_x = 80$ NM or $S_x = 100$ NM on the right side of eq. (6.137) gives values of the order of 10^{-9} for the equation's left-side quantity, i.e. approximately two orders of magnitude smaller than $P_h(\theta)$ for intersection angles between 45 degrees and 135 degrees and four orders of magnitude smaller than the conservative upper bound $P_h(0)$. This casts some doubt on the correctness of the ratio in front of $E_z(cross)$ in eq. (6.162) for (Aldis & Barry, 2014b)'s horizontal overlap probability P_h .

It is finally remarked that the middle side of eq. (6.161) has the same form as the intersecting route model of eq. (6.83) utilized by ARMA for the annual RVSM assessment for the AFI Region. The models are identical provided that $N_{xy}(cross) = 2n_{xy}(\theta)$, but it is not clear to the authors of this document whether, or not, the factor of 2 is actually accounted for in $N_{xy}(cross)$. A minor difference is that $N_{xy}(cross)$ is understood to be aggregated over the range of crossing angles $\pi/4 < \theta < 3\pi/4$ whereas eq. (6.83) pertains to a single crossing angle and the aggregation over all crossing angles is performed by an explicit summation, i.e. eq. (6.87).

7 Longitudinal Collision Risk Modelling

7.1 Introduction

This Chapter will deal with aircraft collision risk modelling for the application of longitudinal separation. The longitudinal separation considered is procedural (PANS-ATM Chapter 5.4), unless indicated otherwise, e.g. ASEPS-based longitudinal separation (PANS-ATM Chapter 8.7.4). This Chapter differs from the previous two Chapters on lateral and vertical collision risk modelling in that the authors have not been directly involved in longitudinal collision risk modelling, although one of them (GM) was indirectly involved through his participation in the ICAO RGCSP and SASP Panels. In addition, as a spinoff of this author's participation, under contract to EUROCONTROL, in a sequence of meetings of the NAT MWG and MIG⁷⁹ on vertical collision risk modelling during the years 1999 – 2005 for the benefit of the planned implementation of RVSM in the European region of ICAO, he obtained valuable insights into the work of these subgroups of the NAT SPG on longitudinal collision risk modelling in the NAT (see Sections 7.2.3 – 7.2.5). Similar to the main parts of the lateral and vertical collision risk modelling Chapters, this longitudinal collision risk modelling Chapter comprises two main sections, namely one dealing with longitudinal collision risk in the NAT and the other dealing with longitudinal collision risk modelling by the ICAO RGCSP and the SASP. The latter section thus supplements Section 2.5.2 of this document.

There exist a number of differences between longitudinal separation on the one hand and lateral and vertical separation on the other. Lateral and vertical separation standards/minima may be said to be expressed in terms of distance in nautical miles and feet respectively. Longitudinal separation, on the other hand, can be based on time or distance⁸⁰. Subsection 5.4.2.1 of Section 5.4.2, *Longitudinal separation*, of the PANS-ATM (Sixteenth edition) describes the application of longitudinal separation and states that longitudinal separation shall be applied so that the spacing between the estimated positions of the aircraft being separated is never less than a prescribed minimum. Longitudinal separation between aircraft following the same or diverging tracks may be maintained by application of speed control, including the Mach number technique⁸¹. When applicable, use of the Mach number technique shall be prescribed on the basis of a regional air navigation agreement. In applying a time- or distance-based longitudinal separation minimum between aircraft following the same track, care shall be exercised to ensure that the separation minimum will not be infringed whenever the following aircraft is maintaining a higher airspeed than the preceding aircraft. When aircraft are expected to reach minimum separation, speed control shall be applied to ensure that the required separation minimum is maintained. Application of time-based separation may be based on position information and estimates derived from voice reports, CPDLC or ADS-C.

The application of longitudinal separation covers aircraft maintaining the same level as well as aircraft climbing and descending.

Table 7.1 provides a high-level overview of the key paragraphs of the longitudinal separation section of the PANS-ATM. See Table 2.5 of Section 2.5.2 for the evolution of the values of the various longitudinal

⁷⁹ Mathematicians Working Group (MWG) and Mathematicians Implementation Group (MIG).

⁸⁰ Distance-based longitudinal separation by reference to DME was first incorporated into the 8th Edition of the PANS-RAC.

⁸¹ See e.g. Chapter 2 of Section 2 of Part II of (ICAO, 1992a) or the Attachment to the *Summary of Agenda Item 3 of NAT SPG/18* (ICAO, 1981) for the Mach number technique.

separation standards/minima over time. Notice the use of ADS-B and ADS-C for the in-trail procedure (ITP) and the climb and descent procedure (CDP) in Sections 5.4.2.7 and 5.4.2.8 of the PANS-ATM respectively.

Table 7.1: High-level overview of Section 5.4.2, Longitudinal separation, of the PANS-ATM (Sixteenth edition) (key paragraphs listed only)

5.4.2.1	Longitudinal separation application
5.4.2.2	Longitudinal separation based on time
5.4.2.2.1	Aircraft maintaining the same level Aircraft on same track Aircraft on crossing tracks
5.4.2.2.2	Aircraft climbing or descending Aircraft on same track Aircraft on crossing tracks
5.4.2.3	Longitudinal separation based on distance using distance measuring equipment (DME) and/or GNSS
5.4.2.3.3	Aircraft at the same cruising level Aircraft on same track Aircraft on crossing tracks
5.4.2.3.4	Aircraft climbing and descending Aircraft on same track Aircraft on reciprocal tracks
5.4.2.4	Longitudinal separation minima with Mach number technique based on time
5.4.2.5	Longitudinal separation minima with Mach number technique based on distance using RNAV
5.4.2.6	Longitudinal separation minima based on distance using RNAV where RNP is specified
5.4.2.6.3	Longitudinal distance-based separation minima in an RNP RNAV environment not using ADS-C Same track Reciprocal tracks
5.4.2.7	Longitudinal separation minima based on distance using ADS-B in-trail procedure (ITP)
5.4.2.8	Longitudinal separation minima based on distance using ADS-C climb and descent procedure (CDP)
5.4.2.8	Performance-based longitudinal separation minima Aircraft on same track Aircraft on crossing tracks

As will be seen in this Chapter, longitudinal collision risk modelling also differs from lateral and vertical collision risk modelling in that it uses a distribution of nominal longitudinal entry-separations, all equal to or larger than the longitudinal separation standard/minimum rather than a fixed nominal entry separation equal to the lateral or vertical separation standard/minimum.

As regards the modelling proper of longitudinal collision risk, recall that Appendix C presented lists of aircraft collision risk modelling assumptions made in a number of studies, in particular the assumptions made by Reich (Reich, 1966a, 1966b, 1966c). The Section also listed seven *Basic requirements when estimating collision risk* formulated by Reich, the first one of which read *All possible directions from which one aircraft can come into collision with another should be accounted for*. These directions are the same for aircraft to

which longitudinal separation is applied as for aircraft to which lateral or vertical separation is applied, although the values of the relative speeds in the different dimensions will obviously be different when longitudinal separation is lost as opposed to when lateral or vertical separation is lost.

As set out in the *Historical background of Pool* (1983), the first separation standards were introduced in the mid-1030s, namely first 1000 feet vertical separation and then 10 minutes longitudinal separation between aircraft flying nominally at the same height along the same route. As a result of the fast increase in traffic density in the 1950s, 20 minutes longitudinal separation was implemented in oceanic areas where radar control was not possible and where aircraft often flew for many hours without independent checks on their position⁸². The *History of collision model development* Section of Pool (1983) then states that, following the successful development of the Reich model for parallel routes, cf. Sections 5.2, 5.3.1, and 5.3.2 of this Document, the possibilities of applying the Reich model to vertical and longitudinal separations were investigated by the NAT SPG but that, although the principles were laid down at NAT SPG/5 (December 1968), due to lack of data no definite results were produced at the time.

This Chapter will now proceed with the development and evolution of the longitudinal collision risk model for the North Atlantic in Section 7.2. Following that, longitudinal collision risk modelling performed by the ICAO RGCSP and SASP will be examined in Section 7.3.

7.2 Longitudinal separation in the NAT

7.2.1 Introduction

This section describes a number of developments regarding longitudinal collision risk modelling for the NAT as they occurred over time namely:

- Longitudinal separation in the NAT: the years 1965 - 1992;
- Longitudinal separation in the NAT: the years 1993 – 2005;
- RLongSM, *Reduced Longitudinal Separation Minimum* (2006 – 2020); and
- ASEPS, *Advanced Surveillance Enhanced Procedural Separation* (2015 – 2019).

During the first period from 1965 – 1992 (NAT SPG/1 – NAT SPG/28), a reduction of the longitudinal separation standard from 15 minutes to 10 minutes took place, viz. on **26 November 1981**. Work on a further reduction of the longitudinal separation standard from 10 minutes to 7 minutes started in 1993 at NAT

⁸² In this context, a distinction needs to be made between the separation minima in the *Procedures for Air Navigation Services Rules of the Air and Air Traffic Services (PANS-RAC) / Procedures for Air Navigation Services Air Traffic Management (PANS-ATM)* (ICAO Doc 4444) for global application and those in the *Regional Supplementary Procedures (SUPPs) to the PANS-RAC / PANS-ATM* (ICAO Doc 7030). Both the 6th (1956) and 7th (1960) Editions of the PANS-RAC provide in Section 9.2, *Longitudinal separation minima*, of Part III, *Area Control Service*, the following longitudinal separation minima:

a) fifteen minutes, or greater, when circumstances require; or
b) ten minutes, if navigational aids permit frequent determination of position and speed;

On the other hand, Recommendation 6 iii/2, *Amendment to the RAC Supplementary Procedures*, of the Special North Atlantic Meeting (1965) (page 145) was to Amend the existing para 3.1.1.d) and associated Note by the following:

“3.1.1 d) Twenty (20) minutes for turbo-jet aircraft operating within the Gander Oceanic, Lisboa Oceanic, New York Oceanic, Reykjavik, Shanwick Oceanic and Sondrestrom (south of 70°N) control areas, except as provided in 3.1.2 or when States concerned agree that by virtue of the navigation aids available within specific portions of the airspace, the PANS-RAC may apply;

3.1.1 e) twenty (20) minutes for other than turbo-jet aircraft operating within the New York Oceanic control area on routes between the United States, Canada or Bermuda and Caribbean terminals, or between the United States or Canada and Bermuda;

3.1.1 f) thirty (30) minutes for flights not covered by the provisions of 3.1.1. d) or e) or 3.1.2.”

See also the discussion under the NAT SPG/1 and NAT SPG/4 headings in Section 6.4.2.

SPG/29 and ended in 2005 at NAT SPG/41. It was agreed at the latter meeting that despite considerable time and effort having been spent toward achieving a reduction in time-based longitudinal separation, this work had not resulted in the expected efficiencies or benefits and that, accordingly, all work on reductions in time-based longitudinal separation standards be ceased. Instead, resources should be re-directed to support reductions in distance-based separation minima.

The NAT SPG/41 agreement, however, was already reconsidered at the 42nd Meeting of the NAT SPG in 2006 and ultimately resulted in the implementation of a 5-minute longitudinal separation minimum for suitably equipped aircraft known as RLongSM, *Reduced Longitudinal Separation Minimum*, on **29 March 2018** as will be set out in Section 7.2.6. Finally, an operational trial implementation of ASEPS, *Advanced Separation Enhanced Procedural Separation*, commenced on 28 March 2019 using longitudinal separation minima of 17 NM or 14 NM (dependent on the relative angle between the aircraft tracks) for suitably equipped aircraft, followed by operational use on **5 November 2020**.

Recall from Sections 5.2.1, 5.2.2, and 6.1 that although Reich (Reich, 1966a, 1966b, 1966c) derived his collision risk model in terms of a generic intended separation [AB] (cf. eq. (5.18)), he provided more explicit formulae of his model only for aircraft at the same flight level of adjacent parallel routes (eqs. (5.26) and (5.27)) and for aircraft at adjacent flight levels of the same(-identical) route (eqs. (6.1) and (6.2)) and that these formulae were subsequently developed further by the NAT SPG. Starting off with Reich's general collision rate formula, i.e. eq. (5.4) of Section 5.2.1, the NAT SPG also developed the first longitudinal collision risk model for the NAT Region.

7.2.2 Longitudinal separation in the NAT: the years 1965 – 1992

Based on the *Summary of Discussions (and Conclusions) of the NAT SPG's annual meetings*⁸³, Table 7.2 lists the NAT SPG meetings at which longitudinal separation was on the Group's agenda for the period of time under consideration in this Subsection. Following inconclusive work on the reduction of longitudinal separation at the first five meetings of the NAT SPG, the next major step to come to a conclusive result was taken at NAT SPG/14 in 1978, resulting in the confirmation at NAT SPG/18 (1981) of the application date of **26 November 1981** for the reduction of the longitudinal separation to 10 minutes. A brief discussion of the work reported under the pertinent agenda items is provided by meeting below the table. See also S(Harrison, 1986). Work on possible further reduction in longitudinal separation started at NAT SPG/29 in 1993 and will be described in Section 7.2.3.

It should be noted that the longitudinal collision risk model(s) presented in this Subsection pertain to in-trail aircraft on the same identical track (or aircraft on diverging tracks).

Two developments worth mentioning for the period of time considered in this Subsection concern the introduction of supersonic transport operations (SST) and that of Boeing 747 aircraft in the NAT Region. The texts under the respective NAT SPG/4 and NAT SPG/5 headings ff. refer. In addition, the subject of distance-based longitudinal separation was raised at NAT SPG/13 (1977) and later at NAT SPG/41 (2005) (see Section 7.2.3).

⁸³ A list NAT meetings and the relevant documentation (*Summary of Discussions of the Third Meeting of the NAT Systems Planning Group*) are included in Appendix E.4.

Table 7.2: NAT SPG Meetings at which longitudinal separation was on the Meetings' agenda (explicitly or implicitly): NAT SPG/1 (1965) – NAT SPG/28 (1992)

Year	Meeting	Agenda item
1965	NAT SPG/1	2: Review of the general task allocated to the Group, selection of those matters requiring early attention and proposed manner of dealing with them 2.3.6 Separation minima
1966	NAT SPG/2	7: Review of subjects for future NAT SPG consideration
1967	NAT SPG/3	5: Any other Business 5.1.1 ii) Mathematical treatment of the data on longitudinal separation obtained during the data collection programme 5.2.1 Review of the work programme of the Group xi) Longitudinal Separation in Specified Parts of the NAT Region 5.2.2 Mathematical treatment of the data on longitudinal separation to be obtained during the data collection programme
1968	NAT SPG/4	4: Development of a method for the determination of longitudinal separation standards in the NAT Region 5: Exchange of views on a possible work programme of the NAT/SPG regarding SST operations in the NAT Region and development of a programme of preparatory measures, as necessary 5.2 Main aspects requiring consideration 5.2.1.4 Longitudinal separation 6: Review of the future work programme of the Group 6.1 general review 11) Longitudinal Separation in Specified Parts of the NAT Region 9: Arrangements for the next meeting 9.2 Tentative Agenda iv) review of progress made in the assessment of longitudinal separation in certain parts of the Region, including the possible use of DME for the maintenance of such separation
1968	NAT SPG/5	1: Determination of preparatory ATS measure required for the start of SST operations in the NAT Region 1.3 Separation minima for SST aircraft 1.3.1.2 Longitudinal separation 4: Review of progress made in the assessment of longitudinal separation in certain parts of the Region, including the possible use of DME for the maintenance of such separation
1969	NAT SPG/6	4: Review of work so far accomplished by the Group and possible resultant action Appendix 4-A 3. Work accomplished by the Group 3.6 Longitudinal separation 5: Preparation of appropriate documentation for the Fifth NAT RAN Meeting Appendix 5-C

Year	Meeting	Agenda item
		2. Separation of SST aircraft 2.1.1 Longitudinal separation 8: Any other business 8.2 Situation with regard to longitudinal separation in the NAT
1971	NAT SPG/7	6: Any other business Application of reduced longitudinal separation DME air-to-air ranging
1972	NAT SPG/8	–
1973	NAT SPG/9	4: Review of the navigational performance of INS equipped aircraft in the NAT Region as presented by the study of the United Kingdom and assessment of its consequences on the NAT ATS route structure Survey by Canada with regard to longitudinal separation 5: Review of the situation regarding the development of operating procedures and other measures required to permit commercial SST operations in the NAT Region 5.1 c) longitudinal separation applied between SST flights
1974	NAT SPG/10	6: Development of proposals for Regional Supplementary Procedures covering SST operations in the NAT Region 6.3 Specific proposals for NAT SST SUPPS Longitudinal separation
1975	NAT SPG/11	7: Operational problems of current interest c) Application of longitudinal separation based on the use of Mach number techniques in the NAT Region
1976	NAT SPG/12	11: Operational problems of current interest e) Application of longitudinal separation in the NAT Region
1977	NAT SPG/13	5: Determination of measures required as a pre-requisite to a possible reduction of longitudinal separation in the NAT Region 10: Determination of the Work programme of the Group covering at least the next 2 years 10.2 Tentative Work programme covering the period from 1978 to 1981 4) Conclusion on final arrangements for a large scale data collection in Summer 1978 on longitudinal separation in the NAT Region Summary on Agenda Item 5 refers) 7) Review of the separation applied between SST aircraft while in supersonic flight 11: Any other business; e) Application of longitudinal separation based on distance
1978	NAT SPG/14	5: Conclusion of final arrangements for a large scale data collection in Summer 1978 on longitudinal separation in the NAT Region
1979	NAT SPG/15	2: Review of the situation regarding the use of longitudinal separation in the NAT Region on the basis of the results of the data collection in Summer 1978 3: Review of the situation regarding the use of composite separation and determination of its priority use in relation to reduction of longitudinal separation

Year	Meeting	Agenda item
		3.2 Composite versus reduced longitudinal separation
1979	NAT SPG/16	2: Longitudinal separation in the NAT Region 2.1 Review of the results of the 1978 data collection on longitudinal separation 2.2 proposals regarding changes to the NAT RAC SUPPs relating to longitudinal separation 7. Future work programme and arrangements for the next Meeting 7.2 Arrangements for the next Meeting Items for consideration a) Development of proposed action regarding longitudinal separation between turb-jet aircraft in the NAT Region
1980	NAT SPG/17	3: Proposed action on longitudinal separation between turbo-jet aircraft in the NAT Region 8: Future work programme and arrangements for the next meeting 8.3 Future work programme 8.3.3 a) review of the situation after the introduction of the use of 10 minutes longitudinal separation to flights operating under specified considerations in the NAT Region
1981	NAT SPG/18	2: Review of the situation regarding the introduction of a reduction in longitudinal separation under specified conditions as of 26 November 1981 and related position reporting procedures 11: Up-dating of the work programme of the NAT/SPG during the next two years 11.1 Future work programme a) review of the situation after the introduction of the use of 10 minutes longitudinal separation between flights in the NAT Region
1982	NAT SPG/19	1: Review of navigation performance and application of separation standards in the NAT Region 1.3 Situation regarding longitudinal separation 11: Updating of the work programme of the NAT SPG 11.3 Future work programme a) consideration of the situation regarding the use of 10 minutes longitudinal separation between flights in the NAT Region
1983	NAT SPG/20	2: Review of the situation regarding longitudinal separation in the NAT Region 16: Updating of the work programme of the NAT SPG 16.2 Future work programme 16.2.1 System Safety performance review ii) Longitudinal performance
1984	NAT SPG/21	1: Air navigation system safety performance review 1.6 Situation regarding longitudinal separation (incomplete report available only)

Year	Meeting	Agenda item
1985	NAT SPG/22	1: NAT air navigation system safety review 1.2 Navigation performance accuracy achieved in NAT MNPS airspace during the period 1 March 1984 to 28 February 1985 Situation regarding longitudinal separation 6: Updating of the work programme of the NAT SPG 6.2 Future work programme 6.2.1 System Safety performance review ii) Longitudinal performance
1986	NAT SPG/23	1: NAT air navigation system safety review 1.2 Navigation performance accuracy achieved in NAT MNPS airspace during the period 1 March 1985 to 28 February 1986 Situation regarding the application by ATC of lateral and longitudinal separation in NAT MNPS airspace (incomplete report available only)
1987	NAT SPG/24	2: NAT Air Navigation System operations review 2.1 Air Traffic Services Operations 2.1.1 Application and refinement of separation minima Minimum longitudinal separation between MNPS certified aircraft 6: Updating of the work programme of the NAT SPG 6.1 Review of the future work programme PART 1 – AIR NAVIGATION SYSTEM SAFETY PERFORMANCE REVIEW 1. Target level of safety factors: b) Longitudinal performance
1988	NAT SPG/25	2: NAT Air Navigation System operations review 2.1 Air Traffic Services Operations 2.1.1 Application and refinement of separation standards Longitudinal separation between MNPS certified aircraft Longitudinal separation during a level change 6: Updating of the work programme of the NAT SPG 6.1 Review of the future work programme PART 1 – AIR NAVIGATION SYSTEM SAFETY PERFORMANCE REVIEW 1. Target level of safety factors: b) Longitudinal performance
1990	NAT SPG/26	1: NAT Air Navigation System safety performance review 1.2.8 Future work programme by the mathematicians c) The effects on lateral and longitudinal collision risk of the implementation of a reduced VSM 2: NAT Air Navigation System operations review 2.1.1. Application and refinement of separation standards Reduction of longitudinal separation in the Western Atlantic Route System (WATRS) 4: Planning in the NAT Region 4.2 Development of medium and long-term NAT Air Navigation Plans

Year	Meeting	Agenda item
		Attachment A to the Report on Agenda Item 4 Milestones 8. longitudinal separation reduction to 5 minutes within MNPS Airspace South of 75 degrees North 6: Updating of the work programme of the NAT SPG 6.1 Review of the future work programme Part I – AIR NAVIGATION SYSTEM SAFETY PERFORMANCE REVIEW 1. b) longitudinal performance 4. Mathematical-statistical issues relating to vertical and longitudinal collision risk
1991	NAT SPG/27	6: Updating of the work programme of the NAT SPG 6.1 Review of the future work programme Part I – AIR NAVIGATION SYSTEM SAFETY PERFORMANCE REVIEW 1. b) longitudinal performance 5. Mathematical-statistical issues relating to vertical and longitudinal collision risk
1992	NAT SPG/28	6: Updating of the work programme of the NAT SPG 6.1 Review of the future work programme Part I – AIR NAVIGATION SYSTEM SAFETY PERFORMANCE REVIEW 1. b) longitudinal performance 5. Mathematical-statistical issues relating to vertical and longitudinal collision risk

NAT SPG/1 (1965)

The agenda for the first meeting of the NAT SPG comprised an introduction and two items, namely:

- Agenda Item 2: Review of the general task allocated to the Group, selection of those matters requiring early attention and proposed manner of dealing with them; and
- Agenda item 3: Determination of the working methods of the group during and between meetings.

One of the “significant” tasks considered under Agenda Item 2 was *Separation minima*. The Group received a brief interim report from its Canadian and UK members on the results of the application of 15 minutes’ separation (reference Rec. 6 iii/2 of the Special NAT Meeting 1965 (ICAO, 1965b)).

NAT SPG/2 (1966)

Longitudinal separation was addressed only under Agenda Item 7 of NAT SPG/2: *Review of subjects for future NAT SPG consideration*. Longitudinal separation in specified parts of the NAT region was one of the subjects to be retained on the Group’s work programme.

NAT SPG/3 (1967)

A brief exchange of views took place on the mathematical treatment of data on longitudinal separation obtained during the data collection programme, using a Working Paper presented by the French member of the Group. The data will include data on relative speeds of aircraft from coast to coast. It was agreed to defer detailed discussions on the mathematical treatment of this data to the Group’s next meeting.

NAT SPG/4 (1967)

As shown in Table 7.2, *Development of a method for the determination of longitudinal separation standards in the NAT Region* was on the agenda of the 4th Meeting as Item 4. The discussion on this agenda item in was subdivided into an operational and a mathematical/statistical section.

Concerning the operational situation, the Group noted that, at the then present time, the following situation existed:

- i) For jet aircraft operating on the same or diverging tracks 15 minutes longitudinal separation associated with the Mach number technique is applied in certain parts of the Region;
- ii) For all other traffic by jet aircraft operating south of 70°N the ICAO Council, based on a recommendation of the Special NAT Meeting 1965, adopted a longitudinal separation of 20 minutes with the proviso that this should be applied as soon as the provider States had reached agreement on a common date of application;
- iii) For other than turbo-jet aircraft operating in the New York Oceanic Control area 20 minutes are used when operating on routes between the United States, Canada or Bermuda and Caribbean terminals or between the United States or Canada or Bermuda;
- iv) For all other traffic, not covered by i), ii) and iii) above, 30 minutes are applied.

It was noted that the provisions in i), iii), iv) above were already implemented but that no agreement had as yet been reached regarding the implementation of ii). It was also noted that the retention of 30 minutes was causing considerable difficulties to the oceanic ACCs since the application of such a large separation frequently required extensive re-planning of the entire traffic flow affected by the flight concerned. The Group agreed that the provider States concerned should, as a matter of urgency, review this matter in order to obtain agreement on a common date of application which should be as early as possible.

Concerning the mathematical/statistical aspects of the longitudinal separation, the Group agreed that many of the basic principles described in the *Summary of Discussions on Agenda Item 4* of the second meeting (NAT SPG/2, 1966) were valid for assessing the longitudinal separation standards. These principles are the observations, assumptions, and basic requirements underlying the Reich model (Reich, 1966a, 1966b, 1966c) summarized in Appendix C and utilized in Section 5.2 for the lateral-risk case. See Section 5.3.1 with reference to the *Summary of Discussions on Agenda Item 4* of the second meeting. The general equation of the (longitudinal) risk was then given in (NAT SPG/4, 1968) as

$$CR = N_x(std)P_y(0)P_z(0) + N_y(0)P_zP_x(std) + N_z(0)P_x(std)P_y(0) \quad (7.1)$$

where CR is the collision rate for pairs of aircraft due to the loss of longitudinal separation, $N_x(std)$, $N_y(0)$, and $N_z(0)$ denote the frequencies of an aircraft pair entering into longitudinal, lateral, or vertical overlap respectively and $P_x(std)$, $P_y(0)$, and $P_z(0)$ denote the respective probabilities of overlap in the longitudinal, lateral, and vertical dimensions. The symbol std denotes the longitudinal separation standard/minimum. Eq. (7.1) represents a longitudinal version of the general collision rate formula of eq. (5.4) of Section 5.2.1 of the Reich model.

On the assumption that the probability density function of the along-track deviation is constant over $2\lambda_x$, the collision risk equation was written as

$$CR = \left[\frac{|\bar{\dot{x}}|}{2\lambda_x} + \frac{|\bar{\dot{y}}|}{2\lambda_y} + \frac{|\bar{\dot{z}}|}{2\lambda_z} \right] P_x(std) P_y(0) P_z(0) \quad (7.2)$$

Eq. (7.2) represents the longitudinal version of the general collision rate formula of eq. (5.17) of Section 5.2.1 of the Reich model. (Eq. (5.17) was obtained from eq. (5.4) by means of eqs. (5.14) – (5.16).) The probability of longitudinal overlap $P_x(std)$ represents the proportion of the total flight time during a given period of calendar time that aircraft pairs are in longitudinal overlap.

The probability of longitudinal overlap $P_x(std)$ was then expressed as

$$P_x(std) = \sum_t P_x(t) E_x(t) \quad (7.3)$$

where

- $P_x(t)$ is the probability that along-track separation of a pair of aircraft, initially separated by an amount t (in minutes) plus an allowance for Mach number difference, is less than λ_x ; and
- $E_x(t)$ is the average number of aircraft that a given reference aircraft will have on the same track and flight level with initial separation t plus an allowance for Mach number difference (in minutes).

The summation (rather than integration) in eq. (7.3) is related to the fact that time in the NAT was/is worked with only to the level of minutes.

Substitution of eq. (7.3) for $P_x(std)$ into the second expression for the collision rate CR and multiplication by 10^7 flight hours resulted in the following model for the number of accidents per 10 million aircraft flying hours due to loss of longitudinal separation, N_{ax} , in (NAT SPG/4, 1968):

$$N_{ax} = 10^7 \left[\frac{|\bar{\dot{x}}|}{2\lambda_x} + \frac{|\bar{\dot{y}}|}{2\lambda_y} + \frac{|\bar{\dot{z}}|}{2\lambda_z} \right] P_y(0) P_z(0) \sum_t P_x(t) E_x(t) P_x(std) = \sum_t P_x(t) E_x(t) \quad (7.4)$$

It should be noted that a factor of two that accounts for the conversion of collisions into accidents appears to be missing in eq. (7.4). As will be seen below, this was corrected, however, at the next Meeting of the Group.

The discussion on the mathematical/statistical aspects of the longitudinal separation then proceeded with a review of the values of the collision risk model parameters. Although the emphasis in this Document is on the form of the various collision risk models rather than on estimation methods for collision risk model parameters, it is worth considering the estimation of the two new collision risk model parameters $P_x(t)$ and $E_x(t)$ as proposed in (NAT SPG/4, 1968). To that end, the text in the following five paragraphs has been reproduced from the *Summary of discussions of the fourth meeting of the NAT Systems Planning Group*.

“4.4.2.6 The probability of longitudinal overlap $P_x(t)$

4.4.2.6.1 The Group agreed that unlike the lateral case where convolution of measured deviations of single aircraft was appropriate, it will be necessary in the case of longitudinal separation to use a measure of relative along-track positions of a pair of aircraft.

4.4.2.6.2 In this respect, The Group decided to use the data obtained during the last data collection exercise. However, the estimation of P_x presents formidable difficulties arising from the very large number

of observations required. It was agreed that it was necessary to study pairs of aircraft which must be representative of pairs assigned at relatively small longitudinal separations. Aircraft on adjacent tracks should not be included and after a discussion of the influence of wind shear it was agreed that aircraft on adjacent flight levels should not be used. The along-track criterion for a proximate pair should have some value, probably in the range 30 to 60 minutes, to be chosen on the basis of preliminary study. The choice would be a compromise between sample size and strict validity. It was however pointed out that an increase in the sample size by this means would result in cautious estimates.

4.4.2.6.3 The study of proximate pairs would be undertaken as follows:

- a) A search would be made for “proximate pairs” of aircraft, defined as described above and for each such pair the “initial separation” is defined as the difference between the ACC’s understanding of the times at the start of the track. For westbound aircraft this is the aircraft’s reported time (ATO). The actual separation is defined as the difference between true times of the aircraft over some meridian, and can best be estimated from the radar records produced for the lateral separation exercise. The loss or gain of separation is defined as the difference between actual separation and initial separation, allowing for differences in assigned Mach number. The allowance for this difference should be that used by the air traffic controllers (believed to be 3 mins per 0.01 M for a complete crossing of the Atlantic).
- b) A distribution of gains and losses of separation would be produced (after careful checking of large values). If ATC regulations were strictly adhered to this should be a symmetric distribution, so the distribution of gains would be representative of the distribution of losses, and the effective sample size would be doubled. The question of whether gains should be taken as representative of losses could be decided after examining the data.

4.4.2.7 Occupancy E_x

4.4.2.7.1 The control system is such that a single value for “occupancy” is not appropriate to the longitudinal problem. It is necessary to use a frequency-distribution of “initial separation”, adjusted for assigned Mach number differences. This distribution will have to be convolved with the “separation loss” distribution to give the probability of longitudinal overlap P_x . It is likely that the separation loss will be correlated with initial separation and thus that the estimates obtained will be pessimistic.

4.4.2.7.2 The Group noted that in the lateral study it had not been possible to find sufficient proximate pairs to provide a reasonable estimate of collision risk, which took into account the correlation between across-track errors. It seems likely that a similar situation will occur in the longitudinal case, and since it is essential that the longitudinal study be based on proximate pairs, it is possible that insufficient pertinent data will be available for estimates of reasonable confidence.”

One of the conclusions from the discussion on the mathematical/statistical aspects was that it was quite possible that the size of the available sample could be insufficient for assessing the present of risk or for computing with reasonable confidence limits the level of risk associated with a shorter separation standard.

In summary:

1. It is necessary in the case of longitudinal separation to use a measure of relative along-track positions of a pair of aircraft;
2. It is essential that the longitudinal study be based on proximate pairs;
3. The along-track criterion for a proximate pair should have some value, probably in the range 30 – 60 minutes; and

4. It was believed to be possible that the size of the available sample could be insufficient for assessing the present level of risk or for computing with reasonable confidence limits the level of risk associated with a shorter separation standard.

Remarks

1. Although the text quoted above from the *Summary of discussions of the fourth meeting of the NAT Systems Planning Group* refers a number of times to longitudinal proximity and proximate pairs, the collision risk models in eqs. (7.1), (7.2), and (7.4) apply to any pairs of aircraft to which longitudinal separation is applied. In that sense, $P_x(std)$ is an unconditional probability of longitudinal overlap, i.e. not conditional on a pair of aircraft being longitudinally proximate. In eq. (7.3) for the calculation of $P_x(std)$, $P_x(t)$ can be considered as the conditional probability of longitudinal overlap for a pair of aircraft during their flight given a longitudinal “proximity” of t minutes upon entry of the second aircraft. Similarly, $E_x(t)$ can be interpreted as a longitudinal occupancy for a longitudinal proximity criterion of t minutes. In practice, the range of initial longitudinal separations t to be included in the summation of eq. (7.3) might be able to be limited to a maximum of 30 or 60 minutes as suggested in the earlier quoted text and it might be assumed that the conditional probability of longitudinal overlap $P_x(t)$ for aircraft pairs that are not longitudinally proximate is negligible.
2. The definition of $E_x(t)$ as the average number of aircraft that a given reference aircraft will have on the same track and flight level with initial separation t plus an allowance for Mach number difference (in minutes) seems to be related to the *Direct Estimation from Time at Waypoint Passing* occupancy estimation method in Appendix C to Chapter 4 of Section 2 in Part II of (ICAO, 1992a) for lateral or vertical separation. Its calculation should be such that, in combination with $P_x(t)$, the probability of longitudinal overlap $P_x(t)$ is calculated as the proportion of the total flying time during a given calendar period during which pairs of aircraft are in longitudinal overlap.

The subject of longitudinal separation was included in the tentative agenda of the next Meeting of the Group (see Table 7.2).

NAT SPG/5 (1968)

As shown in Table 7.2, *Review of progress made in the assessment of longitudinal separation in certain parts of the Region, including the possible use of DME for the maintenance of such separation*, was on the agenda of the 5th Meeting as Item 4 (NAT SPG/5, 1968).

The Group discussed preliminary estimates of longitudinal collision risk for two cases, termed *longitudinal separation standard without monitoring devices* and *longitudinal standard with monitoring devices*. The former of these two cases concerns purely procedural longitudinal separation whereas the latter concerns longitudinal separation using onboard DME to monitor longitudinal separation as introduced at NAT SPG/4.

Concerning purely procedural longitudinal separation, it was apparent to the Group that the data sample used was insufficient to draw firm conclusions. Severe limitations on availability of relevant data were identified and the Group decided that it was not desirable to proceed with data collection at this time (1968) to validate a change in the procedural longitudinal separation standard in the NAT Region.

The group then reviewed work done in estimating the effects of using onboard DME to monitor longitudinal separation on the assumptions that pilots would take action if separation was reduced to 40 NM

(approximately 5 minutes flying time) and that it was reasonable for such action to be required on 1% of crossings. The effect of these assumptions was that a minimum separation of 9 minutes between reported entry times would be possible instead of the then present 15 minutes (plus 3 minutes per 0.01 Mach in both cases). A study of the reliability of DME modified for operation in an air to air mode would have to be carried out before finalizing any plan for implementation. The general philosophy of monitoring longitudinal station keeping as a means of reducing the longitudinal separation standard was discussed next. The Group did not feel that it could recommend any specific action at the time.

The preliminary longitudinal collision risk estimates had been obtained with the longitudinal collision risk model presented in *Appendix 4A to the summary of the discussion on agenda item 4*, viz.

$$N_{ax} = 2 \times 10^7 \pi_x(std) P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.5)$$

with $\pi_x(std)$ denoting the probability that a typical aircraft has another aircraft, assigned to the same track and flight level, with longitudinal overlap (i.e. longitudinal separation less than an aircraft length)⁸⁴, cf. $P_x(std)$ in eq. (7.2) of the longitudinal collision risk model presented at the previous meeting of the NAT SPG. Notice that the previously missing factor of 2, converting collisions into accidents, now features up front on the right side of eq. (7.5). An important assumption underlying the model was that the longitudinal separation standard is applied to times as reported by aircraft at the start of each track but subsequent times reported by aircraft are ignored and reliance is placed on aircraft maintaining filed Mach numbers to avoid loss of longitudinal separation. Parameter values used for the model are listed in Table 7.3.

Table 7.3: longitudinal collision risk model parameter values used at NAT SPG/5 for the collision risk model of eq. (7.5)

Parameter	Value
$P_y(0)$	0.0012
$P_z(0)$	0.25
$\pi_x(std)$	See below
λ_x	0.025 NM
λ_y	0.025 NM
λ_z	0.0066 NM
$ \bar{y} $	20 kts
$ \bar{z} $	1 kt
$ \bar{x} $	See below

Substitution of the above values into the collision risk model of eq. (7.5) gives

$$N_{ax} = 120,000 \pi_x(std) \left(|\bar{x}| + 23.8 \right) \quad (7.6)$$

The Appendix then proceeded with the probability of loss of longitudinal separation, i.e. $\pi_x(std)$, where it was noted that a range of nominal longitudinal entry-separations, all larger than or equal to the longitudinal separation standard/minimum, needed to be taken into account for the estimation of $\pi_x(std)$.

⁸⁴ $\pi_x(std)$ is subsequently described as the probability that the longitudinal separation of a typical aircraft from the following aircraft has shrunk to less than λ_x , plus an equal quantity for the probability of overlap with the preceding aircraft. See eq. (7.8).

Thus, the Appendix defined two parameters $E_x(m)$ and $P_x(u)$ as follows:

- $E_x(m)$ is the probability that the reported time of a typical aircraft at the beginning of the track differs from that of the next following aircraft on the same path, after adjusting for Mach number differences by m minutes; and
- $P_x(m)$ ⁸⁵ is the probability distribution of separation loss (in minutes), after adjusting for Mach number differences.

$E_x(m)$ and $P_x(m)$ were also described as follows. For any given value of m , $E_x(m)$ is the probability that a pair of successive aircraft start off with m minutes nominal separation, and $P_x(m)$ is the probability that they lose $m \pm 0.5$ minutes separation. Thus if these two events are independent the probability that both occur and the aircraft are abreast (within 0.5 minutes) is $E_x(m)P_x(m)$.

The probability distribution $f(x)$, say, of the resultant separation (in minutes) was then given by the following convolution-type of expression,

$$f(x) = \sum_m E_x(m)P_x(m-x) \quad (7.7)$$

and the probability of longitudinal overlap $\pi_x(std)$ was given by

$$\pi_x(std) = 2 \int_{-\lambda_x}^{\lambda_x} f(x)dx \quad (7.8)$$

which was subsequently approximated by

$$\pi_x(std) \approx 4\lambda_x f(0) \quad (7.9)$$

on the assumption that the probability distribution $f(x)$ is a reasonably smooth function of the resultant longitudinal separation x . It is to be noted that the length λ_x of a typical aircraft in eq. (7.9) is to be taken in minutes since the resultant separation x is in minutes. The factor of two (2) up front on the right side of eq. (7.8) resulted from considering the loss of longitudinal separation between a typical aircraft and the following aircraft as well as that between the typical aircraft and the preceding aircraft, i.e. effectively considering a triple of aircraft rather than pairs of aircraft as in the lateral collision risk model for parallel routes and the vertical collision risk model for aircraft on the same route.

Substitution of $f(0)$ from eq. (7.7) into eq. (7.9) gives for the resulting probability of longitudinal overlap

$$\pi_x(std) \approx 4\lambda_x \sum_m E_x(m)P_x(m) \quad (7.10)$$

and substitution of eq. (7.10) into eq. (7.6), together with a time equivalent of 0.003125 minutes for λ_x based on an average aircraft speed of 480 kts gives

⁸⁵ Appendix 4A to the summary of the discussion on agenda item 4 used the symbol $P_x(u)$ in the definition, but $P_x(m)$ in the subsequent formulae.

$$N_{ax} = 1500 \left(\overline{|\dot{x}|} + 23.8 \right) \sum_m E_x(m) P_x(m) \quad (7.11)$$

Eq. (7.11) expresses the collision risk due to the loss of longitudinal separation in terms of the relative speed $\overline{|\dot{x}|}$ and the “longitudinal occupancy distribution” E_x and the “loss of separation distribution” P_x . In practice, the times m in $E_x(m)$ and $P_x(m)$ are recorded in whole minutes only since time in the NAT was/is worked with only to the level of minutes.

Appendix 4A to the summary of the discussion on agenda item 4 at the 5th Meeting of the NAT SPG concluded with some data on the longitudinal occupancy distribution E_x and the loss of separation distribution P_x as well as on the relative speed $\overline{|\dot{x}|}$ on the basis of which the Group arrived at its conclusions as presented at the beginning of this Document’s text under the *NAT SPG/5 (1968)* heading above. Discussion of this data, however, falls beyond the scope of this document.

Thus, returning to the general form of the procedural longitudinal collision model, substitution of eq. (7.10) for $\pi_x(std)$ into eq. (7.5) gives

$$N_{ax} = 2 \times 10^7 \times \left(4\lambda_x \sum_m E_x(m) P_x(m) \right) P_y(0) P_z(0) \left[\frac{\overline{|\dot{x}|}}{2\lambda_x} + \frac{\overline{|\dot{y}|}}{2\lambda_y} + \frac{\overline{|\dot{z}|}}{2\lambda_z} \right] \quad (7.12)$$

where the length λ_x of a typical aircraft inside the first pair of brackets is to be taken in minutes!

The longitudinal collision risk model of eq. (7.12) presented at NAT SPG/5 may be compared with the one presented at NAT SPG/4, i.e. eq. (7.4). Apart from the conversion factor of two for collisions to accidents, eq. (7.12) appears to contain an additional factor of $4\lambda_x$ with λ_x in minutes. This is related to the definition of $P_x(m)$ and the corresponding explicit integration for $\pi_x(std)$ in eq. (7.8) compared to the definition of $P_x(t)$ for the earlier model of eq. (7.4) on the one hand and a different definition of $E_x(t)$ compared to $E_x(m)$ on the other. The additional factor of two (2) up front on the right side of eq. (7.8) appeared to be missing in the earlier NAT SPG/4 model of eq. (7.4).

Remarks

1. The derivation of the collision risk model of eq. (7.12) did not limit the longitudinal “proximity” m (in minutes) upon entry of the flight path to 30 or 60 minutes. This limitation was applied, however, in the computation of $P_x(m)$. Cf. *Remark 5*.
2. There are two aspects related to longitudinal proximity of a pair of aircraft following the same flight path in the NAT. Firstly, the shorter the difference between the entry times of a pair of aircraft on a given flight path, the more likely it is that the aircraft will experience approximately the same weather conditions and hence the less likely the risk of losing longitudinal separation due to unaccounted for weather differences. Secondly, the likelihood of a trailing aircraft overtaking its leading aircraft is considered to become negligible when the initial separation is (very) large.
3. It follows from eq. (7.12) that $4\lambda_x \sum_m E_x(m) P_x(m)$ with λ_x in minutes should denote the proportion of the total flight time, F say, during which longitudinal overlap exists when the initial longitudinal

separation is lost precisely. It is not clear from the definitions of the probabilities $E_x(m)$ and $P_x(m)$ where the normalization by F has taken place. In addition, $f(x)$ is presented as a probability distribution but is treated as a probability density in eq. (7.8). The following attempts to provide an explanation. If $n_x(m)$ denotes the number of times during a given calendar period that the time reported by a typical aircraft at the beginning of the track differs from that of the next following aircraft on the same flight path, after adjusting for Mach number differences, by m minutes, and $P_x(m)$ is the probability of losing m minutes of longitudinal separation, after adjusting for Mach number differences, then $\sum_m n_x(m) P_x(m)$ denotes the number of aircraft pairs that has precisely zero longitudinal separation on exit of the flight path⁸⁶. Each of these pairs generates an amount of $2\lambda_x/|\dot{x}|$ hours of longitudinal overlap time. The probability of longitudinal overlap would then be estimated as

$$\pi_x(std) = \frac{2\lambda_x/|\dot{x}|}{F} \sum_m n_x(m) P_x(m) \quad (7.13)$$

The total number of successive pairs that flew along the flight path is given by $\sum_k n_x(k)$ and this can be used to express $\pi_x(std)$ as

$$\pi_x(std) = \frac{2\lambda_x/|\dot{x}|}{F} \left(\sum_k n_x(k) \right) \sum_m \frac{n_x(m)}{\sum_k n_x(k)} P_x(m) \quad (7.14)$$

The ratio $\frac{n_x(m)}{\sum_k n_x(k)}$ can be interpreted as the probability that the time reported by a typical aircraft at the beginning of the track differs from that of the next following aircraft on the same flight path, after adjusting for Mach number differences, by m minutes. The total number of flight hours F can be expressed as the product of the number of aircraft n that flew along the flight path during the given period of calendar time and the average flight duration T of a NAT crossing where it holds that n equals the number of successive pairs, i.e. $n = \sum_k n_x(k)$. Hence, eq (7.14) can be rewritten as

$$\pi_x(std) = \frac{2\lambda_x/|\dot{x}|}{T} \sum_m \frac{n_x(m)}{\sum_k n_x(k)} P_x(m) \quad (7.15)$$

Eq. (7.15) for $\pi_x(std)$ resembles eq. (7.10) for $\pi_x(std)$ with λ_x in minutes, but is actually quite different because it contains the relative longitudinal speed $|\dot{x}|$ and the average flight duration T , whereas eq. (7.10) was based on λ_x in NM divided by an average aircraft speed in NM per minute, i.e. 8 NM/min. Eq. (7.15) may also be compared with eq. (7.20) under the *NAT SPG/14* heading further on in this subsection.

4. Notice that the definition of $E_x(m)$ at NAT SPG/5 as the probability that the time reported by a typical aircraft at the beginning of the track differs from that of the next following aircraft on the same path, after adjusting for Mach number differences, by m minutes differs from the definition of $E_x(t)$ at NAT SPG/4 as the average number of aircraft that a given reference aircraft will have on the same track and flight level with initial separation t plus an allowance for Mach number difference (in minutes).
5. As indicated earlier, *Appendix 4A to the summary of the discussion on agenda item 4* at the 5th Meeting of the NAT SPG concluded with some data on the longitudinal occupancy distribution E_x

⁸⁶ Compare eq. (7.20) under the *NAT SPG/14* heading when aircraft pairs with less than zero longitudinal separation on exit are also taken into account.

and the loss of separation distribution P_x . Considering the “numbers” and “proportions” in the Appendix’s Tables 5.1 and 5.2 for eastbound and westbound traffic respectively suggests that the total numbers of aircraft pairs $\sum_k n_x(k)$ for the two cases were 2722 and 2642. The Appendix’s Table 6.1 showed gain (+) or loss (-) of separation ranging from -9 to +10 minutes for 132 and 301 proximate aircraft pairs (westbound only) with less than 30 and 60 minutes initial separation respectively.

6. An important assumption underlying the use of the model at NAT SPG/5 was that the longitudinal separation standard is applied to times as reported by aircraft at the start of each track but subsequent times reported by aircraft are ignored and reliance is placed on aircraft maintaining filed Mach numbers to avoid loss of longitudinal separation.

NAT SPG/6 (1969)

No new modelling work was performed on longitudinal separation during this meeting but rather the work performed at the Group’s first five meetings was summarized for the benefit of the Fifth NAT RAN Meeting (ICAO, 1970), see (ICAO, 1969).

Regarding separation of super-sonic transport (SST) aircraft, it was believed that initially the provision of 10 minutes longitudinal separation between SST aircraft at the oceanic entry point would be satisfactory. This belief was based on the fact that the “exposure time” of SST aircraft while operating in the NAT oceanic area is much shorter than that for sub-sonic traffic and will not normally exceed 2½ – 3 hours, depending on the track flown and on the destination.

Concerning the situation with regard to longitudinal separation in the NAT Region and further to its review at NAT SPG/4, the Group noted that, as far as the application of 15 minutes longitudinal separation to turbo-jet aircraft operating on the same or diverging tracks was concerned, the USA had made a proposal for amendment of the NAT RAC SUPPs aimed at application of this procedure in the New York Oceanic Control Area. With respect to the application of 20 minutes longitudinal separation between all other turbo-jet aircraft, south of 70° N, it was noted that all provider States concerned, with the exception of the USA, had already twice given their approval to its application. In this context, a problem was raised which might be expected to develop once the B-747 aircraft are introduced in the NAT Region, because of the difference in cruising speed which might exist between them and other turbo jet aircraft, say Mach 0.86 as opposed to Mach 0.82.

NAT SPG/7 (1971)

With respect to a question concerning the application of reduced longitudinal separation as per Amendment 128 of Doc 7030, the Group hoped that Canada, Portugal, the United Kingdom, and the USA would publish Information Circulars drawing pilots’ attention to the assumptions upon which the application of reduced longitudinal separation was based in those cases where a preceding faster aircraft was cleared to climb through the level or levels of one or more successive aircraft.

Concerning an IFALPA proposal to approve a data collection programme of a technical nature regarding DME air-to-air ranging, the Group agreed that even a limited application of the DME air-to-air ranging technique in the NAT Region would not be justified by the possible benefits which could be derived from its use.

NAT SPG/9 (1973)

The survey conducted by Canada with regard to longitudinal separation suggested that maintenance of longitudinal separation between pairs of B-747 aircraft was better than that between pairs of other aircraft and it appeared that this was at least partially due to the fact that all B-747 aircraft were equipped with INS. In addition, and unrelated to the fact whether aircraft were equipped with INS or not, it was found that with the exception of 23 pairs of aircraft, all others had a minimum of 15 minutes longitudinal separation when leaving the NAT Region. Investigation of the 23 cases revealed that only 3 of them had less than 10 minutes longitudinal separation while the others had still at least 10 minutes separation. However, this apparent loss of longitudinal separation might have been due to inaccurate clock setting onboard the aircraft concerned which might introduce significant errors in position reporting. There was therefore some doubt as to the validity of the above findings and it was agreed that this issue should be the subject for further investigation. Some further factors that might lead to changes in longitudinal separation were also identified.

Under Agenda item 5, *Review of the situation regarding the development of operating procedures and other measures required to permit commercial SST operations in the NAT Region*, the United Kingdom presented four working papers, one of which dealt with *Longitudinal separation applied between SST flights*. The Group agreed that the subject of SST operations should be retained for consideration at NAT SPG/10, including the four working papers.

NAT SPG/10 (1974)

The subject of SST operations was treated under Agenda Item 6, *Development of proposals for Regional Supplementary Procedures covering SST operations in the NAT Region*. Based on the information and data presented to the Group, including latest data concerning the performance of INS-equipped aircraft, the Group agreed that the following Regional SUPPS applicable in the NAT Region for SST aircraft should be adopted:

“X. Longitudinal separation

X.1 Minimum longitudinal separation between SST aircraft in supersonic flight shall be:

- a) 15 minutes, except as indicated in b) below;
- b) 8 minutes provided that:
 - i) both aircraft are in level flight at the same Mach number or are conforming to the same cruise-climb parameter;
 - ii) the aircraft concerned have reported over the same entry point into the oceanic controlled airspace with a time interval of at least 12 minutes confirmed by radar observation, and follow the same or continuously diverging tracks.

Note: An ATC clearance authorizing commencement of the deceleration/descent phase of the flight of the aircraft concerned may be issued while the above separation minimum are applied.”

NAT SPG/11 (1975)

It was recalled that at the then present time, the application of 15 minutes longitudinal separation between turbojet aircraft in certain parts of the NAT Region (and its reduction to 10 minutes or 5 minutes under specified conditions) was governed by the provision that the aircraft concerned had reported over the same entry point into oceanic controlled airspace. (Cf. the list of longitudinal separation standards/minima directly under the *NAT SPG/4 (1967)* heading in this Subsection.) The definition of “entry point into oceanic controlled airspace” as those points where the aircraft entered the NAT Oceanic Control Areas was confirmed. Following that, it was noted that there were (now) cases where aircraft could be allowed to enter the oceanic controlled airspace via different entry points but within primary or secondary radar coverage and, while still within such

radar coverage, pass over a point or points from which to proceed on the same or on continuously diverging tracks. It was believed that, under those circumstances, it should be permissible to use the longitudinal separation minima referred to above. It was also pointed out that a similar situation was likely to arise with regard to aircraft in supersonic flight and that therefore similar arrangements should be made for the application of longitudinal separation to such aircraft. The Group therefore agreed that an appropriate amendment of the relevant NAT RAC SUPPS should be developed.

NAT SPG/12 (1976)

Concerning the application of longitudinal separation in the NAT Region, the Group discussed a proposal by IATA aimed at a reduction of the longitudinal separation minima in those parts of the NAT Region where the Minimum Navigation Performance Specifications would apply. (Cf. Section 5.3.3.) This reduction would provide for the use of 15 minutes longitudinal separation in circumstances which at the time called for the application of 20 minutes and of 10 minutes in conditions at the time requiring 15 minutes. (Cf. the list of longitudinal separation standards/minima directly under the *NAT SPG/4 (1967)* heading in this Subsection.) Taking into account that the most important factor affecting longitudinal separation were the accuracy of the position reports and the reliability of the transmission of all position reports to the OAC and that these had improved since the introduction of the existing longitudinal separation minima in 1965, it seemed opportune to investigate the possibilities of reducing longitudinal separation. The Group agreed that careful studies should be made to assess the safety of a reduction in longitudinal separation and that some of those studies could be based on the comparison of Estimated Times of Arrival (ETAs) made by the flight crew at about 10° longitude before landfall and the Actual Times of Arrival (ATAs) established by radar. As a first step, a data collection would be organized by the United Kingdom and Ireland on the along-track navigation accuracy of flights in the Organized Track Structures.

NAT SPG/13 (1977)

As shown in Table 7.2, longitudinal separation was dealt with under Agenda Items 5, 10, and 11.

Concerning Agenda Item 5, *Determination of measures required as a pre-requisite to a possible reduction of longitudinal separation in the NAT Region*, the Group agreed that the discussion should be based on the following four aspects;

- a) data collection required in order to determine station keeping accuracy by aircraft along their cleared flight path;
- b) assessment of the effect of wind on longitudinal separation on aircraft using the Mach Number Technique;
- c) interpretation of the present provisions in Doc 7030 regarding adherence to the assigned Mach Number; and
- d) development of a method for estimating the collision risk related to longitudinal separation.

As regards aspect a), the results of an initial data collection on longitudinal separation during the period from 1 to 3 July 1977 were discussed by the Group and suggested, based on the actual changes in separation between 188 pairs of aircraft, that a reduction in longitudinal separation might be feasible, although this might require a revision of the allowance for the Mach number difference between pairs of aircraft. It was agreed that the collection of a larger data sample should be organized in order to verify the shape and tails of the distribution of the change in longitudinal separation.

As regards aspect b), the analysis of the initial data sample had revealed a shortcoming of the Mach Number Technique (NMT) as it was applied at the time to pairs of aircraft operating at different Mach numbers with the trailing aircraft being the faster. For that case, it would appear necessary that the effects of wind had to be taken into account in applying the Mach Number Technique and also the stage length during which the aircraft concerned are being longitudinally separated based on that technique. Proposals to resolve the shortcoming were developed during the meeting and the Group agreed that these proposals should be applied as soon as possible by all OACs concerned.

As regards aspect d), the United Kingdom presented to the Group a paper describing a possible method of assessing the risk involved in the reduction of longitudinal separation. This method provided a more realistic approach than that developed at NAT SPG/5 (ICAO, 1968a). As this method constituted only a first approach to the problem, the Group agreed that properly qualified experts from the Netherlands, the UK, and the USA should get together as soon as possible in order to continue work in this field with the aim of presenting a commonly accepted method to the next meeting of the Group.

Concerning longitudinal separation under Agenda Item 10, *Determination of the Work programme of the Group covering at least the next 2 years*, the following major subjects for consideration at NAT SPG/14 were identified:

- Conclusion of final arrangements for a large scale data collection in Summer 1978 on longitudinal separation in the NAT Region (Summary on Agenda Item 5 refers).
- Review of the separation applied between SST aircraft while in supersonic flight.

For NAT SPG/15, the major subject concerning longitudinal separation was identified as the determination of priorities in the work on future reductions of separation in the NAT Region based on the results of the data collection made in Summer 1978, i.e. concentrating on the reduction of longitudinal separation in MNPS airspace or on introducing composite separation (cf. Section 5.3.2). A definite decision by the Group on this choice was to be made at NAT SPG/16. Finally, for NAT SPG/17, the major longitudinal subject on the Meeting's agenda was identified as development of measures to permit the application of either reduced longitudinal separation or composite separation in the MNPS airspace in accordance with the decision taken at NAT SPG/16.

Concerning longitudinal separation under Agenda Item 11, *Any other business*, the representative of Portugal recalled to the Group that provisions had been developed for insertion in the PANS-RAC which permitted the application of longitudinal separation based on distance rather than time, provided overlap of the protection areas established around each of the aircraft involved did not occur. These provisions were expected to become available on 15 June 1978. The Group recognized that, in order to apply these new provisions, once they were applicable, it would be necessary to establish firm values for the determination of the protection areas, most probably based on the separation value applied in the NAT Region but there was general agreement that this matter required further study before definite proposals could be made in this respect.

NAT SPG/14 (1978)

As shown in Table 7.2, longitudinal separation was dealt with under Agenda Item 5, *Conclusion of final arrangements for a large scale data collection in Summer 1978 on longitudinal separation in the NAT Region*.

The Group agreed to review the subject under the following main headings (ICAO, 1978):

- a) the mathematical model for the assessment of collision risk in relation to longitudinal separation;
- b) review of the factors relevant to an operational decision on the longitudinal separation minima to be applied in the NAT Region;

- c) organization of a data collection on longitudinal separation;
- d) possible future action in this field in the light of developments at this Meeting.

As regards main heading b), the Group once more confirmed that the operational decision to modify the existing longitudinal separation minima in the NAT Region would have to take into account all relevant factors and not solely the improved mathematical model and already identified two such factors not included in the mathematical model, namely

- a) That, due to the progressive derogation of longitudinal separation, there existed normally the possibility for intervention by ATC in those cases where such derogation assumed significant proportions; and
- b) That, when dealing with that part of the traffic operating “above the weather”, a visual look out by pilots could alert them to close longitudinal encounters, thus provoking corrective action on their part before a collision occurred.

The Group refrained from attributing any specific weight to these factors at the time of the Meeting.

As regards main heading c), the Group agreed to organize a data collection on the longitudinal spacing between aircraft operating in the Organized Track System (OTS) in the NAT Region during the summer of 1978 for a duration which would permit the collection of sufficient data so that application of the mathematical model to it will yield statistically conclusive results⁸⁷. The scope and relevant arrangement for it can be found in Appendix B to the *Summary of Agenda Item 5* (ICAO, 1978).

The mathematical model for the assessment of longitudinal collision risk that the Group agreed to under main heading a) was documented in Appendix A to the *Summary of Agenda Item 5* (ICAO, 1978) and its development is sketched below.

The control system modelled is one in which the longitudinal separation standard is applied to times as reported by aircraft at the entry to each organized track but where subsequently reliance is placed on aircraft maintaining filed Mach numbers to avoid total loss of longitudinal separation, although in real live there is occasional intervention as a result of confliction revealed by position reports. Cf. the following assumption made at NAT SPG/5: the longitudinal separation standard is applied to times as reported by aircraft at the start of each track but subsequent times reported by aircraft are ignored and reliance is placed on aircraft maintaining filed Mach numbers to avoid loss of longitudinal separation. There is, therefore, a degree of “caution” in the system model dependent on the effectiveness of intervention which is not taken into account. When the second aircraft of a pair is cleared at a higher Mach number, the separation at the entry point is increased by Air Traffic Control.

The new model was based on the model considered at the 5th Meeting of the NAT SPG, i.e.

$$N_{ax} = 2 \times 10^7 \pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.5)$$

but with an amended formula for the probability π_x ⁸⁸ that a typical pair of aircraft assigned to the same track and flight level, are in longitudinal overlap. See also (Brooker & Lloyd, 1978; Penna, 1977).

⁸⁷ The data collection was planned to take place from 3 July to 29 September 1978 (at the latest) and was expected to yield information on some 6000 pairs of aircraft.

⁸⁸ The argument “std” of $\pi_x(std)$ was dropped at NAT SPG/14.

Updated parameter values used for the model at NAT SPG/14, accounting for improvements in navigational performance and increases in aircraft dimensions are listed in Table 7.4 (cf. Table 7.3).

Table 7.4: longitudinal collision risk model parameter values used at NAT SPG/14 for the collision risk model of eq. (7.5)

Parameter	Value
$P_y(0)$	0.0064
$P_z(0)$	0.25
π_x	See below
λ_x	0.033 NM
λ_y	0.033 NM
λ_z	0.0085 NM
$\overline{ \dot{y} }$	20 kts
$\overline{ \dot{z} }$	1 kt
$\overline{ \dot{x} }$	See below

Substitution of the parameter values above into eq. (7.5) resulted in

$$N_{ax} = 485,000 \pi_x (\overline{|\dot{x}|} + 23.9) \quad (7.16)$$

Compared to eq. (7.6) for the model at NAT SPG/5, the factor upfront on the right side of eq. (7.16) is four times larger than its counterpart in eq. (7.6).

The probability of longitudinal overlap π_x was again expressed in terms of two parameters $E_x(m)$ and $P_x(m)$ (actually, in terms of a function of $P_x(m)$), which were defined as follows:

- $E_x(m)$ is the probability that the time reported by a typical aircraft at the beginning of the track differs from that of the next following aircraft (after adjusting for Mach number difference as appropriate) by m minutes, i.e. between $m - 1/2$ and $m + 1/2$.
- $P_x(m)$ ⁸⁹ is the probability distribution of separation loss of m minutes, after adjusting for Mach number differences, i.e. between $m - 1/2$ and $m + 1/2$.

The definition of $E_x(m)$ is the same as that utilized at NAT SPG/5 except for the addition “, i.e. between $m - 1/2$ and $m + 1/2$ ”. The definition of $P_x(m)$ can also be considered the same as that utilized at NAT SPG/5, although the wording is slightly different, and except for the addition “, i.e. between $m - 1/2$ and $m + 1/2$ ”.

Thus, in both definitions, m minutes represents a time interval between $m - 1/2$ and $m + 1/2$ rather than a single number of minutes. The probability distribution $P_x(m)$ is used to calculate a “one-minus-cumulative” distribution (function) $Q_x(m)$,

$$Q_x(m) = \sum_{v=m}^{\infty} P_x(v) \quad (7.17)$$

i.e. $Q_x(m)$ is the probability that there has been a separation loss of at least $m - 1/2$ minutes. Reversely, The probability $P_x(m)$ of a separation loss between $m - 1/2$ and $m + 1/2$ can be expressed in terms of the one-minus-cumulative distribution $Q_x(\cdot)$ as $P_x(m) = Q_x(m) - Q_x(m + 1)$. It should be noted that the

⁸⁹ Appendix A to the summary of the discussion on agenda item 5 uses the symbol $P_x(u)$ in the definition and subsequently in the definition of a quantity $Q_x(u)$, but $Q_x(m)$ is used in the subsequent formulae.

separation loss refers to that observed at the end of the track, i.e. at the boundary of the oceanic control area.

Thus, the probability that separation has been lost (i.e. aircraft arrive in the wrong order – or in overlap longitudinally) is

$$g_x = \sum_m E_x(m) Q_x(m) \quad (7.18)$$

It is noted in Appendix A to the *Summary of Agenda Item 5* that if separation loss is correlated with initial separation the estimate provided by eq. (7.18) may be pessimistic so that its use in system design would be over-cautious. The probability g_x should be interpreted in terms of a proportion of aircraft or proportion of aircraft pairs rather than a proportion of flight time, cf. eqs. (7.13) – (7.15) under *Remark 3* of the earlier discussion under the *NAT SPG/5 (1968)* heading. The next paragraph introduces the time element.

The probability of longitudinal overlap, π_x , was then calculated for a typical aircraft pair and a trip taking time T to cross the OCA as the proportion of flight time in longitudinal overlap,

$$\pi_x = \frac{2\lambda_x/|\bar{x}|}{T} \times g_x \quad (7.19)$$

or

$$\pi_x = \frac{2\lambda_x/|\bar{x}|}{T} \times \sum_m E_x(m) Q_x(m) \quad (7.20)$$

Eq. (7.20) for the NAT SPG/14 model and eq. (7.10) for the NAT SPG/5 model have a similar form, but also show the following differences, with the former:

- i) using the parameter $Q_x(m)$ instead of $P_x(m)$;
- ii) carrying a factor $2\lambda_x$ instead of $4\lambda_x$;
- iii) carrying an additional factor $\frac{1/|\bar{x}|}{T}$; and
- iv) using λ_x in NM instead of in minutes.

Notice also that the NAT SPG/14 model explicitly defines the parameters $E_x(m)$ and $P_x(m)$ in terms of time intervals $[m - 1/2, m + 1/2]$ instead of single time-values.

As regards bullet ii), the factor of 4 in $4\lambda_x$ was queried earlier under the *NAT SPG/5* heading and it was stated in the Appendix A to the *Summary of Agenda Item 5* at NAT SPG/14 that “A further factor 2 present in the earlier version of this report arose as a result of an incorrect definition of the factor π_x .”. Concerning bullet i), it was noted in the Appendix A that “In the longitudinal analysis at the Fifth NATSPG a very cautious estimate of π_x was made. π_x was estimated by finding the probability that aircraft are in overlap at the end of the oceanic control zone. This gives a very pessimistic estimate of π_x , as the chance of overlap is negligible along most of the track and only becomes significant near the oceanic exit boundary.”. Although this observation is correct, this is the result of there being a degree of caution in the model dependent on the effectiveness of intervention, which is not taken into account. Concerning the difference between the use of the parameter $Q_x(m)$ instead of $P_x(m)$, $Q_x(m)$ takes account of a loss of separation of m minutes or more

at the end of the flight path, whereas $P_x(m)$ takes account of a loss of precisely m minutes only. The former is more realistic in relation to the longitudinal collision risk.

Bullets iii) and iv) can best be discussed together. In fact, this element of eq. (7.10) for the NAT SPG/5 model was already queried under *Remark 3* of the pertinent discussion under the *NAT SPG/5 (1968)* heading, which resulted in eq. (7.15) for π_x . Eq. (7.15) is equal to eq. (7.20) except for the use of $P_x(m)$ instead of $Q_x(m)$.

Taking a crossing time T of 3.25 hours and $\lambda_x = 0.033$ NM gives for π_x of eq (7.20),

$$\pi_x = \frac{0.02}{|\dot{x}|} \times \sum_m E_x(m) Q_x(m) \quad (7.21)$$

and substitution of this result into the collision risk model of eq. (7.16) gives (after some rounding)

$$N_{ax} = 10,000 \left(1 + \frac{23.9}{|\dot{x}|} \right) \times \sum_m E_x(m) Q_x(m) \quad (7.22)$$

The longitudinal collision risk model of eq. (7.22) expresses the risk in terms of the relative speed $|\dot{x}|$ and the “longitudinal occupancy distribution” E_x and the “loss of separation distribution” Q_x . Values of E_x and Q_x will be determined from the proposed longitudinal data collection. It is remarked in Appendix A to the *Summary of Agenda Item 5* that the average relative longitudinal velocity $|\dot{x}|$ for aircraft which have lost longitudinal separation will be difficult to estimate except by considerable extrapolation. For loss of longitudinal separation, however, an average relative velocity of about 32 knots is required over the oceanic zone. It would seem reasonable to suppose that this is representative of the overlap relative velocity.

Finally, returning to the general form of the procedural longitudinal collision model, substitution of eq. (7.20) for π_x into eq. (7.5) gives

$$N_{ax} = 2 \times 10^7 \times \left(\frac{2\lambda_x/|\dot{x}|}{T} \times \sum_m E_x(m) Q_x(m) \right) P_y(0) P_z(0) \left[\frac{|\dot{x}|}{2\lambda_x} + \frac{|\dot{y}|}{2\lambda_y} + \frac{|\dot{z}|}{2\lambda_z} \right] \quad (7.23)$$

NAT SPG/15 (1979)

As shown in Table 7.2, longitudinal separation was dealt with under Agenda Item 2, *Review of the situation regarding the use of longitudinal separation in the NAT Region on the basis of the results of the data collection in Summer 1978*. The Group dealt with three specific subjects as follows (ICAO, 1979a):

- further action with regard to the proposal for amendment of the regional SUPPS on adherence by pilots to the ATC approved Mach number;
- a progress report by the United Kingdom on the data collection on longitudinal separation between aircraft on the OTS in the NAT Region; and
- information on mathematical-statistical work done in this and related fields by the USA.

Under specific subject b), the interim report on the collection and analysis of data on longitudinal separation between aircraft operating in the OTS of the NAT Region was presented. The following interim conclusions were drawn in the interim report on the basis of an analysis of pairs of aircraft operating at the same approved Mach number:

- a) the use of 15 minutes longitudinal separation appeared to give a risk level well within the target level of safety;
- b) the degree of ATC intervention in case of erosion of longitudinal separation between aircraft and the reasons for such erosions should be examined in greater detail since it could be expected that a reduction in longitudinal separation would lead to an increase in the number of interventions required;
- c) narrow-bodied aircraft appeared to be able to adhere less precisely to their ATC approved Mach number, probably because of less sophisticated equipment; and
- d) a reduction in longitudinal separation would require greater accuracy in position reports because, while in the existing situation an error of 3 minutes represented 20% of the total separation applied, the same error would represent 33% if 10 minutes longitudinal separation were applied.

In the detailed discussion of the paper it became apparent that there were two main factors to be kept in mind, namely the effect which a reduction of longitudinal separation could have on other forms of separation, and the cost effectiveness consequences which might result from the increased workload imposed on ATC by more frequent interventions with the flow of air traffic.

The final analysis of the data on longitudinal separation collected during the summer of 1978 was expected to be completed by mid-1979 and it would therefore be possible to present the final results of this work to the next meeting of the NAT SPG.

As regards specific subject c), the member of the USA presented the Group with a paper describing initial work done in developing a mathematical-statistical model for the assessment of collision risk, not only for traffic operating on parallel routes but also for traffic operating in a random fashion in a given portion of the airspace. It was pointed out that much more work was required on the model before it could be used for application to a given situation. In view of this situation, the Group refrained from entering into a detailed discussion of the paper, but requested the USA that it should continue its studies so that, at a later stage, it could be taken into consideration when conditions required the need for such a model.

Longitudinal separation was also dealt with under Agenda Item 3: *Review of the situation regarding the use of composite separation and determination of its priority use in relation to reduction of longitudinal separation*, particularly under Item 3.2, *Composite versus reduced longitudinal separation*. In this context, it is useful to recall from Section 5.3.2 that 60 NM/1000ft composite separation had been in use in the NAT as of the early 1970s, i.e. the lateral separation between aircraft at the same flight level was 120 NM, the vertical separation between aircraft on the same track was 2000 ft, but the separation between aircraft on adjacent tracks was 60 NM and 1000 ft. In addition, see Section 5.3.3, work on 60 NM lateral separation without composite started soon after the introduction of 60 NM/1000ft composite separation based on the concept of the Minimum Navigation Performance Specification (MNPS). As set out in Section 5.3.3, the MNPS was implemented in the NAT Region at the end of 1977 with the composite track system that was in use at that time, although it had been designed for operation with a “60 NM/2000 feet” rectangular system. During an “experimental” period of nearly 2 years the operators and controllers accustomed themselves to working under the new system, while all aircraft coming of the ocean were closely monitored by radar. For every deviation from track larger than 25 NM the causes were closely investigated. From the experiences obtained

during that period guidelines for using the MNPS were laid down by ICAO and IATA in a document (Latest version, (ICAO, 2020c)) that received a very wide distribution. Finally the track layout was changed to the rectangular 60 NM/2000 feet configuration near the end of 1980.

Concerning Agenda Item 3.3 then, the Group noted that, at the LIM NAT RAN meeting 1976 (ICAO, 1976b), the possibility had already been foreseen to introduce a composite separation, composed of 30 NM lateral separation and 1000 feet vertical separation once it had been found that this was feasible when 60 NM lateral separation was applied in the NAT Region. In conclusion, however, the Group felt that, even if feasible, the introduction of 30 NM lateral combined with 1000 feet vertical separation, could not be considered seriously for application in the MNPS airspace of the NAT Region before the end of 1980.

NAT SPG/16 (1979)

Table 7.2 shows that longitudinal separation at NAT SPG/16 was dealt with under Agenda Item 2, *Longitudinal separation in the NAT Region*, as two subjects, namely:

- a) review of the results of the 1978 data collection on longitudinal separation; and
- b) proposals regarding changes to the NAT RAC SUPPs relating to longitudinal separation.

The Group noted the following with regard to the first subject, i.e. the results of the data collection:

- a) the size of the sample of aircraft pairs was now definitely established and it was found that, due to circumstances beyond the control of those collecting the data, the sample covered only 5100 pairs of aircraft instead of the 6-7000 which had originally been expected to be covered by the data collection;
- b) intervention by ATC in the form of re-clearing of aircraft was more frequent than had been expected and this had resulted in the fact that fewer pairs of aircraft could be used in the sample;
- c) a comparatively large number of deviations from planned separation of five minutes or more appeared to be related mainly to narrow-bodied turbojet aircraft and to a comparatively small number of operators; and
- d) investigations into the causes, why ATC intervened with specific flights were found to be much more difficult than had originally been expected, with the resultant consequences on the mathematical-statistical treatment of these interventions in the model.

The report of NAT SPG/16 does not include any details of the mathematical (collision risk) model or of the numerical results obtained, but the Group found that some more work on the following aspects was required before it would be possible to reach unanimity regarding the validity of that model within the Group:

- a) additional model calculations to obtain a better appreciation of the effect varying traffic densities had on a reduction of longitudinal separation;
- b) review of the operational assumptions that could be applied when the model was used to assess the effects of reduced longitudinal separation in the case when 60 NM was the lateral separation minimum.

In addition, it was noted that the assessment of risk was based on data obtained from the west-bound flow of air traffic and the question was therefore raised whether it could be safely assumed that similar conditions existed with regard to the east-bound flow of traffic and the behaviour of aircraft while operating in that flow.

The Group was confident that the residual points mentioned here could be resolved before the next Meeting of the NAT SPG and concluded that:

- a) the use of 15 minutes longitudinal separation in the then present system results in a risk which is well within the target level of safety; and

- b) the use of 10 minutes longitudinal separation within the then present system and even within a system where 60 NM lateral separation was used appeared feasible, subject to the outcome of the work to be done on the residual points mentioned above.

Concerning the second subject, the Group listed a number of operational elements that should be taken into account in the development of the necessary changes to the NAT RAC SUPPs relating to longitudinal separation, such as the influence of good time-keeping, the role of air-ground communications, workload imposed on ATC under smaller longitudinal separation minima, tools available to ATC to display and monitor flight progress, and new ATC procedures.

A number of actions were identified which would allow the NAT SPG to take a decision with regard to the reduction of longitudinal separation in the NAT Region at its next Meeting. That Meeting would also set a specific target date for the new, reduced longitudinal separation minima under development, which should, in any case, not be later than sometime in early 1981.

NAT SPG/17 (1980)

Agenda Item 3, *Proposed action on longitudinal separation between turbo-jet aircraft in the NAT Region*, was agreed to be dealt with by the Group under the following main headings (ICAO, 1980b):

- a) mathematical-statistical method used;
- b) application of reduced longitudinal separation between turbo-jet aircraft operating under specified conditions in the NAT Region;
- c) action proposed by the Group; and
- d) up-dating of the provisions regarding the application of the Mach number technique to subsonic aircraft.

The first two headings will be detailed below.

As regards the mathematical-statistical method used, main heading a), it was recalled from NAT SPG/16 that, despite the nature of longitudinal separation, its variation with time and the circumstances surrounding the detection and correction of observed degradations, any mathematical models would have to be based on the assumption that aircraft were operating in an unmonitored environment. This meant that the methods used assumed that, from entry to aircraft into the NAT Region and throughout their flight therein, ATC took no account of position reports and took no action to ensure the maintenance of proper longitudinal separation. Also, the risk estimates made no allowance for the consequences resulting from the application of the “see-and-be-seen” concept or pilot monitoring of air-ground communications.

Based on the above, (ICAO, 1980b) listed a total of seven findings, three of which are:

- The average east-bound and west-bound longitudinal collision risk in an unmonitored system would be no greater than 1.1 accidents per 10 million flying hours;
- When making a very cautious estimate of successful ATC intervention (95%) and applying this to the results for the unmonitored system, the estimated accident rate would not be greater than 0.06 per 10 million flying hours; and
- The effect of the reduction of longitudinal separation on the lateral risk was not considered to be significant. However, a further analysis of this problem would be made.

The longitudinal collision risk estimates were to be compared with the then prevailing target level of safety for longitudinal risk of 0.2 accidents per 10 million flying hours, see *Remark 1* under the *NAT SPG/12 (31 May – 11 June, 1976)* heading in Section 5.3.3.

As regards the *Application of reduced longitudinal separation*, main heading b), the Group felt that, after careful and objective assessment, the application of ten minutes longitudinal separation as specified in Attachment A to the *Summary of Agenda Item 3*, would be safe. As regards the target date specified at NAT SPG/16 for the application of the reduced longitudinal separation, the Group found that this had been somewhat optimistic. A revised application date of 26 November 1981 was agreed.

For completeness, the proposed amended text for the NAT/RAC/SUPPS provided in Attachment A to the *Summary of Agenda Item 3* has been reproduced below:

A. Reduction of Longitudinal Separation

“ 5) a) Ten minutes between turbo-jet aircraft meeting the MNPS and operating wholly or partly in MNPS airspace, provided that the Mach number technique is applied and the aircraft concerned have reported over the same entry point into oceanic controlled airspace and follow the same track or continuously diverging tracks.

This separation may be reduced to five minutes at the entry point into oceanic controlled airspace if the preceding aircraft is maintaining a speed of at least Mach 0.06 greater than the following aircraft.

5) b) Fifteen minutes between turbo-jet aircraft provided that the Mach number technique is applied and the aircraft concerned have reported over the same entry point into oceanic controlled airspace and followed the same track or continuously diverging tracks.

This separation may be reduced to:

- 10 minutes at the entry point into oceanic controlled airspace if the preceding aircraft is maintaining a speed of at least Mach 0.03 greater than that of the following aircraft; and
- 5 minutes at the entry point into oceanic controlled airspace if the preceding aircraft is maintaining a speed of at least Mach 0.06 greater than that of the following aircraft.

5) c) The separation minima mentioned in a) and b) above may also be applied between aircraft which have not reported over the same entry point into oceanic controlled airspace (but otherwise comply with all other provisions) provided their respective entry points as well as the point from which they either follow the same track or start following continuously diverging tracks, are located within the radar coverage of the controlling ATC Unit and it is therefore possible, by radar monitoring, to ensure that the appropriate time interval will exist between the aircraft concerned at the time they start following the same or continuously diverging tracks.

5) d) Twenty minutes between:

- i) turbo-jet aircraft not covered by 5) a) and 5) b) above;
- ii) other than turbo-jet aircraft operating within the New York oceanic controlled area along routes extending between the United States, Canada or between the United States or Canada and Bermuda.”

B. Position reporting

“5.3.2.5

If the estimated time for the next position last reported to air traffic control is found to be in error by three minutes or more, a revised estimate shall be transmitted to the ATS Unit concerned as soon as possible.”

NAT SPG/18 (1981)

Agenda Item 2, *Review of the situation regarding the introduction of a reduction in longitudinal separation under specified conditions as of 26 November 1981 and related position reporting procedures*, was considered by the Group with regard to the following three aspects:

- a) practical considerations related to the use of 10 minutes longitudinal separation under specified conditions;
- b) Certain mathematical-statistical aspects related to this separation; and
- c) Review of the application date.

The Group confirmed that there were no practical objections to use this type of separation. The Group was presented with a Report of its mathematical-statistical experts. The experts agreed that the information placed before them did not give reason to reverse the decision to implement 10 minutes separation in 1981. Finally, the Group agreed that the application date of **26 November 1981** for 10 minutes longitudinal separation agreed at NAT SPG/17 was to be maintained.

NAT SPG/19 (1982)

The Group’s *Review of the situation regarding longitudinal separation in the NAT Region* under Agenda Item 2 led to the conclusion that the use of 10 minutes longitudinal separation under the conditions specified in the NAT RAC SUPPS be continued since no significant problems or losses of separation had been experienced since the reduction of the longitudinal separation minimum from 15 minutes to 10 minutes.

NAT SPG/20 (1983)

With respect to the use of 10 minutes longitudinal separation within NAT MNPS airspace, the Group noted that no reports of significant erosion of longitudinal separation had been received by the central monitoring agency (CMA). Nothing had therefore occurred that would lead the Group to believe that the use of this separation minimum under the circumstances specified was not acceptable.

NAT SPG/21 (1984)

The Group agreed that continued use of 10 minutes longitudinal separation in NAT MNPS airspace was justified. Some concern was expressed, however, at an apparent tendency for assigned Mach number adherence to be relaxed and the Group agreed that provider States should examine this situation.

NAT SPG/22 (1985)

With respect to the continued application of ten minutes longitudinal separation in NAT MNPS airspace, the Group agreed that this remained justified under the then present circumstances. The matter of adherence by pilots to the ATC assigned Mach number was discussed in connexion with methods to improve the standard of navigation performance.

Concerning the latter, the results of a survey carried out by the United Kingdom on 1406 pairs of aircraft showed no evidence of significant Mach number deviations by aircraft that had been cleared at their flight plan Mach number. However, there were two instances where aircraft had been given revised Mach numbers en route, which subsequently gave rise to concern in respect of Mach number adherence where it had not

been possible to establish the reasons for the two individual cases. It appeared that the Mach number technique was primarily useful for strategic ATC planning but that its practical use in tactical separation application might be less effective under certain circumstances.

NAT SPG/23 (1986)

Based on the results of the navigation error scrutiny and the mathematical-statistical assessment of the navigation performance situation, the Group agreed that the application by ATC of the current MNPS separation criteria continued to be justified under the then present circumstances.

NAT SPG/24 (1987)

When the Group addressed the question of minimum longitudinal separation between turbojet aircraft meeting the MNPS, the Member of Iceland reported that some difficulties had been experienced in the practical application of this procedure in Northern latitudes due to the narrow angle between diverging tracks, particularly when applied to flights on polar tracks. The Group agreed to consider this matter further at its next meeting.

NAT SPG/25 (1988)

The Member from Canada presented the results of a study concerning the problem reported by the Member of Iceland at the previous meeting of the NAT SPG. As a result, the Group developed a proposal for amendment to ICAO Doc 7030/4-NAT as contained in Attachment A to the *Summary on Agenda Item 2* of the NAT SPG/25 Meeting.

NAT SPG/26 (1990)

Table 7.2 shows that longitudinal separation at NAT SPG/26 was listed under a number of Agenda Items. However, apart from the implementation of a reduced longitudinal separation of 10 minutes using the Mach number technique in lieu of 15 minutes in the Western Atlantic Route System (WATRS) in April 1990, longitudinal separation was treated as a bullet point only.

NAT SPG/27 (1991)

Longitudinal separation was listed as two bullet points only under Agenda Item 6, *Updating of the work programme of the NAT SPG*, in the *Summary of discussions and Conclusions of the Twenty-Seventh Meeting of the North Atlantic Systems Planning Group*, see Table 7.2.

NAT SPG/28 (1992)

Longitudinal separation was listed as two bullet points only under Agenda Item 6, *Updating of the work programme of the NAT SPG*, in the *Summary of discussions and Conclusions of the Twenty-Eighth Meeting of the North Atlantic Systems Planning Group*, see Table 7.2.

7.2.3 Longitudinal separation in the NAT: the years 1993 – 2005

Following the reduction of the longitudinal separation to 10 minutes in the NAT Region on **26 November 1981**, based on the longitudinal collision risk modelling work presented at the 14th Meeting of the NAT SPG in 1978, no new collision risk modelling work for the benefit of a further reduction was reported until the 29th Meeting of the NAT SPG in 1993. However, all work on time-based longitudinal separation was ceased

at the 41st Meeting of the NAT SPG in 2005 because it had not resulted in the expected efficiencies or benefits. Instead, resources were re-directed to support reductions in distance-based separation minima. This decision, however, was already reconsidered at the next Meeting of the NAT SPG, NAT SPG/42 (2006), as will be seen in Section 7.2.6 on RLongSM, *Reduced Longitudinal Separation Minimum*, a 5-minute longitudinal separation minimum between suitably-equipped in-trail aircraft

In a manner similar to that of Section 6.4.2, i.e. based on the *Summary of Discussions and Conclusions of the NAT SPG's annual meetings*, Table 7.5 lists the NAT SPG meetings at which time-based longitudinal separation was on the Group's agenda for the period of time under consideration in this Subsection. A brief discussion of the work reported under the pertinent agenda items is provided by meeting below the table.

Two modelling approaches to longitudinal separation were developed during the period of time covered by this Subsection, namely one by the United States and one by the United Kingdom. Mathematical details of the two approaches were not available from the *Summary of Discussions and Conclusions of the NAT SPG's annual meetings* reviewed. However, the authors happened to have access to the pertinent working papers presented at ICAO RGCSF and NAT MIG meetings and the respective modelling approaches will be presented after this Subsection in Sections 7.2.4 and 7.2.5.

It should be noted that the collision risk modelling for reductions in longitudinal separation considered in this Subsection pertain to in-trail aircraft on the same identical track (or aircraft on diverging tracks) as well aircraft on intersecting tracks.

Table 7.5: NAT SPG Meetings at which longitudinal separation was on the Meetings' agenda (explicitly or implicitly): NAT SPG/29 (1993) – NAT SPG/41 (2005)

1993	NAT SPG/29	1: Air Navigation System Safety Performance Review 1.7 Aspects of the Future NAT System Longitudinal and horizontal separation 1.8 Mathematicians work programme for 1993/94 1.8.1 6. Canada to analyse data from Gander with reference to longitudinal performance and relative along track velocities for lateral and vertical aircraft pairs 7. United States to review longitudinal risk model. (By February 1994). 2: NAT Air Navigation System Operations Review 2.2 Air Traffic Services Operations Separation standards for turbojet aircraft operating outside MNPS airspace
1994	NAT SPG/30	1: Developments 1.4 Technology In Trail Climb Procedure 2: Planning and Implementation 2.5 Report of the Reduced Separation Standards Implementation Group Reduced horizontal separation minima 3: Air Navigation System Review

		3.2 Review of system safety performance Mathematical matters Longitudinal collision risk Future collision risk models Proposed Mathematicians Work Programme for 1994/95 6. Canada to progress work on future risk estimation model subject to resources and to report progress at NAT SPG/31 9. Canada and United Kingdom to investigate the availability of data for possible gain/loss analysis for longitudinal separation 10. Canada, United Kingdom and United States to investigate the feasibility of carrying out time-keeping accuracy studies for NAT traffic 11. United States to further progress the development of a longitudinal CRM subject to resource availability
1995	NAT SPG/31	3: Air Navigation System Review 3.2 Review of system safety performance Longitudinal collision risk Clock accuracy and Gain/Loss Studies Effects of reduced Longitudinal separation on Lateral and Vertical Occupancies Review of longitudinal Collision Risk Model Mathematicians Work Programme and actions for 1995/96 Assess USA longitudinal work to date Perform further Gain/Loss studies Perform further Time-keeping studies Advance longitudinal work to produce a preliminary set of performance criteria
1996	NAT SPG/32	3: Air Navigation System Review 3.2 Review of system safety performance Mathematical matters Longitudinal collision risk topics Review of actions and mathematicians' work programme
1997	NAT SPG/33	2: Planning and Implementation 2.3 Report of the NAT Implementation Management Group Organisational changes Reduced Horizontal Separation Minima (RHSM) 3: Air Navigation System Review 3.2 Review of system safety performance Mathematical matters Review of ongoing Monitoring Procedures Longitudinal MWG Terms of Reference and work programme
1998	NAT SPG/34	2: Planning and Implementation 2.3 Report of the NAT Implementation Management Group Reduced Horizontal Separation Minima (RHSM) 3: Air Navigation System Review 3.2 Review of system safety performance Mathematical matters Review of ongoing Monitoring Procedures Longitudinal

		Mathematicians Working Group Work Programme
1999	NAT SPG/35	-
2000	NAT SPG/36	2: Planning and Implementation 2.2 Report of the NAT Implementation Management Group Implementation planning for reductions in longitudinal separation minima
2001	NAT SPG/37	2: Planning and Implementation 2.1 Report of the NAT Implementation Management Group Planning for reductions in longitudinal separation minima 2.5 Other issues Definition of the term “Same Track” in Doc 4444
2002	NAT SPG/38	-
2003	NAT SPG/39	-
2004	NAT SPG/40	2: Planning and Implementation 2.1 Report of the NAT Implementation Management Group Organisational changes Reductions in horizontal separation minima
2005	NAT SPG/41	2: Planning and Implementation 2.1 Report of the NAT Implementation Management Group Feasibility of implementing distance-based separation Potential for using ADS-B for oceanic in-trail climb and descents 2.3 Other issues Improved upper wind forecasts to be used in Flight Data processing Systems (FDPS) to calculate Air Traffic Services estimates

NAT SPG/29 (1993)

The latest longitudinal collision risk modelling work was described under the *NAT SPG/14 (1978)* heading in Section 6.4.2. Some new work was presented at the NAT SPG/29 Meeting under Agenda Item 1 (cf. Table 7.5) as duplicated below from the *Summary of discussions and Conclusions of the Twenty-Ninth Meeting of the North Atlantic Systems Planning Group*. A footnote and underlining of some text are due to the authors of this Document:

“The Member for the United States presented information which outlines work being performed or planned in the United States to investigate possible methods of reducing horizontal separation minima. In particular, the work was planned to explore the possibility of taking account of different aircraft navigation performance, communication or surveillance equipment, to allow the use of different separation minima between sub-groups of the aircraft population⁹⁰. The approach would allow the analysis of reduced lateral or longitudinal separation between suitably equipped aircraft in the system. Initially, the work would involve making changes to the way in which aircraft overlap probabilities were estimated. Following that, a thorough examination of the longitudinal collision risk model would be undertaken. In outlining the future work, it was pointed out that the plan called for starting with the existing collision risk methodology and selectively relaxing the assumptions to allow analysis of a more interactive control environment. Finally, it was proposed that a more generalised collision risk model be employed that would be used to analyse route intersections. This model existed but had not been used practically. The United States believed that the theoretical foundations behind collision risk methodology were sound and that adequate flexibility existed to analyse

⁹⁰ A way of taking account of different combinations of five PBN navigation specifications in the modelling of lateral collision risk on parallel routes was described in Section 5.5.5, *PBN routes*, of Chapter 5 of this Document.

the future technology and oceanic environment contemplated by the NAT SPG. The Group expressed interest in this work and hoped to be kept informed of progress in the research.

The Group was also presented with information which described the results of an analysis of aircraft time keeping accuracy in the San Juan Flight Information Region (FIR). The United States indicated that there were no known requirements for maintaining aircraft clocks within a standard of accuracy. A total of 406 aircraft were surveyed with the sample having a standard deviation of 28.7 seconds. This was better than expected, however further research was planned to assess the two major components of time keeping error – clock setting error and clock drift. This work was important for research into the possibility of reducing longitudinal separation, and for applications of ADS which use aircraft clock times. Work was continuing in the United States on this project.

In addition to clock accuracy, information on the differences between estimated and actual time separations between pairs of aircraft was necessary for the estimation of longitudinal collision risk. Canada was currently developing a method for extracting this information from data recorded at Gander OAC. This work should be completed by early 1994, and should provide necessary data for the analysis into the feasibility of reducing longitudinal separations within the NAT Region.

The observer from IATA proposed that efforts should be directed at reduction in longitudinal separation in the very near term, to provide additional airspace capacity, particularly in the OTS.

NAT SPG/30 (1994)

The Summary of discussions and Conclusions of the Thirtieth Meeting of the North Atlantic Systems Planning Group reported on reduced longitudinal separation under Agenda Items 2.5 and 3.2.

Concerning Agenda Item 2.5, the Group noted that there were two main issues, namely operational requirements and the need to re-assess the Collision Risk Model (CRM). A possible way ahead for the collision risk model would be to account for (previously unaccounted for) time-clock accuracy and individual aircraft along-track position keeping. Reference was made to a study that had shown that time-clocks were generally good but that a substantial proportion of the sample taken (up to 20 percent) exhibited large errors with some in the range of two to four minutes. The representative from IATA indicated that it would seem feasible and desirable to introduce a longitudinal separation minimum of seven to eight minutes by 1995. The Group agreed that it was necessary to start planning for the introduction of reduced longitudinal separation but that the suggested timeframe appeared overly optimistic.

Under Agenda Item 3.2, the results of two data collections conducted by Canada and the United States respectively were presented to the Group. The Canadian data collection comprised 3120 valid sample pairs with the core of the data showing approximately a zero-mean gain-loss with a standard deviation of about 1 minute. However, there was a significant tail distribution with 17 pairs showing a gain or loss of 4 minutes or more up to a maximum of 9 minutes. It was noted that the information on the cleared, as opposed to actual, arrival times was no longer available in its original format from the pertinent database and that further study using the original method was no longer possible. The United States' data collection in the San Juan FIR (cf. the text under the *NAT SPG/29 (1993)* heading above) comprised a total of 428 measurements with a mean error of about 1.5 seconds and a standard deviation of 28 seconds. The largest time difference recorded was 4 minutes and 33 seconds. It had also been attempted to isolate those errors due to clock drift from those due to time-setting errors where it had been found that the latter type of error was dominating the

analysis. The analysis suggested that improved single aircraft performance could be achieved by establishing better procedures for setting aircraft time clocks, particularly because there did not appear to be guidance for time clock setting or time accuracy maintenance. It was concluded that further data collections were necessary for the benefit of a reduction in the longitudinal separation standard. The Group also agreed that the users should be informed about the need of establishing and maintaining good clock setting procedures in order to make immediate improvements in time-keeping and system safety.

The Group was then presented with information on an improved analytical model for the computation of the probability that two aircraft with a planned en route separation of exactly T minutes lose all longitudinal separation. The model considered three major sources of error as follows:

- a) The aircraft's reported position may be different from its true position. The cause of this error was largely the aircraft's navigational position;
- b) The time reported by the aircraft may be different from actual time, due to errors in the aircraft's time-keeping system; and
- c) The aircraft may arrive at a fixed position either before or after the time of arrival forecast by the crew at its last position report and used by ATC to maintain inter-aircraft spacing. The cause of this error was usually a combination of the aircraft's Mach number error, wind speed estimate errors and changing meteorological conditions.

Using three sets of aircraft-pair loss/gain data from different sources, the improved analytical model was used to derive a probability distribution for along-track position-keeping for individual aircraft. The model was then further extended with an aircraft time-keeping error distribution derived from the abovementioned San Juan data collection. The final step comprised the derivation of an analytical probability distribution for aircraft-pair loss in longitudinal separation including aircraft time-keeping errors.

The Group endorsed the proposed model and agreed that its refinement should be continued, where it was recognised that further data collections were required using independent surveillance measures in order to determine the individual contributions to the total error made by aircraft navigational system and time-keeping errors. (See the *Proposed Mathematicians' Work Programme for 1994/95* under the NAT SPG/30 entry in Table 7.5.) However, such studies were likely to be ATC intrusive since, at the time, this was the only way of obtaining accurate time-keeping information. It was noted that no implementation plan for reduced longitudinal separation existed nor that the requisite cost-benefit studies had been performed at the time and it was agreed that this would be brought to the attention of the responsible NAT SPG subgroup (NAT IMG).

NAT SPG/31 (1995)

As shown in Table 7.5, three elements of longitudinal separation were discussed under Agenda Item 3.2, *Review of system safety performance*, at the 31st Meeting of the NAT SPG. Two of the three elements are relevant to the current section of this Document.

As regards *Clock accuracy and Gain/Loss Studies*, the results were presented of a special data collection undertaken by Canada on the accuracy of on board clocks used to provide waypoint times. A total of 124 samples were obtained over five days, consisting of 94 eastbound and 30 westbound aircraft. The full sample of differences between a time readout by the pilot and a world clock showed a mean of +2.06 seconds and a standard deviation of 13.26 seconds. Sixty-two of the observations were 2 seconds or less different from the reference clock whilst two aircraft reported differences of 60 seconds or greater.

The Group agreed that the data provided valuable information which was necessary before reduced longitudinal minima could be contemplated, particularly because it detected large errors with a disproportionate effect on the risk of collision. It was also agreed that the value of the work would be greatly increased by obtaining a larger sample, despite this type of data collection requiring the active participation and co-operation of both pilots and controllers. Canada, resources permitting, would conduct an additional sample, which could then be combined with the existing sample.

Consider now the second element to be described here, viz. *Review of the Longitudinal Collision Risk Model*. Unfortunately, not any details of the model were provided in e.g. an Appendix to the discussion on this Agenda Item. Therefore, the following text has been reproduced from the *Summary of Discussions and Conclusions of the Thirty-First Meeting of the North Atlantic Systems Planning Group* (NAT SPG/31, 1995) on this subject:

“3.2.73 The Group was informed that a substantial body of work undertaken by the United States in anticipation of the reduction in longitudinal separation planned by the NAT SPG had been carried out. Several novel themes had been investigated and reported. The work required further development, maturation and consideration before actual application. The United Kingdom undertook to perform an assessment of the United States’ longitudinal work to date.

3.2.74 Information was presented which examined North Atlantic data to produce a distribution of the proportion of aircraft pairs that were separated by t minutes longitudinally upon entry to the oceanic system. The information described an empirical exercise using routine position reporting data obtained from Transport Canada and characterised the distribution of initial separations from these data as a starting point for determining the shape and characteristics of a distribution of initial separations for use within the longitudinal collision risk model.

3.2.75 Information was also presented which described a correction of the standard equation for determining the rate of collision due to the loss of planned longitudinal separation. The information revealed an inconsistency in the standard equation that had been used in many studies of longitudinal separation. It also explained the nature of the inconsistency and suggested a way to correct the equation that relates traffic volume to the risk of collision. The standard equation as usually stated pertained only to consecutive pairs of aircraft. The correction allows for collisions between all aircraft pairings.

3.2.76 A model for determining the rate of collisions due to the loss of planned longitudinal separation was presented. In addition to determining the rate of collisions, it refined the standard longitudinal collision risk model to allow the use of improved estimates of the probability of an overtake and the average speed of an overtake.

3.2.77 The Group examined a theory which described longitudinal separation on oceanic routes. The standard formula for estimating the rate of collisions due to the loss of planned longitudinal separation included an expression denoting the probability that two aircraft flying along the same route and flight level passed over the route’s entry fix t minutes apart. In past studies of oceanic route systems, such probabilities were estimated from collected data. The information presented proposed a theory which may allow analysts to estimate such probabilities for

hypothetical or future environments, those for which it was not possible to make direct, empirical estimates.

3.2.78 Information was presented which described a procedure to estimate the probability of an aircraft pair losing longitudinal separation from one waypoint to the next. It was based on individual aircraft time-keeping, longitudinal distance-keeping and speed-keeping systems. Consideration was given to the correlation of the speed between the following aircraft and the lead aircraft. The procedure linked individual aircraft sub-systems to the probability of longitudinal overlap. Through a co-operative effort with Transport Canada, the United States was able to develop preliminary following-aircraft conditional distributions given lead-aircraft estimated time of arrival errors. A set of tools needed to develop individual aircraft sub-system requirements necessary to satisfy the allowable risk associated with reduced longitudinal separation was noted.”

NAT SPG/32 (1996)

In follow up to the discussions at the previous meeting concerning reductions in longitudinal separation, the Group noted that the Mathematicians Working Group (MWG)⁹¹ had reviewed several papers relating to the development of the longitudinal collision risk model and that the results of their review indicated that:

- a) the model should only be applied to adjacent pairs of aircraft since the possibility of an undetected overtake occurring in the crossing time available was remote;
- b) the appropriate distribution for the initial separation of aircraft pairs, $E_x(t)$, should be used based on adjacent pairs of aircraft;
- c) the collision risk model parameter values within the model should be reviewed; and
- d) the methodology should be advanced to the state where a preliminary set of aircraft performance criteria necessary to support the TLS could be determined (by, for example, making use of existing collision risk model parameter values) and also to determine what longitudinal separation standard could be achieved for aircraft under current technology.

An important point considered by the Group concerned the advantages and disadvantages of basing the collision risk estimate on a sum of “between waypoint” risks and a single whole ocean crossing risk multiplied by an assumed “unsuccessful” ATC intervention factor. Recall previous assumptions, e.g. listed under the *NAT SPG/17 (1980)*, *NAT SPG/14 (1978)*, *NAT SPG/5 (1968)*, and *NAT SPG/4 (1968)* headings in Section 6.4.2. The “between waypoint” method would have the advantages that it would take account of the reduced risk that could be afforded by an increased number of reporting points (for example, using ADS) and also the fact that it does not rely on the determination of an ATC intervention factor which is difficult to evaluate and also tends to dominate the overall result. The difficulty with the “between waypoint” method lay in the determination of how the uncertainties in an aircraft’s position should be “re-set” as a result of passing through a waypoint and giving a position report. For example, a controller would normally warn an aircraft if, on reporting, it was perceived that separation with the preceding aircraft had degraded to below 10 minutes. The Group tasked the MWG to find out more information on what manual and automatic checks were performed at waypoints, as well as what the standard procedures were and make a decision at their next meeting as to which methodology to adopt.

AT NAT SPG/31, the results had been presented of a special data collection undertaken by Canada on the accuracy of on board clocks used to provide waypoint times. A total of 124 samples had been obtained in the

⁹¹ The Mathematicians Working Group, MWG, was established by the NAT SPG at its 26th Meeting in 1990, see Section 5.3.4.

pertinent data collection. AT NAT SPG/32, the Group was presented with an update to the earlier data collection, which had been extended to 426 measurements and showed a mean difference between actual time and clock time used by aircraft for position reporting of +3.6 seconds (positive = aircraft clock slow compared to actual time) and standard deviation of 18.2 seconds. These values were larger than their counterparts from the original data collection. Seven out of the 426 measurements showed differences greater than 60 seconds with the largest being one of 181 seconds.

The new results confirmed previous studies on clock accuracy. The Group was of the opinion that the current performance would not support the safe introduction of a reduction in longitudinal separation minimum and that suitable time keeping procedures be developed at the earliest opportunity. The Group also agreed that further data collection and analysis on these aspects should wait until they could be used to demonstrate that the procedures put in place were in fact working.

NAT SPG/33 (1997)

It was noted under Agenda Item 2.3, *Report of the NAT Implementation Management Group*, that the NAT IMG had established a Mathematicians Implementation Group (MIG) which would develop the necessary tools to carry out the safety assessments which were pre-requisites for future reductions in horizontal separation minima, following the implementation of RVSM Phase I in the NAT Region on 27 March 1997, cf. Section 6.2.1. Operational expertise would be included in the MIG and it was also felt that membership by the NAT SPG MWG and MIG should be as similar as possible. The Group agreed that the MWG would concentrate on the safety assessments of the current system whereas the MIG would address medium to long term planning issues.

As regards *Reduced Horizontal Separation Minima (RHSM)*, the Group noted that this should begin with longitudinal separation. To this end, a draft Collision Risk Model (CRM), that allowed for an analytical assessment of the effects of lateral errors on the longitudinal separation of a pair of aircraft on intersecting tracks, was being developed. See Section 7.2.5. Another important consideration that needed to be agreed to was the TLS to be used to sustain the reductions in longitudinal separation minima. It was agreed that for planning purposes a TLS of 5×10^{-9} fatal accidents per flight hour would be used. It was recognized that any delay in developing the CRM would have an effect on the timing of all separation minima reductions and therefore on the overall programme.

Under the *Review of On-going Monitoring procedures, longitudinal*, heading, cf. Table 7.5, it was noted that an on-going estimate of longitudinal collision risk was not currently provided. While data collections were effective at determining core performance of distributions, rates of unusual occurrences needed to be evaluated on a long term basis. The Group reviewed the types of events which would need to be recorded to produce longitudinal risk estimates in the future and to build up a database of significant events, where it was noted that at the time there was only a requirement for OACs to provide reports when longitudinal separation was reduced to 7 minutes or less where the lead aircraft was not faster. Although the Group recognised the extra burden that the reporting of these events might place on the pertinent organisations, it was concluded that the need was justified.

NAT SPG/34 (1998)

Reduction in longitudinal separation was discussed under the *Reduced Horizontal Separation Minima (RHSM)* heading under Agenda Item 2, *Planning and Implementation*, sub-item 2.3, *Report of the NAT Implementation Management Group*. An important difficulty had arisen, namely issues relating to time-keeping, both on the

ground and in the air. A draft Notice to Airmen (NOTAM) concerning airborne time-keeping procedures had been developed. However, this does not and cannot address the issue of how the Flight Management System (FMS) displays time to the pilot. Nevertheless, it was agreed that a data collection would be undertaken in the third quarter of 1998 in support of the safety case to reduce longitudinal separation minima. In addition, ground systems would need to adopt a common system of displaying time to air traffic controllers. It was realized that because of the difficulties experienced, reductions in longitudinal separation from 15 minutes for intersecting tracks and from 10 to 7 minutes for along the same track (RHSM Phase I and II respectively) could not be envisaged before the first quarter of 2000.

NAT SPG/35 (1999)

The Group, in reviewing its working methods with the view to improving them and making the work of the NAT SPG meetings as efficient as possible, agreed that the length of the meetings could now be reduced to 3 working days and that only papers requiring action by the NAT SPG should be presented. In other words, information such as risk assessments would be considered as extremely useful information but the groups responsible for using the material would be expected to only highlight issues that require NAT SPG decisions.

NAT SPG/36 (2000)

The Group noted that the NAT IMG had committed considerable resources to develop tools and procedures needed to plan for the reductions in the then current longitudinal in-trail and intersecting track separation minima and that a significant achievement was the development of a CRM for use with longitudinal separation minima. However, some difficulties such as time-keeping, had been encountered and it had not therefore been possible to begin processing any amendment proposals. It was noted that the NAT IMG intended to continue work in this area in order to ensure that maximum efficacy could be obtained from the use of the then current longitudinal separation minima or to try to reduce them.

NAT SPG/37 (2001)

The Group noted that work had been carried out in support of reductions in longitudinal separation minima. However, this task had proven to be more complex than initially envisioned. In particular, it was noted that the interpretation of the use of the application of the Mach Number Technique (MNT) needed to be clarified. However, the risk modelling associated with the application of longitudinal separation was almost complete. The Group also noted that the NAT IMG would continue to direct this work.

NAT SPG/38 (2002) – NAT SPG/39 (2003)

Reduction of longitudinal separation did not occur as an item in the *Summary of Discussions and Conclusions* of these two NAT SPG meetings.

NAT SPG/40 (2004)

It was agreed under Agenda Item 2.1, *Report of the NAT Implementation Management Group*, that the NAT MIG who had been addressing collision risk modelling principally and the NAT Reduced Separation Standards Implementation Group (RSSIG) who had been very effective in planning for the implementation of RVSM be melded into the NAT Safety Analysis and Reduced Separation Implementation Group (SARSIG) and that the terms of reference be expanded to include safety management.

As regards reductions in horizontal separation minima, the Group agreed that the NAT IMG had agreed that work should continue on seeking ways and means to reduce horizontal separation minima and in particular longitudinal separation. In noting this, it was recognized that other methods of carrying out safety

assessments could be used rather than the formal mathematical models used in the NAT Region at the time. Therefore, to initiate the task, work packages, including the need to collect data regarding the various methods of using time to apply separation by the various ATS units and the need to attempt to classify longitudinal errors were developed.

It was pointed out that one of the important contributors to reduce the risk in the longitudinal plane was accurate time management. The upper wind forecasts used by Flight Data Processing Systems (FDPS) to calculate the estimates, used to establish the separation minimum, also play an important role. The NAT IMG had examined a proposal to refine the temporal resolution of MET forecasts in order to improve the accuracy of ATS estimates. It was felt that the use of more up to date wind data might provide the mechanism needed to reduce the risk and therefore permit reductions in separation minima. Accordingly, it was agreed that the temporal resolution of MET forecasts be made as fine as economically feasible and that, when stating the requirement, flexibility of implementation should be stressed. However, before proceeding with any changes, it was agreed that the issue would need to be considered by the ICAO World Area Forecast System Operations Group (WAFSOPSG).

NAT SPG/41 (2005)

Under the agenda sub-item, *Feasibility of implementing distance based separation*, the Group agreed to a proposal that would require the implementation of RNP 4 as well as the implementation of 30 NM lateral and 30 NM longitudinal separation minima. In this context, it was recalled that the NAT IMG had spent considerable time and effort toward achieving reductions in time-based longitudinal separation, but that, to that date, this work had not resulted in the expected efficiencies or benefits, due to time keeping anomalies and uncertainties surrounding separation gain/loss. Accordingly, it was agreed that the NAT IMG cease all work on reductions in time-based longitudinal separation standards. It was also agreed that resources should be re-directed to support reductions in distance-based separation minima.

Remark: The agreement above, however, was already reconsidered at the next Meeting of the NAT SPG as will be seen in Section 7.2.6, *RLongSM, Reduced Longitudinal Separation Minimum: the years 2006 – 2020*, to which the reader is referred who is interested in continuing with the development of longitudinal separation reduction at NAT SPG/42 ff. Before that, as alluded to in the third paragraph at the beginning of this Subsection (7.2.3), Section 7.2.4 will detail *A new collision risk modeling approach developed by the United States* and Section 7.2.5 will detail *Improved longitudinal collision risk modelling performed by the United Kingdom*.

The Group was informed about the *Potential for using ADS-B for oceanic in-trail climbs and descents* (cf. the NAT SPG/41 entry in Table 7.5) and noted that this subject had been added to the NAT IMG work programme.

7.2.4 A new collision risk modelling approach developed by the United States

7.2.4.1 Introduction

In the previous Subsection, information on a new collision risk modelling approach developed by the United States that would allow the analysis of reduced longitudinal separation between suitably equipped aircraft was provided under the *NAT SPG/29 (1993) – NAT SPG/32 (1996)* headings. Details of the approach were not available from the pertinent *Summary of Discussions and Conclusions of the 29th – 32nd Meetings of the North Atlantic Systems Planning Group*, but are available in several papers ((Flax, 1995a, 1995b; Unknown, 1994c, 1994a, 1995b). A review of the United States' longitudinal work agreed to by the United Kingdom at NAT SPG/31 is given in and constitutes the basis for the NAT MWG conclusions presented in the previous subsection under the *NAT SPG/32 (1996)* heading. (Flax, 1995a, 1995b; Unknown, 1995b) were presented to the NAT SPG as well as to Working Group A of the ICAO RGCSP (RGCSP/WGA). One more working paper was presented to the two Groups, viz. one dealing with the standard longitudinal collision risk model (Flax, 1995c). A response to (Flax, 1995c) was also presented to the RGCSP (Anderson, 1996b).

To begin with, recall that the reduction of the longitudinal separation standard/minimum from 15 minutes to 10 minutes on **26 November 1981** utilized the longitudinal collision risk model of eq. (7.23) derived under the *NAT SPG/14 (1978)* heading in Section 6.4.2, supplemented with a cautious estimate of the probability of successful controller intervention in case of erosion of longitudinal separation as set out under the *NAT SPG/17 (1980)* heading in Section 6.4.2. The key parameter of the longitudinal collision risk model is the probability of longitudinal overlap π_x defined by eq. (7.20). Two of the five quantities contributing to this probability are $E_x(m)$ and $P_x(m)$, which were defined as:

- $E_x(m)$ is the probability that the time reported by a typical aircraft at the beginning of the track differs from that of the next following aircraft (after adjusting for Mach number difference as appropriate) by m minutes, i.e. between $m - 1/2$ and $m + 1/2$.
- $P_x(m)$ is the probability distribution of separation loss of m minutes, after adjusting for Mach number differences, i.e. between $m - 1/2$ and $m + 1/2$.

7.2.4.2 NAT SPG/30-WP/21: Views on the Investigation of the Potential for Reduced Longitudinal Separation in the NAT

SPG/30-WP/21 (Unknown, 1994c) identified two major factors affecting aircraft longitudinal performance, namely time-clock accuracy and aircraft positioning systems, noting that maintenance of longitudinal separation in oceanic airspace relies on position reports, however coarse, delivered using the aircraft time-clock as the basis for time reference. It also identified two major contributors to (larger) time-clock inaccuracies, namely original time-setting error and time-clock drift. Both improvements in aircraft positioning systems (therefore navigational performance) and better time-keeping performance may allow longitudinal separation reductions. To that end, the existing longitudinal collision risk model, i.e. eqs (7.23) and (7.20), should be improved by a more advanced relationship of time-keeping accuracy and navigational performance as they relate to the gain-loss probability distribution $P_x(m)$. In addition to the improved

modelling of aircraft longitudinal performance, SPG/30-WP/21 pointed to the need to improve the modelling of the probability of successful controller intervention.

7.2.4.3 NAT SPG/30-IP/48: Aircraft Longitudinal Position-keeping Model

NAT SPG/30-IP/48 (Unknown, 1994a) looked in detail at the relationship of time-keeping accuracy and navigational performance. It defined three “differences” of interest, namely aircraft reported position versus aircraft true position, aircraft reported time versus actual time, and the difference between forecast time at next reporting point and actual time at next reporting point. The gain-loss distributions resulting from three data collections comprising 4706, 3828, and 2963 time differences between pairs of proximate aircraft, i.e. pairs of aircraft entering the same flight path within up to 60 minutes inclusive, were utilized. It was emphasized that the data collections utilized reported times over fixed positions and that, consequently, neither the errors in aircraft clocks nor navigation systems were taken into account. In addition, (unaccounted for) errors in assigned Mach numbers and wind speed affected the computed gain-loss data.

SPG/30-IP/48 then proposed an analytical approach to modelling the three empirical gain-loss distributions. The starting point of this approach was the selection of a family of unimodal and symmetric probability distributions, $f(t)$ say, representing individual-aircraft along-track position keeping⁹² and to use this to calculate the probability distribution of aircraft-pair change in longitudinal separation, i.e. gain-loss in longitudinal separation, by means of convolution. See under *Remark 2* below for more details. Each aircraft-pair probability distribution was used to compute a histogram model for change in longitudinal separation with one-minute class intervals. The parameters of each histogram model, i.e. those of the individual-aircraft along-track position keeping distributions, were estimated for each of the three empirical data sets by means of the maximum likelihood method. The following five families of probability distributions were used: normal, double exponential, normal double exponential, double double exponential, and normal-normal. See for formulae e.g. eqs. (4.19), (4.20), (4.26), and (5.106). For each empirical data set, having fit the five families of probability distributions, the best fitting model was then selected as the one that maximised the value of the model families’ likelihood functions. The double double exponential distribution was found to provide the best fit to the empirical gain-loss distributions for each of the three data sets. The likelihood ratio test was finally applied to test for the significance of the double double exponential distribution compared to the double exponential distribution. The double double exponential distribution was found to be significant for two out of the three data sets.

Having determined the probability distribution model for individual-aircraft along-track position-keeping, the second element of the proposed approach was to develop an analytical probability distribution model, $g(t)$ say, for individual-aircraft clock errors. The five families of probability distributions used to model individual-aircraft along-track position keeping were also used to model individual-aircraft clock errors based on aircraft time-keeping data collected in the San Juan FIR in April 1993. Refer to the texts under the *NAT SPG/29 (1993)* and *NAT SPG/30 (1994)* headings in Section 7.2.3 for details of that data collection. A double double exponential distribution was found to provide the best fit to the aircraft time-keeping sample.

⁹² Thus, $f(t)$ describes the variation in the true time of position reporting due to the difference between aircraft reported position and aircraft true position at the time of reporting.

Following the specification of the component probability densities $f(t)$ and $g(t)$ of individual-aircraft along-track position keeping and clock errors, the third element of the proposed approach was to calculate the probability density, $h(t)$ say, of the individual-aircraft combined along track errors by means of the following convolution integral,

$$h(t) = \int_{-\infty}^{\infty} f(u)g(t-u)du \quad (7.24)$$

Let $h_1(t_1) = h(t_1)$ denote the probability density of the combined along-track position-keeping and time-keeping errors of the lead aircraft of a pair of aircraft and let $h_2(t_2) = h(t_2)$ denote the probability density of the combined along-track position-keeping and time-keeping errors of the trailing aircraft of the pair. The probability density, $C(T)$ say, of the longitudinal separation gain/loss $T = t_1 - t_2$ for the two aircraft follows from another convolution integral, viz.

$$C(T) = \int_{-\infty}^{\infty} h_1(t)h_2(T-t)dt = \int_{-\infty}^{\infty} h(t)h(T-t)dt \quad (7.25)$$

Finally, the probability density $C(T)$ can be used to calculate the probability of losing T or more minutes of longitudinal separation as well as to calculate the probability of longitudinal overlap by integration over the pertinent time interval, where the calculation of the probability of longitudinal overlap also needs the probability distribution of the time separation upon entry of the same flight path by a pair of proximate aircraft.

Explicit formulae for the individual aircraft combined density $h(t)$, the longitudinal separation density $C(T)$, and the probability of losing T or more minutes of longitudinal separation were provided in (Unknown, 1994a).

In summary, two probability distribution models $f(t)$ and $g(t)$ of individual-aircraft along-track position keeping and clock errors were fitted to pertinent empirical distributions and subsequently combined to a probability distribution model $h(t)$ of the individual-aircraft combined along track errors. This last model was used to develop a probability distribution model $C(T)$ of the longitudinal separation gain/loss for proximate pairs of aircraft, i.e. aircraft entering the same flight path within up to sixty minutes inclusive.

As set out under the *NAT SPG/30 (1993)* heading in Section 6.4.2, the NAT SPG endorsed the proposed model and agreed that its refinement should be continued, where it was recognised that further data collections were required using independent surveillance measures in order to determine the individual contributions to the total error made by aircraft navigational system and time-keeping errors. (See the *Proposed Mathematicians' Work Programme for 1994/95* under the NAT SPG/30 entry in Table 7.5.) However, such studies were likely to be ATC intrusive since, at the time, this was the only way of obtaining accurate time-keeping information. It was noted that no implementation plan for reduced longitudinal separation existed nor that the requisite cost-benefit studies had been performed at the time and it was agreed that this would be brought to the attention of the responsible NAT SPG subgroup (NAT IMG).

Remarks

1. It would seem that the (three) empirical gain/loss distributions are affected by both individual-aircraft along-track position keeping errors and individual-aircraft clock errors. It is not clear, therefore, why the probability distribution models $f(t)$ fitted to these empirical distributions represent only individual-

aircraft along-track position-keeping errors and not individual-aircraft combined along track errors. Adding the probability distribution model $g(t)$ of individual-aircraft clock errors would then seem to imply double counting of those clock errors. A better approach would thus seem to be to first fit the distribution model $g(t)$ to the empirical individual-aircraft clock errors and to then fit the “sum” of the distribution models $f(t)$ and $g(t)$ to the empirical gain/loss distributions, where only the parameters of the distribution model $f(t)$ are to be estimated.

2. The modelling of the empirical gain/loss distributions is based on the following. Consider a given flight path and a pair of proximate aircraft, i.e. a pair of aircraft entering the flight path within up to and including 60 minutes. Denote the lead aircraft A and the trailing aircraft B. The lead aircraft’s entry and exit times of the flight path are modelled as (in minutes or hours)

$$t_{A1} = \mu_{A1} + \epsilon x_{A1} + \epsilon t_{A1} \quad (7.26)$$

$$t_{A2} = \mu_{A2} + \epsilon x_{A2} + \epsilon t_{A2} \quad (7.27)$$

where ϵx_{A1} and ϵt_{A1} denote the lead aircraft’s along-track position-keeping error and individual-aircraft clock error upon entry of its flight path and ϵx_{A2} and ϵt_{A2} denote the lead aircraft’s along-track position-keeping error and individual-aircraft clock error upon exit of its flight path. μ_{A1} and μ_{A2} denote the “average” entry and exit times of the lead aircraft A on the flight path in a large sample of aircraft A entering the given flight path. The average flight duration for the lead aircraft thus amounts $\mu_{A2} - \mu_{A1}$. The trailing aircraft’s entry and exit times of the flight path are modelled in the same manner as

$$t_{B1} = \mu_{B1} + \epsilon x_{B1} + \epsilon t_{B1} \quad (7.28)$$

$$t_{B2} = \mu_{B2} + \epsilon x_{B2} + \epsilon t_{B2} \quad (7.29)$$

with an average flight duration for the trailing aircraft of $\mu_{B2} - \mu_{B1}$ (minutes/hours). All individual aircraft along-track position-keeping errors ϵx_{A1} , ϵx_{A2} , ϵx_{B1} , and ϵx_{B2} are assumed to have the same probability distribution and all individual aircraft clock errors ϵt_{A1} , ϵt_{A2} , ϵt_{B1} , and ϵt_{B2} are also assumed to have the same probability distribution (but not the same as that of the along-track position-keeping errors). The longitudinal time separation between the aircraft upon entry of the flight path is given by

$$t_{B1} - t_{A1} = \mu_{B1} + \epsilon x_{B1} + \epsilon t_{B1} - (\mu_{A1} + \epsilon x_{A1} + \epsilon t_{A1}) \quad (7.30)$$

or

$$t_{B1} - t_{A1} = \mu_{B1} - \mu_{A1} + \epsilon x_{B1} + \epsilon t_{B1} - (\epsilon x_{A1} + \epsilon t_{A1}) \quad (7.31)$$

and the longitudinal time separation between the aircraft upon exit of the flight path is given by

$$t_{B2} - t_{A2} = \mu_{B2} - \mu_{A2} + \epsilon x_{B2} + \epsilon t_{B2} - (\epsilon x_{A2} + \epsilon t_{A2}) \quad (7.32)$$

Consequently, the gain/loss in longitudinal separation can be written as

$$P_x = t_{B2} - t_{A2} - (t_{B1} - t_{A1}) = \mu_{B2} - \mu_{A2} + \epsilon x_{B2} + \epsilon t_{B2} - (\epsilon x_{A2} + \epsilon t_{A2}) - \{\mu_{B1} - \mu_{A1} + \epsilon x_{B1} + \epsilon t_{B1} - (\epsilon x_{A1} + \epsilon t_{A1})\} \quad (7.33)$$

or

$$P_x = t_{B2} - t_{A2} - (t_{B1} - t_{A1}) = \mu_{B2} - \mu_{A2} - (\mu_{B1} - \mu_{A1}) + \epsilon x_{B2} + \epsilon t_{B2} - (\epsilon x_{A2} + \epsilon t_{A2}) - \{\epsilon x_{B1} + \epsilon t_{B1} - (\epsilon x_{A1} + \epsilon t_{A1})\} \quad (7.34)$$

which can be re-expressed further as

$$P_x = t_{B2} - t_{A2} - (t_{B1} - t_{A1}) = \mu_{B2} - \mu_{B1} - (\mu_{A2} - \mu_{A1}) + \epsilon x_{B2} + \epsilon t_{B2} - (\epsilon x_{A2} + \epsilon t_{A2}) - \{\epsilon x_{B1} + (\epsilon x_{A1} + \epsilon t_{A1})\} \quad (7.35)$$

In eq. (7.35), the terms $\mu_{B2} - \mu_{B1} - (\mu_{A2} - \mu_{A1})$ denote the difference in average flight times of the lead aircraft A and the trailing aircraft B. The proximity criterion of 60 minutes has been chosen to ensure that both aircraft are experiencing approximately the same meteorological conditions during their flights. If, in addition, it is assumed that the aircraft are flying at the same Mach number (or the above equations have been corrected for a difference in Mach number), then the difference in average flight times of the aircraft constituting a proximate pair can be taken as (approximately) zero, i.e. $\mu_{B2} - \mu_{B1} - (\mu_{A2} - \mu_{A1}) = 0$ (cf. paragraph 3.1.1.2 of (Unknown, 1994a)), and eq. (7.35) for the gain/loss P_x reduces to

$$P_x = t_{B2} - t_{A2} - (t_{B1} - t_{A1}) = \epsilon x_{B2} + \epsilon t_{B2} - (\epsilon x_{A2} + \epsilon t_{A2}) - \{\epsilon x_{B1} + \epsilon t_{B1} - (\epsilon x_{A1} + \epsilon t_{A1})\} \quad (7.36)$$

The probability density function $f(t)$ fitted to the empirical gain/loss histograms in (Unknown, 1994a) covers the four individual aircraft along-track position-keeping error terms ϵx_{A1} , ϵx_{A2} , ϵx_{B1} , and ϵx_{B2} on the right side of eq. (7.36) for the gain/loss model P_x . However, as suggested under *Remark 1* above, the model also includes four individual aircraft clock error terms ϵt_{A1} , ϵt_{A2} , ϵt_{B1} , and ϵt_{B2} , all with probability density $g(t)$, the parameters of which should have been estimated first using the individual aircraft time-keeping data.

7.2.4.4 NAT SPG/31-WP/27: A model for determining the rate of collisions due to the loss of planned longitudinal separation

SPG/31-WP/27 (Flax, 1995a) begins noting that, in (Flax, 1995c), an inconsistency was reported in the standard separation model used to determine the rate of collisions due to the loss of planned longitudinal separation and that the inconsistency is corrected in SPG/31-WP/27. The inconsistency is stated to result from inadequately accounting for the traffic on a given route and flight level. The (perceived) inconsistency and a counter argument are treated in the remark at the end of this Subsection.

The starting point for the longitudinal collision risk model development of SPG/31-WP/27 differs from that underlying the Reich model (as utilized at NAT SPG/4 (1968), NAT SPG/5 (1968), and NAT SPG/14 (1978)), viz. the probability of an aircraft pair colliding given that an overtake occurs as opposed to the collision rate of a pair of aircraft. It will be shown under *Remark 1* below, however, that the two approaches are equivalent.

The major steps in the model development of (Flax, 1995a) are

- The probability that a pair of airplanes experiences a collision;
- Traffic flow on the path; and
- Overtake probabilities and collision rates.

Thus, the derivation begins with the probability of a pair of aircraft following the same flight path colliding due to the loss of planned longitudinal separation. This probability is given by

$$\begin{aligned} P\{\text{the pair collides}\} &= P\{\text{the pair collides AND an overtake occurs}\} + \\ &\quad P\{\text{the pair collides AND an overtake does not occur}\} = \\ &\quad P\{\text{the pair collides AND an overtake occurs}\} \end{aligned} \quad (7.37)$$

or

$$P\{\text{the pair collides}\} = P\{\text{the pair collides | an overtake occurs}\} \times P\{\text{an overtake occurs}\} \quad (7.38)$$

Using the three ways in which a pair of overtaking aircraft can collide, i.e. head/tail, sideways, or from above/below, the conditional probability on the right side of eq. (7.38) was expressed as

$$\begin{aligned} P\{\text{the pair collides | an overtake occurs}\} &= \\ &\quad P\{\text{the pair collides side-to-side | an overtake occurs}\} + \\ &\quad P\{\text{the pair collides top-to-bottom | an overtake occurs}\} + \\ &\quad P\{\text{the pair collides nose-to-tail | an overtake occurs}\} \end{aligned} \quad (7.39)$$

Calculation of the three conditional probabilities on the right side of eq. (7.39) resulted in

$$P\{\text{the pair collides | an overtake occurs}\} = N_y \frac{2\lambda_x}{v_x(T,t)} P_z + N_z \frac{2\lambda_x}{v_x(T,t)} P_y + P_y P_z \quad (7.40)$$

In eq. (7.40), the aircraft dimensions are represented by their usual symbols and the relative speed components between the aircraft in the longitudinal, lateral, and vertical dimensions are denoted $v_x(T, t)$, v_y , and v_z , with T denoting the flying time along the flight path and t denoting the initial longitudinal separation between the aircraft in the pair under consideration. The notation $v_x(T, t)$ is used to emphasize that for an overtake to occur on the flight path, a minimum relative longitudinal speed is required, which is dependent on the flight duration T and the initial longitudinal separation t between the aircraft. The symbols N_y , N_z , P_y , and P_z have their usual meaning as defined in Section 5.2.1, *Reich (1966) Part I*, for the Reich model for an intended separation [AB].

Utilizing the general relationships between the probabilities and the numbers of times of entering into overlap in the lateral and vertical dimensions, i.e. eqs. (5.15) and (5.16) of Section 5.2.1, for the first two terms on the right side of eq. (7.40) and an identity for the third term, eq. (7.40) becomes

$$P\{\text{the pair collides | an overtake occurs}\} = \frac{v_y}{2\lambda_y} P_y \frac{2\lambda_x}{v_x(T,t)} P_z + \frac{v_z}{2\lambda_z} P_z \frac{2\lambda_x}{v_x(T,t)} P_y + \frac{v_x(T,t)}{2\lambda_x} P_y P_z \frac{2\lambda_x}{v_x(T,t)} \quad (7.41)$$

or,

$$P\{\text{the pair collides}|\text{an overtake occurs}\} = P_y P_z \frac{2\lambda_x}{v_x(T,t)} \left[\frac{v_x(T,t)}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] \quad (7.42)$$

Substitution of eq. (7.42) into eq. (7.38) then gives for the probability of an aircraft pair colliding as a result of the loss of longitudinal separation

$$P\{\text{the pair collides}\} = P_y P_z \frac{2\lambda_x}{v_x(T,t)} \left[\frac{v_x(T,t)}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] \cdot P\{\text{an overtake occurs}\} \quad (7.43)$$

The reasoning underlying the notation $v_x(T, t)$ was then extended to the probability of an overtake occurring, i.e. $P\{\text{an overtake occurs}\}$ was expressed as a function of the flight duration and the aircraft pair's initial longitudinal separation, $P\{\text{an overtake occurs}\} = P_x(T, t)$, and eq. (7.43) was expressed as

$$P\{\text{a pair with } t \text{ minutes of initial separation collides}\} = P_y P_z \frac{2\lambda_x}{v_x(T,t)} \left[\frac{v_x(T,t)}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] P_x(T, t) \quad (7.44)$$

(Flax, 1995a) then proceeded with modelling the traffic flow on a flight path. Assuming that aircraft enter the flight path at an overall rate of n aircraft per hour, the following quantities were calculated:

The number of aircraft on the flight path at any point in time	nT
The number of aircraft pairs on the flight path at any point in time	$nT(nT - 1)/2$
The number of aircraft pairs generated per hour	$n(nT - 1)$
The probability that an aircraft pair has t minutes initial separation ⁹³	$E(t)$
The number of aircraft pairs with t minutes of initial separation	$(nT(nT - 1)/2)E(t)$
The number of aircraft pairs generated per hour with an initial separation of t minutes	$n(nT - 1)E(t)$

As indicated by the last entry in the table above, if aircraft enter the flight path at an overall rate of n aircraft per hour, then the average number of aircraft pairs generated on the flight path amounts $n(nT - 1)$ per hour. Letting $E(t)$ denote the probability that a randomly chosen pair of aircraft has an initial longitudinal separation of t minutes, the average number of such pairs generated per hour equals $n(nT - 1)E(t)$. Multiplying both sides of eq. (7.44) by $n(nT - 1)E(t)$ gives

$$C_H^t = \text{number of collisions **per hour** between aircraft pairs with an initial separation of } t \text{ minutes} = n(nT - 1)E(t)P_y P_z \frac{2\lambda_x}{v_x(T,t)} \left[\frac{v_x(T,t)}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] P_x(T, t) \quad (7.45)$$

Summing over all possible initial separations, the hourly rate of collision for the given flight pass can be expressed as

$$C_H = \text{number of collisions **per hour** due to loss of initial longitudinal separation} = n(nT - 1)P_y P_z \sum_{t=0}^{\infty} \frac{2\lambda_x}{v_x(T,t)} \left[\frac{v_x(T,t)}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] E(t)P_x(T, t) \quad (7.46)$$

⁹³ $E(t)$ is defined rather than calculated.

If a route system consists of more than one flight path, the system's longitudinal collision risk in collisions per hour is obtained by summing C_H for all those flight paths.

A flight path's number of collisions per hour, C_H , was finally converted into the path's number of collisions per flight hour, C_F say, by dividing eq. (7.46) by the number of flight hours, nT , generated on the flight path per hour, i.e.

$$C_F = \text{number of collisions per flight hour due to loss of initial longitudinal separation} = \frac{nT-1}{T} P_y P_z \sum_{t=0}^{\infty} \frac{2\lambda_x}{v_x(T,t)} \left[\frac{v_x(T,t)}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] E(t) P_x(T, t) \quad (7.47)$$

If a route system consists of more than one flight path, the system's longitudinal collision risk in collisions per flight hour is obtained by a weighted summation of C_F for all the flight paths, where the weights are equal to the proportions of the total flying time generated per flight path.

The mathematical work in (Flax, 1995a) concluded with an analysis of the relative speed between a pair of aircraft flying along the same flight path that is required for an overtake to occur as a function of the initial longitudinal separation.

Remarks

- Eq. (7.40) for the conditional probability of a collision given that an overtake occurs may be compared with the collision rate C of the Reich model for a proximate pair of aircraft⁹⁴ with intended separation [AB] given by eq. (5.4) of Section 5.2.1,

$$C = N_x P_y P_z + N_y P_x P_z + N_z P_x P_y \quad (5.4)$$

where P_x denotes the probability of longitudinal overlap for a proximate pair of aircraft with intended separation [AB] and N_x denotes the number of times per hour that such a pair of aircraft enters into longitudinal overlap. Taking the proximity distance equal to the aircraft length λ_x , eqs. (5.21) and (5.22) of Section 5.2.1 give

$$P_x = \text{average of } (P_x)_{[AB]} \approx 1 \quad (7.48)$$

and

$$N_x = \text{average of } (N_x)_{[AB]} \approx \frac{|\bar{x}|}{2\lambda_x} \quad (7.49)$$

Substitution of eqs. (7.48) and (7.49) into eq. (5.4) and defining C more explicitly gives

$$C\{\text{a pair collides}|\text{a longitudinal overlap occurs}\} = \frac{|\bar{x}|}{2\lambda_x} P_y P_z + N_y P_z + N_z P_y \quad (7.50)$$

Eq. (7.50) gives the collision rate per unit of time that a longitudinal overlap occurs. Multiplication of this collision rate by the duration of a longitudinal overlap gives the number of collisions per longitudinal

⁹⁴ Eq. (5.4) actually applies to any pair of aircraft with intended separation [AB], but N_x and P_x are assumed to be negligible for non-proximate pairs of aircraft.

overlap occurring, i.e. the probability of a collision occurring given the occurrence of a longitudinal overlap, i.e.

$$P\{\text{a pair collides}|\text{a longitudinal overlap occurs}\} = \frac{2\lambda_x}{|\bar{x}|} \left(\frac{|\bar{x}|}{2\lambda_x} P_y P_z + N_y P_z + N_z P_y \right) \quad (7.51)$$

Eq. (7.51) can be seen to be the same as eq. (7.40), which demonstrates the consistency between the original Reich model approach and the (Flax, 1995a) approach.

2. Eq. (7.47) for the number of collisions per flight hour may be compared with the general form of the longitudinal collision risk model utilized at NAT SPG/14 (1978), i.e. eq. (7.23),

$$N_{ax} = 2 \times 10^7 \times \left(\frac{2\lambda_x/|\bar{x}|}{T} \times \sum_m E_x(m) Q_x(m) \right) P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.23)$$

where the product 2×10^7 can be ignored since N_{ax} denotes the number of accidents due to the loss of planned longitudinal separation per 10 million flying hours rather than the number of collisions per flight hour (C_F in eq. (7.47)). Taking a conservative value for the closing speed $v_x(T, t)$ in eq. (7.47), the comparison boils down to

$$\sum_m E_x(m) Q_x(m) = (nT - 1) \sum_{t=0}^{\infty} E(t) P_x(T, t) \quad (7.52)$$

In eq. (7.52), $P_x(T, t)$ denotes the probability of an overtake occurring during a flight of T hours duration and an initial separation of t minutes and $Q_x(m)$ is the probability that there has been a separation loss of at least $m - 1/2$ minutes, i.e. an overtake has taken place. Thus, $P_x(T, t)$ and $Q_x(m)$ describe the same event and the comparison further boils down to a comparison between $(nT - 1)E(t)$ and $E_x(m)$. These two quantities are different because the former is related to the average number of randomly chosen aircraft pairs with an initial longitudinal separation of t minutes and the latter pertains to pairs of successive aircraft with an initial longitudinal separation of m minutes. Thus, the difference complies with the difference in approach of (Flax, 1995a), all aircraft pairs, and that at NAT SPG/14 (1978) approach for successive aircraft pairs.

7.2.4.5 NAT SPG/31-WP/28: A theory of initial longitudinal separations on oceanic routes

(Flax, 1995b) dealt with a specific parameter of the longitudinal collision risk model rather than the full model, viz. the estimation of the distribution of entry longitudinal separation $E(t)$, $t = 0, 1, 2, \dots$. It addressed the following:

- A clue from North Atlantic data;
- A preliminary equation for the distribution of initial separations;
- The conditional probabilities $F_j(x)$; and
- The distribution of initial separations.

Although the scope of this Document is on collision risk modelling rather than on the estimation of collision risk model parameters and although (Flax, 1995b) is rather specific/technical, its discussion is included below for completeness.

Data on initial longitudinal separation between successive aircraft from the North Atlantic suggested that these data followed an exponential distribution (with parameter λ) shifted rightward by the longitudinal separation standard/minimum l_m . The derivations in the remainder of (Flax, 1995b) were then based on the assumption that the aircraft arrival process at the entry point of a flight path was a modified Poisson process (counting process) with a shifted exponential distribution for the entry separation between two successive aircraft.

An elementary interarrival period, EIP , was defined as the interarrival period between two successive aircraft. Assuming, as in (Flax, 1995a), that, on average, n aircraft enter a given flight path per hour and that the average flying time on the flight path amounts T hours, the probability that a randomly chosen pair of aircraft is separated by j EIP s was calculated as $2(nT - j)/(nT(nT - 1))$. The distribution function $F(x)$, say, of initial separation between two randomly chosen aircraft was then calculated as

$$F(x) = \frac{2}{nT(nT-1)} \sum_{j=1}^{nT-1} (nT - j) F_j(x) \quad (7.53)$$

where $F_j(x)$, $j = 1, \dots, nT - 1$, are the conditional probability distribution functions of initial longitudinal separation between a randomly chosen pair of aircraft given that the aircraft in the pair are separated by j EIP s.

After a considerable amount of algebra, it turns out that the conditional probability distribution functions $F_j(x)$, $j = 1, \dots, nT - 1$, are given by

$$F_j(x) = \int_{-\infty}^{x-jl_m} \Gamma(u; j, \lambda) du \quad (7.54)$$

where $\Gamma(u; j, \lambda)$ denotes the probability density function of a gamma distribution with shape parameter j and scale parameter λ .

Finally, eq. (7.54) was substituted into eq. (7.53) to obtain

$$F(x) = P\{\text{initial separation} \leq x\} = \frac{2}{nT(nT-1)} \sum_{j=1}^M (nT - j) \left[1 - e^{-\lambda(x-jl_m)} \sum_{i=0}^{j-1} \frac{\lambda^i (x-jl_m)^i}{i!} \right] \quad (7.55)$$

where M denotes the greatest integer less than or equal to both x/l_m and $nT - 1$.

In summary, eq. (7.55) provides an analytical probability distribution model for initial longitudinal separation between a randomly selected pair of aircraft on a given flight path in terms of the prevailing longitudinal separation standard/minimum l_m , the flight duration T , the number of aircraft entering the flight path per hour, n , and the rate parameter λ of a modified Poisson arrival process where λ is a function of the longitudinal separation standard/minimum l_m and the number of aircraft entering the flight path per hour, n , viz. $\lambda = n/(1 - nl_m)$.

7.2.4.6 NAT SPG/31-WP/29: Proposed procedure to estimate the probability of an aircraft-pair losing longitudinal separation based on individual aircraft performance

(Unknown, 1995b) dealt with another specific element of the longitudinal collision risk model rather than the full model, viz. the estimation of the probability of an aircraft-pair losing longitudinal separation. It comprised four sections entitled:

1. Estimating arrival times at waypoints;
2. Proposed procedure for a preliminary estimate of the probability that an aircraft-pair loses t or more minutes of longitudinal separation based on individual-aircraft performance parameters;
3. Further work efforts; and
4. Recommendations.

Like (Flax, 1995b), (Unknown, 1995b) is rather specific/technical, but its discussion is included below for completeness.

The waypoint reporting process is described in terms of actual values of variables and errors in them. Let WP1 be the waypoint near which an aircraft measures its position and reports arriving at the waypoint. Let the actual time of the position report be T_a and let the error in the aircraft's determination of time be denoted T . The estimated or nominal time of the position report can then be expressed as $T_e = T_a + T$

At the time of position reporting, the aircraft also provides an estimate of its arrival time at its next waypoint, WP2 say, viz. the sum of its estimate $T_e = T_a + T$ of the time of passing WP1 and its estimate of the time to go from WP1 to WP2. Following the notation of (Unknown, 1995b), the estimated and actual times of arriving at WP2 are denoted as A_e and A_a with $A_e = A_a + A$, i.e. A denotes the error in the estimate of the aircraft's arrival time at WP2. The time to go from WP1 to WP2 is derived from the distance to go and the aircraft speed where both quantities are characterized by an estimated or nominal value, an actual value, and an error, i.e. distance $D_e = D_a + D$ and speed $S_e = S_a + S$ with D denoting the error in the aircraft's estimate of the distance between WP1 and WP2 and S denoting the error in the aircraft's estimate of its speed between WP1 and WP2. One component of the error in the aircraft's estimate of the distance between WP1 and WP2 results from the reporting at WP1 not taking place at the actual location of WP1 but rather near to it and another component results from the fact that in estimating/projecting the distance between WP1 and WP2 the aircraft uses the great circle through the waypoints without knowing yet about any random or intentional deviations (e.g. due to weather) from the great circle through the two waypoints. The aircraft's estimate of the time needed to fly from WP1 to WP2, t_e , is given by

$$t_e = \frac{D_e}{S_e} = \frac{D_a + D}{S_a + S} \quad (7.56)$$

and the aircraft's estimate of the time of passing WP2 is given by

$$A_e = A_a + A = T_e + t_e = T_a + T + \frac{D_a + D}{S_a + S} \quad (7.57)$$

In addition, the aircraft's actual time of passing WP2 is given by

$$A_a = T_a + t_a \quad (7.58)$$

where, cf. eq. (7.56)

$$t_a = \frac{D_a}{S_a} \quad (7.59)$$

Using the second and last part of the string of equalities in eq. (7.57) together with eqs. (7.57) and (7.59) gives for the error in the estimated time of passing of the aircraft's next waypoint WP2,

$$A = T + \frac{D_a + D}{S_a + S} - \frac{D_a}{S_a} \quad (7.60)$$

which may be reworked to

$$A = T + \frac{D}{S_a + S} - \frac{D_a S}{S_a(S_a + S)} \quad (7.61)$$

Notice that A and T both are time errors but that T is an error in the actual time of an aircraft reporting passing a waypoint (WP1) and A is an error in the actual time of an aircraft estimating passing its next waypoint (WP2).

Eq. (7.61) was then applied to a pair of aircraft using additional subscripts l and f referencing the lead and following aircraft in the pair respectively and the difference between the estimated/projected times of passing WP2 calculated as

$$A_l - A_f = T_l - T_f + \left(\frac{D_l}{S_{a,l} + S_l} - \frac{D_f}{S_{a,f} + S_f} \right) - \left(\frac{D_{a,l} S_l}{S_{a,l}(S_{a,l} + S_l)} - \frac{D_{a,f} S_f}{S_{a,f}(S_{a,f} + S_f)} \right) \quad (7.62)$$

Section 1, *Estimating arrival times at waypoints*, of (Unknown, 1995b) concludes with a brief discussion of the practical relevance of the above derivations. Firstly, since each aircraft upon passing WP1 sends its estimate A_e of the time of passing WP2, ATC monitoring the flights knows the difference between the two aircraft's estimated arrival times at WP2 shortly after the following aircraft passes WP1, viz. $A_{e,f} - A_{e,l} = (A_{a,f} + A_f) - (A_{a,l} + A_l)$, and can use this to verify whether longitudinal separation appears to be maintained. Secondly, from a collision risk point of view, the conditional probability distribution of the actual time separation at WP2 given the estimated time separation at WP2 is of interest, i.e.

$$P\{A_{a,f} - A_{a,l} \leq x | (A_{a,f} + A_f) - (A_{a,l} + A_l) = y\} \quad (7.63)$$

Notice that the first event in the probability given by eq. (7.63) involves the difference between the actual times of passing waypoint WP2 and that the second event involves the difference between the estimated/projected times of passing WP2. The former can be expressed in terms of the estimated times of passing waypoint WP2 and the time errors A_f and A_l and eq. (7.63) be reworked to

$$P\{A_{a,f} - A_{a,l} \leq x | (A_{a,f} + A_f) - (A_{a,l} + A_l) = y\} = P\{A_f - A_l \geq y - x | (A_{a,f} + A_f) - (A_{a,l} + A_l) = y\} \quad (7.64)$$

which may also be expressed as

$$P\{A_{a,f} - A_{a,l} \leq x | A_{e,f} - A_{e,l} = y\} = P\{A_f - A_l \geq y - x | A_{e,f} - A_{e,l} = y\} \quad (7.65)$$

Eq. (7.65) shows that when estimated arrival times at WP2 differ by y , the probability that the actual arrival times differ by no more than x equals the probability that the difference in estimated-arrival-time errors is greater than or equal to $y - x$.

Section 2 of (Unknown, 1995b) developed a procedure for a preliminary estimate of the probability that an aircraft-pair loses t or more minutes of longitudinal separation, $L(t)$, based on individual-aircraft performance parameters. The development started by recalling eq. (7.61), which provided a formula for the error in an aircraft's estimate of the time of arriving at its next waypoint WP2 upon position reporting at WP1, and approximating the formula by the following one,

$$A \approx T + \frac{1}{\overline{S_a} + S} D - \frac{\overline{D_a}}{(\overline{S_a} + S)^2} S \quad (7.66)$$

where $\overline{D_a}$ and $\overline{S_a} + S$ denote the average of the estimated distance between a pair of successive waypoints of all aircraft and the average estimated speed of all aircraft respectively. In eq. (7.66), the individual-aircraft time, distance, and speed determination errors⁹⁵ T , D , and S are assumed to be independent random variables whereas the average estimated distance between two successive waypoints and the average speed of all aircraft are assumed to be constants. The latter assumption was rationalized by considering the uncertainty/variances of the average estimates negligible compared to those of T , D , and S . As a result, eq. (7.66) expresses the error in an aircraft's estimate of the time of arriving at its next waypoint WP2 as a linear combination of the three independent individual-aircraft determination-error random variables, T , D , and S . Following this, suitable probability distributions with probability densities $f_T(t)$, $f_D(x)$, and $m(s)$ were determined.

Double double exponential probability densities were proposed for the individual-aircraft time and distance determination error probability densities $f_T(t)$ and $f_D(x)$, i.e. (cf. eq. (4.26) of Section 4.5)

$$f_T(t) = \frac{(1-\beta)}{2\kappa_1} e^{-|t|/\kappa_1} + \frac{\beta}{\kappa_2} e^{-|t|/\kappa_2} \quad (7.67)$$

$$f_D(x) = \frac{(1-\alpha)}{2\lambda_1} e^{-|x|/\lambda_1} + \frac{\alpha}{\lambda_2} e^{-|x|/\lambda_2} \quad (7.68)$$

⁹⁵ Component-determination errors are different from component-keeping errors. The former measure the ability of the aircraft system to determine or estimate the component at a waypoint whereas the latter refer to the ability of the aircraft to maintain component accuracy while traveling to the next waypoint. Compare, for the vertical dimension, eqs. (6.94) and (6.95), $TVE = ASE + FTE$ and $TVE \approx ASE + AAD$, of Section 6.5.2.2 or, for the lateral dimension, eqs. (2.1) or (2.2), $TSE = PDE + FTE + NSE$ (TSE – Total System Error, PDE – Path Definition Error, and NSE – Navigation System Error) or $TSE = PDE + PSE + PEE$ (PSE – Path Steering Error, PEE – Path Estimation Error), of Section 2.2.1 of (Moek, 2014) where it is also noted that, in the longitudinal dimension, there are currently only two navigation errors, namely PDE and NSE , of which PDE is considered negligible. FTE does currently not exist in the longitudinal dimension since there are no navigation specifications requiring 4-D control yet.

Based on data presented in (Unknown, 1994b), (Unknown, 1995b) modelled the individual-aircraft speed determination density $m(s)$ as a mixture of a power-exponential core density and a double-exponential tail density, i.e.

$$m(s) = (1 - \gamma) \frac{\phi^{-1} \exp\left(-\frac{1}{2} \left(\frac{|s|}{\phi}\right)^{2/(1+\zeta)}\right)}{\Gamma\left(1 + \frac{(1+\zeta)}{2}\right) 2^{(1+(1+\zeta)/2)}} + \gamma \frac{1}{2\eta} e^{-|s|/\eta} \quad (7.69)$$

The power-exponential core density of eq. (7.69) with parameter ζ may be compared with the power-exponential probability density defined by eq. (6.20) of Section 6.2.2 with parameter β . The speed determination error density $m(s)$ was derived from the probability density $m_t(t)$ of the individual-aircraft estimated time of arrival (ETA) error based on the understanding that the main sub-component errors contributing to an aircraft's speed determination error are Mach estimate errors and wind speed forecast errors and the believe that the major contributors to differences between ETAs and reported times are Mach estimate errors and aircraft speed forecast errors too. See (Unknown, 1995b) for further details. See also *Remark 1* at the end of this Subsection.

Given the probability density functions defined by eqs. (7.68) and (7.69), the probability density functions of $(1/\overline{S_a} + \overline{S})D$ and $(\overline{D_a}/(\overline{S_a} + \overline{S})^2)S$ on the right side of eq. (7.66) have the same types but with scaled spread parameters. Using the component density functions, the probability density function $h(a)$ of the error A in an individual aircraft's estimate of the time of arriving at its next waypoint WP2 upon position reporting at WP1 defined by eq. (7.66) was first calculated and subsequently integrated over one-minute time intervals. The latter values were then used to calculate the cumulative probability distribution function $H(t) = P(A \leq t)$ of an individual aircraft's time estimation error A , where it was noted that, in addition to its use for obtaining a preliminary estimate of the probability $L(t)$ that an aircraft-pair loses t or more minutes of longitudinal separation, $H(t)$ can also be used to aid in estimating controller workload.

The derivation of the proposed procedure for a preliminary estimate of the probability $L(t)$ that an aircraft-pair loses t or more minutes of longitudinal separation started with approximating the expressions in brackets on the right side of eq. (7.62) in the same manner as the distance and speed determination errors in eq. (7.61), which resulted in the following approximation:

$$A_l - A_f \approx T_l - T_f + \frac{1}{\overline{S_a} + \overline{S}} (D_l - D_f) - \frac{\overline{D_a}}{(\overline{S_a} + \overline{S})^2} (S_l - S_f) \quad (7.70)$$

On the assumption that both aircraft have the same time and distance error probability densities $f_T(t)$ and $f_D(x)$ and that these errors are all independent, the probability densities of the error differences $T_l - T_f$ and $D_l - D_f$ can be calculated explicitly as convolution integrals (cf. for example eq. (4.14) of Section 4.5 for $S_y = 0$ or eq. (6.99) of Section 6.5.2.2.1). The derivation of the probability density of the speed error difference was less straightforward, because it was assumed that the speed-estimation error of the following aircraft was correlated with that of the leading aircraft. The probability density function $n(w)$ of the speed-error difference $S_l - S_f$ can be expressed as⁹⁶

$$n(w) = \int_{-\infty}^{\infty} m_{f|l}(s_l - w | s_l) m_l(s_l) ds_l \quad (7.71)$$

⁹⁶ Convolution integrals can be expressed in slightly different (but equivalent) ways, dependent on how the variable of integration is chosen.

where $m_l(s_l)$ denotes the lead-aircraft's speed error probability density and $m_{f|l}(s_l + w|s_l)$ denotes the conditional probability density of the following-aircraft's speed error, given the lead-aircraft's speed error.

To examine the possible correlation between the speed-estimation errors of two aircraft involved in a pair, data on estimated time of arrival (ETA) errors for aircraft pairs were examined first in (Unknown, 1995b) and used to construct empirical one-minute histograms for following aircraft ETA error given lead aircraft ETA error. From these histograms, it was concluded that there was notable correlation only within the range of about -5 to 5 minutes. Taking account of the available data for each lead aircraft ETA error, conditional following-aircraft ETA error densities were only estimated for lead-aircraft ETA errors from -2 to 2 minutes. This choice resulted in at least 700 following-aircraft ETAs for each of the five lead-aircraft ETA error values. All the five empirical one-minute histograms, transformed to empirical probabilities of ETAs exceeding a given value suggested a mixture distribution. Each empirical mixture distribution/histogram was then modelled by a linear combination of a power-exponential core distribution/density and a double-exponential tail distribution/density. The data were also utilized to establish a power-exponential double-exponential mixture density for the lead-aircraft ETA error. See (Unknown, 1995b) for further details of the correlation analysis.

Following the correlation analysis, eq. (7.70) can be expressed as

$$A_l - A_f \approx T + t(D) + \tau \quad (7.72)$$

where

$$T = T_l - T_f \quad (7.73)$$

$$t(D) = \frac{1}{\overline{s_a + s}} (D_l - D_f) \quad (7.74)$$

$$\tau = \frac{\overline{D_a}}{(\overline{s_a + s})^2} (S_l - S_f) \quad (7.75)$$

The random variables T and $t(D)$ are each differences of two independent random variables and their probability density functions can be expressed as

$$g_T(u) = \int_{-\infty}^{\infty} f_T(t) f_T(u + t) dt \quad (7.76)$$

$$g_{t(D)}(v) = (\overline{s_a + s})^2 \int_{-\infty}^{\infty} f_D((\overline{s_a + s})t) f_D((\overline{s_a + s})(v + t)) dt \quad (7.77)$$

The probability densities on the right sides of eqs. (7.76) and (7.77) are double double exponential mixture densities and the pertinent integrals can be evaluated analytically, see Appendices C and D to (Unknown, 1995b).

The random variable τ is the difference of the dependent random variables S_l and S_f and its probability density can be given by means of eq. (7.71) by the following convolution integral

$$g_{\tau}(\tau) = \left(\frac{(S_a + S)^2}{D_a} \right)^2 \int_{-\infty}^{\infty} m_{f|l} \left(\frac{(S_a + S)^2}{D_a} (t - \tau) \middle| \frac{(S_a + S)^2}{D_a} t \right) m_l \left(\frac{(S_a + S)^2}{D_a} t \right) dt \quad (7.78)$$

where both the probability densities under the integral are mixture densities (with different parameter values) made up of a power-exponential core density and a double-exponential tail density.

Let $c(a)$ denote the probability density function of the random variable $A_l - A_f$ on the left side of eq. (7.72). (Unknown, 1995b) then expressed $c(a)$ as another convolution integral for the sum of two random variables, viz. that of $T + t(D)$ and τ , i.e.

$$c(a) = \int_{-\infty}^{\infty} f_{T+t(D)}(-v) g_{\tau}(a + v) \quad (7.79)$$

where $f_{T+t(D)}(v)$ denotes the probability density of the random variable $T + t(D)$,

$$f_{T+t(D)}(v) = \int_{-\infty}^{\infty} g_T(u) g_{t(D)}(v - u) du \quad (7.80)$$

Substitution of eq. (7.80) into eq. (7.79) gives for the probability density $c(a)$

$$c(a) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_T(u) g_{t(D)}(-v - u) du g_{\tau}(a + v) \quad (7.81)$$

Finally, substitution of eqs. (7.76), (7.77), and (7.78) for the aircraft-pair probability density functions $g_T(u)$, $g_{t(D)}(v)$, and $g_{\tau}(\tau)$ into eq. (7.81) expresses the probability density $c(a)$ of the difference $A_l - A_f$ between a leading aircraft's and a following aircraft's estimates of the time of arriving at their next waypoint into the probability densities $f_T(t)$, $f_D(x)$, and $m(s)$ of the individual-aircraft time, distance, and speed determination errors. However, this substitution, adding three more integrals to the right side of eq. (7.81), has not been carried through here because it does not provide much additional insight. The interested reader is referred to eq. (14) of (Unknown, 1995b) for the ultimate form.

In a similar manner as for the probability density function $h(a)$ of the error A in an individual aircraft's estimate of the time of arriving at its next waypoint WP2 upon position reporting at WP1 defined by eq. (7.66), the probability density function $c(a)$ of the random variable $A_l - A_f$ on the left side of eq. (7.72) for an aircraft pair defining the difference between a leading aircraft's and a following aircraft's estimates of the time of arriving at their next waypoint was integrated over one-minute time intervals. The latter values were then used to calculate the probability $L(t)$ of an aircraft pair losing t or more minutes of longitudinal separation from one waypoint to the next, i.e.

$$L(t) = P(t \geq a) = \int_t^{\infty} c(a) da \quad (7.82)$$

The development of the proposed procedure was concluded with an example illustrating component probability densities and convolutions within $c(a)$ based on choosing an example set of parameters for each individual-aircraft component probability density. It was noted that the preliminary values chosen should be satisfied easily by then current oceanic aircraft systems and it was anticipated that once required values for $L(t)$ are established, aircraft component-error parameters that meet requirements without imposing

unnecessary restrictions on current or future aircraft systems will be acceptable. It was also anticipated that the values for $L(t)$ required to meet a given level of safety will be derived through application of collision risk methodology.

Section 3 of (Unknown, 1995b) described further work efforts on the proposed procedure, namely

- Examination of the correlation between the following- and lead-aircraft standard deviation ETA errors;
- Modification of algorithms so that the approximation to $L(t)$ due to histogram class interval size is negligible; and
- Obtaining information on wind variation.

Remarks

1. The individual-aircraft speed determination error density $m(s)$ was derived from the probability density $m_t(t)$ of the individual-aircraft estimated time of arrival (ETA) error based on the understanding that the main sub-component errors contributing to an aircraft's speed determination error are Mach estimate errors and wind speed forecast errors and the believe that the major contributors to differences between ETAs and reported times are also Mach estimate errors and aircraft speed forecast errors. But the ETA error is precisely the random variable A defined by eq. (7.61) and subsequently approximated by eq. (7.66) where both equations clearly show that all the three aircraft time, position, and speed determination errors contribute to A and hence the ETA error. This suggests that the resulting speed determination error density $m(s)$ includes effects due to the time- and position determination error probability densities $f_T(t)$ and $f_D(x)$. Cf. also *Remark 1* in Subsection 7.2.4.3.
2. The quantity $c(a)$ denotes the probability density function of the random variable $A_l - A_f$ on the left side of eq. (7.72) for an aircraft pair, i.e. the difference between a leading aircraft's and a following aircraft's estimates of the time of arriving at their next waypoint. It is not fully clear that this random variable is the same as an aircraft-pair losing a given amount of longitudinal separation.

7.2.4.7 NAT SPG/32 MWG-WP/5: Review of longitudinal collision risk model papers presented during 1995/1996

Following the detailed mathematical reviews in the five previous Subsections, this Subsection deals with MWG-WP/5 (Owens, 1996), which provides a more high-level review of references (Flax, 1995a), (Flax, 1995b; Unknown, 1995b), (Flax, 1995c), (Anderson, 1996b), and (Unknown, 1995a).

MWG-WP/5 (Owens, 1996) started recalling the longitudinal collision risk model of (Brooker & Lloyd, 1978), i.e. the one given by eqs. (7.20) and (7.23) under the *NAT SPG/14 (1978)* heading in Section 7.2.2, but without a factor of 10^7 flight hours, thus estimating the longitudinal collision risk in terms of fatal accidents per flight hour. It noted that, traditionally, the collision risk has been calculated as the risk experienced between adjacent aircraft for the duration of the flight. It noted also that there was some doubt as to the validity of the methodology used to model the effect of controller intervention; cf. the discussion under the *NAT SPG/17 (1980)* heading in Section 6.4.2.

MWG-WP/5 then very briefly discussed references (Flax, 1995a), (Flax, 1995c), and (Anderson, 1996b). As stated before in the first paragraph of Section 7.2.4.4, (Flax, 1995a) began noting that, in (Flax, 1995c), an

inconsistency was reported in the standard separation model used to determine the rate of collisions due to the loss of planned longitudinal separation and that the inconsistency was corrected in (Flax, 1995b). Although (Flax, 1995c), as well as (Anderson, 1996b) remain to be discussed in Section 7.3), (Owens, 1996) explains that the correction concerned the risk of collision for all pairs of aircraft rather than the risk of collision for just pairs of adjacent aircraft. The correction lead to generalized definitions of $E(t)/E_x(t)$ and $P_x(t)$ and a new expression for π_x , the probability of longitudinal overlap for any pair of aircraft. This expression was utilized in (Flax, 1995a) as described in Section 7.2.4.4, resulting into the longitudinal collision risk model of eq. (7.47). (Flax, 1995b) also showed how to calculate longitudinal collision risk, in collisions per flight hour, for a system made of more than one flight path, as a weighted summation of the individual flight paths' risk per flight hour, where the weights are equal to the proportions of the total flying time generated per flight path.

MWG-WP/5 recalled the adjusted formula for π_x from reference (Flax, 1995c) as well as the collision risk model derived in (Flax, 1995a), i.e. eq. (7.47) from Section 7.2.4.4 of this Document (multiplied by a factor of two to transform the number of collisions per flight hour (C_F) into a number of accidents per flight hour).

(Anderson, 1996b), still to be discussed in Section 7.3 dealt with distance-based longitudinal separation as opposed to time-based longitudinal separation. According to (Owens, 1996), (Anderson, 1996b) derived a formula for the probability of longitudinal overlap experienced by aircraft between waypoints rather than a full crossing and used this to estimate the longitudinal collision risk for adjacent pairs of aircraft between waypoints.

The core of MWG-WP/5 (Owens, 1996) then is its Section 6 in which references (Flax, 1995a), (Flax, 1995c) and (Anderson, 1996b) are discussed together, particularly:

- i) whether the collision risk model should estimate the collision risk experienced by aircraft over the whole of the crossing or whether it should be estimated from the collision risk experienced between waypoints (Anderson, 1996b);
- ii) whether non-adjacent aircraft pairs should be considered when estimating the probabilities that aircraft have a separation of t minutes or the probability that aircraft lose t minutes over a certain time period (Flax, 1995c);
- iii) whether different closing speeds should be used for each separation value between aircraft (Flax, 1995a); and
- iv) whether it is necessary to calculate the risk for individual tracks and then combine these to generate the overall risk (Flax, 1995a).

The main conclusion concerned item i), viz. that the collision risk model, for the NAT at least, should estimate the collision risk experienced by aircraft between waypoints. This conclusion was based on the observation that the collision risk model for a whole crossing used distributions of aircraft separations based on the entry/exit points which might not accurately reflect the actual distribution of aircraft separations and hence longitudinal collision risk because these entry/exit distributions will include the effects of occasional controller intervention. Using a collision risk model based on the time between waypoints may also obviate the need to estimate the percentage success rate of controller intervention. Given the main conclusion, it was subsequently concluded that, for the NAT at least, there would be no need to consider non-adjacent aircraft, item ii), and that further work would be needed concerning items iii) and iv)

(Owens, 1996)'s review of (Flax, 1995b) led to the conclusion that no fundamental errors had been found and its review of (Unknown, 1995b) led to the conclusion that the methodology developed in it should be further developed for the benefit of practical estimation of collision risk as well as for the determination of aircraft sub-system requirements necessary to support then current proposed reductions in longitudinal separation.

As an explicit data analysis paper, (Unknown, 1995a) has not been considered in this document. According to (Owens, 1996), it was preliminary concluded from the data on the separation between aircraft pairs upon entry to the ocean that the distribution of consecutive aircraft pairs followed a roughly exponential decay whilst the distribution of all aircraft pairs followed a roughly linearly decreasing relative frequency.

(Owens, 1996) was an important input to the longitudinal-separation discussions of the NAT SPG at its 32nd Meeting. See the discussion under the *NAT SPG/32 (1996)* heading in Section 7.2.3.

7.2.5 Improved longitudinal collision risk modelling performed by the United Kingdom

7.2.5.1 Introduction

Before beginning the description of the improved longitudinal collision risk modelling performed by the United Kingdom, it is useful to summarize the state of the longitudinal collision risk model for the NAT Region by 1997, starting with the one used for the benefit of the implementation of the 10 minute reduced longitudinal separation standard/minimum on **26 November 1981**.

The form of that model is given by eq. (7.23) under the *NAT SPG/14 (1978)* heading in Section 6.4.2. It was agreed at NAT SPG/14 that the model would be used in conjunction with a data collection on the longitudinal spacing between aircraft operating in the OTS in the NAT Region during the summer of 1978 for a duration that would permit the collection of sufficient data to yield statistically conclusive results. A progress report on the data collection was presented by the United Kingdom at NAT SPG/15 (1979) and the results of the full data collection were presented at NAT SPG/16 (1979). Although two aspects were identified as requiring some more work, the NAT SPG was confident that these could be resolved before its next meeting and concluded that the use of 10 minutes longitudinal separation appeared feasible. Implementation of the reduced 10 minute longitudinal separation standard/minimum was targeted for early 1981. Further discussion took place at NAT SPG/17 (1980), where it was recalled that, despite the nature of longitudinal separation, its variation with time and the circumstances surrounding the detection and correction of observed degradations, any mathematical models would have to be based on the assumption that aircraft were operating in an unmonitored environment. This meant that the methods used assumed that, from entry of aircraft into the NAT Region and throughout their flight therein, ATC took no account of position reports and took no action to ensure the maintenance of proper longitudinal separation. An important finding at NAT SPG/17 (1980) was that when making a very cautious estimate of successful ATC intervention (95%) and applying this to the results for the unmonitored system, the estimated accident rate would not be greater than 0.06 per 10 million flying hours. This estimate was to be compared with the then prevailing target level

of safety for longitudinal risk of 0.2 accidents per 10 million flying hours, see *Remark 1* under the *NAT SPG/12 (31 May – 11 June, 1976)* heading in Section 5.3.3. The NAT SPG then felt that, after careful and objective assessment, the application of ten minutes longitudinal separation as specified would be safe and a (revised) application date of 26 November 1981 was agreed. Finally, at NAT SPG/18 (1981), after consideration of both practical considerations related to the use of 10 minutes longitudinal separation under specified conditions and certain mathematical-statistical aspects related to this separation, the NAT SPG confirmed that there were no practical objections to use this type of separation and agreed that the application date of 26 November 1981 for 10 minutes longitudinal separation agreed at NAT SPG/17 was to be maintained. See also (Harrison, 1986).

Following the reduction of the longitudinal separation to 10 minutes in the NAT Region on 26 November 1981, no new collision risk modelling work for the benefit of a further reduction was reported until the 29th Meeting of the NAT SPG in 1993. The United States' approach to longitudinal collision risk modelling was then presented to the NAT SPG during its Meetings in 1994 and 1995 and was subsequently reviewed, together with (Anderson, 1996b), by the United Kingdom in (Owens, 1996) presented at NAT SPG/32 (1996), see Section 1.2.4. This review led to an important change to the longitudinal collision risk model for the NAT, viz. that it should estimate the collision risk experienced by aircraft between waypoints. This change constitutes the starting point for the improved longitudinal collision risk modelling work performed by the United Kingdom to be described in this Subsection.

The United Kingdom's approach was developed under the auspices of the NAT MIG where it is recalled from the discussion under the *NAT SPG/33 (1997)* heading in Section 7.2.3 that, under Agenda Item 2.3, *Report of the NAT Implementation Management Group*, the NAT IMG (as a sub-group of the NAT SPG) had established a Mathematicians' Implementation Group (MIG) which would develop the necessary tools to carry out the safety assessments which were pre-requisites for future reductions in horizontal separation minima with the reductions in the longitudinal dimension being:

- Reduction of longitudinal standard/minimum from 10 to 7 minutes for same-direction traffic;
- Reduction of longitudinal standard/minimum from 15 to 10 minutes for intersecting tracks; and
- Further reduction longitudinal from 7 to 5 minutes for same-direction traffic.

NAT MIG/1- WP/1 ((Stilwell, 1997)) lists the following elements to be considered for the longitudinal collision risk model:

- Confirmation or development of performance criteria for:
 - Aircraft clock accuracy;
 - Longitudinal navigation performance;
 - Time precision in position reporting (rounding or truncating);
- Further development to the longitudinal collision risk model;
 - Relationship between time-keeping accuracy and navigation performance and the gain-loss distribution;
 - Controller intervention process;
 - Pilot and ATC procedures related to longitudinal performance;
- The effects of reduced longitudinal separations on lateral and vertical risk;
- The question of the need for a new TLS; and
- Verification of the operational effectiveness of changes to performance requirements and procedures.

The reader is referred to (Subsection 3, *Reductions in longitudinal separation minima*, of) Section 9 of (Moek, 2002b) for an “un-official” report on the 1st meeting of the NAT MIG.

As regards the TLS, recall from the discussion under the *NAT SPG/33 (1997)* heading in Section 7.2.3 again that it had been agreed that for planning purposes a TLS of 5×10^{-9} fatal accidents per flight hour would be used. That discussion also referred to a draft collision risk model, that allowed for an analytical assessment of the effects of lateral errors on the longitudinal separation of a pair of aircraft on intersecting tracks being developed.

This Subsection will focus on the development of the collision risk model in two parts, namely, firstly, the longitudinal collision risk model for same identical tracks, and, secondly, longitudinal collision risk on intersecting tracks. In addition, some longitudinal data-analysis studies will be briefly referenced in Section 7.2.5.4.

7.2.5.2 Further development to the longitudinal collision risk model for in-trail aircraft

The further development of the longitudinal collision risk model for aircraft on same identical tracks or in-trail aircraft is reviewed below by NAT MIG Meeting. From the 6th Meeting of the NAT MIG onwards, i.e. Section 7.2.5.2.5, operational longitudinal collision risk and monitoring of longitudinal collision risk have been addressed explicitly.

7.2.5.2.1 NAT MIG/2 (September, 1997)

A set of three working papers on longitudinal collision risk modelling for in-trail aircraft following the same flight path was presented at the 2nd Meeting of the NAT MIG, namely MIG/2-WP/1, MIG/2-WP/2 and MIG/2-WP/3.

MIG/2-WP/2 - Overview of longitudinal collision risk model and effects of delayed and missing waypoint reports (Thomas, 1997c):

MIG/2-WP/2 (Thomas, 1997c) began noting that NAT MNPS airspace is a monitored system but that, as recalled in the introduction above, the last used collision risk model treated it as an unmonitored system using data on initial longitudinal separation upon entry, and final separation upon exit, of a full crossing, together with a crude estimate of the probability of controller intervention failure in case of erosion of longitudinal separation. The need for a more realistic approach was established in (Owens, 1996) and agreed upon at NAT SPG/32 (1996), i.e. longitudinal collision risk between waypoints should be modelled. The remainder of MIG/2-WP/2 comprised two parts, namely:

- modelling the probability of longitudinal overlap based on waypoint position reports and forward estimates; and
- modelling ATC intervention.

Special emphasis was put in the first part on the effects of delayed or missing position reports.

Before proceeding with (Thomas, 1997c), recall that the probability of longitudinal overlap in the last-used longitudinal collision risk model of eq. (7.23) for a full NAT crossing was given by

$$\pi_x = \frac{2\lambda_x/\bar{x}}{T} \times \sum_m E_x(m) Q_x(m) \quad (7.20)$$

where

- $E_x(m)$ is the probability that the time reported by a typical aircraft at the beginning of the track differs from that of the next following aircraft (after adjusting for Mach number difference as appropriate) by m minutes, i.e. between $m - 1/2$ and $m + 1/2$;
- $Q_x(m)$ is the probability of separation loss of at least $m - 1/2$ minutes;
- $P_x(m)$ is the probability distribution of separation loss of m minutes, after adjusting for Mach number differences, i.e. between $m - 1/2$ and $m + 1/2$;

$$Q_x(m) = \sum_{v=m}^{\infty} P_x(v) \quad (7.17)$$

and, reversely, $P_x(m) = Q_x(m) - Q_x(m + 1)$.

The summation in eq. (7.20) took account of the standard practice within the NAT for aircraft flight crew to report actual and estimated waypoint arrival times to ATC as whole numbers of minutes through a process of either rounding or truncation of the “true” time. In WP/3 (Thomas, 1997a) developed a methodology for compensating for the effect of this rounding and/or truncation. Based on this methodology, (Thomas, 1997c) treated all reported actual and estimated waypoint arrival times as continuous variables, allowing the new formula for the probability of longitudinal overlap to be expressed in terms of an integral rather than a summation⁹⁷. It also made a distinction between actual (a), planned (p), and unplanned (u) quantities, where actual quantities were derived from position reports.

Thus, given an initial distribution $E_0^{(a)}(s)$ of actual aircraft separations, the distribution $E_j^{(a)}(s)$ of actual aircraft separations at the j -th waypoint can be calculated using the probability $Q_{j-1,j}^{(a)}(m)$ of a pair losing m or more minutes of separation between the $(j - 1)^{\text{th}}$ and the j^{th} waypoints, viz.

$$E_j^{(a)}(s) = \int_k E_{j-1}^{(a)}(s + k) Q_{j-1,j}^{(a)}(k) dk \quad (7.83)$$

Notice that the convolution type of integral in eq. (7.83) suggests that the distributions $E_j^{(a)}(s)$, $E_{j-1}^{(a)}(s)$, and $Q_{j-1,j}^{(a)}$ are probability densities, which makes the terminology of “a pair losing m or more minutes of separation” void. The use of the argument $s + k$ of $E_{j-1}^{(a)}(s + k)$ suggests that a positive change in separation actually means a loss of separation. The probability $Q_{j-1,j}^{(a)}(m)$ of a pair actually losing m or more minutes of separation between the $(j - 1)^{\text{th}}$ and the j^{th} waypoints can be expressed in terms of unplanned and planned changes in separation, $Q_{j-1,j}^{(u)}(q)$ and $P(m)$ respectively, as another convolution type of integral,

$$Q_{j-1,j}^{(a)}(m) = \int_q Q_{j-1,j}^{(u)}(q) P_{j-1,j}(m - q) dq \quad (7.84)$$

where, in order to be consistent in notation, $P_{j-1,j}(m)$ should have been denoted $Q_{j-1,j}^{(p)}(m)$ on the understanding that all quantities represent probability densities rather than probability distributions, distribution functions, or complementary distribution functions.

⁹⁷ The probability distribution symbols used in the various formulae should thus be interpreted as probability densities rather than probability distributions.

Alternatively, the distribution $E_j^{(a)}(s)$ of actual aircraft separations at the j^{th} waypoint can be expressed in terms of planned separation and unplanned changes in separation, i.e.

$$E_j^{(a)}(s) = \int_k E_j^{(p)}(s + k) Q_{j-1,j}^{(u)}(k) dk \quad (7.85)$$

Returning to the first expression for $E_j^{(a)}(s)$, eq. (7.83), together with eq. (7.84), (Thomas, 1997c) addressed the calculation of $Q_{j-1,j}^{(u)}(q)$ and $P_{j-1,j}(m - q) = Q_{j-1,j}^{(p)}(m)$, i.e. the probability distributions/densities of the unplanned and planned changes in separation respectively between the $(j - 1)^{\text{th}}$ and the j^{th} waypoints. The planned change in separation is given by

$$\text{planned change in separation} = [\text{planned separation at waypoint } j] - [\text{planned separation at waypoint } (j - 1)] \quad (7.86)$$

or, in formula,

$$\text{planned change in separation} = (s_j - s_{j-1})_e \quad (7.87)$$

with $\frac{s_j}{s_{j-1}}$ denoting separation at waypoint $\frac{j}{j} - 1$ and the additional subscript e denoting that the planned separations are based on the waypoints' forward estimates. These forward estimates can come either from pilot forward estimates or from ATC. Eq. (7.87) corresponds with eq. (2.4) of (Thomas, 1997c). (Thomas, 1997c) then explained that pilot reported estimates are based on current meteorological information, aircraft real-time airspeeds and Mach number. ATC use, however, their own estimates for predicting future separation, which tend to be more reliable as they use weather information supplied twice-daily by the Met Office, and so can make allowance for predictions regarding changing wind speed and direction along the inter-waypoint track. Hence, ATC estimates will be used unless these are not available in which case pilot reported estimates will be used.

Consider now the unplanned change in separation. It holds that

$$\text{planned separation at waypoint } j = \text{planned separation at waypoint } (j - 1) + \text{planned change in separation} \quad (7.88)$$

and, similarly,

$$\text{reported separation at waypoint } j = \text{reported separation at waypoint } (j - 1) + \text{reported change in separation} \quad (7.89)$$

Subtraction of eq. (7.88) from eq. (7.89) gives

$$\begin{aligned} & -\text{planned separation at waypoint } j + \text{reported separation at waypoint } j = \\ & -\text{planned separation at waypoint } (j - 1) + \text{reported separation at waypoint } (j - 1) - \\ & \quad \text{planned change in separation} + \text{reported change in separation} \end{aligned} \quad (7.90)$$

or, defining

$$\text{unplanned change in separation} = \text{reported change in separation} - \text{planned change in separation} \quad (7.91)$$

$$\begin{aligned} & -\text{planned separation at waypoint } j + \text{reported separation at waypoint } j = \\ & -\text{planned separation at waypoint } (j - 1) + \text{reported separation at waypoint } (j - 1) + \\ & \quad \text{unplanned change in separation} \end{aligned} \quad (7.92)$$

which may be rearranged to give

$$\begin{aligned} \text{unplanned change in separation} &= -\text{planned separation at waypoint } j + \text{planned separation at waypoint } (j - 1) \\ &+ \text{reported separation at waypoint } j - \text{reported separation at waypoint } (j - 1) \end{aligned} \quad (7.93)$$

An unplanned change in longitudinal separation is usually referred to as gain/loss. Using this terminology, eq. (7.93) can be expressed in formula as

$$\frac{\text{gain}}{\text{loss}} = \text{unplanned change in separation} = -(s_j - s_{j-1})_e + (s_j - s_{j-1})_r \quad (7.94)$$

with $\frac{s_j}{s_{j-1}}$ again denoting separation at waypoint $\frac{j}{j} - 1$ and the additional subscripts r and e denoting that the pertinent separations are based on aircraft position reports and planned/forward estimates respectively. On the right side of eq. (7.94), the difference of the first two terms equals the planned change in separation defined by eq. (7.87). Combining the terms on the right side of eq. (7.93) in a different way gives the following alternative gain/loss formula:

$$\frac{\text{gain}}{\text{loss}} = \text{unplanned change in separation} = (s_r - s_e)_j - (s_r - s_e)_{j-1} \quad (7.95)$$

Eqs. (7.94) and (7.95) correspond with eq. (2.3) of (Thomas, 1997c).

(Thomas, 1997c) then used eqs. (7.83) and (7.85) to calculate the probability of total loss of separation by the j^{th} waypoint, i.e.

$$E_j^{(a)}(0) = \int_k E_{j-1}^{(a)}(k) Q_{j-1,j}^{(a)}(k) dk \quad (7.96)$$

$$E_j^{(a)}(0) = \int_k E_j^{(p)}(k) Q_{j-1,j}^{(u)}(k) dk \quad (7.97)$$

Notice that the quantities on the left sides of eqs. (7.96) and (7.97) denote effectively the probability density function of the actual separation at the j -th waypoint for a separation of zero minutes. This can be used to calculate the probability of the actual separation at the j^{th} waypoint being less in magnitude than the time equivalent of an aircraft length and also to calculate the probability of the actual separation at the j^{th} waypoint being less than the time equivalent of an aircraft length (including negative separation values). All of these cases of loss of longitudinal separation generate an amount of $2\lambda_x/\overline{|\dot{x}|}$ longitudinal overlap time.

It is noted in (Thomas, 1997c) that it is not necessary to calculate $Q_{j-1,j}^{(\cdot)}(k)$ directly for each pair of waypoints, provided it has been calculated for one pair of waypoints (preferably the pair of waypoints with the largest number of valid aircraft pairs) using the ratio of the great circle distances between the constituent waypoints. The following approximation was proposed

$$Q_{l-1,l}^{(\cdot)}(k) \approx Q_{j-1,j}^{(\cdot)}\left(k \times \frac{d_{j-1,j}}{d_{l-1,l}}\right) \quad (7.98)$$

where $d_{j-1,j}$ and $d_{l-1,l}$ denote the along-track distances in nautical miles between the respective pairs of waypoints $j-1, j$ and $l-1, l$.

(Thomas, 1997c) subsequently analyzed the effect of delayed and missing waypoint reports on the probability of total loss of separation, noting that both situations affect the possibility of intervening in case of erosion of longitudinal separation. As a result, longitudinal collision risk will exist over a longer period than the nominal flying time between two successive waypoints. Any time delay of either aircraft in making position reports at either waypoint needs to be accounted for because the separation at each waypoint can only be calculated once position reports for both aircraft are available. The effect of delayed waypoint reports was modelled as follows.

Let $\Delta T(j, k)$ be the time delay of the k -th aircraft in a pair making its position report for the j -th waypoint. Then the effective, or net, delay for the pair (considered as a unit) may be represented by

$$\Delta T_{j-1,j} = \max\{\Delta T(j, 1), \Delta T(j, 2)\} - \min\{\Delta T(j-1, 1), \Delta T(j-1, 2)\} \quad (7.99)$$

See (Thomas, 1997c) for an example. Thus, the effective time over which collision risk is to be calculated between the waypoint pair $j-1, j$ is $\Delta T_{j-1,j}$ minutes larger than it would otherwise be. The probability $P(\Delta T_{j-1,j})^{98}$ of a net time delay of $\Delta T_{j-1,j}$ between the waypoint pair $j-1, j$ was then given by

$$P(\Delta T_{j-1,j}) = \int_0^\infty P_{\min}(t) P_{\max}(t + \Delta T_{j,j-1}) dt \quad (7.100)$$

where

$$P_{\max}(t) = 2P_a(t)^{99} \int_t^\infty P_a(\tau) d\tau - P_a(t)^2 \quad (7.101)$$

$$P_{\min}(t) = 2P_a(t) \int_{\tau=t}^\infty P_a(\tau) d\tau - P_a(t)^2 \quad (7.102)$$

⁹⁸ This probability is denoted $D(\Delta T_{j-1,j})$ in (Thomas, 1997c).

⁹⁹ This probability is denoted $D_a(t)$ in (Thomas, 1997c).

and $P_a(t)$ is the probability of an individual aircraft making a position report after a delay of t minutes.

By analogy with eq. (7.98), if the net time delay of an aircraft pair in making position reports for consecutive waypoints $j - 1$ and j on their shared track is $\Delta T_{j-1,j}$ minutes, the original gain/loss $Q_{j-1,j}^{(\cdot)}(m)$ is increased to approximately

$$Q_{j-1,j}^{(\cdot)}\left(m \frac{d_{j-1,j}}{d_{j-1,j} + 9.7\bar{M}\Delta T_{j-1,j}}\right) \quad (7.103)$$

where $\bar{M}$ is the average Mach number of aircraft within NAT MNPS airspace and the speed of sound was taken as 582 knots, which results in the coefficient of 9.7 in eq. (7.103). Since $Q_{j-1,j}^{(\cdot)}(m)$ is a non-increasing function of the separation m , eq. (7.103) leads to an increase in the value of $Q_{j-1,j}^{(\cdot)}(m)$ due to the net time delay $\Delta T_{j-1,j}$.

Finally, eq. (7.96) for the probability of total loss of separation between the $(j - 1)^{\text{th}}$ and j^{th} waypoints was generalized to the case of possibly delayed waypoint position reports as

$$E_j^{(a)}(0) = \int_{\Delta T_{j-1,j}}^{\infty} P(\Delta T_{j-1,j}) \int_k^{\infty} E_{j-1}^{(\cdot)}(k) Q_{j-1,j}^{(\cdot)}\left(k \frac{d_{j-1,j}}{d_{j-1,j} + 9.7\bar{M}\Delta T_{j-1,j}}\right) dk d\Delta T_{j-1,j} \quad (7.104)$$

For the case of one aircraft in a pair failing to supply a position report at the j^{th} waypoint, or alternatively failing to supply a forward estimate at the $(j - 1)^{\text{th}}$ waypoint for its arrival time at the j^{th} waypoint, it was proposed to approximate the original gain/loss $Q_{j-1,j}^{(\cdot)}(m)$ by

$$Q_{j-1,j}^{(\cdot)}\left(m \frac{d_{j-1,j}}{d_{j-1,j} + d_{j,j+1}}\right) \quad (7.105)$$

(Thomas, 1997c) concluded with a section on modelling ATC intervention, noting that, traditionally, the probability of ATC intervention to prevent an overtake occurring, PI say, was extremely difficult to determine because of the paucity of available relevant data. A surrogate that was used in the past 15-minute longitudinal separation standard environment was the probability of ATC intervention to correct an infringement of the standard/minimum of 3 minutes, denoted $PI12$. Since $PI12 < PI$, this approach provided a cautious estimate $1 - PI12 > 1 - PI$ of ATC not intervening to prevent an overtake. It was noted that in the 10-minute longitudinal separation standard/minimum environment due to increases in traffic levels infringements of the standard/minimum might be occurring more frequently, resulting in ATC interventions occurring more frequently and thus the probability of ATC intervention being able to be estimated more accurately from survey data. Otherwise, a surrogate, say $PI7$ or $PI8$, similar to $PI12$ would still have to be used. The section on modelling ATC intervention concluded with a brief description of Shanwick ATC and the Flight Data Processing System (FDPS) in place at Shanwick. A thorough understanding of the operational procedures and tolerance parameters of the FDPS system is concluded to be necessary for the benefit of successful modelling of the ATC intervention capability.

MIG/2-WP/3: Effect of rounding/truncation and clock-setting errors in longitudinal collision risk modelling:

MIG/2-WP/3 (Thomas, 1997a) comprised the following sections:

1. Effect of rounding/truncation errors on separation times;
2. Effect of rounding/truncation errors on gain/loss data;
3. Effect of clock-setting errors; and
4. Application to collision risk analysis.

1. Effect of rounding/truncation errors on separation times

MIG/2-WP/3 (Thomas, 1997a) began noting that it was known that there is no uniform practice of either rounding to the nearest minute or truncating¹⁰⁰. Given a nominal reported time in hours and minutes, the probability distribution of the true time in hours, minutes and seconds was calculated under the assumption that rounding and truncation are equally likely, i.e.

$$p(\text{rounding}) = p(\text{truncation}) = \frac{1}{2} \quad (7.106)$$

and that under rounding all values of the difference in seconds j in $[-30, 30)$ are equally likely as well as that under truncation all values of the difference in seconds j in $[0, 60)$ are equally likely. This calculation resulted in the following probability distribution (actually probability density $pt(j), j \in [-30, 60)$) for the true time of a position report:

$$p(\text{true time} = \text{nominal time} + j \text{ seconds}) = pt(j) = \begin{cases} \frac{1}{120} & \text{for } j \text{ in } [-30, 0) \text{ and } [30, 60) \\ \frac{1}{60} & \text{for } j \text{ in } [0, 30) \\ 0 & \text{otherwise} \end{cases} \quad (7.107)$$

Denoting the true position reporting times of a pair of leading and following aircraft as true time L = nominal time $L + j_L$ and true time F = nominal time $F + j_F$ with j_L and j_F being the rounding/truncation errors (RTEs) in seconds, the actual/true reported separation s was expressed as

$$s = \text{true time } F - \text{true time } L = (\text{nominal time } F - \text{nominal time } L) + (j_F - j_L) \quad (7.108)$$

with the range of the rounding/truncation error difference $j_F - j_L$ being the time interval from -90 to +90 seconds. The probability distribution (actually probability density $ps(j), j \in (-90, 90)$) of the difference $j_F - j_L$ was then calculated by convolution of the probability distributions of eq. (7.107) for j_L and j_F .

As follows immediately from eq. (7.108), the effect of the rounding/truncation error difference $j_F - j_L$ on the actual/true reported separation s depends on the probability distribution of the reported separation, nominal time $F - \text{nominal time } L$. Correction of the probability distribution $E(s)$ of the nominal reported separation s for the effect of RTEs leads to a new probability distribution, $Et(s)$, for the RTE corrected nominal reported separation s .

The following formula for the relationship between the probability that the RTE corrected nominal separation is s minutes and j seconds, $Et(s + j)$, given that the probability that the nominal reported separation is s minutes, $E(s)$, was derived:

¹⁰⁰ It was not known either whether successive reports from the same aircraft would use consistent rounding or consistent truncation. This uncertainty was not accounted for in (Thomas, 1997a).

$$Et(s+j) = \begin{cases} E(s-1)ps(j+60) + E(s)ps(j) + E(s+1)ps(j-60), & j \in [0,30) \\ E(s)ps(j) + E(s+1)ps(j-60), & j = 30 \\ E(s)ps(j) + E(s+1)ps(j-60) + E(s+2)ps(j-120), & j \in (30,60) \end{cases} \quad (7.109)$$

2. Effect of rounding/truncation errors on gain/loss data

Section 2 of MIG/2-WP/3 (Thomas, 1997a) examined the effect of RTEs on gain/loss data, i.e. unplanned changes in separation. Based on (Thomas, 1997c), eq. (7.93) above defined the unplanned change in separation in words and was followed by two alternative gain/loss formulae in eqs. (7.94) and (7.95). The same formulae were used in (Thomas, 1997a) for a pair of waypoints i and $i+1$. Continuing with a pair of waypoints $j-1$ and j rather than i and $i+1$, it holds that

$$\frac{gain}{loss} = (s_j - s_{j-1})_r - (s_j - s_{j-1})_e \quad (7.94)$$

$$\frac{gain}{loss} = (s_r - s_e)_j - (s_r - s_e)_{j-1} \quad (7.95)$$

where s_j denotes the longitudinal separation between a successive pair of aircraft in minutes, i.e. not corrected for RTEs, the subscript r denotes that the separation is based on aircraft reported times and the subscript e denotes that the separation is planned based on forward estimates.

An expression was then given for the probability that the RTE error in a difference of separations, e.g. $(s_r - s_e)_{j-1}$, is k , viz.

$$pc(k) = \int_i^{\square} ps(i)ps(i+k)di \quad (7.110)$$

where the range of i is maximal such that i and $i+k$ are always in the interval $(-90,90)$ and another expression was given for the probability that the RTE error in a difference of differences of separations, e.g. $(s_r - s_p)_j - (s_r - s_p)_{j-1}$ is l , $l \in (-360,360)$, viz.

$$pg(l) = \int_k^{\square} pc(k)pc(k+l)dk \quad (7.111)$$

where the range of k is maximal such that k and $k+l$ are both always in the interval $(-180,180)$. Eqs. (7.110) and (7.111) are of the convolution-integral type with the main problem being the determination of the appropriate ranges for the variables l , k , and i .

The probability distribution $pg(l)$ of the RTE error in a difference of differences of separations was then used to calculate the probability distribution of the RTE corrected gain loss distribution. The following is based on (Thomas, 1997a) but uses the notation developed at NAT SPG/14 (1978) (for the benefit of the reduction of the longitudinal separation standard/minimum at the time) and used earlier in this Document. Recall that the gain loss distribution was denoted $Q_x(m)$ with

$$Q_x(m) = \sum_{v=m}^{\infty} P_x(v) \quad (7.17)$$

and $P_x(v)$ denoting the probability distribution of separation loss of v minutes, after adjusting for Mach number differences, i.e. between $v - 1/2$ and $v + 1/2$. Reversely,

$$P_x(m) = Q_x(m) - Q_x(m+1) \quad (7.112)$$

Denoting the probability of a “true” gain of G minutes g seconds where $g \in [0,60)$, $P_{xPG}(G+g)$ and denoting the probability of a “true” loss of G minutes g seconds where $g \in [0,60)$, $P_{xNG}(G+g)$, (Thomas, 1997a) provided the following formulae for the respective probabilities:

$$P_{xPG}(G+g) = \sum_{k=-5}^6 P_x(G+k)pg(g-60k), g \in [0,60) \quad (7.113)$$

and

$$P_{xNG}(G+g) = \sum_{k=-5}^6 P_x(-G+k-1)pg(60-g-60k), g \in [0,60) \quad (7.114)$$

Again, eqs. (7.113) and (7.114) are of the convolution type summation.

Finally, $Qt(G+g)$, the probability of an actual loss of separation of G minutes g seconds or more, was given by

$$Qt(G+g) = \int_{k=G+g}^{\infty} P_{xNG}(k)dk \quad (7.115)$$

and

$Qt(-(G+g))$, the probability of an actual gain of separation of G minutes g seconds or more, was given by

$$Qt(-(G+g)) = \int_{k=G+g}^{\infty} P_{xPG}(k)dk \quad (7.116)$$

3. Effect of clock-setting errors

Section 3 of MIG/2-WP/3 (Thomas, 1997a) examined the effect of clock-setting errors (CSEs) on separation times where it was deduced from eqs. (7.110) and (7.111) that clock-setting errors have no effect on gain/loss values $Q_x(m)$. It was noted that clock-setting errors once made do not change during a flight and so should be corrected for only once.

Consider a leading and a following aircraft forming a valid pair and assume that both may have a CSE of size c_L and c_F respectively. The separation s between the aircraft as deduced from the respective position reports is then affected by an amount $c = c_L - c_F$. Let the probability of an aircraft clock being set to j seconds in excess of true time be denoted $pc(j)$. Then,

$$pcc(c) = p(\text{true sep} = \text{nominal sep} + c \text{ seconds}) = \int_c^{\infty} pc(k)pc(k+c)dk \quad (7.117)$$

(yet another convolution type of integral) where the integrand $pc(k)$ is given by eq. (7.110).

The effect of clock-setting errors was then added to the separation times already corrected for rounding/truncation errors, i.e. to the probability distribution $Et(s)$, to give the probability distribution $Etc(T)$ of separation times corrected for both RTEs and CSEs by

$$Etc(T) = \int_c^{\infty} Et(T+c)pcc(c)dc \quad (7.118)$$

4. Application to collision risk analysis.

As recalled at the beginning of the review of (Thomas, 1997c) earlier in this Subsection, the probability of longitudinal overlap in the last-used longitudinal collision risk model of eq. (7.23) at NAT SPG/14 (1978) was given by

$$\pi_x = \frac{2\lambda_x/|\bar{x}|}{T} \times \sum_m E_x(m)Q_x(m) \quad (7.20)$$

where, with m in minutes, $E_x(m)$ denoted the probability distribution of the entry separation times and $Q_x(m)$ denoted the probability of separation loss of at least $m - 1/2$ minutes. In its 4th and last Section, (Thomas, 1997a) presented the following continuous-time version of the likelihood of longitudinal overlap $\sum_m E_x(m)Q_x(m)$ based on separation times and gain/loss data corrected for RTEs and CSEs,

$$\int_0^\infty Etc(T)Qt(T)dT \quad (7.119)$$

with $Etc(T)$ given by eq. (7.118) and $Qt(T)$ given by eqs. (7.115) and (7.116). A full expression for π_x , however, was not given.

MIG/2-WP/6: Longitudinal collision risk model – A note on the calculation of wind components in the NAT:

As the last of three NAT MIG/2 working papers on longitudinal collision risk modelling to be reviewed here, MIG/2-WP/6 (Thomas, 1997b) documented a method that was used in the past to correct gains/losses in separation between pairs of aircraft for planned changes in separation due to differences in assigned Mach speeds (Penna, 1977). It highlighted a number of shortfalls in the method and pointed to the need to adopt a different method, e.g. the one used in the more recent Canadian study (Unknown, 1994b).

The method used in the past involved converting the Mach number to a groundspeed, thus allowing for any along-track wind components affecting the aircraft, and was described as follows in MIG/2-WP/6 (Thomas, 1997b). Let the predicted and actual times (Tp and Ta) for an aircraft x to cross the ocean be $Tp(x)$ and $Ta(x)$ respectively. Given two aircraft x (leader) and y (follower) travelling at speeds $Mach(x)$ and $Mach(y)$ along the same track at the same flight level, and subjected to the same along-track wind component w (knots), the actual crossing time $Ta(x)$ of aircraft x can be used to predict the time for the following aircraft y to make the crossing, $Tp(y)$, using the formula

$$Tp(y) = Ta(x) \times \frac{Mach(x)+w/582}{Mach(y)+w/582} \quad (7.120)$$

where the number 582 denotes the speed of sound (knots) in the ICAO standard atmosphere corresponding to an air temperature of -49.3°C. The time correction for aircraft y was then taken as $Ta(y) - Tp(y)$. It is not immediately clear, however, what this time correction actually corrects for. In fact, MIG/2-WP/6 (Thomas, 1997b) concluded that it was unclear how eq. (7.120) had been used in the study of (Penna, 1977), whilst noting that a gain/loss calculation would also require the time correction $Ta(x) - Tp(x)$ for aircraft x , i.e. would require the predicted crossing time $Tp(x)$ for aircraft x since gain/loss, i.e. unplanned change in separation, is calculated by means of

$$\frac{gain}{loss} = [Ta(y) - Ta(x)] - [Tp(y) - Tp(x)] \quad (7.121)$$

Cf. eqs. (7.94) whilst realizing that the time variables on the right side of eq. (7.121) denote crossing times, i.e. $Ta(y) - Ta(x)$ corresponds to $(s_j - s_{j-1})_r$ and $Tp(y) - Tp(x)$ corresponds to $(s_j - s_{j-1})_p$ for a waypoint pair $(j - 1, j)$ with waypoint $j - 1$ defining the entry point of the oceanic crossing and waypoint j defining the exit point of the crossing.

Following some discussion on the speed of sound and air temperature/altitude in the ICAO standard atmosphere and in non-standard atmospheres, (Rome & Krishnan, 1990) focussed on the wind component w . For a given aircraft, w was estimated by

$$w = \text{true ground speed} - \text{nominal ground speed} \quad (7.122)$$

where

$$\text{true ground speed (kts)} = \frac{\text{distance between reporting points (NM)}}{\text{elapsed time between reporting points (hours)}} \quad (7.123)$$

and the nominal ground speed is that calculated directly from the assigned Mach number and assigned flight level. It was noted that it had been found in the course of the investigation that the above calculation of w resulted in w varying considerably across the NAT OTS in each of the three dimensions. This led to the conclusion that the use of a particular estimated wind component w in the calculation of estimated arrival times at waypoints was only useful (and only appropriate) along the particular track and flight level for which w was estimated. The calculation of w from aircraft position reports and estimates and assigned Mach number was then argued to induce a possible error of approximately ± 16 kts compared to a typical value of w of the order of 50 kts in either direction (head wind or tail wind). The use of w in gain/loss calculations necessarily introduces a corresponding large uncertainty in the results of such calculations and must, therefore, be of very dubious value.

7.2.5.2.2 NAT MIG/3 (1998)

Unfortunately, no documentation was available to the authors on the longitudinal collision risk model development for same-direction traffic at the 3rd Meeting of the NAT MIG. It can be inferred from the documentation available from subsequent meetings, that at least three working papers were presented at the NAT MIG/3 Meeting dealing with longitudinal separation, namely MIG/3-WP/5, MIG/3-WP/7, and MIG/3-WP/9.

7.2.5.2.3 NAT MIG/4 (September, 1998)

Another set of three working papers on longitudinal collision risk modelling for in-trail aircraft was presented at the 4th Meeting of the NAT MIG, namely MIG/4-WP/8, MIG/4-WP/9 and MIG/4-WP/10.

MIG/4-WP/10: Longitudinal collision risk model – Status report:

MIG/4-WP/10 (Thomas, 1998a) provided a report on the status of the longitudinal collision risk model by September 1998, building on MIG/2-WP/2 (Thomas, 1997c) and MIG/2-WP/3 (Thomas, 1997a). The form of the longitudinal collision risk model presented in eq. (1) of MIG/4-WP/8 is the same as that of eq. (7.23) of this document, but with a different formula for the calculation of the probability of longitudinal overlap (recall eq. (7.20)), i.e. for the proportion of the total flight time in a given period of time during which

longitudinal overlap exists between a pair of in-trail aircraft. The proposed modified form of π_x takes account of pilot position reports and FDPS forward estimates and improved modelling of ATC intervention, resulting in:

$$N_{ax} = 2 \times 10^7 \times \pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.124)$$

with

$$\pi_x = \frac{2\lambda_x/|\bar{x}|}{T} \times \sum_{j=1}^n Etc_j^{(a)}(0) \quad (7.125)$$

and

$$Etc_j^{(a)}(m_j) = \int_{m_{j-1} > -m_j}^{\infty} Etc_j^{(p)}(m_{j-1} + m_j) Qt_{j-1,j}(m_{j-1}) dm_{j-1}, j = 1, \dots, n \quad (7.126)$$

and

$$Etc_j^{(p)}(m_j) = \int_{m_{j-1} > -m_j}^{\infty} [1 - pi(m_{j-1} + m_j)] Etc_{j-1}^{(a)}(m_{j-1} + m_j) Rt_{j-1,j}(m_{j-1}) dm_{j-1}, j = 1, \dots, n \quad (7.127)$$

and with the superscripts “a” and “p” referring again to “actual” and “planned” quantities.

The variable $Etc(m_j), j = 0, \dots, n$, denotes the probability distribution of separations at waypoint j , with $j = 0$ and $j = n$ being the MNPS airspace entry and exit points respectively, after correcting for rounding/truncation and clock-setting errors as set out in MIG/2-WP/3 (cf. eq. (7.119)). $Qt_{j-1,j}(m_{j-1})$ denotes the unplanned gain-loss probability density function for the route segment between waypoints $j - 1$ and j after correction for rounding/truncation errors as described in MIG/2-WP/3 and $Rt_{j-1,j}(m_{j-1})$ denotes the planned gain-loss probability density function for the route segment between waypoints $j - 1$ and j after correction for rounding/truncation errors as described also in MIG/2-WP/3. $Rt_{j-1,j}(m_{j-1})$ can be related to the probability distribution of Mach number differences within pairs, $p_M(\Delta M)$.

Remark

Notice that the model for π_x in eqs. (7.125) – (7.127) does not (yet) account for delayed or missing position reports as modelled by eqs. (7.104) and (7.105) based on (Thomas, 1997c). See, however, the sixth next paragraph below, particularly eqs. (7.129) and (7.130), which describes a new approach to modelling the effect of delayed or missing position reports developed in MIG/4-WP/10 (Thomas, 1998a). (No explanation for the new approach is given in MIG/4-WP/10, but more information may have been presented at the previous NAT MIG Meeting of which the authors have no documentation at their disposal.)

As explained in MIG/4-WP/10, eq. (7.125) shows that the longitudinal overlap probability is calculated as the probability of an actual separation of zero occurring for each inter-waypoint leg of the oceanic crossing, with all quantities corrected for RTE and/or CSE errors. Eq. (7.126) shows that the actual separation at a particular waypoint is calculated using the planned separation for that waypoint, $Etc_j^{(p)}(m_{j-1} + m_j)$, together with

the probability of an unplanned loss of separation of a given amount occurring between the previous waypoint and the current one, $Qt_{j-1,j}(m_{j-1})$. Eq. (7.126) is the RTE and CSE corrected version of eq. (7.85) described earlier in Section 7.2.5.2.1 under the MIG/2-WP/2 (Thomas, 1997c) heading. Finally, eq. (7.127) shows that the planned separation at a particular waypoint is calculated using the actual separation at the previous waypoint, $Etc_{j-1}^{(a)}(m_{j-1} + m_j)$, together with the probability of there being a planned gain/loss of separation of a given amount between the previous waypoint and the current one, $Rt_{j-1,j}(m_{j-1})$. In addition, the function $pi(s)$ (with s continuous) represents the probability of successful ATC intervention at a separation of s (with s continuous).

The function $pi(s)$ was stated to be able to be derived from the function $PI(s)$ which represents successful intervention at an assumed (by the controller and FDPS) separation of s (whole) minutes as given in NAT MIG/3-WP/5. Unfortunately, that working paper was not available to the authors of this Document and thus the relationship between $pi(s)$ and $PI(s)$ cannot be specified here. The latter function, however, was defined in MIG/4-WP/10 as

$$PI(s) = \sum_{\Delta M} PI_M(\bar{s}\Delta M - s) p_M(\Delta M) \quad (7.128)$$

where $\bar{s}$ is the minimum legal separation for a pair of aircraft having Mach number difference ΔM , $p_M(\Delta M)$ is the probability distribution of Mach number differences between pairs of aircraft, and $PI_M(s)$ is the probability of ATC intervention if minimum legal separation is violated by s minutes and where it was noted that unsuccessful intervention was not considered, i.e. if ATC intervenes, then the intervention is assumed to be successful.

In applications, the model calculations would proceed as follows. Put $j = 1$ and consider the RTE and SCE error corrected distribution, $Etc_0^{(a)}(m_0)$, of the actual separations m_0 at the entry point of the oceanic air route. The planned separation¹⁰¹ at the first en-route waypoint can then be calculated as the sum of the actual separation at the entry point and the planned gain/loss between the entry point and the first en-route waypoint ($s_1^{(p)} = s_0^{(a)} + gl_{0,1}^{(p)}$, say) and the distribution, $Etc_1^{(p)}(m_1)$ of the planned separation at waypoint 1 is calculated by means of convolution of the probability distribution $Etc_0^{(a)}(m_0)$ of the actual separation at the entry point and the distribution, $Rt_{0,1}(m_0)$, of planned changes of separation (gain/loss) between the route's entry point and its first en-route waypoint (eq. (7.127)).

The actual separation at the first en-route waypoint can then be calculated as the sum of the planned separation at the first waypoint and the unplanned gain/loss between the entry point and the first en-route waypoint ($s_1^{(a)} = s_1^{(p)} + gl_{0,1}^{(u)}$, say) and the distribution, $Etc_1^{(a)}(m_1)$ of the actual separation at waypoint 1 is calculated by means of convolution of the probability distribution $Etc_1^{(p)}(m_1)$ of the planned separation at the first waypoint and the distribution, $Qt_{0,1}(m_0)$, of unplanned changes of separation (gain/loss) between the route's entry point and its first en-route waypoint (eq. (7.126)). $Etc_1^{(a)}(0)$ can then be calculated and the process repeated for $j = 2, \dots, n$, i.e. for the second up to the last inter-waypoint segments.

¹⁰¹ From here on in this paragraph, the pertinent RTE and CSE error corrections will no longer be referenced in words.

Following the presentation of the above formulae for the probability of longitudinal overlap parameter π_x of the collision risk model, MIG/4-WP/10 provided some further discussion on a variety of factors related to the modelling, namely: incorporation of position reports, effect of en-route position reports and delays in their receipt, FDPS estimates, rounding/truncation, clock setting, and manual reversion.

Formulae were provided to correct the gain/loss probability distributions $Qt_{j-1,j}(m)$ and $Rt_{j-1,j}(m)$ for delays in the receipt of position reports. The formulae utilized a probability distribution $P_a(t)$ of an individual aircraft making a position report after a delay of t minutes to calculate the probability distribution $P(\Delta T_{j-1,j})^{102}$ of the net time delay of $\Delta T_{j-1,j}$ between the waypoint pair $j-1, j$ defined by eq. (7.99). Cf. eqs. (7.100) – (7.102) for the calculation of the probability distribution $P(\Delta T_{j-1,j})$. The following formula was then derived for the gain/loss distribution corrected for delayed waypoint reports¹⁰³,

$$\tilde{Q}t_{j-1,j}(m) = \int_{\Delta T_{j-1,j}} P(\Delta T_{j-1,j}) Qt_{j-1,j} \left(m \left(1 + \frac{\Delta T_{j-1,j}}{T_{j-1,j}} \right) \right) d\Delta T_{j-1,j} \quad (7.129)$$

where $T_{j-1,j}$ denotes the average crossing time between waypoints $j-1$ and j . Notice that $Qt_{j-1,j}(m)$ denotes the gain/loss distribution $Q_{j-1,j}$ corrected for rounding and truncation errors (RTEs) and that $\tilde{Q}t_{j-1,j}(m)$ thus denotes the gain/loss distribution $Q_{j-1,j}$ corrected for both RTEs and delayed waypoint reports. An analogous formula was provided for $Rt_{j-1,j}(m)$, viz.

$$\tilde{R}t_{j-1,j}(m) = \int_{\Delta T_{j-1,j}} P(\Delta T_{j-1,j}) Rt_{j-1,j} \left(m \left(1 + \frac{\Delta T_{j-1,j}}{T_{j-1,j}} \right) \right) d\Delta T_{j-1,j} \quad (7.130)$$

Thus, time delay effects may be incorporated into the longitudinal collision risk model by substitution of $\tilde{Q}t_{j-1,j}(m)$ and $\tilde{R}t_{j-1,j}(m)$ defined by eqs. (7.129) and (7.130) for $Qt_{j-1,j}(m)$ and $Rt_{j-1,j}(m)$ into eqs. (7.126) and (7.127).

As regards *Manual reversion*, it was assumed that its principal effect is to increase ATC loop times, as a result of controllers having to perform manual calculations to check for current or future conflicts, and to find resolutions if necessary. In addition aircraft position reports would have to be supplied to the controllers manually. Consequently, the time-delay probability density $P(\Delta T_{j-1,j})$ was modified to

$$0.996P(\Delta T_{j-1,j}) + 0.004P_{MR}(\Delta T_{j-1,j}) \quad (7.131)$$

where FDPS availability was assumed to be 99.6% and $P_{MR}(\Delta T_{j-1,j})$ is the probability density function for time delays under manual reversion.

MIG/5-WP/5 (Thomas, 1999c) concluded with a brief discussion on two problem areas, namely closing speeds in a 7-minute environment, and waypoint issues (inter-waypoint distance as a function of latitude difference and longitude difference).

¹⁰² This probability is denoted $D(\Delta T_{j-1,j})$ in MIG/4-WP/10.

¹⁰³ The notation used in eq. (7.129) has been adapted slightly from MIG/4-WP/10.

MIG/4-WP/9: Longitudinal issues – discussion paper

The issues raised in MIG/4-WP/9 (Thomas, 1998b) are subdivided into three sections, namely data collection issues, modelling issues, and crossing track issues. The *Data collection issues* section addresses gain/loss data sources as well as clock-setting data. Although the data collection issues proper fall outside the scope of this Document, one element is worth mentioning, viz. the calculation of gains/losses from pilot reports of arrival times at the en-route waypoints and forward estimates. Three possible sources of forward estimates are listed, namely:

- (a) Pilot (FMS) estimates of arrival time at next waypoint contained in position reports;
- (b) FDPS-calculated planned arrival times; and
- (c) Estimates calculated a posteriori using Mach number, flight level and inter-waypoint distance.

The estimates under (c) are also referred to as CPS (calculated planned separation) estimates. Given limitations on e.g. the availability of data for methods (b) and (c), MIG/4-WP/10 proposed that pilot estimates (method (a)) be used.

In the *Modelling issues* section, the key aspects of the latest version of the longitudinal collision risk model were recalled, namely explicit incorporation of en-route waypoints, ATC intervention, communication delays/difficulties, and manual reversion. Some discussion on revisions to estimated oceanic entry times was also provided. See Section 7.2.5.3 for crossing track issues.

MIG/4-WP/8: The use of surrogates for ATC estimates in longitudinal collision risk analysis – Update

MIG/4-WP/9 (Thomas, 1998c) investigated the relative accuracy of the CPS (calculated planned separation) forward estimates method (MIG/4-WP/9) for eastbound and westbound flights respectively and also considered an alternative formula for calculating the gain/loss function $Q(m)$, say.

The CPS method uses the inter-waypoint distance and aircraft ground speed but ignores wind effects. Thus, the degree of error resulting from the omission of wind effects was of interest, particularly for eastbound flights since these are generally flight-planned to follow the Jetstream as closely as possible.

The justification for the alternative gain/loss formula was that it represented more accurately how the FDPS systems at Gander and Shanwick OACCs operated, i.e. the FDPS estimate for arrival time at a forward waypoint is replaced in the system by the pilot reported arrival time once the position report for that waypoint is fed into the system. Recall from the text under the (Thomas, 1997c): *Overview of longitudinal collision risk model and effects of delayed and missing waypoint reports* heading in Section 7.2.5.2.1, MIG/2 (September, 1997), that (one of) the previously used formulae read

$$\frac{gain}{loss} = (s_j - s_{j-1})_r - (s_j - s_{j-1})_e \quad (7.94)$$

with s_j denoting separation at waypoint j and the additional subscripts r and e denoting that the pertinent separations were based on aircraft position reports and planned/forward estimates respectively. MIG/4-WP/9 recalled the previously used formula of eq. (7.94) for a leader/follower aircraft pair $\frac{A}{B}$ and waypoints 1 and 2 in the following form,

$$\frac{gain}{loss} = [(r_{B_2} - r_{A_2}) - (r_{B_1} - r_{A_1})] - [(e_{B_2} - e_{A_2}) - (e_{B_1} - e_{A_1})] \quad (7.132)$$

where the symbol $r_{...}$ denotes a reported waypoint passing time and the symbol $e_{...}$ denotes a (planned/forward) estimated waypoint passing time. The proposed new formula read

$$\frac{\text{gain}}{\text{loss}} = [(r_{B_2} - r_{A_2}) - (r_{B_1} - r_{A_1})] - [(e_{B_2} - e_{A_2}) - (r_{B_1} - r_{A_1})] \quad (7.133)$$

which may also be expressed as,

$$\frac{\text{gain}}{\text{loss}} = (r_{B_2} - r_{A_2}) - (e_{B_2} - e_{A_2}) \quad (7.134)$$

The difference between the two formulae can be described in a somewhat subtle way as eq. (7.133) reading *(change in reported separation) – (planned change in separation)* and eq. (7.132) reading *(change in reported separation) – (change in planned separation)*.

Calculations were performed utilizing Gander (Unknown, 1994b) and Shanwick (NAT MIG/3-WP/9, not available to the authors of this Document) data for each combination of eastbound/westbound traffic data and new/old gain-loss formulae (eq. (7.133)/eq. (7.132)). MIG/4-WP/8 concluded that comparison of the relative accuracy of the CPS method for the eastbound and westbound data utilized did not produce clear results. It was also concluded, however, that it was clear that CPS calculations did produce results that were superior to calculations that used pilot estimates.

Remark

1. Unfortunately, due to limitations on e.g. the availability of data, the last conclusion above had to be overruled by the proposal in MIG/4-WP/9 (Thomas, 1998b) of the same NAT MIG/4 Meeting that pilot estimates be used.

7.2.5.2.4 NAT MIG/5 (April, 1999)

MIG/5-WP/5 (Thomas, 1999c) presented preliminary results of the calculation of in-trail longitudinal collision risk. The paper comprised the following sections:

1. Introduction;
2. The collision risk model;
3. Problems;
4. The database;
5. Design details;
6. The risk calculation;
7. Results; and
8. Conclusions.

The collision risk model utilized was that of MIG/4-WP/10 (Thomas, 1998a) presented at the previous NAT MIG Meeting (NAT MIG/4 (September, 1998)), i.e. the one shown above in eqs. (7.124) – (7.128). In fact, Sections 2 and 3 of MIG/5-WP/5 are virtually identical to Sections 1 and 2 of MIG/4-WP/10. The interested reader is referred to MIG/5-WP/5 for any details of the database, design details, risk calculation, and results. One element discussed in *The risk calculation* section, however, needs to be mentioned here, viz. ATC intervention modelling. It was stated that a more sophisticated ATC intervention model instead of eq. (7.128) was used, viz.

$$PI(s) = \begin{cases} 1 + e^{-\bar{s}} - e^{s-\bar{s}}, & s < \bar{s} \\ 0, & s \geq \bar{s} \end{cases} \quad (7.135)$$

where $\bar{s}$ denotes the prevailing longitudinal separation standard/minimum and s denotes the assumed (by the controller and FDPS) longitudinal separation. Eq. (7.135) shows that the probability of intervention was zero if there was no illegal separation and would increase monotonically with increasing illegality of separation.

It was concluded in MIG/5-WP/5 that the preliminary results of the in-trail longitudinal collision risk calculation indicated that a reduction in the longitudinal separation standard/minimum from ten minutes to seven minutes was not likely to be justifiable on safety grounds¹⁰⁴ in the very near future. It was also concluded that a reduction to eight or nine minutes might indeed be possible, and that the situation would become clearer when the definitive risk calculation would be performed later in the year. It should be noted that it was stated that the summation of the inter-waypoint probabilities of zero actual longitudinal separation at the j -th waypoint, $Etc_j^{(a)}(0)$, in eq. (7.125) had not yet been implemented for the calculations, i.e. the results were based on a single inter-waypoint segment only (paragraph 7.2 of MIG/5-WP/5 refers). Time delays, i.e. eqs. (7.129) – (7.131) had not been implemented either yet (paragraph 2.18 of MIG/5-WP/5 refers).

Five remaining items concerning the collision risk model were identified in the discussion on the results obtained as follows. Firstly, a fundamental role is played by the distribution of separations between aircraft in a pair where it was noted that the nature of this distribution was well characterized for the (then) current in-trail longitudinal separation standard/minimum of 10 minutes based on recorded data from both Gander and Prestwick. It was not known, however, what form this distribution would take under the proposed 7-minute longitudinal separation standard/minimum. The MIG/5-WP/5 calculations were based on a re-scaled form of the distribution observed under the existing 10-minute longitudinal standard/minimum. The Group was referred to (Flax, 1995b) which it was felt might be of use for 7-minute longitudinal separation standard/minimum work. It was recalled that a longitudinal proximate pair of aircraft was defined in terms of a 30-minute limit, one of the reasons for this cut-off being the desire to minimize the effects of weather changes during the interval between consecutive aircraft in a pair, and the nature of the normalization used for the separation distribution¹⁰⁵ was discussed. It was agreed that a time limit of 60 minutes, although probably affecting the risk estimates produced, should have a minimal effect only and that in any case the normalization had been handled correctly.

The second item discussed concerned the longitudinal closing speed, $|\dot{x}|$, between two aircraft given that they are separated by at least the separation standard/minimum at the most recent waypoint. Data were analysed during the meeting to produce a graph of measured closing speeds versus measured gains or losses in separation for NAT traffic. It was agreed by the Group that this type of analysis provided a more reasonable value of $|\dot{x}|$ and should be used to calculate longitudinal collision risk.

The third item concerned the adverse effect of improved navigation performance in the lateral dimension on the calculation of longitudinal (as well as vertical) collision risk. This might affect the feasibility of a reduction of the longitudinal separation standard/minimum to 8 minutes as suggested in the third paragraph of this Subsection above.

¹⁰⁴ I.e. meeting a target level of safety of 5×10^{-9} fatal accidents per flight hour.

¹⁰⁵ The normalisation is discussed in paragraph 2.12 of MIG/6-WP/5 (Thomas, 1999b).

The fourth item concerned controller intervention. On this item, *The summary of discussions of the fifth meeting of the North Atlantic Mathematicians' Implementation Group (NAT MIG/5)* states the following: "Controller intervention to correct losses of separation at waypoints was a feature of the LRCM¹⁰⁶ used when the current minimum of 10 minutes was introduced. In that model the entire Oceanic crossing was considered. The recently developed model simply estimates the risk between adjacent waypoints. In this case a model of controller intervention is not required since it is only possible for a controller to intervene to correct a loss of planned separation when position reports from successive aircraft at a waypoint are received." This text is rather unclear, cf. e.g. eq. (7.127) and (7.128) and the fact that improved modelling of ATC intervention was presented as one of the features of the proposed modified form of the probability of longitudinal overlap parameter, π_x , of the longitudinal collision risk model presented in MIG/4-WP/10 and utilized in MIG/5-WP/5. Cf. also the next item.

The fifth and last item concerned communication matters. An important factor that was identified to be taken into account in future risk estimates was the effect of various forms of communication delay between controller and aircraft, which, together with other phenomena, could result in less than 100% reliable intervention at a waypoint. Further work should be carried out to fully characterize the interaction of controller intervention to correct eroded separations at waypoints with the between-waypoint longitudinal collision risk model.

Finally, the reader is referred to Subsection 3 of Section 8 of (Moek, 2002b) for a more detailed "un-official" report on the 5th Meeting of the NAT MIG.

7.2.5.2.5 NAT MIG/6 (September, 1999)

A set of four working papers on longitudinal collision risk modelling for in-trail aircraft, including one on monitoring, was presented at the 6th Meeting of the NAT MIG (MIG/6), namely WP/1, WP/2, WP/5 and WP/6.

MIG/6-WP/1: A longitudinal collision risk estimation for the NAT

MIG/6-WP/1 (Thomas, 1999a) presented updated results of the calculation of in-trail longitudinal collision risk. The summary on its cover page stated that the risk had been calculated using a revised version of the collision risk model. Although no explicit reference was made to a revised version of the model in the text of MIG/6-WP/1, it can be deduced that the revision concerned inclusion of communication delay into the model, i.e. "normal" communication delays, HF blackouts, as well as delay due to manual reversion. See eqs. (7.129) – (7.131). The revised model was presented in MIG/6-WP/5 (see below). New data collected from Gander and Shanwick FIRs for the period 1 April 1999 to 30 June 1999 inclusive were used. The risk for a 7-minute longitudinal separation standard/minimum was found to exceed the TLS in all circumstances. The risk for an 8-minute standard/minimum satisfied the TLS only under certain constraints on the probability of lateral overlap parameter ($P_y(0)$) of the longitudinal collision risk model and on communication delay. The risk for a 9-minute standard/minimum satisfied the TLS well in all circumstances.

MIG/6-WP/5: A longitudinal collision risk model for the NAT

Unlike the title, the summary on the cover page of MIG/6-WP/5 (Thomas, 1999b) stated that this reference described a revised version of the longitudinal collision risk model for aircraft on the same track. The form of the longitudinal collision risk model of MIG/6-WP/5 was the same as utilized previously, i.e. eq. (7.5) but with a new formula for the probability of longitudinal overlap parameter of the model, viz.

¹⁰⁶ LCRM: Longitudinal Collision Risk Model.

$$\pi_x = \frac{2\lambda_x/\bar{x}}{T} \int_{m \geq 0} E_{tc}(m) Q_{td}(m) dm \quad (7.136)$$

where the subscripts tc and td on $E_{tc}(m)$ and $Q_{td}(m)$, indicate that the pertinent parameters as obtained from the data collected have been corrected for rounding/truncation and clock setting errors, and rounding/truncation errors and communication delays respectively. $E_{tc}(m)$ is the distribution of planned separations at the second waypoint of a generic waypoint pair after correcting for rounding/truncation and clock-setting errors. Recall from MIG/5-WP/5 that the summation of the inter-waypoint probabilities of zero actual longitudinal separation at the j -th waypoint, $Etc_j^{(a)}(0)$, in eq. (7.125) had not yet been implemented for the calculations at the NAT MIG/5 (April, 1999) meeting and this had not yet been implemented for the NAT MIG/6 (September, 1999) meeting either. Thus, all results were based on a single generic inter-waypoint segment only. Eq. (7.136) can be expressed in the previously used form of eq. (7.125) for a single generic inter-waypoint segment, i.e.

$$\pi_x = \frac{2\lambda_x/\bar{x}}{T} \times Etc_j^{(a)}(0) \quad (7.137)$$

where $j, j = 1, \dots, n$, denotes the generic inter-waypoint segment and $Etc_j^{(a)}(0)$ is given by eqs. (7.126) and (7.127), but with $Qt_{j-1,j}(m_{j-1})$ and $Rt_{j-1,j}$ replaced by $\tilde{Q}t_{j-1,j}(m_{j-1})$ and $\tilde{R}t_{j-1,j}$ as defined by eqs. (7.129) and (7.130) to account for the effect of rounding/truncation errors and communication delays on the gain/loss distributions as represented by $Q_{td}(m)$ in eq. (7.136). The gain/loss distribution corrected for rounding/truncation errors, $Qt_{j-1,j}(m_{j-1})$, is calculated from the “raw” gain/loss distribution, $Q_{j-1,j}(m_{j-1})$, by means of eqs. (7.115) and (7.116), where $Q_{j-1,j}(m_{j-1})$ itself is determined by means of the new, proposed formula of eq. (7.134). Cf. paragraph 3.12 of MIG/6-WP/5.

In summary, the revision of the longitudinal collision risk model referred to in the *Summary* of MIG/6-WP/5 is understood to concern the use of eqs. (7.129) and (7.130) accounting for time delays in combination with the collision risk model utilized at the previous (5th) Meeting of the NAT MIG, i.e. eqs. (7.124) – (7.127).

MIG/6-WP/2: An application of the longitudinal collision risk model to the calculation of risk owing to operational errors:

MIG/6-WP/2 (Vernon, 1999) described an application of the longitudinal collision risk model to estimate the contribution of a single (large) clock-setting error to the longitudinal collision risk. Starting point for the application was the revised collision risk model of MIG/6-WP/5 presented at the same Meeting and an adaptation was then made to the clock-setting error correction method. It was recalled that the original clock-setting error correction method assumed that both aircraft in a pair are subject to the same clock-setting error distribution, which was assumed to be a normal distribution. The distribution of clock-setting error difference is then normal too and its variance equals twice the variance of the individual aircraft clock-setting error distributions. MIG/6-WP/2 then modelled a single clock-setting error of either the leading or the trailing aircraft in a pair as a constant rather than a random variable. Formally, a constant can be seen as a random variable with a Dirac delta distribution. In practical terms, the constant error model results in the probability distribution of the clock-setting error difference being equal to the normal distribution of the clock-setting error of the other aircraft, but shifted over the magnitude of the constant. Using this modification, the longitudinal collision risk due to a single (large) clock-setting error (for one aircraft in each pair!) can be calculated in the “normal” manner with the collision risk model of MIG/6-WP/5. It was suggested in MIG/6-WP/2 that other operational error modes might be able to be treated in a similar manner.

MIG/6-WP/6: A proposed approach to the ongoing monitoring of longitudinal risk in NAT MNPS airspace

MIG/6-WP/6 (Slater, 1999a) presented an outline proposal for an ongoing monitoring process for longitudinal collision risk assessment in the NAT along similar lines to those conducted for the lateral and vertical dimensions. Four reasons for longitudinal monitoring were provided, namely confirmation of the TLS being met, identification of any factors, mechanisms, or trends which compromise the safety of NAT operations, prediction and observation of the effects of other NAT system changes, and completion of the annual collision risk assessment process for the NAT to all three dimensions. A distinction was made between risk estimation for a trial period as soon as possible following the trial implementation of a reduced longitudinal separation minimum and regular ongoing monitoring. For the former, new large samples of traffic data should be collected of the distributions of separations and of communication delays. As regards ongoing monitoring, it was recommended that longitudinal collision risk in NAT MNPS airspace be estimated annually in time for the MWG meeting at the NAT SPG but that, dependent on the amount of change year by year, not all components would necessarily have to be monitored annually. Monitoring and risk estimation were then discussed for technical and operational longitudinal collision risk separately, including the reasons for separation of the two types of risk. Technical risk was defined as the risk estimated directly by the longitudinal collision risk model and operational risk was defined as the risk due to operational errors which are relatively rare but significant in their effect. Some examples of operational errors were given, such as large onboard clock errors, gross errors in time reporting, failure of a controller to intervene in case of erosion of longitudinal separation, or an aircraft flying at a Mach number significantly different from the cleared one. As regards the modelling of operational longitudinal collision risk, it was proposed to reduce any operational error to an Equivalent Clock Error (ECE) with a specified magnitude and duration after which the methodology of MIG/6-WP/2 could be applied. MIG/6-WP/6 concluded with two sections on the importance of accurate aircraft clock setting prior to take-off, and on more or less slowly varying elements of longitudinal collision risk.

7.2.5.2.6 NAT MIG/7 (February, 2000)

This Subsection will discuss three working papers presented at the 7th Meeting of the NAT MIG, namely one dealing with the collision risk model (MIG/7-WP/6), one dealing with the modelling of operational longitudinal risk (MIG/7-WP/9), and one dealing with a classification of longitudinal erosions of separation for risk assessment purposes (MIG/7-WP/8).

MIG/7-WP/6: Revised longitudinal collision risk model development for North Atlantic MNPS airspace: the current state of the model and comments for consideration and further development

MIG/7-WP/6 (Thomas, 2000) presented the latest version of the longitudinal collision risk model for the NAT. It also included a list of comments from the FAA and some comments received from the RGCSP. The text of Sections 1 and 2 is essentially the same as that of MIG/6-WP/5 presented at NAT MIG/6. In addition, the text in sections 3 -5 of MIG/7-WP/6 resembles the text of MIG/6-WP/1 presented at NAT MIG/6.

Three differences are to be noted between MIG/7-WP/6 (NAT MIG/7 (February, 2000)) on the one hand and MIG/6-WP/5 and MIG/6-WP/1 (NAT MIG/6 (September, 1999)) on the other. Firstly, MIG/7-WP/6 utilized, in addition to a Gaussian model of the gain/loss distribution two more models, namely a mixture of two Gaussians and a mixture of a Gaussian and a double exponential distribution. Results obtained in the Tables 1 of MIG/7-WP/6 and MIG/6-WP/1 for the Gaussian model were the same, indicating that the basic model used in the respective references was the same. Secondly, the effects of HF blackouts and manual reversion on ratios of collision risk to the TLS in the Tables 2 of both references were different. The Tables' captions suggest that the differences were due to the "modelled communication delays (2G)" utilized in MIG/7-WP/6

as opposed to “raw time delays” utilized in MIG/6-WP/1. Thirdly, the MIG/7-WP/6 conclusions differ slightly from the MIG/6-WP/1 ones although the main conclusion is the same, viz. that the risk estimate for a 7-minute longitudinal separation standard/minimum exceeds the TLS in all circumstances.

MIG/7-WP/9: A methodology for the inclusion of operational error events into the assessment of the collision risk as a result of the loss of longitudinal separation in the North Atlantic

MIG/7-WP/9 (Vernon, 2000) provided example calculations for the risk associated with two types of operational longitudinal collision risk, namely that due to large clock setting errors and large losses of longitudinal separation, utilizing the methodology developed in MIG/6-WP/2. It was further proposed that the risk thus determined for all of the longitudinal incidents during the relevant reporting period be summed and added to the technical longitudinal risk (calculated by means of the model of MIG/7-WP/6) for comparison to the TLS.

MIG/7-WP/8: A suggested classification of longitudinal erosions of separation and time deviations for risk assessment purposes

As a part of an assessment of operational longitudinal risk, MIG/7-WP/8 (Slater, 2000a) examined a total of 23 erosions of longitudinal separation reported since 1994. It stated that the definition of what constitutes an operational error in the longitudinal dimension will evolve as the risk estimation process evolves, but that, broadly speaking, operational errors are the large erosions of separation or deviations in estimated time of arrival that are reported by controllers. The main purpose for estimating operational longitudinal risk was stated to be providing a monitoring tool for the types of operational errors that can be controlled, which may help elucidating particular error mechanisms and focusing attention on the major risk bearing error mechanisms. It was attempted, where applicable/possible, to characterize the erosions in terms of the magnitude and duration of true clock errors (TCEs) and equivalent clock errors (ECEs).

Finally, the reader is referred to Subsection 2 of Section 5 of (Moek, 2002a) for a more detailed “un-official” report on the 7th Meeting of the NAT MIG. That Subsection began noting that the meeting part on longitudinal risk started with two preliminary issues, namely the T parameter of the longitudinal collision risk model and the subdivision of longitudinal collision risk into technical and operational longitudinal risk. The T -parameter issue resulted from a question from the ICAO RGCSP. Historically, in conjunction with the collision risk model, it concerned the duration of a full NAT crossing and was given a value of 3.5 hours, see e.g. Table 3 of MIG/7-WP/6. However, with the change to a between-waypoints longitudinal collision risk model at NAT MIG/2 (September, 1997), T should have been redefined as the flying time between waypoints. As a result, previous risk estimates were under-estimated by the ratio between the total flying time for a NAT crossing and the flying time between a typical pair of waypoints. See Section 2.4 of reference (Moek, 2002a) for some further discussion on operational longitudinal risk, including a formula for the total longitudinal collision risk similar to that for total vertical collision risk (cf. eq. (6.114) of Section 6.5.3.1).

7.2.5.2.7 NAT MIG/8 (March, 2001)

Unfortunately, no documentation was available to the authors of this Document concerning the longitudinal collision risk model development for same-direction traffic at the 8th Meeting of the NAT MIG. It can be inferred from the documentation available from subsequent meetings, that there were at least two working papers dealing with longitudinal separation at the NAT MIG/8 Meeting, namely MIG/8-WP/4 and MIG/8-WP/7.

7.2.5.2.8 NAT MIG/9 (August, 2001)

Two working papers dealt with longitudinal collision risk modelling for in-trail aircraft, namely MIG/9-WP/4 and MIG/9-WP/7.

MIG/9-WP/4: Revised longitudinal collision risk estimates for NAT MNPS airspace

MIG/9-WP/4 (Owens, 2001) applied the in-trail longitudinal collision risk model utilized in MIG/7-WP/6 as represented in this Document by eqs. (7.124) – (7.127) together with eqs. (7.129) – (7.130) and eqs. (7.128)/(7.135), to two sets of FDPS forward estimates and position report data restricted to the 20W and 30W reporting points. One set of position report data resulted from cleaned up HF pilot reports covering the also previously used time period from April to June 1999 whereas the other set of position reports was obtained from new FANS ADS automatic waypoint reporting system covering the period of time from April to June 2001. The effects of small clock setting errors (CSEs) and communication delays (CDs) were investigated but rounding/truncation errors (RTEs) were not (as agreed at NAT MIG/8 (March, 2001)). The clock setting error data and the communication delay data utilized were the same as those used in MIG/7-WP/6. The FDPS forward estimates and pilot/aircraft position reports were used to generate two sets (HF and FANS) of distributions of gain/loss data and ATC planned separation for aircraft pairs following the same flight path and separated by no more than 20 minutes (previous work utilized aircraft pairs separated by no more than 30 minutes). Some scrutiny of the resulting distributions took place.

New models were developed for the planned separation data, comprised of a cubic spline model for the leading edge of this data and a linear decay for the remainder of it. The gain/loss data were modelled by means of a normal double exponential probability distribution where the HF data were adjusted for communication delays (negligible communication delays assumed for the FANS data).

The longitudinal risk estimates calculated in MIG/9-WP/4 turned out to be considerably higher than those calculated previously (MIG/8-WP/4). To address the differences between the new and past results, the FANS gain/loss data used within the previous risk estimate (MIG/8-WP/4) was examined. This data had been originally modelled by a normal distribution but was modelled by two alternative normal double exponential distributions in the MIG/9-WP/4 application. Using the alternative gain/loss models in conjunction with the same planned separation data/models, the alternative gain/loss models applied to the previous FANS data also produced considerably higher longitudinal risk estimates. MIG/9-WP/4 concluded with some discussion stating that the revised risk estimation provided indicated that it will not be possible to reduce the longitudinal in-trail separation, but that there were a number of problems with the model and data which could be considered for future investigation.

MIG/9-WP/7: Work in progress on deviation from planned time (DFPT) data, rounding and truncation effects and weather updates

MIG/9-WP/7 (Slater, 2001b) dealt with the modelling of a specific part of the longitudinal collision risk model rather than the full model, viz. modelling of the deviation from planned time (DFPT) performance of single aircraft in the NAT. DFPT was defined as the actual time of arrival at a waypoint reported by an aircraft minus the FDPS forward estimate for that point. The combined HF and FANS data from April to June 1999 and 2001 were utilized for the study.

Assuming independence of the DFPT distributions of the aircraft in a pair, a gain/loss distribution was calculated by means of convolution and compared with the observed gain/loss distribution. This comparison showed that the calculated gain/loss distribution was far worse than the observed gain loss distribution, i.e.

the tails of the calculated gain/loss distribution were far heavier than those of the observed distribution. It was believed that the difference in the distributions was largely due to the wind fields that pairs of aircraft flew through with any DFPTs due to weather prediction errors tending to cancel out for in-trail aircraft since both aircraft should be subject to the same prediction error within FDPS. This cancellation effect, however, does not occur for aircraft pairs on intersecting tracks since the aircraft will then generally fly through different wind fields before reaching a common point. Therefore, intersecting-track longitudinal collision risk calculations should be based on the DFPT distributions of individual aircraft rather than the gain/loss distribution.

MIG/9-WP/7 then looked at the “quality” of the individual aircraft DFPT distribution in more detail, i.e. at the extent the calculated distribution was affected by rounding and truncation errors. It was concluded from the analysis that the effect of rounding and truncation errors on risk estimates was minimal for the combined set of HF and FANS data, this was not the case for the FANS data alone. No explanation for the latter had been found yet and it was recommended to investigate this problem further.

Finally, a preliminary investigation of the effect of weather updates on the DFPT distribution was reported on, viz. whether there was any variation throughout the day. It appeared that the FDPS forward estimates varied periodically. It was recommended, therefore, to investigate the risk benefits, if any, of optimizing the weather forecast update time and frequency for the whole of the NAT.

7.2.5.2.9 NAT MIG/10 (March, 2003)

Recall from Section 7.2.5.2.8 that the previous meeting of the Group, NAT MIG/9, took place in August 2001, i.e. approximately one year and a half earlier than the current meeting and recall also from Section 7.2.3 that reduction of longitudinal separation was not present as an item in the *Summary of Discussions and Conclusions* of the NAT SPG/38 (2002) – NAT SPG/39 (2003) meetings.

There were no working papers or information papers on longitudinal collision risk (modelling) presented at the 10th Meeting of the NAT MIG but there was ample discussion on the subject, which started recalling that it had been concluded at the previous NAT MIG/9 (August 2001) Meeting that the work to date had shown that it would not appear to be feasible to reduce in-trail or intersecting-track longitudinal separation. The discussion then proceeded with a look at the potential for further design studies to (better) understand and characterise specific aspects of the longitudinal system. This would then produce a baseline model of the current system. Any attempt to reduce longitudinal separations would thus form the second stage of a two-stage approach of which generating the baseline system would be the first stage. A total of eight individual studies were considered by the Group. Consideration of which longitudinal studies should be pursued was added as a task to the Group’s work programme. Nonetheless, one of the eight studies was explicitly added to the work programme, viz. “Determine distributions of longitudinal gain/loss and planned separation using Centralised Airborne Dependent Surveillance (CADS) log file data”.

7.2.5.2.10 NAT MIG/11 (October, 2003)

There was one working paper, NAT MIG/11-WP/2 (unavailable to the authors of this Document), entitled “An investigation of gain/loss distributions from CADS data in the North Atlantic” (Unknown, 2003). The Group recommended that the study should be refined.

7.2.5.2.11 Conclusion

As set out under the *NAT SPG/40 (2004)* heading in Section 7.2.3, it was agreed at the NAT SPG/40 Meeting that the NAT MIG who had been addressing collision risk modelling principally and the NAT Reduced Separation Standards Implementation Group (RSSIG) who had been very effective in planning for the implementation of RVSM be melded into the NAT Safety Analysis and Reduced Separation Implementation Group (SARSIG) and that the terms of reference be expanded to include safety management.

As regards reductions in horizontal separation minima, the NAT SPG agreed that its NAT IMG sub-group had agreed that work should continue on seeking ways and means to reduce horizontal separation minima and in particular longitudinal separation. In noting this, it was recognized that other methods of carrying out safety assessments could be used rather than the formal mathematical models used in the NAT Region at the time. Therefore, to initiate the task, work packages, including the need to collect data regarding the various methods of using time to apply separation by the various ATS units and the need to attempt to classify longitudinal errors were developed.

As set out also in Section 7.2.3 but under the *NAT SPG/41 (2005)* heading, the NAT SPG/41 Meeting agreed to a proposal that would require the implementation of RNP 4 as well as the implementation of 30 NM lateral and 30 NM longitudinal separation minima. In that context, it was recalled that the NAT IMG had spent considerable time and effort toward achieving reductions in time based longitudinal separation, but that, to that date, this work had not resulted in the expected efficiencies or benefits, due to time keeping anomalies and uncertainties surrounding separation gain/loss. Accordingly, it was agreed that the NAT IMG cease all work on reductions in time-based longitudinal separation standards. It was also agreed that resources should be re-directed to support reductions in distance-based separation minima.

The subsequent developments at NAT SPG level starting at NAT SPG/42 (2006), ultimately resulting in a 5-minute longitudinal separation minimum between suitably-equipped in-trail aircraft (RLongSM), will be sketched in Section 7.2.6 and the pertinent SARSIG safety assessment will be presented in Section 7.2.7.

This Section, Section 7.2.5, will now proceed with longitudinal collision risk for intersecting tracks.

7.2.5.3 Effect of lateral errors on additional longitudinal separation required for intersecting tracks

This Subsection briefly summarizes six working/information papers dealing with longitudinal separation of aircraft on intersecting tracks that were presented at the 2nd – 9th Meetings of the NAT MIG during the period 1997 – 2001.

MIG/2-WP/4: Additional longitudinal separation required for intersecting tracks in NAT MNPS airspace

NAT MIG/2-WP/4 (du Boulay, 1997) recalled that the longitudinal separation standards/minima in NAT MNPS airspace at the time (1997) were 10 minutes for in-trail aircraft and 15 minutes for aircraft on intersecting tracks. These minima had been implemented on 26 November 1981, where the additional 5 minutes was to account for lateral uncertainties in the aircraft on intersecting tracks and the effects of differing wind components on the ground speeds of the aircraft. It noted that it was unclear on what basis the choice of the 5 minutes was previously made. The purpose of MIG/2-WP/4 then was to develop a mathematical methodology to determine the additional longitudinal separation, L' (minutes) say, required in any given

situation of intersecting tracks over and above the longitudinal separation standard/minimum for in-trail aircraft on the same flight path. A previous version of MIG/2-WP/4 had been presented at the first Meeting of the MIG.

The derivations in Section 3 of MIG/2-WP/4 utilized surface plane geometry throughout to ease the derivation of the models although typical intersecting angles were determined using spherical geometry. For same-direction pairs of aircraft, the longitudinal separation was derived based on the time it would take for aircraft 2 (the aircraft furthest away from the common point) to reach the common point minus the time it would take aircraft 1 (the aircraft closest to the common point) to reach the common point. In the case of aircraft 1 having a ground speed greater than aircraft 2, the longitudinal separation was minimized to 15 minutes (or whatever the standard chosen) at the point where aircraft 2 was at least 60 NM laterally separated from aircraft 1. In the case of aircraft 2 having a ground speed greater than or equal to aircraft 1, the longitudinal separation was minimized at the common point. For opposite-direction aircraft, the closest point of approach was calculated by determining the time at which minimum separation occurred. Vertical separation was then applied for 15 minutes (or whatever standard applicable) either side of that time. Lateral errors were introduced as displacement errors where either or both aircraft were exhibiting a constant cross-track error or as angular drift errors where either or both aircraft were drifting off track. All models gave values for L' that were independent of the separation standard/minimum being applied. Another section of MIG/2-WP/4 modelled different wind component effects for aircraft pairs on intersecting tracks based on assumptions about the way in which ATC centres incorporate wind components when predicting waypoint arrival times.

A tentative value of 3 minutes was found to appear to be adequate based on the input parameter values used and the extreme scenarios analysed. For same-direction pairs on intersecting routes there was a constraint on the magnitude of the intersection angle, viz. that it be limited to a maximum of 36° . Further work was concluded to be necessary to make the calculations more representative of the actual operating environment and to consider combinations of errors (e.g. one aircraft drifting and the other aircraft exhibiting a constant cross-track error). An independent verification of the formulae derived was required. Use of spherical geometry for the full derivations was also suggested.

MIG/3-IP/7: Addenda to NAT MIG/2 WP/4 (Additional longitudinal separation required for intersecting tracks in NAT MNPS airspace). Correspondence giving wind corrections as applied at Shanwick OAC.

MIG/3-IP/7 (du Boulay & Slater, 1998) gathered together the correspondence and other documents that describe the way in which wind corrections were actually applied at Shanwick OAC at the time.

MIG/6-WP/10: Review of cross-track error values in the calculation of the additional separation required for intersecting tracks

MIG/6-WP/10 (Slater, 1999b) provided an update to MIG/2-WP/4 by using an estimate of the standard deviation of cross-track navigation performance based on data collected of the deviations from track of aircraft leaving and entering NAT airspace at 15°W longitude, viz. 3.6 NM. This value was larger than the assumed value of 3 NM used in MIG/2-WP/4. The increase in the standard deviation led to an increase in the value of the additional separation L' to account for lateral position uncertainty from 1.6 minutes to 2.3 minutes. However, the tentative additional separation value of $L' = 3$ NM for aircraft on intersecting tracks proposed in MIG/2-WP/4 remained valid because this value was obtained when accounting for aircraft angular drift and dominated the value accounting for lateral position uncertainty.

MIG/7-WP/1: Probability of eroding the additional longitudinal separation required for intersecting tracks in NAT MNPS airspace

MIG/7-WP/1 (Slater, 2000b) reconsidered longitudinal separation for same-direction intersecting-track scenarios based on observed distributions of lateral errors and groundspeeds rather than assumed worst case values. (It was shown in MIG/2-WP/4 that the same-direction scenario was the more demanding one since the opposite-direction intersecting-track scenario required an additional 2.4 minutes of longitudinal separation for all intersection angles up to 90°.) Small angular drift errors were assumed to be included in the observed distributions and their effect was thus not separately modelled. The following formula was presented for the change in planned separation at the intersection due to lateral errors c_1 and c_2 as a function of the aircraft speeds V_1 and V_2 and the intersection angle α :

$$\Delta T = \frac{60}{V_1 V_2} \{V_2(c_1 \cos \alpha - c_2) + V_1(c_2 \cos \alpha - c_1)\} \quad (7.138)$$

Using the observed lateral error and groundspeed distributions, MIG/7-WP/1 calculated the probability distribution of ΔT as a function of the intersection angle α and from that the probabilities of eroding one, two, up to eight minutes of longitudinal separation (Tables 1 – 4 of MIG/7-WP/1 refer).

MIG/7-WP/1 then took a new, probabilistic, approach by calculating the probability that the planned separation can be eroded to the extent that a collision can occur instead of determining an additional amount of time in a deterministic manner. The approach was developed for a 90° intersection angle and assumed (for numerical reasons) that the planned longitudinal separation at the common point would be exactly 10 minutes. It assumed that the along-track position of an aircraft was uncertain by ± 3 minutes due to normal navigation error, time reporting error, rounding or truncation of reported time, or on-board clock-error. Thus, for two aircraft on intersecting tracks, their true separation at the planned common point could lie anywhere between 4 and 16 minutes. Working to a resolution of 1 minute, the probability that the planned separation can be eroded to the extent that a collision can occur, P_1 , was calculated as

$$P_1 = \frac{1}{36} [P\{\Delta T \leq -5\} + P\{\Delta T \leq -6\} + P\{\Delta T \leq -7\} + \dots + P\{\Delta T \leq -10\} + \dots] \quad (7.139)$$

Next, the probability that two aircraft are in time overlap within a 1-minute time interval, P_2 , was calculated as

$$P_2 = 120\lambda_x/V \quad (7.140)$$

Finally, the probability of a fatal accident per 90° encounter at a longitudinal separation of 10 minutes, P_c was estimated by

$$P_c = 2P_2P_1P_z(0) \quad (7.141)$$

Given the probability distribution of ΔT and taking $V = 180$ kts, $\lambda_x = 0.0306$ NM, and $P_z(0) = 0.46$, eqs. (7.139) – (7.141) were used to obtain

$$P_c = 7.2 \times 10^{-14} \quad \text{per } 90^\circ \text{ intersecting track encounter} \quad (7.142)$$

Using a target level of safety (TLS) of 5×10^{-9} fatal accident per flight hour, eq. (7.142) was then used to show that approximately 700 such minimum separation 90° intersections per million flight hours would result in

an increased risk of 1% of the TLS. The risk estimate of eq. (7.142) was believed to be an upper bound because various conservative assumptions underlay the derivation and because it was shown that 90° intersections represented a worst case.

MIG/9-WP/2: Probability of eroding the longitudinal separation required for intersecting tracks in NAT MNPS airspace

MIG/9-WP/2 (Slater, 2000b) started recalling that MIG/7-WP/1 had made some recommendations based on a set of assumptions that were believed to be conservative. Further work, however, had shown that those recommendations could no longer be sustained. This further work was based on the use of observed distributions for all of the required parameters without making any assumptions regarding the degree of conservatism. The same groundspeed data were used as before, but some smoothing (by eye) was applied to make the extremes of the distribution slightly more conservative and to allow for small sample effects in those regions. The same lateral deviation data were used as before, but some (mathematical) smoothing was applied. A new sample of lateral deviation data had very recently become available and was modelled by a double double exponential distribution and used also. Erosion probabilities, i.e. $P(\Delta T) \leq E$, $E = -9.5, -8.5, \dots, 2.5, 3.5$, were calculated for a 90° intersection angle and two different lateral offset scenarios with lateral offsets up to 2 NM right of track. Calculations were performed for the older data set for both a worst-case and a best-case combination of lateral offsets but for the new data set for a best-case combination only.

The results obtained in MIG/7-WP/1 were based on the assumption that the along-track position of an aircraft was uncertain by ± 3 minutes due to normal navigation error, time reporting error, rounding or truncation of reported time, or on-board clock-error. It had subsequently become apparent, however, that the major source of uncertainty in the aircraft's position was due to uncertainty in the FDPS forward estimate, based on its weather model. It was found that in the traffic sample studied, the error in longitudinal position for a single aircraft varied between -6 and +7 minutes, the error being denoted DFPT, Deviation From Planned Time, and being defined as the actual time reported at a waypoint minus the FDPS for that waypoint. It is of importance to note that weather effects cannot be assumed to cancel out for pairs of aircraft on intersecting tracks since the aircraft are travelling through different wind fields.

Thus, in addition to the probability distribution $P(\Delta T)$ of the change in time separation due to lateral and groundspeed errors, MIG/9-WP/2 defined a probability distribution $P_D(X)$ for a pair of aircraft gaining or losing X minutes of planned separation due to DFPT alone. An empirical distribution of DFPT was obtained from a traffic sample for the period April to June 1999 inclusive between 20°W and 30°W in Shanwick airspace. Risk calculations were performed for the empirical distribution as well as a double exponential distribution fitted to the empirical distribution. Using both probability distributions $P(\Delta T)$ and $P_D(X)$ a revised version of eq. (7.139) for the probability that the planned separation can be eroded to the extent that a collision can occur, P_1 , was defined, viz.

$$P_1 = \sum_X [P_D(X - S)P(\Delta T \leq -X + 0.5) - P(\Delta T \leq -X - 0.5)] \quad (7.143)$$

where S denotes the longitudinal separation standard/minimum for intersecting-track aircraft.

The probability of a fatal accident per 90° encounter at a longitudinal separation of 10, 11, 12, 13, 14, or 15 minutes was then calculated using (7.143) and, as before, eqs. (7.140) and (7.141) but with an upward revised value of aircraft groundspeed of $V = 260$ kts.

The safety criterion for judging the acceptability of a reduction of the longitudinal separation standard/minimum for aircraft pairs on intersection tracks was again (cf. MIG/7-WP/1) taken as 0.01 per cent of the TLS per 90° crossing, i.e. 5×10^{-13} . It was found that for four scenarios of interest the risk per crossing at the planned separation was above the safety criterion adopted except for the existing 15-minute standard/minimum. It was concluded that the major component of risk was produced by the deviations of actual times from those predicted by the FPPS for Shanwick airspace and this was believed to be largely due to weather prediction update rates and timelines.

MIG/9-WP/3: Probability of eroding the longitudinal separation required for intersecting tracks in NAT MNPS airspace by FANS equipped aircraft

MIG/9-WP/3 (Slater, 2001a) applied the methodology developed in MIG/9-WP/2 to pairs of FANS equipped aircraft only, using a sample of 4053 FANS position reports from exactly 15°W and from eastbound aircraft. Using the previously defined safety criterion for the longitudinal collision risk per 90° crossing, it was shown that for FANS equipped aircraft a reduction from 15 to 14 minutes was feasible. It was (again) concluded that the reason for the difficulty in supporting reductions in longitudinal separation minima was the uncertainty in planned time at waypoints when they are compared with reported times and this was concluded to be more likely to be due to deficiencies in the weather models used by FDPS systems than to aircraft navigational performance.

7.2.5.4 Some data analysis studies

This subsection lists some data analysis studies that have been utilized by the NAT MIG in its work on the reduction of longitudinal separation in the NAT.

Table 7.6: Some longitudinal data analysis studies considered by the NAT MIG

Meeting	Subject	Author
MIG/2-WP/5	Measurement of longitudinal gain-loss performance in North Atlantic MNPS airspace (Shanwick FIR)	R. Randolph
MIG/4-WP/2	Preliminary results of a study of time keeping of flights across the NAT	R. Seaman
MIG/5-WP/1	Study of time keeping accuracy at 015W	R. Seaman
MIG/5-WP/2	Study of time keeping accuracy at 010W	R. Seaman
MIG/5-WP/3	Study of predicted and actual elapsed times in the NAT	R. Seaman
MIG/5-WP/4	Preliminary study of the improvement in aircraft clock setting accuracy at 10W	S. Lasenby
MIG/5-WP/12	March 1999 clock accuracy survey of aircraft flying in NAT MNPS airspace	Canada
MIG/6-WP/8	Preliminary evidence relating to aircraft clock setting accuracy from the FANS automatic waypoint report trial	A. Rivoire
MIG/7-WP/7	Differences between expected and actual times of arrival in WPRs collected during the NAT FANS 1/A trial in 1999/2000	A. Rivoire
MIG/9-WP/6	In-trail longitudinal separation samples from Shannon radar	A. Rivoire & K. Slater

7.2.6 RLongSM, Reduced Longitudinal Separation Minimum: the years 2006 - 2020

The acronym RLongSM, *Reduced Longitudinal Separation Minimum*, supplemented with the qualifier T5¹⁰⁷, appeared for the first time in the *Summary of Discussions and Conclusions of the Forty-Fourth Meeting of the North Atlantic Systems Planning Group (2008)* and refers to a 5-minute longitudinal separation minimum between suitably-equipped in-trail aircraft. RLongSM for the longitudinal dimension may be compared with RLatSM for the lateral dimension as discussed in Section 5.3.5. Both RLongSM and RLatSM were initiated by the NAT Region and subsequently “upgraded” to globally applicable separation minima for inclusion in the PANS-ATM. In fact, as will be reported under the *NAT SPG/45 (2009)* heading below, the ICAO Air Navigation Commission (ANC), in the knowledge that the RLongSM separation would halve the then existing separation minimum in the PANS-ATM, agreed to amend SASP’s work programme to monitor the efforts of the NAT SPG to advance this procedure, review the modelling work undertaken and develop an amendment to the PANS-ATM prior to implementation. (Further, the ANC also directed Operational Data Link Panel (OPLINKP) as part of its work programme to provide assistance in terms of RCP implementation.)

A phased implementation of RLongSM was followed, starting with an operational trial for suitably-equipped eastbound traffic in the Shanwick FIR on **30 May 2010** (see below under the *NAT SPG/46 (2010)* heading) and continuing with bilateral operations between the Gander and Shanwick FIRs on **28 March 2011** (see below under the *NAT SPG/48 (2012)* heading). The operational trial ended on **29 March 2018** by moving into the operational phase on that same day under PBCS (see below under the *NAT SPG/52 (2016)* heading) (ICAO, 2017a).

In a similar manner as in the previous Sections 6.4.2 and 7.2.3, the material in this subsection is based on review of the *Summary of Discussions and Conclusions of the Forty-Second to Fifty-Fifth Meetings of the North Atlantic Systems Planning Group*. Table 7.7 lists the NAT SPG meetings at which longitudinal separation was on the Group’s agenda for the period of time under consideration in this Subsection. A brief discussion of the work reported under the pertinent agenda items is provided by meeting below the table. Although the key topic for this Subsection concerns RLongSM, some other developments concerning longitudinal separation in the NAT Region will also be referenced, namely implementation of 30 NM and 50 NM distance-based longitudinal separation in the New York Oceanic East and Santa Maria Oceanic FIRs, the implementation of the Automatic Dependent Surveillance – Broadcast In Trail Procedure (ADS-B ITP) in the New York Oceanic East FIR, and the implementation of the ADS-C Climb and Descend Procedure (ADS-C CDP) in the New York Oceanic East FIR in accordance with the newly amended procedures in the PANS-ATM.

Technological and other developments that played a part regarding the separation minima to be discussed in this Subsection concern Automatic Dependent Surveillance (ADS), ADS-B as well as ADS-C, datalink, GNSS-based navigation, and the transition from sensor-based separation minima to performance-based separation minima, particularly concerning communications and surveillance.

¹⁰⁷ The qualifier “T5” was subsequently dropped.

Table 7.7: NAT SPG Meetings at which longitudinal separation was on the Meetings' agenda (explicitly or implicitly): NAT SPG/42 (2006) – NAT SPG/56 (2020)

2006	NAT SPG/42	2: Planning and Implementation 2.1 Report on NAT Implementation Management Group programmes Implementation of reduced horizontal separation minima
2007	NAT SPG/43	2: Planning and Implementation 2.1 Report on NAT Implementation Management Group programmes Implementation of reduced horizontal separation minima
2008	NAT SPG/44	2: Planning and Implementation 2.1 NAT Implementation Management Group report Application of 5 minute climb/descent between GNSS equipped aircraft Reduction in time-based longitudinal separation minimum between ADS equipped aircraft to five minutes (RLongSM-T5) 3. Air Navigation System Review 3.1 Review of system safety performance Erosion of longitudinal separation
2009	NAT SPG/45	1: Developments 1.2 Adjacent Regions ANC review of the report of the NAT SPG/44 Application of 5 minute climb/descent between Global Navigation Satellite Systems (GNSS) equipped aircraft 5-minutes longitudinal separation between ADS-Contract (ADS-C) pairs 2: Planning and Implementation 2.2 North Atlantic Implementation Management Group Application of 5 minute climb/descent between GNSS equipped aircraft Reduction longitudinal separation minimum between ADS-C equipped aircraft 3. Air Navigation System Review 3.1 Review of system safety performance Report on scrutiny matters Erosion of longitudinal separation
2010	NAT SPG/46	1: Developments 1.5 Review by the Air Navigation Commission of the NAT SPG/45 Report ANC review of the report of the NAT SPG/44 Use of ADS-C for 5 minute separation 3: Planning and Implementation Management Issues 3.1 Implementation programmes updates Reduced Lateral and Longitudinal Separation Implementation plan for trial application of a reduced longitudinal separation Appendix E – Implementation Plan for validation trial of RLongSM
2011	NAT SPG/47	–
2012	NAT SPG/48	3: NAT Planning and Implementation Management Issues

		3.1 Implementation programmes updates Updated NAT RLongSM Implementation Plan Applicability of RCP and RSP in the current operations, during the LatSM and RLongSM trials and operations Appendix F – Updated Implementation Plan for Trial Application of RLongSM in the NAT Region
2013	NAT SPG/49	3: NAT Planning and Implementation Management Issues 3.1 Implementation programmes updates NAT Regional SUPPS for Reduced Separations predicated on RCP/RSP Implementation of 30 NM lateral, 30 NM and 50 NM longitudinal separation minima in New York Flight Information Region (FIR) 7. Work programme Including Sub-groups 7.1 NAT IMG Outcome
2014	NAT SPG/50	7. Work programme Including Sub-groups 7.1 NAT IMG Outcome Status of Proposal for Amendment to NAT SUPPs to incorporate reduced longitudinal separation
2015	NAT SPG/51	7. NAT Documentation 7.3 PFA to the NAT SUPPs, on implementation of 30 NM or 50 NM longitudinal and 30 NM or 50 NM lateral separation minima in Santa Maria 4: NAT Planning and Implementation Management Issues 4.1 Implementation programme updates Implementation Surveillance Enabled Services in the ICAO NAT Region
2016	NAT SPG/52	4. NAT Operational and safety Improvements 4.1 Joint CONOPS supporting Space-based ADS-B implementation 4.4 Implementation of the ADS-C CDP in the New York Oceanic East FIR 6. NAT Documentation 6.3 PfA to the NAT SUPPs, on ADS-B ITP
2017	NAT SPG/53	3: NAT Planning and Implementation Management Issues 3.2 Space-based ADS-B 3.5 NAT PBCS Implementation on 29 March 2018
2018	NAT SPG/54	2: NAT Planning and Implementation Programmes 2.1 PBCS Implementation 2.2 Space-based Automatic Dependent Surveillance – Broadcast (ADS-B) (SB ADS-B) 5: NAT Documentation Updates PfA to NAT SUPs (Doc 7030) on separation minima applied in Santa Maria Oceanic FIR
2019	NAT SPG/55	2: NAT Planning and Implementation Programmes 2.3 Update to the NAT SPG Conclusion 49/05 (NAT PBCS Requirements) 2.7 Operational trial of ASEPS using SB ADS-B
2020	NAT SPG/56	–

NAT SPG/42 (2006)

Under the heading of *Implementation of reduced horizontal separation minima*, the *Summary of Discussions and Conclusions of the Forty-Second Meeting of the North Atlantic Systems Planning Group*, stated that the Group noted that additional data collection and analysis would be required to sustain a reduction in longitudinal separation between pairs of ADS-C equipped aircraft. It was also noted that the United Kingdom agreed to carry out the necessary data collection and analysis and that Canada agreed to support the study if required. Bearing in mind NAT SPG Conclusion 41/3 (paraphrased above under the *NAT SPG/41 (2005)* heading at the end of the previous Subsection), the Group endorsed the NAT IMG decision to look for reductions in separation minima using any methods available and to not rely entirely on distance based separation, which was proving to be very difficult to implement.

NAT SPG/43 (2007)

The *Summary of Discussions and Conclusions of the Forty-Third Meeting of the North Atlantic Systems Planning Group on Implementation of reduced horizontal separation minima* covered three subjects, two of which were related to longitudinal separation. The first subject concerned the initiation of work to finalise plans to implement the 5 minute climb/descent minimum using Global Navigation Satellite System (GNSS) waypoint reports. It was noted that a comparative analysis would be used to support the safety case because this approach should provide the regulators with the necessary material to approve the procedure and it was economical and expeditious.

The second subject of interest here concerned the observation by the Group that a plan of work to support the implementation of reduced longitudinal (and lateral) separation minima had been agreed upon. No further details were reported.

NAT SPG/44 (2008)

Two subjects are listed in Table 7.7 under Agenda Item 2.1, *Planning and Implementation*, of the 44th Meeting of the NAT SPG, namely *Application of 5 minute climb/descent between GNSS equipped aircraft*, and *Reduction in time-based longitudinal separation minimum between ADS equipped aircraft to five minutes (RLongSM-T5)*.

Concerning the first subject, the Group was informed that the NAT IMG had finalised the safety studies needed to support the implementation of 5-minute longitudinal separation between GNSS equipped aircraft climbing or descending in an oceanic/remote procedural control environment where surveillance was not available and third party communication might be used. The safety study utilized the ICAO approved *comparison with a reference system* analysis method (ICAO, 1998c). Two hazard mitigations defined were controller training and commencement of the level change within 10 minutes of the time the second aircraft has reported over a common point. The Group agreed that implementation should proceed with a target date of **15 January 2009**, following a go/no go decision by the NAT IMG on behalf of the NAT SPG in November 2008.

The Group was informed that the ICAO SASP was progressing an amendment to ICAO Doc 4444 which would address the proposed application.

Concerning the second subject, *Reduction in time-based longitudinal separation minimum between ADS equipped aircraft to five minutes (RLongSM-T5)*, it was recalled that the introduction of reduced longitudinal separation to improve the efficiency of operations in the NAT Region had been a longstanding issue for the

Region. It would appear that, after many attempts to determine how to reduce the longitudinal separation minimum, the implementation of 5 minutes longitudinal separation between ADS-C pairs of aircraft might be feasible. Key enablers for this reduced longitudinal separation minimum were the improved navigational performance and accurate time keeping associated with Global Positioning System (GPS), coupled with the enhanced surveillance and communication capabilities of data link. Therefore, only pairs of aircraft both equipped with GNSS, providing ADS-C reports and communicating using Controller Pilot Data Link Communication (CPDLC) would be eligible for the application of RLongSM-T5.

The Group noted that, as regards the communication performance that would be required, the NAT IMG had determined that, in the absence of an approved Required Communications Performance (RCP) standard for the NAT Region to implement RLongSM-T5 at the time, the communications requirements defined by RCP 240 (ICAO, 2006b) would be used.

The Group noted that the modelling work carried out so far, see Section 7.2.7, provided sufficient assurance that a minimum longitudinal separation of 5 minutes was feasible. If, in addition, all hazards identified in the Preliminary Hazard Identification (PHI) could be mitigated, there should be no barrier to RLongSM-T5 being implemented. However, there remained a considerable amount of work to be completed before the implementation could be realized, including a revised concept of operations agreed to by NAT Region's ANSPs, aircraft operators, and regulatory authorities, changes to oceanic and domestic ATC systems, and confirmation that the satellite communications infrastructure could meet the requirements.

As regards data on erosion of longitudinal separation, i.e. in excess of three minutes, thirteen reports had been received for the 2007 monitoring year (compared with twelve for the 2006 monitoring year).

NAT SPG/45 (2009)

The following two subjects concerning longitudinal separation were listed in Table 7.7 under Agenda Items 1 and 2 at NAT SPG/45, namely *Application of 5 minute climb/descent between GNSS equipped aircraft*, and *Reduction longitudinal separation minimum between ADS-C equipped aircraft*.

Concerning the first subject, *Application of 5 minute climb/descent between GNSS equipped aircraft*, the ICAO Air Navigation Commission (ANC), in its review of the NAT SPG/44 Report, had noted that the target date of 15 January 2009 for the implementation of this minimum was not ideally synchronized with the efforts of the ICAO Separation and Airspace Safety Panel (SASP) to incorporate the minimum in the PANS-ATM (Doc 4444). Cf. Table 2.5 in section 2.5.2. However, taking note of the work already performed by the SASP on this separation minimum, the ANC supported the ongoing implementation efforts, acknowledging that a preliminary operational trial amongst operators that agreed to support the collection of data and further the PANS-ATM amendment would be of benefit to all oceanic regions which would wish to apply the reduced minimum.

As regards the planned implementation date of 15 January 2009, the 5 minute longitudinal separation minimum between GNSS aircraft in the climb or descent had been implemented on that date in the Gander, Reykjavik, and Santa Maria Oceanic Control Areas. Flight crew guidance material had been improved pending the pertinent PANS-ATM amendment.

Concerning the second subject, *Reduction longitudinal separation minimum between ADS-C equipped aircraft*, the ICAO Air Navigation Commission (ANC), in its review of the NAT SPG/44 Report, had noted that this separation minimum was not in the PANS-ATM and SASP had not been tasked to progress the minimum. In the knowledge that the separation would halve the then existing 10-minute longitudinal separation minimum in the PANS-ATM, the ANC agreed to amend SASP's work programme to monitor the efforts of the NAT SPG to advance this procedure, review the modelling work undertaken and develop an amendment to the PANS-ATM prior to implementation. See Section 7.2.7. (Further, the ANC also directed Operational Data Link Panel (OPLINKP) as part of its work programme to provide assistance in terms of RCP implementation.)

The Group then discussed a proposal to improve planning for reduced separation and to ensure that all safety concerns were properly addressed. An implementation planning methodology based on the basic steps set out in Chapter 1 of the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (ICAO, 1998c) was agreed on, after which the Group proceeded with planning for a trial to validate the planning assumptions, including the safety requirements. The decision to proceed would be taken when the NAT IMG was satisfied that the planning requirements had been met.

As regards the safety requirements, the Group was informed that Canada and the United Kingdom would provide data regarding the safety work and the performance requirements for the planned implementation and that Canada would act as the point of contact to oversee the production of the deliverable (implementation plan).

Two more subjects from the NAT SPG/45 meeting are worth to be described, namely *ADS-C implementation for longitudinal conformance monitoring* and *Erosion of longitudinal separation*. In 2009, in all NAT FIRs longitudinal conformance monitoring was based on (ADS-C) waypoint reports. Implementation of reduced longitudinal separation will need additional longitudinal conformance monitoring based on ADS-C periodic reports from each participating flight, approximately one report every 23 minutes. Since, at the time, most NAT flights provided periodic reports for wind/temperature data every 30 minutes, an increase of no more than one report every 60 minutes could be projected, which would come to about 3 reports per NAT crossing.

As regards data on erosion of longitudinal separation, i.e. in excess of three minutes, thirty-three reports had been received for the 2008 monitoring year (compared with thirteen for the 2007 monitoring year).

NAT SPG/46 (2010)

The NAT SPG was provided with the then current implementation plan for the trial application of a reduced longitudinal separation of 5 minutes between ADS-C equipped aircraft (RLongSM). This implementation plan was provided in Appendix E to the *Summary of Discussions and Conclusions of the Forty-Sixth Meeting of the North Atlantic Systems Planning Group*. The trial had commenced on **30 May 2010**, using a reporting rate of 18 minutes, with RLongSM being applied between eastbound aircraft in the Shanwick Oceanic Control Area that were east of 30° West. The United Kingdom reported that the trial was proceeding well, with all expected ADS-C position reports being received. Canada confirmed that it was confident of being able to join the validation trial in the autumn of 2010.

The following element has been reproduced from the implementation plan in Appendix E to NAT SPG/46 (2010):

“5. Identification of the Method of Safety Assessment

5.1 An evaluation of longitudinal risk has been made through the use of a statistical model based on the Reich model (NAT SARSIG/7 WP/05 refers). One of a number of assumptions made in the modelling of risk was that RLongSM would be applied to the entire population of aircraft i.e. the worst case scenario. The outcome of the modelling was that the estimated value of longitudinal risk which would be less than the Target Level of Safety (TLS) if ADS-C periodic position reports were received every 20 minutes and appropriate action taken by controllers on their receipt. Studies conducted subsequent to the original CRM indicated that, based on current controller practice during situations where longitudinal separation may be eroding, 100% intervention whenever the separation was estimated to fall below 5 minutes based on the periodic report estimates might not be assured and therefore, for the purpose of the operational trial, a more frequent reporting interval of 18 minutes would be applied in order to meet the TLS. The modelling process did not take into account the receipt of waypoint position reports. Had it done so, the effect would have been to reduce the value of estimated longitudinal risk. Initial conclusions from this modelling were presented to NAT SARSIG/7 and following off-line exchanges, it was agreed that the model was valid.

Evaluation of the risk;

5.2 The TLS for NAT MNPS airspace in the longitudinal dimension is currently 20×10^{-9} fatal accidents per flight hour (fafh) but with any change of separation standard the NAT SPG has determined that a TLS of 5×10^{-9} fafh be adopted to encapsulate both technical and operational risk.

5.3 Hazard Identification and Risk Analyses (HIRA) to assess the impact of the proposed change on the current system shall be carried out. These have or will be made available to the appropriate regulatory authorities and planning bodies as they are completed.”

Remarks:

1. Recall from Section 7.2.3 that it was agreed already at NAT SPG/33 (1997) that for planning purposes a TLS of 5×10^{-9} fatal accidents per flight hour would be used for the reductions in longitudinal separation minima.
2. The statistical model for longitudinal collision risk of SARSIG/7 WP/05 will be discussed in Section 7.2.7. In line with the ANC’s decision on RLongSM as reported under the *NAT SPG/45 (2009)* heading above, the SARSIG/7 WP/05 safety assessment and subsequent updates were reviewed by the ICAO SASP during the period November 2010 – November 2012, after which endorsement followed. See also the text under the *NAT SPG/49 (2013)* heading below and NATS newsletter Airmail (NATS, 2013).

NAT SPG/47 (2011)

Longitudinal separation and RLongSM were not formal agenda items at the 47th Meeting of the NAT SPG but it was noted under Agenda Item 7.1, *NAT IMG outcome*, that the NAT IMG initiated coordination with the ICAO SASP regarding the planned RLongSM and RLatSM implementations in the ICAO NAT Region. The NAT SPG also noted that the application of the RLongSM and RLatSM in the NAT Region would be on an operational trial basis until the applicable separation standards were incorporated into the PANS-ATM.

NAT SPG/48 (2012)

The NAT SPG reviewed and supported updates and adjustments to the *Implementation Plan for the Trial Application of Reduced Longitudinal Separation of 5 minutes between ADS-C equipped aircraft (RLongSM) in the NAT Region* to align it with the *NAT Performance Based Communication and Surveillance Implementation Plan* and to take account of developments in data link implementation in the ICAO NAT Region.

The NAT SPG agreed to Conclusion 48/7 concerning the *Applicability of communication and surveillance performance applications*. The conclusion stated that the then current separation standards were strategic in nature and were not predicated on Required Communication Performance (RCP) and Required Surveillance Performance (RSP). Nonetheless, NAT data link operations will use RCP and RSP for measuring communications and surveillance against RCP 240 and RSP 180 respectively as measured in the GOLD (ICAO, 2013a). The conclusion also stated that communications and performance specification would be prescribed for the application of RLongSM and RLatSM and that the specifications envisaged were RCP 240 and RSP 180 subject to validation by the pertinent operational trials. See the NAT SPG/48 report for the precise wording of NAT SPG Conclusion 48/7. The Group also agreed to NAT SPG Conclusion 48/30 concerning *Publicizing potential benefits of RLongSM Trial*.

As reported under the *NAT SPG/46 (2010)* heading, the RLongSM trial commenced on 30 May 2010 with the application of RLongSM to eastbound aircraft in the Shanwick Oceanic Control Area that were east of 30° West. As shown in the updated implementation plan for the trial, bilateral operations between Gander and Shanwick began on **28 March 2011**.

NAT SPG/49 (2013)

Two Proposals for Amendment to NAT SUPPS were considered, namely one for the *Application of 30 NM lateral, 30 NM and 50 NM longitudinal separation minima in New York Oceanic FIR*, and one *In support of reduced separations predicated on RCP and RSP*. It was agreed that, after some further alignments between the two proposals, the first proposal would be submitted first by the United States for processing in accordance with the formal ICAO procedures and following its approval, the second proposal would be reviewed and approved by the IMG at its next Meeting (IMG/43) and subsequently submitted by Canada, Iceland, and the United Kingdom for processing in accordance with the formal procedures of ICAO.

In connection with the proposal for amendment *In support of reduced separations predicated on RCP and RSP*, the NAT SPG approved a statement (for inclusion in the *NAT SPG Handbook*) in order to provide clarification and guidance on RCP 240 and RSP 180 compliance determination and applicability to RLongSM and RLatSM implementations. See the NAT SPG/49 report for the precise wording of the statement.

Under Agenda Item 7.1, *NAT IMG Outcome*, the NAT SPG noted that the United Kingdom had presented the NAT IMG with the results of the RLongSM operational trial against the agreed success criteria, based on data collected in Shanwick OCA between 31 March 2011 and 31 December 2012. The data covered over 3752 RLongSM pairs, of which 2225 pairs involved climb/descent. Analysis of these validated pairs suggested that only two pairs of flights had minimum longitudinal separations of less than 5 minutes, where, in fact, a more detailed investigation of those two pairs revealed that adequate separation had existed. No safety events related to RLongSM were observed during the 15-month operational trial period.

Under the same Agenda Item, the NAT SPG noted that the collision risk assessment in support of RLongSM had been presented by the United Kingdom to both the main plenary of the 21st Meeting of the ICAO SASP

in the fall of 2012 and its Mathematicians Sub Group. Following review and discussion by both groups, the safety assessment had been fully accepted as a proof of concept of the RLongSM procedure for global use. See *Remark 2* under the NAT SPG/46 (2010) heading above and Section 7.2.7. Finally, the NAT SPG noted the NAT IMG agreement that the NAT SARSIG had completed the work required for safety assessments in support of the planned reductions in RLongSM in the ICAO NAT Region and the agreement that the OCAs continue to monitor the uptake and safety performance of RLongSM and report any safety occurrences.

NAT SPG/50 (2014)

The *Status of Proposal for Amendment to NAT SUPPs to incorporate reduced longitudinal separation* was reviewed by the Group under Agenda Item 7.1, *NAT IMG Outcome*. It was noted that the Proposal had been sent to ICAO Head Quarters on 3 March 2014 but was still under consideration pending the ongoing work within the ICAO SASP and OPLINK panels, which was expected to be completed in 2016. The NAT SPG was concerned that if the SASP and OPLINKP work would extend beyond 2016, this would have a negative impact on the progress of the NAT implementation plans. Therefore, the Group agreed that it was important to continue cooperation with the global groups and tasked the IMG to do so in order to recommend further course of action. It was agreed that, if the 2016 target for availability of global provisions would not be met, the NAT SUPPs amendment would be pursued.

NAT SPG/51 (2015)

The NAT SPG was presented with a Proposal for Amendment to the NAT SUPPs regarding the application of all 30 NM and 50 NM longitudinal and lateral separation minima, based on Amendment X to the Yth Edition of the PANS-ATM, cf. Tables 2.3 and 2.5 of Sections 2.5.1 and 2.5.2 respectively. The Proposal was endorsed by the Group and would be submitted by Portugal for processing in accordance with the formal ICAO procedures.

See Section 7.2.8 for Agenda Item 4.1, sub-item *Implementation Surveillance Enabled Services in the ICAO NAT Region*.

NAT SPG/52 (2016)

Under Agenda Item 4.4, *Implementation of the ADS-C CDP in the New York Oceanic East FIR*, the NAT SPG was provided with information on the implementation of the ADS-C Climb and Descend Procedure (ADS-C CDP) in the New York Oceanic East FIR in accordance with the newly amended procedures in the PANS-ATM related to performance-based longitudinal and lateral separation minima and the ADS-C CDP for aircraft in the en-route phase of flight. See Table 2.5 of Chapter 2, Amendment X to the Yth Edition of the PANS-ATM, and Section 7.3 (possibly to be detailed). Following local testing and controller training, the FAA expected operational use to commence in the late second to early third quarter of 2016.

Under Agenda Item 6.3, *PfA to the NAT SUPPs, on ADS-B ITP*, the NAT SPG was provided with a Proposal for Amendment to the NAT SUPPs addressing the implementation of the Automatic Dependent Surveillance – Broadcast In Trail Procedure (ADS-B ITP) in the New York Oceanic East FIR. See Table 2.5 of Chapter 2, Amendment X to the Yth Edition of the PANS-ATM, and Section 7.3 (possibly to be detailed). The Group noted that the ADS-B ITP was a pilot-requested procedure utilizing ADS-B IN and air traffic control capabilities to allow more flights to achieve their preferred vertical profiles and thereby increasing both capacity and efficiency in the oceanic domain. Reference was made to detailed related procedures covered in paragraph 5.4.2.7 of the PANS-ATM. The latter procedures did not permit either the ITP aircraft or the reference aircraft to make turns during the manoeuvre. However, work performed by the FAA had determined that, based on the capabilities of the New York Oceanic East ATC system, aircraft conducting the ITP permitted to make

turns during the manoeuvre would not result in an infringement of the required separation minima. As a result, the PfA under discussion was modified to say that the ADS-B ITP procedure will be applied in accordance with paragraph 5.4.2.7 of the PANS-ATM except that aircraft conducting the ITP will be permitted turns during the manoeuvre that do not degrade required separation.

The NAT SPG was provided with a report of the NAT Performance-Based Communication and Surveillance Project Team (NAT PBCS PT) and noted that Amendment X to the Yth Edition of the PANS-ATM, which included PBCS provisions would become applicable on 22 November 2016. These provisions would include application of RLongSM (and RLatSM). In order to allow for a transition period for States and NAT airspace users to complete their PBCS approval processes, and to harmonize the NAT implementation with the Asian Pacific (APAC) Region, the NAT SPG agreed that the NAT Regional date for implementation of PBCS/PBN enabled reduced separation minima would be **29 March 2018**.

See Section 7.2.8 for Agenda Item 4.1, *Joint CONOPS supporting Space-based ADS-B implementation*.

NAT SPG/53 (2017)

RLongSM was not referenced in the *Summary of Discussions and Conclusions of the Fifty-Third Meeting of the North Atlantic Systems Planning Group*, but two Agenda Items listed in Table 7.7 for this meeting involving longitudinal separation were Agenda Item 3.2, *Space-based ADS-B*, and Agenda Item 3.5, *NAT PBCS Implementation on 29 March 2018*.

See Section 7.2.8 for Agenda Item 3.2, *Space-based ADS-B*, i.e. ASEPS longitudinal separation minima.

Concerning RLongSM and RLatSM in connection with Agenda Item 3.5, *NAT PBCS Implementation on 29 March 2018*, the NAT SPG discussed the readiness for the NAT PBCS implementation on 29 March 2018, in particular concerning the availability of necessary State regulations for PBCS authorisations and the unavailability of appropriate Statements of Compliance (SoC) from manufacturers for certain aircraft types. It was noted that there were about 64 States engaged in NAT operations that would potentially need to issue PBCS approvals, with 80% of the airframes associated with 11 States.

The NAT SPG emphasised that the potential non-availability of SoCs and, consequently, PBCS authorisations could unintentionally result in the delay of the NAT implementations and penalise airspace users. In this regard, the NAT SPG reaffirmed that the NAT would continue with the implementation of 23 nautical miles (NM) lateral and 5 minutes longitudinal separation (RLongSM) minima based on PBCS/PBN as was planned on **29 March 2018**. However, a transitional arrangement would be needed to accommodate aircraft with satisfactory PBCS performance but unable to obtain an authorisation on time prior to 29 March 2018. The NAT SPG emphasised that the duration of this transition arrangement would be 6 months after 29 March 2018 which would be reviewed by NAT SPG/54 in June 2018.

NAT SPG/54 (2018)

RLongSM was not (explicitly) referenced in the main body of the *Summary of Discussions and Conclusions of the Fifty-Fourth Meeting of the North Atlantic Systems Planning Group*, but three Agenda Items listed in Table 7.7 for this meeting involving longitudinal separation were Agenda Item 2.1, *PBCS Implementation*, Agenda Item 2.2, *Space-based Automatic Dependent Surveillance – Broadcast (ADS-B) (SB ADS-B)*, and Agenda Item 5.3, *PfA to NAT SUPs (Doc 7030) on separation minima applied in Santa Maria Oceanic FIR*.

Concerning Agenda Item 2.1, *PBCS Implementation*, it was noted that in general the implementation of PBCS on 29 March 2018 went smoother than anticipated, given the expectation that initial approval levels could have been very low. Increasing the collective approval rate of the NAT fleet from the 40-45% range into numbers more aligned to the FANS 1/A equipage numbers, typically over 90%, remained a concern, particularly since traffic would increase as the summer months approached.

See Section 7.2.8 for Agenda Item 2.2, *Space-based Automatic Dependent Surveillance – Broadcast (ADS-B) (SB ADS-B)*.

Agenda Item 5.3, *PfA to NAT SUPs (Doc 7030) on separation minima applied in Santa Maria Oceanic FIR* concerned a proposal for amendment to the NAT SUPPs to correct information regarding the application of the separation minima in Santa Maria Oceanic FIR, which had been introduced with the previous approved amendment. The NAT SPG agreed to the proposal and its subsequent processing in conformance with the formal ICAO procedures.

NAT SPG/55 (2019)

RLongSM was referenced in the main body of the *Summary of Discussions and Conclusions of the Fifty-Fourth Meeting of the North Atlantic Systems Planning Group*, under Agenda Item 2.3 listed in Table 7.7 for this meeting, viz. *Update to the NAT SPG Conclusion 49/05 (NAT PBCS Requirements)*. The NAT SPG was presented with a proposal to update the NAT SPG Conclusion 49/05 (RCP and RSP for RLatSM and RLongSM) that allowed the acceptance of the transaction time and surveillance data delivery time at a level of 99.0% rather than that at the specified 99.9% for RLatSM and RLongSM. It was agreed that Conclusion 49/5 should be repealed and a new one endorsed to take account of the completion of the trial and commencement of the operational implementation.

See Section 7.2.8 for the other Agenda Item, Agenda Item 2.7, *Operational trial of ASEPS using SB ADS-B*, listed in Table 7.7 for the NAT SPG/55 Meeting.

NAT SPG/56 (2020)

A teleconference meeting of the North Atlantic Systems Planning Group (NAT SPG) was held from 24 to 25 June 2020, as a partial replacement for its Fifty-Sixth Meeting (NAT SPG/56) which was originally planned to take place from 22 to 25 June 2020. This meeting arrangement was necessitated by the exceptional circumstances of the COVID-19 coronavirus pandemic event that prevented the NAT SPG from gathering at a face-to-face meeting. Due to the exceptional situation and meeting arrangements, prior agreement was coordinated among the NAT SPG members that the meeting documentation would only include those outcomes of the contributory bodies that were not expected to result in any prolonged or controversial and complex debates. Also, new items or submissions would not be accepted. All such discussions were postponed until the face-to-face NAT SPG/56 meeting which was tentatively planned in January 2021. The intent was to limit the teleconference discussions to routine matters that were required to advance the NAT work programme.

The brief *Summary of Discussions and Conclusions of the Fifty-Sixth Meeting of the North Atlantic Systems Planning Group* does not contain any references to RLongSM or other longitudinal separation topics.

7.2.7 The RLongSM collision risk assessment

7.2.7.1 Introduction

As was set out at the beginning of Section 7.2.6, the RLongSM procedure was initiated by the NAT SPG at its 44th Meeting in 2008 and was subsequently “upgraded” to a globally applicable longitudinal separation standard/minimum as a result of an ICAO ANC decision to have the SASP monitor the efforts of the NAT SPG to advance this procedure, review the modelling work undertaken, and develop an amendment to the PANS-ATM prior to implementation. RLongSM became effective as a global longitudinal separation standard as of 29 March 2018.

Starting point for the RLongSM collision risk assessment to be presented in this Subsection is NAT Sarsig/7 WP/05 (NATS, 2008), which was referenced under the *NAT SPG/46 (2010)* heading in Section 7.2.6. NAT Sarsig/7 WP/05 was made available to the SASP as Flimsy/6 at SASP’s 18th Meeting in Brussels in November 2010, where, amongst other things, it was added to the Task List of the SASP Mathematicians Sub-Group (MSG) for review by its next Meeting in the first half of 2011. Review by the MSG took place at the SASP’s Working Group of the Whole (WG/WHL) Meeting in May-June 2011 and at SASP’s Working Group’s first Meeting in November 2011, but was hampered by a lack of time. Subsequently, detailed MSG review of the latest versions of the RLongSM collision risk assessment took place at the 20th and 21st Meetings of the SASP in May and November 2012. This, together with review by the SASP as a whole of the operational and safety aspects of the RLongSM procedure resulted in endorsement of the RLongSM safety assessment. The RLongSM collision risk assessments presented at SASP/20 and SASP/21 will be reviewed in Sections 7.2.7.3 and 7.2.7.4 respectively. See also NATS newsletter Airmail (NATS, 2013).

7.2.7.2 The RLongSM collision risk assessment of NAT Sarsig/7-WP/05

NAT Sarsig/7-WP/05 (NATS, 2008), referenced under the *NAT SPG/46 (2010)* heading in Section 7.2.6 constitutes the starting point for the RLongSM safety assessment that is the subject of this Subsection. It began noting that for aircraft to be eligible to RLongSM, they will be required to be equipped with Automatic Dependent Surveillance-Contract (ADS-C), Controller-Pilot DataLink Communications (CPDLC), and Global Positioning System (GPS). It comprised a cover page and a report entitled *Reduced longitudinal separation minimum – extended collision risk modelling for periodic reporting*¹⁰⁸, where the report comprised the following sections:

1. Executive Summary;
2. Introduction;
3. Aim;
4. RLongSM Operations;
5. Modelling Collision Risk;
6. The Simulation Model;
7. SPM Results;
8. Collision Risk Modelling for Synchronous Reporting;

¹⁰⁸ Although the report was classified “NATS – In confidence – distribution addressees only”, it entered the (semi-) public domain when it was made available to the ICAO SASP in November 2010 and it was deemed acceptable, therefore, to include its review in this Document.

9. Summary; and
10. Distribution List.

SARSIG/7-WP/05 is summarized below in three parts, with the first part addressing its Sections 2 – 6, the second part presenting the results of the simulations (Section 7), and the third part addressing its Sections 8 and 9, i.e. the collision risk modelling proper. The simulation model was used to demonstrate that synchronous periodic position reporting results in a more conservative distribution of separation losses below the specified longitudinal separation standard/minimum than asynchronous position reporting under ADS-C. As a result, longitudinal collision risk modelling needed only to be performed for synchronous periodic position, which was (much) easier to model than the asynchronous periodic position reporting case.

Part 1: Approach and the simulation model (Single Period Model (SPM))

The key element of SARSIG/7-WP/05 concerned estimation of longitudinal collision risk for ADS-C time-based periodic position reporting rather than for inter-waypoint segments based on position reporting at waypoints which are 10° of longitude apart. In the latter case, the (time-based) separation, defined as the difference between the times that a leading and a following aircraft pass the same physical point, is known at each waypoint and the risk derives entirely from the potential for the separation to be eroded during the time in which the following aircraft flies between the waypoints. In the case of periodic position reporting, the situation was stated to be less straightforward. The time-based separation $S(t)$ at time t is defined as

$$S(t) = t - t_L \quad (7.144)$$

where t_L denotes the time at which the leading aircraft was at the same distance $d_L(t_L)$ to the last waypoint passed by the following aircraft at time t , i.e.

$$d_L(t_L) = d_F(t) \quad (7.145)$$

See Figure 7.1.

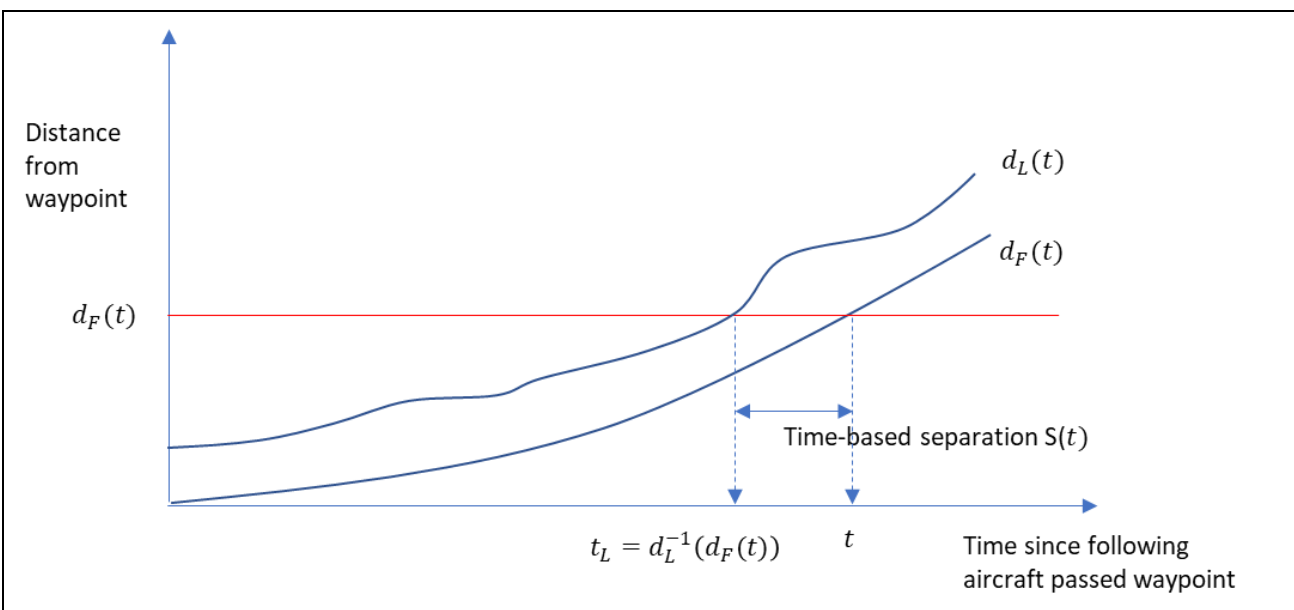


Figure 7.1: Time-based separation between following and leading aircraft at point in time t

Eq. (7.145) may be formally solved for t_L ,

$$t_L = d_L^{-1}(d_F(t)) \quad (7.146)$$

and the time-based separation $S(t)$ written as

$$S(t) = t - d_L^{-1}(d_F(t)) \quad (7.147)$$

If the leading aircraft happened to report its position at the same distance $d_L(t_L) = d_F(t)$ to the reference waypoint as the following aircraft, then the inversion in eq. (7.147) becomes “trivial” in that t_L is directly available from the leading aircraft’s position report.

In general, however, a pair of aircraft will not report at the same distance to a common waypoint and the inversion in eq. (7.147) for any time t since the following aircraft passed its last waypoint clearly requires both the distances $d_F(t)$ and $d_L(t)$ to be known for all values of t . In practice, this will not be the case and the separation will be evaluated for the periodic position reporting times $t_F(n)$, $n = 1, 2, \dots$, of the following aircraft using its reported distances $d_F(t_F(n))$ ¹⁰⁹. The other information available to the calculation of the separation consists of the reported distances $d_L(t_L(n))$, $n = 1, 2, \dots$ of the leading aircraft to the reference waypoint at its periodic reporting times $t_L(n)$, $n = 1, 2, \dots$. See Figure 7.2, in which the phase difference Δ is defined as the length of time between a following aircraft periodic report and the previous leading aircraft periodic report, i.e.

$$\text{Phase difference: } \Delta = t_F(n) - t_L(n) \quad (7.148)$$

The Figure also shows the reporting period P and the time-based longitudinal separation $S(t_F(n))$ at the time of the following aircraft’s most recent periodic report, i.e.

$$\text{Reporting period: } P = t_F(n) - t_F(n-1) = t_L(n) - t_L(n-1) \quad (7.149)$$

$$\text{Time-based separation: } S(t_F(n)) = t_F(n) - t_L = t_F(n) - d_L^{-1}(d_F(t_F(n))) \quad (7.150)$$

¹⁰⁹ Actually, the aircraft report their position (latitude, longitude) which, together with the latitude and longitude of the waypoints can be used to calculate the distance of the aircraft to any waypoint at the time of periodic position reporting.

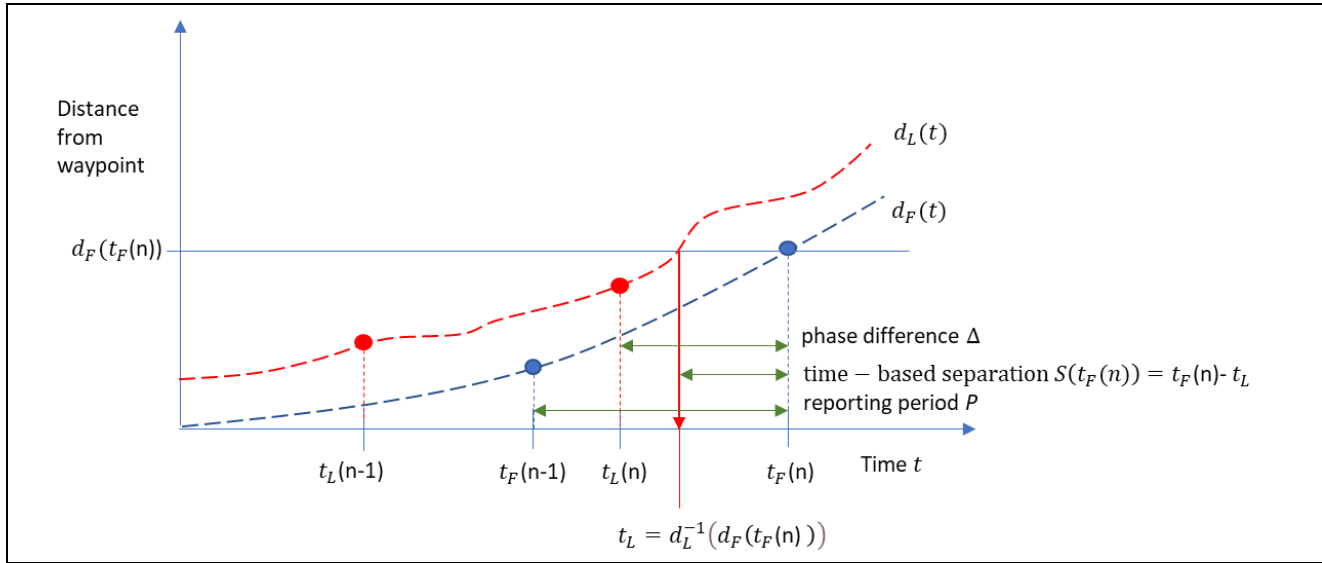


Figure 7.2: Some details relevant to the determination of time-based separation between a pair of following and leading aircraft at point in time $t_F(n)$

Eq. (7.148) shows that the phase difference Δ is zero in the case of synchronous periodic position reporting and can range from zero (exclusive) to the reporting period P (exclusive) in the case of asynchronous periodic position reporting. Figure 7.2 shows that in order to calculate the time-based separation at time $t_F(n)$ the leading aircraft's periodic position report at time $t_L(n)$ needs to be used to forecast the time at which it would have been at the same distance $d_F(t_F(n))$ from the reference waypoint as the following aircraft at time $t_F(n)$. The uncertainty of this forecasting can be expected to grow in line with the magnitude of the phase difference.

The risk of longitudinal overlap over a single reporting period, $[t_F(n-1), t_F(n)]$, was then stated to be able to be attributed to the combined effect of

- Any error in estimating the entry time-based separation $S(t_F(n-1))$ at time $t_F(n-1)$;
- Any loss in separation between reporting times $t_F(n-1)$ and $t_L(n)$;
- Any loss in separation between reporting times $t_L(n)$ and $t_F(n)$, provided that the forecast separation at $t_F(n)$ is above the threshold for intervention (because otherwise a controller would intervene); and
- Any loss in separation during the time between an intervention being signalled and the resolution being effected.

SARSIG/7-WP/05 then stated that “creating an analytical model to calculate the associated risk for such a process is difficult, principally because the Shanwick Automated Air Traffic System (SAATS) data available (forecast and actual inter-waypoint journey times) does not provide any suitable measurements, and so the relevant distributions are unknown. Instead, the approach taken here is to create a simulation-based model to explore the nature of longitudinal risk under different assumptions, and in particular the effect of varying the phase difference.

The approach is based on the supposition that on average, the risk associated with synchronous reporting is expected, to be greater than with asynchronous reporting, since it results in longer periods between receiving an update from either aircraft. If the simulation shows the supposition to be true, then it suffices to build a collision risk model for the synchronous case alone, because it will produce a conservative estimate of risk.

Fortunately, the synchronous case is easier to model, and it turns out to be possible to derive analytical expressions for the variances of the key error distributions. The simulation model can also be used to validate these expressions.”

A list of twelve assumptions made for the purposes of modelling periodic reporting were described in Section 5.3 of SARSIG/7-WP/05, followed by a description of the simulation model in Section 6. The aim of the simulation model was to compare synchronous and asynchronous reporting over a single reporting period $[t_F(n-1), t_F(n)]$ and the simulation model was thus referred to as the Single Period Model (SPM). The core of the SPM was the simulation of actual and forecast distances travelled by a pair of aircraft, thereby producing actual and estimated time-based separations. Forecasting errors derived from weather effects, variations in speed of the individual aircraft from its cleared Mach number, and navigational error. The simulation model was limited to in-trail separations only.

Twenty days of SAATS data throughout the calendar of 2007 was utilized to make a comparison between actual transit times and ATC-system-generated forecasts to generate a distribution of forecasting errors for individual aircraft. Analysis of the data showed that the forecasting errors increased slowly over the course of six hours, the obvious interpretation being this to be due to the weather conditions.

The core of the simulation model was the derivation of distances flown by individual aircraft based on the following formulae

$$d_t = d(1 + e_t) \quad (7.151)$$

where d_t denoted the actual distance travelled by an aircraft in minute t , d denoted the distance travelled in 1 minute at the cleared speed, and e_t denoted the percentage error in the distance travelled in minute t . The error e_t had two components,

$$e_t = v_t + w_t \quad (7.152)$$

where v_t was the error due to inaccuracy in the aircraft speed (a zero-mean random variable with variance V), and w_t was the error due to weather effects (a zero-mean random variable with variance W). Weather effects in successive minutes of an aircraft's flight were related by

$$w_t = \alpha w_{t-1} + \varepsilon_t \quad (7.153)$$

with

$$\text{Var}(\varepsilon_t) = W(1 - \alpha^2) \quad (7.154)$$

and weather effects over time - in a fixed location – were related by

$$w_t = \beta w_{t-1} + \zeta_t \quad (7.155)$$

with

$$\text{Var}(\zeta_t) = W(1 - \beta^2) \quad (7.156)$$

Similarly, speed inaccuracies in successive minutes of an aircraft's flight were related by

$$v_t = \gamma v_{t-1} + \xi_t \quad (7.157)$$

with

$$Var(\xi_t) = V(1 - \gamma^2) \quad (7.158)$$

Along-track navigational error affects an aircraft's position report. In the *SPM*, this error at an aircraft's first reporting point was modelled by a zero-mean normal distribution with a standard deviation derived from the 95% along-track navigation performance requirement. The error at subsequent reporting points was related to the previous error via another autoregressive process with parameter δ .

The Initial Error, IE , i.e. the error in forecasting the separation at the start $t_F(n-1)$ of a single reporting period, is thus due to the combined effect of the error in estimating the distance flown by the leading aircraft over the relevant period and the navigation errors of both aircraft. SARSIG/7-WP/05 derived the following expression for the Initial Error:

$$IE = S - \hat{S} \cong -|\hat{S} - \Delta| \bar{e}_L - \frac{\delta_L - \delta_F}{d} \quad (7.159)$$

where Δ denotes the phase difference, $\bar{e}_L$ is the average distance error over the period $\hat{S} - \Delta$ and δ_L and δ_F are the along-track navigation errors of the leading and following aircraft respectively. The variance of the Initial Error was approximated by

$$Var(IE) \cong (\hat{S} - \Delta)^2 \{VF(\gamma, |\hat{S} - \Delta|) + WF(\alpha, |\hat{S} - \Delta|)\} + \frac{2N}{d^2} \quad (7.160)$$

where $N = Var(\delta_L) = Var(\delta_F)$ is the variance of the navigation errors δ_L and δ_F and $VF(\cdot)$ and $WF(\cdot)$ are the variances of the mean error components $\bar{v}_t$ and $\bar{w}_t$ of $\bar{e}_t$ due to speed and weather (cf. eq. (7.152)), with¹¹⁰

$$F(\gamma, |\hat{S} - \Delta|) = \frac{1}{|\hat{S} - \Delta|} \left\{ \frac{1+\gamma}{1-\gamma} - \frac{2\gamma(1-\gamma^{|\hat{S}-\Delta|})}{(1-\gamma)^2 |\hat{S}-\Delta|} \right\} \quad (7.161)$$

$$F(\alpha, |\hat{S} - \Delta|) = \frac{1}{|\hat{S} - \Delta|} \left\{ \frac{1+\alpha}{1-\alpha} - \frac{2\alpha(1-\alpha^{|\hat{S}-\Delta|})}{(1-\alpha)^2 |\hat{S}-\Delta|} \right\} \quad (7.162)$$

It was thus concluded in SARSIG/7-WP/05 that the variance of the Initial Error IE increased according to the magnitude of the difference $\hat{S} - \Delta$ between the separation $\hat{S}$ and the phase difference Δ and will have a minimum determined by the variance N of the along-track navigational error.

Conflict resolution delay was examined in some depth in SARSIG/7-WP/05 and resulted in a decision to use a baseline conflict resolution delay of 9 minutes and to consider a wider range for sensitivity analysis. This was then incorporated into the *SPM* by allowing separation to erode for a further period of time after a loss of separation (i.e. conflict) was signalled to the controller.

¹¹⁰ Eqs. (7.161) and (7.162) are based on well-known results for the variance of the mean of successive terms of a 1st order autoregressive process.

In addition to the Initial Error IE , let the Reporting Period Error, RPE , denote the change in actual separation over a reporting period and let OE denote the Overall Error over a reporting period, i.e. the difference between the separation forecast at the start of the period and the actual separation at the end of the period. It then holds that

$$OE = IE + RPE \quad (7.163)$$

A formula for the variance of the Overall Error, OE , was derived for the synchronous reporting case only in SARSIG/7-WP/05, viz.

$$Var(OE) \cong P^2 VF(\gamma, P) + (P - S_0)^2 VF(\gamma, P - S_0) + S_0^2 WF(\alpha, S_0) + \frac{2N}{d^2} \quad (7.164)$$

where S_0 denotes the initial separation at the following aircraft's reporting time $t_F(n - 1)$.

Regarding the asynchronous case, it was noted that for the analysis of synchronous versus asynchronous reporting, the important variable was the loss of separation below the specified minimum separation, and this variable was called the Minimum Separation Loss, MSL . This takes into account the ability of controllers to intervene during a single reporting period at time $t_L(n)$ if the forecast has fallen too low. If the forecast separation has fallen below the minimum by $t_F(n)$, then it is assumed that intervention will occur and the minimum separation loss was derived from the lower of the current separation and the separation after the conflict resolution time. A similar calculation was done for intervention at $t_F(n)$. If intervention does not occur, the event is unlikely to have one of the largest losses of separation and so its separation at $t_F(n)$ is used for the calculation of separation lost.

Part 2: Results of the Single Period Model simulation

For the *SPM* simulations, 5000 iterations were performed for each baseline scenario defined by the parameters of the error components v_t and w_t , aircraft speed, navigation performance, conflict resolution delay, buffer (initial separation over and above the standard/minimum), reporting period, time of first position report by following aircraft after passing a waypoint, and phase difference Δ between the reporting times of the following and leading aircraft in a pair. The iterations were performed for 10 phase differences, namely 0, 2, 4, ..., 18 minutes.

The key output of the simulations was the distribution of separation losses below the minimum for each of the ten values of the phase difference Δ . The ten distributions were compared on the basis of their 0.25, 0.5, and 1.0 percentiles and it was found that, generally, these percentiles were at a maximum when the phase difference was zero, i.e. synchronous reporting, and at a minimum for phase differences of 6 to 8 minutes. This suggested that synchronous reporting was more risky than asynchronous reporting, the reason being that synchronous reporting results in a single period of risk equal to the reporting interval, whereas asynchronous reporting splits the reporting period up into two smaller sections. Although for asynchronous reporting the information is not as good at any reporting time, since only one aircraft is reporting at a time, this is more than offset by the smaller periods of exposure to separation loss.

Following the baseline simulations, a range of sensitivity tests were carried out in order to gain a reasonable confidence about the assertion of synchronous reporting being more risky than asynchronous reporting. These sensitivity tests confirmed the results of the baseline simulations, providing grounds for restricting the

collision risk modelling proper to the simpler, synchronous case, in the knowledge that the results should be conservative.

The *SPM* simulation results were also used to validate eq. (7.160) for the variance of the Initial Error, *IE*, (for asynchronous as well as synchronous reporting) and eq. (7.164) for the variance of the Overall Error, *OE*, for the synchronous reporting case only. For the Initial error *IE* of the baseline scenario, there was a very close match between the estimates based on eq. (7.160) and the sample standard deviations obtained with the *SPM* simulations, suggesting that the formula is correct.

For the Overall Error *OE* of the baseline scenario, there was a reasonable match (within 3%) between the estimates based on eq. (7.164) and the sample standard deviations obtained with the *SPM* simulations, suggesting that the formula for the variance of the Overall Error was correct. The outputs of the sensitivity analysis runs were also used in similar tests to confirm that eq. (7.164) provided a good approximation with a range of different parameters.

Finally, the relative importance of parameters was assessed. The sensitivity analysis demonstrated that risk was sensitive to the parameters relating to speed inaccuracies, but was insensitive to weather-related parameters. The latter can be explained by assuming that weather effects for leading and following aircraft tend to cancel out.

Part 3: Collision risk model

The standard Reich longitudinal collision risk model for was recalled in SARSIG/7-WP/05 as

$$N_{ax} = P_y(0)P_z(0) \left[\frac{|\bar{x}(t)|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \frac{1}{T} \frac{2\lambda_x}{|\bar{x}(t)|} \left[\sum_t E(t)Q(t) \right] \quad (7.165)$$

where N_{ax} denotes the number of fatal accidents per flight hour due to loss of longitudinal separation, $|\bar{x}(t)|$ denotes the longitudinal closing speed, T denotes the inter-waypoint flying time, and $\sum_t E(t)Q(t)$ denotes the probability of longitudinal overlap with $E(t)$ being the discrete distribution of planned separations and $Q(t)$ being the discrete probability of gaining/losing a given number of minutes or more of longitudinal separation. Notice that a factor of 2 for the conversion of collisions into accidents is missing on the right side of eq. (7.165).

The standard longitudinal collision risk model of eq. (7.165) may be compared with the models developed in the past by the NAT SPG as described in Section 6.4.2 for the benefit of the reduction of the in-trail longitudinal separation minimum from 15 minutes to 10 minutes as implemented on 26 November 1981, namely

- NAT SPG/4 (1967): $N_{ax} = 10^7 \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] P_y(0)P_z(0) \sum_t P_x(t)E_x(t) \quad (7.4)$

- NAT SPG/5 (1968): $N_{ax} = 2 \times 10^7 \times (4\lambda_x \sum_m E_x(m)P_x(m)) P_y(0)P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.12)$

- NAT SPG/14 (1978): $N_{ax} = 2 \times 10^7 \times \left(\frac{2\lambda_x |\bar{x}|}{T} \times \sum_m E_x(m)Q_x(m) \right) P_y(0)P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.23)$

As set out under the *NAT SPG/5 (1968)* heading in Section 6.4.2, the first factor λ_x on the right side of eq. (7.12) should be taken in minutes rather than in nautical miles and as set out under the *NAT SPG/14 (1978)* heading in Section 6.4.2, the parameter T on the right side of eq. (7.23) denoted the average crossing time of a flight in the NAT. However, following the United Kingdom's review (NAT SPG/32 MWG – WP/5) of references SPG/30-IP/48, SPG/31-WP/27 SPG/31-WP/28 and SPG/31-WP/29 and RGCS/9-WP/7 (Anderson, 1996b) presented at NAT SPG/32 (1996), see Section 7.2.4, an important change to the longitudinal collision risk model for the NAT was made, viz. that it should estimate the collision risk experienced by aircraft between waypoints. Consequently, the meaning of the T parameter was changed to flying time between waypoints. See the MIG/7 discussion under the MIG/7-WP/9 heading in Section 7.2.5.2.6.

Returning to in SARSIG/7-WP/05, this then stated that for the purpose of evaluating longitudinal collision risk for periodic reporting, the main change required was to re-interpret the expression for the probability of longitudinal overlap, $\sum_t E(t)Q(t)$. With new second-accuracy SAATS data having become available, under the proposed periodic reporting regime, $E(t)$ corresponded to the continuous distribution of Initial Forecast Separation (minimum separation plus buffer) and $Q(t)$ corresponded to the continuous distribution of Overall Error, OE , and the summation was replaced by an integral $\int_t E(t)Q(t)dt$. In addition, the parameter T was re-defined as the relevant period of exposure to risk, which for periodic reporting is the reporting period P . Thus, based on eq. (7.165), the Reich model for longitudinal collision risk utilized in SARSIG/7-WP/05 can be expressed as

$$N_{ax} = P_y(0)P_z(0) \left[\frac{|\overline{\dot{x}(t)}|}{2\lambda_x} + \frac{|\overline{\dot{y}}|}{2\lambda_y} + \frac{|\overline{\dot{z}}|}{2\lambda_z} \right] \frac{1}{P} \frac{2\lambda_x}{|\overline{\dot{x}(t)}|} \left[\int_t E(t)Q(t)dt \right] \quad (7.166)$$

Notice that the factor of 2 for the conversion of number of collisions into number of accidents is still missing, although the numerical results presented suggest that it was accounted for. It was emphasized that, from an operational perspective, waypoint position reports would continue to be used in addition to the periodic reports, but they were not taken into account in the collision risk model. It should also be noted that the collision risk model primarily considered technical risk. Given previous results, there was a focus on assessing whether a 5 minute RLongSM would be viable with 20 minute periodic reports.

The average lateral and vertical closing speeds, $|\overline{\dot{y}}|$ and $|\overline{\dot{z}}|$, were taken as constants whereas the longitudinal closing speed $|\overline{\dot{x}(t)}|$ was taken to vary with the initial separation, S , between aircraft, according to

$$|\overline{\dot{x}(t)}| = \frac{SV_L}{(t_L - S)/60} \quad (7.167)$$

where V_L is the speed of the leading aircraft and t_L is the transit time (in minutes) during which the risk of collision is present between aircraft. Given that there will be some conflict resolution delay between aircraft coming into conflict and a controller resolving that conflict, t_L was replaced by $P + \tau$, the sum of the reporting period and the conflict resolution delay, i.e.

$$|\overline{\dot{x}(t)}| = \frac{SV_L}{(P + \tau - S)/60} \quad (7.168)$$

Consider now the probability of longitudinal overlap defined by

$$\int_t E(t)Q(t)dt \quad (7.169)$$

with $E(t)$ being the continuous distribution of Initial Forecast Separation (minimum separation plus buffer) and $Q(t)$ being the continuous distribution of Overall Error, OE , defined by eq. (7.163), i.e.

$$OE = IE + RPE \quad (7.163)$$

The distribution of the Reporting Period Error, RPE , was represented by a zero-mean double exponential probability distribution (cf. eq. (4.19)) with shape¹¹¹ parameter b_{RPE} , say. It was then assumed that the shape of the probability distribution of the Overall Error, OE , was also double exponential, on the understanding that the Overall Error was dominated by the Reporting Period Error.

The shape parameter b_{OE} say, of the double exponential distribution of the Overall Error is related to the standard deviation of the Overall Error as (cf. eq. (4.22)),

$$b_{OE} = \frac{\sigma_{OE}}{\sqrt{2}} \quad (7.170)$$

An expression for the variance of the Overall Error over a reporting period P was given by eq. (7.164). However, as mentioned above in the discussion on the longitudinal closing speed $|\dot{x}(t)|$, the longitudinal collision risk is to be calculated over a time interval made up of the reporting period P and the conflict resolution delay τ . Thus, eq. (7.164) was modified to read

$$Var(OE) \cong (P + \tau)^2 VF(\gamma, P + \tau) + (P + \tau - S_0)^2 VF(\gamma, P + \tau - S_0) + S_0^2 WF(\alpha, S_0) + \frac{2N}{d^2} \quad (7.171)$$

where S_0 denotes the initial separation between the leading and following aircraft at the following aircraft's reporting time $t_F(n - 1)$. Eqs. (7.170) and (7.171) allow expressing the shape parameter b_{OE} of the double exponential distribution of the Overall Error to be expressed in terms of the initial separation S_0 , the reporting period P , the conflict resolution delay τ , the parameters γ and α of the speed inaccuracies and weather effects defined by eqs. (7.157) and (7.153) respectively, the variance N of the along-track navigation errors, and the distance d travelled in 1 minute at the cleared speed.

Given a double-exponentially distributed Operational Error OE , the probability of losing an amount of longitudinal separation y greater than or equal to an initial separation $S = S_0 = S_{min} + x$ was given by

$$P(y \geq S = S_{min} + x) = \frac{1}{2b_{OE}} \int_{S_{min}+x}^{\infty} \exp\left\{-\frac{|y|}{b_{OE}}\right\} dy = \frac{1}{2} e^{\{-(S_{min}+x)/b_{OE}\}} \quad (7.172)$$

which specified one part of the probability of longitudinal overlap defined by eq. (7.169).

The other part of the probability of longitudinal overlap relates to the continuous distribution $E(t)$ of Initial Forecast Separation, i.e. minimum separation S_{min} plus buffer x . Since, obviously, no data were available yet on the initial longitudinal separation distribution under RLongSM, SARSIG/7-WP/05 postulated this distribution to be a gamma distribution,

$$f(x) = \frac{x^{k-1} e^{-x/\theta}}{\Gamma(k)\theta^k} \quad , \quad x \geq S_{min} \quad (7.173)$$

¹¹¹ The b_{RPE} parameter should be called a scale parameter rather than a shape parameter, cf. eq (4.27) for the generalized Laplace probability density of which the double exponential is a special case.

with shape parameter k and scale parameter θ . The gamma distribution was considered to be useful because it can represent a variety of cases through a change in one or both of its key parameters. The parameters used for the baseline calculations were $k = 2$ and $\theta = 1$. This specified the other part of the probability of longitudinal overlap defined by eq. (7.169).

Thus, eq. (7.169) for the defined probability of longitudinal overlap was calculated as

$$\int_t^{\infty} E(t)Q(t)dt = \int_t^{\infty} f(x)P(y \geq S = S_{min} + x) \quad , \quad (7.174)$$

which resulted in

$$\int_t^{\infty} E(t)Q(t)dt = \frac{1}{2(1+\theta/b_{OE})^k} e^{\{-S_{min}/b_{OE}\}} \quad , \quad (7.175)$$

Baseline longitudinal collision risk was then calculated using the model of eqs. (7.166) and (7.175) for four value of the longitudinal separation standard/minimum S_{min} , $S_{min} = 4, 5, 6$, and 7 minutes for reporting periods of 10, 15, 20, ..., 45 minutes assuming a 95% longitudinal navigation performance of 0.5 NM and (for simplicity) a probability of lateral overlap of $P_y(0) = 1$ and a probability of vertical overlap of $P_z(0) = 0.48$. See in SARSIG/7-WP/05 for the aircraft dimensions and lateral and vertical closing speeds. For a longitudinal separation standard/minimum of 5 minutes, the approximate required reporting period for the baseline case was found to be 23 minutes for a TLS of 1.0×10^{-9} fatal accidents per flight hour and 25 minutes for a TLS of 2.5×10^{-9} fatal accidents per flight hour.

The baseline longitudinal collision risk calculation was supplemented with extensive sensitivity analysis, including 95 % along-track navigation performance, 1 NM, 2 NM, and 4 NM, 95% across-track navigation performance, 0.5 NM, 1 NM, 2 NM, and 4 NM, conflict resolution delay, 3 mins, 6 mins, 9 mins (baseline), and 12 mins, and the parameters k and θ of the gamma probability density $f(x)$ of the longitudinal separation buffer x in the initial longitudinal separation $S = S_0 = S_{min} + x$. It was concluded that, given baseline assumptions as to navigational accuracy, conflict resolution delay, and distribution of initial separation between aircraft, the risk assessment work performed for synchronous position reporting supported a 5-minute longitudinal separation standard/minimum with a 20 minute reporting period. The baseline collision risk values should give a conservative estimate of risk.

7.2.7.3 The RLongSM collision risk assessment presented at SASP/20 (May 2012)

Three Working papers (WP/25, WP/29 and WP/30) and two Information Papers (IP/09 and IP/10) were presented at the 20th Meeting of the ICAO SASP in May 2012 (SASP-WG/WHL/20).

SASP-WG/WHL/20-WP/29: Estimating the longitudinal separation loss distribution under periodic reporting using waypoint reporting data

WP/29 (Civil, 2012a) revisited a part of SARSIG/7-WP/05, viz. approximately the latter's Sections 5 and 6 (*Modelling collision risk* and *The simulation model*, excluding *Conflict resolution delay*) plus Section 8.2 (*Distribution of the Overall Error*), cf. Section 7.2.7.2. It queried the modelling in SARSIG/7-WP/05 of the distance flown as described in the previous Section 7.2.7.2 by eqs. (7.151) – (7.158) and formulated and

evaluated three improvements to the earlier modelling, leading to an improved version of the longitudinal gain/loss distribution $Q(s)$. WP/29 comprised the following sections:

1. Introduction;
2. Estimating separations;
3. Waypoint reporting data;
4. Basic Model;
5. Proposed modifications to the Basic Model;
6. Model optimisation;
7. Final model;
8. Separation loss under periodic reporting;
9. $Q(s)$; and
10. Recommendations.

Following the introductory Sections 1 and 2, Section 3 presented an analysis of two samples of NAT waypoint reporting data extracted from SAATS audit files. Since there were no systematic differences observed between the two datasets, they were combined into a single sample of 33223 leader-follower waypoint transit pairs. Forecasting errors for individual aircraft were computed as the differences between actual waypoint reporting times and ATC-system-generated forecasts of times the aircraft were expected at the next waypoint. The forecasting errors for individual aircraft were subsequently used to compute forecasting errors for aircraft pairs, i.e. gains or losses of longitudinal separation. For both individual aircraft and pairs of aircraft the (sample) variance of the forecasting error (taken as a proportion of the transit time) was computed as a function of the transit time between waypoints. A rather complex relationship between error variance and transit time was found. The data was used to estimate the parameters of an improved version of the Basic Model, which was ultimately used to calculate the gain/loss distribution $Q(s)$ under synchronous periodic position reporting.

Section 4 described the Basic Model, i.e. the modelling of the distance flown as described in the previous Subsection by eqs. (7.151) – (7.158) based on SARSIG/7 WP/05. The parameters of the Basic Model were (re-)estimated and this resulted in a minor change to the value of β , viz. from 0.99 to 1.0. With the Basic Model, the variance of the Overall Error, OE , (defined by eq. (7.163) over a reporting period of any duration can be derived, see eq. (7.164). The adequacy of the Basic Model was then examined by comparing the model output with the real waypoint transit data of Section 3, leading to the conclusion that the key behaviours of the data were not well replicated by the Basic Model. As a result, three improvements to the Basic Model were formulated.

As summarized in Section 5 of WP/29, the first modification was a minor simplification, viz. the removal of the weather effects over time – at a fixed location - component w_t defined by eq. (7.155) from the Basic Model. The second modification was to allow the variance of the (remaining) error components w_t and v_t defined by eqs. (7.153) and (7.157) to be quadratic functions of the forecast ground speed of the aircraft instead of being a fixed constant for all aircraft. This modification allowed a substantially improved replication of the key characteristics of the observed waypoint transit data. The third modification concerned a technical issue concerning the Central Limit theorem and the assumed double exponential distribution of the Reporting Period Error, RPE , and the Overall Error, OE , in SARSIG/7-WP/05. See Section 5 of WP/29 for further details.

Section 5 also addressed preliminary estimation of the parameters of the improved Basic Model, largely by trial and error. This was followed by a model optimisation step by means of a more rigorous and robust

parameter estimation method. See WP/29 again for further details. The final model with optimised parameter estimates was presented in Section 7 of WP/29.

Section 8 of WP/29 continued with the derivation of separation loss under periodic reporting, asynchronous as well as synchronous. It was noted that under waypoint reporting, the separation loss distribution is straightforward to estimate using the improved Basic Model as the difference between leader error and follower error over the inter-waypoint transit, because the shared weather component w_t can be ignored. Under periodic reporting, the situation is more complicated since part of the leader and follower transit time will be over the same section of airspace, but part will be unique. To assess the risk over the reporting period T , the time segment $[0, T]$ was split up into two parts, namely $[0, \Delta]$ and $[\Delta, T]$ where Δ is the phase difference between leader and follower reports. Notice that SARSIG/7-WP/05 used the symbol P instead of T for the reporting period. It should also be noted that the phase difference Δ as defined in WP/29 appears to differ from that used in SARSIG/7-WP/05, viz., symbolically, $\Delta_{Ref. 272} = T - \Delta_{Ref. 270}$.

For the time segment $[0, \Delta]$, the separation error, $s_\Delta - \hat{s}$ was then derived to be

$$s_\Delta - \hat{s} \approx -(\Delta - \hat{s})\bar{v}_L(\Delta - \hat{s}) + \Delta\bar{v}_F(\Delta) + \hat{s}\bar{w}(\hat{s}) + \frac{\delta_F(0)}{d} \quad (7.176)$$

where s_Δ is the actual separation at time Δ and $\hat{s}$ is the forecast separation at time Δ , $\bar{v}_L(\Delta - \hat{s})$, $\bar{v}_F(\Delta)$, and $\bar{w}(\hat{s})$ are the average (leading and following) aircraft and wind speeds over the time intervals $[0, \Delta - \hat{s}]$, $[0, \Delta]$, and $[0, \hat{s}]$ respectively, $\delta_F(0)$ is the along-track navigation error of the following aircraft at time 0, and d is the distance travelled in one minute at the cleared speed.

For the time segment $[\Delta, T]$, the separation error, $s_T - \hat{s}$ was subsequently derived to be given by

$$s_T - \hat{s} \approx -(T - \Delta - \hat{s})\bar{v}_L(T - \Delta - \hat{s}) + (T - \Delta)\bar{v}_F(T - \Delta) + \hat{s}\bar{w}(\hat{s}) - \frac{\delta_L(\Delta)}{d} \quad (7.177)$$

where $\delta_L(\Delta)$ is the along-track navigation error of the leading aircraft at time Δ and the average speeds pertain to the time intervals $[0, T - \Delta - \hat{s}]$, $[0, T - \Delta]$, and $[0, \hat{s}]$ respectively.

As argued before in SARSIG/7-WP/05, and again in WP/29, application of the separation loss equations within the longitudinal Reich model as a function of the phase difference Δ would be difficult and it was considered helpful, therefore, to have only a single equation for separation loss over the whole reporting period T . This was typically taken as the loss of separation assuming synchronous reporting. As stated in WP/29, intuitively, the risk under synchronous reporting should be higher than under asynchronous reporting with any phase difference since there are half as many reporting points at which controller intervention can occur, and the longest time between reports. On the other hand, under asynchronous reporting there is less information given at each reporting point so the separation estimates are likely to be less accurate and the conservatism of using synchronous reporting cannot automatically be assumed.

SARSIG/7-WP/05 assessed the risk under synchronous versus asynchronous reporting for the Basic Model of eqs. (7.151) – (7.164) by means of the SPM simulation model. WP/29 assessed the risk under synchronous versus asynchronous reporting for the improved Basic Model as described in the following paragraphs, where, for the case of synchronous reporting the separation error, $s_T - \hat{s}$ was shown to be given by

$$s_T - \hat{s} \approx -(T - \hat{s})\bar{v}_L(T - \hat{s}) + (T)\bar{v}_F(T) + \hat{s}\bar{w}(\hat{s}) - \frac{\delta_F(0) - \delta_L(0)}{d} \quad (7.178)$$

An unnumbered expression was given in WP/29 for the variance of the separation error of eq. (7.178) under synchronous reporting and this expression was the same as the formula for the variance of the Overall Error, OE , derived in SARSIG/7-WP/05 for the synchronous reporting case as reproduced in this Document by eq. (7.164) of Section 7.2.7.2.

Like SARSIG/7-WP/05, WP/29 took the probability distribution of the separation error to be a double exponential distribution with the scale parameter b say, equal to the standard deviation of the separation error divided by $\sqrt{2}$, cf. eq. (7.170). This distribution was assumed under synchronous as well as under asynchronous position reporting where for the latter case two distributions were utilized, viz. one for each of the respective periods $[0, \Delta]$ and $[\Delta, T]$. Expressions for the pertinent variances of the separation error were also given in WP/29 (but not in SARSIG/7-WP/05). For each of the three double exponential separation error distributions, the probability of losing greater than or equal to 5 minutes of longitudinal separation was calculated under a 20 minute reporting period for various forecast speeds and values of the phase difference Δ . For the asynchronous reporting case, the combined probability of longitudinal overlap over the whole reporting period was approximated by

$$P(y \geq s)_{[0,T]} \approx P(y \geq s)_{[0,\Delta]} + P(y \geq s)_{[\Delta,T]} \quad (7.179)$$

The calculations showed that, under asynchronous reporting, the total variance for each partial period as well as the overlap probability within each partial period and the combined probability across the total reporting period were all less than their counterparts for synchronous reporting, i.e. it was shown that, in line with the intuitive expectation and previous simulation studies, the asynchronous reporting case was uniformly less risky than the synchronous reporting case. This demonstrated that it was sufficient to consider only synchronous reporting within the collision risk model.

Having taken the probability distribution of the separation error under synchronous position reporting to be a double exponential distribution with the scale parameter b equal to the standard deviation of the separation error $s_T - \hat{s}$ defined by eq. (7.178) divided by $\sqrt{2}$, the probability distribution of a loss of planned separation of s or greater minutes by the end of the at-risk period, $Q(s)$, was given in Section 9 of WP/29 as

$$Q(s) = \frac{1}{2} e^{-s/b} \quad (7.180)$$

Cf. eq. (7.172) of Section 7.2.7.2.

The last, *Recommendations*, Section of WP/29 invited SASP to consider whether the methods described therein would be applicable to global procedural airspace and, if not, what further considerations would have to be made for the methods to be globally applicable. In particular, SASP was invited to consider endorsement of five specific elements of the modelling concept of WP/29.

SASP-WG/WHL/20-WP/25: Collision risk estimates under Reduced Longitudinal Separation Minimum operations

WP/25 (Civil, 2012c) provided an example calculation of the longitudinal collision risk under RLongSM operations in the NAT. It started with the following form of the Reich collision risk model for two aircraft

nominally on the same track and flight level with non-negligible intended longitudinal separation derived in IP/10 (Civil, 2012d),

$$N_{ax} = 2P_y(0)P_z(0) \left[\frac{|\dot{x}(m)|}{2\lambda_x} + \frac{|\dot{y}_0|}{2\lambda_y} + \frac{|\dot{z}_0|}{2\lambda_z} \right] \frac{1}{T} \frac{2\lambda_x}{|\dot{x}(m)|} \left[\sum_s E(s)Q(s) \right] \quad (7.181)$$

with T denoting the average at-risk period, i.e. the reporting period for periodic position reporting, and the other parameters having their usual meaning. Notice the inclusion of the collisions-accidents conversion factor of two on the right side of eq. (7.181). Apart from that and a minor change in notation for the closing speeds in the three dimensions, eq. (7.181) is the same as the model of eq. (7.165) utilized in SARSIG/7-WP/05. In fact, WP/25 can be considered to provide an update to Section 8, *Collision risk modelling for synchronous reporting*, of SARSIG/7-WP/05 utilizing the improved separation loss distribution $Q(s)$ derived in WP/29 based on the RLongSM concept described in IP/09 (which was essentially that described before in Sections 2 and 4 of SARSIG/7-WP/05). Since the argument s of the collision risk model parameters $E(s)$ and $Q(s)$ under RLongSM is treated as a continuous variable rather than a discrete one, the model of eq. (7.181) should actually be written as

$$N_{ax} = 2P_y(0)P_z(0) \left[\frac{|\dot{x}(m)|}{2\lambda_x} + \frac{|\dot{y}_0|}{2\lambda_y} + \frac{|\dot{z}_0|}{2\lambda_z} \right] \frac{1}{T} \frac{2\lambda_x}{|\dot{x}(m)|} \left[\int_s E(s)Q(s)ds \right] \quad (7.182)$$

Values of the collision risk model parameters other than $|\dot{x}(m)|$, $E(s)$, and $Q(s)$ were taken as those adopted for use within the NAT at the time, see Table 3-1 of WP/25. In order to make a conservative risk estimate, the longitudinal closing speed should be the smallest possible such that a longitudinal overlap occurs. The following formula was provided

$$|\dot{x}(m)| = \frac{60V_L \times m}{T} \quad (7.183)$$

where m denoted the longitudinal separation standard/minimum and V_L denoted the speed of the leading aircraft in NM/min. Eq. (7.183) may be compared with eqs. (7.167) and (7.168) of Section 7.2.7.2 utilized in SARSIG/7-WP/05.

The longitudinal closing speed of eq. (7.183) based on WP/25 may be compared with that of eq. (7.167) based on SARSIG/7-WP/05, where, using the current symbols, the latter would read $|\dot{x}(t)| = (60V_L \times m)/(T - m)$. With the reporting interval T larger than the longitudinal separation standard m , eq. (7.167) produces the larger closing speed. The difference between the two expressions turns out to be caused by which aircraft's speed is used to translate the longitudinal time separation m into an equivalent distance. WP/25 used the leading aircraft's speed for this while SARSIG/7-WP/05 used the following aircraft's speed for this purpose.

In the absence of any data on the probability distribution $E(s)$ of planned separations at the end of the at-risk period for all possible planned separations s , a gamma distribution with parameters k and θ was adopted for the separation buffer x over and above the longitudinal separation standard/minimum,

$$s = s_{min} + x \quad (7.184)$$

with probability density function $f(x)$ given by

$$f(x) = \frac{x^{k-1} e^{-x/\theta}}{\Gamma(k)\theta^k}, \quad x \geq 0 \quad (7.185)$$

The same distribution based on the same reasoning was utilized in SARSIG/7-WP/05, viz. that it can represent a variety of cases through a change in one or both of its key parameters. Parameter values used for the baseline risk calculations were $k = 2$ and $\theta = 1$, meaning an average buffer of 2 minutes and an average planned separation of 7 minutes under RLongSM operations.

Finally, the double-exponential probability distribution of a loss of planned separation of s or greater minutes by the end of the at-risk period, $Q(s)$, given by eq. (7.180) based on WP/29 was utilized.

The probability distributions $E(s)$ and $Q(s)$ were used to calculate the probability of longitudinal overlap as

$$Probability(overlap) = \int_{s_{min}}^{\infty} E(s)Q(s)ds = \frac{(k-1)!}{2\Gamma(k)(1+\theta/b)^k} e^{-s_{min}/b} \quad (7.186)$$

Using the baseline parameter values $k = 2$ and $\theta = 1$, eq. (7.186) simplifies to

$$Probability(overlap) = \int_{s_{min}}^{\infty} E(s)Q(s)ds = \frac{1}{2(1+1/b)^2} e^{-s_{min}/b} \quad (7.187)$$

It should be noted that, as explained in WP/29, the parameter b as a function of the variance of separation error $s_T - \hat{s}$ defined by eq. (7.178) is dependent on planned aircraft speed, which was taken as 480 kts.

As noted earlier in the beginning of the review of WP/29 above, *Conflict resolution delay* was not addressed therein. It was addressed, however, in SARSIG/7-WP/05 where it was concluded that a time to conflict resolution of 9 minutes would be a conservative assumption within the collision risk model. This figure has also been used within the WP/25 work, the impact of it being to increase the average at-risk period T by 9 minutes.

SASP-WG/WHL/20-WP/30: On the sensitivity of overtake probability in the analysis supporting proposals for a Reduced Oceanic Longitudinal Separation Minimum

WP/30 (Flax, 2012) examined the sensitivity of the probability of losing s or greater minutes of longitudinal separation, $Q(s)$, defined by eq. (7.180) to the parameter b of the double exponential distribution of the loss of planned separation. It was concluded that the overtake probability was quite sensitive to changes in b . It was also stated that it should be possible to extract initial separations and changes in separation from the position reports sent to the computer-based systems that monitor traffic flow in the North Atlantic Organized Track System (NAT OTS). The air navigation service providers in the NAT OTS were urged to take advantage of the opportunity to derive an empirically justified functional form and the relevant parameter values for the joint probability density function of initial separation and change in separation.

7.2.7.4 The RLongSM collision risk assessment presented at SASP/21 (November 2012)

WP/29 (Civil, 2012b) provided an update to WP/25 and IP/10 based on 12 months of data collected from the Shanwick OCA during the first year of the RLongSM operational trial in the NAT Region, which started on 28 March 2011 (refer to the text under the *NAT SPG/48 (2012)* heading in Section 7.2.6). The new collision risk assessment was required in support of the transition of the operational trial into full operational use in the NAT Region. It was also performed in support of the endorsement by ICAO of RLongSM as a globally

applicable procedure for inclusion into the ICAO PANS-ATM, see Section 7.2.7.1. WP/29 comprised the following sections:

1. Introduction;
2. Data;
3. Methodology;
4. Derived distributions and parameter estimates;
5. Collision risk estimates;
6. Conclusions of NAT RLongSM longitudinal collision risk analysis;
7. Recommendations; and
8. References

The *Introduction* included the following form of the longitudinal collision risk model, which was the same as that listed before in SASP-WG/WHL/20-WP/25, viz.

$$N_{ax} = 2P_y(0)P_z(0) \left[\frac{|\bar{x}(m)|}{2\lambda_x} + \frac{|\bar{y}_0|}{2\lambda_y} + \frac{|\bar{z}_0|}{2\lambda_z} \right] \frac{1}{T} \frac{2\lambda_x}{|\bar{x}(m)|} \left[\sum_s E(s)Q(s) \right] \quad (7.181)$$

However, like in WP/25, the form actually used was the one based on continuous rather than discrete distributions $E(s)$ and $Q(s)$, i.e.

$$N_{ax} = 2P_y(0)P_z(0) \left[\frac{|\bar{x}(m)|}{2\lambda_x} + \frac{|\bar{y}_0|}{2\lambda_y} + \frac{|\bar{z}_0|}{2\lambda_z} \right] \frac{1}{T} \frac{2\lambda_x}{|\bar{x}(m)|} \left[\int_s E(s)Q(s)ds \right] \quad (7.182)$$

The SAATS ADS-C data processing was described in Section 2 of WP/29. The data used from each ADS-C report (waypoint and periodic) consisted of date, time, aircraft identification, position in lat/lon, flight level, and SAATS forecast time at the next waypoint. The data required was for an 18-minute reporting interval without any interim waypoint or demand reports and to achieve that, pairs of successive periodic reports were extracted, together with the previous and next waypoint reports. This format played an important role in determining the two key parameters of the longitudinal collision risk model, $E(s)$ and $Q(s)$ (see Figures 7.3 and 7.4 below). Given that data had been obtained from actual NAT RLongSM operations (albeit under an operational trial status), a new methodology for the estimation of $E(s)$ and $Q(s)$ had to be developed. The following information was calculated for each 18-minute reporting interval: local route (a unique identifier based on previous and next waypoints), distance travelled between periodic reports, and ground speed between periodic reports. Some characteristics of the data shown also in Section 2 were direction of flight, flight level usage, and aircraft ground speed.

The *Methodology* Section started offering two possible ways to define $E(s)$ and $Q(s)$, where $E(s)$ is the distribution of separations and $Q(s)$ is the probability of losing s or greater minutes of separation during the at-risk period, namely

1. $E(s)$ is based on the actual separations at the start of the at-risk period and $Q(s)$ is based on the actual change in separation experienced during the at-risk period;
2. $E(s)$ is based on the intended separations at the end of the at-risk period, forecast at the beginning of the period, and $Q(s)$ is based on the error in the forecast separations at the end of the at-risk period.

Noting that under the first option $E(s)$ and $Q(s)$ could not be considered to be independent of each other and should thus be estimated as a joint distribution, the second option was preferred and utilized.

With data collected under actual RLongSM trial operations, $E(s)$ and $Q(s)$ under asynchronous reporting were assessed directly, i.e. without the use of the distance flown model described by eqs. (7.151) – (7.158) of Section 7.2.7.2 and without synchronous reporting taken as a conservative approximation to asynchronous reporting. However, at each periodic reporting point the current separation and forecast separations at future periodic reports are unknown. This was resolved as sketched in Figure 7.3. The blue and green lines show the (traditional) forecast times of passing the next waypoint based on the position reports at the previous waypoint of the leading and following aircraft respectively. The red lines for both aircraft show the forecast times of passing the next waypoint based on their first periodic position report after passing the previous waypoint. The difference between the two forecasts was called the initial forecast separation s_1 and this s_1 was used to derive the distribution $E(s)$.

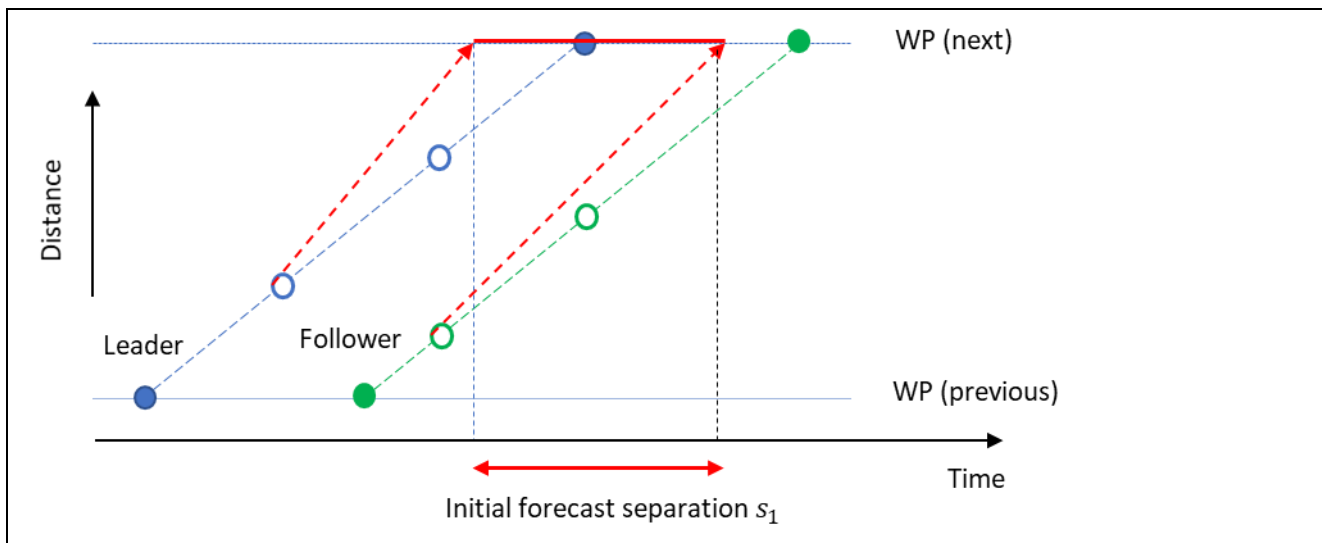


Figure 7.3: Initial forecast separation s_1 at the next waypoint

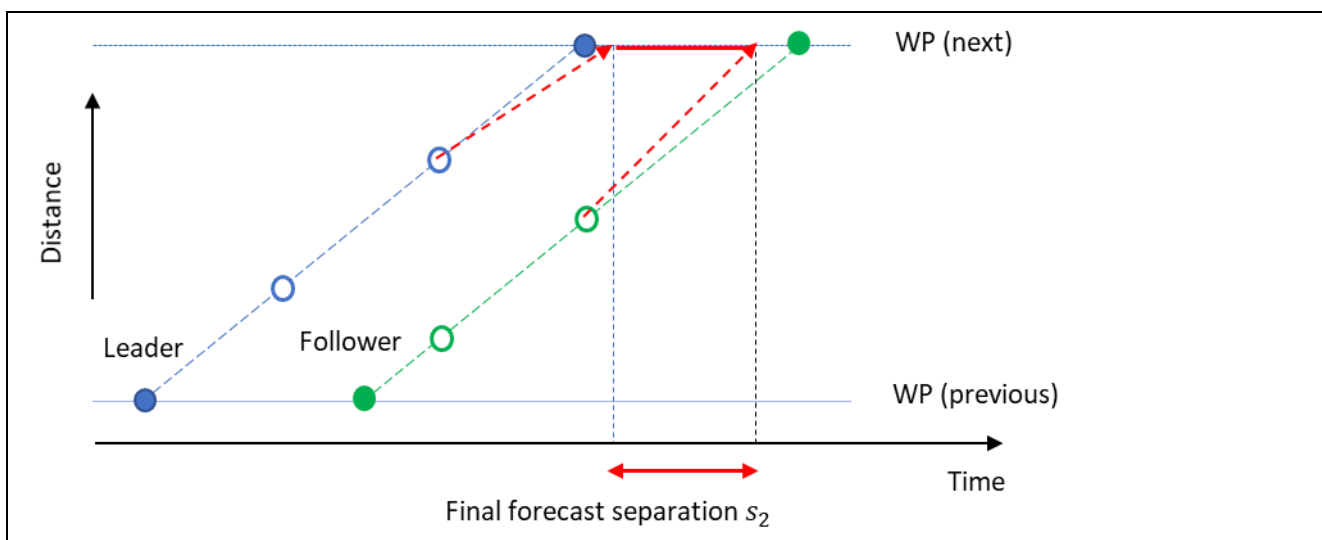


Figure 7.4: Final forecast separation s_2 at the next waypoint

Figure 7.4 above shows what was called the final forecast separation s_2 in WP/29, i.e. the forecast separation based on each aircraft's second periodic report during their transit from the previous to the next waypoint. The change in separation $s_2 - s_1$ was used to serve as a proxy for the change in separation over the reporting

period and used as the basis for the gain/loss distribution $Q(s)$. When there are three or more periodic reports by the leading and following aircraft between waypoints, multiple sets of periodic reports can be constructed, which, however, are not all independent. Therefore, the reporting interval to be considered was explicitly defined as the time between the following aircraft's periodic reports with the leading aircraft's first periodic report being earlier than the following aircraft's first periodic report. This was conservative because the possibility of the controller initiating an intervention triggered by the leading aircraft's second periodic report was ignored, and thus effectively equivalent to synchronous reporting.

It was noted that a limitation of the methodology utilized for the estimation of $E(s)$ and $Q(s)$ as outlined above was the possibility that the risk of collision being assessed was not that within the reporting period but rather the risk of collision occurring between the first periodic report and the following waypoint report. In that case, the additional time between the second periodic report and the following waypoint report could serve as a proxy to the Conflict Resolution Delay (CRD), (referred to as pseudo CRD in WP/29), with no further adjustment required to the analysis. Some analysis, however, suggested that this assumption was not correct and a non-trivial adjustment was necessary. To account for the additional duration of the at-risk period due to the CRD, the variance of the separation gain/loss distribution derived from the 18 minute reporting period was scaled upwards. Utilizing some of the results of SARSIG/7-WP/05 on scaling of the variance of the gain/loss distribution, the standard deviation of the separation gain/loss distribution was scaled upwards proportionately to the additional time due to CRD.

Section 4 of WP/29 presented the derived distributions $E(s)$ and $Q(s)$ as well as the other collision risk model parameters. The empirical distribution of forecast separation at the next waypoint showed that despite longitudinal separations of less than 10 minutes being available to the aircraft in the data sample, the applied separations remained greater than 10 minutes in the majority of cases. The smallest forecast separation available within the data sample was 5 minutes and 29 seconds, showing a (small) buffer over and above the longitudinal separation standard/minimum. Following the use of a hypothesized gamma distribution for the planned separation $E(s)$ in the earlier RLongSM collision risk assessments of SARSIG/7-WP/05 and SASP-WG/WHL/20-WP/25, WP/29 fitted a gamma distribution as defined by eq. (7.185) with parameters k and θ to the empirical distribution of forecast separation at the next waypoint. The baseline parameter values estimated were $k = 6$ and $\theta = 1.5$ giving a mean forecast separation at the next waypoint of $5 + 6 \times 1.5 = 14$ minutes. Two variations for sensitivity analysis were also considered, namely $k = 5$ with $\theta = 1.4$ and $k = 2$ and $\theta = 1$. The latter set of parameter values had been used previously as baseline parameters in SARSIG/7-WP/05 and SASP-WG/WHL/20-WP/25 to support the collision risk assessment prior to the start of the RLongSM trial.

The empirical distribution of the forecast separation gain/loss at the next waypoint closely resembled a double-exponential distribution. However, fitting a simple double-exponential distribution to the empirical distribution revealed that the tails of the empirical distribution were under-estimated. Thus a zero-mean double double exponential distribution $f_{DDE}(s)$,

$$f_{DDE}(s) = (1 - \alpha) \frac{1}{2a_1} \exp\left(-\left|\frac{s}{a_1}\right|\right) + \alpha \frac{1}{2a_2} \exp\left(-\left|\frac{s}{a_2}\right|\right) \quad (7.188)$$

was fitted to the empirical distribution, resulting in the following best-fit parameter values: $\alpha = 0.11$, $a_1 = 0.11$ minutes and $a_2 = 0.27$ minutes. As explained earlier, for the ultimate calculation of $Q(s)$ the parameters a_1 and a_2 were to be scaled for 4 minutes Conflict Resolution Delay (CRD), resulting in $b_1 = 0.13$

minutes and $b_2 = 0.33$ minutes. Calculating $Q(s)$ based on a double double exponential distribution with the latter parameter values resulted in (cf. eq. (7.180)) in the following baseline $Q(s)$ distribution,

$$Q(s) = \frac{1-\alpha}{2} e^{-s/b_1} + \frac{\alpha}{2} e^{-s/b_2} \quad (7.189)$$

with $\alpha = 0.11$, $b_1 = 0.13$ minutes and $b_2 = 0.33$ minutes.

Two variations of the baseline $Q(s)$ model for sensitivity analysis were also examined, namely one for a mixture distribution $f_{DDE}(s)$ with parameter values $\alpha = 0.16$, $b_1 = 0.13$ minutes and $b_2 = 0.38$ minutes, and one for a simple double exponential distribution, covered by eq. (7.188) with $\alpha = 0$ and $b_1 = 0.24$ minutes.

As regards average Conflict Resolution Delay (CRD), SASP-WG/WHL/20-WP/25 used a value of 9 minutes for it, but this value had been strongly criticized in the SASP MSG review at the time for being too conservative and a more appropriate value of 4 minutes had been recommended. The latter value was adopted as baseline value for the SASP-WG/WHL/21-WP/29 assessment whereas the former was adopted for sensitivity analysis purposes.

The total at-risk period T (hours) (cf. eq. (7.182)) was made up of the reporting period plus the CRD, i.e.

$$T = \frac{18+CRD}{60} \quad (7.190)$$

and the average longitudinal closing speed (knots) given minimum longitudinal separation of 5 minutes was conservatively taken as

$$|\dot{x}(5)| = \frac{V_L \times 5}{T} \quad , \quad (7.191)$$

cf. eq. (7.183).

Baseline values for $P_y(0)$ and $P_z(0)$ were taken as $P_y(0) = 0.6$ (assuming FANS-equipped aircraft) and $P_z(0) = 0.48$. For sensitivity analysis purposes, $P_y(0) = P_z(0) = 1.0$ was used. Average aircraft dimensions and average absolute relative lateral and longitudinal speeds were taken as those adopted for use within the NAT at the time, see Table 4-1 of SASP-WG/WHL/21-WP/29 (and were the same as utilized in SASP-WG/WHL/20-WP/05).

The baseline longitudinal collision risk under RLongSM operations with an 18-minute periodic reporting period was then estimated to be (in fatal accidents per flight hour)

$$N_{ax} = 1.07 \times 10^{-12} \quad (7.192)$$

This estimate was to be compared with a target level of safety (TLS) of 5×10^{-9} fatal accidents per flight hour, which showed that the baseline estimate was substantially below the TLS. Each of the variations for sensitivity analysis were then assessed in turn, providing the following range of estimates (in fatal accidents per flight hour): from 1.07×10^{-14} to 1.92×10^{-9} . The upper bound of this range occurred for the gamma distribution $E(s)$ with parameters $k = 2$ and $\theta = 1$ of the separations, i.e. a separation distribution with a mean of $5 + 2 \times 1 = 7$ minutes and the majority of separations close to the minimum of 5 minutes. This,

however, was assumed to be an extreme distribution, unlikely to be realised within the NAT, and so might not be cause for concern.

7.2.8 ASEPS, Advanced Surveillance-Enhanced Procedural Separation (2015 – 2019)

Advanced Surveillance-Enhanced Procedural Separation (ASEPS) refers to oceanic separation where position surveillance reporting of order 2 – 60 seconds is available (ICAO, NN). Current technologies that may support ASEPS include space-based ADS-B. It was discussed for the lateral dimension in Section 5.3.6. In the longitudinal dimension, it concerns longitudinal separation minima of 15 NM¹¹². This minimum may be compared with the conventional distance-based longitudinal separation minima of 30 NM and 50 NM for RNP 4 and RNP 10 aircraft respectively (see Sections 7.3.2 – 7.3.4).

Table 7.7 in Section 7.2.6 listed the NAT SPG meetings at which longitudinal separation was on the Group's agenda for the period 2006 – 2020. It included references to Agenda Items related to ASEPS for the period 2015 – 2019, but discussion of those Agenda Items was deferred to this Subsection. Thus, in a similar manner as in the previous Sections 6.4.2, 7.2.3, and 7.2.6, the material in this Subsection is based on review of the *Summary of Discussions and Conclusions of the Fifty-First to Fifty-Fifth Meetings of the North Atlantic Systems Planning Group*. A brief discussion of the work reported under the pertinent agenda items is provided by Meeting. The discussion presents the developments that led to the start of an operational trial with 15 NM longitudinal separation in the NAT Region on **28 March 2019**, but does not present the underlying collision risk assessment. A longitudinal collision risk assessment was performed by the ICAO SASP in support of a PANS-ATM amendment for ASEPS-based separation minima (Amendment 9 to the 16th Edition of the PANS-ATM).

NAT SPG/51 (2015)

The Group was provided with information on the planned implementation of Air Traffic Service (ATS) surveillance enabled services using space-based Automatic Dependent Surveillance – Broadcast (ADS-B) in the North Atlantic OCAs and it was noted that the ANSPs providing services in the Gander and Shanwick OCAs, NAV CANADA and NATS, had been coordinating on a common implementation strategy for ATS services using Space-Based ADS-B (SB ADS-B). The then current focus was on the implementation on **1 February 2018** of a longitudinal application of 15 NM ATS surveillance separation as described in paragraph 4.1.22 of the *Summary of Discussions and Conclusions of the Fifty-First Meeting of the North Atlantic Systems Planning Group*. See Table 2.5 of Chapter 2. The NAT SPG noted that all required procedures, analyses and planning documents would be coordinated through the NAT SPG working structure to ensure all NAT stakeholders would have the ability to engage in this activity. The NAT SPG was also informed that coordination was ongoing to further enhanced services post the February 2018 implementation, considering for example, the application of lateral 15 NM ATS surveillance enabled separation between non-intersecting tracks. Cf. Section 5.4.4.

¹¹² This minimum features in the *Summary of Discussions and Conclusions* of the NAT SPG Meetings reviewed in this Subsection. The actual longitudinal separation minima for the longitudinal ASEPS Trial can be found in NAT OPS bulletins 2018-006 and 2019-002 and will be listed at the end of this Subsection.

NAT SPG/52 (2016)

Under Agenda Item 4.1, *Joint CONOPS supporting Space-based ADS-B implementation*, the NAT SPG was provided by Canada and the United Kingdom with a joint Concept of Operations (CONOPS) supporting the initial implementation of Space-Based ADS-B (SB ADS-B) services in the Gander and Shanwick OCAs. The Group noted that the joint CONOPS supported the introduction of surveillance-enabled separation, referring to the procedural minima being developed by the ICAO SASP that would depend upon ATS surveillance for position information. It was also noted that it was the intention of Canada and the United Kingdom to apply these minima on a trial basis beginning in **February 2018**, pending full global applicability. The procedures and application would be in accordance with the SASP's proposed amendment to the PANS-ATM and their supporting draft Circular (ICAO, NN). The new minima and other changes to the services would be introduced in a phased manner.

NAT SPG/53 (2017)

Regarding space-based ADS-B, the following material has been reproduced from the *Summary of Discussions and Conclusions of the Fifty-Third Meeting of the North Atlantic Systems Planning Group*¹¹³:

"The NAT SPG was provided with an update on the NAT progress concerning the Space-based Automatic Dependent Surveillance – Broadcast (SB ADS-B) implementation. The Group noted that the outcome of the ICAO Separation and Airspace Safety Panel (SASP) work would need to be taken into account in further updates to the provisional version of the NAT SB ADS-B Concept of Operations (CONOPS). With regards to the NAT Safety Plan, the NAT SPG noted that the safety documentation in support of the SB ADS-B implementation would include the following:

- c) documentation produced by the ICAO SASP, including collision risk modelling (CRM) work and guidance to implementers describing all actions that would need to be completed; and
- d) safety management information produced by NAT air navigation service providers (ANSPs) implementing SB ADS-B.

Furthermore, the NAT SPG was presented with a proposal outlining a set of prerequisites for an operational trial for application of ASEPS based on SB ADS-B in the ICAO NAT Region. The NAT SPG recalled that a number of NAT ANSPs formalized, or were in the process of formalizing, arrangements with the SB ADS-B service provider. Once it was confirmed that service provided would meet the performance requirements, this new capability could be made available to support new and improved ATS in the NAT Region, as outlined in the NAT SB ADS-B CONOPS. The NAT SPG noted that the collision risk modelling within the ICAO SASP to support ASEPS was nearing completion and that the joint Canada/United Kingdom concept of operations anticipated using the procedures developed by the SASP on a trial basis, pending publication of the minima in PANS-ATM (Doc 4444). The NAT SPG supported, in principle, the proposed operational trial for application of ASEPS based on SB ADS-B in the NAT Region and noted that such a trial would also provide valuable data and experience to support finalization of the global criteria. However, the completion of the work on the set of prerequisites would need to be reported and approved by the NAT SPG prior to the trial.

In this respect, IFALPA stated that while being supportive of the significant safety benefits derived from ASEPS implementation and their intention to participate proactively through various ICAO bodies in the development of operating procedures and standards, taking into account the significant remaining issues surrounding PBCS implementation and RLatSM Phase 2 expansion, consideration of "new" operational trials was premature. IFALPA believed that information on the forthcoming expansion of available satellites,

¹¹³ The same quotation was presented in Section 5.3.6 concerning ASEPS lateral separation minima.

further development of SB ADS-B CONOPS, data on current equipage levels, and feedback from various ICAO Groups (i.e. SASP) should be gathered and presented to the various NAT SPG contributory bodies to enable identifying specific proposed trial components that would form the basis for establishing an appropriate trial timeline.

In connection with the above, the NAT SPG recalled that the NAT Space Based ADS-B Project Team (SB ADS-B PT) was developing an implementation plan and a supporting task list for implementation of SB ADS-B in the NAT that would be reviewed by NAT IMG and NAT SOG and approved by NAT SPG. The NAT SPG was presented with an initial list of tasks that was agreed for insertion into the above-mentioned SB ADS-B PT work.

Based on the foregoing, it was agreed in *NAT SPG Conclusion 53/5 – Prerequisites for SB ADS-B Operational Trial*, that the following prerequisites are to be fulfilled in order to enable an operational trial to use Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B):

- h) the Separation and Airspace Safety Panel (SASP) has agreed minima and associated requirements for Advanced Surveillance-Enabled Procedural Separation (ASEPS);
- i) implementing Air Navigation Services Providers (ANSP) have:
 - v) completed ASEPS implementation plans aligned to the NAT SB ADS-B Concept of Operations (CONOPS) and the SASP output referred to in a) above;
 - vi) confirmed their SB ADS-B service meets identified performance requirements;
 - vii) completed safety management activities as required by their respective regulatory authorities; and
 - viii) confirmed that the Performance Based Communication and Surveillance (PBCS) performance is measured and reported in the same manner as other applications of reduced separation in the NAT;
- j) the plans and the outputs of the safety management activities referred to in b) above have been reviewed by the NAT Implementation Management Group (NAT IMG) and the NAT Safety Oversight Group (NAT SOG);
- k) the NAT IMG and NAT SOG identify success criteria and trial duration;
- l) neither the NAT IMG nor the NAT SOG identifies an issue that, in their opinion, requires resolution before an operational trial should commence;
- m) the NAT IMG has confirmed that implementing ANSPs have completed all required implementation activities; and
- n) NAT SPG has approved the implementation plan and supporting task list that would also include the above listed prerequisites to enable a trial for implementation of SB ADS-B in the NAT.”

NAT SPG/54 (2018)

Regarding space-based ADS-B, the following material has been reproduced from the *Summary of Discussions and Conclusions of the Fifty-Fourth Meeting of the North Atlantic Systems Planning Group*¹¹⁴:

“The NAT SPG was presented with a status of implementations of actions agreed by NAT SPG Conclusion 53/5 (*Prerequisites for SB ADS-B Operational Trial* under the *NAT SPG/53 (2017)* heading above refers). With regards to c) of the foregoing conclusion, the NAT SPG was informed that the Second meeting of the ICAO Separation and Airspace Safety Panel (SASP/2) (Montreal, Canada, 7-18 May 2018) agreed on an Advanced Surveillance Enhanced Procedural Separation (ASEPS) Proposal for Amendment (PfA) to the *Procedures for Air Navigation Services — Air Traffic Management* (PANS-ATM, Doc 4444). The proposed changes to the

¹¹⁴ The same quotation was presented in Section 5.3.6 concerning ASEPS lateral separation minima.

PANS-ATM should become effective on **5 November 2020**. The NAT SPG noted that the proposal for Doc 4444 amendment would be normally expected during the spring of 2019 and a State Letter informing about the approval of the amendment would be circulated in the first half of 2020. Should any developments at these stages suggest that there might be any changes to the current SASP agreed wording, the Secretariat would take appropriate actions to inform the NAT SPG to discuss possible follow up actions with regards to the NAT trial.

Concerning sub-item n) of NAT SPG Conclusion 53/5, the NAT SPG was provided with the latest draft Implementation Plan and Task list (Appendix B¹¹⁵ refers) in support of an operational trial of ASEPS using Space-based Automatic Dependent Surveillance-Broadcast (SB ADS-B). It was noted that the Implementation Plan and Task List were intended to cover both longitudinal and lateral separation applications, with the application of lateral separation proposed to commence no earlier than 6 (six) months after commencement of the longitudinal separation application. As per NAT SPG Conclusion 53/5, the Implementation Plan and Task List integrated and described in detail the prerequisites for the Operational Trial of ASEPS using SB ADS-B. In conjunction with this, the NAT SPG was also provided with the provisional version of the NAT SB ADS-B Concept of Operations (CONOPS) (Appendix C¹¹⁶ refers), developed by the SB ADSB Project Team, that would be further updated by the North Atlantic Procedures and Operations Group (NAT POG) taking the SASP outcomes into account.

This Implementation Plan (and associated Task List) supports a trial implementation period beginning in **March 2019** and follows the guidelines provided in ICAO Doc 9689 (Manual on Airspace Planning Methodology for the Determination of Separation Minima). The NAT SPG agreed that the foregoing documents would be further reviewed by the NAT IMG and NAT SOG contributory bodies culminating in the NAT IMG/53 and NAT SOG/19 meetings to ascertain whether all prerequisites of NAT SPG Conclusion 53/5 had been appropriately addressed so that the decision on the commencement of the NAT ASEPS trial using SB ADS-B could be taken.

Based on the above, the NAT SPG agreed to the following: *NAT SPG Conclusion 54/9 – Operational Trial of Advanced Surveillance Enhanced Procedural Separation (ASEPS) using Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B)* That:

- c) the Implementation Plan and Task List for an operational trial of Advanced Surveillance-Enhanced Procedural Separation (ASEPS) using Space-Based Automatic Dependent Surveillance-Broadcast (SB ADS-B) be approved by the NAT IMG/53 and the NAT SOG/19 meetings, provided that the NAT IMG and NAT SOG have ascertained that all prerequisites of NAT SPG Conclusion 53/5 have been satisfied; and
- d) subject to the NAT IMG and NAT SOG approval, the operational trial be planned to:
 - iii) commence on **28 March 2019** provided all prerequisites of NAT SPG Conclusion 53/5 have been satisfied; and
 - iv) ii) continue until **5 November 2020** or the effective date of ASEPS provisions in the *Procedures for Air Navigation Services - Air Traffic Management* (PANS-ATM, Doc 4444), whichever is later.”

NAT SPG/55 (June 2019)

Regarding *Operational trial of ASEPS using SB ADS-B*, the following material has been reproduced from the *Summary of Discussions and Conclusions of the Fifty-Fifth Meeting of the North Atlantic Systems Planning Group*¹¹⁷:

¹¹⁵ Appendix B to the *Summary of Discussions and Conclusions of the Fifty-Fourth Meeting of the North Atlantic Systems Planning Group*.

¹¹⁶ Appendix C to the *Summary of Discussions and Conclusions of the Fifty-Fourth Meeting of the North Atlantic Systems Planning Group*.

¹¹⁷ The same quotation was presented in Section 5.3.6 concerning ASEPS lateral separation minima.

“The NAT SPG was informed that in follow up to NAT SPG Conclusion 54/9, the NAT IMG/53 and NAT SOG/19 carried out an analysis of all the pre-requisites contained in NAT SPG Conclusion 53/5 and agreed that all of the pre-requisites had been met for the Operational Trial of ASEPS using SB ADS-B in the longitudinal dimension to start on 28 March 2019. Therefore, the conditions of the NAT SPG Conclusion 53/5 had been fulfilled and the trial could proceed as agreed on **28 March 2019**.

Following the positive outcome from the NAT IMG/53 and NAT SOG/19 meetings, the NAT SPG Conclusion 55/1 was endorsed by correspondence and the following documents were published:

- d) *NAT OPS Bulletin – Trial Implementation of ASEPS using ADS-B* (Serial no: 2018_006);
- e) *NAT OPS Bulletin - Special Procedures for In-flight Contingencies* (Serial no: 2018_005); and
- f) amendment to the *North Atlantic Operations and Airspace Manual* (NAT Doc 007).

Therefore, the operational trial of ASEPS using ADS-B in the longitudinal dimension commenced in the NAT on 28 March 2019. Furthermore, the NAT SPG was presented with updates to the Implementation Plan for Operational Trial of ASEPS using ADS-B, and the draft NAT Operations (OPS) Bulletin addressing the expansion of the ASEPS Operational Trial to include lateral spacing of 19 NM between non-intersecting tracks. Concerning the safety cases, it was noted that NAT SOG/20 was presented with a draft Safety Case covering Shanwick and Gander Oceanic Control Areas (OCAs) and identified no issues requiring resolution before an operational trial should commence for ASEPS lateral. The final safety cases would be submitted to the NAT SOG by correspondence and pending that submission, it was agreed that, all of the pre-requisites for NAT SPG Conclusion 54/9 had either been satisfied or a process had been put in place to ensure that they would be satisfied prior to the implementation date of the Operational Trial of ASEPS using SB ADS-B in the lateral dimension within Gander and Shanwick OCAs. Therefore, following the successful commencement of the ASEPS Longitudinal Separation Operational Trial on 28 March 2019, it was agreed that the date to commence the Lateral Separation Operational

Trial would be **10 October 2019**. The NAT OPS Bulletin would be published by 15 August 2019 together with State AICs which would allow for 2 AIRAC cycles notice.”

Remark

As stated in a footnote at the beginning of this Subsection, a 15 NM ASEPS-based longitudinal separation minimum featured in the *Summary of Discussions and Conclusions* of the NAT SPG Meetings reviewed as a kind of place holder for the actual minima used dependent on the traffic type. The latter are given in NAT SPG Bulletins (NAT SPG, 2018, 2019) and read as follows:

“1.3 **On or soon after the 28 March 2019**, Shanwick, Gander and Santa Maria Oceanic Control Areas will commence a trial implementation of the following longitudinal separations. Application of the ATS Surveillance based procedural longitudinal separation will be as per the PANS ATM, Doc 4444 proposal for amendment from the ICAO SASP, as paraphrased below:

a) *17 NM longitudinal separation of aircraft operating on same track or intersecting tracks provided, that the relative angle between the tracks is less than 90 degrees.*

b) *14 NM provided the relative angle between the tracks is less than 45 degrees.*

c) *Opposite-direction aircraft on reciprocal tracks may be cleared to climb or descend to or through the levels occupied by another aircraft provided that the aircraft have reported by ADS-B having passed each other by 5 NM.”*

7.3 Longitudinal collision risk modelling by the ICAO RGCSP and SASP

7.3.1 Introduction

Since its establishment in 1973, the Review of the General Concept of Separation Panel (RGCSP), renamed the Separation and Airspace Safety Panel (SASP) in 2001, has supported ICAO's Air Navigation Commission (ANC) in the development of new or amended Standards and Recommended Practices (SARPs) and Procedures for Air Navigation Services (PANS) that are effective and practical for end-users, see Section 2.2. As set out in that Section, the development of SARPs and PANS follows a structured, transparent and multi-staged process, often known as the ICAO "amendment process" or "standards-making process". Typically, it takes approximately two years for an initial proposal for a new or improved Standard, Recommended Practice, or procedure to be formally adopted or approved for inclusion in an Annex or PANS. An Amendment proposal for e.g. the PANS-ATM is to be agreed by the RGCSP/SASP (sometimes in coordination with other ICAO Panels) at a formal Panel Meeting, after preparatory work has been performed at a number of (less formal) Working Group Meetings, the number of such meetings generally being dependent on the complexity and amount of preparatory work needed to be performed. Usually, the RGCSP/SASP meets twice a year for a two-week (working group) meeting. Two RGCSP Meetings from the past that are of particular interest with respect to longitudinal collision risk modelling are the 9th (May 1996) and 10th (May 2000) Meetings at which PANS-ATM Amendment Proposals for 50 NM and 30 NM distance-based longitudinal separation standards/minima were agreed. The pertinent collision risk modelling was initially constrained to aircraft on same-identical (zero angle) tracks as and will be described in Sections 7.3.2 and 7.3.3. Longitudinal collision risk modelling for arbitrary intersection angles will be described in Sections 7.3.4 ff.

The introduction to this Chapter, Section 7.1, started listing three differences between lateral and vertical separation on the one hand and longitudinal separation on the other, namely:

- Lateral and vertical separation standards/minima may be said to be expressed in terms of distance in nautical miles and feet respectively. Longitudinal separation, on the other hand, can be based on time or distance;
- The application of longitudinal separation covers aircraft maintaining the same level as well as aircraft climbing and descending; and
- Longitudinal collision risk modelling uses a distribution of nominal longitudinal entry-separations, all equal to or larger than the longitudinal separation standard/minimum rather than a fixed nominal entry separation equal to the lateral or vertical separation standard/minimum.

There is one more difference to be noted concerning the longitudinal separation minima developed by the ICAO RGCSP and SASP for incorporation into ICAO Doc 4444, PANS-RAC/PANS-ATM¹¹⁸. The previous two Chapters extensively used the terms *same-direction* traffic and *opposite-direction* traffic, where for the lateral case these terms were used for aircraft flying (at the same flight level) on adjacent parallel routes and for the vertical case for aircraft flying at adjacent flight levels of the same track, or, more precisely, the same-identical (180 degree angle) track, in the pertinent direction. The terms *crossing* or *intersecting* routes/tracks were used, in principle, without any restriction on the magnitude of the intersection/crossing angle (other than it

¹¹⁸ The ICAO PANS-ATM started as PANS-ATC, DOC D.349 ATC/D.51, 1st – 3rd Editions, continued as PANS-RAC, Doc 4444-RAC/501/1, 4th – 13th Editions, to finally become PANS-ATM, Doc 4444 ATM/501, 14th Edition ff.

not being 0 or 180 degrees). In the context of the application of longitudinal separation, however, the terms same track, reciprocal tracks, and crossing tracks have specific meanings as defined in paragraph 5.4.2.1.5 of the PANS-ATM as follows:

- a) Same track (see Figure 5-7):
same direction tracks and intersecting tracks or portions thereof, the angular difference of which is less than 45 degrees or more than 315 degrees, and whose protected airspaces overlap.
- b) Reciprocal tracks (see Figure 5-8):
opposite tracks and intersecting tracks or portions thereof, the angular difference of which is more than 135 degrees but less than 225 degrees, and whose protected airspaces overlap.
- c) Crossing tracks (see Figure 5-9):
intersecting tracks or portions thereof other than those specified in a) and b) above.

The Figure references in the above list pertain to the PANS-ATM and the figures have been reproduced below as Figures 7.5 – 7.7.

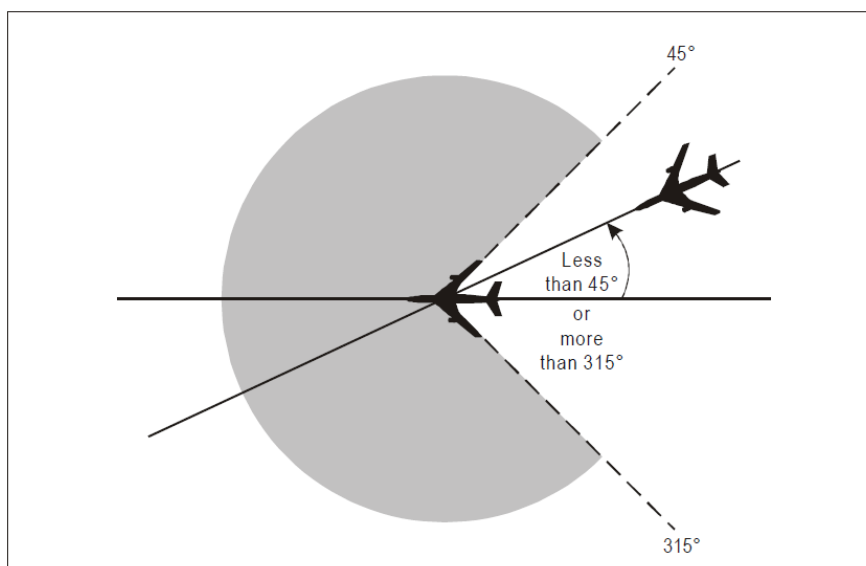


Figure 7.5: Aircraft on same track (see 5.4.2.1.5 a)) (Source PANS-ATM)

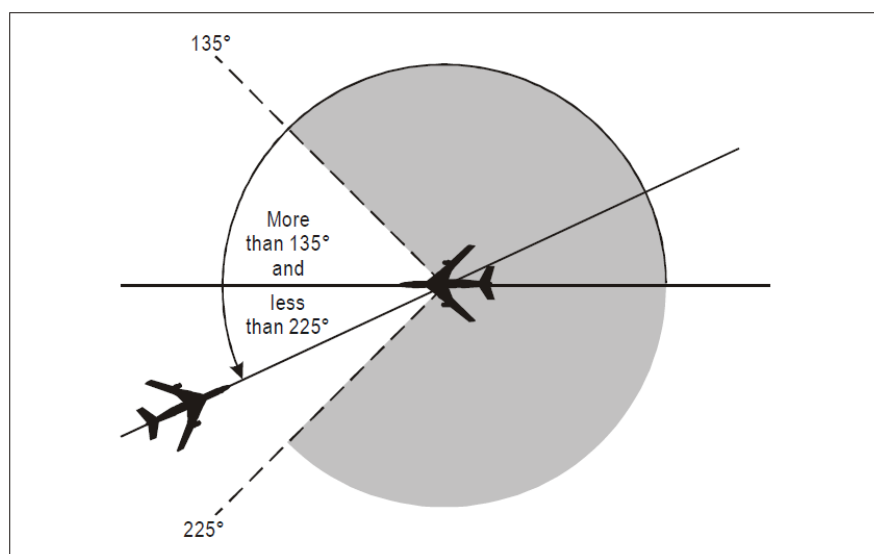


Figure 7.6: Aircraft on reciprocal tracks (see 5.4.2.1.5 b)) (Source PANS-ATM)

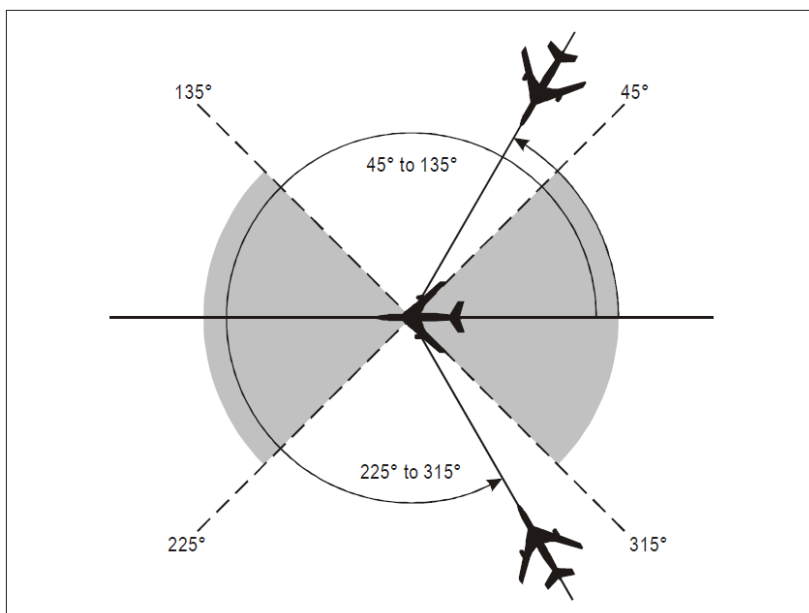


Figure 7.7: Aircraft on crossing tracks (see 5.4.2.1.5 c)) (Source PANS-ATM)

Starting with the 14th Edition of ICAO Doc 4444, PANS-ATM, incorporating Amendments 1 – 4, Table 2.5 in Section 2.5.2 of this Document listed four longitudinal separation minima based on time for aircraft maintaining the same level of the same track, namely 15, 10, 5, or 3 minutes. These values have been available in ICAO Doc 4444, PANS-RAC/PANS-ATM, from the 8th Edition (1966) onwards. See PANS-ATM for the precise conditions under which they can be applied. These minima are not based on collision risk modelling and will not be dealt with further. The Table lists two longitudinal separation minima based on distance using distance measuring equipment (DME), namely 20 NM and 10 NM. These minima were first incorporated into the 8th Edition of the PANS-RAC (1966). Since they are not based on collision risk modelling either, they will be treated only indirectly in connection with their extension to GNSS in the 15th edition of the PANS-ATM, applicable as of 22 November 2007 (see Section 7.3.5). The next minima listed in Table 2.5 concern longitudinal separation minima with Mach number technique based on time, which have effectively been treated under longitudinal separation in the NAT in Section 7.2. These minima were incorporated into the 13th edition of the PANS-RAC under Amendment 1 to become applicable on 6 November 1997. A longitudinal separation minimum of 80 NM with Mach number technique based on distance using RNAV is listed as bullet d) for the 14th Edition of the PANS-ATM in Table 2.5 of Section 2.5.2. This minimum was actually incorporated in a new Section 8.5 in Part III, Area Control Service, of the 13th Edition of ICAO Doc 4444, PANS-RAC, per Amendment 1 with an applicability date of 6 November 1997 and seems to be based on conversion of the 10 minute longitudinal separation minimum into distance based on an average aircraft speed of 480 kts.

This leaves the 50 NM and 30 NM longitudinal separation minima based on distance using RNAV where RNP is specified, i.e. bullet d) for the 14th Edition of the PANS-ATM incorporating Amendments 1 – 4 in Table 2.5 of Section 2.5.2. Both minima were derived by means of collision risk modelling but were incorporated into the PANS-ATM per different Amendments, namely Amendment 2 to the 13th Edition of the PANS-RAC, applicable on 5 November 1998, and Amendment 1 to the 14th Edition of the PANS-ATM, applicable on 28 November 2002. As will be seen below in Sections 7.3.2 and 7.3.3, these minima were originally constrained to longitudinal separation applied to aircraft on same-identical (zero angle) tracks, but subsequently able to be generalized to other track configurations, see Section 7.3.4. In addition to the collision risk modelling for

the 50 NM and 30 NM distance-based longitudinal separation minima, collision risk modelling for four more longitudinal separation minima from Table 2.5 will be examined, namely:

- GNSS longitudinal separation minima (Section 7.3.5);
- Automatic Dependent Surveillance – Broadcast In Trail Procedure (ADS-B ITP) (Section 7.3.6);
- ADS-C Climb and Descend Procedure (ADS-C CDP) (Section 7.3.7); and
- ASEPS longitudinal separation minima (Section 7.3.8).

Finally, the 50 NM and 30 NM distance-based longitudinal separation minima from Sections 7.3.2, 7.3.3 and 7.3.4.1 as well as the 5 minute time-based longitudinal separation minimum RLongSM from Section 7.2.7 will be briefly revisited in Section 7.3.9 in the context of performance-based longitudinal separation minima.

It should be remarked that the reciprocal-track case differs from the same-track and crossing-track cases in that aircraft on reciprocal tracks may be cleared to climb or descend to or through the levels occupied by the other provided that it has been positively established that the aircraft have passed each other and the distance between them is equal to at least the applicable separation minimum when distance-based longitudinal separation is applied. When time-based longitudinal separation is applied, vertical separation shall be provided for at least ten minutes prior to and after the time the aircraft are estimated to pass, or are estimated to have passed. Provided it has been determined that the aircraft have passed each other, this minimum need not apply. The reciprocal-track case will be only touched upon in Sections 7.3.5, *GNSS longitudinal separation minima*, and 7.3.6, *ASEPS longitudinal separation minima*.

7.3.2 50 NM longitudinal separation minima based on distance using RNAV where RNP is specified (RGCSF/9, same-identical track)

This subsection presents the longitudinal collision risk modelling underlying the 50 NM longitudinal separation minima based on distance using RNAV where RNP is specified as per Amendment 2 to the 13th edition of the PANS-RAC, which became applicable on 5 November 1998. It states among other things that within designated airspace, or on designated routes, separation standards in accordance with the section (8.6) may be used, subject to regional air navigation agreements. Separation shall be established by maintaining not less than the specified distance between aircraft positions as reported by reference to the same "on track" waypoint, whenever possible ahead of both aircraft, or by means of an automated position reporting system. Direct controller-pilot communications shall be maintained while applying a distance-based separation minima. Direct controller-pilot communications shall be voice or controller-pilot data link communications (CPDLC). The communication criteria necessary for CPDLC to satisfy the requirement for direct controller-pilot communications shall be established by an appropriate safety assessment. Prior to and during the application of a distance-based separation minimum, the controller should determine the adequacy of the available communication link, considering the time element required to receive replies from two or more aircraft, and the overall workload/traffic volume associated with the application of such minima.

Paragraph 8.6.3.1 of PANS-RAC states that a 50 NM longitudinal separation standard minimum may be used for RNP 10 aircraft cruising, climbing or descending on the same track when the specified communication, surveillance, and distance verification requirements are satisfied¹¹⁹. It is emphasised that the separation

¹¹⁹ Paragraph 8.6.3.1 of 13th edition of the PANS-RAC also states that an 80 NM longitudinal separation standard may be used for RNP 20 aircraft cruising, climbing or descending on the same track when the pertinent communication, surveillance, and distance verification requirements are satisfied, but this standard was deleted from Doc 4444 as being redundant. Both standards were developed utilizing the same collision risk model but with different navigation and distance verification requirements.

standard is based on safety assessments performed specifically for a particular network of tracks or routes. As such, the assessments evaluated traffic characteristics which might be unique to the network being assessed. The separation minima was developed in accordance with a collision risk analysis which dictates conditions under which this minima can be applied. Detailed information on the analysis used to determine the separation minima and on performing safety assessments is contained in the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (ICAO, 1998c). Reference is made to Appendix 5 to this *Manual* for the communication criteria which are used as a basis for the derivation of the separation minima in section 8.6. The Appendix is entitled "Assessment of longitudinal separation in the Asia/Pacific regions" and describes not only the communication criteria but the full methodology used to determine distance-based longitudinal separation minima.

The *Manual on Airspace Planning Methodology for the Determination of Separation Minima* was finalised at the 9th Meeting of the ICAO RGCS Panel (RGCS/9) in May 1996. The first edition of the *Manual* was issued in 1998. See also (Unknown, 1998). Appendix 5 to the *Manual* is based on papers presented at meetings of the RGCS/9 from September 1993 to September 1994 ((Anderson & Karppinen, 1994d, 1994c, 1994a; Karppinen & Anderson, 1993c)). A first version of the Appendix was presented at the Brussels Meeting of the RGCS/9 in May 1995 ((Karppinen & Anderson, 1995)). No changes were made to the Appendix at the subsequent Gold Coast Meeting in October 1995. Some related work is described in (Anderson, 1995b, 1995a, 1996a; Anderson & Karppinen, 1995; Lawson-Smith, 1995b, 1995a; Lawson-Smith & Jones, 1995; Mayo, 1995) (May 1995 – May 1996) whereas some related previous work is available in (Anderson & Karppinen, 1994b; Goyetche, 1990b, 1990a; Jonasson, 1990b, 1990a; Karppinen, 1993; Karppinen & Anderson, 1993a; Lawson-Smith, 1993)(October-November 1990 – April-May 1994).

Attachment A to Appendix 5 of the *Manual* presented the collision risk model utilized to estimate the expected number of accidents per flight hour due to the loss of distance-based longitudinal separation N_{ax} , viz.

$$N_{ax} = \Pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.193)$$

with

$$\Pi_x = \frac{4\lambda_x}{S} \times \int_s^{\infty} w(s) U(s) ds, \quad (7.194)$$

S being the separation standard in use, $w(s)$ the density function giving the probability, over the whole system being evaluated, that any selected pair of aircraft at the same level are nominally separated longitudinally by a distance s , $U(s)$ being the probability that longitudinal overlap occurs between times $t = 0$ and $t = T + \tau$ given an initial nominal separation $\hat{S}_0 = s$, and T and τ denoting the length of the reporting period and the buffer for communication and other delays and controller action respectively. The remaining symbols in eq. (7.193) have their usual meanings, namely probability of lateral overlap, $P_y(0)$, probability of vertical overlap, $P_z(0)$, and aircraft dimensions, λ_x , λ_y , and λ_z , and relative speeds $|\bar{x}|$, $|\bar{y}|$, and $|\bar{z}|$. The superscript $\hat{\cdot}$ on the initial separation S_0 indicates that the symbol $\hat{S}_0$ denotes a nominal separation as opposed to true or actual separation. The same notation is used below for the final nominal separation $\hat{S}_F$ at the end of the at-risk period $T + \tau$.

The distance-based longitudinal collision risk model defined by Eqs. (7.193) and (7.194) may be compared with the time-based longitudinal collision risk models for the NAT described in Section 7.2, in particular those developed for the RLongSM collision risk assessment from Section 7.2.7, e.g. eqs. (7.166) and (7.182)¹²⁰:

$$N_{ax} = P_y(0)P_z(0) \left[\frac{|\bar{x}(t)|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \frac{1}{P} \frac{2\lambda_x}{|\bar{x}(t)|} \left[\int_t^{\infty} E(t)Q(t)dt \right] \quad (7.166)$$

$$N_{ax} = 2P_y(0)P_z(0) \left[\frac{|\bar{x}(m)|}{2\lambda_x} + \frac{|\bar{y}_0|}{2\lambda_y} + \frac{|\bar{z}_0|}{2\lambda_z} \right] \frac{1}{T} \frac{2\lambda_x}{|\bar{x}(m)|} \left[\int_t^{\infty} E(t)Q(t)dt \right] \quad (7.182)$$

where P denoted the reporting period, T denoted the average at-risk period (i.e. the reporting period for periodic position reporting), $E(t)$ denoted the continuous distribution of planned time separations, and $Q(t)$ denoted the continuous probability of gaining/losing a given amount of minutes or more of longitudinal time separation.

The time-based model of eq. (7.182) is equivalent to the distance-based model of eqs. (7.193) and (7.194) when it can be shown that the longitudinal distance-based separation standard S is equivalent to the product of the average at-risk period T and $|\bar{x}(m)|$, the smallest possible longitudinal closing speed such that a longitudinal overlap occurs. It follows from eq. (7.183) with m being the longitudinal separation minimum in minutes that this is the case indeed.

It should be remarked that the three collision risk models in eqs. (7.193), (7.166), and (7.182) above pertain to same identical (zero angle) tracks rather than same track as defined in bullet a) and Figure 7.5 in Section 7.3.1.

The probability $U(s)$ that longitudinal overlap occurs between times $t = 0$ and $t = T + \tau$ given an initial nominal separation $\hat{S}_0 = s$ was evaluated as

$$U(s) = P(S_F \leq \lambda_x | \hat{S}_0 = s) = \int_v^{\infty} \varphi_x(v) P(S_F \leq \lambda_x | \hat{S}_F = s + v(T + \tau)) dv = \int_v^{\infty} \varphi_x(v) F(s + v(T + \tau)) dv \quad (7.195)$$

where the function $F(\cdot)$ in the integrand of the integral on the right-most side of eq. (7.195) was defined in terms of the probability density functions $\Psi(x)$ and $\zeta(x)$ of along-track navigation system errors for first and second aircraft respectively by

$$F(a) = \int_{x=a-\lambda_x}^{\infty} \int_{n=-\infty}^{\infty} \zeta(n) \Psi(n-x) dn dx \quad (7.196)$$

The other function $\varphi_x(v)$ in the integrand of the integral on the right-most side of eq. (7.195) represents the probability density function of unplanned relative velocities in the longitudinal direction.

For a procedural RNAV environment, it was assumed in Attachment A to Appendix 5 of the *Manual* that $\Psi(x)$ and $\zeta(x)$ might be taken to be double exponential probability densities, i.e.

¹²⁰ The original variable of integration s representing time in the integral on the right side of eq. (7.182) has been changed into t to avoid confusion with the variable of integration s representing distance in eq. (7.194).

$$\Psi(x) = \zeta(x) = \frac{1}{2\lambda} e^{-\frac{|x|}{\lambda}} \quad (7.197)$$

For an ADS environment, account must be taken of the non-simultaneous nature of the position reports of pairs of aircraft, cf. the discussion on (a)synchronous position reporting for the RLongSM collision risk assessment in Section 7.2.7 for the NAT. To this end, the position of one of the aircraft in a pair was extrapolated forward in time to coincide with the reporting time of the other aircraft. Consequently, $\zeta(x)$ was modified by taking it to be the probability density function of the sum of two random variables, each distributed according to different double exponential densities, i.e.

$$\zeta(x) = \frac{1}{2(\lambda^2 - \gamma^2)} \left(\lambda e^{-\frac{|x|}{\lambda}} - \gamma e^{-\frac{|x|}{\gamma}} \right) \quad (7.198)$$

As set out in the main text of Appendix 5 to the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (ICAO, 1998c), data from the 1993/1994 RGCSF data collection exercise in the Pacific area were used to estimate the probability density function of separations $w(s)$ and the probability density function of unplanned relative velocities in the longitudinal direction $\varphi_x(v)$ ((Karppinen & Anderson, 1993b)). The parameter λ of the probability density of the along-track navigation system errors of the aircraft, eq. (7.197), was derived from the 95% accuracy value of the RNP type under consideration. The value of the γ parameter in eq. (7.198) was not specified in Attachment A to Appendix 5 of the *Manual*, but (Anderson & Karppinen, 1994e) suggests that it was taken equal to λ , implying that eq. (7.198) was not actually used but rather the formula for the probability density of the sum of two double exponential probability densities with the same parameter.

Risk estimates were calculated in Appendix 5 to the *Manual* for different combinations of navigation specification, longitudinal separation standard, and buffer τ for communication and other delays and controller action, resulting in a table, Table A-5-6, of recommended acceptable procedural RNAV longitudinal separation minima, namely 50 NM for 95% navigation system error containment of 10 NM or better and 80 NM for 95% navigation system error containment of 20 NM or better. The respective distance verification requirements were at least every 30 minutes and every 60 minutes.

7.3.3 30 NM longitudinal separation minima based on distance using RNAV where RNP is specified (RGCSF/10, same identical track)

Following the finalisation of Appendix 5 to the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* at RGCSF/9 in May 1996, the next paper on longitudinal distance-based separation minima appeared at the Gold Coast Meeting of the RGCSF in May 1998 (Dumsa et al., 1998). The paper utilised the same collision risk model as Appendix 5 and focussed on the use of ADS as a surveillance medium in an RNP RNAV environment. Two more papers on this subject were presented at the Montreal November 1999 Meeting of the RGCSF. The first paper, (Butcher et al., 1999), presented a PANS-RAC amendment proposal to include 30 NM and 20 NM longitudinal separation minima for use with ADS in an RNP RNAV environment. The paper was based on additional analysis performed in (Anderson, 1999), again based on the collision risk model described in Appendix 5 to the *Manual*, but updated with regard to the probability density $\zeta(x)$ of the along-track navigation system errors for the second aircraft in a pair (eq. (7.198)) to more accurately account for the non-simultaneous nature of ADS position reports of pairs of

aircraft. See also (Unknown, 1999), which, amongst other things, proposes that the PANS-RAC be renamed PANS-ATM and issued as a new edition (14th Edition), and that the 80 NM longitudinal separation standard in Paragraph 8.6.3.1 of the PANS-RAC be deleted as being redundant as it may be applied without the need to meet a specified RNP (cf. footnote 119 in Section 7.3.2).

As emphasized in Section 7.3.2, the longitudinal collision risk model presented in Attachment A to Appendix 5 to the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* pertained to same identical track (zero angle) rather than same track as defined in the PANS-RAC/PANS-ATM (see bullet a) and Figure 7.5 in Section 7.3.1).

To overcome the same-identical-track (zero angle) constraint of the Appendix-5 methodology, an extended methodology for longitudinal distance-based same-track (as defined in the PANS-RAC/PANS-ATM) procedural RNAV separation standards using a projection concept was presented at the 10th Meeting of the RGCSP (RGCSP/10) in May 2000, viz. in Working Paper 9 (Anderson & Lin, 2000b). The paper proposed to have the extended methodology replace the existing Appendix 5 to the *Manual on Airspace Planning Methodology for the Determination of Separation Minima*. This proposal, however, was not accepted by RGCSP/10; further work was deemed necessary.

Two more papers based on the extended methodology for ADS longitudinal separation were presented to RGCSP/10 and proposed to be added to the *Manual* (WP/7 and WP/21). WP/7 (Anderson, 2000b) applied the extended methodology to ADS longitudinal distance-based same-track separation standards in various communication environments and WP/21 (Anderson & Lin, 2000a) applied the extended methodology to ADS reciprocal-track longitudinal separation standards. However, the proposal to add these working papers to the *Manual* was not accepted either, the reason again being that further work was deemed necessary.

Based on the work summarised above, (Unknown, 2000) presented a PANS-RAC Amendment proposal concerning longitudinal distance-based separation minima in an RNP RNAV environment. However, in light of the discussions at RGCSP/10, the Meeting could only endorse the use of longitudinal distance-based separation for same-identical (zero angle) tracks. See the *Report on Agenda Item 1* in (RGCSP, 2000) where Appendix E to that Report provides the text of the resulting proposed PANS-RAC amendment. The text clearly states that the proposed minima apply to aircraft cruising, climbing or descending on the same identical (zero angle) track where the 30 NM longitudinal separation minima requires RNP 4 navigation performance in combination with a maximum ADS periodic reporting interval of 21½ minutes. Two combinations of required navigation performance and maximum ADS periodic reporting interval are given for the 50 NM longitudinal separation minimum, namely RNP 10 / 32 minutes and RNP 4 / 38 minutes.

The next Subsection will proceed with

- Further work on the longitudinal distance-based collision risk model (Section 7.3.4.1); and
- Further work on the PANS-RAC Amendment proposal at RGCSP/10 (Section 7.3.4.2).

7.3.4 Further work on collision risk modelling for distance-based separation on intersecting and coincident tracks

7.3.4.1 Collision risk modelling

Following the longitudinal collision risk modelling work described in Sections 7.3.2 and 7.3.3, further work focussed on two extensions, namely

- Extension of the same-identical-track (zero angle) longitudinal collision risk model to non-coincident tracks; and
- Extension of longitudinal separation minima to minima of less than 30 NM.

These extensions resulted in the development of a general collision risk model applicable to a variety of situations and will be described by RGCSP/SASP Meeting below. The description is targeted at longitudinal separation. See Chapter 8 for a derivation of the final form of the collision risk model for the general case.

RGCSP-WG/A-WP/12, Annapolis, November 2000 and SASP-WG/A/1, Madrid, May 2001

A new general collision risk model for distance-based separation on intersecting and coincident tracks was presented in RGCSP-WG/A-WP/12, Annapolis, November 2000 (Anderson, 2000a). This model was updated in SASP-WG/A-WP/21 of the Madrid, May 2001 Meeting (Anderson, 2001a). See also the related application for 20 NM longitudinal separation in (Anderson, 2001c).

The new model was stated to be based on the well-established Reich model (Burt, 1999; Reich, 1966a, 1966b, 1966c) but the derivation presented was stated to be new. The model was expressed as a constrained minimization of a distance function involving sums and products of random errors. RGCSP-WG/A-WP/12 proposed analytical solutions, where possible, and solutions based on Monte Carlo simulations where not, whereas SASP-WG/A-WP/21 presented analytical solutions where possible and where not utilised a numerical approach.

Thus, consider two aircraft with along-track and across-track navigation errors ε_1^A , ε_2^A , ε_1^C , and ε_2^C on routes intersecting at an angle of θ as in Figure 7.8. Mathematically, the range for the angle of intersection θ extends from 0 to 180 degrees inclusive. Operationally, using the ICAO PANS-ATM definition of same track, the range of intersection angles θ is restricted to $0 \leq \theta < 45$ degrees. Similarly, for reciprocal tracks the range of intersection angles θ to be considered is $135 < \theta \leq 180$ degrees.

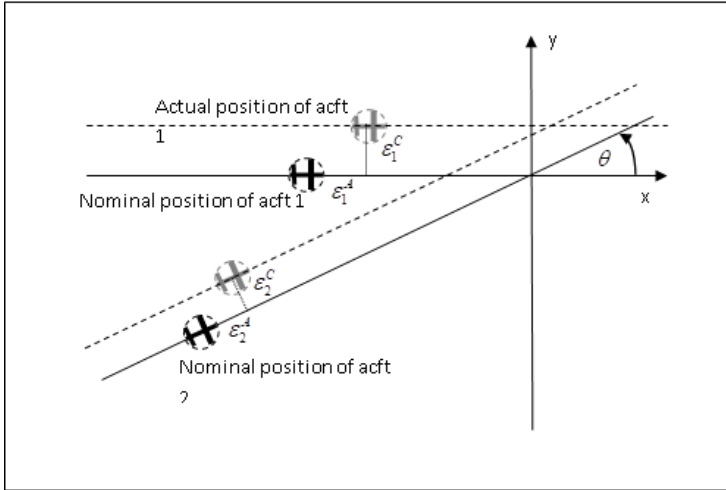


Figure 7.8: Illustration of the along-track errors and the across-track errors for a pair of aircraft on intersecting routes in the horizontal plane

Although the derivation of the new model followed a new approach, this will not be reproduced here since the model evolved further over time and a derivation of the ultimate model will be provided in Chapter 8. Some key elements of the new model are sketched below.

The model given by eq. (6) of SASP-WG/A-WP/21 reads as follows:

$$CR = 2 \times NP \times HOP(T_C) \times P_z(h_z) \times \left(1 + \frac{|\dot{z}|}{2\lambda_z} \cdot \frac{\pi\lambda_{xy}}{2V_{rel}^C} \right) \quad (7.199)$$

with CR denoting the expected number of fatal accidents per flight hour, NP denoting the number of pairs per flight hour, $HOP(T_C)$ denoting the probability that a pair of aircraft will have a horizontal overlap during an oceanic crossing of duration (T_C), $P_z(h_z)$ denoting the instantaneous vertical overlap probability of two aircraft of height λ_z nominally separated by distance h_z when the horizontal overlap occurs, $|\dot{z}|$ denoting the relative vertical speed of the aircraft pair, λ_{xy} denoting the diameter of a (standing) cylinder enveloping the aircraft, and V_{rel}^C denoting the relative speed of two aircraft conditional on a horizontal overlap taking place. Section 3 of SASP-WG/A-WP/21 then focussed on the calculation of the horizontal overlap probability, $HOP(T_C)$.

Before proceeding with this probability, it is useful to compare the model of eq. (7.199) with the vertical collision risk models for aircraft flying at adjacent flight levels of intersecting routes presented in Chapter 6, e.g. eq. (6.12) from Annex A in Volume 2 of the Report on the 6th Meeting of the RGCSP (RGCSP/6) or eq. (6.83) as utilized for the annual RVSM collision risk assessment for the AFI Region of ICAO (Smeltink et al., 2021):

$$N_{az} = 2P_z(S_z)n_{xy}(\theta) \left\{ 1 + \frac{\pi\lambda_{xy}}{2\lambda_z} \frac{|\dot{z}|}{V_{rel}(\theta)} \right\} \quad (6.83)$$

The product $NP \times HOP(T_C)$ in the longitudinal model of eq. (7.199) corresponds with $n_{xy}(\theta)$ in the vertical model of eq. (6.83) where the dependence on the intersection angle θ is explicitly shown for the latter model. The key difference between the two models concerns the type of planned separation being applied, i.e. longitudinal for eq. (7.199) and vertical for eq. (6.83), and, consequently, the way the probability of horizontal

overlap or the number of horizontal overlaps at the intersection can be estimated. For the vertical collision risk model for aircraft passing the intersection at adjacent flight levels, $n_{xy}(\theta)$ can be estimated on the assumption of the aircraft passing the intersection at random points in time whereas for the longitudinal collision risk model with the aircraft passing the intersection at the same flight level, the planned longitudinal separation distribution at the intersection needs to be accounted for.

The following describes the evaluation of the product $NP \times HOP(T_C)$ for same-track longitudinal separation in Section 3.2 of SASP-WG/A-WP/21. First, for longitudinal separation, the number of pairs is essentially the same as the number of aircraft and so $NP = 1/T_C$. Second, the oceanic crossing was split into k , say, reporting periods of duration T flying hours, $T_C = k \times T$, and it was assumed that the probability of horizontal overlap in each reporting period per aircraft (pair) was the same so that the total probability of horizontal overlap was just k times that in any one reporting period. Multiplication by the number of pairs thus deletes the number of reporting intervals from the product. Taking account of the buffer τ for communication and other delays and controller action, the probability of an aircraft pair experiencing a horizontal overlap during a period of time $T + \tau$ was denoted $HOP(T + \tau)$ and the model of eq. (7.199) was re-expressed as

$$CR = \frac{2}{T} \times HOP(T + \tau) \times P_z(h_z) \times \left(1 + \frac{|\dot{z}|}{2\lambda_z} \cdot \frac{\pi\lambda_{xy}}{2V_{rel}^C}\right) \quad (7.200)$$

with $h_z = 0$.

Letting $\hat{d}_1^0$ and $\hat{d}_2^0$ denote the nominal distances of aircraft 1 and 2 to the intersection at time $t = 0$, the distance $D(t)$ between the aircraft at time t was expressed as a function of $\hat{d}_1^0$ and $\hat{d}_2^0$, ε_1^A , ε_2^A , ε_1^C , ε_2^C , the aircraft speeds V_1 and V_2 and time t and minimised for $0 \leq t \leq T + \tau$. When the constrained minimum is denoted D_{min}^C , a horizontal overlap will take place during the time interval $[0, T + \tau]$ when

$$D_{min}^C \leq \lambda_{xy} \quad (7.201)$$

and the horizontal overlap probability is given by

$$HOP(T + \tau) = Prob\{D_{min}^C \leq \lambda_{xy}\} \quad (7.202)$$

Evaluation and minimisation of $D^2(t)$ showed that the unconstrained minimum distance D_{min} at time t_{min} could be written as

$$D_{min} = \frac{|\Delta x_0 V_2 \sin \theta + \Delta y_0 (V_1 - V_2) \cos \theta|}{V_{rel}} \quad (7.203)$$

with

$$V_{rel} = V_1^2 + V_2^2 - 2V_1 V_2 \cos \theta \quad (7.204)$$

See for Δx_0 and Δy_0 SASP-WG/A-WP/21.

It follows that if the time t_{min} at which the minimum distance occurs is not in the range 0 to $T + \tau$, the constrained minimum D_{min}^C will be larger than D_{min} and, because $D(t)$ is quadratic in t , than the following holds:

$$\text{If } t_{min} < 0 \text{ then } D_{min}^C = D_0 \quad (7.205)$$

$$\text{If } t_{min} > T + \tau \text{ then } D_{min}^C = D(T + \tau) \quad (7.206)$$

$$\text{If } 0 \leq t_{min} \leq T + \tau \text{ then } D_{min}^C = D_{min} \quad (7.207)$$

Nominal aircraft speeds $\hat{V}_1$ and $\hat{V}_2$ were defined as

$$v_i = V_i - \hat{V}_i, i = 1, 2 \quad (7.208)$$

and the unplanned relative velocity as

$$v = v_1 - v_2 \quad (7.209)$$

The next step was to specify probability distributions for the navigational and speed errors $\varepsilon_1^A, \varepsilon_2^A, \varepsilon_1^C, \varepsilon_2^C, v_1$, and v_2 . These were all taken as zero-mean double exponential distributions where the scale parameters for the navigational error distributions were based on the 95% RNP accuracy value and those of the speed error distributions as 5.82 kts based on some analysis of speed error data.

As stated in SASP-WG/A-WP/21, unfortunately, even with the above assumptions it was not possible to write down a simple algebraic form for the probability of horizontal overlap $HOP(T + \tau)$ defined by eq. (7.202) except for the relatively simple cases of $\theta = 0$ and $\theta = 180^\circ$. As a solution, a numerical approach was utilised. See SASP-WG/A-WP/21 (Anderson, 2001a) for a reference to this numerical approach.

Tables 7.8 and 7.9 present some results obtained in SASP-WG/A-WP/21 for the longitudinal separation case for different values of the communication and other delays and controller action buffer τ . A weighted average of the risks over the different buffer values was calculated. Table 7.8 pertains to ADS position reporting and Table 7.9 concerns manual position reporting. The importance of these results is that the reporting intervals used were different to those used previously. One of the reasons was the change in the model to take proper account of non-identical tracks. The calculations that were carried out indicated that the weighted risk generally increased with the track intersection angle, except for RNP 4 and the larger $T + \tau$, where the opposite was the case. In some cases for RNP 10 the risk near $\theta = 45$ degrees was almost 3 times that for $\theta = 0$. Another reason for the differences from the previous results was the use of significantly larger values for the vertical overlap probability.

Table 7.8: Same track, $0 \leq \theta < 45^\circ$, longitudinal collision risk in fatal accidents per flight hour for RNP 10 and RNP 4 navigation and ADS separation (Reproduced from SASP-WG/A-WP/21)

Separation Minimum (NM)	Required Navigation Performance	Maximum Reporting Interval T (minutes)	Risk for $\tau = 4$ minutes	Risk for $\tau = 10.5$ minutes	Risk for $\tau = 13.5$ minutes	Weighted Average Risk
30	4	14	3.6×10^{-10}	1.6×10^{-8}	5.7×10^{-8}	3.9×10^{-9}
50	4	32	1.4×10^{-9}	1.3×10^{-8}	2.8×10^{-8}	3.3×10^{-9}
50	10	27	4.0×10^{-9}	8.2×10^{-9}	8.2×10^{-9}	4.4×10^{-9}

Table 7.9: Same track, $[0 \leq \theta < 45^\circ]$, longitudinal collision risk in fatal accidents per flight hour for RNP 10 navigation and procedural separation (Reproduced from SASP-WG/A-WP/21)

Separation Minimum (NM)	Required Navigation Performance	Maximum Reporting Interval T (minutes)	Risk for $\tau = 6$ minutes	Risk for $\tau = 12.5$ minutes	Weighted Average Risk
50	10	24	4.9×10^{-9}	5.8×10^{-9}	4.9×10^{-9}

The SASP-WG/A/1 Meeting recalled that at the previous RGCSP-WG/A meeting in Annapolis, November 2000, it was agreed that RGCSP-WG/A-WP/12 should replace Appendix D to the *Report on Agenda Item 4 (Development of airspace planning methodology)* to the *Report on RGCSP/10* and be included in the *Manual on Airspace Planning Methodology for the Determination of Separation Minima*, Doc 9689. It then agreed that with the exception of Table 8, the material in SASP-WG/A-WP21 should replace RGCSP-WG/A-WP/12, and be included in Doc 9689.

The SASP-WG/A/1 Meeting was informed that the Air Navigation Commission on 6 March 2001 approved the replacement of Appendix D to the *Report on Agenda Item 4 (Development of airspace planning methodology)* to the *Report on RGCSP/10* with the model contained in RGCSP-WG/A-WP/12. Consequently, this model will be included in Doc 9689. The meeting agreed that the Secretariat should take appropriate action to replace RGCSP-WG/A-WP/12 with SASP-WG/A-WP21.

Remarks

1. Appendix D to the *Report on Agenda Item 4 (Development of airspace planning methodology)* to the *Report on RGCSP/10* presented a model for crossing-track lateral separation methodology and would replace the existing Appendix 1 to Doc 9689. Since this model was covered by Section 3.4, *Lateral separation on intersecting tracks*, of SASP-WG/A-WP21 (and the same section of RGCSP-WG/A-WP/12), the ultimate replacement of the original Appendix 1 to Doc 9689 meant a considerable extension of the scope of the Appendix, now covering both longitudinal and lateral collision risk methodology.
2. The new reporting interval values listed in Tables 7.8 and 7.9 had an impact on the proposed PANS-RAC amendment of RGCSP/10, see Section 7.3.4.2.

SASP-WG/A/2, Montreal, November 2001

The new model of SASP-WG/A-WP21 (Anderson, 2001a) was subsequently used for the benefit of SASP-WG/A/2-WP/17 (Anderson, 2001b) and SASP-WG/A/2-WP/21 (Butcher, 2001b) of the Montreal, November 2001 Meeting, where the former working paper presented an example indicating that RNP 4 might be sufficient to ensure longitudinal separation minima less than 30 NM meet a target level of safety of 5×10^{-9} .

fatal accidents per flight hour and the latter proposed an amendment to PANS-RAC Doc 4444 to accommodate the inclusion of longitudinal separation minima less than 30 NM using ADS. The proposed amendment concerned the inclusion of a 20 NM longitudinal separation minimum using ADS where it was noted that whilst the calculations were based on a maximum reporting interval of 2.5 minutes, a definitive maximum reporting interval remained to be determined. This was related to the question of whether the communication and controller intervention buffer τ needed to be applied to each reporting interval in case of significantly reduced reporting intervals of the order of 2.5 minutes, say. Rather than applying the buffer τ to each reporting interval as in SASP-WG/A-WP21 (Anderson, 2001a) for the 30 NM and 50 NM longitudinal separation minima, SASP-WG/A/2-WP/17 (Anderson, 2001b) applied the buffer τ only once in any 15 minute time interval on the assumption that, in the case of reasonably short ADS reporting intervals, intervention would not be necessary after each report.

The reason for the above modification was a mathematical issue with the model that was described to the SASP Mathematicians Sub Group (MSG) as follows (Appendix L to (SASP, 2001)). The model estimated the longitudinal risk for each reporting interval T by estimating the probability of horizontal overlap over the time interval $[0, T + \tau]$ where τ is the well-known buffer to account for the various delays in the system. A factor $1/T$ is used in the model to obtain the risk in units of fatal accidents per flight hour. The combined effect of these two factors may be represented by a factor $T + \tau/T$. It follows that when the reporting interval approaches to zero, this factor becomes unbounded, implying that, mathematically, the risk would become unbounded. Obviously, this is not realistic.

In discussing the mathematical issue and the solution proposed in WG/A/2-WP/17, the MSG was unable to provide a clear-cut solution, but it was agreed that the members of the group would continue thinking about the issue after the Montreal meeting and keep each other informed about possible developments. It was also noted that as the reporting interval becomes small, the ATC environment approaches that of radar control. The model developed for procedural separation might not be appropriate in that context.

SASP-WG/A/2 Project Team 6, *20 NM longitudinal – Procedural*, reviewed both the working papers WG/A/2-WP/17 (Anderson, 2001b) and SASP-WG/A/2-WP/21 (Butcher, 2001b). Project Team 6 acknowledged the logic used in WG/A/2-WP/17 and agreed that the issue of revising the collision risk model was best left to the MSG for resolution (Appendix H to (SASP, 2001)). Concerning the Project Team's review of SASP-WG/A/2-WP/21, it was agreed that it was important to develop PANS amendments in parallel with the development of the collision risk model and that the proposed amendment in this working paper would serve as a first draft for a specific amendment for 20 NM longitudinal minima and ADS and that more work would be undertaken at the SASP's next Meeting.

SASP-WG/WHL/1, Canberra, May 2002

A further review of SASP-WG/A/2-WP/17 by the MSG and Project Team 6, *20 NM longitudinal – Procedural*, took place at the SASP's Meeting in Canberra, May 2002, as requested in SASP-WG/WHL/1-WP/20 (Butcher & Anderson, 2002). As regards the model, it was agreed that the author of the model would attempt to modify the methodology to include an additional parameter, the time interval between separation checks, which, in the RNAV application, would be the same as the time between reports (SASP, 2002).

SASP-WG/WHL/2, Montreal, October – November 2002

Two modifications to the new general collision risk model were proposed in SASP-WG/WHL/2-WP/26 (Anderson, 2002a). The first modification concerned the introduction of an additional parameter, the controller look-ahead time T_L , and modification of the methodology of SASP-WG/A-WP21 (Anderson, 2001a) by including the buffer τ only once in the time interval $[0, T_L]$. Specifically, the risk was computed in the sub-intervals $[t_0 = 0, t_1]$, $[t_1, t_2]$, ..., $[t_{k-1}, t_k + \tau]$, ..., $[t_{n-1}, t_n = T_L]$ where $t_k = k \times T$ and the value of k chosen to maximise the risk. Denoting the risk in the interval $[t_{k-1}, t_k]$ as r_k and the risk in the interval $[t_{k-1}, t_k + \tau]$ as $r_k(\tau)$, the probability of horizontal overlap was denoted $HOP(T, \tau, n)$ (with n defining T_L) and calculated as

$$HOP(T, \tau, n) = \max_k \{ \sum_{i=1}^{k-1} r_i + r_k(\tau) + \sum_{i=k+1}^n r_i \} = \sum_{i=1}^n r_i + \max_k \{ r_k(\tau) - r_k \} \quad (7.210)$$

The second modification proposed was that in the case of same-track longitudinal separation, the model

$$CR = \frac{2}{nT + \tau} \times HOP(T + \tau) \times P_z(h_z) \times \left(1 + \frac{|\bar{z}|}{2\lambda_z} \cdot \frac{\pi\lambda_{xy}}{2V_{rel}^C} \right) \quad (7.211)$$

be used instead of

$$CR = \frac{2}{nT} \times HOP(T + \tau) \times P_z(h_z) \times \left(1 + \frac{|\bar{z}|}{2\lambda_z} \cdot \frac{\pi\lambda_{xy}}{2V_{rel}^C} \right) \quad (7.200)$$

To avoid multiply-counting the risk during each interval of duration (τ) when it is applied.

See also SASP-WG/WHL/2-WP/27 (Butcher & Powell, 2002) for a research proposal to sample controller look-ahead times relevant to anticipated intervention situations.

SASP-WG/WHL/2-WP/25 (Anderson, 2002b) initiated the final developments of the longitudinal distance-based collision risk model based on the relationship with the *Hsu* approach (Hsu, 1981).

SASP-WG/WHL/3, London, May 2003

Instalment 1 of a longitudinal distance-based collision risk model based on reliability theory dealt with crossing angles less than 90 degrees (ICAO, 1998c) and was presented in SASP-WG/WHL/3-WP/32, London, May 2003 (Anderson, 2003d).

SASP-WG/WHL/4, Honolulu, November 2003

SASP-WG/WHL/4-WP/9 (Anderson, 2003b), Honolulu, November 2003 re-derived the general distance-based collision risk model based on reliability theory from SASP-WG/WHL/3-WP/17 (Neal et al., 2003). A slightly amended version was also produced in SASP-WG/WHL/4-WP/9. Working Paper 9 proposed to consider the information presented for inclusion in a future edition of the *Manual on Airspace Planning Methodology for the Determination of Separation Minima*, possibly as a replacement for the new Appendix based on SASP-WG/A-WP/21 (Anderson, 2001a).

SASP-WG/WHL/7, Montreal, May 2005

The development of the collision risk model based on reliability theory concluded with SASP-WG/WHL/7-WP/20 REVISED (Anderson, 2005), which extended SASP-WG/A-WP21 (Anderson, 2001a) and SASP-

WG/WHL/4-WP/9 (Anderson, 2003c) to the cases of along-track navigational accuracy being different from across-track accuracy and the navigational accuracies of aircraft on each track being different. The resulting model was frequently referred to as the “general collision risk model based on reliability theory” in Chapter 5 of this document.

Apart from the complete derivation of the model, Anderson describes the following applications of the new model (Anderson, 2005):

- Same track longitudinal separation;
- Reciprocal track longitudinal separation with ADS;
- Lateral separation on intersecting tracks: both aircraft are approaching the area of conflict;
- Lateral separation on intersecting tracks: one aircraft is leaving the area of conflict as another is entering; and
- Lateral separation on intersecting tracks: 15 minutes at the crossing.

Chapter 5 of this document included a number of applications of the new (general collision risk) model (based on reliability theory) for the determination of lateral separation standards based on specialized versions of the model particular to the application, namely:

- Section 5.4.1 *GNSS lateral separation minima based on VOR separation in ICAO Circular 322;*
- Section 5.4.2.6 *Intersecting tracks: 15 NM – RNP 2, 30 NM – RNP 4 and 50 NM – RNAV 10 (RNP 10);*
- Section 5.4.2.8 *Intersecting tracks: 15 NM – RNP 2, 23 NM – RNP 4 and 50 NM – RNAV 10 (RNP 10);*
- Section 5.4.3 *Lateral separation of aircraft on published adjacent instrument procedures for arrivals and departures; ICAO Circular 324;*
- Section 5.5.5.3 *Spacing between non-parallel routes that are initially parallel or converge and then diverge – the same PBN navigation specification on each route;*
- Section 5.5.5.4 *Spacing between non-parallel routes that are initially parallel or converge and then diverge – different varieties of PBN navigation specifications on each route;*
- Section 5.5.5.5 *Spacing between PBN routes and Temporary Reserved Airspaces/Temporary Segregated Airspaces (TRAs/TSAs) where the activity in the TRA or TSA is clearly defined;*
- Section 5.5.5.6 *Spacing between PBN routes and holding areas;*
- Section 5.5.5.7 *Crossing tracks using same or different navigation specifications – Operational requirement 3A; and*
- Section 5.5.5.8 *Crossing tracks using same or different navigation specifications – Operational requirement 3B.*

The form of the model for same track longitudinal separation is presented below. This utilises the representation of the model by Anderson (Anderson, 2005).

Thus, consider again two aircraft with along-track and across-track navigation errors ε_1^A , ε_2^A , ε_1^C , and ε_2^C on routes intersecting at an angle of θ as in Figure 7.8, recalled below, where, using the ICAO PANS-ATM definition of same track, the calculations pertain to intersection angles θ , $0 \leq \theta < 45$ degrees.

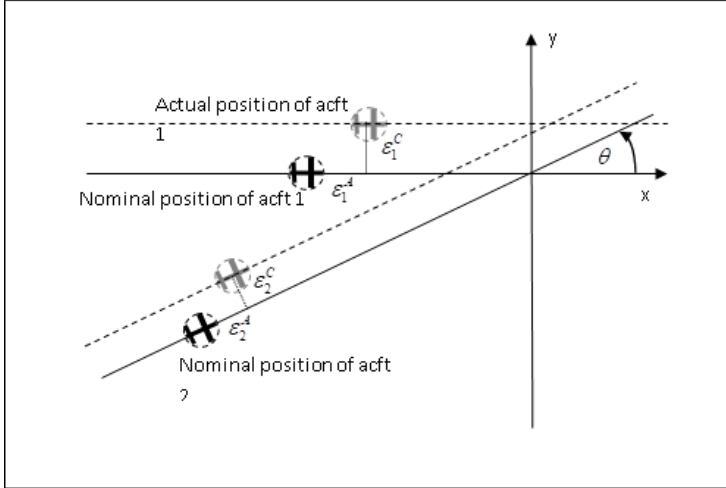


Figure 7.8: Illustration of the along-track errors and the across-track errors for a pair of aircraft on intersecting routes in the horizontal plane (here constrained to $0 \leq \theta < 45^\circ$)

Longitudinal collision risk for an aircraft pair over a time interval $[t_0, t_1]$ is given by ($m = 1$ in eq. (8.12))

$$N_a = 2\pi m \lambda_{xy}^2 P_z \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) \left(1 + \frac{\pi \lambda_{xy} |\bar{z}|}{4 \lambda_z v_{xy}} \right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (7.212)$$

where $f_i(v_i)$ is the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denotes the joint probability density of the relative position $r_x(t)$, $r_y(t)$ of two aircraft at time t for $r_x(t) = r_y(t) = 0$. The latter probability density is given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C$$

where ε_2^A and ε_2^C denote the along-track and across-track navigational errors of aircraft 2¹²¹. $D_x(t)$ and $D_y(t)$ denote the nominal relative position between the aircraft at time t given by

$$D_x(t) = (v_1 - v_2 \cos \theta)t - d_1 + d_2 \cos \theta \quad (7.213)$$

$$D_y(t) = (d_2 - v_2 t) \sin \theta \quad (7.214)$$

and d_1 and d_2 denoting the nominal distances of the aircraft before the intersection at time t_0 . In eq. (7.212), λ_{xy} and λ_z denote again the diameter and height respectively of a horizontal cylinder representing the aircraft, v_{xy} denotes the relative horizontal speed between the aircraft, P_z denotes the pair's probability of vertical overlap, and $|\bar{z}|$ denotes the average of (the absolute value of the) relative vertical speed between the aircraft.

All the navigational and speed error probability densities in eqs. (7.212) and $f_t(0,0)$ were taken as double exponential. A major development of the (Anderson, 2005) model then was that the double integral on the

¹²¹ It is shown in Chapter 8 that $f_t(0,0)$ can be expressed in terms of either ε_2^A and ε_2^C or ε_1^A and ε_1^C .

right side of eq. $f_t(0,0)$ was able to be evaluated algebraically, albeit at the cost of many different regions of integration to consider. The remaining time integral and the speed double integral in eq. (7.212) were evaluated by means of numerical integration.

The application in (Anderson, 2005) calculated the risk for a time interval $[0, T + \tau]$, where T was the time between position reports, using either manual means or ADS, and τ was the communication and controller intervention buffer. Same-direction longitudinal collision risk depends on the distribution of the initial longitudinal separation $S = d_1 - d_2$ between the aircraft at time $t = 0$. Cf. the density function $w(s)$ giving the probability, over the whole system being evaluated, that any selected pair of aircraft at the same level are nominally separated longitudinally by a distance s , for the collision risk model of eq. (7.193) in Section 7.3.2. Put differently, the longitudinal collision risk N_a of eq. (7.212) is actually a conditional longitudinal collision risk, conditional on the initial longitudinal separation $S = d_1 - d_2$ and the initial distance of one of the aircraft, d_2 say, before the intersection at time $t = 0$,

$$N_a(S = d_1 - d_2, d_2) = 2\pi m \lambda_{xy}^2 P_z \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) \left(1 + \frac{\pi \lambda_{xy} |\bar{z}|}{4 \lambda_z v_{xy}}\right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (7.215)$$

The dependence on the initial longitudinal separation $S = d_1 - d_2$ was accounted for by assuming this to have a uniform distribution over the range $[S_x, S_x + 250]$ NM with S_x denoting the longitudinal separation minimum, and by calculating the longitudinal collision risk as a function of the initial distance d_2 before the intersection of the second aircraft, as

$$N_a(d_2) = \frac{1}{250} \int_{S_x}^{S_x+250} N_a(S = d_1 - d_2, d_2) dS \quad (7.216)$$

Since the integrand $N_a(S = d_1 - d_2, d_2)$ in eq. (7.216) is not known in analytical form, the integration in eq. (7.216) was performed numerically. Finally, the dependence of the longitudinal collision risk $N_a(d_2)$ on the initial distance d_2 before the intersection of the second aircraft needs to be accounted for.

The communication and controller intervention buffer τ was specified for four cases in (Anderson, 2005), namely 360 seconds for normal non-ADS operations, 240 seconds for normal ADS operations, and 810 seconds, 630 seconds when ADS periodic reports are received within 3 minutes but CPDLC uplink plus response is lost or takes longer than 3 minutes, and 810 seconds when ADS position reports take longer than 3 minutes. A weighted average of the risks over the four buffer values was calculated. See (Anderson, 2005) for how the buffer values were derived and see this reference also for how the averaging was performed. Results were calculated for RNP 10 navigation and non-ADS separation and for both RNP 10 and RNP 4 navigation and ADS separation and presented in Table 6 – Table 8 of (Anderson, 2005). The results for ADS separation from Table 7 and Table 8 have been reproduced in Table 7.10 and those for non-ADS separation from Table 6 in Table 7.11 below. The calculations that were carried out indicated that the weighted risk generally increased with the track intersection angle, except for RNP 4, where the risk decreased from $\theta = 25$ degrees or so and then increased slightly until $\theta = 45$ degrees, with the maximal value occurring at $\theta = 0$. For RNP 10 without ADS the weighted risk at $\theta = 45$ degrees was more than 2.5 times that at $\theta = 0$. For RNP 10 with ADS the weighted risk at $\theta = 45$ degrees was still larger than at $\theta = 0$, but the ratio was only about 1.7. Some of the numbers in Tables 7.10 and 7.11 differ marginally from their counterparts in Tables 7.8 and 7.9.

Table 7.10: Same track, $[0 \leq \theta < 45^\circ]$, longitudinal collision risk in fatal accidents per flight hour for RNP 10 and RNP 4 navigation and ADS separation - Reproduced from (Anderson, 2005)

Separation Minimum (NM)	Required Navigation Performance	Maximum Reporting Interval T (minutes)	Risk for $\tau = 4$ minutes ($\theta = 45^\circ$)	Risk for $\tau = 10.5$ minutes ($\theta = 45^\circ$)	Risk for $\tau = 13.5$ minutes ($\theta = 45^\circ$)	Weighted Risk ($\theta = 45^\circ$)
30	4	14	3.5×10^{-10}	1.6×10^{-8}	5.7×10^{-8}	3.9×10^{-9}
50	4	32	1.6×10^{-9}	1.3×10^{-8}	2.8×10^{-8}	3.3×10^{-9}
50	10	27	3.9×10^{-9}	8.0×10^{-9}	8.0×10^{-9}	4.3×10^{-9}

Table 7.11: Same track, $[0 \leq \theta < 45^\circ]$, longitudinal collision risk in fatal accidents per flight hour for RNP 10 navigation and procedural separation - Reproduced from (Anderson, 2005)

Separation Minimum (NM)	Required Navigation Performance	Maximum Reporting Interval T (minutes)	Risk for $\tau = 6$ minutes	Risk for $\tau = 12.5$ minutes	Weighted Average Risk
50	10	24	4.7×10^{-9}	5.7×10^{-9}	4.8×10^{-9}

A second application to longitudinal separation of the collision risk model of eqs. (7.212) – (7.216) examined in (Anderson, 2005) concerned reciprocal-track longitudinal separation with ADS where the situation considered was when two ADS-equipped aircraft pass each other at different levels on intersecting tracks. The reader is referred to this reference for details and results of this application.

7.3.4.2 Progression of the PANS-RAC Amendment proposal at RGCSP/10

RGCSP/10, Montreal, May 2000

As set out in Section 7.3.3, RGCSP/10-WP/6 (Unknown, 2000) presented a PANS-RAC Amendment proposal concerning longitudinal distance-based separation minima in an RNP RNAV environment. However, in light of the discussions at RGCSP/10, the Meeting could only endorse the use of longitudinal distance-based separation for same-identical tracks. See the *Report on Agenda Item 1* in the RGCSP/10 Report Folder where Appendix E to that Report provides the text of the resulting proposed PANS-RAC amendment. The text clearly states that the proposed minima apply to aircraft cruising, climbing or descending on the same identical track where the 30 NM longitudinal separation minima requires RNP 4 navigation performance in combination with a maximum ADS periodic reporting interval of 21½ minutes. Two combinations of required navigation performance and maximum ADS periodic reporting interval are given for the 50 NM longitudinal separation minimum, namely RNP 10 / 32 minutes and RNP 4 / 38 minutes.

RGCSP-WG/A-WP/12, Annapolis, November 2000 and SASP-WG/A/1, Madrid, May 2001

RGCSP-WG/A-WP/20 (Butcher, 2001a) describes some further work on the proposed PANS-RAC Amendment from the previous paragraph. Firstly, as a result of a review by the ICAO ANC of the RGCSP/10 Meeting Report, leading to an ANC request for additional information concerning the proposed Amendment, some changes to that amendment were considered and endorsed at the RGCSP's (next) meeting in Annapolis, November

2000 (Appendix H to RGCSP-WG/A/17-WP/18 refers)¹²². Secondly, subsequent review of the *RGCSP/10 Report on Agenda Item 1* by a number of States in the South Pacific raised some further issues regarding the wording and application of the proposed PANS-RAC Amendment. These issues were presented RGCSP-WG/A-WP/20 for further review by the SASP, as the successor to the RGCSP, at its 1st Meeting in Madrid, May 2001, and concerned in particular paragraph 8.4.6.1 and paragraph 8.4.6.4 of Appendix H to RGCSP-WG/A/17-WP/18 in succession to Appendix E to the *Report on Agenda Item 1* in the RGCSP/10 Report Folder.

The SASP-WG/A/1 Meeting was informed by the Secretary that a State letter containing the Amendment proposed at RGCSP/10 was expected to be circulated the month of the Meeting (May 2001) to States and international organizations for comment. Proposed amendments to these proposals by the SASP-WG/A/1 Meeting would be taken into account by the Secretariat when reviewing the replies to the State letter (replies were requested by 24 August 2001), which would be presented to the Air Navigation Commission later the year. The meeting then tasked a Drafting Group to review RGCSP-WG/A-WP/20 and provide revised PANS-RAC amendment proposals as appropriate for consideration by the Secretariat on reviewing replies to the State letter for the Commission's final review of the proposals.

The Drafting Group reviewed paragraphs 8.6.4.1 and 8.6.4.4 of Appendix H to RGCSP-WG/A/17-WP/18 and considered the information provided in SASP-WG/A/1-WP/20 presented at the meeting. It noted that paragraph 8.6.4.1 in the proposal recommended by RGCSP/10, did not provide sufficient detail on the methods by which an ADS system was required to calculate the distance between aircraft to apply the separation minimum for different track scenarios. It accepted in principle the changes suggested by RGCSP-WG/A-WP/20 but re-worded the subject PANS-RAC paragraphs as per Attachment 1 to Appendix D to the Summary of discussions and conclusions of SASP First Meeting of Working Group A (SASP-WG/A/1-SD).

The Meeting subsequently reviewed the report of the Drafting Group in regard to RGCSP-WG/A-WP/20 and it was anticipated that some States in their reply to the State letter would raise the issues contained in the reference. Accordingly, the Meeting felt that it would be helpful to the Secretariat when reviewing the replies from States to have available the conclusions of SASP-WG/A/1 on these issues. It was felt that this would assist the Secretariat in presenting its comments to the Air Navigation Commission for its final review of the proposal. The Meeting noted the comments of the Drafting Group with regards to the issues raised and endorsed the Drafting Group's proposed changes to the amendment provided by RGCSP/10.

It then agreed that with the exception of Table 8, the material in SASP-WG/A-WP/21 (Anderson, 2001a) should replace RGCSP-WG/A-WP/12 (Anderson, 2000a), and be included in Doc 9689¹²³. As remarked in Section 7.3.3, the reporting intervals shown in Tables 7.8 and 7.9 were different to those used previously, including those specified in paragraph 8.6.4.3 of the PANS-RAC Amendment proposal resulting from RGCSP/10. As a result of the agreement mentioned in the previous sentence, the values in paragraph 8.6.4.3 of the PANS-RAC Amendment proposal have been updated, see e.g. SASP-WG/A/2-WP/21 (Butcher, 2001b).

SASP-WG/A/2, Montreal, November 2001

SASP-WG/A/2-WP/21 of the Montreal, November 2001 Meeting (Butcher, 2001b), proposed a further amendment to PANS-RAC Doc 4444 to accommodate the inclusion of longitudinal separation minima less

¹²² Unfortunately, the authors have very little direct information from the Annapolis Meeting of the RGCSP, but SASP-WG/A/1-WP/20 is believed to provide a useful and complete review of the work performed on the pertinent PANS-RAC Amendment proposal.

¹²³ To replace the existing Appendix 1 to ICAO Doc 9689, *Manual on Airspace Planning Methodology for the Determination of Separation Minima*.

than 30 NM using ADS, based on preliminary collision risk estimates provided in SASP-WG/A/2-WP/17 (Anderson, 2001b).

As discussed under the *SASP-WG/A/2, Montreal, November 2001* heading in Section 7.3.4.1, there was an issue with the collision risk model concerning the application of the communication and controller intervention buffer τ to each reporting interval in case of significantly reduced reporting intervals of the order of 2.5 minutes, say. Since the issue could not be resolved during the meeting, it was agreed that it was important to develop PANS amendments in parallel with the development of the collision risk model and that the proposed amendment in SASP-WG/A/2-WP/21 would serve as a first draft for a specific amendment for 20 NM longitudinal minima and ADS and that more work would be undertaken at the SASP's next Meeting.

Air Navigation Commission

The Air Navigation Commission (ANC) approved the PANS-RAC/ATM Amendment proposal for *Longitudinal distance-based separation minima in an RNP RNAV environment using ADS* as resulting from the SASP-WG/A/1 Meeting (Madrid, May 2001) on 28 May 2002, after which it became applicable on 28 November 2002 as Amendment 1 to the Fourteenth Edition of the PANS-ATM.

7.3.5 GNSS longitudinal separation minima

This section considers the safety assessment underlying the extension of the traditional longitudinal separation minima based on distance using distance measuring equipment (DME) to aircraft using Global Navigation Satellite System (GNSS) (ICAO Circular 321). As recalled in section 7.3.1, Table 2.5 in Section 2.5.2 of this Document listed two longitudinal separation minima based on distance using distance measuring equipment (DME), namely 20 NM and 10 NM. These minima were first incorporated into the 8th Edition of the PANS-RAC, in 1966. Based on work performed by the SASP over the period November 2002 to May 2005, GNSS longitudinal separation minima were incorporated into the 15th edition of the PANS-ATM to become applicable as of 22 November 2007.

SASP-WG/WHL/2, Montreal, November 2002

The development started with working paper SASP-WG/A/2-WP/7 presented at SASP Working Group of the Whole's 2nd Meeting (Hajek, 2002). The working paper noted that currently (i.e. in 2002), GNSS avionics falls under the general scope of area navigation (RNAV), but that RNAV separation standards are not always very efficient; generally aircraft are separated by either 80 or 50 NM depending on the RNP used. The use of Distance Measurement Equipment (DME) longitudinal separation is much more effective, because controllers can separate aircraft by 20, 10 or even 5 NM. Because GNSS accuracy is better than that provided by DME, it proposed to adopt the DME separation minima for GNSS equipped aircraft, i.e. to amend *Part III Area Control Service* of the PANS-ATM to allow the separation of aircraft that provide GNSS derived position reports, from other GNSS aircraft as well as from non-GNSS (meaning DME) equipped aircraft by existing DME longitudinal standards.

The SASP-WG/WHL/2 Meeting agreed that with regards to the working paper a safety analysis should be developed in compliance with the *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (ICAO, 1998c), where it recalled that this *Manual* described two methods for determining whether a proposed system, here, longitudinal separation minima based on GNSS, is safe, namely:

- a) Comparison with a reference system; and
- b) Evaluation of risk against a threshold.

For the comparison method, the safety of the proposed system is inferred from the safety of the reference system as long as the two systems are sufficiently similar. For the threshold method, the proposed system is considered to be safe when a quantitative estimate of the risk in the proposed system is less than the prevailing threshold value, i.e. a Target Level of Safety (TLS).

It was then determined that, since SASP was not seeking to determine new separation minima, but rather to demonstrate that a different technology could be used to provide existing DME distance-based separation minima, it would be reasonable to compare GNSS performance with the existing DME performance in terms of accuracy of position determination. Since GNSS longitudinal separation (the proposed system) envisaged using GNSS to provide DME-like separation standards (the reference system), the existence of some level of similarity was suggested and it was necessary to determine whether this level was “sufficient” in the context of the comparative safety assessment. The *Manual* (ICAO, 1998c) identifies the minimum requirements for a proposed system to be considered sufficiently similar to a reference system as:

- a) separation minima must not be less in the proposed system than in the reference system;
- b) proposed means of communication and surveillance must be no worse in terms of accuracy, reliability, integrity and availability than those in the reference system;
- c) frequency and duration of the application of minimum separation between aircraft must not be greater in the proposed system than in the reference system; and
- d) navigation performance (typical and non-typical) of the population of aircraft in the proposed system should be no worse in its effect on collision risk in any dimension than that of the aircraft in the reference system.

Thus, the SASP Meeting agreed to undertake a technical comparison using a reference DME system already being used for distance-based separation that was judged to be safe where the view was that, in the listing above requirements a) and b) were immediately met because neither the separation minima nor the proposed means of communication and surveillance had changed. Concerning requirement c), it was concluded that the extension of the use of the DME standard to GNSS aircraft did not directly lead to changes to the two parameters of this requirement. Finally, with regard to requirement d), a distinction was made between the increasing use of GNSS and GNSS navigation accuracy proper. The conclusion drawn with regard to the former was that the introduction of more and more aircraft equipped with GNSS was independent of the extension of the use of the DME standard to GNSS aircraft.

SASP-WG/WHL/3, London, May 2003

An update to SASP-WG/A/2-WP/7 including a first safety analysis to evaluate the impact of GNSS navigation accuracy using the comparative safety assessment was presented in working paper SASP-WG/WHL/3-WP/8 at SASPs’ 3rd Working Group of the Whole Meeting, in London, May 2003 (Hajek, 2003b). The Meeting provided a number of suggestions for improvement of the comparative safety assessment argument. One issue identified as requiring further work, was that separation differed between aircraft reporting GNSS and DME distances when the aircraft reporting GNSS distance was closer to the NAVAID and was on the same side of it as the DME aircraft. The issue is due to the nature of the error characteristics of GNSS and DME distance reporting. DME position reports consist of the slant range between an aircraft and the NAVAID, which differs from the ground distance between the aircraft and the NAVAID by what is called slant range error, a geometrical effect. Slant range error distorts the position report of the closer aircraft in a pair more and that of the farther aircraft less. On the other hand, GNSS position reports are a true representation of

the ground distance. It was also proposed and agreed that the SASP Mathematicians Sub Group (MSG) should review the comparative assessment and provide comment at the next Meeting. A specific element that would be reviewed concerned the distribution of DME errors.

SASP-WG/WHL/4, Honolulu, November 2003

The issue requiring further work can be sketched as in Figure 7.9 (see e.g. Appendix I to the SASP-WG/WHL/4 Meeting Report). DME aircraft report slant range whereas GNSS aircraft report ground range. For DME/DME aircraft pairs, the (nominal) longitudinal separation between the aircraft is determined as the difference $r_2 - r_1$ between the slant ranges reported by the aircraft. For a mixed aircraft pair, the (nominal) longitudinal separation between the aircraft is determined as the difference of a slant range and a ground range, i.e. $r_2 - x_1$ or $x_2 - r_1$ dependent on whether the DME or the GNSS aircraft is closer to the NAVAID. From a safety point of view, the ground range between the aircraft given their nominal longitudinal separation is of interest.

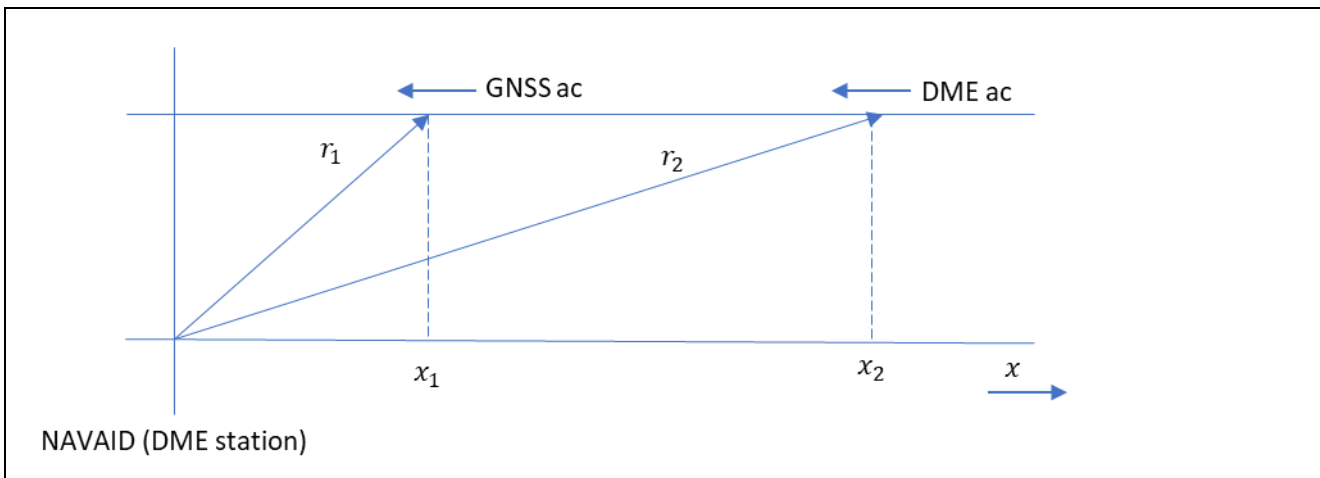


Figure 7.9: Slant range (r_1, r_2) and ground range (x_1, x_2) to a NAVAID (DME station)

Assume first that all ranges are measured without any error. For a DME/DME aircraft pair it then follows for $r_2 - r_1 \geq S_x$ with S_x denoting the longitudinal separation standard that

$$x_2 - x_1 = r_2 - r_1 + (r_1 - x_1) - (r_2 - x_2) \geq S_x + (r_1 - x_1) - (r_2 - x_2) > S_x \quad (7.127)$$

since $(r_1 - x_1) > (r_2 - x_2) > 0$, i.e. the ground range between the aircraft is larger than the longitudinal separation standard when the (nominal) DME separation between the aircraft is larger than or equal to the standard. For a DME/GNSS aircraft pair with the DME aircraft closer to the NAVAID it follows for $x_2 - r_1 \geq S_x$ that

$$x_2 - x_1 = x_2 - r_1 + r_1 - x_1 \geq S_x + (r_1 - x_1) > S_x \quad (7.218)$$

since $r_1 - x_1 > 0$. Finally, for a GNSS/DME aircraft pair with the GNSS aircraft closer to the NAVAID it follows for $r_2 - x_1 \geq S_x$ that

$$x_2 - x_1 = r_2 - x_1 - (r_2 - x_2) \geq S_x - (r_2 - x_2) \quad (7.219)$$

with $r_2 - x_2 > 0$. Whether or not the last expression on the right side of eq. (7.129) is larger than or equal to the longitudinal separation standard S_x depends on the margin by which the reported GNSS/DME distance $r_2 - x_1$ between the aircraft is larger than S_x and the magnitude of the slant range error $r_2 - x_2$ of the second (DME) aircraft. The limiting case occurs when $r_2 - x_1 = S_x$ and it then follows that $x_2 - x_1 = S_x - (r_2 - x_2) < S_x$ for $r_2 - x_2 > 0$. Clearly, when the reported DMA and GNSS distances are corrupted by measurement error, that element needs also to be taken into account in the ultimate safety assessment.

The issue was addressed in SASP-WG/WHL/4-WP/16 (Hajek, 2003a) and SASP-WG/WHL/4-WP/17 (Hajek, 2003c) of SASP's Honolulu November 2003 Meeting and was extensively discussed by both SASP Project Team 6, 20 NM Longitudinal – procedural separation, and the SASP MSG. Attachment A to SASP-WG/WHL/4-WP/16 evaluated the following risk measures for the DME/DME and GNSS/DME case respectively:

$$Prob\{x_2^{DME} - x_1^{DME} \geq 20 | \hat{r}_2 - \hat{r}_1 = 20\} \quad (7.220)$$

$$Prob\{x_2^{DME} - x_1^{GNSS} \geq 20 | \hat{r}_2 - \hat{x}_1 = 20\} \quad (7.221)$$

where $\hat{r}_1 = r_1 + \varepsilon_1$, $\hat{r}_2 = r_2 + \varepsilon_2$, $\hat{x}_1 = x_1 + \varepsilon$, the ε -variables denote zero-mean random measurement errors, and the superscripted quantities denote measured quantities and their corresponding non-superscripted counterparts true quantities. Since the results presented in SASP-WG/WHL/4-WP/16 showed that the probability of eq. (7.220) was always (significantly) larger than the probability of eq. (7.221), it was not possible that the proposed system would perform better than the reference and thus be safe.

During the meeting, the author of SASP-WG/WHL/4-WP/16 then suggested that the following risk measures be examined:

$$\text{for DME/DME: } Prob\{x_2^{DME} - x_1^{DME} \leq \lambda_x | \hat{r}_2 - \hat{r}_1 = 20\} \quad (7.222)$$

$$\text{for GNSS/DME: } Prob\{x_2^{DME} - x_1^{GNSS} \leq \lambda_x | \hat{r}_2 - \hat{r}_1 = 20\} \quad (7.223)$$

and it was agreed that the MSG would evaluate these two risk measures with the standard deviation σ_r of the DME slant range measurement errors to be taken as

$$\sigma_{r,i} = 0.125 + 0.00625 \times r_i, i = 1,2 \quad (7.224)$$

The standard deviation σ_x of the corresponding horizontal distance measurement error was taken as

$$\sigma_{x,i} = \sigma_{r,i} \times \frac{r_i}{x_i}, i = 1,2 \quad (7.225)$$

based on linearisation of the relationship

$$x_i = \sqrt{r_i^2 - h^2}, i = 1,2 \quad (7.226)$$

with h denoting aircraft height. Finally, the standard deviation σ_{GNSS} of the GNSS-based ground distance measurement of the GNSS aircraft was taken as 0.124 NM.

Assuming all measurement error probability distributions to be gaussian, the conditional probabilities for DME/DME and GNSS/DME aircraft pairs in eqs. (7.222) and (7.223) were evaluated as

$$Prob\{x_2^{DME} - x_1^{DME} \leq \lambda_x | \hat{r}_1 = a \text{ and } \hat{r}_2 = a + 20\} = \int_{-\infty}^{\lambda_x} n\left(x; \sqrt{(a+20)^2 - h^2}, \sqrt{\left(\sigma_{r,1} \frac{a}{(a^2-h^2)}\right)^2 + \left(\sigma_{r,2} \frac{a}{(a^2-h^2)}\right)^2}\right) dx \quad (7.227)$$

$$Prob\{x_2^{DME} - x_1^{GNSS} \leq \lambda_x | \hat{x}_1 = a \text{ and } \hat{r}_2 = a + 20\} = \int_{-\infty}^{\lambda_x} n\left(x; \sqrt{(a+20)^2 - h^2} - a, \sqrt{(\sigma_{GNSS})^2 + \left(\sigma_{r,2} \frac{a}{(a^2-h^2)}\right)^2}\right) dx \quad (7.228)$$

where $n(x; \mu, \sigma)$ denotes a Gaussian probability density with mean μ and standard deviation σ .

The above probabilities were computed for DME longitudinal separation standards of 10 NM and 20 NM using the combinations of parameter values shown in Table 7.12. Unfortunately, computation of the two probabilities gave the value zero (0) for both quantities and because of numerical limitations it was not possible to conclude that the proposed system would be safer than the reference system. The respective Gaussian probability densities were then plotted and their points of intersection identified. As expected, it was found that the mean of the DME/DME probability density was larger than that of the GNSS/DME probability density and it was also found that the standard deviation of the DME/DME probability density was larger than that of the GNSS/DME probability density. In all the diagrams, the GNSS/DME probability density was seen to be smaller than the DME/DME probability density over the range of x -values of interest. It was concluded from the analysis that it would follow that the proposed GNSS/DME system was safer than the DME/DME reference system.

Table 7.12: Combinations of altitude and position measurements evaluated for the comparative safety assessment

Altitude (ft)	10 NM DME standard		20 NM DME standard	
15000	16/6	40/30	26/6	50/30
20000	16/6	40/30	26/6	50/30
25000	16/6	40/30	26/6	50/30
30000	16/6	40/30	26/6	50/30

However, two queries were raised in the subsequent discussion. The first query concerned the way distances are actually reported, i.e. what level of rounding or truncation occurs in practice. It was realised that rounding/truncation errors had not been included in the analysis so far and that the effect of such errors could potentially be very large. Project Team 6 was asked to advise after it was decided to model rounding/truncation errors by a uniform distribution over the range $[-0.5, 0.5]$ NM. The second query concerned the fact that the calculations had been based on Gaussian probability distributions, resulting in very small probability values, and that although the analysis in Attachment A to SASP-WG/WHL/4-WP/17 had shown that the results presented there were rather insensitive to the type of distribution used, but that this would no longer necessarily be the case for the new risk measures defined by eqs. (7.222) and (7.223).

The calculations were then extended to double exponentially distributed measurement errors supplemented with uniform rounding/truncation errors. For these calculations, it was found that it could not be concluded that the proposed GNSS/DME system was at least as safe as the DME/DME reference system. The earlier calculations based on Gaussian measurement error distributions were subsequently repeated with the addition of the uniformly distributed rounding/truncation errors. The results of the repeated calculations were similar to the original ones, still supporting the conclusions for the Gaussian case that the proposed GNSS/DME system would be at least as safe as the DME/DME reference system.

One more issue was raised by the MSG, viz. the basis of the 20 NM DME standard given the magnitude of the DME position fix tolerance expressed in ICAO Annex 10 as a 95th percentile value, see Attachment A to SASP-WG/WHL/4-WP/16, whereas it was quoted in SASP-WG/WHL/4-WP/17 as a *Root Sum Squared* (RSS) value where it was not clear whether this should be understood as $RSS = \sqrt{x^2 + y^2 + z^2}$ or as $RSS = \sqrt{(1.96x)^2 + (1.96y)^2 + (1.96z)^2}$. It was wondered whether or not the position fix tolerance included some buffer. Knowledge of this was deemed of vital importance in defining the proper risk measure.

In addition to the work on the comparative safety assessment by Project Team 6 and the MSG, work was performed by Project Team 6 on a PANS-ATM Amendment proposal in support of the use of the DME separation minima for GNSS- equipped aircraft. The SASP Meeting recognised that there was still additional work to be done prior to the next meeting.

SASP-WG/WHL/5, Tokyo, May 2004

SASP-WG/WHL/5-WP/23 (Hajek, 2004) presented an update to the PANS-ATM Amendment proposal resulting from the Honolulu Meeting to resolve a number of issues identified at SASP's previous meeting. The main issues concerned the airspace where the standards were to be applied and how to resolve a possible ambiguity regarding the navigation system that was actually providing the distance information. This was of particular concern given that RNAV reports not using GNSS in the navigation solution could not be used to establish the separation. SASP Project Team 6, *20 NM Longitudinal – procedural separation*, reviewed the updated PANS-ATM Amendment proposal, and agreed on a number of further changes as documented in Attachment 1 to Appendix C to the SASP-WG/WHL/5 Meeting Report.

The MSG started with a review of the status of the comparative safety assessment work performed at its previous meeting in Honolulu in autumn 2003, where it was recalled that, shortly after the Honolulu Meeting, one of the MSG members had detected two irregularities in the formulae derived at that meeting. One of these irregularities turned out to be just a misunderstanding about the notation used whilst the other was a real error. Following correction of the latter, the computations had been redone and had confirmed the conclusions from the Honolulu Meeting, i.e. that, dependent on the type of measurement error probability distributions used, Gaussian or double exponential, it could or could not be concluded that the proposed GNSS/DME system was at least as safe as the DME/DME reference system.

A question asked already at the Honolulu Meeting was to what all relevant factors had been identified and taken into account into the comparative safety assessment. One of the reasons for concern was that the calculated probabilities of longitudinal overlap were very small, as a result of which it had been wondered whether something had been missed out. In order to answer this question, it had been attempted to trace the origins of the DME longitudinal separation standard in the period between the Honolulu and Tokyo Meetings. Not a lot of information could be found, but it appeared nonetheless that the original work had in some manner accounted for random variations in the true airspeed (TAS) of the aircraft in a pair. Based on

that, some trial calculations had been performed prior to the Tokyo Meeting taking TAS variations into account and those preliminary calculations indicated that GNSS/DME would not be safer than DME/DME given the comparative risk measure used. This result, in combination with the same result obtained at the Honolulu meeting for double exponentially distributed distance measurement errors but without accounting for TAS variations, led the MSG to the conclusion that a full collision risk assessment rather than a comparative one should be performed, i.e. that longitudinal collision risk rather than just the probability of radial overlap should be estimated and compared against a TLS of 5×10^{-9} fatal accidents per flight hour. The MSG prepared a (draft) outline specification of how it thought the full collision risk assessment should be conducted, which was attached to the MSG's Meeting Report, see Appendix H to the SASP-WG/WHL/5 Meeting Report. The main parameter of the longitudinal collision risk model to be developed was the probability of longitudinal overlap. It would be calculated as the product of two factors, namely the probability of longitudinal overlap given a reported distance and the probability of the reported distance taking a particular value. It was agreed that the first factor, the probability of longitudinal overlap given a reported distance, would be derived taking the following error sources into account: position fix error, pilot rounding/truncation error, and speed errors. The ultimately resulting model will be presented under the SASP-WG/WHL/7, *Montreal, May 2005*, heading below.

SASP-WG/WHL/6, Washington, November 2004

SASP Project Team 6, *20 NM Longitudinal – procedural separation*, reported that it had completed significant work during the Meeting, specifically concentrated on the completion of a safety analysis for longitudinal separation minima based on GNSS. Attachment 2 to the Project Team's Report in Appendix C to the SASP-WG/WHL/6 Meeting Report provided an attempt to include all the discussions and information regarding the development of the pertinent PANS-ATM proposal in one easily referenced location. The attachment comprised a summary of the proposal to implement GNSS distance-based longitudinal separation, hazard identification (HAZID) and mitigation measures, as well as the latest version of the proposed amendment to the PANS-ATM. The SASP meeting noted the Project Team's desire to progress the amendment proposal direct to the Secretariat out of session. This would be undertaken before the next meeting of the SASP-WG/WHL, subject to completion of the full collision risk assessment by the SASP MSG.

At SASP-WG/WHL/6, the MSG started reviewing a revised draft of the outline collision risk model specification from the previous meeting where it was found that, in particular, the description of the calculation of the probability of longitudinal overlap/overtake needed some improvement. Some guidance was received from Project Team 6 on the operational context of the use of the GNSS/DME longitudinal separation standard. Some trial calculations were performed, which showed the significance of the speed errors with respect to the probability of overlap/overtake in the longitudinal dimension, the precise effect being dependent on the frequency of checking the separation to ensure that the longitudinal separation minimum would not be infringed. Due to the limited time remaining at the meeting, it was agreed that the final calculations would be performed shortly after the Washington Meeting in order to reduce the likelihood of any errors or unwarranted conclusions and that the results would subsequently be distributed amongst the MSG member and the pertinent members of Project Team 6 for review.

SASP-WG/WHL/7, Montreal, May 2005

Both SASP Project Team 6, *20 NM Longitudinal – procedural separation*, and the SASP MSG completed their work on the subject matter of allowing GNSS position reports for the purpose of longitudinal separation between aircraft providing GNSS and DME distances. Documentation of all the work carried out was developed and resulted in ICAO Circular 321.

Project Team 6 started with a presentation by the MSG of the final safety assessment that the latter had developed and documented in SASP-WG/WHL/7-WP/23 (SASP MSG, 2005). As set out in the Project Team's report of the Meeting, see Appendix D to the SASP-WG/WHL/7 Meeting Report, the main issue concerned aircraft pairs for which the aircraft reporting GNSS was closer to and on the same side of the NAVAID. Longitudinal collision risk was evaluated for three scenarios, namely:

- 1) Two aircraft in trail on same track – separation 20 NM;
- 2) Two aircraft in trail on same track where one requests an altitude change through the altitude of the other aircraft – 10 NM; and
- 3) Two aircraft on reciprocal tracks – 10 NM.

The ultimate safety assessment was a hybrid one in that it made use of a combination of the following two methods:

- 1) Estimation of the longitudinal collision risk and evaluation of it against the TLS; and
- 2) Comparison between the GNSS/DME and DME/DME pair.

The reason for the hybrid approach was that a precise estimate of the risk of GNSS/DME aircraft pairs could not be made due to lack of information on the distribution of reported separations. The comparison method was used to overcome this problem. The conclusion of the safety assessment was that in all scenarios the probability of longitudinal overlap for GNSS/DME aircraft pairs was smaller than that for DME/DME aircraft pairs when the aircraft were further away from the DME station than a certain distance whereas closer to the DME station the probabilities of longitudinal overlap were negligible, both for GNSS/DME pairs and DME/DME aircraft pairs. In other words, the risk with the GNSS/DME aircraft pair was either negligible or less than the DME/DME risk.

Project Team 6 subsequently resolved some final outstanding issues of a largely operational/technical nature and prepared a once more revised PANS-ATM amendment and an updated matrix summarizing the new hazards and mitigations identified. See Attachments 1 and 2 to Appendix D to the SASP-WG/WHL/7 Meeting Report.

As indicated above, SASP-WG/WHL/7-WP/23 (SASP MSG, 2005), prepared by the SASP MSG, documented the final safety assessment for longitudinal separation minima based on GNSS. The collision risk model was presented in Section 5 of the working paper. As a preliminary, it was noted that when a full collision risk assessment is to be performed for an airspace where distance based longitudinal separation is used and aircraft use either DME or GNSS based distance reporting, the longitudinal TLS applies to all aircraft pairs using the same standard, i.e. GNSS/DME, DME/DME, DME/GNSS and GNSS/GNSS pairs where the notation GNSS/DME denotes first aircraft using GNSS and second aircraft using DME, etc. Both the risk per type of aircraft pair and the proportion of aircraft pairs of each type need to be taken into account when comparing the estimated overall risk to the TLS. The collision risk models for the different types of aircraft pairs are equal except for the probability of horizontal overlap. It would be helpful to remove the dependence of the overall risk on the pair type proportions by being able to demonstrate that the horizontal overlap probability is always the largest for one particular type of pair. This would then ensure that the standard is globally applicable, independent of the proportions of the different types of aircraft pairs that may prevail in individual airspaces. Global applicability would also require that a realistic globally applicable upper bound for the number of aircraft pairs per flight hour could be found.

The collision risk assessment of SASP-WG/WHL/7-WP/23 examined the same identical track case only. Consider same direction traffic using GNSS and DME distance reporting. The probability of horizontal overlap then factors into the product of the probability of longitudinal overlap and that of lateral overlap. For the

three types of pairs GNSS/DME, DME/DME and DME/GNSS, the probability of lateral overlap is larger for the GNSS/DME (and DME/GNSS) pair than for the DME/DME pair. Assuming (on the basis of previous work of the MSG) that the probability of longitudinal overlap is the largest for GNSS/DME pairs, only the collision risk for this type of pair would need to be modelled and compared to the TLS, possibly together with that of GNSS/GNSS pairs. For the latter type of pair, the probability of longitudinal overlap would be expected to be smaller than that for a GNSS/DME pair, but the probability of lateral overlap would be expected to be larger. The latter factor might dominate the former and in that case both GNSS/DME and GNSS/GNSS pairs would have to be taken into account.

SASP-WG/WHL/7-WP/23 comprised the following sections:

1. Introduction;
2. Modelling the different error terms;
3. An example: mean and standard deviation of error in horizontal distance;
4. Types of error distributions;
5. Collision risk model;
6. Results;
7. Recommendation; and References.

The calculation of the probability of longitudinal overlap for a GNSS/DME aircraft pair was part of Section 4 of SASP-WG/WHL/7-WP/23.

The scenarios evaluated have been listed above. Some relevant parameter ranges utilised in the safety assessment are shown in Table 7.13. Notice that the DME distance fix tolerance was changed in July 1997.

Table 7.13: range of some parameter values relevant to the GNSS/DME safety assessment

Parameter	Range of values
Aircraft speed	100 – 480 kts
Altitude	0 – 45000 ft
Distance between DME stations	≤ 400 NM
DME distance fix tolerance; prior to July 1997	0.5 NM or 3% of distance to DME antenna
DME distance fix tolerance; as of July 1997	0.25 NM + 1.25% of distance to DME antenna

The in trail same identical track case is shown in Figure 7.10 with both aircraft flying towards the NAVAID with the GNSS aircraft leading and the DEM aircraft following. Let $t, t \geq 0$, denote time starting at the point in time of position reporting and let the true ground ranges $x_1(t)$ and $x_2(t)$ at time t be given by

$$x_1(t) = x_1 - V_1 \times t \quad (7.229)$$

$$x_2(t) = x_2 - V_2 \times t \quad (7.230)$$

with $V_1 > 0$ and $V_2 > 0$ denote the true aircraft speeds and x_1 and x_2 the true ground ranges at time $t = 0$. Let the nominal (ground) distances and speeds be given by

$$\hat{x}_1 = x_1 + \eta_1 + u_1, \hat{x}_2 = x_2 + \varepsilon_2 + u_2, \hat{V}_1 = V_1 + v_1, \hat{V}_2 = V_2 + v_2 \quad (7.231)$$

where η_1 and ε_2 denote the pertinent position fix errors, u_1 and u_2 denote the pilot truncation/rounding errors, and v_1 and v_2 the aircraft speed errors.

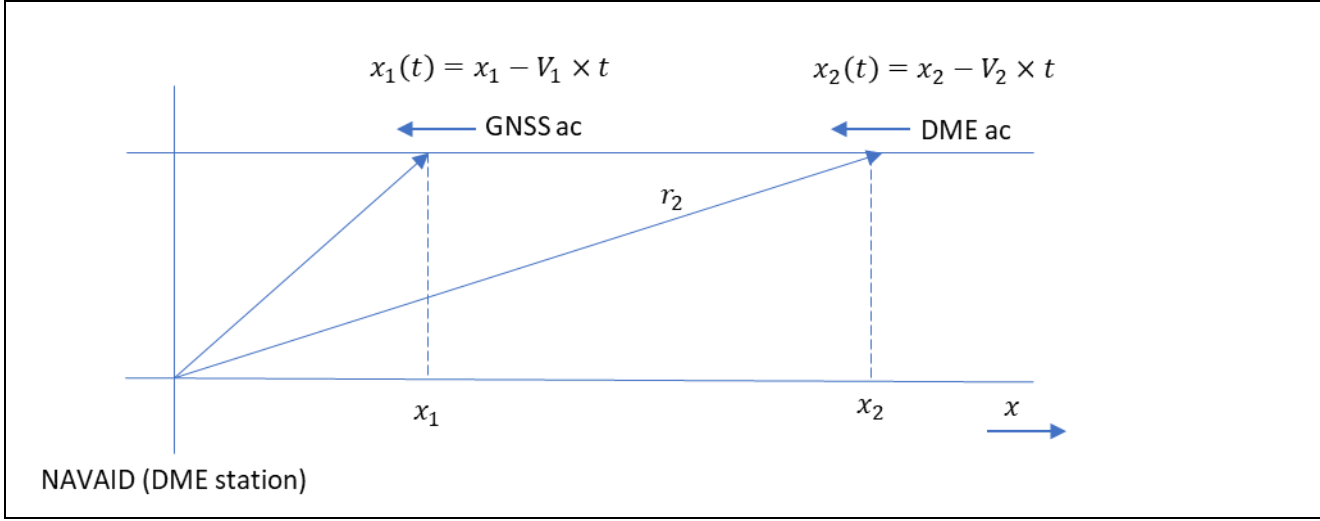


Figure 7.10: Motion of GNSS/DME aircraft pair towards NAVAID (DME station) and slant range r_2 of DME aircraft and ground range x_1 of GNSS aircraft at time of position reporting

Section 2 of SASP-WG/WHL/7-WP/23 described the true longitudinal separation at time t , $x(t) = x_2(t) - x_1(t)$, between a GNSS/DME aircraft pair in terms of their reported distances, $\hat{x}_1$ and $\hat{r}_2$ at time $t = 0$ and the different error sources as (see eq. (2.9) of SASP-WG/WHL/7-WP/23)

$$x(t) = x_2(t) - x_1(t) = \sqrt{\hat{r}_2^2 - h^2} - \hat{x}_1 - \frac{\hat{r}_2}{\hat{x}_2} \varepsilon_2 - \frac{\hat{r}_2}{\hat{x}_2} u_2 + \eta_1 + u_1 + (v_2 - v_1) \times t \quad (7.232)$$

with $\hat{x}_2 = \sqrt{\hat{r}_2^2 - h^2}$ and h the altitude of the second aircraft reporting DME distance. Denoting the quantity on the right-most side of eq. (7.232) by Ψ , the mean and variance of the random variable Ψ were given by

$$E\{\Psi\} = \sqrt{\hat{r}_2^2 - h^2} - \hat{x}_1 \quad (7.233)$$

and

$$\sigma^2\{\Psi\} = \left(\frac{\hat{r}_2}{\hat{x}_2}\right)^2 \sigma_{\varepsilon_2}^2 + \sigma_{\eta_1}^2 + \left(\frac{\hat{r}_2}{\hat{x}_2}\right)^2 \sigma_{u_2}^2 + \sigma_{u_1}^2 + (\sigma_{v_2}^2 + \sigma_{v_1}^2) \quad (7.234)$$

Notice that the combined error variance $\sigma^2\{\Psi\}$ is a quadratic function of the time t since position reporting. Hence, the probability of a longitudinal overlap occurring increases with the time since position reporting. The precise effect is dependent on the types of probability distributions for the individual error terms in eq. (7.232) or the random variable Ψ . The increase in the probability of longitudinal overlap can thus be limited by requiring aircraft to report distances to the same NAVAID with an appropriate time interval, e.g. 15 or 30 minutes.

Section 3 of SASP-WG/WHL/7-WP/23 gave some examples of the mean and standard deviation of the error in horizontal distance between the aircraft, independently of the types of error distributions.

Section 4 of SASP-WG/WHL/7-WP/23 started listing the types of probability distributions that might be utilised for the different error terms. Notice that for the DME fix error and the speed errors both a first choice and a second choice were specified. See Table 7.14.

Table 7.14: Types of probability distributions to be used for the various error terms

Type of error		Type of probability distribution	
Description	Symbol	1 st choice	2 nd choice
GNSS ground range error	η_1	Gaussian ¹²⁴	-
DME fix error	ε_2	Double exponential	Gaussian
Pilot rounding/truncation error 1 st aircraft	u_1	Uniform	-
Pilot rounding/truncation error 2 nd aircraft	u_2	Uniform	-
Speed error 1 st aircraft	v_1	Double exponential	Gaussian
Speed error 2 nd aircraft	v_2	Double exponential	Gaussian

The conditional probability density function $f_{x(t)}(x)$ of the true longitudinal separation at time t , $x(t) = x_2(t) - x_1(t)$, between a GNSS/DME aircraft pair was then derived, given the aircraft's reported distances, $\hat{x}_1$ and $\hat{r}_2$ (and $\hat{x}_2$ derived from $\hat{r}_2$ and the second aircraft's altitude h). This derivation involved a considerable amount of algebra and resulted in an expression made up of twelve different quantities where three different combinations of those twelve quantities were to be distinguished. Eq. (4.48) of SASP-WG/WHL/7-WP/23 provides the pertinent formula.

Having calculated the conditional probability density function $f_{x(t)}(x)$ of the true longitudinal separation between the aircraft at time t , given the reported distances $\hat{x}_1$ and $\hat{r}_2$ at time $t = 0$, the probability of $x(t) \in [-\lambda_x, \lambda_x]$, i.e. the probability of the pair being in longitudinal overlap, can be calculated for each value of t .

An aircraft pair may start getting into longitudinal overlap at different points in time t dependent on the particular realisations of the position reports and the speed errors. A longitudinal overlap between a given pair of aircraft begins at some time t if and only if for every $\Delta t > 0$

$$x(t) = \lambda_x \text{ and } x(t - \Delta t) > \lambda_x \quad (7.235)$$

Eq. (7.235) allows determining the random time t at which a longitudinal overlap begins as a function of the random variables making up the random variable $x(t)$. Specifically, it follows from eqs. (7.232) and (7.235) that

$$t = \frac{\lambda_x - \left(-\frac{\hat{r}_2}{\hat{x}_2} u_2 + u_1 + \sqrt{\hat{r}_2^2 - h^2} - \hat{x}_1 - \frac{\hat{r}_2}{\hat{x}_2} \varepsilon_2 + \eta_1 \right)}{v_2 - v_1} \quad (7.236)$$

The probability distribution of the random time t can, in principle, be determined from the probability distributions of the various variables on the right-hand side of eq. (7.236). The probability that the aircraft pair will experience the start of a longitudinal overlap during the time interval $[0, t_{end}]$ is

¹²⁴ To simplify the derivation of $f_{x(t)}(x)$, a double exponential density was actually used for the GNSS ground range error η_1 . Since a double exponential probability density has a thicker tail than a Gaussian probability density, this approximation would be conservative.

$$P_x[0, t_{end}] = Prob\{t \leq t_{end}\} \quad (7.237)$$

Rather than explicitly calculating the probability density of t , the probability density of $x(t)$ at time t_{end} was used as follows. First, eq. (7.236) was used to write eq. (7.237) in the form

$$P_x[0, t_{end}] = Prob\left\{\frac{\lambda_x - \left(-\frac{\hat{r}_2}{\hat{x}_2}u_2 + u_1 + \sqrt{\hat{r}_2^2 - h^2} - \hat{x}_1 - \frac{\hat{r}_2}{\hat{x}_2}\varepsilon_2 + \eta_1\right)}{v_2 - v_1} \leq t_{end}\right\} \quad (7.238)$$

Both sides of the inequality inside the “probability accolades” on the right side of eq. (7.238) were then multiplied by $v_2 - v_1$ on the assumption of $v_2 - v_1 < 0$ (see the second paragraph below eq. (7.242) to obtain

$$P_x[0, t_{end}] = Prob\left\{\lambda_x - \left(-\frac{\hat{r}_2}{\hat{x}_2}u_2 + u_1 + \sqrt{\hat{r}_2^2 - h^2} - \hat{x}_1 - \frac{\hat{r}_2}{\hat{x}_2}\varepsilon_2 + \eta_1\right) \geq (v_2 - v_1)t_{end}\right\} \quad (7.239)$$

or

$$P_x[0, t_{end}] = Prob\left\{\lambda_x \geq \left(-\frac{\hat{r}_2}{\hat{x}_2}u_2 + u_1 + \sqrt{\hat{r}_2^2 - h^2} - \hat{x}_1 - \frac{\hat{r}_2}{\hat{x}_2}\varepsilon_2 + \eta_1\right) + (v_2 - v_1)t_{end}\right\} \quad (7.240)$$

i.e., using the definition of $x(t)$ for $t = t_{end}$,

$$P_x[0, t_{end}] = Prob\{\lambda_x \geq x(t_{end})\} \quad (7.241)$$

Finally, using the conditional probability density $f_{x(t)}(x)$ of $x(t)$, eq. (7.241) for the conditional probability of longitudinal overlap was expressed as

$$P_x[0, t_{end}] = \int_{-\infty}^{\lambda_x} f_{x(t_{end})}(x) dx \quad (7.242)$$

Eq. (7.242) makes sense intuitively, since for the starting time t of a longitudinal overlap as defined by eq. (7.236) with $t \leq t_{end}$, eq. (7.232) for $x(t)$ implies that the smallest value of $x(t)$ occur for $t = t_{end}$ when $v_2 - v_1 < 0$. See also Figure 7.11. The figure shows three straight lines representing $x(t)$. The green line marks the start of a longitudinal overlap at some point in time $t < t_{end}$. The yellow line marks the start of a longitudinal overlap at time $t = t_{end}$ and the red line marks the start of a longitudinal overlap at some point in time $t > t_{end}$.

As regards the change of the “ $\leq$ ”-sign in eq. (7.238) into a “ $\geq$ ”-sign in eq. (7.239), this is due to the fact that when the aircraft are not in overlap initially and in the right order, a longitudinal overlap can only originate when the true speed V_2 of the second aircraft is larger (by a sufficient amount) than the true speed V_1 of the first aircraft. Assuming equal nominal speeds $\hat{V}_2$ and $\hat{V}_1$ in eq. (7.231), it follows that the event $V_2 > V_1$ is equivalent to the event $v_2 < v_1$. Hence, multiplying by $v_2 - v_1$ in eq. (7.238) reverses the inequality sign as in eq. (7.239).

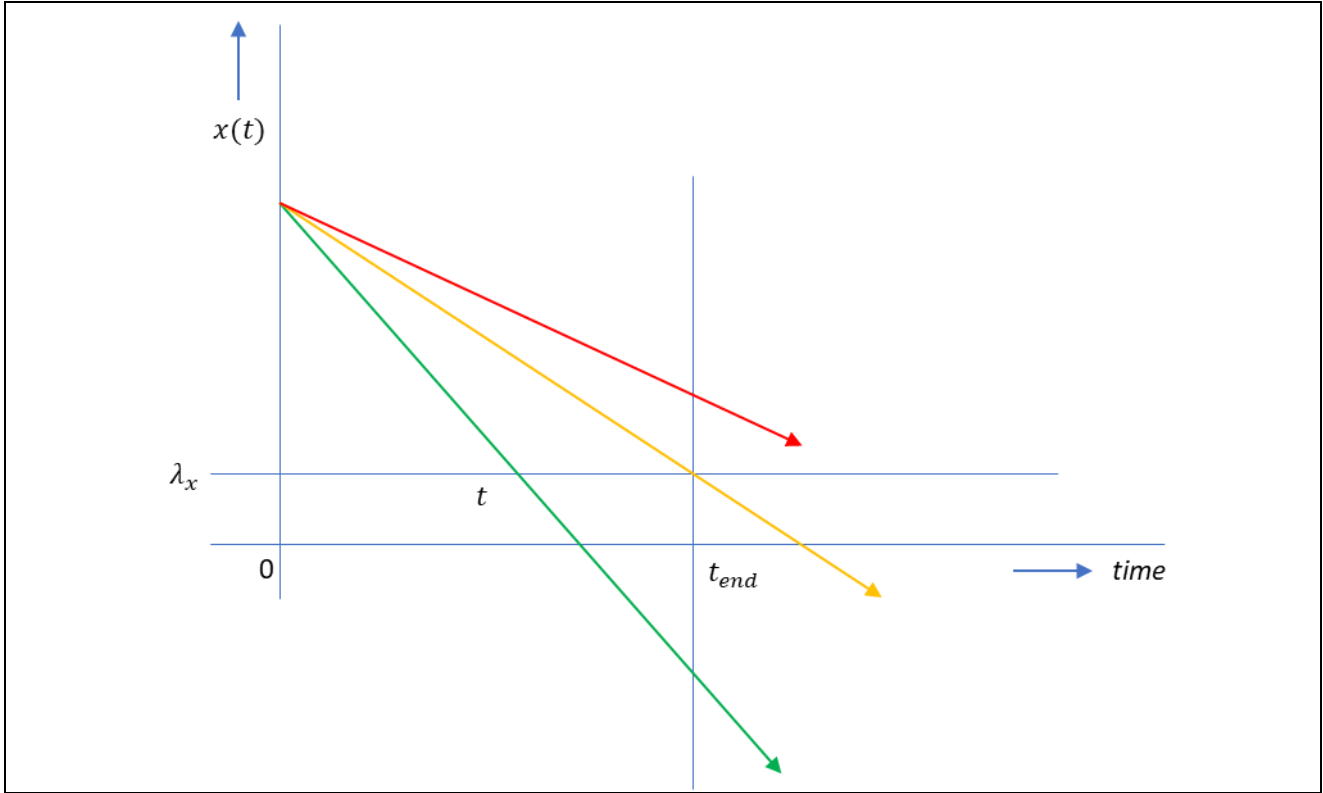


Figure 7.11: True ground range between aircraft positions and longitudinal overlaps starting at different points in time dependent on the relative speed error $v_2 - v_1$ between the aircraft

Given that an aircraft pair has experienced the start of a longitudinal overlap during the time interval $[0, t_{end}]$, it will on average generate $2\lambda_x / |\overline{\Delta V_x}|$ of longitudinal overlap time when $|\overline{\Delta V_x}|$ denotes the average value of the absolute longitudinal closing speed of a pair of aircraft that has lost longitudinal separation.

The full set of formulae specifying the conditional probability density $f_{x(t)}(x)$ of the true longitudinal separation $x(t) = x_2(t) - x_1(t)$ at time t between a GNSS/DME aircraft pair, given the aircraft's reported distances, $\hat{x}_1$ and $\hat{r}_2$ can be found in Section 4.3 of SASP-WG/WHL/7-WP/23 but has not been reproduced here since the formulae as such do not provide a lot of useful insight. It is, however, useful to expand eq. (7.242) with respect to the conditioning variables $\hat{x}_1$ and $\hat{r}_2$.

The dependence of the probability of a longitudinal overlap starting during the time interval $[0, t_{end}]$ on the initially observed positions $\hat{x}_1 = a$ and $\hat{r}_2 = a + X$, $X \geq S_x$, with S_x denoting the longitudinal separation standard/minimum, can be made more explicit by writing

$$P_x[0, t_{end}]_X = \text{Prob}\{x(t_{end}) = x_2(t_{end}) - x_1(t_{end}) \leq \lambda_x | \hat{x}_1 = a, \hat{r}_2 = a + X\}, X \geq S_x \quad (7.243)$$

or, using and making eq. (7.242) more explicit,

$$P_x[0, t_{end}]_X = \int_{-\infty}^{\lambda_x} f_{x(t_{end})| \hat{x}_1=a, \hat{r}_2=a+X}(u) du, X \geq S_x \quad (7.244)$$

Notice the subscript X on the longitudinal overlap probability on the left sides of eqs. (7.243) and (7.244). The dependence on the specific value of X , $X \geq S_x$, is removed by integrating over X , $X \geq S_x$, i.e.

$$P_x[0, t_{end}] = \int_{X \geq S_x} P_x[0, t_{end}]_X \text{Prob}\{\hat{x}_1 = a, \hat{r}_2 = a + X\} dX = \int_{X \geq S_x} \text{Prob}\{x_2(t_{end}) - x_1(t_{end}) \leq \lambda_x | \hat{x}_1 = a, \hat{r}_2 = a + X\} \text{Prob}\{\hat{x}_1 = a, \hat{r}_2 = a + X\} dX \quad (7.245)$$

Using eq. (7.244), the probability of longitudinal overlap can also be written as

$$P_x[0, t_{end}] = \int_{X \geq S_x} \int_{-\infty}^{\lambda_x} f_{x(t_{end})| \hat{x}_1=a, \hat{r}_2=a+X}(u) du \text{Prob}\{\hat{x}_1 = a, \hat{r}_2 = a + X\} dX \quad (7.246)$$

It should be noted that $\text{Prob}\{\hat{x}_1 = a, \hat{r}_2 = a + X\}$ is a probability distribution in X only, where the quantity a is to be treated as a given number. SASP-WG/WHL/4-WP/9 (Anderson, 2003c) used a rectangular distribution over the domain $[S_x, S_x + 250]$ NM for this distribution and the same was done in SASP-WG/WHL/7-WP/23 for the GNSS/DME safety assessment. As regards the given quantity a , this was chosen equal to the longitudinal separation standard S_x for the ultimate risk calculations performed in SASP-WG/WHL/7-WP/23.

A conservative upper bound for the conditional probability of a longitudinal overlap starting during the time interval $[0, t_{end}]$ of eq. (7.244) is obtained by taking just $X = S_x$, i.e.

$$P_x[0, t_{end}] = \text{Prob}\{x_2(t_{end}) - x_1(t_{end}) \leq \lambda_x | \hat{x}_1 = a, \hat{r}_2 = a + S_x\} \quad (7.247)$$

This is the form of the probability that was evaluated by the SASP MSG during the Honolulu, November 2003, Meeting for the case without speed errors.

Section 5 of SASP-WG/WHL/7-WP/23 presented the collision risk model utilized, including values for the model's parameters other than the probability of longitudinal overlap. The model was expressed as

$$N_{ac}^* = 2 \times P_x[0, t_{end}] P_y(0) P_z(0) \frac{2\lambda_x}{|\Delta V_x|} \left[\frac{|\Delta V_x|}{2\lambda_x} + \frac{v_y}{2\lambda_y} + \frac{v_z}{2\lambda_z} \right] \quad (7.248)$$

or, equivalently,

$$N_{ac}^* = 2 \times P_x[0, t_{end}] P_y(0) P_z(0) \left[1 + \frac{\lambda_x}{\lambda_y} \frac{v_y}{|\Delta V_x|} + \frac{\lambda_x}{\lambda_z} \frac{v_z}{|\Delta V_x|} \right] \quad (7.249)$$

In these equations, N_{ac}^* denotes the expected number of fatal accidents (not: fatal accidents per flight hour) due to the loss of longitudinal separation for a single GNSS/DME aircraft pair during the time interval $[0, t_{end}]$, $P_x[0, t_{end}]$, $P_y(0)$, and $P_z(0)$ denote the pair's respective probabilities of overlap in the longitudinal, lateral and vertical dimensions, and the remaining symbols concern aircraft dimensions and relative speeds. It is remarked that in the final safety assessment, N_{ac}^* was converted to the conventional TLS unit of fatal accidents per flight hour.

Eq. (7.249) may be compared with the longitudinal collision risk model of eqs. (7.193) and (7.194) used for the 50 NN and 30 NM longitudinal separation minima based on distance using RNAV where RNP is specified in Sections 7.3.2 and 7.3.3, i.e.

$$N_{ax} = \Pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.193)$$

with

$$\Pi_x = \frac{4\lambda_x}{S} \times \int_s^{\infty} w(s) U(s) ds, \quad (7.194)$$

N_{ax} denoting the expected number of accidents per flight hour and S denoting the longitudinal separation standard/minimum.

The comparison boils down to comparing Π_x defined by eq. (7.194) with $2 \times P_x[0, t_{end}] \frac{2\lambda_x}{|\Delta V_x|}$ where it is useful to recall from Section 7.3.2 that, based on eq. (7.183), it was shown that the longitudinal distance-based separation standard S was equivalent to the product of the average at-risk period T and $|\dot{x}(m)|$, the smallest possible longitudinal closing speed such that a longitudinal overlap occurs, with m being the longitudinal separation minimum in minutes. The outer integral on the right side of eq. (7.246) for $P_x[0, t_{end}]$ is seen to correspond with the integral on the right side of eq. (7.194) for Π_x , whereas the inner integral on the right side of eq. (7.246) for $P_x[0, t_{end}]$ corresponds with $U(s)$ in eq. (7.194) for Π_x since $U(s)$ represents the probability that longitudinal overlap occurs between times $t = 0$ and $t = T + \tau$ given an initial nominal separation $\hat{S}_0 = s$, and T and τ denoting the length of the reporting period and the buffer for communication and other delays and controller action respectively, i.e. $T + \tau$ corresponds with t_{end} . Finally, $Prob\{\hat{x}_1 = a, \hat{r}_2 = a + X\}$ on the right side of eq. (7.246) for $P_x[0, t_{end}]$ can be associated with $w(s)$ in eq. (7.194) for Π_x , with $w(s)$ being the density function giving the probability, over the whole system being evaluated (in the context of $P_x[0, t_{end}]$ a single GSNN/DME aircraft pair), that any selected pair of aircraft at the same level are nominally separated longitudinally by a distance s .

See Section 5 of SASP-WG/WHL/7-WP/23 for the values of the parameters of the collision risk model of eq. (7.249) other than $P_x[0, t_{end}]$ and recall from Table 7.14 that a first choice and a second choice were made for the speed error distributions, namely double exponential and Gaussian respectively. Substituting the pertinent parameter estimates into the collision risk model resulted in

$$N_{ac}^* = P_x[0, t_{end}] \times \{0.16092 + 2.7359/\lambda_v\} \quad (7.250)$$

for the 1st choice of **double exponential** speed error distributions and

$$N_{ac}^* = P_x[0, t_{end}] \times \{0.16092 + 3.6369/\sigma_v\} \quad (7.251)$$

for the 2nd choice of **Gaussian** speed error distributions. In eq. (7.250), λ_v denotes the scale parameter of a double exponential speed error distribution, cf. eq. (4.19), and σ_v denotes the standard deviation of a Gaussian speed error distribution, cf. eq. (4.25). Table 5.3 of SASP-WG/WHL/7-WP/23 specified the values of λ_v and σ_v as proportions of the aircraft speed V .

Section 6 of SASP-WG/WHL/7-WP/23 presented the results obtained with the GNSS/DME longitudinal collision risk model of eqs. (7.250) and (7.251). As has been indicated a number of times in previous chapters, this Document focusses on the form of the various collision risk models rather than the estimation of one or more collision risk model parameters. However, given the new way the probability $P_x[0, t_{end}]$ of a GNSS/DME aircraft pair experiencing the start of a longitudinal overlap was derived for the GNSS/DME collision risk model, some results on $P_x[0, t_{end}]$ for two aircraft in trail on the same track will be briefly presented, i.e. for scenario 1) listed in the second paragraph under the *SASP-WG/WHL/7, Montreal, May 2005* heading above.

As follows from eq. (7.246), the probability $P_x[0, t_{end}]$ of a GNSS/DME aircraft pair experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ varies with both $\hat{x}_1 = a$, the distance of the first (GNSS) aircraft to the NAVAID and the reported separation X . This variation of $P_x[0, t_{end}]$ with $\hat{x}_1$ and X was expressed as $P_x[0, t_{end}; \hat{x}_1, X]$. Table 7.13 specified a maximum distance between DME stations of 400 NM. It was thus assumed, somewhat cautiously, that the first aircraft was initially 240 NM away from the NAVAID ahead. As regards the dependence on the reported separation X , eq. (7.246) shows, that, in principle, the probability distribution $Prob\{\hat{x}_1 = a, \hat{r}_2 = a + X\}$ of the initial separation X is needed. (Recall that a was to be considered as a known value.) This distribution would not be readily available, and it was agreed, therefore, that if it would be possible to show that the TLS would be met for just the minimum initial separation allowed, i.e. the longitudinal separation standard/minimum S_x , then the probability distribution $Prob\{\hat{x}_1 = a, \hat{r}_2 = a + X\}$ would not have to be determined. In this context, it was recognised that it was very unlikely that this minimum distance would actually be utilised in practice by controllers, but from a safety assessment point of view it was nonetheless necessary to evaluate the collision risk for the longitudinal separation minimum. With the above simplification, the calculation of $P_x[0, t_{end}]$ reduced to one based on eq. (7.242) only.

In practice, the longitudinal separation is to be checked by obtaining simultaneous ground/slant range readings from the aircraft at frequent intervals. The frequency of checking is not explicitly specified in the PANS-ATM and an easy rule of thumb for this frequency, particularly as a function of the aircraft speed and initial separation, does not exist. The MSG was advised by some operational experts that if a minimum separation of 20NM were to be used at an aircraft speed of 480kts, a controller would want to check at least every couple of minutes. In line with the longitudinal distance based separation minima determined in Sections 7.3.2 and 7.3.3, risk was estimated over a checking/reporting interval plus a buffer where the buffer comprised the following components: downlink, controller conflict recognition, controller message composition, uplink, pilot reaction time, and aircraft inertia plus climb. For the type of environment where the longitudinal separation minimum based on DME is to be utilised, it was assumed that both the downlink and the uplink would take place instantaneously. The resulting buffer value was taken as three minutes (See SASP-WG/WHL/7-WP/23). Combining the values of the advised checking/reporting interval and the buffer led to a time interval $[0, t_{end}]$ with $t_{end} = 6$ minutes over which the probability of the loss of longitudinal separation and the longitudinal collision risk was evaluated for an aircraft speed of 480kts.

Table 7.15 and Figure 7.12 show the probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ that the pair has experienced the start of a longitudinal overlap during the time interval $[0, t_{end}]$ as a function of the distance of the first aircraft

to the NAVAID (DME-station) for an aircraft speed of 480kts, $t_{end} = 6$ minutes and an aircraft altitude of 35000 ft. Figure 7.12 shows that $P_x[0, t_{end}; \hat{x}_1, X]$ takes very small, approximately constant, values when the first (GNSS) aircraft is less than 60 NM away from the DME-station. The values then start to increase, approximately five orders of magnitude over the next 60 NM and another five orders of magnitude over the remaining 120 NM. The increase in the probability $P_x[0, t_{end}; \hat{x}_1, X]$ with the distance $\hat{x}_1 = a$ is caused by the increase in the standard deviation of the DME distance measurement error (cf. Table 7.13). An average value of $\bar{P}_x[0, t_{end}; X = 20] = 1.42 \times 10^{-8}$ was calculated for distances $\hat{x}_1$ of the first aircraft to the NAVAID of 240, 220, ..., 0 NM.

Table 7.15: Probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ of a GNSS/DME aircraft pair experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ as a function of the distance $\hat{x}_1$ of the first aircraft to the NAVAID (DME-station) for aircraft speeds of 480 kts, altitude 35000 ft, 6 minutes checking/reporting interval plus buffer, and reported separation of $X = 20$ NM

Distance of first (GNSS) aircraft to the NAVAID (DME station) (NM)							
0	20	40	80	120	160	200	240
9.08E-18	4.53E-18	5.60E-18	9.93E-16	1.86E-12	2.71E-10	8.32E-9	9.98E-8

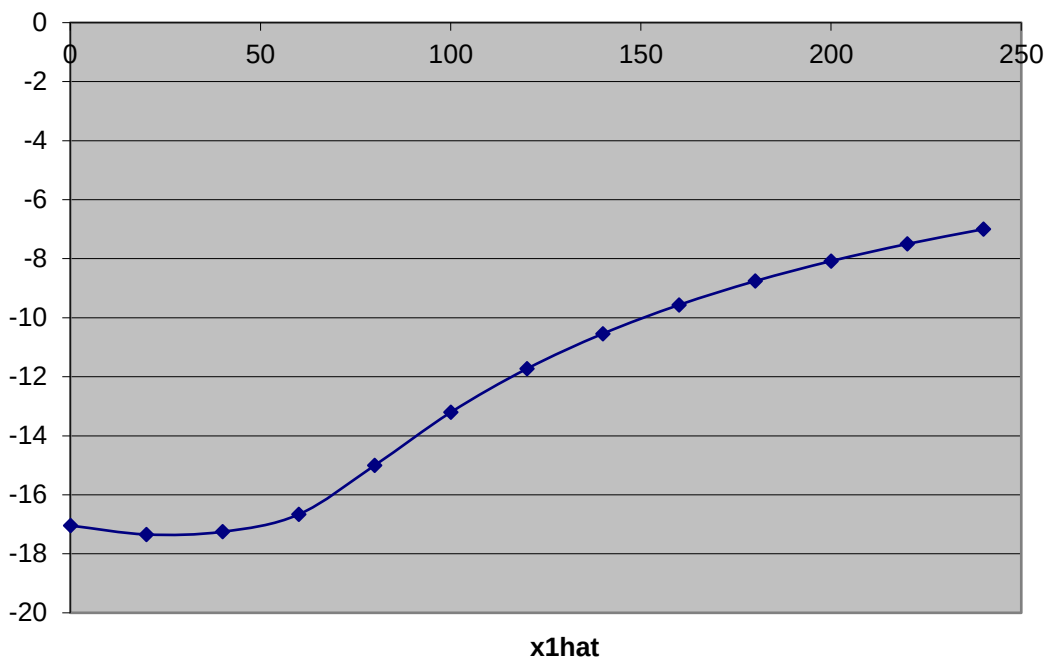


Figure 7.12: Logarithm (base 10) of the probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ for a GNSS/DME aircraft pair experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ as a function of the distance $\hat{x}_1$ of the first aircraft to the NAVAID (DME-station) for aircraft speeds of 480 kts, altitude 35000 ft, 6 minutes checking/reporting interval plus buffer, and reported separation of $X = 20$ NM

The calculations were repeated for an initial longitudinal separation of $X = 30$ NM and a checking interval of 5 minutes plus a 3 minute buffer. The shape of $P_x[0, t_{end}; \hat{x}_1, X = 30]$ as a function of $\hat{x}_1$ was found to be very similar to that of $P_x[0, t_{end}; \hat{x}_1, X = 20]$ as a function of $\hat{x}_1$, but the values were approximately three orders of magnitude smaller, resulting in an average value of $\bar{P}_x[0, t_{end}; X = 30] = 1.24 \times 10^{-11}$.

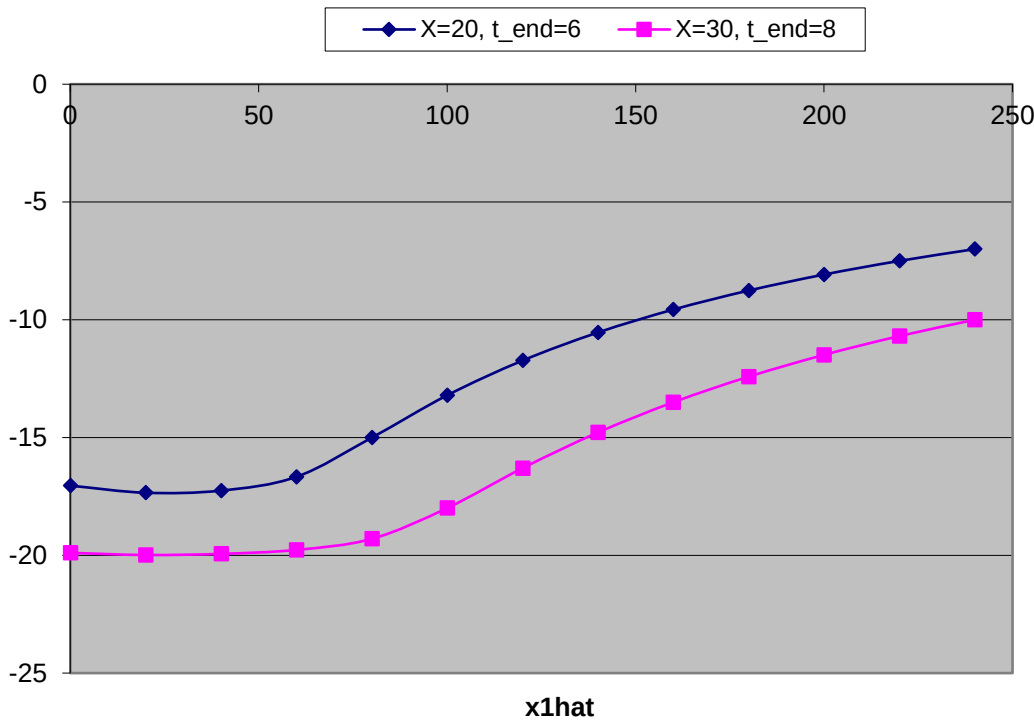


Figure 7.13: Logarithm (base 10) of the probability $P_x[0, t_{end}; \hat{x}_1, X]$ for a GNSS/DME aircraft pair experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ as a function of the distance $\hat{x}_1$ of the first aircraft to the NAVAID (DME-station) for aircraft speeds of 480 kts, altitude 35000 ft, and two combinations of reported initial separations/checking-reporting interval plus buffer, namely of $X = 20$ NM and 6 minutes, dark-blue curve, and $X = 30$ NM and 8 minutes, pink curve

It was also examine how sensitive $P_x[0, t_{end}; \hat{x}_1, X = 20]$ was to the duration of the checking/reporting interval. This is illustrated in Figure 7.14 for checking/reporting intervals of 3, 4, and 5 minutes. In addition, a buffer of 3 minutes was added resulting in total time intervals of 6, 7 and 8 minutes. All numbers pertain to an altitude of 35000 ft, nominal aircraft speeds of 480 kts and a reported initial separation of $X = 20$ NM. The figure shows that the longitudinal probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ is very sensitive to the length of the checking/reporting interval plus buffer when the aircraft are relatively close to the NAVAID (DME station), e.g. less than 100 – 125 NM. This is due to the fact that close to the DME station, the effect of the DME measurement error is very small compared to the effect of the speed errors, the latter increasing with time. Nonetheless, the probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ of experiencing a longitudinal overlap is still less than $10^{-12} - 10^{-11}$ when the distance of the first (GNSS) aircraft to the NAVAID (DME station) is less than 100 – 125 NM. It should also be remarked that the value of 3 minutes used for the buffer was supposed to represent a conservative estimate of the 95th percentile of the components of the actual buffer.

When the first (GNSS) aircraft is further away from the NAVAID (DME-station) than approximately 125 NM, the probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ is essentially insensitive to the length of the checking/reporting interval plus buffer. This is caused by the effect of the DME measurement errors becoming dominant for larger distances to the DME-station.

In addition to the averaging of $P_x[0, t_{end}; \hat{x}_1, X = 20]$ over $\hat{x}_1$, additional averaging over the reported separation X and joint averaging over $\hat{x}_1$ and X were also performed, resulting in a final average value of the GNSS/DME aircraft pair experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ of

$$\overline{\overline{P_x}}[0, t_{end}] = 2.84 \times 10^{-10} \quad (7.252)$$

Finally, Figure 7.14 shows the probability of an aircraft pair experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ as a function of the distance $\hat{x}_1$ of the first aircraft in a pair to the DME-station, for a reported initial separation of $X = 20$ NM for both GNSS/DME and DME/DME aircraft pairs. The initial part of the DME/DME curve reflects the large slant range error when the first aircraft is very close to the DME station. The two probability curves intersect at approximately $\hat{x}_1 = 52$ NM. When the first aircraft is further away from the DME station than this distance, the probability of a GNSS/DME aircraft pair experiencing a longitudinal overlap is seen to be smaller than that for a DME/DME aircraft pair. Hence, this would favour the GNSS/DME case over the DME/DME case when the first aircraft is further from the DME station than 52 NM. For smaller distances $\hat{x}_1$ of the first aircraft to the DME station, Figure 7.14 no longer favours the GNSS/DME case over the DME/DME case. However, when the dependence of $P_x[0, t_{end}; \hat{x}_1, X = 20]$ on the distance $\hat{x}_1$ is integrated out, it follows that

$$\overline{P_x}[0, t_{end}; X = 20]_{\substack{GNSS \\ DME}} < \overline{P_x}[0, t_{end}; X = 20]_{\substack{DME \\ DME}} \quad (7.253)$$

i.e. the average probability of experiencing a longitudinal overlap during the time interval $[0, t_{end}]$, given a reported separation of X NM, is smaller for a GNSS/DME aircraft pair than for a DME/DME aircraft pair.

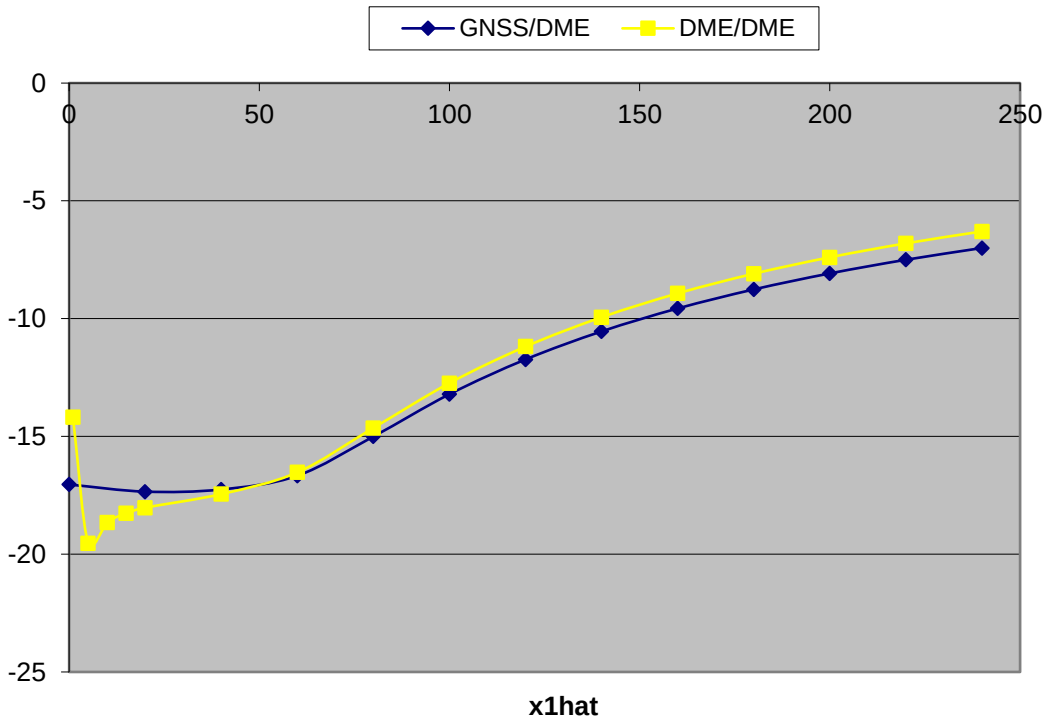


Figure 7.14: Logarithm (base 10) of the probability $P_x[0, t_{end}; \hat{x}_1, X = 20]$ for both GNSS/DME and DME/DME aircraft pairs experiencing the start of a longitudinal overlap during the time interval $[0, t_{end}]$ as a function of the distance $\hat{x}_1$ of the first aircraft to the NAVAID (DME-station) for aircraft speeds of 480 kts, altitude 35000 ft, 6 minutes checking/reporting interval plus buffer, and reported separation of $X = 20$ NM

A similar analysis was performed for scenario 2), *two aircraft in trail on same track where one requests an altitude change through the altitude of the other aircraft*, listed in the second paragraph under the *SASP-WG/WHL/7, Montreal, May 2005* heading above and also for scenario 3), *two aircraft on reciprocal tracks*. Paragraph 5.4.2.3.2.4 of the PANS-ATM 14th Edition incorporating Amendments 1-4 deals with aircraft on reciprocal tracks wanting to climb or descend to or through the levels occupied by other aircraft utilising on-track DME. A prerequisite for clearing such aircraft is a positive establishment that the aircraft have passed each other and are at least 10 NM apart. The probability of the aircraft not having passed was calculated in a similar manner as the probability of an aircraft pair experiencing the start of a longitudinal overlap for scenarios 1) and 2), except that the effect of speed errors was excluded from the model.

See Section 6 of *SASP-WG/WHL/7-WP/23* for how the results obtained in *SASP-WG/WHL/7-WP/23* led to the ultimate conclusion of the safety assessment that in all scenarios the probability of longitudinal overlap for GNSS/DME aircraft pairs was smaller than that for DME/DME aircraft pairs when the aircraft were further away from the DME station than a certain distance whereas closer to the DME station the probabilities of longitudinal overlap were negligible, both for GNSS/DME pairs and DME/DME aircraft pairs. In other words, the risk with the GNSS/DME aircraft pair was either negligible or less than the DME/DME risk.

ICAO Circular 321 (SASP-WG/WHL/11, Montreal, May 2011 – SASP-WG/WHL/15, Montreal, May – June 2009)

The development of ICAO Circular 321 documenting all the work carried out on GNSS/DME longitudinal separation as described above during *SASP-WG/WHL/2, Montreal, November 2002*, to *SASP-WG/WHL/6, Montreal, May 2005* started in May 2007 at SASP's *WG/WHL/11 Meeting* in Montreal with *SASP-WG/WHL/11-WP/19* (Hajek, 2007a), particularly in support of the implementation of GNSS/DME longitudinal separation minima following the upcoming publication of these minima in the PANS-ATM as applicable as of November 2007. Review of the first draft Circular by *SASP Project Team 6 Longitudinal* provided many useful comments for improving both the format and the text. In particular it was recommended to describe how the risk assessment had been carried out and to include references to some pertinent working papers detailing the risk analysis. There was some discussion on the scope of the PANS-ATM amendment, i.e. same track as opposed to same identical track.

SASP-WG/WHL/12-WP/12 (Hajek, 2007b) provided an update to the draft Circular, including text describing the safety assessment that had been performed with appropriate references. The update had taken into account work done between the current Meeting and the previous one. There was some discussion on terminology concerning hazards versus issues, where it was agreed that the term hazards should be used in the Circular and the Circular be thus revised. Following that, *Project Team 6 Longitudinal* recommended that the revised Circular be published on the ICAO website following ICAO formatting. See Appendix D to, as well as Section 3.2 of the *SASP-WG/WHL/12 Meeting Report*. Appendix E to the *SASP-WG/WHL/13 Meeting Report* suggests that some more (editorial) work on the Circular was performed at SASP's *Montreal WG/WHL/13 Meeting* in May 2008. Finally, some amendments to the Circular were made during SASP's *Montreal WG/WHL/15 Meeting* in May – June 2009 in response to a number of comments from an officer in the ICAO Air Navigation Bureau (ANB) who had reviewed the Circular. Paragraph 2.40 of the *SASP-WG/WHL/15 Meeting Report* refers.

ICAO Circular 321 was published by ICAO in 2010.

7.3.6 Automatic Dependent Surveillance – Broadcast In Trail Procedure (ADS-B ITP)

This Section considers the safety assessment underlying the Automatic Dependent Surveillance – Broadcast In-Trail Procedure (ADS-B ITP) (ICAO Circular 325). The procedure would enable an aircraft on oceanic routes (hereafter referred to as the ITP aircraft) to manoeuvre through a flight level that would otherwise be blocked by the procedural separation minima and the proximity of other non-maneuvring aircraft (hereafter referred to as reference aircraft). It was incorporated into the 15th edition of the PANS-ATM under Amendment 6, to become applicable as of 13 November 2014.

As set out in Section 2.3 of Chapter 2, *Description of the ITP, minima and system requirements*, of ICAO Circular 325, the procedure comprises several steps to be conducted by the pilot in conjunction with the controller where an ITP manoeuvre may only be initiated when the ITP criteria in terms of ground speed and distance have been determined by the pilot to be met. The ITP criteria to be verified by the pilot prior to initiating the manoeuvre are:

- a) The ITP distance between the ITP aircraft and the reference aircraft shall be:
 - 1) Not less than 28 km (15 NM) with a maximum closing ground speed of 37 km/h (20 kt); or
 - 2) Not less than 37 km (20 NM) with a maximum closing ground speed of 56 km/h (30 kt);
- b) The ITP on-board equipment shall indicate that the angle between the current tracks of the ITP aircraft and the reference aircraft is less than 45 degrees;
- c) The altitude difference between the ITP aircraft and any reference aircraft shall be 600 m (2 000 ft) or less;
- d) The climb or descent shall be conducted at a rate of not less than 1.5 m/s (300 fpm) or any higher rate when specified by the controller; and
- e) The climb or descent shall be performed at the assigned Mach number. If no Mach number has been assigned by ATC, the ITP aircraft shall maintain the current cruise Mach number throughout the ITP manoeuvre.

Once a pilot has determined that the ITP criteria have been met, he may request an ITP climb or request, identifying any reference aircraft in the clearance request. Controllers would receive the ITP clearance request and verify that the ITP aircraft and each reference aircraft are on the same track and the maximum closing Mach speed of 0.06 Mach is not exceeded, the check being to account for potentially unsafe closure rates due to abnormal, adverse wind gradient conditions.

See Chapter 2 of ICAO Circular 325 for more details of the ADS-B ITP procedure, in particular its Section 2.2.5 defining the ITP distance between an ITP aircraft and a reference aircraft. The Chapter 2 also gives a variety of examples where the procedure may be used, two of which have been reproduced below.

In Figure 7.15, the ITP aircraft is behind a reference aircraft which is at a higher intervening flight level (FL350). Standard ATC procedures apply to the other aircraft (two aircraft at FL360 and one at FL350). In Figure 7.16, the ITP aircraft is ahead of one reference aircraft and behind another reference aircraft, where both reference aircraft are at lower intervening flight levels (FL350). Note that the combined ahead-of-behind descent geometry may also have two intervening flight levels. The ITP procedure relies on the reference aircraft having ADS-B equipment which transmits its identification, position, velocity, altitude, and other information and the ITP aircraft having ADS-B equipment that transmits and receives ADS-B information.

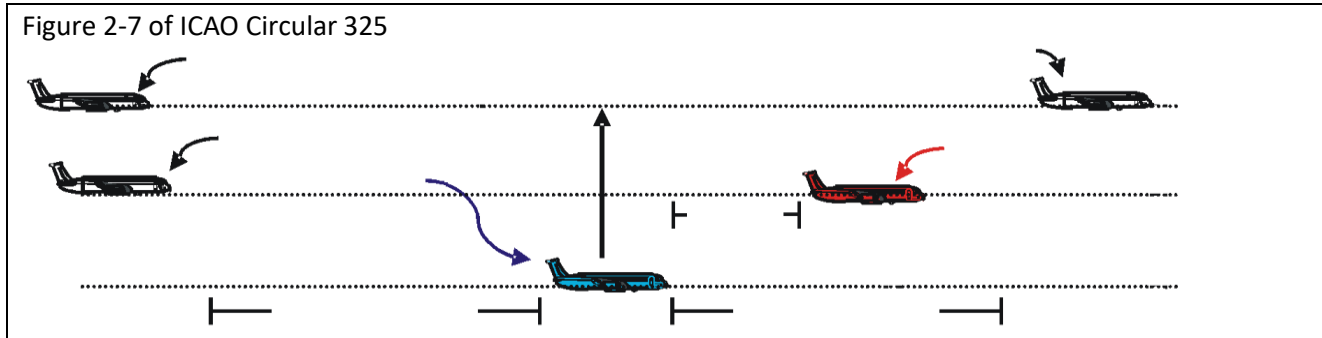


Figure 7.15: ITP behind-climb (reproduced from Figure 2-7 of ICAO Circular 325)

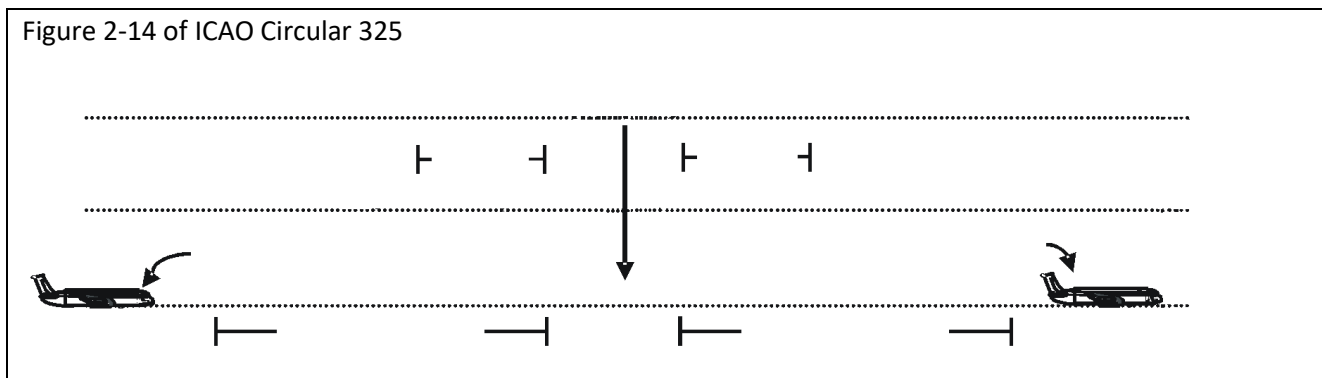


Figure 7.16: Example of a combined ahead-of-behind descent (reproduced from Figure 2-14 of ICAO Circular 325)

A brief discussion of the work performed by the SASP on the ADS-B ITP procedure is provided by meeting below.

SASP-WG/WHL/10, Gold Coast, November – December 2006

Automatic Dependent Surveillance – Broadcast In-Trail Procedure (ADS-B ITP) first featured on the SASP agenda at the 10th Meeting of its Working Group of the Whole in Gold Coast, Australia, from 27 November to 8 December 2006 (SASP-WG/WHL/10 Meeting Report). In May 2006, the ICAO Aeronautical Surveillance Panel (ASP) received the coordination request to propose a timeline for the development of ICAO provisions relating to airborne surveillance applications (ASAS) in coordination with SASP, OPSP (Operations Panel), and ATMRPP (Air Traffic Management Requirements and Performance Panel) (SASP Secretary, 2006). This ASP coordination request referenced preliminary analyses of the requirements for ICAO material arising from two airborne surveillance applications: Merging and Spacing (M&S), which enables controllers to instruct flight crew to use their flight deck surveillance systems to follow another, specified, aircraft; and the In-Trail Procedure (ITP), which would enable an aircraft on oceanic routes to climb (or descend) through a flight level that would otherwise be blocked by the procedural separation minima and the proximity of other aircraft. ITP was specifically referred to the SASP to develop separation minima for to be used in trials planned for 2008.

SASP-WG/WHL/10-WP/21 (Butcher, 2006) presented information on the operational concept, the potential benefits to airline operators, and the potential for conducting an operational trial of the procedure in the Australian Flight Information Region (FIR). Briefly, aircraft operating in airspace without ATC surveillance are frequently held at non-optimum flight levels due to conflicting traffic either at the optimal flight level or flight levels between the existing flight level and the optimal level. Traffic conflicts can be more common in non-

surveillance airspace because of the large separation standards in use. ADS-B based ITP would enable flight level changes for aircraft equipped with ADS-B receivers and on-board automation and would facilitate improved flight efficiency. It was planned that the ITP would be based on the ICAO approved DME separation procedure for aircraft climbing or descending on the same track. However, additional specific ITP requirements were proposed concerning ITP distance/speed criteria, maximum flight level change, minimum climb/descent rate, and Mach differential. The intent of the proposed flight trials in the Australian FIRs was to assess the economic and operational feasibility of ADS-B ITP procedures and equipment, and to establish a basis for global ADS-B ITP implementation. The trials would involve the pilot requesting a climb based on information derived from the on-board display after which the controller would then assess the disposition of all other traffic and either approve or not approve the request.

SASP-WG/WHL/10-WP/21, amongst other things, invited the SASP to provide guidance on the safety analysis. In connection with that, the Meeting was provided with a presentation on the safety assessments that had been undertaken to date by the ITP program, see (Carreno & Munoz, 2006). Following plenary discussion on the ITP safety assessment, SASP MSG discussions on it started with a number of general and specific subjects, including: the effect of wind and speed on the separation between an aircraft in level flight and a climbing/descending one, how to combine or not to combine risk due to typical performance and hazards, details of the GNSS/DME safety assessment (cf. Section 7.3.5), details of the ADS-B ITP safety assessment, bowtie hazard assessment model, and the (dis)similarity between the ADS-B ITP procedure and a number of operational requirements (ORs) that the MSG was working on (see Appendix I to the SASP-WG/WHL/10 Meeting Report). It was noted that the then current ADS-B ITP collision risk model was given in a different form than e.g. the SASP GNSS/DME collision risk model and it was concluded that it would be useful to cast the former model in the form of equations used in the GNSS/DME safety assessment. This was expected to provide two benefits, namely that it would make it easier for the SASP MSG to review the ADS-B ITP collision risk model and the ICAO type format should also have a beneficial effect on the credibility of the ADS-B ITP safety assessment to other parties. The (first) author of (Carreno & Munoz, 2006) agreed to revise his ADS-B ITP collision risk model accordingly and make the result available to MSG members for review and comment as soon as possible. As a technical detail, it was noted that the then current ADS-B ITP collision risk model was based on Gaussian distributions and the MSG requested that the model should also consider the double exponential distribution in relationship to the data available.

Last, but not least, the MSG discussed the type of safety assessment to be used, i.e. comparative or threshold model. In this context, it was noted that the comparative method had evolved for e.g. the GNSS/DME safety assessment from a “simple” comparison of corresponding characteristics of a reference system and a proposed system into a comparison of risk estimates obtained with suitable models for the two systems. Given the group’s suggestion concerning the use of double exponential distributions, it was concluded that it was necessary to wait for risk estimates based on those distributions to become available. If the latter, translated into accidents per flight hour, would be smaller than 5×10^{-9} , then the threshold method would be applicable. If the estimates would be larger, then a comparative argument using DME as the reference system would be attempted to be used, or the constraints would be attempted to be tightened.

SASP-WG/WHL/11, Montreal, May 2007

The Meeting was given a presentation by two representatives from NASA on the cockpit displays and procedures that had been developed to date for use in ADS-B ITP. Significant discussion took place on a number of aspects of the proposed procedure, both in plenary and in Project Team 6 *Longitudinal*. Project Team 6 *Longitudinal* discussion on the subject was supported by detailed information regarding the ITP in

terms of the work already undertaken by the Requirement Focus Group (RFG) and other groups such as within Australia and a draft PANS-ATM Amendment proposal, as provided in SASP-WG/WHL/11-WP/18 (Butcher, 2007a). It was concluded that a Circular to support the implementation of the ADS-B ITP should be developed.

The MSG at SASP-WG/WHL/11 reviewed a first ADS-B ITP oceanic safety assessment along the lines of its GNSS/DME safety assessment (ICAO Circular 321) as provided in SASP-WG/WHL/11-WP/17 (Carreno, 2007b). The risk metric used in the paper was the probability of longitudinal overlap for an aircraft pair involved in the execution of the ADS-B ITP procedure. A major element of the safety assessment concerned the wind modelling, where it was emphasised by the author of SASP-WG/WHL/11-WP/17 that although the currently used wind model was intended to be conservative, it might actually be too conservative, particularly concerning the reversal of the wind gradient over an altitude difference of 3000 ft or less and the standard deviation value used of 16 kts. Some wind data from the NAT were shown and it was suggested that NASA could collect some additional data and perform some further analysis to make the wind model more realistic. The MSG noted that most of the review comment on an earlier version of SASP-WG/WHL/11-WP/17 generated between the previous meeting and the current one had been taken into account.

There was some discussion on the risk metric and the value of the risk threshold. The MSG concluded that more work and time were necessary to decide on an appropriate risk metric and threshold but that this decision was the remit of the Working Group of the Whole rather than that of the MSG. A number of technical details were also discussed, including ADS-B latency, aircraft speed and speed errors, probability distributions to be based on data rather than assumptions, and same track versus same-identical track.

Consider now the model in some detail. The model calculated the probability of longitudinal overlap for an aircraft pair involved in the execution of the ITP procedure based on given values of accuracy for GNSS/ADS-B, altitude error, latency error, initiation criteria parameters for the ADS-B ITP, and a wind model. The aircraft climbing or descending as cleared to perform the ADS-B ITP manoeuvre was called the ITP aircraft whilst the other, not manoeuvring, aircraft was called the reference aircraft. The ADS-B ITP procedure requires that an aircraft performing an ADS-B ITP manoeuvre must be a distance X larger than or equal to a minimum distance S_x in front or behind a reference aircraft before requesting and initiating an ADS-B ITP climb or descent. S_x , in conjunction with other requirements, is the initiation criteria for ITP. The objective was to demonstrate that $S_x = 15$ NM would ensure the safety of the ADS-B ITP procedure, although the 15 NM value was not explicitly stated in SASP-WG/WHL/11-WP/17. The ITP aircraft measures the distance X between the ITP aircraft and the reference aircraft based on both aircraft's GNSS data as reported by an ADS-B datalink where it must hold that $X \geq S_x$ for an ADS-B ITP clearance to be requested. The model was limited to a pair of same-identical track aircraft with zero intersection angle.

Following the GNSS/DME safety assessment of SASP-WG/WHL/7-WP/23, cf. its summary in Section 7.3.5 under the *SASP-WG/WHL/7, Montreal, May 2005* heading, SASP-WG/WHL/11-WP/17 represented the true longitudinal distance between the ITP aircraft and the reference aircraft by a random variable Ψ and expressed this in terms of the reported distance and various error terms and some time-parameters as

$$\Psi = x_{Ref}(t) - x_{ITP}(t) = \hat{x}_{Ref} - \hat{x}_{Ref} - \eta_{pRef} + \eta_{pITP} - \left(\frac{576.6(0.04 - \eta_{vmITP} + \eta_{vmRef}) + 20 - \eta_{vgITP} + \eta_{vgRef} + W_C}{2} \right) \times t - \eta_{latency} 0.85 \times 576.6, \quad 0 \leq t \leq T + t_a \quad (7.254)$$

where the various parameters are defined in Table 7.16. Notice that the random variable Ψ actually varies with time, cf. $\Psi = x(t) = x_2(t) - x_1(t)$ in eq. (7.232) for the GNSS/DME model. The numbers 576.6, 0.85, and 0.04 on the right side of eq. (7.254), represent the speed of sound at 35000 ft and International Standard Atmosphere (ISA), assumed cleared Mach number of both aircraft, and the ADS-B ITP constraint on the maximum difference in Mach number between the ITP aircraft and the reference aircraft respectively¹²⁵. Formulae for the mean and standard deviation of the random variable Ψ were also provided in SASP-WG/WHL/11-WP/17.

Table 7.16: Parameters defining the error in the true longitudinal distance between ITP aircraft and reference aircraft during the ADS-B ITP procedure

Symbol	Definition
x_{Ref}	True longitudinal ground location along the track of the ITP aircraft at time of the ITP initiation
x_{ITP}	True longitudinal ground location along the track of the reference aircraft at time of the ITP initiation
$\hat{x}_{Ref}$	Measured longitudinal ground location along the track of the ITP aircraft at time of the ITP initiation
$\hat{x}_{Ref}$	Measured longitudinal ground location along the track of the reference aircraft at time of the ITP initiation
η_{pRef}	Error in the true longitudinal location along the track of the ITP aircraft at time of the ITP initiation
η_{pITP}	Error in the true longitudinal ground location along the track of the reference aircraft at time of the ITP initiation
η_{vmITP}	Error in the true Mach number of the ITP aircraft, i.e. $\widehat{vm}_{ITP} = vm_{ITP} + \eta_{vmITP}$
η_{vmRef}	Error in the true Mach number of the reference aircraft, i.e. $\widehat{vm}_{Ref} = vm_{Ref} + \eta_{vmRef}$
η_{vgITP}	Error in the true ground speed of the ITP aircraft, i.e. $\widehat{vg}_{ITP} = vg_{ITP} + \eta_{vgITP}$
η_{vgRef}	Error in the true ground speed of the reference aircraft, i.e. $\widehat{vg}_{Ref} = vg_{Ref} + \eta_{vgRef}$
W_C	Rate of change of wind speed over vertical distance between ITP aircraft FL and reference aircraft FL (fourth wind model)
T	Nominal time for ITP aircraft to climb from its initial flight level to the reference aircraft's flight level
t_a	Additional time to climb or decent through the reference aircraft's flight level due to altitude error
$\eta_{latency}$	Latency error (seconds)

As stated above, a major element of the safety assessment concerned the wind modelling. Four models of wind were considered, namely:

- A linearly increasing wind gradient from the ITP aircraft flight level to the reference aircraft flight level;
- A linearly decreasing wind gradient from the ITP aircraft flight level to the reference aircraft flight level;
- A constant wind gradient; and
- An increasing and then decreasing wind gradient from the ITP aircraft flight level to the reference aircraft flight level.

¹²⁵ The maximum closing speed of 0.04 Mach was increased later to 0.06 Mach, see under the SASP-WG/WHL/15, Montreal, May 2009 heading.

Since the fourth model represented the worst case scenario of the aircraft closure rates considering ground speed and Mach initiation criteria, ground speed errors, Mach errors, and an increasing and decreasing wind gradient, this model was ultimately used by SASP-WG/WHL/11-WP/17, the result of which is shown in eq. (7.254) above. (The effect of wind as a function of time during the ITP manoeuvre was not taken into account but rather the worst wind effect during the manoeuvre.)

Following the GNSS/DME safety assessment of SASP-WG/WHL/7-WP/23 again, SASP-WG/WHL/11-WP/17 specified a first choice and second choice for the type of probability distributions of the various error terms as reproduced in Table 7.17.

Table 7.17: Types of probability distributions to be used for the various error terms

Type of error or wind		Type of probability distribution	
Description	Symbol and units	1 st choice	2 nd choice
Position errors	η_{pITP}, η_{pRef} NM	Double exponential	Gaussian
Ground speed errors	$\eta_{vgITP}, \eta_{vgRef}$ knots	Double exponential	Gaussian
Mach errors	$\eta_{vmITP}, \eta_{vmRef}$ Mach	Double exponential	Gaussian
Altitude errors (specifying t_a)	$\eta_{altITP}, \eta_{altRef}$ feet	Constant	Constant
Latency error	$\eta_{latency}$ sec	Constant	Constant
Wind	W_C knots	Double exponential	Gaussian

The probability density functions of the sum of all seven random variables on the right side of eq. (7.254) were then derived for the first and second choice type of probability distributions and denoted $f_7(x)$ and $f_{p+vg+vm+W+C}(x)$ respectively. Since $f_7(x)$ is based on double exponential probability densities for the various random variables, it can be given in a complicated analytical form only, see eqs. (6.18) – (6.21) of SASP-WG/WHL/11-WP/17. On the other hand, since $f_{p+vg+vm+W+C}(x)$ is based on Gaussian probability densities, it is itself a Gaussian density with mean value C and variance determined by the variances of the component error terms. The mean value C is given by eq. 6.5 of SASP-WG/WHL/11-WP/17 and the corresponding variance by eq. (4.8) of SASP-WG/WHL/11-WP/17. It should be remarked that the quantity C is also the mean value of the probability density $f_7(x)$ for the double exponential case.

The final modelling step concerned the calculation of the probability of longitudinal overlap at co-altitude during the execution of the ITP procedure. This was represented by

$$\Psi = x(t) = x_{Ref}(t) - x_{ITP}(t) \in [-\lambda_x, \lambda_x] \quad (7.255)$$

with t taken as $T + t_a$. Since the ITP procedure is a climb or decent manoeuvre and the ITP aircraft might have a closing speed on the reference aircraft, the longitudinal overlap interval was increased by the relative ground speed times the time it takes the two aircraft to pass vertically. The additional distance Δ_x was calculated as

$$\Delta_x = \frac{2\lambda_z}{vs} \times 23.064 \text{ NM} \quad (7.256)$$

where vs denoted the vertical speed of the ITP aircraft, taken as 300 ft/min, and the number 23.064 represented the maximum horizontal speed in knots based on a maximum Mach number difference of 0.04 at 35000 ft and ISA. The probability of longitudinal overlap during vertical overlap was then given by the

integration of the probability density functions $f_7(x)$ and $f_{p+vg+vm+W+C}(x)$ over the interval $[-\Delta_x - \lambda_x, \lambda_x]$ for the two choices of type of probability distributions, i.e.

$$P_x[-\lambda_x - \Delta_x < x(t) < \lambda_x] = \int_{-\lambda_x - \Delta_x}^{\lambda_x} f_7(x) dx \quad (7.257)$$

and

$$P_x[-\lambda_x - \Delta_x < x(t) < \lambda_x] = \int_{-\lambda_x - \Delta_x}^{\lambda_x} f_{p+vg+vm+W+C}(x) dx \quad (7.258)$$

Evaluation of eqs. (7.257) and (7.258) resulted in the numerical results as reproduced below in Table 7.18. Notice the large differences between the calculated probabilities of longitudinal overlap at co-altitude for the two types of probability distributions chosen.

Table 7.18: Probability of longitudinal overlap at co-altitude for the two choices of types of probability distributions for the various error terms (SASP-WG/WHL/11-WP/17 (Carreno, 2007b))

Altitude difference (ft)	Nominal time for ITP aircraft to climb to the reference aircraft's flight level (hours)	Probability of longitudinal overlap $P_x[-\lambda_x - \Delta_x < x(t) < \lambda_x]$	
		Double exponential distributions	Gaussian distributions
1000	0.0556	2.11×10^{-18}	$< 1.0 \times 10^{-50}$
2000	0.1111	9.11×10^{-10}	3.84×10^{-34}
3000	0.1667	1.09×10^{-6}	3.77×10^{-13}

SASP-WG/WHL/12, Santiago, November 2007

Three working papers and an information paper dealing with the ADS-B ITP procedure were presented at the twelfth meeting of the Working Group of the Whole of the SASP. Two papers, SASP-WG/WHL/12-WP/19 (Stefansson, 2007) and SASP-WG/WHL/12-WP/20 (Butcher, 2007c), concerned draft ADS-B ITP PANS-ATM Amendment proposals where the latter also provided information of the Australian ATC simulation trial for the procedure. The outcomes of the trial indicated that there were no significant safety concerns highlighted. See SASP-WG/WHL/12-IP/07 (Butcher, 2007b) for further details of the simulation.

SASP-WG/WHL/12-WP/18 (Carreno, 2007a) provided an update to the ADS-B ITP safety assessment of SASP-WG/WHL/11-WP/17. The model proper remained the same but a number of its parameter values were revised. The standard deviation of the ground speed errors was increased by a factor of approximately 2.5 and the wind standard deviation was reduced by a factor of approximately 10.4 from 16.03/14.83 kts to 1.5445/1.4293 kts (Gaussian/double exponential distributions). The latter was done because it had been concluded in WG/WHL/11-WP/17 that the then used wind model might be too conservative and that it would be attempted to make the model more realistic by gathering some additional data. The altitude error $\eta_{altITP} + \eta_{altRef}$ specifying the risk model parameter t_a (see Table 7.17) was increased from 140 ft to 400 ft to account for total vertical error (TVE) rather than just altimetry system error (ASE). The value of the ADS-B latency error was increased from 1.5 seconds to 4.575 seconds. See (ICAO, 1998c) for details of the changes in parameter values.

Evaluation of eqs. (7.257) and (7.258) with the probability densities $f_7(x)$ and $f_{p+vg+vm+W+C}$ based on the revised parameter values resulted in the numerical results as reproduced in Table 7.19. All the probability of longitudinal overlap values in Table 7.19 are seen to be much smaller than their counterparts in Table 7.18

where the smallest reduction of approximately three orders of magnitude occurred for an altitude difference of 3000 ft in combination with double exponential distributions for the various error terms. The decays were understood to be due to the considerable reduction of the value of the wind standard deviation.

Table 7.19: Probability of longitudinal overlap at co-altitude for the two choices of types of probability distributions for the various error terms (SASP-WG/WHL/12-WP/18 (Carreno, 2007a))

Altitude difference (ft)	Nominal time for ITP aircraft to climb to the reference aircraft's flight level (hours)	Probability of longitudinal overlap $P_x[-\lambda_x - \Delta_x < x(t) < \lambda_x]$	
		Double exponential distributions	Gaussian distributions
1000	0.0556	7.83×10^{-30}	6.30×10^{-182}
2000	0.1111	1.62×10^{-15}	7.01×10^{-62}
3000	0.1667	9.67×10^{-10}	6.98×10^{-27}

Following the presentation of SASP-WG/WHL/12-WP/18 to the MSG at the 12th Meeting of the Working Group of the Whole of the SASP, discussion centred on the question of an appropriate TLS value for the collision risk associated with the ADS-B ITP procedure. The discussion resulted in an MSG agreement of a maximum collision probability of 1×10^{-9} per ADS-B ITP operation. See Appendix J to the SASP-WG/WHL/12 Meeting Report for the rationale underlying the agreed value.

It was then realised that what was called a probability of longitudinal overlap at co-altitude was effectively a probability of joint longitudinal and vertical overlap, but not a probability of collision. Hence, in order to be able to apply the just agreed TLS per execution of the ADS-B ITP procedure, a probability of lateral overlap would also have to be taken into account as well as a kinematic factor, the latter accounting for the three different collision possibilities, i.e. head/tail, sideways, or from below/above. It was concluded that the agreed maximum collision probability of 1×10^{-9} per ADS-B ITP operation might either be interpreted as a maximum probability of longitudinal overlap at co-altitude, provided that the product of the probability of lateral overlap and the kinematic factor is less than one, or, alternatively, might be used as an upper bound for the collision probability in combination with a collision risk model explicitly comprising the probability of longitudinal overlap at co-altitude, a lateral overlap probability and a kinematic factor. The latter approach would be more in line with the traditional SASP MSG collision risk modelling approach.

SASP-WG/WHL/13, Montreal, May 2008

At the 13th Meeting of SASP's Working Group of the Whole, Project Team 6 *Longitudinal* continued working on the drafting of the ADS-B ITP PANS-ATM Amendment proposal and the MSG continued working on the associated safety assessment. For the benefit of the former, three working papers and one information paper were presented. SASP-WG/WHL/13-WP/29 (Butcher, 2008b) described the development and outcomes of ATC simulator trials of ADS-B ITP procedures in Australia. As set out in SASP-WG/WHL/13-WP/29, key issues identified during the course of the experiment included the requirement for and application of the Mach differential check, the 4000 ft limitation on an ADS-B ITP level change, and communication. The working paper concluded that the ATC experiment determined that, from the perspective of an air traffic controller, ADS-B ITP was both valid and acceptable, and would be useful in the current ATC environment. In addition, SASP-WG/WHL/13-IP/02 (Stefansson, 2008a) provided an overview of simulations and trial conducted under

the CRISTAL¹²⁶-ITP project. Based on SASP-WG/WHL/13-IP/02, SASP-WG/WHL/13-WP/20 (Stefansson, 2008b) came up with nine recommendations for the ADS-B ITP procedure PANS-ATM Amendment, including specification of CPDLC as required communication for ADS-B ITP. SASP-WG/WHL/13-WP/30 (Butcher, 2008a) provided a first draft of an ICAO Circular for the benefit of the implementation of the ADS-B ITP procedure following completion of the PANS-ATM Amendment. Two versions of the Circular were actually available as attachments to SASP-WG/WHL/13-WP/30, one of which was labelled as draft version 1.2.

As regards the MSG work on the safety assessment of the ADS-B ITP procedure, the author of the latest version of the safety assessment (SASP-WG/WHL/12-WP/18) verbally updated the MSG on the status of the risk model for the ADS-B ITP procedure. Following the discussion at the previous SASP-WG/WHL/12 Meeting in November 2007, he had identified the distance-based longitudinal collision risk model from Appendix 5 to ICAO Doc 9689, *Manual on Airspace Planning Methodology for the Determination of Separation Minima* (ICAO, 1998c), as a candidate collision risk model for the ADS-B ITP procedure. This model was presented in Section 7.3.2 of this Document in the following form:

$$N_{ax} = \Pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.193)$$

with

$$\Pi_x = \frac{4\lambda_x}{s} \times \int_s^{\infty} w(s)U(s)ds, \quad (7.194)$$

where Π_x , $P_y(0)$, and $P_z(0)$ denote the overlap probabilities in the longitudinal, lateral, and vertical dimensions, the expression in square brackets denotes the model's kinematic factor, and where the probability $U(s)$ that longitudinal overlap occurs during a time interval $[t_0, t_1]$ given an initial nominal separation $\hat{S}_0 = s$ can be calculated by means of eqs. (7.195) – (7.198). However, he had found it difficult to obtain the proper form for the probabilities of longitudinal and vertical overlap for the case of the ADS-B ITP procedure. The issue was discussed in some depth after which the author stated that he had obtained sufficient information to adapt his initially chosen model. He also informed the group that he wanted to explicitly take into account the distribution $w(s)$ of the initial longitudinal separation between the reference aircraft and the ITP aircraft. A timetable to progress the work for submission of the new model at SASP's next Working Group of the Whole Meeting in October 2008 was then agreed on.

A final discussion point concerned same track versus same-identical track. The MSG recalled that although same-identical track intuitively seemed to be the most risky, it had not managed to prove this mathematically in the past (e.g. at SASP-WG/WHL/11 in Montreal, May 2007). It was suggested that (Anderson, 2005) might be able to provide some further insight into the matter.

SASP-WG/WHL/14, Paris, November 2008

At the 14th Meeting of SASP's Working Group of the Whole, Project Team 6 *Longitudinal* work on ADS-B ITP comprised reviewing and completing the PANS-ATM amendment and the supporting Circular. SASP-WG/WHL/14-WP/35 (Stefansson, 2008c) presented the status of the PANS-ATM Amendment proposal at the

¹²⁶ The CRISTAL acronym stands for: Co-operative Validation of Surveillance Techniques and Applications of Automatic Dependent Surveillance-Broadcast (ADS-B).

start of the Meeting. A draft version 1.4 of the Circular was also available at the start of the meeting. Both the amendment proposal and the Circular were updated during the meeting, resulting in draft version 1.5 of the Circular (including the latest version of the PANS-ATM amendment proposal), which was available as Attachment 1 to Appendix D to the SASP-WG/WHL/14 Meeting Report. The status of the ADS-B ITP work by Project Team 6 *Longitudinal* was summarized in Appendix D to the SASP-WG/WHL/14 Meeting Report as follows: “The work on the PANS-ATM amendment and the Circular by PT 6 has now been completed. The quantitative safety assessment which is being progressed by the SASP MSG still needs to be included in the Circular, Chapter 3 – *SASP Safety Assessment*. SASP members are invited to review the ITP Circular, which also includes the PANS-ATM amendment with the view to provide additional comments.”

As regards MSG work on the safety assessment of the ADS-B ITP procedure, two working papers were available at the start of the Meeting, namely SASP-WG/WHL/14-WP/14 (Carreno, 2008b) and SASP-WG/WHL/14-WP/16 (Carreno, 2008c), where the former dealt with the zero angle same-identical track case and the latter with intersecting tracks at angles of 0 to 45 degrees.

Zero angle same-identical tracks

SASP-WG/WHL/14-WP/14 (Carreno, 2008b) started with the following Reich-type longitudinal collision risk model from Appendix 5 to (ICAO, 1998c) for aircraft at the same flight level:

$$N_{ax} = \Pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.193)$$

where N_{ax} denotes the expected number of accidents per flight hour and the remaining symbols have their usual meaning. Recall that this model was already presented in Section 7.3.2 of this document for the collision risk assessment of the 50 NM same-identical track longitudinal separation minima based on distance using RNAV where RNP is specified. It was also referenced under the previous *SASP-WG/WHL/13, Montreal, May 2008* heading above.

The model of eq. (7.193) was then modified to take account of the specific characteristics of the ADS-B ITP procedure, i.e.

1. The ITP and reference aircraft are not assigned to the same flight level but cross levels during the procedure. Therefore, the longitudinal and vertical overlap were calculated jointly; and
2. The ADS-B ITP procedure is not a continuous risk exposure like the longitudinal distance-based separation. Therefore, an exposure risk factor was used to obtain the risk of collision per hour due to the ITP procedure.

The model was thus expressed as

$$N_{ax} = r \Pi_{xz} P_y(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.259)$$

with r denoting the ratio of ITP operation time to typical flight time and Π_{xz} denoting the joint longitudinal and vertical overlap rate. Notice that N_{ax} on the left side of eq. (7.259) now denotes the longitudinal collision rate per flight hour due to an ADS-B ITP operation rather than just the longitudinal collision rate per flight hour. The model of eq. (7.259) was supplemented with a modified version of Π_x from equation 2 from Appendix 5 to (ICAO, 1998c) for the joint overlap rate Π_{xy} .

To that end, equation 2 from Appendix 5 to (ICAO, 1998c) for the longitudinal overlap rate, i.e. eq. (7.194) of Section 7.3.2 of this document, was recalled, with a minor change in notation, viz.

$$\Pi_x = \frac{4\lambda_x}{S} \times \int_s^{\infty} w(s) U_x(s) ds, \quad (7.260)$$

with S being the separation standard in use, $w(s)$ the probability density function of the distance s , i.e. the range of initial distances, and $U_x(s)$ being the probability that longitudinal overlap occurs in the period of time between $t = 0$ to $t = T$. For the ADS-B ITP procedure, time zero is when the ITP operation begins and time T is when the aircraft have vertically crossed and are no longer in vertical overlap. Eq. (7.260) uses the symbol $U_x(s)$ rather than $U(s)$. SASP-WG/WHL/14-WP/14 used the following version of eqs. (7.195) (with $\varphi(v)$ rather than $\varphi_x(v)$) and (7.196) for the calculation of $U_x(s)$,

$$U_x(s) = \int_{-\infty}^{\infty} \varphi(v) F(D_x) dv \quad (7.261)$$

$$D_x = s - \lambda_x - L + v \cdot t \quad (7.262)$$

$$F(D_x) = \int_{D_x}^{\infty} \int_{n=-\infty}^{\infty} \zeta(n) \Psi(n - x) dn dx \quad (7.263)$$

where $\varphi(v)$ denotes the probability density function of the relative velocity v between the ITP and reference aircraft, in the longitudinal dimension, including ground speed error, Mach error and wind, and $F(D_x)$ denotes the probability that the longitudinal distance between the ITP and reference aircraft at time t is less than or equal to λ_x given a nominal separation s as measured at ITP initiation. The symbol L in eq. (7.262) denotes the distance error due to latency and t denotes time from ITP initiation. In addition, $\zeta(n)$ and $\Psi(n)$ denote the probability densities of the longitudinal position errors of the ITP aircraft and the reference aircraft respectively. Compared with eq. (7.195) for $\tau = 0$ and eq. (7.196) for the usual 50 NM longitudinal separation case, the lower bound of the integration in eq. (7.263) contains an addition distance error due to ADS-B latency.

The joint longitudinal and vertical overlap probability was then derived from eq. (7.261) by changing the limits of integration for variable v to the interval of velocities which give a longitudinal overlap when the vertical overlap occurs, i.e.

$$U_{xz}(s) = \int_{-(c_x=s-\lambda_x-L)/T_b}^{-(c_x=s-\lambda_x-L)/T_e} \varphi(v) F(D_x) dv \quad (7.264)$$

where T_b denotes time to the beginning of vertical overlap from the ADS-B ITP initiation and T_e denotes time to the end of vertical overlap from the ADS-B ITP initiation. Finally, eq. (7.264) was used to generalize eq. (7.260) to the joint longitudinal and vertical overlap rate Π_{xz} as

$$\Pi_{xz} = \frac{4\lambda_x}{S} \times \int_s^{\infty} w(s) U_{xz}(s) ds, \quad (7.265)$$

The probability distributions of the relative longitudinal velocity and the longitudinal position errors were taken as follows. The relative velocity between the aircraft was modelled as the sum of two random variables the distributions of which were taken as a (double) trapezoidal distribution and a double exponential distribution to represent the ITP initiation criteria on closure ground speed and closure Mach speed and

ground speed error, Mach error and wind. An analytical formula for the resulting probability density $\varphi(v)$ was derived. The position errors of the ITP and reference aircraft were modelled with a double exponential distribution, cf. Section 7.3.2 for 50 NM same-identical track longitudinal separation minima based on distance using RNAV where RNP is specified,

$$\Psi(x) = \zeta(x) = \frac{1}{2\lambda} e^{-\frac{|x|}{\lambda}} \quad (7.197)$$

Using the above probability distributions, SASP-WG/WHL/14-WP/14 was able to derive an analytical formula for $U_{xz}(s)$ in eq. (7.265). The probability density $w(s)$ in eq. (7.265) was taken as a uniform probability density over the range of $s \in [15, 30]$ NM of initial distances between the aircraft at ITP initiation. Based on the latter, eq. (7.265) for the joint longitudinal and vertical overlap rate was then expressed as

$$\Pi_{xz} = \frac{4\lambda_x}{s} \times \int_{15}^{30} w(s) U_{xz}(s) ds, \quad (7.266)$$

The collision rate per flight hour due to an ADS-B ITP operation was calculated for vertical distances of 1000, 2000, and 3000 feet between the ITP and reference aircraft using the longitudinal collision risk model defined by eqs. (7.259) and (7.266) together with the pertinent equations (eqs. (7.262) – (7.264), (7.197)), and the uniform probability distribution of $w(s)$). See SASP-WG/WHL/14-WP/14 for the specific collision risk model parameter values used, including a value of $r = 0.04167$ for the ratio of ITP operation time to typical flight time. Assuming that the ADS-B ITP operation would be performed equally often with 1000, 2000, and 3000 feet vertical distances, the average collision rate per flight hour due to the ADS-B ITP operation was 5.88×10^{-11} collisions per flight hour.

Following presentation of SASP-WG/WHL/14-WP/14 to the MSG, considerable discussion ensued, both on the derivation of the model and on some of the parameter values used. See Appendix K to the SASP-WG/WHL/14 Meeting Report. It was suggested that, in particular, the derivation of the quantity $r \Pi_{xz}$ was insufficiently explained and it was also queried whether the definition of the function $F(D_x)$ was consistent with a non-zero planned aircraft speed difference and whether the complicated expression derived for $U_{xz}(s)$ needed further validation. In this context, reference was made to the previous version of the longitudinal collision risk model for the ADS-B ITP procedure of SASP-WG/WHL/12-WP/18, which had shown that the probability of an overtake was (very) small. Since the probability of a collision is the probability of a collision given that an overtake occurs (< 1), multiplied by the probability of an overtake ((very) small), it might be possible to demonstrate that the probability of simultaneous overlap in the three dimensions would be sufficiently small, without the need to come up with a completely new model. Revised values for the collision risk model parameters $P_y(0)$ and $|\bar{y}|$ representative for GNSS aircraft were agreed. The $|\bar{x}|$ parameter was discussed in some depth where it was noted that this was based on constant aircraft speeds whereas the speed of the ITP aircraft changes over time due to its level change. Based on SASP-WG/WHL/14-WP/20 (Mehadhebi, 2008), it was suggested that the value used might be underestimated by a factor of three but the estimated collision rate would still remain well below a target level of safety of 5×10^{-9} fatal accidents per flight hour. It was then agreed that a revised version of SASP-WG/WHL/14-WP/14 would be produced during the meeting.

An intermediate review of the progress on the revision of SASP-WG/WHL/14-WP/14 reopened the discussion on the need for a revision. During this discussion, it was emphasized that the risk models of SASP-WG/WHL/12-WP/18 and SASP-WG/WHL/14-WP/14 pertained to zero angle same-identical tracks and that

the more general case of tracks intersecting at angles from 0 to 45 degrees was provided in SASP-WG/WHL/14-WP/16 (Carreno, 2008c). It was suggested that the more general case could be covered in only a few paragraphs and that this, together with extending the model of (ICAO, 1998c) would require considerably less effort than revising the collision risk model of SASP-WG/WHL/14-WP/14. The MSG then agreed to extending the risk model of SASP-WG/WHL/12-WP/18 along the lines suggested and left it to the discretion of the author of SASP-WG/WHL/14-WP/14 to decide whether or not he wanted and was able to carry out a revision of this reference.

Later during the meeting, the author of SASP-WG/WHL/14-WP/14 and SASP-WG/WHL/12-WP/18 provided revised versions of both references in SASP-WG/WHL/14-WP/14 and SASP-WG/WHL/14-WP/45 (Carreno, 2008d) respectively. See Table 7.21 for an overview of the revision process and consider the revised collision risk model of SASP-WG/WHL/14-WP/14 first.

SASP-WG/WHL/14-WP/14 started again with the Reich-type longitudinal collision risk model from Appendix 5 to (ICAO, 1998c) for aircraft at the same flight level:

$$N_{ax} = \Pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.193)$$

where N_{ax} denotes the expected number of accidents per flight hour and the remaining symbols have their usual meaning. Rather than using the first specific characteristic of the ADS-B ITP procedure listed before eq. (7.259) above, a conservative assumption was made in SASP-WG/WHL/14-WP/14 that for the application to the ADS-B ITP procedure, the ITP and reference aircraft start the manoeuvre at the same flight level. Hence, for the ADS-B ITP procedure too, the probability of joint longitudinal and vertical overlap was factored into the probability of longitudinal and vertical overlap as in eq. (7.193) and the longitudinal collision risk was calculated from the time when the ITP procedure would start, $t = 0$, to the time when the ITP aircraft would clear the reference aircraft vertically, $t = T$. The second specific characteristic of the ADS-B ITP procedure listed before eq. (7.259) above, however, was retained, i.e. a factor r denoting the ratio of ADS-B ITP operation time to typical flight time was introduced into eq. (7.193) to obtain the ADS-B ITP longitudinal collision risk model in the following form

$$N_{ax} = r \Pi_x P_y(0) P_z(0) \left[\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z} \right] \quad (7.267)$$

It should be noted that N_{ax} on the left side of eq. (7.267) thus denotes (again) the longitudinal collision rate per flight hour due to an ADS-B ITP operation rather than just the longitudinal collision rate per flight hour. The model of eq. (7.267) was supplemented with eqs. (7.260) – (7.263) for Π_x , $U_x(s)$, D_x , and $F(D_x)$ respectively where eq. (7.261) for $U_x(s)$ was refined to (cf. eq. (7.264)),

$$U_x(s) = \int_{-\infty}^{-(c_x=s-\lambda_x-L)/T} \varphi(v) F(D_x) dv \quad (7.268)$$

by changing the limits of integration for variable v to the interval of velocities which give a longitudinal overlap. A derivation of eq. (7.263) for $F(D_x)$ was provided in an Appendix to SASP-WG/WHL/14-WP/14 in response to a query earlier in the meeting.

The probability distributions of the relative longitudinal velocity and the longitudinal position errors were taken the same as in SASP-WG/WHL/14-WP/14 (September version) . Using these probability distributions, the October version of the paper was able to derive an analytical formula for $U_x(s)$ in eq. (7.268), which was effectively the formula derived previously for $U_{xz}(s)$ in eq. (7.265) with the lower limit of integration T_b replaced by zero and the upper limit of integration T_e replaced by the symbol T . The probability density $w(s)$ in eq. (7.260) was again taken as a uniform probability density over the range of $s \in [15,30]$ NM of initial distances between the aircraft at ITP initiation. Based on that, eq. (7.260) for the probability of longitudinal overlap can be expressed as

$$\Pi_x = \frac{4\lambda_x}{5} \times \int_{15}^{30} w(s)U_x(s)ds, \quad (7.269)$$

The accident rate per flight hour due to an ADS-B ITP operation was calculated for vertical distances of 1000 and 2000 feet between the ITP and reference aircraft (cf. ICAO Circular 325) using the revised longitudinal collision risk model summarized above and revised parameter values for the model parameters $|\bar{\dot{x}}|$, $|\bar{\dot{y}}|$, and $P_y(0)$ and a conservative value of $P_z(0) = 1$. See October version of the paper (Carreno, 2008a) for the specific collision risk model parameter values used, including a value of $r = 0.04167$ for the ratio of ADS-B ITP operation time to typical flight time. Assuming that the ADS-B ITP operation would be performed equally often with 1000 and 2000 feet vertical distances, the average collision rate per flight hour due to the ADS-B ITP operation was 3.13×10^{-11} accidents per flight hour.

SASP-WG/WHL/14-WP/45 provided a revision of SASP-WG/WHL/12-WP/18 presented at SASP's Santiago Meeting in November 2007. As set out under the *SASP-WG/WHL/12, Santiago, November 2007* heading earlier in this Section, SASP-WG/WHL/12-WP/18 itself provided an update to the ADS-B ITP safety assessment of SASP-WG/WHL/11-WP/17 in that it used the same risk model but with revised values for some of its parameters.

The revision of SASP-WG/WHL/12-WP/18 presented in SASP-WG/WHL/14-WP/45 comprised two elements. The first one concerned the zero angle same-identical track case and the second one concerned an additional section on flight tracks when the intersecting angle is more than zero.

For the zero angle same-identical track case, the probability of longitudinal overlap was again taken as the risk measure. In the same manner as for the revision of SASP-WG/WHL/14-WP/14 (September version), the first specific characteristic of the ADS-B ITP procedure listed before eq. (7.259) above, was dropped in favour of the conservative assumption that for the application to the ADS-B ITP procedure, the ITP and reference aircraft start the manoeuvre at the same flight level. Hence, the correction Δ_x of the longitudinal overlap interval of eq. (7.256) was not needed and the calculation of the probability of longitudinal overlap by means of eqs. (7.257) and (7.258) for the two choices of type of probability distributions was revised to

$$P_x[-\lambda_x < x(t) < \lambda_x] = \int_{-\lambda_x}^{\lambda_x} f_7(x)dx \quad (7.270)$$

And

$$P_x[-\lambda_x < x(t) < \lambda_x] = \int_{-\lambda_x}^{\lambda_x} f_{p+vg+vm+w+c}(x)dx \quad (7.271)$$

Upward revisions of the standard deviations of the position, ground speed, and Mach errors were provided. Use of the revised standard deviation values in combination with eqs. (7.270) and (7.271) resulted in the numerical results as reproduced in Table 7.20 below. Notice the large differences between the calculated probabilities of longitudinal overlap for the two types of chosen probability distributions. The results shown in Table 7.20 may be compared with their predecessors in Table 7.19 and are seen to be larger by at least four orders of magnitude as a result of the increased standard deviations of the position, ground speed, and Mach errors.

Table 7.20: Probability of longitudinal overlap for the two choices of types of probability distributions for the various error terms (SASP-WG/WHL/14-WP/45 (Carreno, 2008d))

Altitude difference (ft)	Nominal time for ITP aircraft to climb to the reference aircraft's flight level (hours)	Probability of longitudinal overlap $P_x[-\lambda_x < x(t) < \lambda_x]$	
		Double exponential distributions	Gaussian distributions
1000	0.0556	3.13×10^{-18}	4.68×10^{-208}
2000	0.1111	4.75×10^{-11}	1.46×10^{-22}

The first element of the revision presented in SASP-WG/WHL/14-WP/45 concluded with a brief consideration of the risk of collision given an estimate of the probability of longitudinal overlap by noting that, effectively, a conservative assumption was made that during the ADS-B ITP manoeuvre, the ITP and reference aircraft were always in lateral and vertical overlap, thus implying that a longitudinal overlap will lead to a collision. Consequently, the probability of collision per ADS-B ITP operation was expected to be equal to or less than the probability of longitudinal overlap as summarised in Table 7.20.

The second element of the revision presented in SASP-WG/WHL/14-WP/45 concerned a brief additional section on flight tracks when the intersecting angle is more than zero, since the ADS-B ITP procedure can be implemented for same-direction tracks with angles in the range of 0 to 44 degrees (ICAO Circular 325). It was argued that the probability of longitudinal overlap for same-direction intersecting tracks is calculated in the same manner as for zero angle same-identical tracks. Since for the latter, the probability of lateral overlap was assumed to be equal to one (cf. previous paragraph), the probability of joint longitudinal and lateral overlap for same-direction intersecting tracks cannot be larger than the probability of longitudinal overlap for zero angle same-identical tracks multiplied by one. Hence, the probability of collision for intersecting tracks is equal to or less than the probability of collision for zero angle same-identical tracks.

Intersecting tracks at angles of 0 to 45 degrees

SASP-WG/WHL/14-WP/16 (Carreno, 2008c) utilized the longitudinal collision risk model based on reliability theory (Anderson, 2005), which, as a part of the description of further ICAO RGCSF and SASP work on collision risk modelling for distance-based separation on intersecting and coincident tracks, was presented in the following form in Section 7.3.4.1, *Collision risk modelling*, for m aircraft pairs on intersecting tracks during a risk-exposure time interval $[t_0, t_1]$:

$$N_a = 2\pi m \lambda_{xy}^2 P_z \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) \left(1 + \frac{\pi \lambda_{xy} |\dot{z}|}{4 \lambda_z v_{xy}} \right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (7.212)$$

where $f_i(v_i)$ is the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denotes the joint probability density of the relative position $r_x(t)$, $r_y(t)$ of two aircraft at time t for $r_x(t) = r_y(t) = 0$. The latter probability density is given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C$$

where ε_2^A and ε_2^C denote the along-track and across-track navigational errors of aircraft 2¹²⁷. $D_x(t)$ and $D_y(t)$ denote the nominal relative position between the aircraft at time t given by

$$D_x(t) = (v_1 - v_2 \cos \theta)t - d_1 + d_2 \cos \theta \quad (7.213)$$

$$D_y(t) = (d_2 - v_2 t) \sin \theta \quad (7.214)$$

and d_1 and d_2 denote the nominal distances of the aircraft before the intersection at time t_0 . In eq. (7.212), λ_{xy} and λ_z denote again the diameter and height respectively of a horizontal cylinder representing the aircraft, v_{xy} denotes the relative horizontal speed between the aircraft, P_z denotes the probability of vertical overlap for an aircraft pair, and $|\dot{z}|$ denotes the average of (the absolute value of the) relative vertical speed between the aircraft. Recall Figure 7.8 for the general intersecting-track configuration or see Figure 7.17 below for the ADS-B ITP application. The above collision risk model calculates the risk conditional on the nominal initial distances d_1 and d_2 of the aircraft to the intersection point of their tracks, or equivalently, their nominal along-track distance S ,

$$S = d_2 - d_1 \quad (7.272)$$

and the nominal distance d_1 of the reference aircraft to the intersection point. Longitudinal collision risk can be calculated for pairs of values of d_1 and d_2 or S and d_1 and, if applicable, be weighted according to a probability distribution of d_1 and d_2 or S and d_1 .

Thus, the dependence or conditioning of the left-hand variable N_a in eq. (7.212) on the nominal initial distances d_1 and d_2 may be made more explicit by expressing N_a as $N_a(d_1, d_2)$. Assuming a joint probability density $h_{D_1, D_2}(d_1, d_2)$, say, of the nominal initial distances, a new, unconditional, expected number of accidents N_a can be calculated from

$$N_a = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_{D_1, D_2}(d_1, d_2) N_a(d_1, d_2) dd_1 dd_2 \quad (7.273)$$

with $N_a(d_1, d_2)$ given by eq. (7.212).

Alternatively, using eq. (7.272), the joint probability density $h_{D_1, S}(d_1, s)$, say, of D_1 and S would be given by

$$h_{D_1, S}(d_1, s) = h_{D_1, D_2}(d_1, S + d_1) \quad (7.274)$$

¹²⁷ It is shown in Chapter 8 that $f_t(0,0)$ can be expressed in terms of either ε_2^A and ε_2^C or ε_1^A and ε_1^C .

and a conditional expected number of accidents $N_a(d_1, s)$ can be defined by means of eq. (7.212) but with eqs. (7.213) and (7.214) replaced by

$$D_x(t) = (v_1 - v_2 \cos \theta)t - d_1 + (s + d_1) \cos \theta \quad (7.275)$$

$$D_y(t) = (s + d_1 - v_2 t) \sin \theta \quad (7.276)$$

and the unconditional expected number of accidents given by

$$N_a = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h_{D_1, S}(d_1, s) N_a(d_1, d_2) dd_1 ds \quad (7.277)$$

The probability densities $h_{D_1, D_2}(d_1, d_2)$ and $h_{D_1, S}(d_1, s)$ of the nominal initial distances and/or separation for same-direction tracks are generalisations of the probability density $w(s)$ of the initial distance/separation s between the ITP and reference aircraft on zero angle same-identical tracks in the collision risk model of eqs. (7.259) and (7.260). Notice that for same-direction tracks with $\theta = 0$, eq. (7.276) reduces to $D_y(t) = 0$ and the dependence of $D_x(t)$ on d_1 and s in eq. (7.275) reduces to a dependence on $s = d_2 - d_1$ as defined by eq. (7.272) only as in the collision risk model for zero angle same-identical tracks. In addition, the probability density $f_t(0,0)$ defined above reduces to

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^C) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C \quad (7.278)$$

i.e. the double integral decouples into the product of two single integrals for the longitudinal and lateral dimensions:

$$f_t(0,0) = \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A - D_x(t)) f_2^A(\varepsilon_2^A) d\varepsilon_2^A \int_{-\infty}^{\infty} f_1^C(\varepsilon_2^C) f_2^C(\varepsilon_2^C) d\varepsilon_2^C \quad (7.279)$$

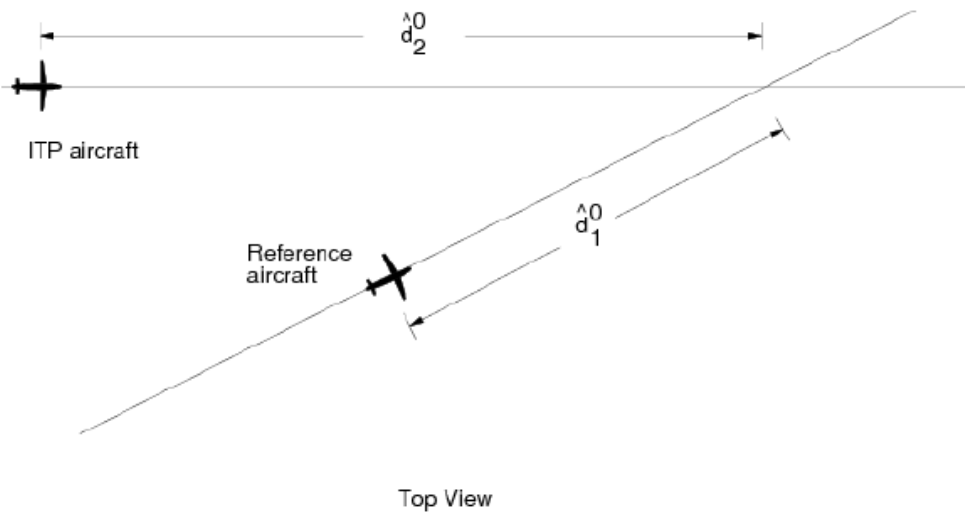


Figure 7.17: Top view of ADS-B ITP manoeuvre example (Reproduced from SASP-WG/WHL/14-WP/16)

The ADS-B ITP concept of operation establishes that an aircraft performing an ADS-B ITP manoeuvre must be a minimum along-track distance of 15 NM from the reference aircraft before requesting an ADS-B ITP operation and before initiating an ADS-B ITP climb or descent. For the ADS-B ITP application of the above longitudinal collision risk model a uniform distribution over the range [15,30] NM was assumed for the along-track distance S . Unfortunately, SASP-WG/WHL/14-WP/16 does not specify what probability distribution was used for the nominal distance d_1 of the reference aircraft to the point of intersection. For the time interval $[t_0, t_1]$ over which the longitudinal collision risk due to an ADS-B ITP operation was calculated, the start of the operation was taken as $t_0 = 0$ and the time T of the ITP aircraft vertically clearing the reference aircraft was taken as t_1 . The number of pairs per flight hour in eq. (7.212) was conservatively taken as $m = 4$ based on an ADS-B ITP operation lasting about 15 minutes, thus assuming the operation being performed on a continuous basis. In actual operations, the ADS-B ITP operation was expected to be performed no more than once every 6 flight hours resulting in a value of $m = 1/6$ aircraft pairs per flight hour. Longitudinal collision risk was then calculated for crossing angles from 0 to 45 degrees inclusive and double exponential probability distributions for position, ground speed, and Mach errors as well as wind. It was found that the highest risk occurred at a zero degree angle and the lowest risk at 20 degrees, with the risk decreasing with increasing angles up to 20 degrees and then slightly increasing. Table 7.22 shows the calculated numbers of fatal accidents due to ADS-BITP operations for the two intersection angles bounding the same-track case of $0 \leq \theta < 45$ degrees.

Table 7.22: Fatal accidents per flight hour, N_a , due to for ADS-B ITP operation for two crossing angles and double exponential error and wind probability distributions (Source: SASP-WG/WHL/14-WP/16 (Carreno, 2008c))

Altitude difference (ft)	Crossing angle (degrees)	
	0	45
1000	1.88×10^{-19}	1.51×10^{-20}
2000	3.39×10^{-12}	2.32×10^{-13}

SASP-WG/WHL/15, Montreal, May 2009

Three working papers dealing with the ITP procedure were presented at the fifteenth meeting of the Working Group of the Whole of the SASP, two of which, SASP-WG/WHL/15-WP/02 (Flax, 2009a) and SASP-WG/WHL/15-WP/09 (Carreno, 2009), dealt with ITP collision risk modelling whilst the third working paper, SASP-WG/WHL/15-WP/20 (Stefansson, 2009b), dealt with the ADS-B ITP PANS-ATM Amendment.

Due to other priorities set by the SASP-WG/WHL, the MSG did not review SASP-WG/WHL/15-WP/09, and had only a very brief discussion on SASP-WG/WHL/15-WP/02. As a result, it did not take any position on the relationship of SASP-WG/WHL/15-WP/02 to the MSG's previous work on risk assessment for ADS-B ITP.

SASP Project Team 6 *Longitudinal* work on ADS-B ITP comprised firstly SASP-WG/WHL/15-WP/20, which provided review comments of some external groups on the ADS-B ITP PANS-ATM Amendment and Circular produced by the SASP-WG/WHL at its previous, 14th, Meeting. The review resulted in an update of both the ADS-B ITP Amendment and Circular, viz. version 1.5.2. SASP-WG/WHL/15-WP/0 was presented by its author to the Project Team. It described re-calculated collision risk for the ADS-B ITP procedure when the Mach initiation criterion was changed from 0.04 to 0.06 Mach. The reason for this change was that the altitude criterion had been changed from 3000 ft to 2000 ft, thus providing the potential for a possibly less stringent Mach criterion. SASP-WG/WHL/15-WP/0 concluded that, using the collision risk modelling agreed at SASP-WG/WHL/14, although the accident rate could change by an order of magnitude it would still meet the agreed TLS for ADS-B ITP. Project Team 6 *Longitudinal* then agreed that the revised Mach criteria of 0.06

Mach could be adopted. This was also incorporated in the revised PANS-ATM Amendment and Circular for ADS-B ITP.

SASP-WG/WHL/15-WP/02 was not presented to Project Team 6 *Longitudinal*, but it was explained to the Project Team that it appeared to be more relevant to an ADS-C ITP proposal being developed by the FAA than to the Project Team's work on ADS-B ITP. The Project Team consequently concluded that SASP-WG/WHL/15-WP/02 had no effect on the work of the Project Team.

Following presentation of Project Team 6 *Longitudinal's* report to the SASP-WG/WHL plenary, some discussion took place on SASP-WG/WHL/15-WP/02 and its impact, if any, on SASP's work on the ADS-B ITP procedure to date. It was agreed that the latest version of the Circular would be coordinated to the OPLINKP (Operational Data Link Panel) and OPSP (Operations Panel) by the Secretary with a request to provide feedback by the end of August 2009, but that the Amendment would not be finalised until after the SASP MSG had been able to review SASP-WG/WHL/15-WP/02 at the next meeting in November 2009.

SASP-WG/WHL/16, Auckland, November 2009

Following the fifteenth Meeting of the Working Group of the Whole of the SASP, there were also three working papers dealing with the ITP procedure at its sixteenth Meeting. Two working papers dealt with ITP collision risk modelling where SASP-WG/WHL/16-WP/2 (Flax, 2009b) concerned a re-submission of the 45-page working paper 2 from the previous meeting and SASP-WG/WHL/16-WP/3 (Flax, 2009c) provided a 15-page summary of working paper 2 with additional comments and results. Unlike at the previous meeting, the two working papers were assigned priority for the MSG. The third working paper, SASP-WG/WHL/16-WP/06 (Stefansson, 2009a), dealt with the ADS-B ITP PANS-ATM Amendment. This last paper started recalling two main conclusions from SASP's previous meeting, namely coordination of the ADS-B ITP Circular with OPLINKP and OPSP by the Secretary with a request to provide feedback, and holding up the finalisation of the Circular until review of SASP-WG/WHL/15-WP/2 by the MSG. SASP-WG/WHL/16-WP/06 then provided some feedback received from OPLINKP members and explained that no feedback had been received from OPSP to date.

SASP Project Team 6 *Longitudinal* started its deliberations on ADS-B ITP with the feedback provided by OPLINKP presented in SASP-WG/WHL/16-WP/06. This resulted in some changes to the Circular, resulting in version 1.5.3. Following presentation of the Project Team's report to the SASP Plenary, the latter considered this work completed, although comments on the latest version could still be provided after the meeting but before the end of December 2009. The Plenary also tasked the Secretary to progress the ADS-B ITP separation standard in January 2010 for inclusion in the PANS-ATM and the supporting Circular for publication.

SASP Project Team 6 *Longitudinal* then discussed the Meeting's working papers 2 and 3. The main points of the discussion concerned the definition of a blunder error in the two working papers and whether, or not, the two working papers were intended for use in the ADS-B ITP implementation or for SASP work. The author of the two working papers and the Rapporteur of the SASP MSG were then called in to advise on these discussion points. The advice (and conclusion) on the first discussion item was simple, viz. that in the context of the two working papers blunder was considered to be the probability that longitudinal separation is less than the legal separation for any reason. A wide ranging discussion then took the place on the second discussion item, resulting in the conclusion that the model presented in working papers 2 and 3 did not warrant a change to the ADS-B ITP procedure but that the MSG should further explore possibilities for enhancing the working papers' methodology to provide Air Navigation Service Providers with a practical

means of estimating acceptable blunder rates related to ITP in a specific airspace environment. See Appendix D to the SASP-WG/WHL/16 Meeting Report.

MSG work at SASP-WG/WHL/16 started with WP/ 2 (Flax, 2009b), which derived a model for estimating the probability of collision during the execution of an in-trail procedure (ITP). The derivation specifically accounted for the possibility of a “blunder” error in which the manoeuvring aircraft begins its climb or descent when the longitudinal separation between the aircraft is less than the minimum distance prescribed for an ITP. The supplementary working paper 3 had already been presented to the SASP Plenary and was also taken into account in the MSG’s discussion. The working paper was confined to zero angle same-identical tracks and did not take the speed difference restrictions in the ADS-B ITP application into account. Two basic random variables used in the model were U and V where U is the signed distance by which the manoeuvring aircraft is ahead of (or behind) the non-manoevring aircraft when the climb or decent begins and V is the signed speed advantage of the manoeuvring aircraft over the non-manoevring aircraft. Lacking any reason to think otherwise, it was assumed that U and V are independent.

Following an introduction and a description of the scenario modelled in Section 1 of WP/2, Section 2 of the working paper defined six conditions/events, $C_1, C_2, \dots, C_6$ for simultaneous longitudinal and vertical overlap for an ITP aircraft pair in terms of the random variables U and V . The probability distribution of V was assumed to be Gaussian with mean 0 and variance σ^2 . The probability distribution of the signed distance U between the aircraft at the start of the manoeuvre was specified as follows. Letting m denote the minimum allowable longitudinal separation between aircraft assigned to the same route and flight level, and letting k denote a number strictly between 0 and 1, it was assumed that an ITP might be authorized as long as the longitudinal distance between the aircraft when the manoeuvring aircraft begins its climb or descent is expected to exceed km . Assuming that the responsible controller estimates the longitudinal separation between the aircraft when the manoeuvring aircraft begins its (requested) climb or descent will be between km and m and assuming that an altitude change is allowed when the longitudinal separation exceeds km and authorizes the requested change, one would expect U to be uniformly distributed on $(-m, -km] \cup [km, m)$ if the route system always operated perfectly. However, recognizing that equipment occasionally fails and people sometimes make mistakes, it was assumed more realistically that there was a small probability $b > 0$ that the value of U falls in the interval $(-km, km)$. Since such events typically result from blunders, it was conservatively assumed that when U falls in the interval $(-km, km)$, it is uniformly distributed on that interval. Thus, the probability density $f_U(u)$ of U was then given by

$$f_U(u) = \begin{cases} 0 & \text{if } u \leq -m \\ \frac{1-b}{2m(1-k)} & \text{if } -m < u \leq -km \\ \frac{b}{2km} & \text{if } -km < u < km \\ \frac{1-b}{2m(1-k)} & \text{if } km \leq u < m \\ 0 & \text{if } m \leq u \end{cases} \quad (7.280)$$

The set of all possible values of the ordered pair (U, V) was then subdivided into six events $E_1, E_2, \dots, E_6$ (and an event of measure 0) and it was shown that a simultaneous longitudinal and vertical overlap could only occur for the events E_2, E_3, E_4 , or E_5 .

Four additional random variables were defined, namely T_b and T_e as the beginning and ending times of the interval in which the aircraft are in a state of longitudinal overlap and t_b and t_e as the beginning and ending times of the interval in which the aircraft are in a state of vertical overlap.

Using the independence of the random variables U and V , Section 3 of the working paper first calculated the joint probability density of U and V as the product of their individual probability densities, then considered three ranges of possible values for T_b and T_e in terms of t_b and t_e , resulting in six events $C_1, C_2, \dots, C_6$ of simultaneous longitudinal and vertical overlap, and subsequently computed the probabilities $P(E_i \cap C_j)$, for $i, j = 2, \dots, 5$. Finally, letting O denote the event that the aircraft pair involved in an ITP manoeuvre experiences a simultaneous longitudinal and vertical overlap, the probability $P(O)$ of simultaneous overlap was evaluated as

$$P(O) \approx \frac{b}{mk} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.281)$$

where l denotes the length of a typical aircraft involved in an ITP operation (see SASP-WG/WHL/16-WP/2, eq. (3d)). Two alternative expressions for $P(O)$ were also provided, namely

$$P(O) \approx \frac{b}{mk} \left(l + \frac{2\sigma h}{\sqrt{2\pi}c} \right) \quad (7.282)$$

with h denoting the height of a typical aircraft involved in an ITP operation and c denoting the absolute value of the manoeuvring aircraft's speed of climb or decent (SASP-WG/WHL/16-WP/2, eq. (3e)) and

$$P(O) \approx \frac{b}{mk} \left(l + \frac{(t_b + t_e)\sigma h}{\sqrt{2\pi}a} \right) \quad (7.283)$$

where a denotes the absolute value of the initial altitude difference between the manoeuvring and non-manoevring aircraft (eq. (3f) of SASP-WG/WHL/16-WP/2).

Section 4 of working paper 2 provided a formula for the probability p_0 of lateral overlap for GNSS-equipped aircraft involved in an ITP operation based on a Gaussian double-exponential probability distribution.

Finally, sections 5, 6, and 7 of working paper 2 calculated the probabilities of collision for the three ways in which collisions can occur, i.e. nose-to-tail collision, $P(C_{NT})$, top-to-bottom collision, $P(C_{TB})$, and side-to-side collision, $P(C_{SS})$, and Section 8 combined the three probabilities into the overall probability of collision $P(C)$,

$$P(C) = p_0 \left(1 + \frac{k_0 h}{cw} \right) P(O) \quad (7.284)$$

(SASP-WG/WHL/16-WP/2, eq. (12b)) with w denoting the width of a typical aircraft involved in an ITP operation and k_0 denoting the average lateral passing speed of airplanes that are assigned to the same route. The following alternative expression for $P(C)$ was also provided (based on eq. (7.281):

$$P(C) = p_0 \left(1 + \frac{k_0 h}{cw} \right) \frac{b}{mk} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.285)$$

The author of SASP-WG/WHL/16-WP/2) provided a detailed explanation of the paper to the MSG. The derivations involved a considerable amount of algebra as may be inferred from the size of the paper, 45 pages. The MSG followed the explanation and found it to be mathematically sound. Nonetheless, one member of the MSG objected to the use of an (infinite-extent) normal distribution for the signed speed difference V , claiming that since the ADS-B ITP criteria limit the initial speed difference to 20 kts, it was not reasonable to use a distribution whose tails extend to infinity. It was replied that the standard deviation of V could be set small enough to make the effect of any speed difference larger than the ADS-B ITP criterion negligible. The same member also queried the form of the probability density $f_U(u)$ of the signed distance U by which the manoeuvring aircraft is ahead of (or behind) the non-manoevring aircraft when the climb or descent begins (cf. eq. (7.280)). The author of working paper 2 accepted that in estimating a value for the parameter b , i.e. the probability of a climb or descent being initiated with longitudinal separation less than the permissible minimum, values of U that are just slightly less than the permissible minimum might occur often enough to yield a relatively large estimate of b to cause an unwarranted inflation of the probability of achieving values of U that are close to 0. He also noted that if a pair of aircraft has initial longitudinal separation that is just slightly less than the permissible minimum, their probability of colliding during an ITP or CDP is negligibly small as they would need an exceptionally large closing speed in order to experience a longitudinal overlap. It was concluded that while this observation was intuitively reasonable, it did not solve the problem of unduly large estimates of the parameter b . Some suggestions to deal with the problem were made later during the MSG meeting. See Appendix I to the SASP-WG/WHL/16 Meeting Report.

SASP-WG/WHL/17, Montreal, May 2010

A single working paper only dealing with collision risk modelling for an in-trail or a climb-or-descent procedure was presented at the seventeenth Meeting of the Working Group of the Whole of the SASP, viz. SASP-WG/WHL/17-WP/6 (Flax, 2010a). A revised model was derived where the derivation differed from the one previously presented in SASP-WG/WHL/16-WP/2 in that it used a different probability density function than $f_U(u)$ defined by eq. (7.280) for the random variable U , with U being the signed distance by which the manoeuvring aircraft is ahead of (or behind) the non-manoevring aircraft when the climb or descent begins.

Apart from the revised model, the title of SASP-WG/WHL/17-WP/6 differed from that of SASP-WG/WHL/16-WP/2, in that it referred to both an in-trail procedure and a climb-or descent procedure. The reason for this extension was explained in WP/6's *Introduction* as follows. "The sequence of events by which such a climb or descent would be accomplished has typically been called an "in-trail procedure", or ITP. Since mid-2009 this designation has been restricted (at least within the United States Federal Aviation Administration) to a procedure in which both airplanes are using the broadcast mode of automatic dependent surveillance (ADS-B), and the manoeuvring airplane is specially equipped to estimate its relative position and relative speed with respect to the non-manoevring airplane. A similar procedure, in which the manoeuvring aircraft uses the contract mode of automatic dependent surveillance (ADS-C) to request a change of flight level, and in which the responsible air traffic controller follows somewhat different rules from those applied to the ITP, is now known as a "climb-or-descent procedure", or CDP. This report derives a formula for estimating the probability that a collision occurs when an ITP or CDP is executed."

SASP utilized the term ADS-B ITP for the work described in this Section of this Document for what SASP-WG/WHL/17-WP/6 described as an in-trail procedure. This was also reflected in the title of the pertinent ICAO Circular ICAO Circular 325).

SASP-WG/WHL/17-WP/6 (Flax, 2010a) was presented by its author to a joint session of SASP Project Team 6 *Longitudinal* and the SASP MSG and will be reviewed in Section 7.3.7, *ADS-C Climb and Descend Procedure (ADS-C CDP)*, rather than in this Section for the following reasons. Firstly, it was concluded by Project Team 6 *Longitudinal* at SASP-WG/WHL/15 that although SASP-WG/WHL/15-WP/2, identical to the later SASP-WG/WHL/16-WP/2, had not been presented to it, it appeared to be more relevant to an ADS-C ITP proposal being developed by the FAA than to the Project Team's work on ADS-B ITP. The Project Team consequently concluded that SASP-WG/WHL/15-WP/2 had no effect on the work of the Project Team. Secondly, SASP Project Team 6 *Longitudinal* concluded at SASP-WG/WHL/16 that the model presented in SASP-WG/WHL/16-WP/2 and SASP-WG/WHL/16-WP/3 (Flax, 2009c) did not warrant a change to the ADS-B ITP procedure but that the MSG should further explore possibilities for enhancing the working papers' methodology to provide Air Navigation Service Providers with a practical means of estimating acceptable blunder rates related to ITP in a specific airspace environment.

It was recalled at the SASP Project Team 6 *Longitudinal* Meeting that SASP had finalised its work on ADS-B ITP at its previous meeting and that the Secretary would now need to coordinate with other ICAO panels as regards SASP's findings.

SASP-WG/WHL/18, Brussels, November 2010

SASP-WG/WHL/18-WP/02 (SASP Secretary, 2010) provided comments from the second meeting of the ICAO Airborne Surveillance Task Force (ASTAF/2) on SASP's work on the ADS-B ITP PANS-ATM Amendment and corresponding Circular. The working paper was discussed by the SASP Plenary as well as by SASP Project Team 6 *Longitudinal*. It listed six issues raised by ASTAF that needed to be clarified before the amendment could go forward, thus effectively delaying the PANS-ATM amendment until suitable phraseology will have been agreed and evaluated through operational trials. The Secretary was asked to advise the status of ADS-B ITP at the next meeting.

In line with the conclusion at SASP-WG/WHL/16 that SASP had finalised its work on ADS-B ITP, there were no papers on collision risk modelling for the ADS-B ITP procedure.

The text under the next six headings briefly references the status of the ADS-B ITP PANS-ATM Amendment and corresponding Circular as well as an ADS-B ITP operational trial conducted by the FAA.

SASP-WG/WHL/19, Montreal, May 2011

The status of the ADS-B ITP work was advised as still awaiting conclusion of ASTAF meeting.

SASP-WG/1, Cairns, November 2011

The status of the ADS-B ITP work was advised as awaiting conclusion of ASTAF meeting and working with OPLINKP and OPSP to finalize.

SASP-WG/WHL/20, Montreal, May 2012

SASP-WG/WHL/20-IP/02 (FAA, 2011) presented U.S. FAA activities associated with an ADS-B ITP operational trial along South Pacific routes which had started in August 2011 and been extended to all oceanic airspace controlled by Oakland Air Route Control Center (KZAK) in December 2011. The information paper noted that the FAA established agreements that led to the development and certification of onboard systems that provide the ADS-B ITP criteria and display the information to the pilot. The FAA had also performed all required safety management system processes and analyses.

SASP Project Team 6 *Longitudinal* was given an *ADS-B In-Trail Procedures Update* presentation (Jones, 2012). Slide 27 of the presentation stated that ASTAF had reviewed the ADS-B ITP PANS-ATM Amendment and Circular, making minor suggestions for improvement, and completed this work in October 2011. The slide also stated that the ADS-B ITP Circular had been reviewed by OPLINKP, ASP and OPSP and that ICAO Sponsored an Air Traffic Situational Awareness (ATSA) Workshop from 27 to 28 March 2012 with ADS-B ITP and progression of the Circular being a key motivator of the meeting. Slide 29, *ITP Circular status*, stated that OPLINKP will be formally recommending the ITP message sets as UM341 and DM161 to the ANC and that discussions of the message sets had impacted the date of the Circular. The slide also stated that a State letter will go out in 2013 and that the date of applicability of the ADS-B ITP procedure in the PANS-ATM will be in 2014.

The Project Team noted that the ADS-B ITP Circular had been completed at SASP-WG/WHL/16 in November 2009 but was only planned for publication in 2013/2014 timeframe as it still had to be reviewed by other ICAO Panels, Task Forces and Groups.

SASP-WG/WHL/21, Seattle, November 2012

The status of the ADS-B ITP work had not changed since the previous SASP meeting.

SASP-WG/WHL/22, Montreal, May 2013

SASP-WG/WHL/22-WP/05 (Jones, 2013a) presented an overview of the progress of the ICAO documents supporting ADS-B ITP and a recommendation for a minor revision to the language of the previously developed ADS-B ITP PANS-ATM amendment developed by the SASP. The supporting documents concerned the PANS-ATM (Doc 4444), Annex 10 Volume II, and the PANS-OPS Volume I (Doc 8168). See SASP-WG/WHL/22-WP/05 and Section 3.1.4 of the SASP-WG/WHL/22 Meeting Report for further details, including an action on all SASP members to provide input to their regulators that any response to the ADS-B ITP State Letter, distributed to States for comment on 10 May 2013, should include an agreement to the proposal with a comment referring to the inclusion of Attachment C to the SASP-WG/WHL/22 Meeting Report to support the new language agreed at the Meeting.

SASP-WG/WHL/22-IP/01 (Jones, 2013b) presented an update to SASP-WG/WHL/20-IP/02 concerning the FAA ADS-B ITP operational flight trial project. The data being collected was used to enhance the understanding of the economic, safety and operational impact of ADS-B ITP.

SASP-WG/WHL/23, New Delhi, November 2013

ADS-B ITP was not dealt with at SASP-WG/WHL/23 other than that the action on SASP members described under the previous heading was given status *completed*.

Conclusion

Following the State Letter process for the ADS-B ITP procedure, the procedure was approved by the ICAO ANC for inclusion into the 15th Edition of the PANS-ATM under Amendment 6 and became applicable as of 13 November 2014. See also the ADS-B ITP Circular 325 (ICAO Circular 325).

7.3.7 ADS-C Climb and Descend Procedure (ADS-C CDP)

This Section considers the safety assessment underlying the Automatic Dependent Surveillance – Contract Climb and Descent Procedure (ADS-C CDP) developed by the U.S. FAA and subsequently supported by the SASP and approved by the ICAO ANC for incorporation into the PANS-ATM for global application. As set out

in ICAO Circular 342, the ADS-C CDP Circular provides guidelines and supporting material for the implementation of the procedure intended for use with aircraft equipped with ADS-C, direct controller-pilot communication (using either voice or controller-pilot data link communication (CPDLC)) and an air traffic service provider equipped with a ground-based automation system capable of calculating the distance between aircraft by using their near-simultaneous ADS-C position reports.

The continuing growth of aviation increases demands on airspace capacity thus emphasizing the need for optimal utilization of available airspace. Improved operational and economic efficiencies are derived from the application of procedures that leverage the use of equipment already on board the aircraft. The ADS-C CDP utilizes existing ADS-C aircraft equipage and air traffic control (ATC) capabilities to allow more flights to achieve their preferred vertical profiles, thereby increasing both capacity and efficiency. Integral to the ADS-C CDP is the use of advanced communication, navigation, and surveillance (CNS) capabilities, i.e. ADS-C and CPDLC. The ADS-C CDP is conceptually modelled after existing in-trail distance measuring equipment (DME) rules set forth in the PANS-ATM, paragraph 5.4.2.3.4 (see e.g. 16th edition of PANS-ATM). Aircraft pair distance verification is performed by the ground automation system using simultaneous ADS-C demand contract reports. The ADS-C CDP was designed to improve service to appropriately equipped aircraft by providing an air traffic controller with another option for initiating an altitude change when existing separation minima, such as the ADS-C distance-based 30 NM longitudinal separation minimum (cf. the fifth row in Table 2.5), do not allow an aircraft to climb or descend through the altitude of a blocking aircraft.

The ADS-C CDP procedure for aircraft on same tracks in procedural airspace was incorporated into the 16th edition of the PANS-ATM under Amendment 7-A to the 15th edition, to become applicable on 10 November 2016. It is similar to the ADS-B ITP procedure examined in Section 7.3.6 of this Document in that it is a climb- or descend-through procedure. Unlike the ADS-B ITP, however, the pilots involved in an ADS-C CDP may not be aware of which separation minima a controller is utilizing. A pair of aircraft may qualify for an ADS-C CDP if they satisfy criteria involving the:

- Intended tracks of the aircraft;
- Position accuracy of the aircraft navigation systems;
- Longitudinal distance between the aircraft;
- Speed difference between the aircraft;
- Altitude difference between the aircraft;
- Duration of the procedure; and
- Available communication services.

These criteria are stated in greater detail in four steps outlined in Table 2-1 of ICAO Circular 342. The four steps, without the detailed criteria, are:

- Step 1 – Determine whether a pair of aircraft is a candidate for an ADS-C CDP;
- Step 2 – Check the altitude difference between the aircraft;
- Step 3 – Check distance, speed and position accuracy; and
- Step 4 – Construct the clearance.

A brief discussion of the work performed by the SASP on the ADS-C CDP procedure is provided by meeting below. For the first two meetings, there is some duplication of text from Section 7.3.6 (as a result of both the ADS-B ITP and the ADS-C CDP being climb- or descend-through procedures).

SASP-WG/WHL/15, Montreal, May 2009

SASP-WG/WHL/15-WP/2 (Flax, 2009a) derived a model for estimating the probability of collision during the execution of an in-trail procedure. SASP-WG/WHL/15-WP/2 was not presented to SASP Project Team 6 *Longitudinal*, but it was explained to the Project Team that it appeared to be more relevant to an ADS-C CDP proposal being developed by the FAA than to the Project Team's work on ADS-B ITP at the time. Consequently, the Project Team concluded that, for the time being, it would not process SASP-WG/WHL/15-WP/2. Due to other priorities set by the SASP-WG/WHL, the MSG also had only a very brief discussion on SASP-WG/WHL/15-WP/2.

SASP-WG/WHL/16, Auckland, November 2009

Two working papers dealt with ITP collision risk modelling where SASP-WG/WHL/16-WP/2 (Flax, 2009b) concerned a re-submission of the 45-page working paper 2 from the previous meeting and SASP-WG/WHL/16-WP/3 (Flax, 2009c) provided a 15-page summary of working paper 2 with additional comments and results. Unlike at the previous meeting, the two working papers were assigned priority for the MSG.

SASP Project Team 6 *Longitudinal* discussed the Meeting's working papers 2 and 3. The main points of the discussion concerned the definition of a blunder error in the two working papers and whether, or not, the two working papers were intended for use in the ADS-B ITP implementation or for SASP work. The author of the two working papers and the Rapporteur of the SASP MSG were then called in to advise on these discussion points. The advice (and conclusion) on the first discussion item was simple, viz. that in the context of the two working papers blunder was considered to be the probability that longitudinal separation is less than the legal separation for any reason. A wide ranging discussion then took place on the second discussion item, resulting in the conclusion that the model presented in working papers 2 and 3 did not warrant a change to the ADS-B ITP procedure but that the MSG should further explore possibilities for enhancing the working papers' methodology to provide Air Navigation Service Providers with a practical means of estimating acceptable blunder rates related to ITP in a specific airspace environment. See Appendix D to the SASP-WG/WHL/16 Meeting Report.

MSG work at SASP-WG/WHL/16 started with working paper 2 (SASP-WG/WHL/16-WP/2), which derived a model for estimating the probability of collision during the execution of an in-trail procedure (ITP). The derivation specifically accounted for the possibility of a "blunder" error in which the manoeuvring aircraft begins its climb or descent when the longitudinal separation between the aircraft is less than the minimum distance prescribed for an ITP. The supplementary working paper 3 had already been presented to the SASP Plenary and was also taken into account in the MSG's discussions. The working paper was confined to zero angle same-identical tracks and did not take any speed difference restrictions in the ITP application into account. Two basic random variables used in the model were U and V where U is the signed distance by which the manoeuvring aircraft is ahead of (or behind) the non-manoevring aircraft when the climb or decent begins and V is the signed speed advantage of the manoeuvring aircraft over the non-manoevring aircraft. Lacking any reason to think otherwise, it was assumed that U and V were independent.

Following an introduction and a description of the scenario modelled in Section 1 of working paper 2, Section 2 of the working paper (SASP-WG/WHL/16-WP/2) defined six conditions/events, $E_1, E_2, \dots, E_6$ for longitudinal overlap for an in-trail operation aircraft pair in terms of the basic random variables U and V . Two additional random variables were defined, namely T_b and T_e as the beginning and ending times of the interval in which the aircraft are in a state of longitudinal overlap. The probability distribution of V was assumed to be Gaussian with mean 0 and variance σ^2 . The probability distribution of the signed distance U between the

aircraft at the start of the manoeuvre was specified as follows. Letting m denote the minimum allowable longitudinal separation between aircraft assigned to the same route and flight level, and letting k denote a number strictly between 0 and 1, it was assumed that an ITP might be authorized as long as the longitudinal distance between the aircraft when the manoeuvring aircraft begins its climb or descent is expected to exceed km . Assuming that the responsible controller estimates the longitudinal separation between the aircraft when the manoeuvring aircraft begins its (requested) climb or descent will be between km and m and assuming that an altitude change is allowed when the longitudinal separation exceeds km and authorizes the requested change, one would expect U to be uniformly distributed on $(-m, -km] \cup [km, m)$ if the route system always operated perfectly. However, recognizing that equipment occasionally fails and people sometimes make mistakes, it was assumed more realistically that there was a small probability $b > 0$ that the value of U falls in the interval $(-km, km)$. Since such events typically result from blunders, it was conservatively assumed that when U falls in the interval $(-km, km)$, it is uniformly distributed on that interval. Thus, the probability density $f_U(u)$ of U was given by, see Figure 7.18,

$$f_U(u) = \begin{cases} 0 & \text{if } u \leq -m \\ \frac{1-b}{2m(1-k)} & \text{if } -m < u \leq -km \\ \frac{b}{2km} & \text{if } -km < u < km \\ \frac{1-b}{2m(1-k)} & \text{if } km \leq u < m \\ 0 & \text{if } m \leq u \end{cases} \quad (7.280)$$

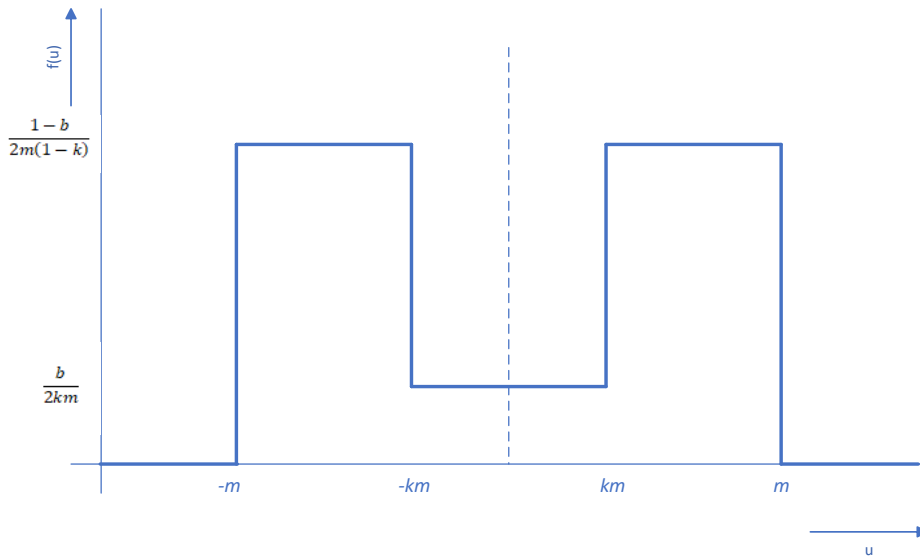


Figure 7.18: The probability density $f_U(u)$ of U as provided by Eq. (7.280)

The set of all possible values of the ordered pair (U, V) was then subdivided into six events $E_1, E_2, \dots, E_6$ (and an event of measure 0) and it was shown that a longitudinal overlap can only occur for the events E_2, E_3, E_4 or E_5 .

Section 2 of the working paper concluded with the derivation of a condition for vertical overlap in terms of the initial altitude difference between the aircraft, the manoeuvring aircraft's speed of climb or decent, and

the aircraft height. Two more additional random variables were defined for this derivation, namely t_b and t_e as the beginning and ending times of the interval in which the aircraft are in a state of vertical overlap.

Section 3 of the working paper examined the probability of simultaneous longitudinal and vertical overlap. Using the independence of the random variables U and V , it first calculated the joint probability density of U and V as the product of their individual probability densities. It then recalled the subdivision of the set of all possible values of the ordered pair (U, V) into the six events $E_1, E_2, \dots, E_6$ (and an event of measure 0) and noted that a simultaneous longitudinal and vertical overlap can only occur for the events E_2, E_3, E_4 or E_5 . Three ranges of possible values for T_b and T_e in terms of t_b and t_e were then considered, resulting in the definition of six events $C_1, C_2, \dots, C_6$ of simultaneous longitudinal and vertical overlap, after which the probabilities $P(E_i \cap C_j)$, for $i, j = 2, \dots, 5$, were computed. Finally, letting O denote the event that the aircraft pair involved in an in-trail operation experiences a simultaneous longitudinal and vertical overlap, the probability $P(O)$ of simultaneous overlap was evaluated as

$$P(O) \approx \frac{b}{mk} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.281)$$

where l denotes the length of a typical aircraft involved in an ITP operation (SASP-WG/WHL/16-WP/2, eq. (3d)). Two alternative expressions for $P(O)$ were also provided, namely

$$P(O) \approx \frac{b}{mk} \left(l + \frac{2\sigma h}{\sqrt{2\pi}c} \right) \quad (7.282)$$

with h denoting the height of a typical aircraft involved in an in-trail operation and c denoting the absolute value of the manoeuvring aircraft's speed of climb or decent (SASP-WG/WHL/16-WP/2, eq. (3e)) and

$$P(O) \approx \frac{b}{mk} \left(l + \frac{(t_b + t_e)\sigma h}{\sqrt{2\pi}a} \right) \quad (7.283)$$

where a denotes the absolute value of the initial altitude difference between the manoeuvring and non-manoevring aircraft (eq. (3f) of SASP-WG/WHL/16-WP/2).

Section 4 of working paper 2 provided a formula for the probability p_0 of lateral overlap for GNSS-equipped aircraft involved in an ITP operation based on a Gaussian double-exponential probability distribution.

Finally, sections 5, 6, and 7 of working paper 2 calculated the probabilities of collision for the three ways in which collisions can occur, i.e. nose-to-tail collision, $P(C_{NT})$, top-to-bottom collision, $P(C_{TB})$, and side-to-side collision, $P(C_{SS})$, and Section 8 combined the three probabilities¹²⁸ into the overall probability of collision $P(C)$,

$$P(C) = p_0 \left(1 + \frac{k_0 h}{cw} \right) P(O) \quad (7.284)$$

¹²⁸ Formulae for $P(C_{NT})$, $P(C_{TB})$, and $P(C_{SS})$ for a revised version of the collision risk model of SASP-WG/WHL/16-WP/2 are provided under the next heading (SASP-WG/WHL/17, Montreal, May 2010).

(SASP-WG/WHL/16-WP/2, eq. (12b)) with w denoting the width of a typical aircraft involved in an in-trail operation and k_0 denoting the average lateral passing speed of airplanes that are assigned to the same route. The following alternative expression for $P(C)$ was also provided (based on eq. (7.281)):

$$P(C) = p_0 \left(1 + \frac{k_0 h}{cw} \right) \frac{b}{mk} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.285)$$

In order to facilitate comparison of an estimate of the longitudinal collision risk associated with the execution of an in-trail procedure with a pertinent target level of safety, the collision probability was converted into an accident rate using estimates of the number of executions of the ADS-C CDP procedure per hour in a given airspace and the airspace's average instantaneous number of flights.

The author of SASP-WG/WHL/16-WP/2 provided a detailed explanation of the paper to the MSG. The derivations involved a considerable amount of algebra as may be inferred from the size of the paper, 45 pages. The MSG followed the explanation and found it to be mathematically sound. Nonetheless, one member of the MSG queried the form of the probability density $f_U(u)$ of the signed distance U by which the manoeuvring aircraft is ahead of (or behind) the non-maneuvring aircraft when the climb or descent begins (cf. eq. (7.280)). The author of working paper 2 accepted that in estimating a value for the parameter b , i.e. the probability of a climb or descent being initiated with longitudinal separation less than the permissible minimum, values of U that are just slightly less than the permissible minimum might occur often enough to yield a relatively large estimate of b to cause an unwarranted inflation of the probability of achieving values of U that are close to 0. He also noted that if a pair of aircraft has initial longitudinal separation that is just slightly less than the permissible minimum, their probability of colliding during an ITP or CDP is negligibly small as they would need an exceptionally large closing speed in order to experience a longitudinal overlap. It was concluded that while this observation was intuitively reasonable, it did not solve the problem of unduly large estimates of the parameter b . Some suggestions to deal with the problem were made later during the MSG meeting. See Appendix I to the SASP-WG/WHL/16 Meeting Report.

SASP-WG/WHL/17, Montreal, May 2010

A revised version of the collision risk model of SASP-WG/WHL/16-WP/2 was provided in SASP-WG/WHL/17-WP/6 (Flax, 2010a). The revised model differed from the original one in that it used a different probability density function than $f_U(u)$ defined by eq. (7.280) for the random variable U , where U is the signed distance by which the manoeuvring aircraft is ahead of (or behind) the non-maneuvring aircraft when the climb or descent begins. No change was made to the probability distribution of V , where V is the signed speed advantage of the manoeuvring aircraft over the non-maneuvring aircraft. Lacking any reason to think otherwise, it was again assumed that U and V are independent.

Apart from the revised model, the title of SASP-WG/WHL/17-WP/6 also differed from that of SASP-WG/WHL/16-WP/2, in that it referred to both an in-trail procedure and a climb-or descent procedure. The reason for this extension was explained in WP/6's *Introduction* as follows. "The sequence of events by which such a climb or descent would be accomplished has typically been called an "in-trail procedure", or ITP. Since mid-2009 this designation has been restricted (at least within the United States Federal Aviation Administration) to a procedure in which both airplanes are using the broadcast mode of automatic dependent surveillance (ADS-B), and the manoeuvring airplane is specially equipped to estimate its relative position and relative speed with respect to the non-maneuvring airplane. A similar procedure, in which the manoeuvring aircraft uses the contract mode of automatic dependent surveillance (ADS-C) to request a

change of flight level, and in which the responsible air traffic controller follows somewhat different rules from those applied to the ITP, is now known as a “climb-or-descent procedure”, or CDP. This report derives a formula for estimating the probability that a collision occurs when an ITP or CDP is executed.” In this Section of this Document, the formula is utilized specifically for the ADS-B CDP procedure.

As set out in Section 7.3.6, *Automatic Dependent Surveillance – Broadcast In Trail Procedure (ADS-B ITP)*, under the *SASP-WG/WHL/17, Montreal, May 2010*, heading, *SASP-WG/WHL/17-WP/6* had been presented by its author to a joint session of SASP Project Team 6 *Longitudinal* and the SASP MSG but would be reviewed in the current Section because, as a successor to *SASP-WG/WHL/15-WP/2* and *SASP-WG/WHL/16-WP/2* it had been concluded to be relevant to the ADS-C CDP procedure rather than the ADS-B ITP procedure. This review is presented below where it is worth noting that the structure and methodology used in *SASP-WG/WHL/17-WP/6* are similar to those used in *SASP-WG/WHL/16-WP/2*, the difference being a revised type of probability density function $f_U(u)$ for the random variable U involving more extensive mathematical operations to obtain the ultimate mathematical collision risk model for the longitudinal collision risk involved in the ADS-C CDPO procedure.

Thus, following an introduction and a description of the scenario modelled in Section 1 of working paper 6, Section 2 of the working paper (*SASP-WG/WHL/17-WP/6*) defined six conditions/events, $E_1, E_2, \dots, E_6$ for longitudinal overlap for an ITP aircraft pair in terms of the basic random variables U and V . Two additional random variables were defined, namely T_b and T_e as the beginning and ending times of the interval in which the aircraft are in a state of longitudinal overlap.

The probability distribution of V was assumed to be Gaussian with mean 0 and variance σ^2 . The probability distribution of the signed distance U between the aircraft at the start of the manoeuvre was specified as follows. Letting m denote the minimum allowable longitudinal separation between aircraft assigned to the same route and flight level, and letting k denote a number strictly between 0 and 1, it was assumed that an ITP might be authorized as long as the longitudinal distance between the aircraft when the manoeuvring aircraft begins its climb or descent is expected to exceed km . Assuming that the responsible controller estimates the longitudinal separation between the aircraft when the manoeuvring aircraft begins its (requested) climb or descent will be between km and m and assuming that an altitude change is allowed when the longitudinal separation exceeds km and authorizes the requested change, one would expect U to be uniformly distributed on $(-m, -km] \cup [km, m)$ if the route system always operated perfectly. However, recognizing that equipment occasionally fails and people sometimes make mistakes, it was assumed more realistically that there was a small probability that the value of U falls in the interval $(-km, km)$. *SASP-WG/WHL/16-WP/2* assumed that all such events typically resulted from blunders, and thus conservatively assumed that when U falls in the interval $(-km, km)$, it is uniformly distributed on that interval. As set out under the previous heading *SASP-WG/WHL/16, Auckland, November 2009* above, the latter assumption was queried at the *SASP-WG/WHL/16* meeting and *SASP-WG/WHL/17-WP/6* revised the assumption as follows. It was assumed that values of U that are slightly greater than $-km$ or slightly less than km result from relatively minor errors in flying or from unexpected variations in atmospheric conditions and that such values of U occur far more often than those that are well within the interior of $(-km, km)$. In order to clearly distinguish between “ordinary” errors and “gross” errors (or “blunders”), let g denote a positive number less than k . Ordinary errors are those for which $-km < U \leq -gm$ or $gm \leq U < km$ and gross errors are those for which $-gm < U < gm$. The probability of a gross error or (“blunder”) was denoted b , $b > 0$, i.e. $b = P(-gm < U < gm)$. It was also assumed that the probability (or relative frequency) of ordinary errors decreases linearly with their magnitude and for the sake of notational convenience a quantity s was defined

as $s = (g - b)/((km - gm) \cdot gm \cdot (2 - k - g))$. Thus, the revised probability density $f_U(u)$ of U was defined by, see Figure 7.19,

$$f_U(u) = \begin{cases} 0 & \text{if } u \leq -m \\ \frac{2g-bg-bk}{2gm(2-k-g)} & \text{if } -m < u \leq -km \\ \frac{b}{2gm} - sgm - su & \text{if } -km < u \leq gm \\ \frac{b}{2gm} & \text{if } -gm < u < gm \\ \frac{b}{2gm} - sgm + su & \text{if } gm \leq u < km \\ \frac{2g-bg-bk}{2gm(2-k-g)} & \text{if } km \leq u < km \\ 0 & \text{if } m \leq u \end{cases} \quad (7.286)$$

To be included

Figure 7.19

Next, Section 3 of the working paper defined conditions for vertical overlap in terms of two more random variables, t_b and t_e , with these random variables denoting the beginning and ending times of the interval in which the aircraft are in a state of vertical overlap.

Section 4 of the working paper examined the probability of simultaneous longitudinal and vertical overlap. It started recalling the subdivision of the set of all possible values of the ordered pair (U, V) into the six events $E_1, E_2, \dots, E_6$ (and an event of measure 0) and noting that a simultaneous longitudinal and vertical overlap can only occur for the events E_2, E_3, E_4 or E_5 . Three ranges of possible values for T_b and T_e in terms of t_b and t_e were then considered, resulting in the definition of six events $C_1, C_2, \dots, C_6$ of simultaneous longitudinal and vertical overlap, after which the probabilities $P(E_i \cap C_j)$, for $i, j = 2, \dots, 5$, were computed. Using the revised probability density function $f_U(u)$ of eq. (7.286), the computations involved considerably more work than their original counterparts of SASP-WG/WHL/16-WP/2. Finally, letting O denote the event that the aircraft pair involved in an in-trail procedure experiences a simultaneous longitudinal and vertical overlap, the probability $P(O)$ of simultaneous overlap was evaluated as

$$P(O) \approx \frac{b}{gm} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.287)$$

where l denotes the length of a typical aircraft involved in an in-trail operation (SASP-WG/WHL/17-WP/6, eq. (3b)). An alternative expression for $P(O)$ was also provided, namely

$$P(O) \approx \frac{b}{gm} \left(l + \frac{2\sigma h}{\sqrt{2\pi}c} \right) \quad (7.288)$$

with h denoting the height of a typical aircraft involved in an in-trail operation and c denoting the absolute value of the manoeuvring aircraft's speed of climb or decent (SASP-WG/WHL/17-WP/6, eq. (3c)).

Section 5 of working paper 6 provided a formula for the probability p_0 of lateral overlap for GNSS-equipped aircraft involved in an ITP operation based on a Gaussian double-exponential probability distribution.

Next, Sections 6, 7, and 8 of working paper 6 calculated the probabilities of collision for the three ways in which collisions can occur, i.e. nose-to-tail collision, $P(C_{NT})$, top-to-bottom collision, $P(C_{TB})$, and side-to-side collision, $P(C_{SS})$, to obtain

$$P(C_{NT}) \approx p_0 \cdot \frac{b\sigma(t_e - t_b)}{\sqrt{2\pi}gm} \quad (7.289)$$

$$P(C_{TB}) \approx p_0 \cdot \frac{bl}{gm} \quad (7.290)$$

$$P(C_{SS}) \approx \frac{2n_0h}{c} \cdot \frac{b}{gm} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.291)$$

In the last formula, the quantity n_0 is defined as $n_0 \approx (p_0 \cdot k_0)/(2w)$ where k_0 (in kts) denotes the average lateral passing speed of aircraft that are assigned to the same route and w denotes the length of a typical aircraft involved in an in-trail operation.

Finally, Section 9 of working paper 6 combined the three probabilities $P(C_{NT})$, $P(C_{TB})$, and $P(C_{SS})$ into the overall probability of collision $P(C)$,

$$P(C) \approx p_0 \left(1 + \frac{k_0h}{cw} \right) P(O) \quad (7.292)$$

(SASP-WG/WHL/17-WP/6, eq. (11b)). The following alternative expression for $P(C)$ was also provided (based on eq. (7.287)):

$$P(C) = p_0 \left(1 + \frac{k_0h}{cw} \right) \frac{b}{gm} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.293)$$

(SASP-WG/WHL/17-WP/6, eq. (11c)).

SASP-WG/WHL/17-WP/6 also made a comparison between the probabilities of collision under the revised model of eq. (7.293) and the original model of eq. (7.285),

$$P(C) = p_0 \left(1 + \frac{k_0h}{cw} \right) \frac{b}{mk} \left(l + \frac{\sigma(t_e - t_b)}{\sqrt{2\pi}} \right) \quad (7.285)$$

and noted that the only apparent difference between the two probabilities is that the symbol k in the denominator of eq. (7.285) had been replaced by the symbol g in the denominator of eq. (7.293). It was thus concluded that the revision of the model through distinguishing between minor longitudinal errors and gross longitudinal errors appeared to have simply increased the collision probability by the factor k/g . This change compensates for the reduction of the blunder interval from $(-km, km)$ to $(-gm, gm)$ i.e., a reduction equivalent to multiplying the length of that interval by the factor k/g . In other words, the derivation compensates for the change in meaning of the symbol b . In the original model of SASP-WG/WHL/16-WP/2, b was defined as the probability of the random variable U taking values in the interval $(-km, km)$ whereas in SASP-WG/WHL/17-WP/6 b was defined as the probability of the random variable U taking values in the interval $(-gm, gm)$. If a blunder does not occur, the probability of a collision is negligibly small. Given that a blunder does occur, the probability of a collision is still a small number under the revised model of SASP-WG/WHL/17-WP/6, but for any fixed value of b , the probability that U takes a value close to 0 in the revised model (i.e., close enough for the speed difference V to yield a significant probability of longitudinal overlap) is k/g times the analogous probability in the original model of SASP-WG/WHL/16-WP/2. In both cases, b

approximates the probability of a “blunder” and for all sets of parameter values for which the approximations give accurate results, the probability of collision varies directly with b and inversely with the length of the blunder interval.

In order to facilitate comparison of an estimate of the longitudinal collision risk associated with the execution of an in-trail procedure with a pertinent target level of safety, the collision probability was converted into an accident rate using estimates of the number of executions of the ADS-C CDP procedure per hour in a given airspace and the airspace’s average instantaneous number of flights.

SASP-WG/WHL/17-WP/6 was presented by its author to a joint session of SASP Project Team 6 *Longitudinal* and the SASP MSG. It was noted that there was not much difference between the originally derived risk estimates and the revised ones. It was commented by one of the attendees that the revised model had not changed in one important aspect, namely that the probability of two aircraft starting an in-trail operation directly above/below each other was still equal to the probabilities for other, less extreme starting positions within the “unacceptable region”, that the revised model did not take sufficient account of the repeated check on aircraft position required by the procedure and consequently overestimated the risk for the scenario in which one aircraft could start an in-trail operation close to above or beneath another aircraft.

Although not referenced explicitly, it is clear from Chapter 3, *SASP Safety Assessment, of Automatic Dependent Surveillance – Contract (ADS-C) Climb and Descend procedure (CDP)* (ICAO Circular 342), that the description of that safety assessment in words is based on SASP-WG/WHL/16-WP/2 and SASP-WG/WHL/17-WP/6 summarized under the previous and current headings respectively. It is remarked for completeness that results of fast-time simulations (see SASP-WG/WHL/23, New Delhi, November 2013 ff.) in support of an ADS-C CDP operational trial (see SASP-WG/WHL/19, Montreal, May 2011 ff.) are also included in the *SASP Safety Assessment* Chapter of ICAO Circular 342.

SASP-WG/WHL/18, Brussels, November 2010

Two working papers dealing with the ADS-C CDP procedure were presented at the eighteenth meeting of the Working Group of the Whole of the SASP. SASP-WG/WHL/18-WP/10 (Horn, 2010) proposed amended wording for PANS-ATM Doc 4444 to provide for the new separation standard of an ADS-C Climb and Descent Procedure (CDP) and was presented to SASP Project Team 6 *Longitudinal*. The paper started noting that the ADS-C CDP is an in-trail procedure that is conducted between aircraft approved for RNP 4 allowing for the transition of one aircraft through another aircraft’s flight level with a 15 NM longitudinal separation minimum under certain conditions. It then provided background information on work performed by the FAA during the years 2008 – 2010 including collision risk modelling and preparation for a planned operational trial with the ADS-C CDP procedure in the Oakland FIR. The paper included a table with estimates of the longitudinal collision risk associated with the procedure in the Oakland FIR based on the revised collision risk model of SASP-WG/WHL/17-WP/6. All estimates were less than 5×10^{-9} fatal accidents per flight hour. Proposed wording for Doc 4444 was provided in Appendix C to the working paper.

SASP Project Team 6 *Longitudinal* raised a number of questions and comments of an operational and/or technical nature concerning the procedure, which, it was agreed, would only be able to be answered completely after a report on the results of the trial would be presented at the next meeting.

SASP-WG/WHL/18-WP/17 (Flax, 2010b) presented a sequential sampling test that might be applied to determine, to an established level of confidence, whether an air navigation service provider’s use of the ADS-C CDP procedure meets a given target level of safety. The working paper was presented to a joint session of SASP Project Team 6 *Longitudinal* and the SASP MSG. Although the working paper assumed that the

procedure would be applied between RNP 4 approved aircraft, the Project Team agreed that the ADS-C CDP procedure might be applied between any two aircraft no matter what navigation specification, as long as ADS-C position reports were provided by means of GNSS. Sequential sampling is a known statistical technique to test e.g. whether a system meets a specified level of safety or not. Application of the sequential sampling technique to the safety assessment of the 60 NM MNPS lateral separation standard has been alluded to in Section 5.3.3 (Brooker, 1979; Moek & Traas, 1979) and application to the safety assessment of RVSM in the vertical dimension in Section 6.4.3.3 (NAT, 1996). Since the sequential sampling technique is not directly related to aircraft collision risk modelling, it will not be discussed further here.

Following the presentation of the Project Team 6 *Longitudinal* report to the plenary at the SASP-WG-WHL/18 Meeting, the question was asked whether it was intended that SASP develop an Operation Requirement (OR) for the SASP MSG to conduct a safety assessment for the ADS-C CDP operational trial. It was concluded that this was too early yet, but it was agreed that the MSG would review and develop an OR as work progresses at the FAA.

SASP-WG/WHL/19, Montreal, May 2011

In response to a question asked at the previous Meeting of the SASP, SASP-WG/WHL/19-WP/21 (Horn, 2011a) specified an operational requirement (OR 28) for the MSG to:

- a) Determine the parameters for the ADS-C CDP that would enable the following separation minima:
 - 1) 15 NM for same speed or faster in front;
 - 2) 25 NM for M.02 or 10 knots faster behind;
- b) Explore the effect on the separation minimum of varying various constraints; and
- c) For aircraft on the same identical track, explore how much the longitudinal separation minimum specified above can be reduced if a lateral offset of a various distance is applied between the two aircraft (for example, what would the longitudinal separation minimum above be if the aircraft had a lateral separation of 5 NM?).

OR 28 was added as a high priority item to the SASP MSG's task list.

SASP Project Team 6 *Longitudinal* was informed that the FAA had begun conducting trials of the ADS-C CDP during the first quarter of 2011, however to date only four ADS-C CDPs had been conducted. It was expected that in other airspaces with higher traffic loads, such as the NAT, there might be higher opportunity to capture aircraft pairs with 15 – 30 NM longitudinal separation.

SASP-WG/1, Cairns, November 2011

A single working paper only dealing with the ADS-C CDP procedure was presented at the first meeting of the Working Group of the SASP. SASP-WG/1-WP/09 (Horn, 2011b) provided an update to the U.S. FAA development of an ADS-C CDP and the ongoing operational trials. During the initial operational trial from 15 February 2011 to 16 May 2011, only four ADS-C CDPs had been conducted (cf. the previous paragraph). Some details of the four ADS-C CDPs were provided in the working paper. Given the limited number of ADS-C CDPs recorded initially, the operational trial had been extended for an additional nine (9) months to conclude on 16 February 2012. (It would later be extended to February 15, 2013.)

A revision to the proposed additional wording for Doc 4444 presented at the previous Meeting SASP-WG/WHL/19-WP/21 was provided in Appendix A to the working paper and a first draft Circular for the ADS-C CDP procedure was provided in Appendix B.

The working paper was presented to SASP Project Team 6 *Longitudinal*, which was subsequently informed that some States represented at the Informal South Pacific ATS Coordinating Group (ISPACG) were intending a trial of ADS-C CDP after completion of the ADS-B ITP operational trial. It was suggested that possibly Australia might assist with undertaking simulation using fast-time applications and that also the ADS-B ITP simulations performed by NASA might be of use in providing further analysis, given the similarities with the ADS-C CDP. The Project Team spent some time reviewing the ADS-C CDP amendment proposal with the intent to align the wording to that in the ADS-B ITP amendment proposal to the extent possible. It also performed a high level review of the first draft Circular, the author of which agreed to provide a new version at SASP's next Meeting.

SASP-WG/WHL/20, Montreal, May 2012

A single information paper only dealing with the ADS-C CDP procedure was provided at the twentieth Meeting of the Working Group of the Whole of the SASP, viz. SASP-WG/WHL/20-IP/07 (Horn, 2012). It provided another update to the U.S. FAA development of an ADS-C CDP and the ongoing operational trials, noting in particular that many operators seemed to be still unaware of the opportunity for ADS-C CDP based on the inclusion of appropriate equipment identifiers and remarks in the flight plan. As a result, FAA Flight Standards had initiated a telephone information campaign and contacted most U.S. carriers. Some foreign carriers were also contacted. Some data was included on aircraft equipage for flights requesting altitude change for the month of April 2011. The information paper concluded from this data that there was potential to apply the ADS-C CDP procedure more frequently. The latest draft proposed amendment wording for Doc 4444 was also included in the information paper and it was stated that no further work had been done on the draft ADS-C CDP Circular.

SASP-WG/WHL/20-IP/07 was provided for information only, i.e. it was neither presented nor reviewed/discussed during the Meeting.

SASP-WG/WHL/21, Seattle, November 2012

There were not any papers on the ADS-C CDP procedure. A table of the current work programme of the SASP in SASP-WG/WHL/21-WP/09 (SASP Secretary, 2012b) referred to ongoing NAT and FAA Pacific ADS-C CDP trials.

SASP-WG/WHL/22, Montreal, May 2013

A single working paper, SASP-WG/WHL/22-WP/13 (Horn, 2013b), providing another update on the status of the U.S. FAA development of an ADS-C CDP was provided at this Meeting. The working paper noted that the ADS-C CDP operational trial had been terminated on 15 February 2013 due to lack of the FAA oceanic flight data processing system (FDPS) (Ocean 21) automation and concerns about controller risk in conducting the procedure. Funding was subsequently procured to automate the procedure with a projected initial operating capability (IOC) date of September 2015. The simulation platform had been built but parameters were still being adjusted. In order to implement the software changes and meet the IOC date, ICAO approval of the ADS-C CDP was required. Consequently, the United States would like to aggressively progress work on the proposed amendment to ICAO Doc 4444 and the Circular with the goal to finalize the SASP work at its May 2014 Meeting.

The working paper was presented to SASP Project Team 6 *Longitudinal*, which supported the paper's proposed action, where it was emphasized that it was important that the automation would support application to require Global Navigation Satellite System (GNSS), ADS-C, and Controller Pilot Data Link Communications (CPDLC) equipped aircraft and not be limited to RNP 4 aircraft pairs.

SASP-WG/WHL/23, New Delhi, November 2013

Two working papers dealing with the ADS-C CDP procedure were presented at the twenty-third Meeting of the Working Group of the Whole of the SASP with one paper SASP-WG/WHL/23-WP/08 (Horn, 2013a) providing again an update on the status of the ADS-C CDP development and the other SASP-WG/WHL/23-WP/23 (Falk & Baart, 2013) presenting some fast-time simulation results in support of the ADS-C CDP development. Both papers were presented to SASP Project Team 6 *Longitudinal*, where the SASP MSG also attended the presentation of the fast-time-simulation-results paper.

SASP-WG/WHL/23-WP/08 (Horn, 2013a) reported that a total of eight ADS-C CDPs had been successfully utilized during the two-year operational trial period from February 15, 2011 to February 15, 2013 and that the (manual) trial had met its objectives. It also referred to fast-time simulations being conducted at the time. The working paper provided an updated draft Circular at its Appendix A and a draft proposal for amendment to ICAO Doc 4444 at its Appendix B. Chapter 3 of the Circular, *SASP Safety Assessment*, was still to be provided.

Following the presentation of and extensive discussion on the working paper, Project Team 6 achieved consensus on a basis for a PANS-ATM amendment proposal that would account for all communication, navigation and surveillance (CNS) conditions as well as emphasis on the requirement for the procedure to be executed using air navigation service providers (ANSPs) flight data processing systems to perform distance calculations. This achievement was considered the primary goal for advancement of ADS-C CDP at the meeting. In addition, there was discussion of position accuracy and figure of merit (FOM) reports in ADS-C messages and the ability of States and ANSPs to assume such based solely on what is filed in ICAO flight plans. Extensive work was also performed by Project Team 6 on the global hazard log for ADS-C CDP in the ADS-C CDP Circular, where many elements were agreed upon and further work on some hazards was identified for the author of the working paper. The planned action going forward was agreed upon where the goal was for final SASP approval of the ADS-C CDP Circular and Impact Statement to be completed at the November 2014 Meeting to allow its presentation for approval by the ANC and for amendment of Doc 4444 in 2016.

SASP-WG/WHL/23-WP/23 (Falk & Baart, 2013) provided a description of the fast-time simulation model used to examine the ADS-C CDP procedure and was presented to a joint session of SASP Project Team 6 *Longitudinal* and the SASP MSG. Since the subject of fast-time simulation is beyond the scope of this Document and the *Summary of Discussions* on the Meeting does not list any details of the presentation and discussion of the working paper, it will not be discussed further here.

SASP-WG/WHL/24, Montreal, May 2014

At this Meeting also, two working papers dealing with the ADS-C CDP procedure were presented with one paper WP/23 (Horn, 2014b) again providing an update on the status of the ADS-C CDP development and the other WP/24 (Falk & Baart, 2014) presenting some fast-time simulation results in support of the ADS-C CDP development. Both papers were presented to SASP Project Team 6 *Longitudinal*.

SASP-WG/WHL/24-WP/23 (Horn, 2014b) provided the latest versions of the draft ADS-C CDP Circular and proposal for amendment to ICAO Doc 4444 at its Appendices A and B respectively. A major update of the Circular concerned its Chapter 3, *SASP Safety Assessment*, for which now text was available. This text started referring to the collision risk model developed for the ADS-C CDP procedure in SASP-WG/WHL/16-WP/2 and SASP-WG/WHL/17-WP/6 as well as to the sequential sampling test developed in SASP-WG/WHL/18-WP/17. SASP-WG/WHL/23-WP/08 (Falk & Baart, 2013) describing fast-time simulations for the benefit of the ADS-C

CDP procedure development was also listed at the working paper's beginning. Summaries of the four references were then given in the remainder of Chapter 3 of the Circular. Considerable time and effort were spent by Project Team 6 with some input from the SASP MSG to further refine the Circular, which was consequently considered nearing a final draft state. It was agreed to circulate a clean copy of the Circular, encompassing the work contributed at the meeting, for editorial review by the Project Team 6, where this review would be carried out post meeting and was expected to facilitate a final review of the ADS-C CDP Circular at SASP's next Meeting in November 2014.

SASP-WG/WHL/24-WP/24 (Falk & Baart, 2014) provided updated details of the description of the fast-time simulation model used to examine the ADS-C CDP procedure of SASP-WG/WHL/23-WP/08. As explained before, the subject of fast-time simulation is beyond the scope of this Document and the working paper will not be discussed further here.

SASP-WG/25, Sydney, November 2014

The last update on the status of the ADS-C CDP procedure was provided at the 25th Meeting of the Working Group of the Whole of the SASP in working paper SASP-WG/WHL/25-WP/31 (Horn, 2014a). The paper recalled from SASP's previous Meeting that the then draft ADS-C CDP Circular had been concluded nearing a final draft state and noted that coordination on the draft Circular had been carried out since that last Meeting. The current working paper provided the final draft ADS-C Circular and Amendment to ICAO Doc 4444 in the Appendices A and B to it. The Meeting conducted a final review of the PANS-ATM proposal for amendment, the ADS-C CDP Circular, and the Impact assessment and concluded that all work had been completed and that the separation standard was ready for presentation to the ANC for approval. It was anticipated that, pending approval, the standard would be applicable in November 2016.

Conclusion

Following the State Letter process for the ADS-C CDP procedure, the procedure was approved by the ICAO ANC for inclusion into 16th edition of the PANS-ATM under Amendment 7-A to the 15th edition, to become applicable on 10 November 2016. See also the ICAO ADS-CDP Circular 342.

7.3.8 ASEPS longitudinal separation minima

Recall from Section 7.2.8 that Advanced Surveillance-Enhanced Procedural Separation (ASEPS)¹²⁹ was described as oceanic separation where position surveillance reporting of order 2 – 60 seconds is available and that it was noted that current technologies that may support ASEPS include space-based ADS-B. A first batch of 10 Iridium NEXT satellites carrying Aireon's ADS-B receiver payloads was launched on 14th January 2017 (Mark, 2017). (ICAO, 2020a) provides guidelines and supporting material for the implementation of ASEPS-based separation minima. Appendices D and E to this reference deal with lateral collision risk modelling for parallel and intersecting routes respectively and were utilized in Section 5.4.4 to present the ASEPS collision risk models for lateral separation on such routes. Appendix C to (ICAO, 2020a) deals with longitudinal collision risk modelling for ASEPS separation minima and will be reviewed in this Section. In the same manner as in Section 5.4.4, it will be assumed that all aircraft operating in airspace where ASEPS longitudinal separation minima apply, meet the performance-based communication and surveillance

¹²⁹ The ASEPS acronym originated at the 28th Meeting of the SASP Working Group, Reykjavik, Iceland, May 2016.

standards RCP 240 and RSP 180, where the numbers in these acronyms denote maximum tolerable times for communication and position reporting in minutes. Unlike the (completely new) ASEPS lateral collision risk model, the form of the ASEPS longitudinal collision risk model was basically the same as that described in Sections 7.3.2 – 7.3.4. A brief discussion of the work performed by the SASP on ASEPS longitudinal separation minima is provided by meeting below.

SASP-WG/25, Sydney, November 2014

SASP-WG/25-WP/11 (Butcher & Dwyer, 2014) provides background on SASP work related to the development of space-based automatic dependent surveillance – broadcast (SADS-B). It begins recalling Recommendation 1/9 – *Space-based automatic dependent surveillance – broadcast* from the ICAO 12th Air Navigation Conference which took place at ICAO Headquarters in Montreal Canada from 19 to 30 November 2012, with the Recommendation reading as follows:

- a) Support the inclusion in the Global Air Navigation Plan, development and adoption of space-based automatic dependent surveillance – broadcast surveillance as a surveillance enabler;
- b) Develop Standards and Recommended Practices and guidance material to support space-based automatic dependent surveillance – broadcast as appropriate; and
- c) Facilitate needed interactions among stakeholders, if necessary, to support this technology.

It proceeds setting out that subsequent to the 24th Meeting of the SASP in May 2014, a consultative team, including SASP members and advisors from Canada, the United Kingdom, and Australia, has been established between NAV CANADA, UK NATS, and Airservices Australia to develop proposals that define possible ADS-B based separation minima using space-based technology. The team acknowledged that, given the nature of the proposals and the role of the SASP in developing globally applicable separation minima, progressing the work through SASP for publication in Doc 4444 was of prime importance. The consultative team agreed that to initiate this work, modelling proposals should be drafted for the Panel's consideration at its 25th meeting, and if agreed, a *Job Card* should be prepared for transmission to the ANC for endorsement. The team was well aware that significant inter-panel coordination will be required throughout the execution of the pertinent work

As first steps in developing such separation minima, SASP-WG/25-WP/11 then presented modelling that proposed to adapt the conventional longitudinal collision risk model for the 30 NM longitudinal separation standard for RNP 4 aircraft based on ADS, cf. Sections 7.3.3 and 7.3.4.1, to accommodate communication and surveillance parameters expected to be available from new space-based ADS-B technology. The main features of the new, adapted model were a reduction in the ATC-pilot response time T and a reduction in the reporting time τ . These times were introduced in Section 7.3.2 and also utilized in Sections 7.3.3 and 7.3.4.1. Speed estimation errors were also expected to be able to be reduced.

The working paper considered two geometries, namely same identical track and same track, [1 – 45] degrees. Although details of the mathematical collision risk model used were not shown, rather the reader was referred to SASP-WG/A-WP/21, SASP-WG/A/2-WP/17, SASP-WG/WHL/4-WP/9 SASP-WG/WHL/7-WP/20, together with SASP-WGH/24-WP/08, some of the main parameters of the model were summarized, including the speed estimation error and the number of aircraft pairs parameters, and a discussion was provided of the Required Surveillance Performance (RSP) and the Required Communication Performance (RCP). The model used in SASP-WG/25-WP/11 is that described in this Document by eqs. (7.212) – (7.214) based on (Anderson, 2005). The final model to be developed for SADS-B (ASEPS) will be presented under the last, SASP-VWG/1, heading of this Section. It should be noted that SASP-WGH/24-WP/08 concerns longitudinal collision

risk modelling for oceanic RNP 2 and RNP 4 collision risk calculations and will be briefly examined in Section 7.3.9.

Future work was identified as including extended ranges of parameters, defining a fault-tree analysis and reassessing the human factors aspects associated with RCP, assessing the appropriate speed error distributions, defining an appropriate *Job Card*, completing the modelling, and developing a circular.

The working paper concluded that preliminary results indicated that:

1. a 15 NM separation standard is possible with a collision risk model based on space-based ADS-B technology while not possible with the original model;
2. a 20 NM separation standard is possible with a collision risk model based on space-based ADS-B technology while not reliably feasible with the original model;
3. managed offsets of 0.5 NM will allow further risk reductions; and
4. the risk is considerably lower for angles > 1 degree.

SASP-WG/25-WP/11 was presented to the SASP plenary, after which detailed discussion took place on various aspects of the model being proposed. The Meeting agreed that the work should be progressed by SASP. A Job Card (*Job Card 11*) was drafted at and reviewed by the Meeting and the Secretary was tasked to coordinate the card with the ANC at the earliest opportunity for incorporation of the work into the SASP work programme.

SASP-WG/26, Montreal, May 2015

Two working papers dealing directly with longitudinal separation for space-based ADS-B systems were presented at the twenty-sixth Meeting of the Working Group of the SASP, one of which, SASP-WG/26-WP/15 (Dwyer, 2015), proposed draft Operational Requirements (ORs) for the safety assessment work to be performed by the SASP MSG and the other, SASP-WG/26-WP/7 (Butcher & Dwyer, 2015c), continued SASP-WG/25-WP/11 (Butcher & Dwyer, 2014) with the modifications needed for longitudinal collision risk models if space-based ADS-B systems are to be used. Three more working papers dealt indirectly with the subject, i.e. considered specific elements related to the model development.

Based on *Job Card 11* produced at the previous meeting, SASP-WG/26-WP/15 specified two ORs as follows:

- *OR37: Separation minima for eligible aircraft operating in airspace where ADS-B service is provided but VHF voice is not available.*

The SASP MSG is requested to:

- a) *Determine the lateral separation minima by which suitably approved aircraft can operate on both intersecting tracks or ATS routes and on parallel or non-intersecting tracks or ATS routes; and*
 - b) *Determine the longitudinal separation minima by which suitably approved aircraft can be separated for same, crossing and reciprocal tracks using actual navigation performance data.*
- *OR38: Separation minima for eligible aircraft operating in ATS Surveillance airspace where ADS-B service is provided and communications are provided by media other than VHF voice.*

The SASP MSG is requested to:

Determine the minimum by which suitably approved and ATS Surveillance System identified aircraft can be separated in relation to the centres of the respective position symbols, where ADS-B surveillance is provided and communications are provided by media other than VHF voice.

Notice the difference in scope of the two ORs. OR37 pertains to current practices for oceanic longitudinal and lateral separations, whereas OR38 pertains to a new concept of providing ATS services in oceanic airspace, i.e. radar-like ATS surveillance separation. A PowerPoint presentation of the Meeting Report to the

ANC showed a proposed date of 2018 publication for the former type of separation minima in Doc 4444 and of 2020 publication for the latter. Work on longitudinal separation minima pertaining to OR37 had already started at SASP's previous Meeting and continued on up to the 2nd Panel Meeting of the SASP (SASP/2) in May 2018. Work on lateral separation minima pertaining to OR37 was first presented at SASP's next Meeting, SASP-WG/27, in November 2015, and also continued on up to the 2nd Panel Meeting of the SASP. It should be noted that a PANS-ATM amendment proposal for ASEPS longitudinal and lateral separation was agreed at SASP/2, but that work on the accompanying Circular continued up to December 2019.

The working paper was presented to the SASP plenary after which extensive discussion took place. Updated versions of the two ORs were then produced by the author of the working paper, taking account of the points raised during the discussion. The Meeting confirmed that, due to the different allocations for CPDLC and satellite voice, modelling outcomes should be derived both with and without the availability of satellite voice communications. Also, due to the (then) current widespread availability of FANS, modelling outcomes should also be derived with and without the presence of ADS-C service in the area of applicability.

SASP-WG/26-WP/7 built on SASP-WG/25-WP/11 but considered same identical track only since previous studies had shown that the case of angle zero degrees gave the largest risk. Otherwise, the structure of the current working paper was similar to that of its predecessor (e.g. it did not show details of the mathematical collision risk model (i.e. eqs. (7.212) – (7.214) based on (Anderson, 2005))). The paper was presented to both SASP Project Team 6 *Longitudinal* and the SASP MSG.

The working paper was aimed at estimating the longitudinal collision risk for space-based ADS-B systems and a longitudinal separation minimum of $S_x = 10$ NM (rather than $S_x = 20$ NM as in SASP-WG/25-WP/11). It included schematic diagrams of original as well as modified CPDLC/HF communication performance. Future work was identified as defining an appropriate Job Card (covered by SASP-WG/26-WP/15), and completing the modelling work and developing a Circular.

The working paper concluded that its work indicated that:

1. a 10 NM separation standard is possible with a collision risk model based on space-based ADS-B technology for a wide range of parameters including reporting times up to 5 minutes;
2. a 9 NM separation standard may be possible with a collision risk model based on space-based ADS-B technology with greater restrictions including the need for assigned offset, SLOP, lower reporting times and/or monitoring;
3. an 8 NM separation standard *may* be possible with a collision risk model based on space-based ADS-B technology but the modelling here suggests that such a standard is too sensitive to the underlying modelled parameters and hence may not be justified;
4. separation standards in the range 9-10 NM are not strongly influenced by the choice of RCP or the different options for primary, secondary or even tertiary communication options; and
5. separation standards are not adversely affected by ADS-B reliability of 95% or better.

SASP-WG/27, Oklahoma, November 2015

Three working papers dealing directly with longitudinal (and lateral) separation for space-based ADS-B (SADS-B) systems were presented at the twenty-seventh Meeting of the Working Group of the SASP, namely SASP-WG/27-WP/16 (Butcher & Dwyer, 2015a), SASP-WG/27-WP/8 (Butcher & Dwyer, 2015b), and SASP-WG/27-WP/7 (Barry, 2015). The third paper dealt with lateral separation for space-based ADS-B systems and is mentioned here only for completeness. It marked the first work on lateral separation for space-based ADS-B. Subsequent SASP working papers on lateral separation for space-based ADS-B systems are listed in (ICAO, 2020a), see Section 5.4.4, and will not be referenced in the remainder of this longitudinal section.

SASP-WG/27-WP/16 presented a draft Circular for SADS-B, comprising essentially an Introduction (Chapter 1) and a draft description of SADS-B (Chapter 2). The Working Group performed some work on the draft Circular concerning the proposed PANS-ATM amendment as well as the Hazard Section. Some brainstorming to identify hazards that may be either or not unique to space-based ADS-B separation was done. Two hazards that were discussed in some depth were the requirement for pilots to conduct weather deviations without an ATC clearance using Pilot in Command emergency authority and how currently published contingency procedures fit the new proposed separation minima. Different capabilities of monitoring systems were also discussed. The review of the draft Circular resulted in a number of actions on all or individual members of the Working Group¹³⁰.

SASP-WG/27-WP/8 was a refinement of SASP-WG/26-WP/7, which in turn continued SASP-WG/25-WP/11 with the modifications needed for longitudinal collision risk models if space-based ADS-B systems are to be used. The refinement concerned consideration of five different cases, each with multiple communication scenarios. The working paper reached the same conclusions as its predecessor as described under the previous *SASP-WG/26, Montreal, May 2015* heading. Some points raised during the discussion on the working paper concerned the effect of potentially increased speed variations for aircraft on intersecting tracks due to the aircraft experiencing different winds, the possibility of ADS-C not always being available if ADS-B fails, the value of the speed error parameter, and whether, or not, some of the language in the PANS-ATM might need to be changed to reflect the various communication methods explored in the working paper. A revised version of the working paper would take the various points into account.

About seven more working papers dealt indirectly with the subject by considering specific elements of the development of the longitudinal collision risk model for space-based ADS-B, such as a simplified same-identical track model, speed error modelling in the simplified same-identical track model, assessment of intervention and response times using required and actual communications and surveillance performance in a space-based ADS-B environment, modelling of speed variation, a fast version of the Anderson-Hsu collision risk model (i.e. the general collision risk model based on reliability theory (Anderson, 2005)), RCP, an overview of the FAA's Surveillance and Broadcast Services Program Office efforts in support of oceanic operations, longitudinal CRM for short reporting periods, and distance versus time separations.

Last but not least, as a result of a plenary review of the status of the ORs for the MSG, OR37 specified at the SASP's previous Meeting was reviewed in detail and broadened to include HF 3rd party voice as a primary means in some scenarios. It was also amended by the creation of a table outlining seven scenarios of interest that could result from the various combinations of communication and surveillance media and navigation specifications available in a space-based ADS-B environment.

SASP-WG/28, Reykjavik, May 2016

Three working papers dealing directly with (longitudinal) separation for space-based ADS-B (SADS-B) systems are briefly discussed below, namely SASP-WG/28-WP/32 (Butcher & Dwyer, 2016b), SASP-WG/28-WP/36 (Barry, 2016c), and SASP-WG/28-WP/37 (Walton, 2016).

SASP-WG/28-WP/32 (Butcher & Dwyer, 2016b) presented the latest version of the Circular to support the work of the SASP on developing horizontal separation minima for space-based ADS-B, based on work progressed between SASP Meetings. The main changes concerned the *SASP Safety Assessment* Chapter to

¹³⁰ The Circular for space-based ADS-B provides guidelines for the implementation of both lateral and longitudinal separation but will be considered in this Section from the perspective of longitudinal separation only.

which some text had been added as well as a detailed table of contents for the Chapter, and the Circular's Attachment B, *Implementation Hazard Log*, to which a number of hazards had been added and analysed. However, the Meeting concluded that the working paper should be deferred to the next SASP Meeting, pending the completion of various actions defined during the Working Group's current Meeting.

SASP-WG/28-WP/36 (Barry, 2016c) (and some other working papers not referenced here) utilized the acronym ASEPS, Advanced Surveillance Enhanced Procedural Separation, for space-based ADS-B separation standards where the periodic reporting interval will be of the order of 15 seconds (or 0.25 minutes). The MSG had unofficially adopted this acronym for such standards instead of associating them directly with the technology specific space-based ADS-B. Working paper 36 built on the earlier work presented to the SASP in references SASP-WG/25-WP/11, SASP-WG26-WP/7 and SASP-WG/27-WP/8. Like the last two references, it considered same-identical traffic only. It used the (surveillance and) communication models from SASP-WG/28-WP/18 (Barry, Civil, et al., 2016a). The working paper presented results for FANS-equipped aircraft and non-FANS aircraft separately and concluded that the results appeared to support two separation standards for FANS-equipped aircraft:

- An initial ASEPS separation standard of 14 NM; and
- A lower ASEPS standard of 10 NM achievable if certain monitoring conditions are met.

For non-FANS aircraft the two standards might be (with further analysis required):

- An initial ASEPS separation standard of 25 NM; and
- A lower ASEPS standard of 14 NM achievable if certain monitoring conditions are met.

Monitoring conditions would be defined in a future component of current en-route monitoring documentation.

The paper was presented to the SASP plenary and was also discussed by the MSG who were satisfied with the working paper's assumptions and results, given the well-known form of the collision risk model (i.e. the general collision risk model based on reliability theory (Anderson, 2005)) and the fact that the MSG had analysed a lot of papers and data from different sources on the subject. The MSG proposed the 14 NM longitudinal separation standard for an ADS-B reporting rate of 15 seconds, stating that it was massively conservative (by about 6 NM). For non-FANS aircraft using HF voice for position reporting the MSG proposed a 25 NM longitudinal separation standard, which was also conservative by a large factor. The MSG also stated that there was possibility in the future to further reduce the proposed standards when enough operational data had been collected. The MSG results were discussed by the plenary. The conclusion of the plenary discussion was that there was no consensus in the Group at the time to accept the new separation minima without an operational assessment of the result of the collision risk modelling. Therefore, an action was placed on SASP members to perform such an assessment. Nevertheless, preparations for the necessary documentation changes would continue.

SASP-WG/28-WP/37 (Walton, 2016) identified a number of safety issues associated with the use of reduced horizontal separation (RHS) associated with space-based ADS-B (SBA), namely, (un)availability of performance or reliability data of the SBA network, gaps in the global coverage of the SBA network, absence of intent information in SBA reports, different types of ADS-B avionics, absence of large deviation event functionality in SBA reports, effect of RHS on weather deviation clearances and contingency events, and effect of RHS on usage of reduced SLOP in tenth of a mile. The Meeting discussed that all but one of the issues were being addressed by SASP's work, the exception being the issue of different types of ADS-B avionics, which was agreed to be an implementation issue.

A number of other working papers dealt indirectly with longitudinal ASEPS separation by considering specific elements of the development of the ASEPS longitudinal collision risk model, such as weather deviations and emergency events, speed error modelling using ADS-B and ADS-C data, position prediction and speed error, and paired dependent speed error from ADS-C data.

The meeting documentation also lists a flimsy proposing a third revision to OR37, but the *Summary of Discussions* of the Meeting does not provide any reference to it.

SASP/1, Montreal, November 2016

There were four key working papers on ASEPS longitudinal separation at the First Meeting of the Separation and Airspace Safety Panel (SASP), namely SASP/1-WP/21 (Butcher & Dwyer, 2016a), SASP/1-WP/10 (Barry, Butcher, et al., 2016), SASP/1-WP/8 (Barry, 2016a), and SASP/1-WP/18 (Barry, 2016b). SASP/1-WP/21 presented the latest update to the Circular, of which the title had been changed in favour of ASEPS separation minima rather than separation for space-based ADS-B. The update involved some changes in Chapter 2, *Space-based Automatic Dependent Surveillance – Broadcast (SADS-B)* and first draft text for the Circular's Chapter 3, *SASP Safety Assessment*, provided separately in SASP/1-WP/10. SASP/1-WP/8 and SASP/1-WP/18 dealt with ASEPS longitudinal separation standards for reciprocal and crossing traffic respectively.

A number of other working papers presented details of various elements of ASEPS longitudinal separation, including another look at analyses dealing with ASEPs, human in the loop experiments, analysis of US weather deviation data from the Pacific and the NAT, ADS-C reporting interval, human in the loop simulations in Gander, hazards 15 NM separation, communication and controller intervention buffer in the collision risk model, and controller intervention. There was also a flimsy advocating the incorporation of the impact of the use of contingency and weather deviation procedures into the ASEPS collision risk modelling and two flimsies advocating the use of more technology neutral wording in SASP/1-WP/21 and SASP/1-WP/10.

Discussion took place by Agenda Item, e.g. *Agenda Item 2: En-route separation minima and procedures – Horizontal*, and then by Job Card, e.g. *Job Card 11.02 SADS-B*, rather than by Project Team or MSG. There were a total of 19 working papers, information papers and flimsies related to *Job Card 11.02 SADS-B* and the aim was to progress the work into an agreed PANS-ATM amendment and Circular. However, two flimsies referenced in the previous paragraph and the draft Circular of SASP/1-WP/21 were not presented because they were overtaken by events at the Meeting and a new version of the Circular would be drafted for the next Meeting.

The discussion on the first draft text for the Circular's Chapter 3, *SASP Safety Assessment*, provided in SASP/1-WP/10 started with ASEPS longitudinal separation and continued with ASEPS lateral separation, where only the longitudinal separation part needs to be summarized here. Section 3.14 of the Circular derived the collision risk model for longitudinal collision risk over a time interval $[t_0, t_1]$ based on SASP-WG/WHL/4-WP/9 and SASP-WG/WHL/7-WP/20 (revised), i.e. essentially eqs. (7.212) – (7.214) without the integration over time. As indicated before, the ultimate form will be presented under the last, SASP-VWG/1, heading of this Section. The main items of concern in the collision risk model calculations were highlighted and the consequent changes proposed by the MSG were detailed. It was decided to remove from the draft Circular all information concerning separation standards that employed HF voice as a primary means of communication, the reasons for this being that performance numbers for it were not established well enough and there being chances that communication outages will affect both aircraft in a potential conflict. Another main issue identified concerned extra airspace monitoring requirements in addition to the standard RCP240 requirements. Following clarification provided, the Meeting agreed that the additional requirements would

be documented in the Circular in the section that specifies all parameters that needed to be monitored in airspaces where ASEPS is applied. The communication model used in the ASEPS longitudinal collision risk model was subsequently detailed to the Working Group. It was also agreed that the ASEPS longitudinal collision risk model for opposite-direction traffic needed to be re-worked under revised operational specifications, the reason being that the scenario assumed in SASP/1-WP/8 (Barry, 2016a) was that a controller would be issuing a conditional climb/descent clearance before the opposite direction aircraft passed. It was explained to the Meeting that this assumption would not be an operationally acceptable method, rather a controller would not issue the climb/descent clearance until after it had been established that the aircraft had passed each other in opposite directions.

SASP/1-WP/18 (Barry, 2016b) dealt with ASEPS longitudinal separation standards for crossing traffic, i.e. intersection angles up to 90°, based on the general collision risk model of SASP-WG/WHL/4-WP/9 and SASP-WG/WHL/7-WP/20 (revised). The paper's *Discussion* Section stated that the risk for crossing traffic was lower than for aircraft on same-identical tracks and that it was well below a target level of safety of 5×10^{-9} fatal accidents per flight hour for a separation standard of 12 NM. The MSG initially agreed with the first part of the statement but during a later discussion concluded that further work on this was necessary for a variety of reasons, including the possible differences between the speeds of the aircraft. The paper announced that further work would be done to demonstrate more of the risk behaviour for crossing traffic for, presumably, different parameter values. The need for additional work was also established by the MSG concerning the incorporation of the effect on the calculations of the use of SLOP and verification of the use of RNP 4. The MSG review also considered the possible aircraft speed variations and their effect on the distance between aircraft and concerns regarding the ADS-B quality indicators and the need for a requirement to revert to a different separation standard if the indicators are not satisfactory.

SASP-WG/29, Vienna, May 2017

There were two working papers dealing directly with collision risk modelling for ASEPS longitudinal separation minima, namely SASP-WG/29-WP/20 (Barry, 2017c) and SASP-WG/29-WP/26 (Barry, 2017d). SASP-WG/29-WP/20¹³¹ provided an update to the text of the ASEPS Circular's Chapter 3, *SASP Safety Assessment* and SASP-WG/29-WP/26 dealt with aircraft climbing or descending through the path of on-coming traffic as part of reciprocal ASEPS. There was no working paper on ASEPS longitudinal collision risk modelling for crossing traffic.

A number of other working (and information) papers dealt more indirectly with collision risk modelling for ASEPS longitudinal separation minima by presenting details of various elements of ASEPS longitudinal separation, including controller reaction times, ASEPS variables affecting the modelling of crossing courses risk calculation, an estimate of collision probability on crossing courses, response time in an Australian ASEPS-like airspace, further discussion on communications within ASEPS collision risk modelling, analysis of known surveillance outages on ASEPS separation standards, discussion on data collected for RCP and impact on collision risk model, communication performance for ASEPS, performance of space-based ADS-B reception, and RSP within ASEPS.

Discussion took again place by Agenda Item and then by Job Card, e.g. *Job Card 11.02 SADS-B*, rather than by Project Team or MSG. The work on this Job Card was started by reviewing the roadmap towards a 2020 PANS-ATM publication of the new separation minima. The roadmap indicated that any amendment proposal would need to be "99%" finished by the end of the SASP May 2018 Meeting and only requiring final touches at the

¹³¹ The title of this working paper is in error. A more descriptive title would be *ASEPS Circular: Chapter 3 – Mathematical methods*.

November 2018 meeting. This effectively meant that the group needed to come to an agreement on all major issues concerning collision model assumptions at the current meeting to give room for document review and drafting at the November 2017 meeting. The Working Group was then reminded that the major milestones remaining in the development process were:

- a) The MSG coming to an agreement on the mathematical aspects of the ASEPS collision risk modeling;
- b) The Panel coming to an agreement on the assumptions fed into the collision risk model; and
- c) PANS-ATM amendment and Circular drafting.

As regards the latest draft of Chapter 3, *SASP Safety Assessment*, of the ASEPS Circular of SASP-WG/29-WP/20 (Barry, 2017c), it stated that it differed from its previous version of SASP/1-WP/10, in that it:

1. Updated the communication model to include an extra allowance for the 50% communication level;
2. Included more details of surveillance and communication models as well as the monitoring requirements;
3. Included the Reich derivation for the lateral separation model;
4. Cleaned up the presentation of lateral separation results;
5. Updated some of the explanation of the lateral separation model;
6. Included the reciprocal separation model;
7. Cleaned up the formatting of the paper; and
8. Included a table of contents to assist readers navigate the work.

As may be inferred from the *Summary of Discussions* (SASP-WG/29 Meeting Report), the update of working paper 20 was not presented and there was no update of the ASEPS Circular proper excluding Chapter 3, i.e. of SASP/1-WP/21. Instead, extensive discussion took place during the Meeting on many aspects of ASEPS (longitudinal as well as lateral), including the operational concept (SASP-WG/29 Meeting Report), leading to a number of important decisions and work items remaining.

The discussions related to *Job Card 11.02 SADS-B* started with the presentation of an information paper, SASP-WG/29-IP/06 (ICCAIA, 2017), which described the performance of the Aireon space-based ADS-B reception from the first three ADS-B receiver payloads out of a set of ten, following successful deployment in space on the 14th of January 2017. The total constellation to be deployed was stated to consist of 72 ADS-B payloads. Performance of the ADS-B reception and data delivery infrastructure was found to exceed ADS-B performance requirements as established by EUROCAE and RTCA. The then prevailing launch cycle of space-based ADS-B receivers was planning for the next launch in June 2017, followed by a launch of 10 receivers every two months thereafter. The last launch of five space-based receivers to finalize the deployment of the total of 72 receivers (66 operational and 6 in-orbit spares) was planned to happen in the second quarter of 2018. Commencement of final global space-based ADS-B surveillance service was planned for the third quarter of 2018.

The discussions related to *Job Card 11.02 SADS-B* continued with a batch of papers all dealing with the ASEPS communication model. The discussion revealed different views on how the space-based ADS-B data would (have to) be used by ATC, i.e. for traditional procedural separation or for something else. In this context, the Working Group was reminded that there were two Operational Requirements (ORs) for the Job card, namely OR 37 for procedural separation and OR 38 for radar-like separation using CPDLC (see under the *SASP-WG/26, Montreal, May 2015*, heading above). To resolve the differences of opinion among the Working Group on the assumptions to be fed into the ASEPS collision risk model for communication performance, a small drafting group was established to summarize the differences and attempt to find an agreeable way forward. The way forward proposed by the drafting group was as follows:

- Remove all references to actual communication performance (ACP), actual communication technical performance (ACTP) and pilot operational response time (PORT) from monitoring requirements since this data may be problematic for use in collision risk modelling monitoring.
- Assume two communication models that would result in two different separation minima:
 - The basic A1 communication model.
 - The A5 communication model if the ANSP can do periodic monitoring of the time it takes aircraft to start a level change from the time the controller sent the climb/descent clearance CPDLC message.

Meeting RCP 240 would be required for both cases.

See SASP-WG/29-WP/20 for the communication models A1 and A5. The proposal, which was presented as a pragmatic way forward, was extensively discussed by the Working Group and although different views persisted, it was ultimately agreed to continue the work based on the drafting group's proposal.

Working paper SASP-WG/29-WP/06 (Addison, 2017) listed some factors that have an impact on longitudinal separation of aircraft on crossing tracks, namely SLOP, RNP cross track total system error (TSE), unannounced aircraft speed variations, and multiple aircraft on weather deviations. The MSG asserted that RNP 4 and aircraft speed variations were already well covered by the existing modelling. The issue of SLOP revived the discussion on the use of space-based ADS-B data would be by ATC, i.e. for traditional procedural separation or as input to an ATS surveillance tracker described in the previous paragraph. The issue of weather deviations resulted in a discussion on whether, or not, correctly performed weather deviations should be included in the ASEPS longitudinal separation standard or not. It turned out that there were two views regarding weather deviations, namely:

- a) Include worst-case weather deviations in computations of separation minima; and
- b) Not include weather deviations in the computations of separation minima, assuming that ATM will discontinue the use of small separation minima and cancel the use of tightly spaced routes when convective weather was forcing aircraft to make weather deviations.

The conclusion of the discussion was that there was no agreement regarding the issue of SLOP and weather deviations. However, it was agreed to model SLOP into the intersecting track collision risk model to enable the Working Group to see how much of a difference it would make to the standard. Some initial work on this was presented during the Meeting in a flimsy and later action items addressed the further work.

SASP-WG/29-WP/26 (Barry, 2017d) dealt with aircraft climbing or descending through the path of on-coming traffic as part of reciprocal ASEPS. Based on the results presented in the working paper and subsequent discussion, the Working Group concluded that ASEPS would not give a reduction in reciprocal track separation.

To conclude the discussion on ASEPS, the Working Group summarized a total of seven decisions and associated work remaining to be completed on both lateral and longitudinal ASEPS separation as follows:

a) Lateral deviations

It was decided that all lateral deviations would be included in the ASEPS collision risk modelling and monitoring, however correctly executed weather and contingency procedures would be appropriately weighted by a small percentage (to be determined) because those aircraft climbed/descended 300 or 500 feet as appropriate which resulted in reduction of risk. This needs to be explicitly documented in the Circular.

It was also agreed that PANS-ATM paragraph 5.2.1.3 should be amended to include the increase of the spacing applied due to severe weather:

b) What deviation angle assumptions should be included in the lateral collision risk model?

The distribution of deviation angles that is used in the ASEPS lateral collision risk model has not been agreed. The modeling of the deviation angles in the ASEPS lateral collision risk model has also not been agreed in the MSG.

c) What controller lateral deviation reaction time assumptions should be included in the collision risk modelling?

The MSG is still working on a solution to this. Due regard will be taken of ongoing human in the loop work.

d) Should SLOP be included in the longitudinal intersecting track model?

It was explained that there are two cases to consider, namely:

- 1) Aircraft change SLOP at the last moment and the controller cannot intervene: some members of the MSG believe that this is already included in the collision risk model by means of the distribution of lateral performance, however other members of the MSG do not agree with that. This needs to be decided by the MSG.
- 2) Aircraft permanent application of SLOP: It was agreed to include this in the collision risk model so that the Working Group can see what effect it has on the longitudinal intersecting track separation.

e) Should RNP be included in the longitudinal intersecting track model or the ADS-B quality indicators?

There has been discussion on whether it is appropriate to include full RNP in the modeling of longitudinal separation on intersecting tracks because the use of ADS-B quality indicators will ensure that ATC has an accurate picture of the aircraft position and track. It was however decided that full RNP be modeled so that the Working Group could see how sensitive the modeling is to this parameter in the modeling of longitudinal separation on intersecting tracks.

f) Should the ASEPS modelling assume 180 seconds wait time after surveillance data failure and 99% availability?

The question is how long does the controller wait to obtain other types of position information when the normal surveillance data fails to arrive? The wait time of 180 seconds goes back to the general collision risk model based on reliability theory (Anderson, 2005). The Working Group thought that on radar it is normal to wait 3 sweeps before the target coasts. It was therefore decided that the model will include a wait time of three times the surveillance update rate up to a maximum of 180 seconds. The Working Group also agreed that it was acceptable to assume 99% availability in the model. It was explained that Aireon was building to 99.9% availability.

g) ADS-B quality indicators

The collision risk modelling assumes that ADS-B accuracy is 0.25 NM. The ADS-B quality indicators that can be used for ASEPS must be included in the circular.

SASP-WG/30, Canberra, November 2017

The ASEPS longitudinal collision risk model was dealt with directly in four working papers presented at SASP-WG/30, namely SASP-WG/30-WP/19 (SASP, 2017), SASP-WG/30-WP/08 (Barry, 2017a), SASP-WG/30-WP/23 (Sleight, 2017), and SASP-WG/30-WP/12 (Barry, 2017e). SASP-WG/30-WP/19 provided an update to the draft ASEPS Circular of SASP/1-WP/21 (Butcher & Dwyer, 2016a). SASP-WG/30-WP/08 and SASP-WG/30-WP/23 dealt with ASEPS longitudinal separation for intersecting and crossing tracks whilst SASP-WG/30-WP/12 dealt with ASEPS reciprocal longitudinal separation standards.

A number of other working and information papers dealt more indirectly with collision risk modelling for ASEPS longitudinal separation minima by presenting details of various elements of the modelling such as:

longitudinal separation – current models do allow for the sudden onset of SLOP, output-based monitoring for longitudinal separation standards, incorporating ADS-B NIC and NUC position uncertainty into ASEPS modelling, communication assumptions for ASEPS, RNP 2 option for Advanced Surveillance – Enhanced Procedural Separation (ASEPS), and Civil Air Navigation Services Organisation (CANSO) position on space-based ADS-B.

The SASP-WG/30-WP/19 (SASP, 2017) update to the previous draft ASEPS Circular of SASP/1-WP/21 (Barry, Civil, et al., 2016a) concerned the title, which was changed into *Guidelines for the Implementation of Separation Minima Using ATS Surveillance Systems where Very High Frequency (VHF) Communications are not Available*, Chapter 2, *Longitudinal and Lateral Separation Minima*, and Chapter 4, *Implementation Considerations*. The changes to the Circular's title and Chapter 2 reflected a change to the proposed location of the PANS-ATM Amendment, viz. from PANS-ATM Chapter 5, *Separation methods and minima*, to PANS-ATM Chapter 8, *ATS surveillance services*. Cf. the discussion on ASEPS being “conventional procedural separation or something else” under the SASP-WG/29, *Reykjavik, May 2016*, heading and the draft PANS-ATM amendment proposal put forward in SASP-WG/30-WP/09 (Dwyer, 2017). The changes to Chapter 4 concerned a considerable amount of text on “Safety Factors Related to Convective Weather and Contingencies for ADS-B/ RCP 240 operations”. There was no update to the Circular's draft Chapter 3, *SASP Safety Assessment*, of SASP-WG/29-WP/20 (Barry, 2017c). Rather, there were various working and information papers related to ASEPS longitudinal separation modelling as set out in the previous two paragraphs.

The amendment proposal put forward in SASP-WG/30-WP/09 was discussed by the Working Group and it was agreed that it would be placed in Chapter 8, *ATS surveillance services*, of the PANS-ATM. The proposed “top-down” layout of the separation standards specifying first the basic separation minima and then detailing the conditions needed to be satisfied in order to reduce the separation was also agreed to. There was extensive discussion on the status of the guidance material that would support the new ASEPS separation minima, viz. whether it should be in the form of a Circular or a Manual. For example, some members were concerned that Circulars did not have a status that was prominent enough and that they considered Manuals to have a higher status. The discussion ended with an action on the Secretary to clarify with ICAO whether there is a regulatory and status difference between a Circular and Manual. Based on a flimsy, various elements of the draft amendment proposal were discussed, resulting in some modifications and the observation that a number of issues raised in the flimsy were already being taken care of. An updated version of the amendment proposal was then discussed, which, after some more changes, resulted in an agreed PANS-ATM amendment proposal, although it was realized that there were still some outstanding issues (flagged in the proposal). It was also agreed that it was appropriate that the Secretary would coordinate this draft amendment proposal within ICAO and other appropriate ICAO groups.

The latest draft of the Circular in SASP-WG/30-WP/19 was presented to the Working Group after which a partial review of the draft was performed. The Working Group agreed to continue work on the draft ASEPS Circular between meetings. This would involve work on the main body of the Circular as well as on the *Hazard Assessment* section.

SASP-WG/30-WP/08 (Barry, 2017a) dealt with ASEPS longitudinal separation for intersecting tracks, particularly the inclusion into the modelling of SLOP and RNP and was presented to the MSG only. The effect of SLOP on intersecting track ASEPS longitudinal separation is dependent on whether the ATC system in an ASEPS environment uses the actual ADS-B position reports of an aircraft, including SLOP, for the calculation

of track intersection points, or extrapolates the enhanced positional data to the nearest track and uses the latter to calculate track intersection points. Although modern ATC systems will use the former method, older, legacy ATC systems might use the latter and would hence need to account for SLOP explicitly.

Equation 10 of paragraph 2.11 of SASP-WG/30-WP/08 presented the longitudinal collision risk model used, viz. the general collision risk model based on reliability theory (Anderson, 2005), or, as referenced earlier in this Section, the collision risk model of eq. (7.212) but with eqs. (7.213) and (7.214) replaced by

$$D_x(t) = (v_1 - v_2 \cos \theta)t - d_1 + d_2 \cos \theta - o_2 \sin \theta \quad (7.286)$$

$$D_y(t) = (d_2 - v_2 t) \sin \theta - o_1 + o_2 \cos \theta \quad (7.287)$$

with o_1 and o_2 denoting the lateral offsets to the right of track applied by the two aircraft in the scenario of Figure 7.8. The lateral offsets o_1 and o_2 in eqs. (7.286) and (2.287) should be set to zero when an ATC system is capable of using the actual ADS-B position reports of the aircraft (including SLOP) for the calculation of track intersection points and should be given non-zero values when the ATC system does not have that capability, i.e. calculates the intersection point based on the nominal tracks in Figure 7.8. The model of eq. (10) of SASP-WG/30-WP/08 was supplemented with an integration over the planned separation S between the aircraft at the intersection, viz. eq. (12) of SASP-WG/30-WP/08, similar to eq. (7.216) of this document. Crossing angles θ between 5 and 90 degrees inclusive were analysed. The working paper concluded that for RNP 2 aircraft the crossing separation standard was less than 12 NM whether SLOP was included or not. For RNP 4 aircraft, inclusion of SLOP might limit the separation standard to more than 16 NM with SLOP and more than 14 NM when the ATC system can analyse track intersections based on ADS-B surveillance information. The presentation of the working paper resulted in a few questions and comments after which the working paper's conclusions were accepted by the MSG.

SASP-WG29-WP/09 (Barry, 2017f) was also presented to the MSG only. Partially based on SASP-WG/30-WP/08, it presented a summary of ASEPS or space-based ADS-B longitudinal separation standards for same-identical and intersecting tracks. The working paper concluded that ASEPS longitudinal separation standards are much simpler and less controversial than their lateral counterparts and that the results indicated that a standard of 16 NM was easily supported and lower standards down to 10 NM can be supported under various scenarios. The working paper also concluded that the difficulty was distilling the various options down to a reasonable and simple to implement set of standards. An example set of ASEPS longitudinal separation standards was given. It was explained during the presentation that due to the new communication model, the separation values listed in the working paper needed to be re-computed. There was some discussion of practical problems that air navigation service providers (ANSPs) might have in estimating speed errors in a (space-based) ADS-B environment, since ADS-B position reports do not contain information on estimated or actual arrival times at waypoints.

SASP-WG/30-WP/23 (Sleight, 2017) (also) dealt with ASEPS longitudinal collision risk for crossing same-direction tracks for RNP 2 and RNP 4 aircraft with both aircraft using SLOP, the ATC system not being aware of the SLOP usage, and the lead aircraft deviating by a given angle β , say, towards the trailing aircraft. The working paper was presented to the MSG and started noting that although, traditionally, a lateral deviation has not been considered when calculating the longitudinal collision risk of intersecting tracks, the smaller separation standard considered for ASEPS has led to some operational concerns that such a lateral deviation would be a high-risk event. The working paper utilized the modelling of the effect of SLOP from SASP-WG/30-

WP/08 as summarized above by eqs. (7.212), (7.286), and (2.287). In addition, the deviation angle β was accounted for through the use of an effective intersection angle $\theta^* = \theta + \beta$. As a result, eqs. (7.286) and (7.287) were modified to become (13th edition of PANS-RAC, eqs (8) – (9)),

$$D_x(t) = (v_1 - v_2 \cos(\theta + \beta))t - \hat{d}_{1b}^0 + \hat{d}_{2b}^0 \cos(\theta + \beta) \quad (7.288)$$

$$D_y(t) = (\hat{d}_{2b}^0 - v_2 t) \sin(\theta + \beta) \quad (7.289)$$

where $\hat{d}_{1b}^0$ and $\hat{d}_{2b}^0$ denote the nominal distances of the aircraft at time zero to the effective intersection point defined by the nominal tracks plus offsets and the intersection angle $\theta^* = \theta + \beta$. Because the effect of SLOP is accounted for through the nominal distances $\hat{d}_{1b}^0$ and $\hat{d}_{2b}^0$ to the effective intersection point, eqs. (7.288) and (7.289) are of the same form of eqs. (7.213) and (7.214) rather than that of eqs. (7.286) and (7.287), i.e. the lateral offsets o_1 and o_2 are included into $\hat{d}_{1b}^0$ and $\hat{d}_{2b}^0$.

The lateral deviation of the leading aircraft triggers a lateral deviation alert when the lateral distance exceeds the lateral alert threshold, set at a distance d_t beyond maximum SLOP. The (maximum) time delay t_d from the time of a lateral deviation to the time that the lateral alert threshold is exceeded was given by

$$t_d = \frac{\max(o_1) + d_t - o_1}{\min(V_1) \sin \beta} \quad (7.290)$$

where V_1 denotes the ground speed of the deviating aircraft. This time delay was then added to the ATC-pilot response time T . The ASEPS longitudinal collision risk model of the working paper also assumed a rectangular distribution of planned longitudinal separation at the intersection over the range $[S_x, S_x + 250]$ NM, where S_x denotes the ASEP longitudinal separation standard, cf. eq. (7.216).

The working paper assumed for its assessment that the crossing scenario occurred over a conservatively short time period of 10 minutes and that the lateral deviation could occur at any time during the crossing scenario. Given the occurrence of a lateral deviation, the associated longitudinal collision risk over the 10 minute crossing scenario was calculated as the average of collision risk at each 1 minute interval as a function of the lateral offsets o_1 and o_2 under SLOP, see eq. (15) of SASP-WG/30-WP/23. One more element of the ASEPS crossing same-direction tracks collision risk model of the working paper that needs to be mentioned concerns the calculation of an overall collision risk $CR(S_x, o_1, o_2)$, given lateral offsets o_1 and o_2 , as a weighted combination of a nominal scenario risk, without a deviation, and the deviation scenario risk, where the deviation scenario risk was further partitioned into the risk of a range of deviation angles and their respective probability of occurrence, see eq. (16) of SASP-WG/30-WP/23. Finally, SLOP was accounted for by averaging $CR(S_x, o_1, o_2)$ over each of the nine combinations of lateral offsets of 0, 1, or 2 NM of the two aircraft.

Longitudinal collision risk results were calculated for RNP 4 aircraft and RNP 2 aircraft, for four different lateral deviation rates, namely 0 , 7×10^{-5} , 4.6×10^{-4} , and 2×10^{-3} deviations per flight hour. The deviation rate of 7×10^{-5} had been calculated from deviations in the NAT that occurred between 2011 and 2016. At that deviation rate, a minimum separation standard of 16.4 NM was found to meet the target level of safety (TLS) of 5×10^{-9} fatal accidents per flight hour for RNP 4 aircraft. However, higher deviation rates increased the risk above the TLS, consequently requiring larger minimum separation standards. For example, a minimum separation standard of 17.7 NM would be needed to meet the TLS for a lateral deviation rate of 5×10^{-4}

deviations per flight hour. For RNP 2 aircraft, deviation rates at or below 5×10^{-4} deviations per flight hour were found to support a minimum separation standard of 15.5 NM meeting the TLS. The author of the working paper announced some further work to be presented at the next Meeting concerning the effect of the type of probability distribution of the lateral deviation modelling on the resulting ASEPS longitudinal separation standard.

SASP-WG/30-WP/12 (Barry, 2017e) dealt with ASEPS reciprocal longitudinal separation standards. It does not seem to have been presented to the MSG (or the plenary). The working paper examined the following ASEPS longitudinal separation standard:

- A clearance to climb/descend can be issued to an aircraft 20 seconds or 5 NM after the both aircraft have reported surveillance indicating the two aircraft have passed each other.

A second, not recommended, separation standard was also examined, viz.:

- A clearance to climb/descend can be issued to an aircraft 60 seconds after the predicted crossing time of the aircraft.

Some approximate assessments, later supported by more formal collision risk assessments were considered in support of the proposed standards. See SASP-WG/30-WP/12 for further details.

SASP/2, Montreal, May 2018

There were two key working papers on ASEPS longitudinal separation at the Second Meeting of the Separation and Airspace Safety Panel (SASP), namely SASP/2-WP/41 (Stefansson, 2018) and SASP/2-WP/37 (Barry et al., 2018). SASP/2-WP/41 presented the latest update to the Circular/Manual exclusive of the mathematical part of the Circular/Manual's Chapter 3, *SASP Safety assessment*. SASP/2-WP/37 supplemented SASP/2-WP/41 by providing a summary of the relevant ASEPS collision risk model parameters, variable assumptions and their respective values as well as proposed ASEPS lateral and longitudinal separation minima based on those values. (The collision risk models proper were not included in working paper 37.)

As usual, there were many working and information papers presented to the Meeting that covered different elements of ASEPS longitudinal separation, such as longitudinal monitoring methodology, FAA ASEPS human in the loop (HitL) controller reaction time results, controller reaction times from Australian CPDLC data, PBS longitudinal monitoring requirements, operational issues related to risk-weighting of correctly executed pilot weather and contingency procedures, validation of exponential distribution assumption in longitudinal intersecting tracks model, operational implications of averaging risk in the collision risk model, contingency procedures for managing a space-based ADS-B single satellite outage, aircraft response latencies to ATC clearances, analysis of controller reaction time for the ASEPS collision risk model, speed error differences among airlines, the Anderson-Hsu longitudinal model for intersecting tracks conservatively accounts for the possibility of aircraft deviating at an angle, space-based ADS-B reception – update, and inter-Panel feedback on the ASEPS proposal for amendment resulting from SASP-WG/30.

SASP/2-WP/37 (Barry et al., 2018) was presented to the plenary and it was agreed that the working paper's proposed amendment proposal would be taken as the basis from which the ultimate amendment proposal would be developed. The working paper's proposed amendment proposal was reviewed paragraph by paragraph, taking also into account inter-Panel feedback received on the PANS-ATM amendment proposal resulting from the SASP-WG/30 Meeting. Subsequently, there was extensive discussion on various elements of the draft amendment proposal, particularly on whether, or not, there was a requirement for ADS-C for application of ASEPS for the benefit of monitoring conformance of the next and next + 1 waypoints. Since no consensus could be reached, this element was put on hold for resolution later during the Meeting. Regarding

the longitudinal separation minima, the Working Group decided to split the minima in two parts, one applicable for intersection angles up to 45 degrees and the other applicable for intersection angles up to 90 degrees. The final longitudinal separation minima remained to be agreed later in the Meeting.

Further work during the meeting resulted in the following specific agreements as a part of the ultimately agreed PANS-ATM amendment proposal. The requirement for monitoring the conformance of the next and next + 1 waypoints was removed from the amendment proposal. Subject to the conditions specified in the amendment proposal, the ASEPS longitudinal separation minimum of aircraft operating on same tracks or crossing tracks applied in accordance with section 5.4.2.9.5 shall be 17 NM provided that the relative angle between the tracks is less than 90 degrees. The 17 NM longitudinal separation minimum may be reduced, but not below 14 NM, provided the relative angle between the tracks is less than 45 degrees. Opposite-direction aircraft on reciprocal tracks may be cleared to climb or descend to or through the levels occupied by another aircraft provided that surveillance position reports have been received from both aircraft demonstrating the aircraft have passed each other by 5 NM. Lateral separation minima were also agreed as a part of the further work but are not relevant to the ASEPS *longitudinal separation* Section of this Document. See Section 5.4.4.

As indicated in the first paragraph under the *SASP/2, Montreal, November 2018* heading, SASP/2-WP/41 presented the latest update to the Circular/Manual exclusive of the mathematical part of the Circular/Manual's Chapter 3, *SASP Safety assessment*. The Meeting reviewed the changes that had been done to the Circular/Manual since SASP-WG/30 and agreed to continue its development.

SASP-WG/31, Washington D.C., October – November 2018

With the ASEPS PANS-ATM proposal finalised at the SASP/2 Meeting, it remained to complete the corresponding Circular. The mathematical aspects of the Circular pertaining to its Chapter 3, *SASP Safety Assessment*, were documented in SASP-WG/31-WP/03 (Barry, 2018) with Attachment 1 providing an Introduction to the Chapter and Attachments 2, 3, and 4 dealing with ASEPS longitudinal, lateral-parallel, and lateral-crossing separation respectively. Attachment 2 is of relevance here. Material related to Chapter 4 of the Circular, *Implementation Considerations*, was provided in SASP-WG/31-WP/11 (Grimes & Addison, 2018), SASP-WG/31-WP/16 (Bickmeier & Sleight, 2018), and SASP-WG/31-WP/08 (SASP, 2018).

Discussion on the above mentioned working papers can best be summarised as that the Working Group provided some comments on the material provided and agreed to continue working on the ASEPS Circular.

Attachment 2, *Longitudinal*, for the first time, presented explicitly an ASEPS longitudinal collision risk model. The model as well as much of the text of Attachment 2 appeared to be identical to the final versions to be examined under the third next *SASP-VWG/1, July 2020* heading below.

SASP-WG/32, Montreal, May 2019

Work to complete the ASEPS Circular continued at the 32nd Meeting of the SASP Working Group and focussed on Chapter 3, *SASP Safety Assessment*, and Chapter 4, *Implementation Considerations*, of the Circular. The latest draft of Chapter 3 was provided in SASP-WG/32-WP/03 (Barry, 2019c) with attachment 1 providing an Introduction to the Chapter and attachments 2, 3, and 4 dealing with ASEPS longitudinal, lateral-parallel, and lateral-crossing separation respectively. Attachment 2 is of relevance here. The 84-page SASP-WG/32-WP/02 (Barry, 2019b) documented the changes made to Chapter 3 of the Manual from that presented at the previous Meeting, i.e. SASP-WG/31-WP/03 (Barry, 2018). In addition, SASP-WG/32-WP/22 (Bickmeier, 2019) provided an additional section of Chapter 3 on contingency procedures as a result of an action assigned at

the previous Meeting. Material related to Chapter 4 of the Circular, *Implementation Considerations*, was provided in SASP-WG/32-WP/09 (Grimes, 2019), SASP-WG/31-WP/10 (Grimes & Addison, 2019), and SASP-WG/31-WP/19 (Warburton & Nickelson, 2019).

The ASEPS longitudinal collision risk model in SASP-WG/32-WP/03 (Barry, 2019c) was the same as in SASP-WG/31-WP/03 (Barry, 2018). Working paper 3, specifically its attachments, was reviewed in detail by the MSG leading to the MSG editing and making detailed changes to the Manual. Key changes throughout the feedback/editing process were the elimination of several sections and figures from the working paper 3 draft that the MSG felt were not necessary to the main thesis (and anticipated use) of the Manual, and removal of many tables from attachment 1 to the working paper in favour of retaining focus on the final separation standard only. Apart from some minor editing, Chapter 3, *SASP Safety Assessment*, was then considered complete.

The material related to Chapter 4 of the Circular, *Implementation Considerations*, as provided in SASP-WG/32-WP/09, SASP-WG/31-WP/10, and SASP-WG/31-WP/19 was reviewed and edited by the Working Group where deemed necessary. Some more work on Chapter 4 was agreed to be progressed up to the next Working Group meeting.

SASP-WG/33, Montreal, November 2019

Latest drafts of the ASEPS Circular/Manual's Chapter 3, *SASP Safety Assessment*, and Chapter 4, *Implementation Considerations*, were provided in SASP-WG/33-WP/02 (Barry, 2019a) and SASP-WG/33-IP/21 (Addison, 2019) respectively.

SASP-WG/33-WP/02 (Barry, 2019a) was the latest draft of Chapter 3, *SASP Safety Assessment*, of the ASEPS Circular/Manual including some editing outstanding from the SASP-WG/32 Meeting. All edits done during SASP-WG/32 and then recommended by the Working Group were included in the attachments to the working paper. Some additional feedback was incorporated during the Meeting and the final version resulting from the Meeting was made available as Flimsy 19 of the Meeting. An action was defined to reformat the Manual as a separate Appendix to Chapter 3 rather than as an integral part of the Chapter by the end of 2019 for final editorial changes by MSG members and the SASP Secretary.

SASP-WG/33-IP/21 (Addison, 2019) presented the latest draft of Chapter 4, *Implementation Considerations*, of the ASEPS Circular/Manual prior to the Meeting. The information paper was reviewed by the Working Group, which made comment and editorial suggestions, and which subsequently convened a drafting group to address outstanding issues. The final version resulting from the Meeting was made available as Flimsy 15 of the Meeting.

SASP-VWG/1, July 2020

The third Panel Meeting of the SASP was planned for May 2020. However, in response to the COVID pandemic and consequent inability to conduct face to face meetings, the First Virtual Working Group Meeting of the Separation and Airspace Safety Panel (SASP-VWG/1) was held, using the ICAO GoToMeeting facility in July 2020, to determine ways to progress the SASP work programme, as documented via the Job Cards assigned to SASP by the Air Navigation Commission. The meeting was conducted on an informal basis over two sessions to ensure a maximum of members could attend:

- The First Session was held on 15 July, between 3:00 pm and 5:30 pm (Montreal time); and
- The Second Session was held on 21 July, between 7:00 am and 9:30 am (Montreal time).

The *Summary of Discussions of VWG/1* (SASP, 2020) does not make any reference to the finalization of the ASEPS Manual. However, a working paper, SASP-3-WP/02, *Manual for ATS surveillance separation using RCP 240 communications: Appendices B – F* (Barry, 2020) dated 03/12/2019, to be presented at the originally planned 3rd Panel Meeting of the SASP in May 2020, was available long before. The working paper addressed the action defined at SASP-WG/33 (see under the previous heading) to reformat the mathematical work concerning Chapter 3, *SASP Safety Assessment*, of the ASEPS Circular/Manual as a separate Appendix to Chapter 3 rather than as an integral part of the Chapter by the end of 2019 for final editorial changes by MSG members and the SASP Secretary. Appendix C to the working paper described the mathematical modelling for ASEPS longitudinal separation minima and the collision risk model from that Appendix has been reproduced below. The Appendix should be read in conjunction with Appendix B, *Summary of mathematical modelling*, which comprised the following sections: B.1 Summary of contents for mathematical modelling, B.2 Definitions and key concepts, B.3 Summary of conditions that meet the TLS, B.4 Summary of monitoring and implementation requirements, B.5 Intervention modelling, and B.6 Parameter assumptions.

Starting point for Appendix C to SASP-3-WP/23 (Barry, 2020) was the geometry shown in Figure 7.20 (reproduced from Figure C.1.1 of Section C.1, *Geometry and key variables*, of SASP-3-WP/02), followed by a derivation of the Anderson-Hsu mathematical model, i.e. of the general collision risk model based on reliability theory (Anderson, 2005). (There are some inaccuracies in some of the intermediate steps of the derivation of SASP-3-WP/02 compared to (Anderson, 2005))

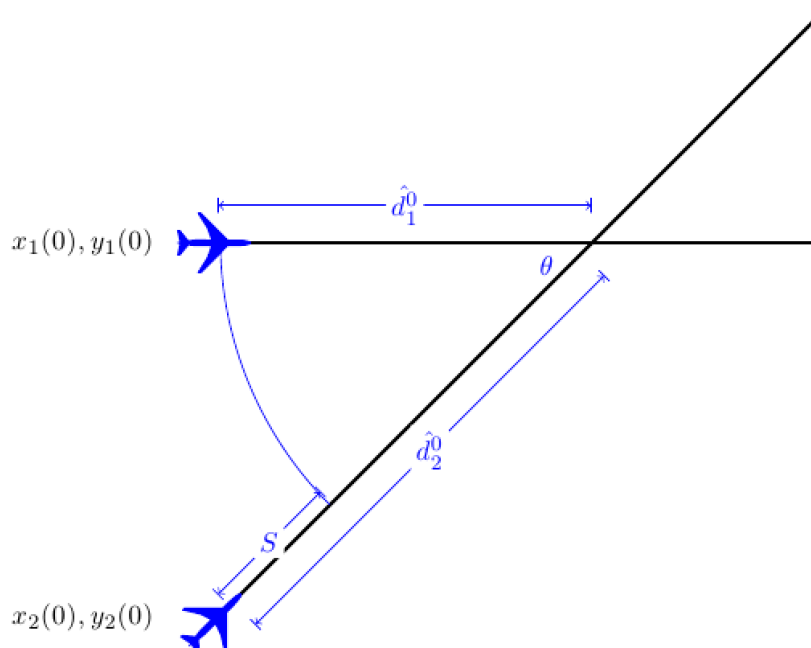


Figure 7.20: Longitudinal separation. Nominal positions¹³² of aircraft on intersecting tracks at time t_0 , usually assumed 0. Aircraft approach at an angle θ . The longitudinal separation is the distance S . (Source SASP-3-WP/02)

Figure 7.20 does not show the along-track and across-track navigational errors of the aircraft. It is useful, therefore, to recall Figure 7.8 from Section 7.3.4.1, where ε_1^A , ε_2^A , ε_1^C , and ε_2^C denote those navigational errors:

¹³² Figure 7.20 was reproduced from SASP-3-WP/02 which used a superscript “^” to denote nominal distances to the intersection at time t_0 . To be consistent, the aircraft position components in the Figure should be considered nominal position components and be supplied with the superscript “^” too.

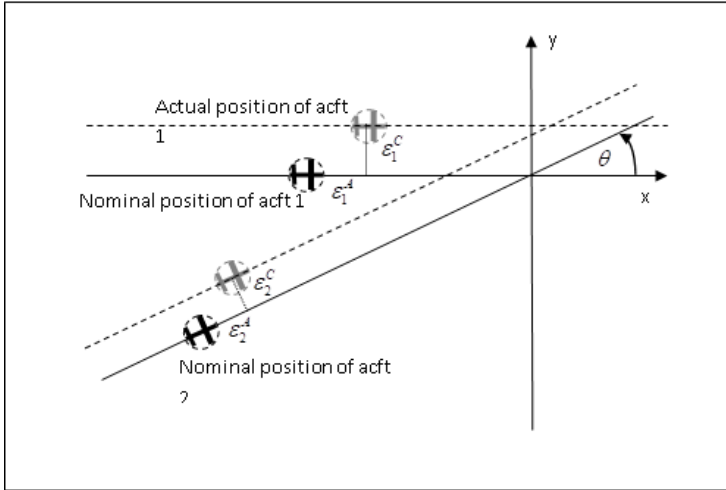


Figure 7.8: Illustration of the along-track errors and the across-track errors for a pair of aircraft on intersecting routes in the horizontal plane (intersection angle constrained to $0 \leq \theta < 45^\circ$ in Section 7.3.4.1)

The derivation of the Anderson-Hsu mathematical model in Section C.2 of Appendix C to SASP-3-WP/02 concluded with the following form of the ASEPS longitudinal collision risk model for the risk over a time interval $[t_0, t_1]$:

$$CR(t_0, t_1) = NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) P_z(h_z) \left(\frac{2V_r}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right) f_1(V_1) f_2(V_2) dt dV_1 dV_2 \quad (7.291)$$

with

$$HOP(t|V_1, V_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C \quad (7.292)$$

In the two equations above, NP denotes the number of aircraft pairs per flight hour, V_1 and V_2 denote the (true or actual) speeds of the two aircraft, V_r denotes the relative speed between the two aircraft on routes intersecting at an angle of θ , and $HOP(t|V_1, V_2)$ denotes the probability of horizontal overlap for the aircraft pair as a function of time t and the aircraft speeds V_1 and V_2 . The symbols $D_x(t)$ and $D_y(t)$ denote the relative position components between the aircraft exclusive of the random navigation errors ε_1^A , ε_2^A , ε_1^C , and ε_2^C , given by

$$D_x(t) = (V_1 - V_2 \cos \theta)t - \hat{d}_1^0 + \hat{d}_2^0 \cos \theta \quad (7.293)$$

$$D_y(t) = (\hat{d}_2^0 - V_2 t) \sin \theta \quad (7.294)$$

Notice that $D_x(t)$ and $D_y(t)$ are dependent on the random aircraft speeds V_1 and V_2 and the nominal distances $\hat{d}_1^0$ and $\hat{d}_2^0$.

The above model, is the same as the one presented under the last, *SASP-WG/WHL/7, Montreal, May 2005*, heading in Section 7.3.4.1 for same-track procedural longitudinal separation, i.e.

$$N_a = 2\pi m \lambda_{xy}^2 P_z \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} f_t(0,0) \left(1 + \frac{\pi \lambda_{xy} |\dot{z}|}{4 \lambda_z v_{xy}} \right) f_1(v_1) f_2(v_2) dt dv_1 dv_2 \quad (7.212)$$

where $f_i(v_i)$ is the probability density function of the horizontal speed v_i of aircraft $i = 1, 2$ and $f_t(0,0)$ denotes the joint probability density of the relative position $r_x(t)$, $r_y(t)$ of two aircraft at time t for $r_x(t) = r_y(t) = 0$ given by

$$f_t(0,0) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_1^A(\varepsilon_2^A \cos \theta - \varepsilon_2^C \sin \theta - D_x(t)) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_2^A \sin \theta + \varepsilon_2^C \cos \theta - D_y(t)) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C$$

The symbols $D_x(t)$ and $D_y(t)$ denote the relative position components between the aircraft at time t given by

$$D_x(t) = (v_1 - v_2 \cos \theta)t - d_1 + d_2 \cos \theta \quad (7.213)$$

$$D_y(t) = (d_2 - v_2 t) \sin \theta \quad (7.214)$$

Apart from the use of slightly different symbols, there is a minor difference between the two longitudinal collision risk models in that eq. (7.212) is based on the assumption that the probability of vertical overlap P_z is constant during the time interval $[t_0, t_1]$ over which the longitudinal collision risk is to be calculated, i.e. $P_z(0)$ when same-track longitudinal separation is applied. Application of the longitudinal model to aircraft on reciprocal tracks requires this assumption to be modified and to include the probability of vertical overlap as a time dependent probability $P_z(h_z)$ or, actually, $P_z(h_z(t))$ under the time integral, e.g. varying linearly from $P_z(S_z)$ to $P_z(0)$.

The similarity between the form of the ASEPS longitudinal collision risk model of eqs. (7.291) to (7.294) and that of the procedural longitudinal collision risk model of eqs. (7.212) to (7.214) is consistent with one of the conclusions in SASP-WG/29-WP/09 (Barry, 2017f), viz. that ASEPS longitudinal separation standards were much simpler and less controversial than their lateral counterparts. An essential difference between the models, however, concerns the time interval $[t_0, t_1]$ over which the longitudinal collision risk is to be calculated, particularly the value of t_1 as a function of the ATC-pilot response time T and the reporting time τ . As reported under the SASP-WG/25, *Sydney, November 2014*, heading at the beginning of this ASEPS Section, the main features of the new, adapted model were a reduction in the ATC-pilot response time and a reduction in the reporting time as well. These times were introduced in Section 7.3.2 and utilized in Sections 7.3.3 and 7.3.4.1 for procedural longitudinal separation. See Tables 7.8 and 7.9, which show longitudinal collision risk values for different values of the controller action buffer τ as well as weighted average longitudinal collision risks. It remains to specify the ATC-pilot response time and the reporting time for the ASEPS application. ATC-pilot response time and reporting time for the ASEPS application were not described in Appendix C to SASP-3-WP/02 but rather in Section B.5, *Intervention modelling*, of Appendix B, *Summary of mathematical modelling*, to that working paper.

As set out in Section B.5 of Appendix B to SASP-3-WP/02, SASP spent considerable time debating the most appropriate communications model for the benefit of the ASEPS collision risk modelling, both longitudinal and lateral. The resultant model was termed the *RCP Communication and Surveillance Timing Model*

(RCSTM). It is an event sequence diagram where each branch was called a scenario. Each (overall) scenario progresses through several events, each associated with a response time τ_i and a probability p_i . For each scenario, the response time τ_i determines the time interval $[t_0, t_1] = [0, \tau_i]$ over which a scenario's ASEPS longitudinal collision risk is calculated. Denoting the longitudinal collision risk under ASEPS operations for scenario i as $CR(\tau_i)$, the overall ASEPS longitudinal collision risk was given by

$$CR = \sum_i p_i CR(\tau_i) \quad (7.295)$$

The RCSTM model for FANS-equipped aircraft was illustrated in Figure B.5.2 of the Appendix B. It comprised a total of 12 branches/scenarios labelled from 0 to 11, made up of 4 groups of 3 scenarios each, the groups representing

- (1) ADS-B and CPDLC are successful;
- (2) ADS-B successful but CPDLC failed, resulting in HF voice communication;
- (3) ADS-B failed, resulting in ADS-C surveillance, but CPDLC successful; and
- (4) ADS-B failed, resulting in ADS-C surveillance, and CPDLC failed, resulting in HF voice communication.

The response times of all scenarios of all the groups comprise the same 90 seconds pilot response time and the same 75 seconds time for an aircraft trajectory change. When CPDLC is successful, the scenarios for groups (1) and (3) comprise three values for the CPDLC technical uplink time, namely 20, 30, and 60 seconds. When CPDLC fails, the scenarios for groups (1) and (3) comprise the same value of 240 seconds for HF voice latency, in combination with three values for RCP TRN¹³³, namely 60, 120, and 180 seconds. For the groups (1) and (1), each scenario includes an additional 45 seconds of ATC processing/reaction/composition time whereas for the groups (3) and (3) each scenario includes the same 45 seconds of ATC processing/reaction/composition time plus an additional ADS-B wait time of 180 or $3 \times T_p$ seconds, whichever is the lower, where T_p denotes the time between ADS-B periodic position reports. See Figure B.5.2 of the Appendix B to SASP-3-WP/02.

Section C.3 of Appendix C to SASP-3-WP/02 is entitled *Projected position error – speed error*. Speed error is examined in connection with the aircraft-speed probability densities product $f_1(V_1)f_2(V_2)$ in the ASEPS longitudinal collision risk model of eq. (7.291). Notice that this product form assumes that the two aircraft speeds are independent random variables. The Section defines a “speed error” v for a single aircraft as the difference between the actual average or constant speed V^a over a given route segment and the estimated average or constant speed V^e over that same segment, i.e. $v = V^a - V^e$ and notes that a key part of previous work has been estimating the distribution of v from given data. It also defines a “paired speed error” w for a pair of aircraft as the difference between the actual average or constant relative speed $V_1^a - V_2^a$ over a given route segment and the estimated average or constant relative speed $V_1^e - V_2^e$ over that same segment, i.e. $w = V_1^a - V_2^a - (V_1^e - V_2^e)$ or $w = V_1^a - V_1^e - (V_2^a - V_2^e)$ and thus $w = v_1 - v_2$. When the single aircraft speed errors v_1 and v_2 are independent with a double exponential distribution with parameter a_v (recall eq. (4.19)), the probability distribution of the paired speed error can easily be calculated in an analytical form. It is then shown that the paired speed error distribution can be well approximated by a double exponential distribution with parameter a_w where $a_w = 1.5a_v$. Section C.3 concludes with suggesting suitable values for the parameter a_v of the single aircraft speed error v for three cases, namely

¹³³ RCP 240 includes a time value (TRN) for actual communication performance (ACP). The TRN applies to a sample of CPDLC “intervention-like” transactions measured from when a controller presses “send” to when the controller receives indication of the response. TRN values have been specified for 95% and 99.9% of the CPDLC-sample transactions.

$a_v = 6.5$ knots for conventional procedural longitudinal separation, $a_v = 4$ knots for single aircraft independent speed errors for ASEPS surveillance, and $a_v = 2.5$ knots for single aircraft dependent speed errors for ASEPS surveillance.

Table B.2.7, *Terms related to speeds*, of Appendix B to SASP-3-WP/02 also lists the parameter of the single aircraft speed error distribution, denoted λ_v rather than a_v , with typical values in the range of $3.5^{134} - 6.5$ knots. The Table also lists the aircraft speed probability densities, denoted $f_{v1}(V_1)f_{v2}(V_2)$ (with v_1, v_2 average aircraft speeds) rather than $f_1(V_1)f_2(V_2)$ as in the ASEPS longitudinal collision risk model of eq. (7.291) and states that these densities are usually modelled as Gaussian with standard deviation of 17 knots.

Remarks

1. The notation $f_{v1}(V_1)f_{v2}(V_2)$ with v_1, v_2 average aircraft speeds in Table B.2.7 of Appendix B to SASP-3-WP/02 is somewhat confusing with reference to the definition of single aircraft speed error v in the previous paragraph but one.
2. Modelling of $f_{v1}(V_1)f_{v2}(V_2)$ as Gaussian densities differs from the modelling of $f_1(V_1)f_2(V_2)$ as double exponential densities with parameter $\lambda_v = 5.82$ knots in Chapter 5 of (Anderson, 2005). The change is presumably based on the ASEPS work on aircraft speed error modelling presented in various working and information papers referenced, but not detailed, under the pertinent SASP Meeting headings above.

Sections C.4 and C.5 of Appendix C to SASP-3-WP/02 contain some discussion on providing a speed restriction limit on the projected position error, expressed as a speed error, and the number of aircraft pairs, NP , parameter of the collision risk model respectively. For the latter, a conservative value of $NP = 4$ aircraft pairs per flight hour was used. Table B.2.1, *General terms*, of Appendix B to SASP-3-WP/02 lists typical values of NP in the range of 0.1 – 4 aircraft pairs per flight hour.

Section C.6 of Appendix C to SASP-3-WP/02 explored the validity of using a uniform distribution of aircraft separations in the ASEPS longitudinal collision risk calculations. The reason for this Section is the following. Although it is not explicitly shown by the ASEPS longitudinal collision risk symbol $CR(t_0, t_1)$ on the left side of eq. (7.291), this risk is dependent or conditional on the nominal distances $\hat{d}_1^0$ and $\hat{d}_2^0$ of the aircraft to the intersection at time t_0 through the relative position components $D_x(t)$ and $D_y(t)$ on the right side of eq. (7.292) for the probability of horizontal overlap $HOP(t|V_1, V_2)$. This dependence was already examined under the *SASP-WG/WHL/7, Montreal, May 2005* heading in Section 7.3.4.1 for the procedural-separation collision risk model of eqs. (7.212) – (7.214) where it was noted that the procedural longitudinal collision risk N_a of eq. (7.212) is actually a conditional longitudinal collision risk, conditional on the initial longitudinal separation $S = d_1 - d_2$ and the initial distance of one of the aircraft, d_2 say, before the intersection at time t_0 and might be denoted more completely as $N_a(S = d_1 - d_2, d_2)$, see eq. (7.215). The dependence on the initial longitudinal separation $S = d_1 - d_2$ was accounted for by assuming this separation to have a uniform distribution over the range $[S_x, S_x + 250]$ NM with S_x denoting the longitudinal separation minimum, and by calculating the longitudinal collision risk as a function of the initial distance d_2 before the intersection of the second aircraft, as

$$N_a(d_2) = \frac{1}{250} \int_{S_x}^{S_x+250} N_a(S = d_1 - d_2, d_2) dS \quad (7.216)$$

¹³⁴ Paragraph C.9.1 of Section C.9, Longitudinal separation on intersecting tracks, lists a lower bound of 2.5 knots for λ_v .

Finally, the dependence of the longitudinal collision risk $N_a(d_2)$ on the initial distance d_2 before the intersection of the second aircraft was accounted for.

Section C.6 states that most data indicate that aircraft are separated as an approximate gamma distribution with very few pairs separated close to the separation minimum and that SASP studies showed that the assumption of a uniform distribution gave a far higher risk than any reasonable gamma distribution, the reason being the large decay in risk with initial separation S .

Section C.7 of Appendix C to SASP-3-WP/02 provided some discussion on the numerical methodology used to perform the various integrations in the ASEPS longitudinal collision risk, i.e. over time, the aircraft speeds, and the initial longitudinal separation. The methodology used was the same as that of the general collision risk model based on reliability theory (Anderson, 2005).

Section C.8 of Appendix C to SASP-3-WP/02 explored different aspects of the ASEPS longitudinal collision risk model for same-identical (zero angle) tracks by keeping key parameters constant and varying only one or two at a time. The parameters varied concerned the single aircraft speed error parameter λ_v and the total reporting time $T_r = T_p + T_L$ (rather than T_p and T_L individually).

Section C.9 of Appendix C to SASP-3-WP/02 was entitled *Longitudinal separation on intersecting tracks*. This title is somewhat misleading in that the previous Sections of Appendix C also dealt with intersecting tracks except for Section C.8 which was constrained to same-identical (zero angle) tracks. The actual subject of Section C.6 is the effect of SLOP on ASEPS longitudinal collision risk for aircraft on intersecting tracks. The Section's Figure C.9.1 shows the geometry when both aircraft offset to the right by o_1 and o_2 NM. No collision risk modelling formulae are included, but it can be concluded that Section C.9 is based on of SASP-WG/30-WP/08 (Barry, 2017a). This working paper was reviewed earlier under the *SASP-WG/30, Canberra, November 2017* heading. Equation 10 of paragraph 2.11 of SASP-WG/30-WP/08 presented the longitudinal collision risk model used, effectively the collision risk model of eq. (7.212) but with eqs. (7.213) and (7.214) replaced by

$$D_x(t) = (v_1 - v_2 \cos \theta)t - d_1 + d_2 \cos \theta - o_2 \sin \theta \quad (7.286)$$

$$D_y(t) = (d_2 - v_2 t) \sin \theta - o_1 + o_2 \cos \theta \quad (7.287)$$

with o_1 and o_2 denoting the lateral offsets to the right of track applied by the two aircraft. (Compare Appendix C.9 Figure C.9.2 and SASP-WG/30-WP/08 Figure 12, Appendix C.9 Figure C.9.3 and SASP-WG/30-WP/08 Figure 14, and Appendix C.9 Table C.9.1 and SASP-WG/30-WP/08 Table 2.)

Section C.10 of Appendix C to SASP-3-WP/02 summarized ASEPS longitudinal separation for reciprocal tracks. It can be concluded that Section C.10 is based on of SASP-WG/30-WP/12 (Barry, 2017e), reviewed earlier under the *SASP-WG/30, Canberra, November 2017* heading.

Finally, Section C.11 of Appendix C to SASP-3-WP/02 (Barry, 2020) touches very briefly on longitudinal monitoring, referring the reader to ICAO Doc 10063, *Manual on Monitoring the Application of Performance-based Horizontal Separation Minima* (ICAO, 2017b).

Summary of ASEPS longitudinal separation development

The development of longitudinal separation minima for what was initially called *space-based ADS-B*, then *ASEPS*, and ultimately *ATS surveillance systems where VHF voice communication is not available* started at SASP-WG/25 in November 2014 following Recommendation 1/9 – *Space-based automatic dependent surveillance – broadcast* from the ICAO 12th Air Navigation Conference in November 2012. The development of lateral separation minima started at SASP-WG/27 in November 2015. As concluded in SASP-WG/29-WP/09 (Barry, 2017f), ASEPS longitudinal separation standards were much simpler and less controversial than their lateral counterparts. A PANS-ATM amendment proposal for the ASEPS separation minima (longitudinal and lateral) was approved by the SASP at its 2nd Panel Meeting in May 2018. The development of the corresponding Circular/Manual providing implementation guidance for the new separation minima continued up to December 2019.

A State Letter asking for comments on the new proposed separation minima agreed at SASP/2 (May 2018) was sent out on 28 March 2019 (ICAO State Letter, 2019). Following that, the new separation minima were approved by the ICAO ANC for inclusion into the 16th edition of the PANS-ATM under Amendment 9 to the 16th edition, to become applicable on 5 November 2020. See also the *Manual for Separation Minima Using ATS Surveillance Systems Where VHF Voice Communication is not Available (Doc 10116)* (ICAO, 2020a).

7.3.9 Performance-based longitudinal separation minima

7.3.9.1 Introduction

As shown under the fifth entry in Table 2.5 of Chapter 2, three performance-based longitudinal separation minima were incorporated into the 16th Edition of the PANS-ATM under Amendment 7A, namely 50 NM en 30 NM distance-based longitudinal separation and 5 minute time-based longitudinal separation with an applicability date of 10 November 2016. These minima were based not only on performance-based required navigation performance, but also on performance-based required communication performance (RCP 240¹³⁵) and performance-based required surveillance performance (RSP 18), i.e. PBCS. See ICAO Circ 343. The two distance-based longitudinal separation minima replaced the same minima previously available as longitudinal separation minima based on distance using RNAV where RNP is specified, of which the collision risk modelling was described in Sections 7.3.2 – 7.3.4. The 5 minute time-based longitudinal separation minimum is a fully performance-based equivalent of RLongSM analysed in Sections 7.2.6 and 7.2.7. As described there, RLongSM was initiated by the NAT SPG at its 44th Meeting in 2008 and was subsequently “upgraded” to a globally applicable longitudinal separation standard/minimum as a result of an ICAO ANC decision to have the SASP monitor the efforts of the NAT SPG to advance this standard/minimum, review the modelling work undertaken, and develop an amendment to the PANS-ATM prior to implementation. It is recalled that both the original 30 NM longitudinal separation standard/minimum and RLongSM required the performance-based RNP 4 navigation specification, but did not require performance-based communication and surveillance (PBCS), i.e. performance-based communication (RCP 240) and surveillance performance (RSP 180).

¹³⁵ The numbers following RCP and RSP refer to maximum time intervals in minutes.

A 20 NM performance-based longitudinal separation minimum was subsequently incorporated into the 16th edition of the PANS-ATM under Amendment 9 to the 16th Edition, to become applicable on 5 November 2020.

A brief discussion of the work performed by the SASP on the four above mentioned fully performance-based longitudinal separation minima is provided by meeting below. The work is essentially based on the use of the longitudinal collision risk model of SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) and started effectively at SASP-WG/1, November 2011, by examining the feasibility of allowing 30 NM longitudinal separation and RLongSM for RNP 2 approved aircraft in addition to RNP 4 approved aircraft. An operational requirement was developed at this Meeting for the SASP MSG to start work on longitudinal collision risk modelling for the RNP 2 navigation specification. See Chapter 2 of Part C of Volume II the PBN Manual (ICAO Doc 9613) or Section 2.4 of NLR-CR-2014-385 (Moek, 2014) for details of this navigation specification. The work was formalised under the ANC-approved Job Card SASP006 at SASP-WG/WHL/21, Seattle, November 2012. The Job Card was subsequently revised at the next meeting, SASP-WG/WHL/22, Montreal, May 2013, to incorporate PBCS. At this same Meeting, an action was put on the SASP to consider the creation of a Circular documenting the work on the subject. Use of actual or observed navigation performance rather than specified PBN navigation performance started at SASP-WG/WHL/20 and SASP-WG/WHL/21 in May and November 2012 respectively.

The meetings have been combined into four groups. The first group of meetings may be considered to concern exploratory work. The second group of meetings starts with the agreement on a PANS-ATM amendment for the performance-based 50 NM, 30 NM and 5-minutes longitudinal separation minima, and the decision to proceed with further work on a performance-based 20 NM longitudinal separation standard. This group concludes with the final version of the Circular concerning the implementation of the three separation minima covered by the PANS-ATM agreement. The third group of meetings starts at SASP/1, November 2016, where performance-based 20 NM and 30 NM longitudinal separation standards were revisited using revised communication and surveillance models based on improved SASP understanding of such model's and of speed error modelling. It ends at SASP/2, May 2018, when a PANS-ATM amendment for a performance-based 20 NM longitudinal separation minimum with 192-second periodic ADS-C reporting interval was agreed. The fourth group of meetings starts at SASP-WG/31, November 2018, and reports on the work performed on completing an ICAO Manual (rather than Circular) for the four performance-based longitudinal separation minima of 20 NM, 30 NM, 50 NM and 5 minutes.

7.3.9.2 SASP-WG/1 (Cairns, November 2011) to SASP-WG/WHL/23 (November 2013)

It is remarked in advance that this subsection is concluded by a table, Table 7.23, that summarizes the main points of each of the meetings described below. The Table should assist the reader in keeping track of how SASP's work on the subject evolved over time. In addition, the Table includes details not presented in the main text of this Subsection.

SASP-WG/1, Cairns, November 2011

SASP-WG/1-WP/22 (Barry & Aldis, 2011) reported an initial analysis of oceanic RNP 2 collision risk using what was referred to as a "literal interpretation" of PBN navigation performance, meaning that an RNP 2 aircraft would navigate much more accurately than an RNP 4 aircraft. This interpretation, however, may not apply well to GNSS-equipped aircraft which, generally, navigate to the same accuracy regardless of PBN category. Nonetheless, RNP 2 oceanic was then taken to mean that navigation performance for along- and across-track

position errors satisfied conservative PBN-based requirements of 95% within 2 NM of the nominal position, and a probability of 0.00001 of being outside 4 NM of the nominal position. Communication between ATC and a pilot was assumed to be by CPDLC as primary means with HF voice as a secondary backup. Surveillance was assumed to be by periodic ADS-C reporting. Both CPDLC messages and ADS-C reports were assumed to be delivered by satellite. The working paper examined both longitudinal and lateral separation, but only the longitudinal work is relevant to the current Section of this Document. The methodology used was that of SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005), i.e. what is referred to in this Document as the methodology of the general collision risk model based on reliability theory, see Sections 7.3.2 – 7.3.4.

The collision risk model was recalled from (Anderson, 2005) in Section 2 of SASP-WG/1-WP/22 as

$$CR(t_0, t_1) = NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) P_z(h_z) \left(\frac{2V_r}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right) f_1(V_1) f_2(V_2) dt dV_1 dV_2 \quad (7.291)$$

with the probability of horizontal overlap $HOP(t|V_1, V_2)$ for the general case given by

$$HOP(t|V_1, V_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{d_h < \lambda_{xy}} f_1^A(\varepsilon_1^A) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_1^C) f_2^C(\varepsilon_2^C) d\varepsilon_1^A d\varepsilon_2^A d\varepsilon_1^C d\varepsilon_2^C \quad (7.296)$$

The four-fold integral is over all values of the navigation error variables ε such that the horizontal distance d_h between the aircraft centres is less than the average aircraft size λ_{xy} . The four-fold integral of eq. (7.296) may be approximated by the two-fold integral of eq. (7.292). (The model of eq. (7.291) is the same as that of eq. (7.212) presented under the last, *SASP-WG/WHL/7, Montreal, May 2005* heading in Section 7.3.4.1 for same-track procedural longitudinal separation based on (Anderson, 2005) in the notation as derived in this document.)

The paper started reproducing same-identical track (zero angle) results for RNP 4 for the collision risk model parameter values used in the past, recalled in paragraph 1.4 of SASP-WG/1-WP/22, for the 30 NM and 50 NM longitudinal separation standards S_x with maximum reporting intervals T of 14 and 32 minutes respectively and double-exponentially distributed navigational errors. The standard deviation of the navigational error distributions was determined from the 95% accuracy requirement of the RNP 4 navigation specification. For each of the two separation standards, the overall longitudinal collision risk was calculated as a weighted combination over three values of the intervention buffer τ , namely $\tau = 4$, $\tau = 10.5$, and $\tau = 13.5$ minutes. Cf. Tables 6 – 8 of (Anderson, 2005) and eq. (7.295) of Section 7.3.8. The same collision risk model parameter values were then used for RNP 2 except for the RNP 4 navigation performance requirements which were replaced by the RNP 2 requirements stated above. The additional calculations resulted in the initially counter-intuitive result that the (weighted) risk for RNP 2 was larger than that for RNP 4 for each of the two separation standards. It was explained, however, that given that a longitudinal overlap has occurred as a result of a large speed difference between the aircraft, the higher RNP 2 lateral navigation accuracy results in a higher probability of lateral overlap and hence higher probability of collision.

Some further same-track calculations were performed for RNP 2 and a longitudinal separation standard of $S_x = 20$ NM with the intersection angle θ varying between $[0, 45]$ degrees and total response times $T_r = T + \tau$ ranging from 14 up to 38 minutes inclusive. These calculations indicated that a 20 NM longitudinal separation standard for oceanic RNP 2 appeared difficult to achieve unless reporting times are reduced and communications are faster.

Reciprocal-track (180 degrees intersection angle) longitudinal collision risk for RNP 2 navigation performance was also examined in the working paper for a longitudinal separation standard of $S_x = 20$ NM. For the reciprocal case, one of the aircraft is cleared to change level when it is at least a distance S_x^R , say, $S_x^R \geq S_x$, from the other aircraft and the distance between the aircraft is increasing.

As set out in the *Discussion* section of SASP-WG/1-WP/22, the working paper's results indicated that for an oceanic same-identical (zero angle) track scenario, a reduction in RNP may increase the collision risk for a fixed separation standard and that reducing the longitudinal separation standard from 30 NM to 20 NM therefore results in unacceptable collision risk for that scenario with RNP 2. Some suggestions for further work concerned the use of Gaussian rather than double exponential navigational error distributions for RNP navigation specifications, some operational judgement about physically reasonable aircraft speed errors, re-consideration of the value of the *NP* parameter of the collision risk model, and updated values for the remaining collision risk model parameters.

A brief overview of SASP-WG/1-WP/22 was presented to the SASP plenary, which subsequently referred the working paper to Project Team 16, *Horizontal*, and the MSG for further detailed review. The MSG was then provided with an operational requirement, OR 32, to “Develop criteria to determine the distance by which suitably approved aircraft can be (longitudinally) separated for same, crossing and reciprocal tracks based on the RNP 2 navigation specification and as amended using actual navigation performance data” (Butcher et al., 2011).

A flimsy (Flimsy 5) was presented to SASP Project Team 6, *Longitudinal*, intended to provide a first draft of an amendment proposal to the PANS-ATM, ICAO Doc 4444, for longitudinal separation minima being developed for RNP 2. The key of the amendment proposal was to add RNP 2 approved aircraft to the RNP 4 aircraft (then) currently approved for 30 NM longitudinal separation using ADS-C.

See also Table 7.23 at the end of this Subsection 7.3.9.2.

SASP-WG/WHL/20, Montreal, May 2012

Two working papers dealing with collision risk under RNP 2 navigation were reviewed by SASP PT 6, *Longitudinal*, and the MSG, namely SASP-WGH/20-WP/10 (Barry & Aldis, 2012a) and SASP-WGH/20-WP/20 (Barry & Aldis, 2012b).

SASP-WGH/20-WP/10 (Barry & Aldis, 2012a) considered longitudinal collision risk only and, except for a 5-degree same-track intersection angle example, was limited to same-identical (zero angle) tracks. It extended the pertinent longitudinal work of SASP-WG/1-WP/22 (Barry & Aldis, 2011) by using the same methodology, see the collision risk model of eqs. (7.291) and (7.296) above, and collision risk model parameters, except for navigation performance, i.e. it utilised a range of actual navigation performance (ANP) values, which would include track-keeping performance of GNSS-equipped aircraft, rather than “literal” specified RNP performance. First, assuming the ANP value to be equal to the RNP value, it was shown that 30 NM was acceptable, i.e. met the TLS, for RNP 2 with a 14 minute reporting period in the same manner as for RNP 4 on the assumption that ANP 4 is equal to RNP 4. However, the assumption of the ANP value to be equal to the RNP value for RNP 2 and RNP 4 navigation specifications was heavily queried because the navigation infrastructure for RNP 4 as well as RNP 2 is based on GNSS and GNSS track-keeping performance was estimated to be roughly equivalent to or better than ANP 0.1 and, for sufficiently low ANP, the lower the ANP value the higher the same-identical (zero angle) track longitudinal collision risk. Consequently, it was

concluded that the historic methodology used for RNP 4 and a 30 NM longitudinal separation standard should have been conducted with RNP 0.1 or less. Assuming again the ANP value to be equal to the RNP value, 20 NM longitudinal separation was not acceptable for RNP 2 or RNP 4. The problem only existed at small intersection angles such as the same-identical (zero angle) track case.

The results reported in the previous paragraph were obtained as a part of an analysis of same-identical (zero angle) track longitudinal collision risk evaluated for $ANP = RNP \in [0.02, 10]$. For $ANP = RNP \in [0.02, 0.1]$ NM, the risk was found to be higher than for $ANP = RNP = 2$ NM. A lateral offset of 0.5 NM was shown to successfully mitigate the additional collision risk for GNSS accurate aircraft on same identical (zero angle) tracks.

A 5-degree same-track intersection angle example showed that the risk generally decreased with ANP.

SASP-WGH/20-WP/20 (Barry & Aldis, 2012b) was another extension of SASP-WG/1-WP/22 (Barry & Aldis, 2011) and examined both longitudinal and lateral separation for oceanic RNP 2, where, again, only the longitudinal work is relevant to the current Section of this Document. Like SASP-WGH/20-WP/10 the extension concerned the use of a range of ANP values, but limited to RNP 2, i.e. ANP values from 0.05 NM to 2 NM. Unlike SASP-WGH/20-WP/10, working paper 20 considered longitudinal separation for same-identical (zero angle) tracks, same-direction tracks, and reciprocal tracks (same-direction (180 degree) tracks). Same-direction tracks were represented by a 10 degree intersection angle, since this angle gave the maximum collision risk over angles $\theta \in [10, 45]$ degrees. A zero angle had a distinctly different behaviour than other angles. Otherwise, the collision risk model of eqs. (7.291) and (7.296) above with its original collision risk model parameters except for navigation performance was utilised. The (weighted) longitudinal collision risk, as a function of separation standard, intersection angle, and reporting interval, was maximised over all values of ANP from 0.05 NM to 2 NM.

The results for same-track longitudinal separation indicated that:

- 1) With no offset a 30 NM separation is above the TLS for same-identical (zero angle) track;
- 2) With no offset a 25 NM separation is below the TLS if the crossing angle $\theta > 10$ degrees and the reporting period is 14 minutes;
- 3) With no offset a 20 NM separation is below the TLS if the crossing angle $\theta > 10$ degrees and the reporting period is 10 minutes;
- 4) With a 1 NM offset a 30 NM separation is below the TLS for a reporting period of 14 minutes;
- 5) With a 1 NM offset a 25 NM separation is below the TLS for a reporting period of 10 minutes;

The results for reciprocal (180 degree angle) longitudinal separation indicated that:

- 1) With no offset a 25 NM separation is below the TLS for reporting periods of 14 minutes; and
- 2) With a 0.5 NM offset a 20 NM separation is below the TLS for reporting periods of 14 minutes.

See also Table 7.23 at the end of this Subsection 7.3.9.2.

SASP-WG/WHL/21, Seattle, November 2012

The Secretary presented two working papers entitled *Preparation of Job Cards* (SASP Secretary, 2012a) and *SASP Work and Future Work programme, and Status of Work* (SASP Secretary, 2012b). The papers noted that the Air Navigation Work Programme is that portion of the ICAO Business Plan that outlines the work and other activities in the air navigation field relating to the intended development of provisions by ICAO. The

Business Plan, and hence the Air Navigation Work programme, is approved by the Council. Proposals for new or future work items for Panels and Study Groups are normally developed during meetings and then included in the meeting report¹³⁶. The ANC requested that all new proposals be outlined in the Job-card format as the ANC Working Group for Strategic Review and Planning (WG/SRP) will usually consider the proposals during a review of the Panel or Working Group Meeting report. Progress of the Air Navigation Work programme is normally undertaken by the ANC Working Group of the Whole for Air Navigation Work Programme Deliverables Production (WG/PDP) in association with the relevant champion team(s). Significant known or discovered deviations from the approved work plan shall be reported to the WG/SRP for consideration of amendment of the Air Navigation Work programme.

During the briefing to the ANC related to the outcome of SASP-WG/WHL/20 (Montreal, Canada, 14 to 25 May 2012), examples of the future work of the SASP were highlighted. Before any work can commence, the ANC has to approve the work, based on the completed Job Cards, as highlighted in the Report of the Meeting. In light of this, SASP-WG/WHL/21-WP/5 provided a total of seven Job Cards, six of which originated from the SASP's previous WG/WHL/20 meeting whereas the remaining one had been drafted by a member of the ANC. See also (SASP, 2012). The Job Card relevant to this Section of this Document was entitled *Development of PBN based RNP 2 and Advanced RNP longitudinal and lateral separation minima for oceanic and continental airspace*. During the presentation of the working paper, the Secretary informed the Meeting that the seven Job Cards would be considered by the ANC on 30 October 2012, and asked that the Meeting review the Job Cards, confirming the deliverables and time frame for ANC review and implementation. Subsequently, the Secretary informed the Meeting that the ANC had approved all the Job Cards with one minor amendment. The Meeting reviewed and confirmed the data in the Job Cards.

SASP-WGH/21-WP/11 (Barry & Aldis, 2012c) extended the previous work of SASP-WG/1-WP/22, SASP-WGH/20-WP/10 and SASP-WGH/20-WP/20 using again the collision risk model of eqs. (7.291) and (7.296) above with the pertinent collision risk model parameters except for navigation performance. For the latter, it used the concept of observed navigation performance (ONP), where ONP X was considered to have the same position error distribution as RNP X, but an aircraft approved as RNP X may have an ONP X which is much lower than X. An ONP X range from 0.05 NM to 2 NM was examined. Previous work showed that same-track collision risk was dominated by the tail-ends of the velocity probability distributions, extending up to ± 100 knots from the mean. To better reflect the physical limitations of the aircraft as well as Mach number restrictions imposed by ATC, the tail-ends of the speed distributions for each aircraft were restricted, particularly to ± 24 knots and ± 50 knots. Communication and surveillance performance was also taken the same as in the previous three papers, but with an outlook to some refinements presented in SASP-WGH/21-WP/14 (Barry & Aldis, 2012d). The working paper examined both longitudinal and lateral separation but the longitudinal work only is relevant to the current section of this document.

The results of the collision risk calculations indicated (again) that for same-track longitudinal separation the collision risk is highly dependent on the velocity difference between the two aircraft. Since the aircraft may be flying with an ONP of 0.05 NM, the collision risk becomes very high if the trailing aircraft can catch up to the leading aircraft. Specifically, the results assuming ONP could be as large as 2 NM and as low as 0.05 NM suggested that:

¹³⁶ See for example the work on oceanic RNP 2 longitudinal separation described under the *SASP-WG/1, Cairns, November 2011*, heading in this subsection.

1. If Mach limitations and appropriate monitoring are enforced by ATC to restrict the tail-ends of the speed distributions for each aircraft to ± 24 knots from the mean, then for RNP 2 aircraft a 20 NM separation standard and reporting time of 10 minutes gave a collision risk estimates below the TLS;
2. If Mach limitations and appropriate monitoring are enforced by ATC to restrict the tail-ends of the speed distributions for each aircraft to ± 24 knots from the mean, then with a 2 NM offset a 20 NM separation standard and reporting time of 14 minutes gives a collision risk estimate below the TLS.

In addition, the results assuming what might be more realistic values for ONP of less than 0.3 NM with GNSS-equipped aircraft suggested that

1. A 20 NM longitudinal oceanic separation with a 1 NM SLOP and a reporting period of 14 minutes gave collision risk estimates below the TLS.

SASP-WGH/21-WP/11 (Barry & Aldis, 2012c) and SASP-WGH/21-WP/14 (Barry & Aldis, 2012d) were presented in a joint meeting of SASP Project Team 6, *Longitudinal*, and the MSG. In dealing with the subject, Project Team 6, *Longitudinal*, also discussed a triple of draft PANS-ATM proposals for oceanic RNP 2 separation standards/minima as documented in WP/13, WP/15 and WP/17. Specifically, SASP-WG/WHL/21-WP/17 (Kraft, 2012) proposed to clarify the assumptions concerning communication and surveillance performance underlying the then existing 30 NM and 50 NM distance-based longitudinal separation standards by identifying RCP and RSP specifications which were contained in GOLD (ICAO, 2013a) at the time and which were planned for incorporation into the RCP manual (ICAO, 2006b). The discussions resulted in the revised PANS-ATM amendment proposal of SASP-WG/WHL/21-Flimsy 22 (Unknown, 2012) and a triple of actions, subsequently agreed by the SASP plenary as follows:

1. The Secretary to coordinate the amendment proposal detailed in SASP-WG/WHL/21-Flimsy 22 (Unknown, 2012) to the ANC when it is established that the supporting OPLINK Doc 9869 material and other consequential document changes are ready for publication in a similar amendment cycle;
2. The Secretary to coordinate to the ANC, an amended Job Card relating to RNP 2 separation. The Job Card to detail two extra tasks to coordinate with the OPLINK to ensure their work to publish the new Doc 9869 and other consequential document changes are completed to support publication of the SASP amendment, and to have SASP review the modelling for the 50 NM and 30 NM minima to establish if changes to the reporting rates are required given the availability of updated, more realistic modelling assumptions. (The two extra tasks were provided as a draft Job Card SASP011.); and
3. The Secretary to highlight to the ANC the need to consider the review of PANS-ATM Chapter 5 for organisation and clarity purposes.

See also Table 7.23 at the end of this Subsection 7.3.9.2.

SASP-WG/WHL/22, Montreal, May 2013

The Secretary presented to the plenary SASP-WG/WHL/22-WP/14 (SASP Secretary, 2013), which provided details of the ANC WG/SRP review of the Report of the Twenty-first Meeting of the SASP (SASP-WG/WHL/21). In connection with the three actions listed above under the previous heading, the WG/SRP agreed that action #3 was not an urgent issue and that the draft Job Card SASP011 be rejected since the two tasks described in it under action #2 could be encompassed by the approved Job Card SASP006. This topic was subsequently assigned to and dealt with by SASP Project Team 6, *Longitudinal*, by carefully comparing the two Job Cards SASP006 and SASP011 and transferring the identified actions from the latter to the former. The Secretary was tasked to coordinate the revised SASP006 Job Card to the WG/SRP and ANC. The working paper provided no reference to the above action #1.

Another working paper presented to the SASP plenary was SASP-WG/WHL/22-WP/16 (Kraft, 2013). This working paper proposed a draft Job Card SASP[nnn] entitled *Performance-based Communication and Surveillance (PBCS)* to progress work related to identifying, tracking and coordinating the relevant required communication performance (RCP) and required surveillance performance (RSP) specifications in separation minima in support of global implementation of performance-based communication and surveillance (PBCS). The plenary reviewed and endorsed the draft Job Card and the Secretary was tasked to progress the Job Card to the ANC for endorsement.

There was also plenary discussion on the following view on longitudinal separation standards and navigation accuracy requirements (Section 2.9 of the SASP-WG/WHL/22 Meeting Report). If only centreline tracking accuracy is considered, noting that PBN specifications do not focus on along-track accuracy, then the longitudinal risk would increase with increased lateral navigation accuracy. However, ICAO Doc 4444, PANS-ATM, (then) currently indicated that a better RNP performance (i.e. increased lateral navigation accuracy) results in decreased longitudinal separation instead of the expected increased separation. However, based on the work on longitudinal separation for oceanic RNP 2 presented at the previous three SASP Meetings, it was understood that the most important factors in determining longitudinal separation were the reporting intervals, speed variability, and the accuracy of position reports. If all FANS aircraft are providing GNSS-based automatic dependent surveillance – contract (ADS-C) position reports, then the longitudinal separation that (then) currently required ADS-C should apply to all FANS aircraft regardless of PBN specification. Consequently, the new 20 NM RNP 2 longitudinal separation should be applicable to RNAV 10 and RNP aircraft. The plenary discussion resulted in the following action:

- Review the previous amendment proposal for 20 NM longitudinal separation and determine how the concept that PBN has no specific bearing on longitudinal separation will affect it and what impact it will have on currently published separation standards.

Technically, longitudinal separation for oceanic RNP 2 under Job Card SASP006 was addressed in SASP-WG/WHL/22-WP/08 (Barry & Aldis, 2013c). The working paper was an extension and re-interpretation of the previous work of SASP-WG/WHL/20-WP/10, SASP-WG/WHL/20-WP/20, SASP-WG/WHL/21-WP/11 and SASP-WG/WHL/21-WP/14 and considered again the existing 50 NM RNAV 10 and 30 NM NP standards as well as the proposed 20 NM RNP 2 standard. The working paper's introduction listed the following three goals to the paper:

1. To demonstrate that reduction of the reporting time T can give rise to much reduced collision risk and/or a wider range of possible aircraft speeds;
2. To revisit the existing 30 NM and 50 NM standards to investigate the behaviour of the collision risk with reporting time, considering that GNSS-equipped aircraft may have an observed navigation performance (ONP) as good as 0.05 NM; and
3. To revisit the proposed 20 NM standard to investigate the behaviour of the collision risk with reporting time, considering that GNSS-equipped aircraft may have an observed navigation performance (ONP) as good as 0.05 NM.

The paper looked at collision risk over a range of ONP from 0.05 NM to 10 NM and, as in SASP-WG/WHL/21-WP/11, the tail-ends of the speed distributions for each aircraft were restricted to ± 24 knots or ± 50 knots. Communication and surveillance performance was taken the same as in the previous four working papers and the longitudinal collision risk model and its remaining parameters too. Same-identical (zero angle) track longitudinal separation was considered only. The results indicated that a reduction in the reporting time can give a large reduction in risk or allow a wider range of allowable aircraft speed variations indeed. The paper

then argued for reporting times to be $T = 4, 10$ and 20 minutes for the respective 20 NM (RNP 2), 30 NM (RNP 4), and 50 NM (RNAV 10) standards.

The working paper was presented to SASP Project Team 6, *Longitudinal*, as well as to the SASP MSG. The Project Team 6 presentation generated a great deal of discussion over a number of areas, including the capability of the FANS system to support reporting intervals of less than 5 minutes. In terms of modelling, the view was put forward that realistic but very conservative assumptions should be used whenever possible so that the outcomes can readily be used for global application. The MSG agreed to review the parameters for use in further calculations. Based on the Project Team 6 Report, the SASP plenary endorsed the following actions:

- The authors of in SASP-WG/WHL/22-WP/08 to provide clarification on the assumptions used to generate the paper's output to the next SASP Meeting;
- SASP to determine whether/which speed assumptions used in in SASP-WG/WHL/22-WP/08 are realistic enough to be beneficial;
- SASP to determine whether PANS-ATM should be amended to reflect recommended ADS-C reporting rates generated by recent modelling; and
- SASP to consider creating an ICAO Circular to both catalogue previous and ongoing work for the RNAV 10, 50 NM and RNP 4, 30 NM longitudinal minima and development of RNP 2, 20 NM minimum.

SASP Project Team 6, *Longitudinal*, and the SASP MSG were also given a presentation of SASP-WGH/WHL/22-WP/20 (Falk, 2013a), which contained several analyses on observed aircraft speed. The data in the paper were taken from two different oceanic airspaces. Estimates of aircraft predicted and actual speed were made for aircraft operations using ADS-C. In addition, the predicted speed error for along-track operations was observed. The data should be useful for the aircraft speed distribution modelling.

See also Table 7.23 at the end of this Subsection 7.3.9.2.

SASP-WG/WHL/23, New Delhi, November 2013

SASP-WG/WHL/23-WP/11 (Stefansson, 2013) presented some thoughts for consideration in SASP's work on longitudinal separation¹³⁷. The paper started noting that ATS surveillance separation (radar/ADS-B) with direct controller pilot voice communications and distance-based longitudinal separation using ADS-C and CPDLC are totally different concepts of separation provision and hence require different methods to ensure the safety of the aircraft being separated. It continued arguing that oceanic Flight Data Processing Systems (FDPSs) manage longitudinal separation by means of advanced wind models applied to a three-dimensional flight profile and an assumed speed (either assigned or derived by other methods). Advanced wind models are needed due to the long time-interval between position updates. As a result, the controller situation display is actually driven by local calculations rather than actual surveillance reports, where the actual calculation of longitudinal separation is always going to be based, either wholly or partly, on future projections involving time, distance and speed, which in turn requires modelling of wind aloft. The paper then stated that mathematicians claim that the highest longitudinal collision risk is found between aircraft operating on the same-identical (zero angle) track and that it should be discussed whether this collision risk modelling ignores the inherent inaccuracies that weather models have on speed profiling aircraft on intersecting tracks.

¹³⁷ Cf the discussion in the third paragraph under the previous, *SASP-WG/WHL/22, Montreal, May 2013*, heading.

For the same-identical (zero angle) track case, a pair of in-trail aircraft will be experiencing the same winds and temperatures and weather modelling is therefore not as important. On the contrary, aircraft operating on intersecting tracks may be experiencing different winds and temperatures and may therefore have different ground speeds even though the true airspeed or Mach speed is the same and weather modelling would thus be more important. As a result, it would seem logical to assume a greater speed variance between aircraft operating on intersecting tracks than between aircraft operating on the same-identical (zero angle) track.

The working paper then referred to the effect of the Required Navigation Performance (RNP) on longitudinal separation as discussed at the previous SASP Meeting, SASP-WG/WHL/22, noting that the (then applicable) PANS-ATM indicated that better RNP performance results in decreased longitudinal separation minima whereas SASP's recent collision risk modelling has shown that increased centreline tracking accuracy, i.e. better RNP performance, resulted in increased collision risk and hence increased longitudinal separation minima.

The working paper next made the point that SASP's work on longitudinal separation from the previous three meetings has shown that the most important factors in determining the collision risk are the reporting intervals, speed variability and the accuracy of the position reports. Consequently, if all FANS-equipped aircraft are providing GNSS-based position reports, then the longitudinal separation that currently requires ADS-C should apply to all FANS aircraft regardless of PBN navigation specification. Therefore, the existing 50 NM, 30 NM, and the new 20 NM longitudinal separation minima should be equally applicable to all FANS-equipped aircraft regardless of the PBN navigation specification.

Finally, the working paper made a plea for extending same-track longitudinal separation to intersection angles from 44 degrees to less than 90 degrees (89 degrees) and for the SAP making conservative assumptions to enable the separation minima to be applied in as many operational environments as possible without requiring further collision risk calculations.

The thoughts described above may be summarized in the following items:

1. Same-identical (zero angle) track against intersecting tracks;
2. Effect of better RNP performance on increasing/decreasing longitudinal separation minima;
3. FANS-equipped aircraft approved for different PBN navigation specifications all using GNSS-based position reporting;
4. Extending same-track longitudinal separation to intersection angles less than 90 degrees;
5. Conservative assumptions for the benefit of the widest possible global application.

SASP Project Team 6, *Longitudinal*, and MSG discussion of the working paper resulted in the following. As regards item 1, it was explained by the MSG that for same-identical (zero angle) track there exists a possibility for horizontal overlap over a certain track length, whereas for intersecting tracks the possibility of horizontal overlap is essentially constrained to a single point, i.e. the route-intersection point. As regards item 2, the key was the use of observed navigation performance, which, when it is much better than the specified RNP performance, actually increases the same-track (zero angle) longitudinal collision risk. The effect may be compared with the effect of RVSM when vertical separation would be lost. Item 3 was met with general consensus and the opinion was expressed that this, together with the increased dependence on performance to support separations, should be reflected by a requirement written into the separation standards for system monitoring to be conducted by ANSPs. Items 4 and 5 were also supported by the plenary. Further discussion led to re-visiting the PANS-ATM amendment proposal agreed at the previous Meeting, which was

acknowledged to be on hold pending proposed supporting changes to RCP Manual (ICAO Doc 9869) (to result in PBCS Manual). Nonetheless, the amendment proposal was revised to account for the latest insights as discussed by the plenary.

Two working papers on observed aircraft speeds were presented in connection with longitudinal separation, see SASP-WG/WHL/23-WP/13 (Palsson & Stefansson, 2013) and SASP-WG/WHL/23-WP/16 (Falk, 2013b).

Technically, longitudinal separation for oceanic RNP 2 under Job Card SASP006 was addressed in SASP-WGH/23-WP/02 (Barry & Aldis, 2013b) which clarified issues raised from SASP-WGH/22-WP/08 (Barry & Aldis, 2013c) of the previous meeting, concerning the sensitivity of results to different

- a) Communication assumptions;
- b) Aircraft speed error distribution parameters; and
- c) Values for the number of pairs parameter NP .

The aim of the working paper was to ensure that the conclusions from the previous working paper(s) were still valid and independent of the specific assumptions included in the model. SASP-WGH/22-WP/08 provided recommended combinations of ADS reporting interval, communication performance, Mach limitation and monitoring for RNP 2/20 NM separation and RNP 4/30 NM separation. As in the previous papers, the collision risk model used was that specified by eqs. (7.291) and (7.296) but with the pertinent collision risk model parameters as detailed in the working paper.

Results from the working paper revealed that communication factors, particularly assumptions surrounding delays, significantly increased the risk involved in applying the separations considered and resulted in recommended separation values much greater than would normally be anticipated. As regards the effect of aircraft speed distributions, it was agreed that the model would be rerun using the data derived from SASP-WG/WHL/23-WP/16. Results of rerunning the longitudinal collision risk model were made available later in the meeting in WG/WHL/23-FL/03 (Barry & Aldis, 2013a). The latest results were summarised in a table for four scenarios of RNP, longitudinal separation standard S_x , reporting time T , route intersection angle θ , offset, and monitoring requirements. One scenario, RNP 4/30 NM/ $\theta \geq 0^\circ$ required a reporting time of 8 minutes whereas the other three scenarios, RNP 4/20 NM/ $\theta \geq 0^\circ$, RNP2/20 NM/ $\theta \geq 10^\circ$, and RNP2/20 NM/ $\theta \geq 0^\circ$ required a 4 minute reporting time. The 20 NM standard for intersection angles θ , $\theta \geq 0^\circ$, also required a lateral offset of 0.5 NM. Final discussion of all results resulted in four actions regarding further possible analysis of the speed distribution of aircraft that have been assigned a fixed Mach speed, provision of an analysis similar to that of SASP-WG/WHL/23-WP/13 using Australian data, possibly including data from different times of the year, analysis of Australian speed error using ADS-B data, and the SASP Secretary to seek information on what is the highest ADS-C reporting rate that the SASP can assume for application of performance-based longitudinal separation for oceanic RNP 2 and RNP 4.

See also Table 7.23 in the Appendix.

7.3.9.3 SASP-WG/WHL/24 (Montreal, May 2014) to SASP-WG/WHL/28 (Reykjavik, May 2016)

It is remarked in advance that this subsection is concluded by a table, Table 7.24, which summarizes the main points of each of the meetings described below. The Table should assist the reader in keeping track of how SASP's work on the subject evolved over time.

SASP-WG/WHL/24, Montreal, May 2014

Performance-based longitudinal separation for oceanic RNP 2 and RNP 4 was addressed in three working papers concerning the circular, SASP-WG/WHL/24-WP/08 (Barry & Aldis, 2014a), and PANS-ATM amendment, WP/20 (Butcher & Barry, 2014) and WP/21 (Kraft, 2014), and in two working papers on aircraft speeds, WP/7 (Barry & Tsang, 2014c) and WP/19 (Falk, 2014b). Although the aircraft speed distribution constitutes a very important parameter of the longitudinal collision risk model, a detailed discussion of SASP-WG/WHL/24-WP/7 and SASP-WG/WHL/24-WP/19 is beyond the scope of this document. Information papers were provided on proposed work in the NAT region to determine the ADS-C minimum reporting interval, IP/05 (Stefansson, 2014a), and on progress of the Operational Data Link Panel (OPLINKP) related to performance-based communication and surveillance (PBCS), IP/06 (SASP Secretary, 2014).

SASP-WGH/24-WP/08 (Barry & Aldis, 2014a) summarized the previous work of SASP-WG/1-WP/22, SASP-WGH/20-WP/10, SASP-WGH/20-WP/20, SASP-WGH/21-WP/11, SASP-WGH/21-WP/14, SASP-WGH/22-WP/08, SASP-WGH/23-WP/02 and SASP-WGH-23-FL/03 on 50 NM, 30 NM, and 20 NM performance-based longitudinal separation for same-identical (zero angle) track and same track ($0^\circ < \theta \leq 45^\circ$) as a function of RNP type, i.e. RNP 10, RNP 4, or RNP 2, maximum ADS-C periodic reporting interval, and lateral offset/intersection angle requirement. The working paper strongly emphasized monitoring of airspace features in connection with variation of aircraft speed estimates, longitudinal entry separation distribution, aircraft dimensions, required communication performance (RCP 240, 400) and required surveillance performance (RSP 180). Following the presentation of the paper to SASP Project Team 6, *Longitudinal*, and the MSG, it was noted with concern that a 4-minute maximum ADS-C periodic reporting interval for the proposed 30 NM RNP 4 performance-based longitudinal separation minimum was lower than the 14-minute maximum ADS-C periodic reporting interval for the existing 30 NM RNP 4 longitudinal separation minimum based on distance using RNAV where RNP is specified. It was explained by the author of SASP-WGH/24-WP/08 that this was the result of the use of observed navigation performance of GNSS-equipped aircraft down to 0.05 NM rather than specified performance of 4 NM 95%.

A second discussion point concerned aircraft speed modelling, where it was explained that independent speed modelling had been used. It was then suggested that this might not be appropriate when considering that the aircraft pairs involved in the separation would most frequently be on the same-identical (zero angle) track and at the same flight level and thereby subject to the same flight conditions. An action was then defined to assess the viability of obtaining same-identical (zero angle) track speed data samples in time to be incorporated into the model prior to the next SASP Meeting and another action to actually incorporate those data into the model. As a result, it was agreed that progression of the new (20 NM) performance-based longitudinal separation minima based on distance should wait until the pertinent collision risk calculations would be made and a more mature output of the modelling would have been obtained.

SASP-WG/WHL/24-WP/20 (Butcher & Barry, 2014) provided material to progress the PANS-ATM amendment proposal for performance-based longitudinal separation. Based on deliberations from SASP-WGH/24-WP/08

described above, SASP Project Team 6, *Longitudinal*, agreed that the 20 NM longitudinal separation minimum was not sufficiently mature for inclusion, but that this should not preclude the progression of a table using the existing 50 NM and 30 NM longitudinal minima and the 5-minutes longitudinal minimum that had been in operational trial use in the North Atlantic (NAT) Region since 2010 (see also SASP-WG/WHL/24-WP/21 below). It was also agreed that the most effective means to progress the PANS-ATM amendment proposal in time for possible inclusion in the 2016 Edition of the PANS-ATM would be to conduct the editorial work via coordination between SASP Panel members. When ready, the 20 NM longitudinal separation minimum could be added at a later date.

SASP-WG/WHL/24-WP/21 (Kraft, 2014) extended the earlier SASP-WG/WHL/21-WP/17 by proposing to also include the 5-minute longitudinal separation standard, RlongSM, see Sections 7.2.6 and 7.2.7, in the proposed PANS-ATM amendment proposal for performance-based longitudinal separation minima, i.e. PBN as well as PBCS based longitudinal separation minima, in addition to the distance-based 50 NM, 30 NM, and 20 NM longitudinal separation standards. The Meeting agreed that communication and surveillance performance requirements were necessary where ADS-C and CPDLC are relied upon to apply the separation minima. Consequently, it was determined that insertion of PBCS requirements as conditions to both the existing RNP-based 50 NM and 30 NM longitudinal separation standards and the 5-minute time-based RlongSM would be included in the PANS-ATM proposal.

Discussion of the aircraft speed working papers of WP/7 (Barry & Tsang, 2014c) and WP/19 (Falk, 2014b). 9 is beyond the scope of this document.

See also Table 7.24 at the end of this Subsection 7.3.9.3.

SASP-WG/25, Sydney, November 2014

SASP-WG/25-WP/8 (Stefansson, 2014d) presented a draft PANS-ATM amendment for performance-based longitudinal separation taking account of the agreement reached at the previous meeting on incorporating PBCS requirements for the 50 NM, 30 NM and 5 minutes longitudinal separation minima using ADS-C and SASP-WGH/25-WP/24 (Barry & Aldis, 2014b) presented a revised version of the associated Circular. Two working papers were presented dealing with aircraft speeds, namely SASP-WG/25-WP/21 (Stefansson, 2014c) and SASP-WG/25-WP/13 (Barry & Tsang, 2014b) where an updated version of the latter became available during the Meeting as SASP-WG/25-FL/13 (Barry & Tsang, 2014a). The original version of SASP-WG/25-WP/13 concluded that there was no evidence to reduce the speed parameter in longitudinal separation standards below the 5.8 and 6.5 knot values used in earlier studies. However, the updated version of SASP-WG/25-WP/13 concluded on the basis of new data and interpretation that evidence existed for the inclusion of speed errors of 1.9-2.5 knots in longitudinal risk models as long as the appropriate Mach limitations are enforced and monitoring systems are in place and that this should decrease the longitudinal separation standards considerably. It was stressed that in defining any new separation standards, appropriate Mach assignment, and monitoring systems must be in place to ensure the underlying assumptions for these low speed variations are met. Based on the five above mentioned papers, the meeting defined two actions as follows:

- The Secretary to present the performance-based longitudinal separation minimum proposal for amendment for PANS-ATM and impact statement to the ANC for approval as in Appendix C to the Meeting's Summary of Discussions;

- ICAO Circular to be developed by three designated SASP Panel Members/Advisors, a draft of which is to be made available to the Secretary no later than April 2015 to assist in the presentation of the PfA to PANS-ATM to the ANC. The draft Circular will be presented to SASP/26 for review.

As regards the 5-minute longitudinal separation minimum, two working papers related to this subject were provided, namely SASP-WG/25-WP/16 (Barry & Fang, 2014) and SASP-WG/25-WP/32_revised (Falk, 2014a). The first paper considered modelling of the minimum by a time-based extension of the general collision risk model based on reliability theory of SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20_revised (Anderson, 2005). The second paper presented data from three different oceanic FIRs and used these in combination with a generalized form of the traditional Reich model for longitudinal separation.

Finally, for completeness, it should be remarked that information paper SASP-WG/25-IP/03 (Stefansson, 2014b) provided some further information related to the determination of the ADS-C minimum reporting interval (cf. SASP-WG/WHL/24-IP/05).

See also Table 7.24 at the end of this Subsection 7.3.9.3.

SASP-WG/26, Montreal, May 2015

SASP-WG/26-WP/9 (Barry & Tsang, 2015) presented a slightly revised version of Flimsy SASP-WG/25-FL/13 to formalise this reference's results. It confirmed that evidence existed for the inclusion of speed errors of 1.9-2.5 knots in longitudinal collision risk models as long as the appropriate Mach limitations are enforced and monitoring systems are in place and that this should decrease the longitudinal separation standards considerably. It also stressed that in defining any new separation standards, appropriate Mach assignment, and monitoring systems must be in place to ensure the underlying assumptions for these low speed variations are met. The MSG provided several comments on the technical details of the work described in SASP-WG/26-WP/9 and its author agreed to incorporate these in future efforts.

The draft Circular for performance-based longitudinal separation agreed to be developed at SASP-WG/25 for review by SASP/26 was presented in two parts in Flimsy 23 (SASP-WG/26-FL/23) and Flimsy 24 (SASP-WG/26-FL/24) respectively, where SASP-WG/26-FL/23 (Unknown, 2015b) contained the procedural/operational Chapters 1, 2 and 4 of the Circular and SASP-WG/26-FL/24 (Unknown, 2015a) contained the mathematical safety assessment of the Circular's Chapter 3. Flimsy 23 was reviewed paragraph by paragraph by SASP Project Team 6, *Longitudinal*, and a number of changes were suggested and incorporated in the draft Circular. The resulting version is available as Appendix E to the *Summary of Discussions* of the Meeting (SASP-WG/26 Meeting Report). Due to its technical nature, Flimsy 24 was reviewed by the SASP MSG only. During the review, it turned out that Flimsy 24 accidentally did not contain the most recent version of the SASP safety assessment for performance-based longitudinal separation. It was agreed that the pertinent latest version would be made available. An action was put on the Rapporteur of Project Team 6 to complete the edits suggested to the draft Circular (ICAO Circular 343) at the Meeting, merge Chapter 3 into the Circular and provide to the SASP Secretary before end-of-June 2015. All Panel members were actioned to review draft ICAO Circular 343 and provide comments at or before SASP-WG/27. The MSG was tasked to continue work on 20 NM performance-based longitudinal separation and provide results also at SASP-WG/27.

See also Table 7.24 at the end of this Subsection 7.3.9.3.

SASP-WG/27, Montreal, November 2015

Performance-based longitudinal was addressed (only) through the latest version of its Circular, Circular 343, *Guidelines for the implementation of performance-based longitudinal separation minima*, as provided to the Meeting in SASP-WG/27-FL/20 (Unknown, 2015c). A final review of the Circular was performed by the Meeting which provided some additional input after which the Meeting agreed that the Circular would be processed by the Secretary for publication.

The resulting ICAO Circular 343 provides a summary of key concepts of the SASP safety assessment for the three performance-based longitudinal separation minima (50 NM, 30 NM, and 5 minutes) in its Section 3.3.2. One of these concepts concerns the calculation of the longitudinal collision risk as a weighted average over different response time or intervention buffer τ values, see eq. (1) of Section 3.3.2 of the Circular. A range of eight different models of τ values in combination with the number of aircraft pairs parameter NP were considered where the original triple of values of $\tau = 4$, $\tau = 10.5$, and $\tau = 13.5$ minutes (with weights 0.9025, 0.0475, and 0.05) in combination with $NP = 4$ was ultimately used because it was the most conservative. (Cf. Tables 6 – 8 of (Anderson, 2005) and eq. (7.295) of Section 7.3.8.) See Section 3.6.6. of the Circular for further discussion on communication performance. Recall also that communications between ATC and a pilot are assumed to be by CPDLC as primary means (assumed RCP 240) with HF voice as a secondary backup (assumed RCP 400). Surveillance is assumed to be by periodic ADS-C reporting and meeting the RSP 180 specification. Both CPDLC messages and ADS-C reports are assumed to be delivered by satellite. Both surveillance and communications contribute to the parameter τ .

The collision risk model itself is given by eq. (2) of Section 3.4 of Circular 343 and is the same as that presented in this Document's Section 7.3.9.2 under the *SASP-WG/1, Cairns, November 2011* heading, viz.

$$CR(t_0, t_1) = NP \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) P_z(h_z) \left(\frac{2V_r^{138}}{\pi\lambda_{xy}} + \frac{|\vec{z}|}{2\lambda_z} \right) f_1(V_1) f_2(V_2) dt dV_1 dV_2 \quad (7.291)$$

with the probability of horizontal overlap $HOP(t|V_1, V_2)$ for the general case given by

$$HOP(t|V_1, V_2) = \int_{\square} \int_{\square} \int_{\square} \int_{d_h < \lambda_{xy}} f_1^A(\varepsilon_1^A) f_2^A(\varepsilon_2^A) f_1^C(\varepsilon_1^C) f_2^C(\varepsilon_2^C) d\varepsilon_2^A d\varepsilon_2^C d\varepsilon_1^A d\varepsilon_1^C \quad (7.296)$$

The four-fold integral is over all values of the navigation error variables ε such that the horizontal distance d_h between the aircraft centres is less than the average aircraft size λ_{xy} . The four-fold integral of eq. (7.296) may be approximated by the two-fold integral of eq. (7.292). The model is completed with an integration over a distribution $H(S)$ of initial separations S , equation (6) of Section 3.4 of Circular 343,

$$CR = \int_{S=S_x}^{S=S_x+250} H(S) CR(t_0, t_1; S) dS \quad (7.297)$$

where S_x denotes the longitudinal separation standard under consideration and $CR(t_0, t_1; S)$ is a refined notation for $CR(t_0, t_1)$ of eq. (7.291), namely with the dependence of the risk on the initial separation S through $HOP(t|V_1, V_2)$ made explicit and be aware that the above model applies to distance based longitudinal separation.

¹³⁸ The symbol used for the relative horizontal speed between the aircraft is actually V_{rel} rather than V_r .

A time-based longitudinal collision risk model for performance-based longitudinal separation was also provided in the Safety assessment Chapter of Circular 343, viz. in Section 3.4.1, eqs. (8) – (21). It is argued in that section that to extend the distance-based model to a time-based model, another integral of the nominal speeds of the aircraft needs to be added, viz.

$$CR(t_0, t_1; T_s) = NP \int_{\bar{V}} \int_{V_1=-\infty}^{\infty} \int_{V_2=-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) P_z(h_z) \left(\frac{2V_r}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right) f_1(V_1|\bar{V}) f_2(V_2|\bar{V}) f_V(\bar{V}) dt dV_1 dV_2 d\bar{V} \quad (7.298)$$

where T_s denotes the applicable time separation and the aircraft speed probability densities now need to be conditional on the nominal aircraft speed $\bar{V}$. Noting that the relative speeds of the aircraft are the main risk, the double speed integrals are approximated as

$$\int_{V_1=-\infty}^{\infty} \int_{V_2=-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|V_1, V_2) P_z(h_z) \left(\frac{2V_r}{\pi\lambda_{xy}} + \frac{|\bar{z}|}{2\lambda_z} \right) f_1(V_1|\bar{V}) f_2(V_2|\bar{V}) dt dV_1 dV_2 \approx \int_W \int_{t_0}^{t_1} HOP(t|V_1, V_2) P_z(h_z) dt f_W(W|\bar{V}) dW \quad (7.299)$$

with W the relative speed and $f_W(W|\bar{V})$ the distribution of relative speeds given the nominal speeds of the aircraft $\bar{V}$. Substitution of eq. (7.299) into eq. (7.298) then gives

$$CR(t_0, t_1; T_s) = NP \int_{\bar{V}} \int_{W=-\infty}^{\infty} \int_{t_0}^{t_1} HOP(t|W, T_s) P_z(h_z) f_W(W|\bar{V}) f_V(\bar{V}) dt dW d\bar{V} \quad (7.300)$$

Like eq. (7.291) for the distance-based collision risk model for performance-based longitudinal separation, the time-based model for performance-based longitudinal separation was completed with an integration over a distribution $H^*(T_s)$ of initial time-separations T_s

$$CR(t_0, t_1) = \int_{T_s} H^*(T_s) CR(t_0, t_1; T_s) dT_s \quad (7.301)$$

Cf. equation (21) of Section 3.4.1 of Circular 343.

See Table 3-1 of section 3.6.1 of Circular 343 for the default values and range explored of the longitudinal collision risk model parameters .

See also Table 7.24 at the end of this Subsection 7.3.9.3.

SASP-WG/28, Reykjavik, May 2016

Following the completion of Circular 343 at the previous meeting, performance-based longitudinal separation was not dealt with at SASP-WG/28. Recall from the discussion under the *SASP-WG/WHL/24, Montreal, May 2014* heading that the PANS-ATM amendment was limited to the performance-based 50 NM, 30 NM and 5 minutes longitudinal separation minima and that, when ready, the 20 NM longitudinal separation minimum could be added at a later date. Recall also from the discussion under the *SASP-WG/WHL/26, Montreal, May 2015* heading that the MSG had been tasked to continue work on 20 NM performance-based longitudinal separation.

See also Table 7.24 below.

7.3.9.4 SASP/1 (Montreal, November 2016) to SASP/2 (May 2018)

It is remarked in advance that this subsection is concluded by a table, Table 7.25, that summarizes the main points of each of the meetings described below. The Table should assist the reader in keeping track of how SASP's work on the subject evolved over time. In addition, the Table includes some details not presented in the main text of this Subsection.

SASP/1, Montreal, November 2016

SASP-1-2016-WP11 (Barry, 2016d) revisited performance-based 20 NM and 30 NM longitudinal separation standards using revised communication and surveillance models. The paper stated that recent work¹³⁹ had improved the SASP understanding of communication models as summarised in SASP-WG/28-WP/18 and SASP-WGH/28-FL/19 (Barry, Civil, et al., 2016b) as well as of the speed error collision risk model parameter (λ_v) and that the goal of the paper was to use this new information to re-estimate the ADS-C periodic reporting interval for oceanic RNP 2 and RNP 4 longitudinal separation standards meeting the TLS. The working paper referenced a total of seven papers on communication models/performance, including SASP-WG/28-WP/18, SASP/1-WP/10, SASP-WG/WHL/22-WP/14 and SASP-WGH/28-FL/19. See also SASP/1-WP23 (Falk, 2016) for a high level summary. As for the collision risk model, the same model was used as in ICAO Circular 343, SASP-WG/WHL/25-WP/24 and SASP/1-WP/10, that is, the distance-based longitudinal collision risk model for performance-based longitudinal separation specified by eqs. (7.291), (7.296) and (7.297).

As regards surveillance and communication, SASP-WGH/28-FL/19 (Barry, Civil, et al., 2016b) distinguished three categories of cases corresponding to typical aircraft equipage, namely FANS/data link equipped aircraft – case A, non ADS-C link equipped aircraft – case B, and non FANS equipped aircraft – case C. Cases were defined by four elements, namely first-level surveillance, loss of first-level surveillance, primary communication, and secondary communication. Event sequences were constructed and used to derive response times τ_i and weights p_i for each branch (called *scenario*) and a weighted collision risk calculated as

$$CR = \sum_i p_i CR(\tau_i) \quad (7.295)$$

The calculations in SASP-1-2016-WP11 (Barry, 2016d) were based on the revised surveillance/communication Case A5 model for FANS/data link equipped aircraft, which was believed to more accurately, but still conservatively, reflect both available data and RCP and RSP requirements. Although the Case A5 communications model is actually an ASEPS communication model based on ADS-B, it was stated to be applicable to ADS-C in the working paper as well. See SASP-WGH/28-FL/19 for further details of this case (and other ones). It is remarked that the traditional model was denoted A1.

Taking account of the improved knowledge, the paper's results indicated that for expected values of the speed error parameter $\lambda_v \leq 4.5$ knots, a 14 minute or less reporting period was sufficient for a performance-based 20 NM longitudinal separation standard to be below the TLS and 23 minutes or less for the 30 NM separation standard. For both standards, the respective maximum reporting intervals were still expected to be conservative based on the conservative modelling assumptions used.

In connection with the question of determining the minimum ADS-C reporting interval supported by the FANS end-to-end system, working paper SASP/1-WP/17 (Stefansson, 2016) provided a report of the first Meeting

¹³⁹ Essentially that on ASEPS-based separation minima. See Section 7.3.8.

of the ICAO APAC¹⁴⁰/NAT Inter-regional ADS-C Reporting Interval Task Force (ADS-C RITF/1) (cf. SASP-WG/WHL/24-IP/05 and SASP-WG/25-IP/03).

See also Table 7.25 at the end of this Subsection 7.3.9.4.

SASP-WG/29, Vienna, May 2017

SASP-WG/29-WP/27 (Morin et al., 2017b) presented a general plea for the development of improved performance-based separation standards using ADS parameters, e.g. ADS-B/1089 MHz Extended Squitter, ADS-B Selected Aircraft Intention, or ADS-C Extended Projected Profile (ADS-C EPP) parameters. The paper referenced some investigations concerning 64-second and 3 minute ADS-C reporting intervals and presented a draft Job Card to facilitate SASP work in this area.

SASP-WG/29-WP/30 (Morin et al., 2017a) proposed a PANS-ATM amendment for a 20 NM performance-based longitudinal separation standard based on an ADS-C reporting interval of 4 minutes. The paper recalled results on this included in SASP-WG/24-WP/08 and ICAO Circular 343, but that, at the time, SASP decided to not incorporate the 20 NM separation standard in its PANS-ATM amendment proposal because it was not clear whether a 4-minute ADS-C reporting interval for the FANS system was feasible. Cf. the discussion under the *SASP-WG/WHL/24, Montreal, May 2014* heading and in SASP-WG/WHL/24-IP/05, SASP-WG/25-IP/03 SASP/1-WP17 and SASP-WG/29-WP/27. Like SASP-WG/29-WP/27 (Morin et al., 2017b), SASP-WG/29-WP/30 referenced some investigations concerning 64-second and 3-minute ADS-C reporting intervals and concluded that a 4-minute ADS-C periodic reporting interval was feasible. The working paper stressed that the proposed 20 NM/4- minute ADS-C reporting interval separation standard should not be viewed as superseding the 20 NM/14-minute ADS-C reporting interval/additional monitoring requirements longitudinal separation standard evaluated in SASP-1-2016-WP11, but as providing flexibility and additional benefits for ANSPs and airspace users using existing technology. It also proposed to publish a new Circular, *Guidelines for the implementation of performance-based longitudinal separation minima*, (Attachment B to SASP-WG/29-WP/30) to replace the existing ICAO Circular 343. The new Circular would be almost identical to the existing Circular 343 with minor changes to the Circular's Chapters 1 and 2.

The two working papers were reviewed concurrently by the Meeting. As regards the proposed Job Card, the Meeting struggled with its seemingly broad application until the Panel Member for ICCAIA offered to identify data on ADS-B/ADS-C downlinked information that might be useful for ATM and, more specifically, offered to bring data to the next SASP meeting in November 2017 on capabilities which exist on aircraft but are not being currently used or when they may be widely available for use based on response to worldwide equipage mandates. With this information, the SASP could better determine the effort needed to focus on application of CNS attributes necessary to support specific operational concepts to gain the most future benefit. The SASP agreed that the Job Card would be presented to the ANC by its Secretary for approval.

As regards the 20 NM longitudinal separation minimum and Circular 343 in general, it was firstly agreed to review the Circular in light of recent ASEPS work (cf. Section 7.3.8 and (ICAO, 2020a)) and secondly to revise and re-number Circular 343 to reflect its application to a 20 NM longitudinal separation standard. Specific areas to address in the new circular were identified as follows:

- Based on the resolution of crossing track issues, the MSG will validate that SLOP has been properly accounted for in the revised/renumbered Circular 343, for the 20 NM longitudinal separation standard;

¹⁴⁰ APAC: Asia Pacific.

- The Secretary will facilitate coordination between SASP and the Communications Panel to review the proposed GOLD (ICAO, 2013a) amendment, and it will include the new GOLD guidance on changes to ADS-C update rate in the revised and renumbered Circular 343;
- The MSG will review the monitoring procedures documented in Circular 343 and, where appropriate, simplify them.

Taking account of the above, the SASP agreed to proceed toward publication of a new 20 NM standard in 2020.

See also Table 7.25 at the end of this Subsection 7.3.9.4.

SASP-WG/30, Canberra, November 2017

Two working papers were presented that dealt with the Circular for performance-based longitudinal separation, namely SASP-WG/30-WP/27 (Barry, 2017b) and SASP-WG/30-WP/40 (Stefansson, 2017). The latter paper provided some minor changes to Chapter 1, *Introduction*, and Chapter 2, *Longitudinal separation minima*, of the existing Circular 343 to account for a 20 NM longitudinal separation minimum, some comments on Chapter 3, *SASP safety assessment*, and a new Section 4.3 providing guidance on the coordination that is needed when the default ADS-C reporting rate is increased. Some minor editorial amendments were also provided. Reference was made to another working paper for extensive changes to the SASP safety assessment in Chapter 3 of the Circular (viz. SASP-WG/30-WP27).

SASP-WG/30-WP/27 (Barry, 2017b) addressed the technical issues listed at the end of the text under the previous heading, particularly the re-introduction of the 20 NM longitudinal separation standard, but did not (yet) provide a revised Chapter 3 for the performance-based longitudinal separation Circular. The paper noted that there had been further developments on the computer code used for calculations as well as further understanding of the communication models used within the analyses since Circular 343 was written and that these had been utilized in the working paper. It also noted that the mathematical models in Circular 343 were still correct and valid, but that methods and explanations had improved since Circular 343 was drafted. A new draft Circular was expected to be completed before the next SASP Meeting in May 2018. Reference was made to a new communication model, model A20, that had recently been proposed by the SASP for space-based ADS-B or ASEPS, see Section 7.3.8. Cf. the text under the *SASP-WG/27, Montreal, November 2015* heading. The working paper used a slightly more conservative version of the A20 model, denoted A21 (detailed in an appendix to the paper), to better apply to ADS-C surveillance. When applied to the 20 NM longitudinal separation standard, the A21 model gave slightly lower collision risk than the traditional A1 model. The working paper concluded that:

- i. The 20 NM performance-based longitudinal separation standard met the TLS:
 - a. For intersecting tracks with a reporting interval less than 11 minutes;
 - b. For same-identical (zero angle) tracks with a reporting interval less than 5.8 or 7 minutes, depending on the communication model;
 - c. Extremely conservatively for both scenarios with reporting intervals of 5.8 minutes or less;
- ii. RNP and SLOP were incorporated in the intersecting-track longitudinal collision risk model;
- iii. Output-based monitoring can easily be incorporated into the Circular and will simplify the monitoring burden on ANSPs.

SASP-WG/30-WP/27 (Barry, 2017b) referred to SASP-WG/30-WP/08 for a more detailed explanation on the longitudinal collision risk model for intersecting tracks, particularly the effect of SLOP and RNP.

The Meeting concluded that more time was required, particularly for the MSG, to review the two working papers WP/40 and WP/27.

An information paper, SASP-WG/30-IP/11 (Bee & Griebel, 2017), was provided to the Meeting describing the capabilities of space-based ADS-C and implications for separation standards. This information paper fulfilled a pertinent action put on the Panel Member for ICCAIA during the previous meeting (SASP-WG/29).

See also Table 7.25 at the end of this Subsection 7.3.9.4.

SASP/2, Montreal, May 2018

SASP/2-WP/20 (Silverman, 2018b) presented calculations of performance-based longitudinal collision risk for aircraft on same identical (zero angle) tracks and intersecting tracks for ADS-C periodic reporting intervals between 64 seconds and 5 minutes as had been concluded to be feasible in SASP-WG/29-WP/30. The collision risk model used was that based on SASP-WG/WHL/4-WP/9 and SASP-WG/WHL/7-WP/20 (revised) as used also in ICAO Circular 343, SASP-WG/30-WP/27, and SASP-WG/30-WP/08, i.e. the collision risk model given by eqs. (7.291), (7.296) ((7.292), and (7.295) under the *SASP-WG/27, Montreal, November 2015* heading in the previous subsection 7.3.9.3. Some collision risk model parameters were given values different to those used in ICAO Circular 343 and SASP-WG/30-WP/27 (Barry, 2017b) (see Table 1 of the working paper), but the most important difference with previous work on 20 NM performance-based longitudinal separation concerned the communication model. The model utilized was adapted from the Case A22 ASEPS communication model to account for ADS-C characteristics. It was denoted Case C5, *Communication model for ADS-C*, and accounted for latency and for the absence of backup position reporting. It was detailed in Appendix A to the working paper. The Case C5 model contained to more elements in addition to the usual four elements comprised by first-level surveillance, loss of first-level surveillance, primary communication, and secondary communication. The two additional elements concerned CPDLC being either successful or failing after resend following initial failure.

Both same-identical (zero angle) tracks and intersecting tracks, $0 < \theta \leq 90$ degrees were examined and the same-identical (zero angle) tracks was found to give the highest risk, even when SLOP up to 2 NM was considered at 90-degree crossing angle. It was concluded from the collision risk calculations that a performance-based longitudinal separation minimum of 20 NM met the TLS of 5×10^{-9} fatal accidents per flight hour with a periodic reporting interval of 3 minutes and that a periodic reporting interval of 64 seconds (the lower minimum for the (then) current avionics specification), supported a longitudinal separation minimum of 18 NM.

SASP/2-WP/20 (Silverman, 2018b) was supplemented with revised calculations in SASP/2-FL/26 (Silverman, 2018a) because it had been noted that after working paper 20 had been posted on the SASP website, that the communication model used did not incorporate the same data link performance as the ASEPS model. The revised communication model utilized in the flimsy was denoted C11, see SASP/2-FL/26 for further details. It was noted that although the C11 communication model was considerably more complicated than the C5 model, it produced similar collision risk results. The revised results showed that the longest reporting interval for which a 20 NM performance-based longitudinal separation minimum met the target level of safety of 5×10^{-9} fatal accidents per flight hour was 208 seconds, for same-identical tracks as well as for intersecting tracks at less than 90 degrees.

The presentation of SASP/2-WP/20 (Silverman, 2018b) and SASP/2-FL/26 (Silverman, 2018a) led to lively and robust discussions within the MSG as well as the SASP Plenary, see the SASP/2 Meeting Report. Some concerns were voiced concerning the global representation of the ADS-C performance data used, overall system capacity under heavier traffic levels, additional monitoring requirements for 20 NM longitudinal separation, and the level of independent peer review of the performance-based 20 NM longitudinal separation work by the MSG. The Meeting also noted that for operational accuracy, the bottom branch of the C11 communication model required adjustment. This was accomplished via a revision of some parameters of the C11 model, ultimately resulting in the C19 communication model for performance-based longitudinal separation. The C11 communication model was then agreed to be accepted for the purpose of

deriving ADS-based separations. The C11 model was made available as an attachment to SASP/2-FL/26 and used to recalculate the performance-based longitudinal collision risk. The calculations utilizing the C11 communication model showed that the longest reporting interval for which a 20 NM performance-based longitudinal separation minimum met the target level of safety of 5×10^{-9} fatal accidents per flight hour was 192 seconds (for same-identical tracks as well as for intersecting tracks at less than 90 degrees). This result was taken into account into the review of the PANS-ATM amendment to be described next.

SASP/2-WP/24 (Silverman, 2018d) provided a draft PANS-ATM amendment for an nn NM performance-based longitudinal separation minimum with xx-minute periodic interval with nn and xx to be agreed on the basis of collision risk results provided in SASP/2-WP/20. Working paper 24 noted that a revision of the existing Circular 343, including the SASP safety assessment, was already underway, but recommended that in order to facilitate future revisions, Circular 343 be cancelled and a Manual be issued in its place. As regards possible values of nn and xx, the working paper quoted some results from SASP/2-WP/20, which showed that a performance-based longitudinal separation minimum of 20 NM met the TLS of 5×10^{-9} fatal accidents per flight hour with a periodic reporting interval of 3 minutes and that a periodic reporting interval of 64 seconds (the lower minimum for the (then) current avionics specification), supported a longitudinal separation minimum of 18 NM. Based on the deliberations from SASP/2-WP/20 and SASP/2-FL/26, it was agreed that the ultimate PANS-ATM amendment would specify a 20 NM minima with a 192-second periodic reporting interval and some specific monitoring requirements. An action was put on the SASP Secretary to capture the agreed text of the ultimate amendment proposal, circulate this proposal to the SASP members, and process it for inclusion into the PANS-ATM.

SASP/2-WP/40 (Stefansson & Addison, 2018) presented the latest version of the revised Circular 343 to account for the new 20 NM longitudinal separation minimum, i.e. limited to Chapter 1, *Introduction*, Chapter 2, *Longitudinal separation minima*, and Chapter 4, *Implementation considerations*. Reference was made to work on Chapter 3, *SASP safety assessment*, being underway elsewhere. The Meeting noted and discussed the information provided in the working paper, agreed to the proposed changes in the working paper's Attachment A, and concluded that significant additional material would be required to accommodate the 20 NM performance-based ADS-C longitudinal separation standard, viz. concerning the Chapter 3 *SASP safety assessment*. The review resulted in the following to actions:

- Three designated SASP advisors to draft a final revised ICAO Circular 343; and
- SASP Secretary to transpose agreed ICAO Circular material into ICAO Manual format for subsequent review by the SASP.

See also Table 7.25 below.

A State Letter asking for comments on several PANS-ATM amendments agreed at SASP/2 (May 2018), including the new proposed 20 NM longitudinal separation minimum was sent out on 28 March 2019 (ICAO State Letter, 2019). Following that, the new separation minimum was approved by the ICAO ANC for inclusion into the 16th edition of the PANS-ATM under Amendment 9 to the 16th Edition, to become applicable on 5 November 2020. See also the *Manual on the Implementation of Performance-based Longitudinal Separation Minima* (ICAO Doc 10120).

7.3.9.5 SASP-WG/31 (Washington DC, November 2018) to SASP-WG/33 (November 2019)

SASP-WG/31, Washington DC, November 2018

Two working papers dealing with the new 20 NM performance-based longitudinal separation minimum were presented at the 31st Working Group Meeting of the SASP, namely SASP-WGH/31-WP/14 (Silverman, 2018c) and SASP-WGH/31-WP/18 (Dwyer, 2018). In addition, a first draft of the *Manual on the Implementation of Performance-based Longitudinal Separation Minima* (SASP-WG/31-FL/02 (Addison, 2018)) was provided. The SASP Safety assessment chapter of the new draft Manual was identical to that of its predecessor ICAO Circular 343. There was no separate discussion of the new draft Manual but it was considered as part of the extensive discussion of SASP-WGH/31-WP/14 and SASP-WGH/31-WP/18.

SASP-WGH/31-WP/14 (Silverman, 2018c) presented final modelling results for 20 NM performance-based longitudinal separation. The working paper responded to a desire expressed by several SASP/2 participants after the conclusion of that meeting to have a single reference for the work that supported the 20 NM PANS-ATM Amendment. In that sense, the working paper effectively combined the previous SASP/2-WP/20 and SASP/2-FL/26. In addition, the working paper contained in an appendix a list of 57 SASP papers that documented work that contributed to the development of longitudinal separation standards based on ADS-C. The working paper was presented to, and reviewed by, the SASP plenary as well as the MSG. This resulted in an action on the author of the working paper to continue the development of the *Manual on the Implementation of Performance-based Longitudinal Separation Minima* (SASP-WG/31-FL/02) to include the feedback from the meeting. This would include generation of figures to demonstrate some of the model features.

SASP-WGH/31-WP/18 (Dwyer, 2018) returned to a number of concerns that had been voiced during the foregoing SASP/2 Meeting in the discussion on the new 20 NM performance-based longitudinal separation minimum. Based on that, the working paper requested the Meeting to:

- Task the MSG to provide assessment of the monitoring requirements for separation minima derived using ADS-C reporting intervals of four, five, and six minutes;
- Assess whether adjusting the ADS-C reporting interval and corresponding minima would provide a better case scenario for safe implementation; and
- Confirm that a sufficiently mature longitudinal separation proposal was put forward at the SASP/2 Meeting.

The working paper was discussed in conjunction with a triple of flimsies dealing with operational information on ADS-C reporting intervals in practice and the development of 20 NM longitudinal separation with ADS-C, monitoring requirements for collision risk modelling, and ADS-C increased reporting performance data. The discussion was quite elaborate, see the SASP-WGH/31 Meeting Report. It was closed by the SASP Secretary noting that the timing of the discussion was rather unfortunate and that unless instructed otherwise, by default the PANS-ATM Proposal for Amendment provided at the SASP2 meeting in May 2018, as amended by agreement during the SASP-WG/31 Meeting, would be progressed based on agreement in principle from the Panel. It was clarified that the requested data would, once provided, assist in Secretariat assessing the maturity of the proposal.

SASP-WG/32, Washington DC, May 2019

SASP-WG/32-WP/11 (Silverman, 2019a) outlined progress on the development of the *Manual on the Implementation of Performance-based Longitudinal Separation Minima* and the differences between this

Manual and other related ICAO documents. The draft Manual itself was provided in an attachment to the working paper. The working paper noted that although the new Manual provided guidance for all of the four performance-based longitudinal separation minima, to avoid confusion about parameter values, the detailed modelling results in the Manual were only those that supported the new 20 NM standard. Changes had been made to make the Manual more accessible and useful for implementers by reorganizing its Chapter 3, *SASP safety assessment*. More work on many sections was stated to be underway.

Section 3.7 of the Manual was entitled *Longitudinal separation model* and subsection 3.7.4 was entitled *Derivation of the Anderson-Hsu Mathematical Model*, i.e. derivation of the model utilized for the 20 NM performance-based longitudinal separation minimum. This model, based on SASP-WG/WHL/4-WP/9 and SASP-WG/WHL/7-WP/20 (revised) has been referred to as the “general collision risk model based on reliability theory” in this Document, see Sections 7.3.2 – 7.3.4. It was summarized under the *SASP-WG/1, Cairns, November 2011* heading in Section 7.3.9.2 in equations (7.291) and (7.296). It was also summarized by these two equations supplemented with eq. (7.297), which specified an integration over an initial longitudinal separation distribution, under the *SASP-WG/27, Montreal, November 2015* heading in Section 7.3.9.4

Unfortunately, the start of the derivation provided in the draft Manual is wrong because the probability of horizontal overlap $HOP(t|V_1, V_2)$ is missing out in eq. (3-7) in the Manual. This was subsequently corrected in eq. (3-12) of the Manual with $HOP(t|V_1, V_2)$ given by eq. (3-21) of the Manual. The Manual’s eq. (3-12) is precisely eq. (7.291) of this Document. The Manual’s eq. (3-21) is an expanded version of eq. (7.296) of this document, which was evaluated in Section 7.3.8 to eq. (7.292), which is the same as the Manual’s eq. (3-21).

Significant discussion took place on the draft Manual, both in plenary and in the MSG, all of which led to an action on the author of working paper 11 and its attachment to make revisions to the *Performance-based Longitudinal Separation* Manual as per feedback during the meeting. Overall, the Manual should be updated in line with revisions done to the ASEPS Manual (ICAO Doc 10116) (ICAO, 2020a). A revised version was subsequently provided during the meeting as SASP-WG/32-FL/21 (Unknown, 2019a). The revised version was not presented to the meeting but was noted to be available for review.

SASP-WG/33, Washington DC, November 2019

SASP-WG/33-IP/10 (Silverman, 2019b) outlined again progress on the development of the *Manual on the Implementation of Performance-based Longitudinal Separation Minima* and the changes made since the previous SASP Working Group Meeting. The latest draft Manual itself was provided in an attachment to information paper 10. The information paper stated that most of the revisions made to the draft manual following SASP-WG/32 were editorial and listed six most significant changes, one of which concerned moving mathematical details of the modelling from Chapter 3, *SASP safety assessment*, to a new Appendix B. Several figures that demonstrated details of the modelling behaviour for intersecting tracks were removed from the (new) Appendix, as agreed to by the MSG at SASP-WG/32. A new Appendix C was also added to provide much of the details about the effects of lateral deviations on longitudinal separation. The working paper included a table showing the timeline for completing of the performance-based longitudinal separation Manual. With work on the draft Manual continuing, SASP approval of the complete draft was scheduled for May 2020¹⁴¹ and publication of the final Manual for November 2020, concurrent with the publication of the new 20 NM performance-based longitudinal separation minimum in the PANS-ATM.

¹⁴¹ The SASP/3 Meeting planned for May 2020 took the form of a virtual meeting in July 2020 (SASP-VWG/1) due to the Covid-19 pandemic.

Appendix B was entitled Longitudinal separation modelling and Appendix B.4 was entitled *Derivation of the Anderson-Hsu Mathematical Model*, i.e. derivation of the model utilized for the 20 NM performance-based longitudinal separation minimum. As set out under the previous *SASP-WG/32, Washington DC, May 2019* heading, this model, based on *SASP-WG/WHL/4-WP/9* and *SASP-WG/WHL/7-WP/20* (revised) has been referred to as the “general collision risk model based on reliability theory” in this Document, see Sections 7.3.2 – 7.3.4. It was summarized under the *SASP-WG/1, Cairns, November 2011* heading in Section 7.3.9.2 in equations (7.291) and (7.296). It was also summarized by these two equations supplemented with eq. (7.297), which specified an integration over an initial longitudinal separation distribution, under the *SASP-WG/27, Montreal, November 2015* heading in Section 7.3.9.4.

Appendix B.4 appeared to be a copy of Section 3.7.4 of the previous version of the manual with the original equation numbers (3-X) replaced by (B-X) and thus contained the same error as the previous version, i.e. the start of the derivation provided in the draft Manual was wrong because the probability of horizontal overlap $HOP(t|V_1, V_2)$ was missing out in eq. (B-7) in the Manual. This was subsequently corrected in eq. (B-12) of the Manual with $HOP(t|V_1, V_2)$ given by eq. (B-21) of the Manual. The Manual’s eq. (B-12) is precisely eq. (7.291) of this Document. The Manual’s eq. (B-21) is an expanded version of eq. (7.296) of this Document, which was evaluated in Section 7.3.8 to eq. (7.292), which is the same as the Manual’s eq. (B-21).

The information paper was presented to the SASP plenary and also separately to the MSG. The plenary endorsed the draft Manual with the exception of the weather deviation guidance, which was covered under a different information paper. Since this concerned implementation considerations from the Manual’s Chapter 4, this issue is not elaborated here. The MSG also provided a number of comments on the Manual’s Chapter 4, Implementation considerations, as well as on the new Appendix B, which were agreed to be incorporated in a revised version of the Manual. An action was put on the author of *SASP-WG/33-IP/10* to revise the draft Manual to incorporate the feedback from *SASP-WG/33*. A revised version produced during the meeting was provided as *SASP-WG/33-FL/17* (Unknown, 2019b).

7.3.9.6 Summary of the development of performance-based longitudinal separation

Work on performance-based longitudinal separation started effectively at *SASP-WG/1, November 2011*, by examining the feasibility of allowing 30 NM longitudinal separation and RLongSM for RNP 2 approved aircraft in addition to RNP 4 approved aircraft. An operational requirement was developed at this Meeting for the SASP MSG to start work on longitudinal collision risk modelling for the RNP 2 navigation specification. The work was formalised under the ANC-approved Job Card *SASP006* at *SASP-WG/WHL/21* in November 2012. The Job Card was subsequently revised at the next meeting, *SASP-WG/WHL/22, May 2013*, to incorporate Performance-based Communication and Surveillance (PBCS). At this same Meeting, an action was put on the SASP to consider the creation of a Circular documenting the work on the subject. At *SASP-WG/WHL/24* in May 2014, a PANS-ATM amendment for the performance-based 50 NM, 30 NM and 5-minutes longitudinal separation minima was agreed, together with the decision to proceed with further work on a performance-based 20 NM longitudinal separation standard. The final version of the Circular concerning the implementation of the three performance-based separation minima covered by the PANS-ATM agreement was agreed at *SASP-WG/28* in May 2016. See ICAO Circular 343. The 50 NM en 30 NM distance-based longitudinal separation minima and the 5 minute time-based longitudinal separation minimum were incorporated into the 16th Edition of the PANS-ATM under Amendment 7A with an applicability date of 10 November 2016.

The reason for not including the 20 NM performance-based longitudinal separation minimum into PANS-ATM Amendment 7A was that, at the time, the required ADS-C periodic reporting interval was not thought to be feasible. However, subsequent work showed that periodic reporting intervals as short as 64 seconds could be provided with the then current system. This ultimately resulted in a SASP agreement on a PANS-ATM amendment for a performance-based 20 NM longitudinal separation minimum with 192-second periodic ADS-C reporting interval at SASP/2, May 2018. Work on an ICAO Manual (rather than Circular) covering the new 20 NM performance-based longitudinal separation minimum as well as the three earlier agreed performance-based longitudinal separation minima of 20 NM, 30 NM, 50 NM and 5 minutes continued up to SASP-WG/33 in November 2019. See ICAO's *Manual on the Implementation of Performance-based Longitudinal Separation Minima using ADS-C* (ICAO, 2020b).

A State Letter asking for comments on the new proposed 20 NM performance-based longitudinal separation minimum was sent out on 28 March 2019 (ICAO State Letter, 2019). Following that, the new separation minimum was approved by the ICAO ANC for inclusion into the 16th edition of the PANS-ATM under Amendment 9 to the 16th Edition, to become applicable on 5 November 2020.

8 Generalisation of the Reich model

8.1 Introduction

The Reich model, as well as the vertical and longitudinal versions, depends on a number of assumptions:

- (1) The density is independent in the x , y and z dimensions.
- (2) The density is independent in the position and velocity component¹⁴²
- (3) The density is constant over the position over the dimension of the aircraft
- (4) Aircraft move in a fixed route structure, i.e. along parallel tracks
- (5) All aircraft are modelled by the same geometric shape, i.e. box
- (6) No evasive manoeuvring by the pilot or intervention by ATC.

Some of these assumptions are regarded as restrictive or even unrealistic. In this chapter a few models are discussed in which some of the assumptions are relaxed.

When we let $f(\mathbf{r}, \mathbf{v})$ denote the joint probability density function of the relative position and relative speed, assumptions 1 and 2 imply that the aircraft are in a steady-state, so the joint probability density function does not depend on time and

$$f(\mathbf{r}, \mathbf{v}) = f_x(r_x)f_y(r_y)f_z(r_z)f_{v_x}(v_x)f_{v_y}(v_y)f_{v_z}(v_z),$$

Assumption (3) ensures that $f_x(r_x) = f_x(0)$, $f_y(r_y) = f_y(0)$ and $f_z(r_z) = f_z(0)$ whenever $\mathbf{r}$ is on or within the boundary of V (Shortle et al., 2003).

In the models, described in the previous chapters, the aircraft move in a fixed route structure (assumption 4). For the Reich model, it involves lateral tracks and only collisions between aircraft on adjacent lateral tracks are considered. For crossing traffic, as discussed in Chapter 6, the x -coordinate and the y -coordinate are not independent and hence assumption 1 does not hold.

When modelling a collision, aircraft are represented by a box or a hockey puck (assumption 5). This makes the computations easier. It is however possible to replace the aircraft representation by any bounded closed volume, as will be done in the next section 8.2. However, the impact of this relaxation is only minor.

Another drawback of the presented models is that it assumes procedural airspace and does not take into account the surveillance, communication and intervention capabilities of ATC, and the flight crew. Both of which are supported by several systems like, ACAS (TCAS), radar and STCA. It is generally recognised that the analysis and modelling of the ATC/flight crew intervention to prevent collisions is a difficult problem since it depends on human performance influenced by many factors, such as workload, training and experience.

¹⁴² Assumption (2) is not in Reich's original assumptions, but equation (X), which is frequently quoted from Reich's paper, requires this assumption.

There has been quite some research performed to relax some these assumptions. In section 8.2, it is shown that all the collision risk models in the ICAO guidance material can be derived from the same fundamental equation, the Rice formula. In section 8.3, it is shown that the Reich model is a special case of the Rice formula. In section 8.4 some more generalisations as derived by NLR colleagues Bakker and Blom are described. Finally, section 8.5 presents some work on the modelling of ATC/flight crew intervention to prevent collisions.

8.2 Rice formula

It was observed by Mhadhebi (ICAO, 2009) and Bellantoni (Bellantoni, 1971) that all the collision risk models in the ICAO guidance material can be derived from the same fundamental equation, the Rice formula (ICAO, 2009). This formula denotes the incoming flow rate of a fluid entering a three-dimensional volume V with boundary surface S .

To calculate $\bar{N}$, the average number of collisions in the time interval $[t_0, t_1]$, the approach, following Rice, is to construct an expression for $\frac{dN}{dt}$, calculate its statistical mean, $\frac{d\bar{N}}{dt}$, and then integrate in time to get $\bar{N}$. A collision occurs if the relative position vector $\mathbf{r}$ enters the boundary surface S of the collision volume V . At such a time the N increase abruptly from zero to one. Let $\varphi(\mathbf{r})$ is a step function that is one for $\mathbf{r}$ in V and zero for $\mathbf{r}$ outside V . Now,

$$\frac{dN}{dt} = \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \frac{d\varphi(\mathbf{r})}{dt}$$

where $\mathbf{n}$ is the inward normal to S . At the point of entry, $\mathbb{I}(a)$ is the indicator function which is 0 for $a < 0$ and 1 for $a \geq 0$. The purpose of $\mathbb{I}(\mathbf{v} \cdot \mathbf{n})$ is to exclude exists ($\mathbf{v} \cdot \mathbf{n} < 0$), but to entries ($\mathbf{v} \cdot \mathbf{n} \geq 0$) and mere touches ($\mathbf{v} \cdot \mathbf{n} = 0$). Next, it follows that

$$\frac{dN}{dt} = \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \frac{d\varphi}{d\mathbf{r}} \frac{d\mathbf{r}}{dt} = \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v} \cdot \nabla \varphi$$

To obtain the average of the whole population, it is necessary to consider a whole collection of relative trajectories rather than a single relative trajectory. It is assumed that the probability density distribution $f(\mathbf{r}, \mathbf{v}, t)$ of the relative position and velocity is known. Hence, the average over the population is given by:

$$\begin{aligned} \frac{d\bar{N}}{dt} &= \iint \frac{dN}{dt} f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v} d\mathbf{r} = \iint \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v} \cdot \nabla \varphi f(\mathbf{r}, \mathbf{v}, t) d\mathbf{v} d\mathbf{r} \\ &= \iint f(\mathbf{r}, \mathbf{v}, t) \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v} \cdot \nabla \varphi d\mathbf{v} d\mathbf{r} \end{aligned}$$

Here, $d\mathbf{v}$ and $d\mathbf{r}$ are elements of the velocity and position space respectively. The integrations cover the spaces completely. By using the product rule $\nabla \cdot (\varphi \mathbf{x}) = \mathbf{x} \cdot \nabla \varphi + \varphi \nabla \cdot \mathbf{x}$, where φ is a scalar and $\mathbf{x}$ is a vector (take $\mathbf{x} = f(\mathbf{r}, \mathbf{v}, t) \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v}$, the formula can be written as

$$\frac{d\bar{N}}{dt} = \iint \mathbf{x} \cdot \nabla \varphi d\mathbf{v} d\mathbf{r} = \iint (\nabla \cdot (\varphi \mathbf{x}) - \varphi \nabla \cdot \mathbf{x}) d\mathbf{v} d\mathbf{r} = \int \left[\int \nabla(\varphi \cdot \mathbf{x}) d\mathbf{r} - \int \varphi \nabla \cdot \mathbf{x} d\mathbf{r} \right] d\mathbf{v}$$

By the divergence theorem, the first integral in the braces, which is over the volume of the $\mathbf{r}$ space, is converted to a surface integral over a sphere S_R of increasingly large radius R , centered at $\mathbf{r} = 0$:

$$\int \nabla(\varphi \cdot \mathbf{x}) d\mathbf{r} = \lim_{R \rightarrow \infty} \int_{S_R} (\varphi \cdot \mathbf{x}) d\mathbf{s}.$$

As $R \rightarrow \infty$, the surface S_R eventually lies completely outside of the collision surface S . Since $\varphi(\mathbf{r}) = 0$ for $\mathbf{r}$ outside S , the limiting value is zero.

The second integral in the brackets is has a non-zero value only within the volume V , where $\varphi(\mathbf{r}) = 1$. Hence,

$$\frac{dN}{dt} = - \int \left[\int \varphi \nabla \cdot \mathbf{x} \, d\mathbf{r} \right] d\mathbf{v} = - \int \int_V \nabla \cdot \mathbf{x} \, d\mathbf{r} \, d\mathbf{v} = \int \int_S \mathbf{x} \cdot \mathbf{n} \, dS \, d\mathbf{v}.$$

In the last equal sign, the divergence theorem is applied and the minus sign drops since $\mathbf{n}$ is the inward normal to S whereas the divergence theorem uses the outward normal. By substituting $\mathbf{x} = f(\mathbf{r}, \mathbf{v}, t) \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v}$, the following expression is obtained:

$$\frac{dN}{dt} = \int \int_S f(\mathbf{r}, \mathbf{v}, t) \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v} \cdot \mathbf{n} \, dS \, d\mathbf{v}$$

By integrating the over the time interval, the expression for $\bar{N}$ is obtained:

$$\bar{N} = \int_{t_0}^{t_1} \frac{dN}{dt} dt.$$

Hence it follows that

$$\bar{N} = \int_{t_0}^{t_1} \Psi(t) dt,$$

with

$$\Psi(t) = \int_{\mathbb{R}^3} \int_S f(\mathbf{r}, \mathbf{v}, t) \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v} \cdot \mathbf{n} \, dS \, d\mathbf{v}$$

Note that the surface integral $\int_S \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{n} dS$ can be interpreted as a collision cross-section vector with respect to $\mathbf{v}$. Since it is assumed that S is convex, this collision cross-section vector has the property that its components in the $\mathbf{v}$ direction is the area of the orthogonal projection of S onto a plane perpendicular to $\mathbf{v}$.

By using the approximation $f(\mathbf{r}, \mathbf{v}, t) = f(\mathbf{0}, \mathbf{v}, t)$ for $\mathbf{r}$ in V , the formula derived above is a three-dimensional version of the well-known expression for the mean number of times a random function $y(t)$ crosses a given level y_0 in the time interval $[t_0, t_1]$:

$$\int_{t_0}^{t_1} \int f(y_0, \dot{y}, t) |\dot{y}| d\dot{y} dt$$

The original one-dimensional formula was originally derived by S.O. Rice [Rice, 1945]. Therefore the above expression for $\bar{N}$ is referred to as the Rice formula [ICAO, 2009]. The formula for $\Psi(t)$ can be rewritten as follows:

$$\Psi(t) = \int_{\mathbb{R}^3} \int_S f(\mathbf{r}, \mathbf{v}, t) \mathbb{I}(\mathbf{v} \cdot \mathbf{n}) \mathbf{v} \cdot \mathbf{n} \, dS \, d\mathbf{v} = \int_{\mathbb{R}^3} \int_S f(\mathbf{r}, \mathbf{v}, t) (\mathbf{v} \cdot \mathbf{n})^+ \, dS \, d\mathbf{v}$$

With the function $(x)^+ = x$ if $x > 0$ and 0 otherwise.

When f is the density of a fluid, $\Psi(t)$ is the incoming flow rate for a fluid entering volume V with boundary S . Therefore $\Psi(t)$ is sometimes referred to as the incrossing rate.

In deriving the model based on the Rice formula, the following assumptions have been made:

- (a) All possible flight paths are random samples from ensembles of known statistics; the means of the ensembles are the prescribed paths.
- (b) Each aircraft may be represented as occupying a bounded, closed volume
- (c) The positions is a differentiable function of time
- (d) The mean separation is always large compared to the diameter of the regions occupied by the aircraft.

So, this model can handle various density functions (a relaxation of assumptions (1) and (2) as given in section 7.1), and even different route networks (a relaxation of assumptions (4)) and any convex volume V with boundary S representing the collision volume (a relaxation of assumption (5)).

The Reich model and the models by Hsu and Anderson can be derived from this model based on the Rice formula as shown in (ICAO, 2009). In the next Section 8.3, it will be shown that the Reich model is a special case of the Rice formula.

Although these generalisations are a nice feature, in the application of the model to an airspace, in most cases, simple modelling of the density f is used. Also, for the representation of aircraft a box or a cylinder is used depending on whether the routes are parallel or crossing.

8.3 Reich as a special case

In this section it is shown that the Reich model is indeed a special case of the Rice formula generalisation as demonstrated by Mhadhebi (ICAO, 2009), Bellantoni (Bellantoni, 1971) and Masato (Fujita, 2013).

For the evaluation of $\Psi(t)$, aircraft are represented by boxes, hence collision volume V is box of dimension $2\lambda_x \times 2\lambda_y \times 2\lambda_z$ with the centered at the origin. When the boundary S is decomposed into the six faces: back, front, top, bottom and right and left, it follows that

$$\int_{top} (\mathbf{v} \cdot \mathbf{n})^+ dS + \int_{bottom} (\mathbf{v} \cdot \mathbf{n})^+ dS = 2\lambda_x 2\lambda_y |v_z|,$$

By using that for the top face, the inner normal $\mathbf{n} = -\mathbf{k}$, so $\mathbf{v} \cdot \mathbf{n} = -v_z$ for the bottom face the inner normal $\mathbf{n} = \mathbf{k}$, and so $\mathbf{v} \cdot \mathbf{n} = v_z$. Similarly, it follows that

$$\begin{aligned} \int_{front} (\mathbf{v} \cdot \mathbf{n})^+ dS + \int_{back} (\mathbf{v} \cdot \mathbf{n})^+ dS &= 2\lambda_y 2\lambda_z |v_x| \\ \int_{left} (\mathbf{v} \cdot \mathbf{n})^+ dS + \int_{right} (\mathbf{v} \cdot \mathbf{n})^+ dS &= 2\lambda_x 2\lambda_z |v_y| \end{aligned}$$

Hence,

$$\int_S (\mathbf{v} \cdot \mathbf{n})^+ dS = 8\lambda_x \lambda_y \lambda_z \left(\frac{|v_x|}{2\lambda_x} + \frac{|v_y|}{2\lambda_y} + \frac{|v_z|}{2\lambda_z} \right)$$

When we let $f(\mathbf{r}, \mathbf{v})$ denote the joint probability density function of the relative position and relative speed, assumptions (1) and (2) imply

$$f(\mathbf{r}, \mathbf{v}) = f_X(r_x, v_x) f_Y(r_y, v_y) f_Z(r_z, v_z)$$

Assumption (3) results in the approximation $f_X(r_x, v_x) \approx f_X(0, v_x)$ near the collision volume V and similarly for the y -dimension and the z -dimension. Hence, $f(\mathbf{r}, \mathbf{v})$ can be written as

$$f(\mathbf{r}, \mathbf{v}) = f_X(0, v_x) f_Y(0, v_y) f_Z(0, v_z).$$

Hence it follows that

$$\int_S f(\mathbf{r}, \mathbf{v}, t) (\mathbf{v} \cdot \mathbf{n})^+ dS = 8\lambda_x \lambda_y \lambda_z f_X(0, v_x) f_Y(0, v_y) f_Z(0, v_z) \left(\frac{|v_x|}{2\lambda_x} + \frac{|v_y|}{2\lambda_y} + \frac{|v_z|}{2\lambda_z} \right)$$

Using $f_X(r_x, v_x) \approx f_X(0, v_x)$ the following formula is obtained:

$$\overline{|v_x|} = \frac{\int_{-\infty}^{\infty} |v_x| f_X(0, v_x) dv_x}{\int_{-\infty}^{\infty} f_X(0, v_x) dv_x}$$

And similar for the y-dimension and the z-dimension.

Finally, if the probability of overlap in x-dimension is given by

$$P_x = \int_{-\infty}^{\infty} \int_{-\lambda_x}^{\lambda_x} f_X(r_x, v_x) dr_x dv_x = 2\lambda_x \int_{-\infty}^{\infty} f_X(0, v_x) dv_x,$$

and similar for the y-dimension and the z-dimension, then

$$\Psi(t) = \int_{\mathbb{R}^3} \int_S f(\mathbf{r}, \mathbf{v}, t) (\mathbf{v} \cdot \mathbf{n})^+ dS d\mathbf{v} = P_x P_y P_z \left(\frac{\overline{|v_x|}}{2\lambda_x} + \frac{\overline{|v_y|}}{2\lambda_y} + \frac{\overline{|v_z|}}{2\lambda_z} \right).$$

Observe that it can be shown, in a similar manner that if aircraft are represented by cylinders, $\Psi(t)$ can be written as

$$\Psi(t) = \int_{\mathbb{R}^3} \int_S f(\mathbf{r}, \mathbf{v}, t) (\mathbf{v} \cdot \mathbf{n})^+ dS d\mathbf{v} = P_{xy} P_z \left(\frac{2\overline{|v_{xy}|}}{\pi\lambda_{xy}} + \frac{\overline{|v_z|}}{2\lambda_z} \right),$$

Where $\overline{|v_{xy}|}$ is the average relative horizontal velocity of a pair of colliding aircraft and P_{xy} is the horizontal overlap probability.

To complete the Reich model, consider the collision between aircraft on two adjacent parallel tracks to determine P_x , which is dependent on t

$$\bar{N} = \int_{t_0}^{t_1} \Psi(t) dt$$

8.4 The Generalised Reich model

In the Reich model (as well as in the generic Rice formula model) the probability of a collision is approximated by the expected number of collisions. So, it is assumed that the collisions boundaries are transient collision boundaries instead of an absorbing boundary: “the aircraft keep on flying after a collision”. These models require that the multi-dimensional boundary crossing process is differentiable with respect to time and that these derivative processes are stationary. Bakker and Blom (Bakker & Blom, 1993a) claim these requirements form serious shortcomings (see p.1).

Bakker and Blom (Bakker & Blom, 1993a) attempted the absorbing boundary approach by model the airspace with an arbitrary route network by considering the traffic pattern to be an (Markov) diffusion process. A diffusion process is a Markov process with continuous sample paths for which the Kolmogorov forward equation is the Fokker–Planck equation. However, they conclude that modelling the collision by an

absorbing boundary is too difficult to solve analytically because it requires for n aircraft that a system of $n(n-1)/2$ coupled boundary valued PDEs to be resolved.

Besides the transient boundary assumption, it has been posed that assumptions (1) and (2) of the Reich model are quite restrictive (Shortle et al., 2003). By removing these assumptions, (Bakker & Blom, 1993a) derived a generalised Reich model, where the incrossing rate $\Psi(t)$ is expressed as a sum of integrals of marginal distributions of $f(\mathbf{r}, \mathbf{v})$. Although, the numerical evaluation of $\Psi(t)$ is difficult, they showed that if $f(\mathbf{r}, \mathbf{v})$ is a mixture of Gaussian distribution, then the evaluation of $\Psi(t)$ is much easier.

8.5 ATC and flight crew interventions

The model described in this section is based on the work performed by EUROCONTROL's Mathematics Drafting Group (MDG). The aim was to develop a 3-D mathematical model for the ECAC upper airspace (Burt, 2000, 2002). The model computes the probability of a collision as a product of conditional probabilities related to conflicts and potential conflicts.

In areas with higher air traffic density, like the ECAC airspace, it is inevitable that aircraft will be from time to time on conflicting paths. A **conflict** occurs when there is a simultaneous violation of the horizontal and the vertical separation standards.

A **potential conflict** is a situation which would result in conflict, if not corrected within a given look-ahead time by ATC and flight crew of one or both aircraft; in other words aircraft on conflicting paths would lose both vertical and horizontal separation within the look-ahead time. It should be observed that potential conflicts are not necessary a result of an error or a blunder.

The probability that two aircraft in potential conflict are actually involved in a collision can be split into the product of two conditional probabilities, namely the probability that a potential conflict results in an actual conflict and the probability that, given a conflict has occurred, a collision follows:

$$\Pr(\text{collision}|\text{potential conflict}) = \Pr(\text{collision}|\text{conflict}) \cdot \Pr(\text{conflict}|\text{potential conflict}).$$

By summing this product over all potential conflicts in a certain time period and dividing over the total flight hours in the time period, the result would yield that expected number of collisions per flight hour. Potential conflicts can be identified by using radar data and a given suitable look-ahead time. It is clear that the number of actual conflicts occurring in the system is independent of the look-ahead time chosen to identify potential conflicts. The model must therefore ensure that the frequency of potential conflicts multiplied by the conflict probability does not depend on the selected look-ahead time. In the remaining part of this section, the two conditional probabilities are analysed further.

The conditional probability of a collision $\Pr(\text{collision}|\text{conflict})$, or short **collision probability**, is the probability that two aircraft on a conflict course not only pass closer than the prescribed horizontal and vertical separation minima, but would actually collide, provided that no intervention is performed. In this model the aircraft are represented by cylinders with diameter λ_{xy} and height λ_z , and let R denote the horizontal radar separation minimum and H the minimum vertical separation. The horizontal and

vertical components of the relative velocity of the aircraft are denoted by v_r and v_z respectively. It can be shown that the conditional probability of a collision $\Pr(\text{conflict}|\text{potential conflict})$ is computed depending whether or not the aircraft are on parallel tracks or crossing tracks or one or both aircraft are climbing or descending.

	Both aircraft in level flight	One or both aircraft climbing and/or descending
Aircraft on parallel tracks	$P_a = P_y(0)P_z(0)\left(1 + \frac{\pi \lambda_{xy} v_z}{4 \lambda_z v_r}\right)$	$P_a = P_y(0)\frac{\lambda_z}{H} \frac{1 + \frac{\pi \lambda_{xy} v_z}{4 \lambda_z v_r}}{1 + \frac{R v_z}{H v_r}}$
Aircraft on crossing tracks	$P_a = P_z(0)\frac{\lambda_{xy}}{R}\left(1 + \frac{\pi \lambda_{xy} v_z}{4 \lambda_z v_r}\right)$	$P_a = \frac{\lambda_{xy}\lambda_z}{RH} \frac{1 + \frac{\pi \lambda_{xy} v_z}{4 \lambda_z v_r}}{1 + \frac{\pi R v_z}{4 H v_r}}$

If the probability density of lateral separations of the closest point of approach predicted between aircraft in potential conflict on the same route is denoted by f_y , then the following approximations are used:

$$P_y(0) = \int_{-\lambda_{xy}}^{+\lambda_{xy}} f_y(y)dy \approx 2\lambda_{xy}f_y(0)$$

And

$$P_z(0) = \int_{-\lambda_z}^{+\lambda_z} f_z(z)dz \approx 2\lambda_z f_z(0)$$

and $\int_{-R}^R f_y(y)dy = 1$ and $\int_{-H}^H f_z(z)dz = 1$, i.e. that R is much greater than the standard deviation of f_y and similarly for H and f_z .

The conditional probability $\Pr(\text{conflict}|\text{potential conflict})$ is referred to the **conflict probability** assumes that no corrective action is taken to prevent the conflict and that the aircraft continue on constant speed at least until the closest point of approach (CPA).

To evaluate the conflict probability, the distribution of time delays required for conflict resolution and also times during which this must be achieved needs to be determined. The conflict resolution time typically depends on factors like the radar update rates, the controller's response time, the pilot reaction time and the aircraft response time. Based on the analysis of potential conflicts, it is assumed that a probability distribution f_1 of the total response time t_1 can be obtained.

From the analysis of radar tracks for aircraft pairs in potential conflict, the probability distributions can be obtained for the "time to conflict" t_2 and the "time to closest approach" t_3 , they are denoted by f_2 and f_3 respectively.

Now, the probability that a conflict will occur given that the two aircraft are on conflicting tracks, is given by the convolution of f_1 and f_2 :

$$\Pr(t_1 \geq t_2) = \int_0^{\infty} \int_0^{\infty} f_1(t+s)f_2(t) dt ds$$

And the conflict probability is given by the convolution of f_1 and f_3 :

$$\Pr(t_1 \geq t_3) = \int_0^{\infty} \int_0^{\infty} f_1(t+s)f_3(t) dt ds.$$

It is expected that the distributions of f_1 , f_2 and f_3 would depend on the type of potential conflict and its geometry. This dependence on conflict geometry can be made by dividing the potential conflicts into several types.

9 Other Collision Risk Models

For the development of a 3D collision risk model for the European airspace, a review of a number of selected papers related to collision risk modelling was made (Burt, 1999). This review gives a comprehensive overview of the research performed in this field over the period 1960 - 2000, the complete section (section 6) of the 1999 paper has been integrally repeated in this appendix with only some minor editorial changes to make the section readable as a standalone.

Over the last four¹⁴³ decades many papers have been written on collision risk modelling. Most of these are concerned with aircraft flying on parallel routes to assess the lateral risk, or with aircraft at adjacent flight levels to estimate the vertical risk in procedural airspace. These models, adaptations from the so-called Reich Collision Risk Model (Reich, 1966a, 1966b, 1966c), are well understood and were used successfully in the NAT region, first before the reduction of lateral separation to 60 NM and more recently prior to the instruction of RVSM. However, the assumption of parallel routes is crucial to the derivation of the model and the treatment presented does not lend itself to be extended to the complicated route structure existing in European airspace. Such papers are not included in this review.

A comprehensive collision risk model must deal with the following topics:

- Near-misses or conflict,
- CNS/ATC related issues,
- Crossing tracks and climbing/descending traffic.

Some of the papers on these subjects are reviewed below, in more or less chronological order.

The paper by B.L. Marks (Marks, 1963) is one of the earliest studies of mid-air collision risk, and is the basis for the Reich model. It recognises that “... *the task of relating collision risk to a traffic configuration van be taken in two parts: determining the frequency with which aircraft are exposed to risk by passing close together, and determining what change of collision is inherent in the passing*”. Marks proceeds to drive what has come to be known as the Reich model for parallel tracks. The paper goes on to consider aircraft flying random independent paths, a topic relevant to the “flexible use of airspace” concept. It also recognises that the problem of estimating conflicts and collisions is essentially one and the same: “In the rest of this chapter we consider the frequency of conflicts, regarding the frequency of collision as a special case in which not only the conflict regions but also the much smaller collision shapes overlap”.

To study the risk of aircraft on random tracks Marks postulated an area A populated by a Poisson distribution of aircraft flying horizontally with randomly directed velocities and deduced a conflict rate of

$$R\rho^2v_rA \tag{9.1}$$

where

R	is the conflict radius
R	is the conflict radius,
ρ	the mean aircraft density (number of aircraft per unit area) and
v_r	the mean relative speed.

¹⁴³ Note from the authors: The four decades refers to the period 1960 – 2000.

Although the relation between the model and the actual airspace is not straightforward, Marks arrives at the valid but perhaps unexpected conclusion that the conflict rate is proportional to the square of the traffic density, but depends only linearly on the radius of the conflict zone (not its area). For this reason the snapshot of the aircraft positions will not give a valid impression of the risk. The second point to notice is that the absolute speed does not appear in the expression for the conflict rate, in other words the speed itself is not dangerous but relative speed is. The paper also derives the correct formula for two streams of traffic on intersecting airways, considers the application of Monte Carlo methods and goes on to suggest post-processing of actual flight data as the way to quantify required parameters.

This is a seminal paper; it is also very readable and provides an excellent introduction to the topic of collision risk modelling.

A similar result for the conflict rate was obtained by Alexander (Alexander, 1970), who assumed a so-called **“Gas model”** (based on the idea of aircraft at random positions and on random headings resembling gas molecules in a bottle). This is possibly one of very few papers that considers conflicts involving three aircraft; it is found that this type of conflict rate is proportional to the cube of the aircraft density.

Cohen and Hockaday (Cohen & Hockaday, 1998) expresses some doubt about the wider application of the Gas model, attributing the failure of the model in particular circumstances (a discrepancy between estimated and actual collision rates at two airports) to the fact that the model assumption of random positions and headings may not be entirely realistic in a terminal control area.

Dunlay (Dunlay, 1972) presents a model which estimates the expected number of conflicts arising from overtaking, merging and crossing traffic (all for level flight) in an airway network. The procedure is to evaluate the probability of conflict for each pair of aircraft for given initial conditions, and then to sum over all pairs. The paper also considers ATC intervention, and uses an exponential probability density function to describe the total reaction time of the ATC loop, the mean of the distribution corresponding to the total estimated delay in the several components of the system (controller reaction time, communication delay, flight crew reaction and aircraft response time). Dunlay also considers airways capacity and the controllers’ intervention workload.

Dunlay is also a co-author of a further paper (Dunlay & Horonjeff, 1974) which examines the ATC responses in more detail – in particular, the human factors involved. Two types of response probability are considered; the first predicts when controllers would intervene based on analysis of human and equipment error in the air traffic control process. The second type predicts when controllers actually intervene, based on data from real-time simulations of conflict detections.

The next paper (Dunlay, 1975), again by Dunlay, is concerned with crossing and overtaking conflicts. The number of conflicts on crossing routes is given in terms of the probability that controllers perceive various aircraft separations as potential violations of the 5 NM separation minimum. The expected number of perceived overtake conflicts is shown to depend only on the relative speeds of in-trail aircraft. In both cases the expected number of conflicts is found to vary as the square of the traffic flow rate. The intervals between the conflicts of either type are shown to follow a Poisson distribution.

The 1976 paper by Dunlay and Horonjeff (Dunlay & Horonjeff, 1976) investigates the day-to-day variations of traffic. It shows that the characteristics of en-route air traffic passings through a small volume of airspace,

such as a sector, are quite variable from day to day, in spite of the constancy of the underlying airline schedule. Air traffic is represented by a stochastic point process, which for the particular airway studied was shown to be a Poisson process and also that the number of aircraft passing through an ATC sector in relatively long time periods is approximately Poisson-distributed.

The expression for the probability of overlap/conflict between aircraft on crossing routes is usually derived assuming both aircraft are in level flight (e.g. (Marks, 1963) and (Dunlay, 1972)). Geisinger (Geisinger, 1985) develops equations for computing the number of potential conflicts at an intersection of flight paths and extends the level-flying result to cover climbing and descending aircraft. He considers the number of potential conflicts within a sector as a useful measure of either the workload placed on the ATM system or of the relative risk.

The equations derived in the above paper (Geisinger, 1985) have been used by Geisinger to develop **an analytic blunder risk model** (as reported in (Cohen & Hockaday, 1998), section 6.1), which estimates collision risk for a given single event scenario of two aircraft under ATC control. In this context a “blunder” is defined as a simultaneous violation of separation minima in the horizontal and vertical planes (i.e. a cylindrical hazard volume). The inputs for this computer program are the climb angles of the “blunderer” and “evader” aircraft, their speeds, initial distance of the “blunderer” to the closest point on the “evader’s” path horizontally, their vertical separation and the traffic frequency on the “evader’s” track. Also required as inputs are the probability density functions of the communication delay, reaction times of the controller, flight crew and manoeuvre response time for both aircraft. The probability density function of the overall delay time is found by a numerical convolution of the individual probability density functions. With these inputs, the program works out the conflict and collision probability with and without ATC intervention. The equations solved by the computer are those described in paper by Geisinger (Geisinger, 1985). Geisinger suggests that actual data on blunders can be obtained by analysis of Operational Errors (failure of the ATC human/technical system) and Pilot Errors.

Gifford and Sinha (Gifford & Sinha, 1991) offer a model that estimates the number of near mid-air collisions from a combination of parameters, such as traffic levels, type and amount of air traffic control and the complexity of the airspace. (In the context of this paper, near mid-air collisions are taken to mean an incident when “two or more airborne aircraft pass within 500 feet of each other or when a pilot or flight crew member states that a collision hazard existed”.) The authors choose to work with near mid-air collisions, because “... accidents are rare. Near mid-air collisions occur much more frequently, thereby permitting more precise analysis of variations”. The emphasis is on aviation risk in metropolitan regions and as such is probably more appropriate to TMA operations than to en-route airspace.

Simpson (Simpson, 1991) describes the difficulties of analysing the risk in ATC operations with ground intervention capability and proposes a framework for solving these problems. The primary aim of the paper is to provide an indication of benefits of introducing intervention processes which use improved surveillance and communications as well as improved decision support for controller intervention. The paper describes two distinct intervention processes in ATC: Conformance Management and Hazard Management. Each of these has two sub-processes of Monitoring and Resolution. Both processes are intended to operate in real time and use a concept of maximum “probe time” and minimum “resolution time” ahead of each aircraft. The resolution time allows a controller to identify and find a resolution, transmit it to the aircraft and for the pilot to receive and execute it.

Bakker and Blom (Bakker & Blom, 1993a) have adopted a more general approach to modelling an airspace with an arbitrary route network by considering the traffic pattern to be a (Markov) diffusion process. While avoiding many assumptions and approximations in the “deterministic” models, the collision probability estimate requires the solution of a partial differential equation with difficult boundary conditions for each pair of aircraft involved. This is unrealistic, and further assumptions are needed to arrive at a computable result. Nevertheless the authors have obtained a model which is less restrictive than the Reich formulation. Again, the degree to which the diffusion model represents the actual air traffic behaviour is unclear.

The report by Hurras (Hurrass, 1994) describes a method of processing and analysing radar data recordings from nine radars in Germany in order to estimate the mean passing frequency for the northern and southern part of the country. The original radar records are first filtered to remove any irrelevant data, then a slant correction is carried out. Tracking each aircraft is necessary to obtain position and velocity a Kalman filter is used for tracking updating. This method uses the available information in an optimal manner and is therefore well suited to multi-radar tracking.

The NSSG paper by Burt (Burt, 1996) is concerned with lateral collision risk estimates for dual routes when a proportion of aircraft are climbing or descending through one or more flight levels on either track. Thus there are potential collisions between climbing or descending aircraft on one track with level flight on the other; between aircraft that are both climbing or descending; and between climbing and descending aircraft (it is assumed that there is no risk between climbing/descending aircraft and aircraft in level flight on the same track, since the situation is under Air Traffic Control). It is found that a proportion of climbing/descending traffic can either increase or decrease the risk depending on the flow direction assigned to each track at each flight level.

Anderson and Lin (Anderson & Lin, 1996) develop a mathematical model that estimates the collision risk at track intersection for aircraft at the same flight level outside the range of radar cover and with surveillance provided by means of position reports. The situation, where a small proportion of crossings are made under no control, is also investigated in order to consider the implications of communication or surveillance failure.

Burt estimates in a NATS R&D paper (Burt, 1997) the required ATC intervention rate for aircraft on parallel tracks as a function of track separation, lateral navigation accuracy, traffic density and other parameters. The paper derives formulae for both deviation (conformance) and conflict (hazard) interventions. It is assumed that a deviation intervention will be issued to prevent any aircraft departing from its assigned track by more than a given lateral distance. The conflict intervention, on the other hand, is issued to prevent aircraft sharing the same “hazard” space. The formula developed for estimating frequency of conflict interventions reduces to the Reich CRM when the hazard space is taken to be a box of aircraft dimensions. The paper also treats the case of a cylindrical hazard space.

The NATS R&D paper from Burt in 1998 (Burt et al., 1998) describes a method for estimating the vertical collision risk for aircraft operating in UK airspace, and presents the result of an initial study for RVSM operations. Radar data tracks from a multi-radar tracker are used to obtain the frequency of vertical proximate events; this occurs when two aircraft pass within a horizontal distance R of each other on adjacent flight levels. The value of R is chosen to be large enough (e.g., 5 NM) so that a sufficient number of events are observed over a reasonable time. At each event the position, speed and heading of each aircraft, obtained from radar data, are used as an input to the CRM to arrive at the estimate of vertical risk.

Smith (Smith, 1996) uses **Hazard Analysis** to estimate the collision risk in European airspace under RVSM. Hazards are identified from historical data or by recourse to expert judgement; these are then used to create various scenarios involving different types of hazards and their frequency of occurrence. The Reich and crossing models then generate collision risk estimates without ATC intervention. These are combined with ATC intervention success probability, assessing using consequence analysis, to produce an overall risk, averaged over the six scenarios involving operational errors - e.g., crossing and joining wrong flight levels. The historic incident data is rather sparse, so that there is a wide spread between the optimistic and pessimistic collision rates predicted in the study.

The **ILS Collision Risk Model** is used to estimate the probability of collision with obstacles by an airborne aircraft on an ILS approach and eventual missed approach. The original CRM developed by the FAA and ICAO (ICAO, 1980a) and was used to estimate the risk during the airborne phase of landing.

References

Beside the references listed in this section, references to NAT SPG meetings, ICAO RGCSP meetings and ICAO SASP meetings are listed in Appendix E. References to relevant ICAO documentation (SARPS, PANS, Manuals and Cir) are provided in Annex B.

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Appendix A List of symbols and notation

Appendix A.1 List of main symbols used

Symbol	Meaning	Page
S_y	Lateral separation minimum/standard	
N_{az}	expected number of aircraft accidents per aircraft flight hour in the system due to failure of vertical separation	
std	vertical separation minimum/standard	
S_z	vertical separation minimum/standard	
$P_z(\square)$	probability of vertical overlap	
$P_y(\square)$	probability of lateral overlap	
$ \Delta V $	mean absolute relative velocity between aircraft	
$\bar{V}$	mean velocity	
$ \dot{y} $	mean absolute relative lateral velocity between aircraft	
$ \dot{z} $	mean absolute relative vertical velocity between aircraft	
λ_x	mean length of aircraft	
λ_y	mean width (span) of aircraft	
λ_z	mean height of aircraft	
$E_*(\text{same})$	same-direction occupancy	
$E_*(\text{opp})$	opposite-direction occupancy	
$E_*(\text{cross})$	probability of plan overlap of circles representing horizontal cross sections of aircraft on crossing airways	
S_x	along-track criterion of proximity	
$N_x(\text{same})$	expected number of longitudinal overlaps (passing events) experienced by an average aircraft per aircraft flight hour, for same direction traffic on adjacent flight levels	
$N_x(\text{opp})$	expected number of longitudinal overlaps (passing events) experienced by an average aircraft per aircraft flight hour, for opposite direction traffic on adjacent flight levels	
$N_{xy}(\text{cross})$	The expected number of plan overlaps at crossings experienced by an average aircraft per aircraft flight hour	

Appendix A.2 Mathematical background

All theory is limited to three-dimensional Euclidian space $\mathbb{R}^3$. We will denote a vector in bold. So, a vector $\mathbf{r}$ is given by $\mathbf{r} = (r_x, r_y, r_z) \in \mathbb{R}^3$. The standard units vectors are indicated by $\mathbf{i} = (1,0,0)$, $\mathbf{j} = (0,1,0)$ and $\mathbf{k} = (0,0,1)$. So the vector $\mathbf{r}$ can be written as $\mathbf{r} = r_x\mathbf{i} + r_y\mathbf{j} + r_z\mathbf{k}$.

Let $\mathbf{r}(t)$ denote the relative position vector between the two aircraft at time t and let $\mathbf{v}(t)$ denote the relative speed: $\mathbf{v} = d\mathbf{r}/dt$. To simplify notation the time dependency t is dropped. A collision occurs when the relative position (particle) enters the collision volume V and let $S = \partial V$, the boundary of V . When the aircraft are modelled by boxes of dimensions $\lambda_x \times \lambda_y \times \lambda_z$, a collision occurs if a moving point (or particle) hitting a stationary box of dimension $2\lambda_x \times 2\lambda_y \times 2\lambda_z$ with the centered at the origin. The same would

apply if the aircraft are modelled by a cylinder with diameter λ_{xy} and height λ_z , the collision volume would be a cylinder with diameter $2\lambda_{xy}$ and height $2\lambda_z$.

A vector field is an assignment of a vector to each point in a subset V in $\mathbb{R}^3$, i.e. $\mathbf{F}: V \rightarrow \mathbb{R}^3$. A vector field is often visualised as a collection of arrows with a given magnitude and direction, each attached to a point. Vector fields are often used to model, for example, the speed and direction of a moving fluid throughout space, or the strength and direction of some force as it changes from one point to another point.

The divergence is a vector operator that operates on a vector field $\mathbf{F} = F_x\mathbf{i} + F_y\mathbf{j} + F_z\mathbf{k}$, producing a scalar field giving the quantity of the vector field's source at each point. The divergence is defined by

$$\operatorname{div} \mathbf{F} = \nabla \cdot \mathbf{F} = \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}$$

The divergence represents the volume density of the outward flux of a vector field from an infinitesimal volume around a given point. The divergence $\operatorname{div} \mathbf{F}$ is written as the inner product of the Nabla-operator $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$ and the vector field $\mathbf{F} = (F_x, F_y, F_z)$.

Let $\mathbf{F}$ be a vector field defined in the vicinity of a volume V (in $\mathbb{R}^3$) and S the boundary of V : $S = \partial V$, then the divergence theorem states that:

$$\iiint_V (\operatorname{div} \mathbf{F}) dV = \iint_S (\mathbf{F} \cdot \mathbf{n}) dS$$

Or written shortly as:

$$\int_V (\operatorname{div} \mathbf{F}) dV = \int_S (\mathbf{F} \cdot \mathbf{n}) dS$$

Where $\mathbf{n}$ is the outward unit normal vector on the surface S . Sometimes the right hand side is notated as $\int_S \mathbf{F} \cdot d\mathbf{S} = \int_S (\mathbf{F} \cdot \mathbf{n}) dS$ and $d\mathbf{S} = \mathbf{n} dS$. The integral $\int_S (\mathbf{F} \cdot \mathbf{n}) dS$ is the flux of $\mathbf{F}$ across S .

Appendix B List of relevant ICAO regulatory and guidance documents

Table 2.6 list various ICAO regulatory and guidance documents that have been referenced earlier in this chapter. Full details of the table's documents are available in the references.

Table 2.6: A selection of relevant ICAO regulatory and guidance documents

Identification	Title
Standards and Recommended Practices (SARPS)	
Annex 11	Air Traffic Services, Air Traffic Control Service, Flight Information Service, Alerting Service • First edition – 1950 • Eighth edition - 2004 • Fourteenth edition - 2016 • Fifteenth Edition (incorporating Amendments 1-51) - July 2018
Doc 4444 ATM/501	PANS-ATM (Doc 4444) / PANS-RAC / PANS-ATC Procedures for Air Navigation Services – Air Traffic Management This document contains procedures that are complementary to the Standards and Recommended Practices contained in Annex 2 — Rules of the Air and in Annex 11 — Air Traffic Services. They are supplemented when necessary by regional procedures contained in the Regional Supplementary Procedures (Doc 7030). The Procedures for Air Navigation Services — Air Traffic Management (PANS-ATM) are the result of the progressive evolution of the Procedures for Air Navigation Services — Air Traffic Control (PANS-ATC) prepared by the Air Traffic Control Committee of the International Conference on North Atlantic Route Service Organization (Dublin, March 1946). The Fourth Edition (1951) was given the title Procedures for Air Navigation Services — Rules of the Air and Air Traffic Services (PANS-RAC) on the recommendation of the Fourth Session of the Rules of the Air and Air Traffic Control (RAC) Division (Montreal, November–December 1950). This title reflected the fact that certain procedures applicable to pilots and a number of procedures relating to the provision of flight information and alerting service were included therein, in addition to the operation of the air traffic control service. On the 1st November 2001, Doc 4444 (PANS-RAC) and amendments thereto were superseded by the 14th edition. The document was also renamed to the current title Procedures for Air Navigation Services – Air Traffic Management (PANS-ATM). • 1st Edition (1946) - Procedures for Air Navigation Services — Air Traffic Control (PANS-ATC). • 2nd Edition (1946) • 3rd Edition (1947) • 4th edition (1951) - Procedures for Air Navigation Services – Rules of the Air and Air Traffic Control (PANS-RAC) • ... • 8th edition - 1966

Identification	Title
	• ... • 10th Edition - 1970 • 11th Edition - 1977 • 12th Edition – 1984 • 13th Edition - 1996 • PANS-ATM - 14th Edition - 2001 • 15th edition — 2007 • 16th edition – 2016
Manuals	
Doc 9689-AN/953	Manual on Airspace Planning Methodology for the Determination of Separation Minima First Edition – 1998
Doc 9574 AN/934	<u>RVSM manual</u> Manual on Implementation of a 300 m (1000 ft) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive • First Edition — 1992 • Second Edition — 2002 • Third Edition — 2012
Doc 9426-AN/924	Air Traffic Services Planning Manual
Doc 9274-AN/904	Manual on the Use of the Collision Risk Model (CRM) for ILS Operations First Edition – 1980
Doc 10063	Manual on Monitoring the Application of Performance-based Horizontal Separation Minima
Doc 10120 AN/524	Manual on the Implementation of Performance-based Longitudinal Separation Minima using ADS-C
Doc 9573-AN/933	Manual on Area Navigation (RNAV) Operations
Doc 9613 AN/937	<u>PBN manual / RNP manual</u> • Manual on the Required Navigation Performance (RNP) – 1st edition – 1994 • Manual on the Required Navigation Performance (RNP) – 2st edition – 1999 • Performance-based Navigation (PBN) Manual – 3rd edition – 2008 • Performance-based Navigation (PBN) Manual – 4th edition – 2012
Doc 9869 AN/462	<u>PBCS Manual / RCP Manual</u> • Manual on Required Communication Performance (RCP) – 1st edition - 2008 • Performance-based Communication and Surveillance (PBCS) Manual – 2nd edition - 2017
Doc 9694	Manual of Air Traffic Services Data Link Applications
Doc 10037	Global Operational Data Link (GOLD) Manual, First edition 2017
Doc 10038	Satellite Voice Guidance Material (SVGM), First edition 2012
Doc 10116	Implementation Manual for Separation Minima Using ATS Surveillance Systems Where VHF Voice Communication is not available
Doc 9937 AN/477	Operating Procedures for Regional Monitoring Agencies in Relation to the Use of a 300 m (1 000 ft) Vertical Separation Minimum Between FL 290 and FL 410 inclusive
Circulars	
Cir 319-AN/181	A unified framework for Collision Risk Modelling in Support of the Manual on Airspace Planning Methodology for the Determination of Separation Minima (Doc 9689)
Cir 321	Guidelines for the Implementation of GNSS Longitudinal Separation Minima
Cir 322-AN/184	Guidelines for the Implementation of GNSS Lateral Separation Minima Based on VOR Separation Minima

Identification	Title
Cir 324	Guidelines for Lateral Separation of Arriving and Departing Aircraft on Published Instrument Flight Procedures
Cir 325	In-Trail Procedure (ITP) using Automatic Dependent Surveillance – Broadcast (ADS-B)
Cir 311- AN/177	Assessment of ADS-B Surveillance to Support Air Traffic Services and Guidelines for Implementation (2006)
Cir 326	Assessment of ADS-B and Multilateration Surveillance to Support Air Traffic Services and Guidelines for Implementation
Cir 331	Implementation of Strategic Lateral Offset Procedures
Cir 334, 341-AN/184, 349	Guidelines for the implementation of Lateral Separation minima • Cir 334 - 2014 (edition 14) • Cir 341-AN/184 - 2015 • Cir 349 – 2024
Cir 342-AN/200	Automatic Dependent Surveillance — Contract (ADS-C) Approved by and published under the authority of the Secretary General Climb and Descend Procedure (CDP) Edition 1 (1/1/2016)
Cir 343-AN/201	Guidelines for the Implementation of Performance-based Longitudinal Separation Minima 2016

Appendix C Aircraft collision risk modelling assumptions

Reich makes a number of observations and assumptions in Sections 1 – 3 (*Objectives*, *The notion of 'safe separation standards'*, and *The approach to estimating collision risk*) of Part I of his series of three papers (Reich, 1966a) on aircraft collision risk modelling for the NAT region as follows:

1. Separation is to absorb not only systematic differences in speed but also imperfections of navigation and piloting, termed flying errors;
2. Lateral and vertical standards are described;
3. These standards are procedural over the North Atlantic, i.e. the flying errors are not monitored from the ground and the aircrew are entirely responsible for keeping to the tracks and altitudes assigned by ATC;
4. The approach to estimating collision risk consists of
 - (a) Representing the planned exposure to risk;
 - (b) Representing the collision process;
 - (c) Treatment of flying errors; and
 - (d) Proximities;
5. Two boxes are defined regarding the exposure to risk. The inner box is centred about an aircraft A, say, with the length, width, and height of this box being the longitudinal, lateral, and vertical separation standards S_x , S_y , and S_z respectively. The controller's task is to ensure that the intended position B of any other aircraft is never inside the inner box. A significant collision risk will arise only when B is intended to be on one of the faces of the inner box, or just outside it. The proximity shell is an outer box enveloping the inner box outside which the collision risk between aircraft A and B can be assumed to be negligible, and within which an aircraft, B, is said to be in proximity with A and the pair is exposed to the risk of collision;
6. The expected number of times each aircraft flying in the airspace during the time period under consideration has another aircraft in its proximity shell must be accounted for;
7. The expected length of time this other aircraft will remain in the shell, and the path it describes through the shell must also be accounted for);
8. The collision risk for the pair of aircraft is the chance that that the vector [A'B'] defined by the true positions A' and B' of the aircraft shrinks sufficiently for the aircraft to touch;
9. The chance depends on the intended separation [AB] (i.e. the location of B within the proximity shell) and on the flying errors;
10. For a period of time during which the expected number of collisions is small, this number is itself a convenient and very close approximation to the chance of collision;
11. Collision risk will denote the expected number of collisions over a specified period of time;
12. Collision rate will denote the expected number of collisions per unit time between a pair of aircraft at some given (and possibly transient) intended separation [AB];
13. In general, the intended separation [AB] varies as the flight progresses;
14. Exposure to risk, i.e. the time spent in the proximity shell, could be treated as a discrete event for an opposite-direction pair of aircraft;
15. The exposure for a same-direction pair cannot be treated as a discrete event in this way;

16. The only general approach to collision risk in a traffic region is to treat the shrinkage of [AB] as a time-dependent process;
17. Accordingly, the collision risk for the flight of a proximate pair of aircraft is to be computed by taking elements of time small enough for the intended separation, [AB], to remain sensibly constant, then summing the expected numbers of collisions occurring in each such element of time;
18. To estimate the collision risk, i.e. the expected number of times, in a given time interval, the actual separation [A'B'] shrinks to collision size, [A'B'] must be considered as a time-varying quantity;
19. In addition to knowledge of [AB], two properties of the flying errors need to be known:
 - (i) The probability distributions of the error magnitudes
 - (ii) The probability distributions of the rates of changes of these magnitudes.
20. Property (i) is used to estimate the proportion of time during which [A'B'] is less than collision size;
21. Property (ii) has to be used to infer the average duration of the intervals during which [A'B'] is less than collision size;
22. Following bullet 16, it is simplest to think in terms of components of motion (assumed to be independent of one another) along cartesian coordinates corresponding to the along-track, across-track, and vertical dimensions;
23. Aircraft are given a notionally rectangular collision shape with length λ_x , width λ_y , and height λ_z ;
24. Taking the one aircraft relative to the other, the collision process may be looked on as a particle bombarding a slab with length $2\lambda_x$, width $2\lambda_y$, and height $2\lambda_z$;
25. The collision rate is given by the expected number of times the particle enters the slab through the sides, the ends, and the top and bottom;
26. Collision can occur only when at least one aircraft in a pair makes an error larger than half of the applicable separation standard, and it is the large rare errors (rather than the bulk of observations) that mainly determine the risk of collision;
27. The key to making useful estimates of the safety of separation standards thus lies in the treatment given to the 'tails' of the probability distributions of the flying errors;
28. Both the size and the shape of the 'tails' are important in risk estimation;
29. In practice, the shape of the 'tails' is usually uncertain due to a lack of data;
30. Such data as have been collected show decisively that the popular assumption that flying errors obey the gaussian distribution law gives a low count of the number of errors in the 'tails', and leads to dangerous underestimates of risk;
31. Estimating methods have been sought which allow upper limits of risk to be inferred from the observed data, which make particular use of the observations of large errors, and which avoid, as far as possible, arbitrary assumptions on the detailed shape of the tails;
32. The quantity of flying errors data is account for by giving the risk estimates in the form of confidence limits;
33. Two complicating factors regarding flying errors are:
 - The possible tendency for large errors and large rates of change of these errors to occur together; and
 - The possible tendency for a pair of proximate pairs to make the same error at the same time;
34. The time for which a pair of proximate aircraft is exposed at a given intended separation is termed proximity;

35. The expected number of collisions between the pair during the period for which this separation is intended to persist is, of course, simply the product; collision rate x proximity;
36. The detailed notion of proximity is not altogether easy to grasp:
 - It is not sufficient to measure simply the total time for which each aircraft flies with some other aircraft in its proximity shell, since each sort of intended separation has a characteristic collision rate;
 - The time spent by B within the shell must be specified as a particular sort of proximity;
 - To study the safety of proposed separation standards in a given traffic region, the aggregate of each sort of proximity, for all flights, is estimated for the period considered.

It is important to emphasize that the model developed in Part I (Reich, 1966a) is in terms of a “generic” intended separation [AB] rather than specifically the lateral spacing between parallel routes, cf. bullet 13 from the list above concerning the variation, in general, of the intended separation [AB] as the flight progresses. Clearly, variation in the intended separation [AB] must be accounted for when the variation in the actual separation [A'B'] is considered. Application of the model to the spacing between parallel routes is treated in Parts II (Reich, 1966b) and III (Reich, 1966c).

Notice that the size of the proximity shell defined under bullet 5 is not specified other than that it is larger than the inner box with dimensions equal to twice the three separation standards. Cf. also bullets 34, 35, and, particularly, 36.

The relevance of bullets 14 and 15 is that for an opposite-direction pair of aircraft (i.e. a high-speed passing) the risk of collision due to the aircraft colliding sideways or from above or below is negligible compared to that of colliding head-on. For a same-direction pair of aircraft (i.e. a slow-speed passing), all three possibilities of collision play a part.

See Figures 4.8 – 4.12 in section 4.5 regarding bullets 27 - 30.

The one but last section of Part I (Reich, 1966a) is entitled *4. Basic requirements when estimating collision risk*, from which the following seven requirements have been quoted:

- (i) All possible directions from which one aircraft can come into collision with another should be accounted for.
- (ii) Where, because of shortage of data or otherwise, the value of a parameter cannot be known exactly, an assigned value justified by a limit argument should be used, rather than an arbitrary judgement.
- (iii) If an arbitrary assumption is made about the probability distribution of the flying errors there should be strong reasons for believing it to err (if anything) on the ‘safe’ side and the sensitivity of the estimates to changes in the assumption should be indicated.
- (iv) The method of estimating should take account of the extent to which each of the three dimensions of space is used in separating aircraft.
- (v) When estimates of risk depend on limited samples of data, a measure should be given of the uncertainty due to sampling fluctuations’
- (vi) When different sets of data on flying errors lead to contradictory conclusions a safe interpretation of the overall situation should be used.
- (vii) Estimates should be presented in a form suitable for executive use.

Parts II (Reich, 1966b) and III (Reich, 1966c) deal with the application of some of the theoretical techniques developed at RAE to satisfy the requirements quoted above.

Following the spirit of Reich, Hsu (1981) states the following major theoretical and technical assumptions used in the derivation of his collision risk model for aircraft on intersecting air routes:

- (1) The number of aircraft involved in any one mid-air collision is two and only two, that is, there is no single-aircraft collision or collisions involving three or more aircraft;
- (2) Along-track, across-track, and vertical position deviations are independent;
- (3) The altitude assigned to an aircraft will not be altered en route;
- (4) Navigational errors between aircraft pairs are independent;
- (5) Navigational position errors are fairly well behaved and can be adequately be described by distribution models with symmetry and unimodality;
- (6) All aircraft in the regions investigated, e.g. in the oceanic or off-shore areas, are operating in a non-radar environment, and thus are not monitored by a controller;
- (7) No external information concerning position errors of the aircraft can be obtained to prompt the pilot's corrective action;
- (8) No collision avoidance manoeuvres are taken as a result of visual or instrument detection between aircraft;
- (9) Within the segment of flight-path under consideration the navigation performance of an aircraft is homogeneous and does not depend upon the flight-time or the distance travelled.

It is further hypothesized that all navigation systems under investigation can be adequately decomposed into areas containing, exclusively, air-routes of straight configuration, which may be either parallel or intersecting tracks, but with the focus on the latter in the paper by Hsu (1981).

Moek et al. (2001) quote the following explicit modelling assumptions from the ATS Planning Manual (ICAO, 1992a) for the lateral collision risk model for the safe spacing of parallel routes in procedural airspace:

1. All tracks are parallel with a constant spacing S_y ;
2. All collisions occur between aircraft normally¹⁴⁴ on adjacent tracks;
3. The entry times into the track system are uncorrelated;
4. The lateral deviations of aircraft on adjacent tracks are uncorrelated;
5. The lateral speed of an aircraft is not correlated with its lateral deviation;
6. There is no corrective action by pilots or ATC when aircraft are about to collide; and
7. In the collision risk model, the aircraft are replaced by rectangular blocks.

Pool (1974) discusses the following assumptions underlying the collision risk model developed for lateral collision risk on parallel ATS routes defined by VOR or VOR/DME:

- a. No allowance for visual avoidance;
- b. No allowance for effect of vortices;
- c. Independence of height-keeping errors of different aircraft;
- d. Independence of height keeping and track keeping;
- e. Independence of track-keeping errors of different aircraft; and
- f. Independence of the longitudinal positions of two aircraft.

¹⁴⁴ Collisions may also occur between aircraft on non-adjacent tracks if the probability of lateral overlap is sufficiently large.

Appendix D Evolution of the separation standards in PANS-ATM

Table 2.3: Evolution of lateral separation standards/minima in the PANS-ATM

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
14 th Edition incorporating Amendments 1-4 (applicable 01/11/01 – 24/11/05)	by reference to the same or different geographic locations		
	by use of the same navigation aid or method		
	a) VOR ¹⁴⁵		
	b) NDB		
	c) DR		
	d) RNAV operations	non-overlapping protected airspace of the two aircraft tracks	
	by use of different navigation aids or methods	non-overlapping protected airspace of the navigation aid(s) or RNP	
	RNAV operations where RNP is specified on parallel tracks or ATS routes	non-overlapping protected airspace of the tracks or ATS routes	Annex 11 Attachment B
14 th Edition Amendment 1 (applicable 28/11/02)	RNAV operations (where RNP is specified) on intersecting tracks or ATS routes	collision risk analysis	
15 th Edition	by reference to the same or different geographic locations		

¹⁴⁵ For VOR, NDB, and DR, numerical separation values are given in terms of minimum angular distance between radial/tracks and minimum distance to the facility for at least one aircraft. For RNAV operations, a minimum angular distance also applies in combination with non-overlapping protected airspace.

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
(applicable 22/11/07)	by use of the same navigation aid or method		
	a) VOR		
	b) NDB		
	c) DR		
	d) RNAV operations	non-overlapping protected airspaces of the two aircraft tracks	
	by use of different navigation aids or methods	non-overlapping protected airspaces of the navigation aid(s) or RNP	
	RNAV operations where RNP is specified on parallel tracks or ATS routes	non-overlapping protected airspace of the tracks or ATS routes	Annex 11 Attachment B
	RNAV operations (where RNP is specified) on intersecting tracks or ATS routes	collision risk analysis	
15 th Edition incorporating Amendments 1-3 (applicability 22/11/07 – 18/11/10)	by reference to the same or different geographic locations		
	by use of the same navigation aid or method		
	a) VOR		
	b) NDB		
	c) DR		
	d) RNAV operations	non-overlapping protected airspaces of the two aircraft tracks	

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
	by use of different navigation aids or methods	non-overlapping protected airspace of the navigation aid(s) or RNP	
	Lateral separation of aircraft on published instrument procedures for arrivals and departures		
	a) Where the distance between RNAV 1, Basic RNP 1, RNP APCH and/or RNP AR APCH tracks is not less than 7 NM; or	Collision risk analysis	Circular 324
	b) Where the protected areas of tracks designed using obstacle clearance criteria do not overlap and provided operational error is considered	Collision risk analysis	Circular 324
	RNAV operations where RNP is specified on parallel tracks or ATS routes	non-overlapping protected airspace of the tracks or ATS routes	Annex 11 Attachment B
	Lateral separation of aircraft on parallel or non-intersecting tracks or ATS routes		
	a) 50 NM for RNAV 10 (RNP 10) or RNP 4	Collision risk analysis	Circular 334
	b) 30 NM for RNP 4	Collision risk analysis	Circular 334
	RNAV operations (where RNP is specified) on intersecting tracks or ATS routes	collision risk analysis	
15 th Edition incorporating Amendments 1-6	by reference to the same or different geographic locations		
	~~by use of the same navigation aid or method~~ by use of NDB, VOR or GNSS on intersecting tracks or ATS routes		

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
(applicability 22/11/07 – 13/11/14) ¹⁴⁶	a) <i>VOR</i> ¹⁴⁷		
	b) <i>NDB</i>		
	c) ~~DR~~ <i>GNSS/GNSS</i>	Collision risk analysis	Circular 322
	d) ~~RNAV operations (by use of the same navigation aid or method)~~ <i>VOR/GNSS</i>	Collision risk analysis	Circular 322
	• <i>by use of different navigation aids or methods</i>	non-overlapping protected airspace of the navigation aid(s) or RNP	
	• <i>Lateral separation of aircraft on published instrument procedures for arrivals and departures</i>		
	a. ~~Where the distance between RNAV 1, Basic RNP 1, RNP APCH and/or RNP AR APCH tracks is not less than 7 NM~~ 7 NM between any combination of RNAV 1 with RNAV 1, or RNP 1, RNP APCH or RNP AR APCH tracks; or	Collision risk analysis	Circular 324
	b. 5 NM between any combination of RNP 1, RNP APCH or RNP AR APCH tracks; or	Collision risk analysis	Circular 324
	c. <i>Where the protected areas of tracks designed using obstacle clearance criteria do not overlap and provided operational error is considered</i>	Collision risk analysis	Circular 324
	• <i>RNAV operations where RNP is specified on parallel tracks or ATS routes</i>	non-overlapping protected airspace of the tracks or ATS routes	Annex 11 Attachment B

¹⁴⁶ The light-grey shaded entries for Amendment 6 to the Fifteenth Edition of the PANS-ATM have been reverse engineered from Amendment 1-7-A incorporated in the Sixteenth Edition of the PANS-ATM.

¹⁴⁷ For VOR and NDB, numerical separation values are given in terms of minimum angular distance between radial/tracks and minimum distance to the facility for at least one aircraft. For GNSS/GNSS and VOR/GNSS, a range of angular distances applies in combination with a minimum distance from a common point for two flight-level ranges.

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
	Lateral separation of aircraft on parallel or non-intersecting tracks or ATS routes		
	a) 50 NM for RNAV 10 (RNP 10), RNP 4 or RNP 2	Collision risk analysis	Circular 334
	b) 30 NM for RNP 4 or RNP 2, provided direct controller-pilot VHF voice communications or CPDLC and a surveillance capability by an ADS-C system in which a periodic contract and waypoint change and lateral deviation event contracts are applied	Collision risk analysis	Circular 334
	c) 15 NM for RNP 2 or GNSS equipage, provided direct controller-pilot VHF voice communication	Collision risk analysis	Circular 334
	d) 7 NM while one aircraft climbs/descends through the level of another aircraft for RNP 2 or GNSS equipage, provided direct controller-pilot VHF voice communication	Collision risk analysis	Circular 334
	e) 20 NM while one aircraft climbs/descends through the level of another aircraft whilst using other types of communication than specified in d) above, for RNP 2 or GNSS equipage	Collision risk analysis	Circular 334
	Lateral separation of aircraft on intersecting tracks or ATS routes		
	a) An aircraft converging with the track of another aircraft: 50 NM for RNAV 10 (RNP 10), 30 NM for RNP 4, or 15 NM for RNP 2	Collision risk analysis	Circular 334
	b) An aircraft diverging with the track of another aircraft: 50 NM for RNAV 10 (RNP 10), 30 NM for RNP 4, or 15 NM for RNP 2	Collision risk analysis	Circular 334
16th Edition	by reference to the same or different geographic locations		

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
(applicability 10/11/16)	by use of NDB, VOR or GNSS on intersecting tracks or ATS routes		
	a) VOR		
	b) NDB		
	c) GNSS/GNSS	Collision risk analysis	Circular 322
	d) VOR/GNSS	Collision risk analysis	Circular 322
	by use of different navigation aids or methods	non-overlapping protected airspace of the navigation aid(s) or RNP	
	Lateral separation of aircraft on published instrument procedures for arrivals and departures		
	a) 7 NM between any combination of RNAV 1 with RNAV 1, or RNP 1, RNP APCH or RNP AR APCH tracks	Collision risk analysis	Circular 324
	b) 5 NM between any combination of RNP 1, RNP APCH or RNP AR APCH tracks	Collision risk analysis	Circular 324
	c) Where the protected areas of tracks designed using obstacle clearance criteria do not overlap and provided operational error is considered		
	RNAV operations where RNP is specified on parallel tracks or ATS routes	non-overlapping protected airspace of the tracks or ATS routes	Annex 11 Attachment B
	Lateral separation of aircraft on parallel or non-intersecting tracks or ATS routes		
	a) 50 NM for RNAV 10 (RNP 10), RNP 4 or RNP 2	Collision risk analysis	Circular 341

PANS-ATM	Means of providing lateral separation	Safety assessment method	References
	b) ~~30 NM for RNP 4 or RNP 2, provided direct controller-pilot VHF voice communications or CPDLC and a surveillance capability by an ADS-C system in which a periodic contract and waypoint change and lateral deviation event contracts are applied~~ 23 NM for RNP 4 or RNP 2, provided RCP 240, RSP 180, and an ADS-C event contract specifying a lateral deviation change event with a maximum of 5 NM threshold and a waypoint change event	Collision risk analysis	Circular 341
	c) 15 NM for RNP 2 or GNSS equipage, provided direct controller-pilot VHF voice communication	Collision risk analysis	Circular 341
	d) 7 NM while one aircraft climbs/descends through the level of another aircraft for RNP 2 or GNSS equipage, provided direct controller-pilot VHF voice communication	Collision risk analysis	Circular 341
	e) 20 NM while one aircraft climbs/descends through the level of another aircraft whilst using other types of communication than specified in d) above, for RNP 2 or GNSS equipage	Collision risk analysis	Circular 341
	Lateral separation of aircraft on intersecting tracks or ATS routes		
	a. An aircraft converging with the track of another aircraft: 50 NM for RNAV 10 (RNP 10), 23 NM for RNP 4, or 15 NM for RNP 2	Collision risk analysis	Circular 341
	b. An aircraft diverging with the track of another aircraft: 50 NM for RNAV 10 (RNP 10), 23 NM for RNP 4, or 15 NM for RNP 2	Collision risk analysis	Circular 341
16 th Edition incorporating Amendment 8	by reference to the same or different geographic locations		
	by use of NDB, VOR or GNSS on intersecting tracks or ATS routes		

PANS-ATM	Means of providing lateral separation		Safety assessment method	References	
(applicability 8/11/18)	a) VOR				
	b) NDB				
	c) GNSS/GNSS		Collision risk analysis	Circular 322	
	d) VOR/GNSS		Collision risk analysis	Circular 322	
	by use of different navigation aids or methods		non-overlapping protected airspace of the navigation aid(s) or RNP		
	Lateral separation of aircraft on published instrument procedures for arrivals and departures				
	a) 7 NM between any combination of RNAV 1 with RNAV 1, or RNP 1, RNP APCH or RNP AR APCH tracks		Collision risk analysis	Circular 324	
	b) 5 NM between any combination of RNP 1, RNP APCH or RNP AR APCH tracks		Collision risk analysis	Circular 324	
	c) Where the protected areas of tracks designed using obstacle clearance criteria do not overlap and provided operational error is considered				
	RNAV operations where RNP is specified on parallel tracks or ATS routes		non-overlapping protected airspace of the tracks or ATS routes	Annex 11 Attachment B	
	Lateral separation of aircraft on parallel or non-intersecting tracks or ATS routes				
	Minimum Spacing Between Tracks	Performance requirements	Additional Requirements	Safety assessment method	References

PANS-ATM	Means of providing lateral separation					Safety assessment method	References	
	<i>Airspace where SLOP is not authorized, or is authorized only up to 0.5 NM</i>	<i>Airspace where SLOP up to 2 NM is authorized</i>	<i>Navigation</i>	<i>Communication</i>	<i>Surveillance</i>		Collision risk analysis	Circular 349
	50 NM	50 NM	RNAV 10 (RNP 10) RNP 4 RNP 2	Types of communication other than Direct controller-pilot VHF voice			Collision risk analysis	Circular 349
	20 NM	23 NM	RNP 4 RNP 2	RCP 240	RSP 180	Conformance monitoring based on an ADS-C event contract specifying a lateral deviation change event with a maximum of 5 NM threshold and a waypoint change event	Collision risk analysis	Circular 349
	20 NM	23 NM	RPN 2 or GNSS equipage	Types of communication other than Direct controller-pilot VHF voice		While one aircraft climbs/descends through the level of another aircraft remaining in level flight	Collision risk analysis	Circular 349
	15 NM	N/A	RPN 2 or GNSS equipage	Direct controller-pilot VHF voice communication			Collision risk analysis	Circular 349
	9 NM	N/A	RNP 4 RNP 2	RCP 240	RSP 180	While one aircraft climbs/descends through the level of another aircraft remaining in level flight	Collision risk analysis	Circular 349

PANS-ATM	Means of providing lateral separation					Safety assessment method	References	
	7 NM	N/A	RPN 2 or GNSS equipage	Direct controller-pilot VHF voice communication		While one aircraft climbs/descends through the level of another aircraft remaining in level flight	Collision risk analysis	Circular 349
	Lateral separation of aircraft on intersecting tracks or ATS routes							
	a) An aircraft converging with the track of another aircraft: 50 NM for RNAV 10 (RNP 10), 23 NM for RNP 4, or 15 NM for RNP 2					Collision risk analysis	Circular 341	
	b) An aircraft diverging with the track of another aircraft: 50 NM for RNAV 10 (RNP 10), 23 NM for RNP 4, or 15 NM for RNP 2					Collision risk analysis	Circular 341	

Table 2.5: Evolution of longitudinal separation standards/minima in the PANS-ATM

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
14 th Edition incorporating Amendments 1-4 (applicable 01/11/01 – 24/11/05)	a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes	Voice reports, CPDLC or ADS			
	b) longitudinal separation minima based on distance using distance measuring equipment (DME);	20 or 10 NM		Direct controller-pilot communication		
	c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive	Voice reports, CPDLC or ADS			
	d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM		Direct controller-pilot communication		Doc 9613 2 nd Edition
	e) longitudinal separation minima based on distance using RNAV where RNP is specified.	<u>Not using ADS:</u> 50 NM: RNP 10, ≤24 min <u>Using ADS:</u> 50 NM: RNP 10, ≤27 minutes or RNP 4, ≤32 minutes; 30 NM: RNP 4, ≤14 minutes		Voice or CPDLC direct controller-pilot communication	Appendix 5 to Doc 9689	Annex 11 Attachment B, Doc 9613 2 nd Edition, Doc 9689, Doc 9694
15 th Edition incorporating	a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes	Voice reports, CPDLC or ADS			

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
Amendments 1-2 (22/11/07 – 19/11/09))	b) longitudinal separation minima based on distance using distance measuring equipment (DME) and/or GNSS ;	20 or 10 NM		Direct controller-pilot communication	Collision risk analysis	Cir 321
	c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive	Voice reports, CPDLC or ADS			
	d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM		Direct controller-pilot communication		Doc 9613 2 nd Edition
	e) longitudinal separation minima based on distance using RNAV where RNP is specified.	<u>Not using ADS-C:</u> 50 NM: RNP 10, ≤24 min <u>Using ADS-C:</u> 50 NM: RNP 10, ≤27 minutes or RNP 4, ≤32 minutes; 30 NM: RNP 4, ≤14 minutes		Voice or CPDLC direct controller-pilot communication	Appendix 5 to Doc 9689	Annex 11 Attachment B, Doc 9613 3rd or 4th Edition, Doc 9689, Doc 9694
15 th Edition incorporating Amendments 1-5 (22/11/07 – 13/11/14))	a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes	Voice reports, CPDLC or ADS			
	b) longitudinal separation minima based on distance using distance measuring equipment (DME) and/or GNSS;	20 or 10 NM		Direct controller-pilot communication	Collision risk analysis	Cir 321
	c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive	Voice reports, CPDLC or ADS			

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
	d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM		Direct controller-pilot communication		Doc 9613 2 nd Edition
	e) longitudinal separation minima based on distance using RNAV where RNP is specified.	<u>Not using ADS-C:</u> 50 NM: RNP 10, ≤24 min <u>Using ADS-C:</u> 50 NM: RNP 10, ≤27 minutes or RNP 4, ≤32 minutes; 30 NM: RNP 4, ≤14 minutes		Voice or CPDLC direct controller-pilot communication	Appendix 5 to Doc 9689	Annex 11 Attachment B, Doc 9613 3 rd or 4 th Edition, Doc 9689, Doc 9694
15 th Edition incorporating Amendments 1-6 (applicability 22/11/07 – 13/11/14) ¹⁴⁸	a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes	Voice reports, CPDLC or ADS			
	b) longitudinal separation minima based on distance using distance measuring equipment (DME) and/or GNSS;	20 or 10 NM		Direct controller-pilot communication	Collision risk analysis	Cir 321
	c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive	Voice reports, CPDLC or ADS			
	d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM		Direct controller-pilot communication		Doc 9613 2 nd Edition

¹⁴⁸ The light-grey shaded entries for Amendment 6 to the Fifteenth Edition of the PANS-ATM have been reverse engineered from Amendment 1-7-A incorporated in the Sixteenth Edition of the PANS-ATM.

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
	e) longitudinal separation minima based on distance using RNAV where RNP is specified.	<u>Not using ADS-C:</u> 50 NM: RNP 10, ≤24 min <u>Using ADS-C:</u> 50 NM: RNP 10, ≤27 minutes or RNP 4, ≤32 minutes; 30 NM: RNP 4, ≤14 minutes		Voice or CPDLC direct controller-pilot communication	Appendix 5 to Doc 9689	Annex 11 Attachment B, Doc 9613 3 rd or 4 th Edition, Doc 9689, Doc 9694
	f) longitudinal separation minima based on distance using ADS-B In-trail procedure (ITP)	10 NM based on ITP distance				Cir 325
16 th Edition incorporating Amendments 1-7-A (applicability 10/11/16)	a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes	Voice reports, CPDLC or ADS			
	b) longitudinal separation minima based on distance using distance measuring equipment (DME) and/or GNSS;	20 or 10 NM		Direct controller-pilot communication	Collision risk analysis	Cir 321
	c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive	Voice reports, CPDLC or ADS			
	d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM		Direct controller-pilot communication		Doc 9613 2 nd Edition
	e) longitudinal separation minima based on distance using RNAV where RNP is specified.	<u>Not using ADS-C:</u> 50 NM: RNP 10, ≤24 min <u>Using ADS-C:</u>		Voice or CPDLC direct controller-pilot communication	Appendix 5 to Doc 9689	Annex 11 Attachment B, Doc 9613 3 rd or 4 th Edition,

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
		50 NM: RNP 10, ≤ 27 minutes or RNP 4, ≤ 32 minutes; 30 NM: RNP 4, ≤ 14 minutes				Doc 9689, Doc 9694
	f) longitudinal separation minima based on distance using ADS-B In-trail procedure (ITP)	10 NM based on ITP distance				Cir 325
	g) longitudinal separation minima based on distance using ADS-C climb and descend procedure (CDP)	15 NM or 25 NM depending on the speed difference between the aircraft		Direct controller-pilot voice communications or CPDLC		Cir 342
	h) performance-based longitudinal separation minima	50 NM: RNP 10, ≤ 27 min 50 NM: RNP 4, ≤ 32 min 30 NM: RNP 2 or RNP 4, ≤ 12 min 5 minutes: RNP 2 or RNP 4 or RNP 10, ≤ 14 min	RSP 180	RCP 240	Collision risk assessment	Doc 9869, Doc 10037, Doc 10038, Circular 343
16 th Edition incorporating	a) longitudinal separation minima based on time;	15, 10, 5, or 3 minutes	Voice reports, CPDLC or ADS			

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
Amendments 1-8 (applicable 08/11/18)	b) longitudinal separation minima based on distance using distance measuring equipment (DME) and/or GNSS;	20 or 10 NM		Direct controller-pilot communication	Collision risk analysis	Cir 321
	c) longitudinal separation minima with Mach number technique based on time;	10 minutes or between 9 and 5 minutes inclusive	Voice reports, CPDLC or ADS			
	d) longitudinal separation minima with Mach number technique based on distance using RNAV;	80 NM		Direct controller-pilot communication		Doc 9613 2 nd Edition
	e) longitudinal separation minima based on distance using RNAV where RNP is specified.	<u>Not using ADS-C:</u> 50 NM: RNP 10, ≤24 min		Voice or CPDLC direct controller-pilot communication	Appendix 5 to Doc 9689	Annex 11 Attachment B, Doc 9613 3 rd or 4 th Edition, Doc 9689, Doc 9694
	f) longitudinal separation minima based on distance using ADS-B In-trail procedure (ITP)	10 NM based on ITP distance				Cir 325
	g) longitudinal separation minima based on distance using ADS-C climb and descend procedure (CDP)	15 NM or 25 NM depending on the speed difference between the aircraft		Direct controller-pilot voice communications or CPDLC		Cir 342
	h) performance-based longitudinal separation minima	50 NM: RNP 10, ≤27 min 50 NM: RNP 4, ≤32 min	RSP 180	RCP 240	Collision risk assessment	Doc 9869, Doc 10037, Doc 10038, Circular 343

PANS-ATM	Means of providing longitudinal separation	Longitudinal separation minima	Surveillance (position information and estimates)	Communication	Safety assessment method	References
		30 NM: RNP 2 or RNP 4, ≤12 min 5 minutes: RNP 2 or RNP 4 or RNP 10, ≤14 min				

Table 7.21: Overview of the revision process for SASP-WG/WHL/14-WP/14 and SASP-WG/WHL/12-WP/18

<u>SASP-WG/WHL/12-WP/18</u>	<u>SASP-WG/WHL/14-WP/14</u>	<u>SASP-WG/WHL/14-WP/16</u>
Zero angle same-identical tracks Probability of longitudinal overlap at co-altitude i.e. joint longitudinal and vertical overlap $x(t) \in [-\lambda_x, \lambda_x]$ Extension Δx $P_x[-\lambda_x \leq x(t) \leq \lambda_x]$ Probability of an overtake very small	Zero angle same-identical tracks Longitudinal Reich model from Appendix 5 to ICAO Doc 9689 2 modifications to account for ADS_B ITP characteristics: – ADS-B ITP procedure is not a continuous risk exposure: r – ITP and reference aircraft not assigned to same flight level: Π_{xz} instead of $\Pi_x P_z(0)$ Derivation of $r \Pi_{xz}$ was queried by MSG Revised values for $P_y(0)$ and $\bar{y}$ for GNSS aircraft agreed by MSG Revision required Intermediate review: – extend (ICAO, 1998c) for $0 \leq \theta < 45^\circ$ – Revision optional	Intersecting tracks at angles of 0 to 45 degrees Table 7.22
Revision during the meeting		Revision of during the meeting

<u>SASP-WG/WHL/14-WP/45</u> modifications to account for ADS-B ITP characteristics: – ADS-B ITP procedure is not a continuous risk exposure: r – Conservatively assume ITP and reference aircraft start manoeuvre at the same flight level: no extension Δx Revised values for $P_y(0)$ and $\bar{y}$ for GNSS aircraft as agreed by MSG Probability of longitudinal overlap $x(t) \in [-\lambda_x, \lambda_x]$ $P_x[-\lambda_x \leq x(t) \leq \lambda_x]$ Probability of an overtake very small Probability of vertical overlap $P_z(0) = 1$ Probability of lateral overlap $P_y(0) = 1$ Probability of a collision $\leq$ probability of an overtake Table 7.20	Revision during the meeting  <u>SASP-WG/WHL/14-WP/14</u> Zero angle same-identical tracks modifications to account for ADS-B ITP characteristics: – ADS-B ITP procedure is not a continuous risk exposure: r – Conservatively assume ITP and reference aircraft start manoeuvre at the same flight level: $\Pi_x P_z(0)$ Revised values for $P_y(0)$ and $\bar{y}$ for GNSS aircraft as agreed by MSG	<u>SASP-WG/WHL/14-WP/45</u> Intersecting tracks at angles of 0 to 45 degrees probability of longitudinal overlap for same-direction intersecting tracks is calculated in the same manner as for zero angle same-identical tracks probability of longitudinal overlap for same-direction intersecting tracks is therefore the same as for zero angle same-identical tracks for zero angle same-direction tracks $P_y(0) = 1$ was assumed for same-direction intersecting tracks the probability of lateral overlap can only be equal to or less than the probability of lateral overlap for zero angle same-identical tracks probability of collision for same-direction intersecting tracks is equal to or less than the probability of collision for zero angle same-identical tracks

Table 7.23: Summary of SASP work on performance-based longitudinal separation minima from SASP-WG/1 (Cairns, November 2011) to SASP-WG/WHL/23 (November 2013)

Meeting	Summary
SASP-WG/1	<u>WP/22</u> • “Literal interpretation” of PBN navigation performance, i.e. σ navigation errors derived from 95% specified performance (exponential distribution) • CPDLC as primary means of communication with HF voice as a secondary backup • Surveillance by means of ADS-C reporting • Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ • CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)), $\tau = 4, 10$, and 13.5 minutes (weighted) • <u>same-identical (zero angle) tracks</u> – Reproduction of original 50 NM/RNP 4/32' and 30 NM/RNP 4/14' longitudinal collision risk from the past – Calculation of new 50 NM/RNP 2/32' and 30 NM/RNP 2/14' longitudinal collision risk for original CRM parameters other than σ navigation errors – For specified performance, the longitudinal collision risk for RNP 2 is larger than that for RNP 4 – Calculation of 20 NM/RNP 2/14' longitudinal collision risk for original CRM parameters other than σ navigation errors: unacceptable collision risk • <u>Same tracks</u> – 20 NM/ RNP 2/T_r' collision risk for $[0 \leq \theta \leq 45]$ degrees, $T_r = T + \tau \in [14, 38]$ minutes – Clear increase in risk when $\theta \downarrow 0$ – 20 NM oceanic RNP 2 difficult to achieve unless reporting times are reduced and communications are faster • <u>Reciprocal tracks</u> – $\tau = 0$ – 30 NM/ RNP 4/14' and 30 NM/ RNP 2/14' – 20 NM/ RNP 4/14' and 20 NM/ RNP 2/14': collision risk below TLS • <u>Actual</u> GNSS navigation performance may be a better guide for navigation error distributions for PBN categories that effectively mandate GNSS equipage

Meeting	Summary
	<u>Flimsy 5</u> Draft PANS-ATM amendment proposal: add RNP 2 approved aircraft to RNP 4 approved aircraft for 30 NM using ADS-C <u>Action resulting from WP/21</u> OR 32 for MSG to “Develop criteria to determine the distance by which suitably approved aircraft can be (longitudinally) separated for same, crossing and reciprocal tracks based on the RNP 2 navigation specification and as amended using <u>actual</u>¹⁴⁹ navigation performance data”.
SASP-WG/WHL/20	<u>WP/10</u> • <u>Actual</u> navigation performance, ANP, defined as 95% value of collected navigation performance data • $ANP \in [0.02, 10]$ NM • ANP for GNSS equipped aircraft roughly ≤ 0.1 NM • CPDLC as primary means of communication with HF voice as a secondary backup • Surveillance by means of ADS-C reporting • Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ • Periodic reporting interval T, $T = 6, 10, 14$ minutes • CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)), $\tau = 4, 10$, and 13.5 minutes (weighted) • Exploration of weighted longitudinal collision risk with – Separation standard S_x, $S_x = 20$ or 30 NM – Reporting interval T, $T = 6, 10, 14$ minutes – RNP category, $RNP \in [0.02, 10]$ • <u>Same-identical tracks</u> ($\theta = 0^\circ$) – Verified that 30 NM with $T = 14'$ is sufficient, i.e. <u>meets</u> the TLS, for pairs of RNP 4 aircraft through the original methodology based on specified navigation performance – Showed that 30 NM with $T = 14'$ is sufficient, i.e. <u>meets</u> the TLS, for pairs of RNP 2 aircraft through the original methodology based on specified navigation performance – However, 30 NM with $T = 14'$ is not sufficient, i.e. <u>does not meet</u> the TLS, for pairs of RNP 4 or RNP 2 aircraft through the modified methodology based on actual navigation performance with $ANP \leq 0.1$ as for GNSS aircraft approved for RNP 4 or RNP 2

¹⁴⁹ Underlining by authors.

Meeting	Summary
	– Showed that 20 NM with $T = 14'$ is not sufficient, i.e. <u>does not meet</u> the TLS, for pairs of RNP 2 or RNP 4 aircraft through the original methodology – Original methodology for 30 NM/RNP 4 should have been conducted with RNP 0.1 or less • <u>Same track example, $\theta = 5^\circ$, only</u> – Risk generally decreases with <i>ANP</i> (i.e. with performance becoming less accurate) WP/20 • $ANP \in [0.05, 2]$ NM • CPDLC as primary means of communication with HF voice as a secondary backup • Surveillance by means of ADS-C reporting • Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ • Periodic reporting interval T, $T = 6, 10, 14$ minutes • CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)), $\tau = 4, 10$, and 13.5 minutes (weighted) • Exploration of weighted longitudinal collision risk with – Separation standard S_x, $S_x \in \{15, 20, 25, 30\}$ NM – Reporting interval T, $T = 6, 10, 14$ minutes – RNP category, $RNP \in [0.02, 10]$ • <u>Maximum</u> value of longitudinal collision risk over all values of <i>ANP</i> from 0.05 NM to 2 NM • <u>Same-identical track ($\theta = 0^\circ$)</u> – At no stage the collision risk is acceptably below the TLS • <u>Same-track, $\theta = 10^\circ$: representative of $\theta \in [10^\circ, 45^\circ]$</u> – Collision risk is below the TLS for $S_x = 25$ or 30 NM and for $S_x = 20$ NM and reporting interval of $T \leq 10$ minutes • <u>Reciprocal tracks ($\theta = 180^\circ$)</u> – With not offset, collision risk is below the TLS for $S_x = 25$ NM and a reporting interval of $T = 14$ minutes and with a 0.5 NM offset, collision risk is below the TLS for $S_x = 20$ NM and a reporting interval of $T = 14$ minutes
SASP-WG/WHL/21	WP/5

Meeting	Summary
	- Proposals for new or future work items to be submitted to the ANC in Job Card format - Job Card: <i>Development of PBN based RNP 2 and Advanced RNP longitudinal and lateral separation minima for oceanic and continental airspace</i> - Job Card (numbered SASP006) approved by ANC WP/9 - Current SASP work programme - Future SASP work programme for ANC approval (New job Cards) - SASP work programme -completed tasks WP/11 <u>Observed</u> navigation performance X, $ONP\ X$, defined as 95% value of observed navigation performance data of $RNP\ X$ approved aircraft $ONP\ X \leq RNP\ X$ ONP for GNSS equipped aircraft roughly ≤ 0.1 NM - Aircraft speeds: physical limitations and Mach number restrictions imposed by ATC - Tail-ends of the velocity probability distributions limited to $V_m = \pm 24$ knots and $V_m = \pm 50$ knots rather than the original ± 100 knots - Effect of lateral offsets - CPDLC as primary means of communication with HF voice as a secondary backup - Surveillance by means of ADS-C reporting - Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ - Periodic reporting interval T, $T = 6, 10, 14$ minutes - CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)), $\tau = 4, 10$, and 13.5 minutes (weighted) - Exploration of weighted longitudinal collision risk with - Separation standard S_x, $S_x \in \{15, 20, 30\}$ NM - Reporting interval T, $T = 6, 10, 14$ minutes - velocity distributions limit $V_m \in \{\pm 24, \pm 50\}$ knots $ONP \in [0.05, 2]$ NM <u>Maximum</u> value of longitudinal collision risk over all values of ONP from 0.05 NM to 2 NM for given combinations of values of separation standard S_x, reporting interval T, velocity distributions limit V_m, and intersection angle θ

Meeting	Summary
	• <u>Same-track longitudinal collision risk</u> – Collision risk is highly dependent on the velocity difference between the two aircraft – Collision risk results assuming <i>ONP</i> could be as large as 2 NM and as low as 0.05 NM suggested that: 3. For RNP 2 aircraft a 20 NM separation standard and reporting interval of 10 minutes gives a collision risk estimates below the TLS for $V_m = \pm 24$ 4. For RNP 2 aircraft with a 2 NM offset a 20 NM separation standard and reporting interval of 14 minutes gives a collision risk estimate below the TLS for $V_m = \pm 24$ – Collision risk results assuming what might be more realistic values for <i>ONP</i> of less than 0.3 NM with GNSS-equipped aircraft suggested that: 2. A 20 NM longitudinal oceanic separation with a 1 NM SLOP and a reporting period of 14 minutes gives collision risk estimates below the TLS • <u>WP/14</u> • Methodology to find communication performance required to meet the TLS for different separation standards in an oceanic same-identical (zero angle) track scenario • Response time $T_r = T + \tau$ broken down in a <u>new manner</u> to account for CPDLC using RCP 240, HF using RCP 400, and RSP 180 • <u>WP/13, WP/15, and WP/17</u> • Draft PANS-ATM proposals for RNP 2 longitudinal separation minima • Revised PANS-ATM proposal • <u>Actions on SASP Secretary</u> 1. Coordinate revised PANS-ATM proposal to the ANC subject to other supporting ICAO material being ready for publication in a similar amendment cycle 2. Coordinate an amended Job Card relating to RNP 2 separation to the ANC (draft Job Card SASP011) concerning – SASP coordination with OPLINK – SASP review of collision risk modelling for the original 50 NM and 30 NM longitudinal separation minima based on distance using RNAV where RNP is specified 3. Highlight to the ANC the need for review of PANS-ATM Chapter 5 for organisation and clarity
SASP-WG/WHL/22	<u>WP/14</u> • ANC had agreed that review of PANS-ATM Chapter 5 (Action 3 above) was not an urgent issue • ANC rejected draft Job Card SASP011 since work could be encompassed by the approved Job Card SASP006

Meeting	Summary
	- SASP transferred the two pertinent elements to Job Card SASP006 WP/16 - Proposed a draft Job Card entitled <i>Performance-based Communication and Surveillance (PBCS)</i> - SASP endorsed the draft Job card and actioned the Secretary to progress the Job Card to the ANC for endorsement - SASP discussion on relationship between longitudinal collision risk, PBN navigation specification, lateral navigation accuracy, accuracy of GNSS aircraft, navigation specifications effectively requiring GNSS, longitudinal collision risk result presented at foregoing meetings, and longitudinal separation minima regardless of PBN specification - SASP to review the previous amendment proposal for 20 NM/RNP 2 longitudinal separation in light of discussion - SASP to determine how the concept that PBN has no specific bearing on longitudinal separation will affect it and - SASP to determine what impact it will have on currently published separation standards WP/08 - Extension and re-interpretation of the previous work summarized above - Aim: - To demonstrate that reduction of reporting interval T can give rise to much reduced collision risk and/or wider range of possible aircraft speeds - To revisit the existing 50 NM RNAV 10 and 30 NM RNP 4 standards as a function of reporting interval and observed navigation accuracy, ONP, of GNSS approved aircraft - To revisit the proposed 20 NM RNP 4 standard as a function of reporting interval and observed navigation accuracy, ONP, of GNSS approved aircraft <u>Observed</u> navigation performance X, $ONP X$, defined as 95% value of observed navigation performance data of $RNP X$ approved aircraft $ONP X \leq RNP X$ ONP for GNSS equipped aircraft 0.05 NM - Aircraft speeds: physical limitations and Mach number restrictions imposed by ATC: tail-ends of the velocity probability distributions limited to V_m knots - CPDLC as primary means of communication with HF voice as a secondary backup - Surveillance by means of ADS-C reporting - Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ - CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)), $\tau = 4, 10$, and 13.5 minutes (weighted)

Meeting	Summary
	• Exploration of weighted longitudinal collision risk with – Separation standard S_x, $S_x \in \{20, 30, 50\}$ NM – Reporting interval T, $T = 2, 4, 6, 8, 10, 12, 14, 16$ minutes – $ONP \in [0.05, 10]$ NM – $V_m \in \{10, 20, 30, 40, 50, 100\}$ knots • <u>Maximum</u> value of longitudinal collision risk over all values of ONP from 0.05 NM to either 2, 4, or 10 NM for given combinations of values of separation standard S_x, reporting interval T, velocity distributions limit V_m, and intersection angle θ • <u>Same-identical (zero angle) track (only)</u> – Aim nr 1 above achieved – Aims nrs 2 and 3: working paper argued for reporting intervals to be $T = 4, 10$ and 20 minutes for the respective 20 NM (RNP 2), 30 NM (RNP 4), and 50 NM (RNAV 10) standards – SASP plenary endorsed the following actions: 1. The authors of WP/08 to provide clarification on the assumptions used to generate the paper's output to the next SASP Meeting 2. SASP to determine whether/which speed assumptions used in WP/08 are realistic enough to be beneficial 3. SASP to determine whether PANS-ATM should be amended to reflect recommended ADS-C reporting rates generated by recent modelling; and 4. SASP to consider creating an ICAO Circular to both catalogue previous and ongoing work for the RNAV 10, 50 NM and RNP 4, 30 NM longitudinal minima and development of RNP 2, 20 NM minimum. <u>WP/20</u> – Several analyses of observed aircraft speeds
SASP-WG/WHL/23	<u>WP/11</u> • Discussion items raised in the working paper: 1) Same-identical (zero angle) track against intersecting tracks 2) Effect of better RNP performance on increasing/decreasing longitudinal separation minima 3) FANS-equipped aircraft approved for different PBN navigation specifications all using GNSS-based position reporting 4) Extending same-track longitudinal separation to intersection angles less than 90 degrees 5) Conservative assumptions for the benefit of the widest possible global application • Discussion results:

Meeting	Summary
	1) Item 1: higher probability of longitudinal overlap along a route segment compared to that for a single (intersection) point 2) Item 2: use observed navigation performance when this is much better than specified RNP performance 3) Item 3 to be covered by requirement for system monitoring written into the separation standards 4) Item 4 supported by the SASP Meeting 5) Item 5 supported by the SASP Meeting • Further discussion: – PANS ATM amendment proposal for oceanic RNP 2 revisited – Confirmation that the proposal was on hold pending availability of other supporting ICAO documentation – Amendment proposal revised to account for the latest insights WP/02 • Sensitivity issues arisen from SASP-WG/WHL/22-WP/08 at previous meeting – Communication assumptions – Aircraft speed error distributions – Number of pairs collision-risk-model parameter • Aim: confirm that conclusions from previous working paper(s) were still valid and independent of the specific assumptions included in the collision risk model • <u>Observed</u> navigation performance X, $ONP X$, defined as 95% value of observed navigation performance data of $RNP X$ approved aircraft $ONP X \leq RNP X$ • ONP for GNSS equipped aircraft 0.05 NM • Aircraft speeds: physical limitations and Mach number restrictions imposed by ATC: tail-ends of the velocity probability distributions limited to V_m knots • CPDLC (RCP 240) as primary means of communication with HF voice (RCP 400) as a secondary backup • Surveillance by means of ADS-C reporting (RSP 180) • Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ • CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)), $\tau = 4, 10$, and 13.5 minutes (weighted)¹⁵⁰ • Exploration of weighted longitudinal collision risk with – Separation standard S_x, $S_x \in \{20, 30\}$ NM – Reporting interval T, $T = 4, 8, 12, 16, 20, 24, 28$ minutes

¹⁵⁰ Results were also provided for three additional parameter-value sets of τ .

Meeting	Summary
	– $ONP \in [0.05, 2]$ NM or $ONP \in [0.05, 4]$ NM – $V_m \in \{10, 20, 24, 28, 30, 35, 40, 50, 60, 70, 80, 90, 100\}$ knots – Speed-distribution parameter $\lambda_v \in \{4.5, 5.8\}$ knots • <u>Maximum</u> value of longitudinal collision risk over all values of ONP from 0.05 NM to 2 NM for given combinations of values of separation standard S_x, reporting interval T, velocity distributions limit V_m, speed-distribution parameter λ_v, and intersection angle θ • <u>Results, same-identical (zero angle) track (only)</u> – Table of proposed separation standard S_x NM, navigation specification RNP, reporting interval T minutes, and Mach restriction V_m (knots): – 20 NM/RNP 2/4'/35 kts, – 30 NM/RNP 4/8'/50 kts or 30 NM/RNP 4/14'/30 kts • SASP discussion of WP/02 – Assumptions concerning communication delays significantly increased the longitudinal collision risk – Effect of speed error distributions: collision risk model to be re-run based on data from WP/16 (see below) which suggest that V_m is of the order of 70-90 knots – Results of re-running the model presented in Flimsy 03 meeting the TLS and not affected by changes in the assumptions in the model,: ○ 20 NM/RNP 2/4', $\theta \geq 10^\circ$, 0 NM lateral offset ○ 20 NM/RNP 2/4', $\theta \geq 0^\circ$, 0.5 NM lateral offset ○ 20 NM/RNP 4/4', $\theta \geq 0^\circ$, 0.5 NM lateral offset ○ 30 NM/RNP 4/8', $\theta \geq 10^\circ$, lateral offset 0 ○ All cases require monitoring of distribution $H(S)$ of initial separation S ($S \geq S_x$ NM), velocity distributions limit V_m, and speed-distribution parameter λ_v • Final SASP discussion based on Flimsy 03 resulted in four actions as follows: – further possible analysis of the speed distribution of aircraft that have been assigned a fixed Mach speed – provision of an analysis similar to that of WP/13 (see below) using Australian data, possibly including data from different times of the year – analysis of Australian speed error using ADS-B data

Meeting	Summary
	– the SASP Secretary to seek information on what is the highest ADS-C reporting rate that the SASP can assume for application of performance-based longitudinal separation for oceanic RNP 2 and RNP 4 <u>WP/13 and WP/16</u> – Analyses of observed aircraft speeds

Table 7.25: Summary of SASP work on performance-based longitudinal separation minima from SASP/1 (Montreal, November 2016) to SASP/2 (May 2018)

Meeting	Summary
SASP/1	WP/21 • CRM given by eqs. (7.291), (7.296) and (7.297) • Surveillance/communication case A5 • 20 NM standard: – speed error parameter $\lambda_v \leq 4.5$ knots $\rightarrow$ – reporting period of 14 minutes or less meets the TLS – but additional monitoring required • 30 NM standard: – speed error parameter $\lambda_v \leq 4.5$ knots $\rightarrow$ – reporting period of 23 minutes or less meets the TLS WP/17 • Minimum ADS-C reporting interval
SASP-WG/29	WP/27: Job Card • Proposed draft Job Card to investigate further improvement of existing ADS-C based separation standards using advanced ADS-C parameters and/or 64-second and 3-minute ADS-C reporting intervals – Panel Member for ICCAIA to bring data on capabilities which exist on aircraft but are not yet used to next SASP Meeting – Secretary to present the draft Job card to the ANC for approval WP/30: PANS-ATM amendment for 20 NM performance-based longitudinal • Recalled 20 NM results for a 4-minute ADS-C reporting interval from the past documented in – SASP-WGH/24-WP/08 – ICAO Circular 343 • Referenced some investigations concerning 64-second and 3-minute ADS-C reporting intervals $\rightarrow$ – 4-minute ADS-C reporting interval feasible • Proposed a PANS-ATM amendment for a 20 NM/4-minute ADS-C reporting interval performance-based longitudinal separation standard – The <u>20 NM/4-minute ADS-C reporting interval</u> not to be viewed as superseding the <u>20 NM/14-minute ADS-C reporting interval/additional monitoring standard</u> • Proposed to publish a new Circular, <i>Guidelines for the implementation of performance-based longitudinal separation minima</i>

Meeting	Summary
	– Almost identical to Circular 343 with minor changes to its Chapters 1 and 2 (Chapter 3 safety assessment for 20 NM standard already covered by existing Circular 343) • SASP discussion and agreement – Review Circular 343 in light of recent ASEPS work – Revise and re-number Circular 343 to reflect its application to a 20 NM longitudinal separation standard – Proceed toward publication of a new 20 NM performance-based longitudinal separation standard in 2020
SASP-WG/30	<u>WP/40: Circular covering 20 NM performance-based longitudinal separation standard</u> • Review of existing Circular 343 with a view to incorporating a 20 NM performance-based longitudinal separation standard – Minor changes to Chapter 1, <i>Introduction</i>, and Chapter 2, <i>Longitudinal separation minima</i>, to account for a 20 NM longitudinal standard – Some comments on Chapter 3, <i>SASP safety assessment</i> – New Section 4.3 providing guidance on coordination needed when default ADS-C reporting rate is increased – Reference to WP/27 for additional (major) changes to Chapter 3 <u>WP/27</u> • Addressed a number of outstanding technical issues, particularly the re-introduction of the 20 NM longitudinal separation standard • Did not (yet) provide a revised Chapter 3 for the new performance-based longitudinal separation Circular • Noted – further developments on the computer code used for calculations – that the mathematical models in Circular 343 were still correct and valid – further understanding of the communication models used since original Circular 343 was written • Used new surveillance/communication model for ADS-C, viz. Case A21 • Applied the A21 model to the 20 NM longitudinal separation standard and obtained slightly lower collision risk than the traditional A1 model <u>Meeting's conclusion</u> • More time required, particularly for the MSG, to review WP/27 and WP/40 <u>WP/08: intersecting tracks</u> – longitudinal collision risk model for intersecting tracks

Meeting	Summary
	– effect of SLOP and RNP
SASP/2	<u>WP/40: Performance-based longitudinal separation Circular</u> • Latest revisions to Chapter 1, <i>Introduction</i>, Chapter 2, <i>Longitudinal separation minima</i>, and Chapter 4, <i>Implementation considerations</i> • Reference to work on Chapter 3, <i>SASP safety assessment</i>, being underway elsewhere <u>WP/24: draft PANS-ATM amendment for an nn NM performance-based longitudinal separation minimum with xx-minute periodic interval</u> • nn and xx to be agreed on the basis of collision risk results provided in SASP/2-WP/20 • nn and xx not to be viewed as superseding other longitudinal separation minima under development • A revision of the existing Circular 343, including the SASP safety assessment, was already underway • It was recommended that in order to facilitate future revisions, Circular 343 be cancelled and a Manual be issued in its place • Possible values of nn and xx based on WP/20: • $nn = 20$ NM with $xx = 3$ minutes • $nn = 18$ NM with $xx = 64$ seconds <u>WP/20</u> • CPDLC as primary means of communication with HF voice as a secondary backup • Controller intervention via CPDLC or HF voice • Surveillance by means of ADS-C reporting • Response time $T_r = T + \tau$, ADS-C periodic reporting interval T, time-buffer τ • Periodic reporting interval T, $T = 64$ seconds, 2, 3, 4, 5 minutes • time-buffer τ defined by Case C5 communication model • Effect of lateral offsets, SLOP • same-identical (zero angle) tracks and intersecting tracks ($0 < \theta \leq 90$ degrees) • same-identical (zero angle) tracks – cross track position error: ONP for GNSS equipped aircraft, $ONP = 0.05$ NM – SLOP not incorporated – Along-track position error: 0.1 NM • intersecting tracks ($0 < \theta \leq 90$ degrees) – specifically $\theta \in \{1, 5, 8, 10, 20, 30, 40, 50, 70, 90\}$ – cross-track position error: RNP 4 – SLOP incorporated (random application of 0, 1, 2 NM)

Meeting	Summary
	– Along-track position error: 0.1 NM • Tail-ends of the velocity probability distributions limited to $V_m = \pm 75$ knots • Speed error parameter $\lambda_v = 6.5$ kts • CRM: SASP-WG/WHL/4-WP/9 (Anderson, 2003a) and SASP-WG/WHL/7-WP/20 (revised) (Anderson, 2005) (eqs. (7.291), (7.296) ((7.292), and (7.295)) – See Table 1 of WP/20 for remaining collision risk model parameters • Exploration of weighted longitudinal collision risk (weighting over τ) with • Separation standard S_x: $S_x \in \{16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26\}$ NM with different subsets for different τ values • Results: – Risk found to be the highest at zero degrees – 20 NM met the TLS of 5×10^{-9} fatal accidents per flight hour with a periodic reporting interval of 3 minutes – 18 NM met the TLS of 5×10^{-9} fatal accidents per flight hour with a (minimum) periodic reporting interval of 64 seconds <u>FLIMSY/26</u> • Same as WP/20 but time-buffer τ defined firstly by the Case C11 communication model and ultimately by the Case C19 communication model instead of the initially used Case C5 model • Results: – 20 NM met the TLS of 5×10^{-9} fatal accidents per flight hour with a periodic reporting interval of 192 seconds <u>SASP discussion on WP/20, FLIMSY/26, WP/24, and WP/40</u> • PANS ATM amendment agreed for 20 NM and 192-second reporting interval – SASP Secretary to progress amendment proposal • Revised Circular 343 – Three designated SASP advisors to draft a final revised Circular 343 – SASP Secretary to transpose agreed ICAO Circular material into ICAO Manual format for subsequent review by the SASP

Table 7.24: Summary of SASP work on performance-based longitudinal separation minima from SASP-WG/WHL/24 (Montreal, May 2014) to SASP-WG/WHL/28 (Reykjavik, May 2016)

Meeting	Summary
SASP-WG/WHL/24	<u>WP/8¹⁵¹: Circular</u> - Summary of all previous 50 NM, 30 NM, and 20 NM results for RNP 4 and RNP 2 - Independent aircraft speed modelling used <u>WP/20 and WP/21: PANS-ATM Amendment</u> - PANS ATM amendment agreed to be progressed for 50 NM, 30 NM and 5-minutes; - Some editorial work remaining - Further MSG work required on 20 NM (refer to WP/8) - Collect data on same-identical (zero angle) track speed data - Utilize that data in 20 NM longitudinal collision risk model <u>WP/7 and WP/19</u> - aircraft speeds <u>IP/5</u> - Minimum ADS-C reporting interval
SASP-WG/25	<u>WP/24¹⁵²: Circular</u> - Summary of all previous 50 NM, 30 NM, and 20 NM results for RNP 4 and RNP 2 - Three designated SASP Panel Members/Advisors to draft a Circular for review at SASP-WG/26 <u>WP/8: PANS-ATM Amendment</u> - PANS ATM amendment agreed for 50 NM, 30 NM and 5-minutes - SASP Secretary to progress amendment proposal - Further work required on 20 NM <u>WP/21, WP/13 original and updated</u> - aircraft speeds <u>WP/16 and WP/32 revised</u>

¹⁵¹ Although SASP-WG/WHL/24-WP/8 was entitled *Circular on collision risk calculations for oceanic RNP 2 and RNP 4*, the working paper was not in the ICAO-Circular format.

¹⁵² Although SASP-WG/WHL/24-WP/24 was entitled *Circular on collision risk calculations for oceanic RNP 2 and RNP 4*, the working paper was not in the ICAO-Circular format.

Meeting	Summary
	Time-based performance-based longitudinal separation <u>IP/3</u> Minimum ADS-C reporting interval
SASP-WG/26	<u>Flimsy 23 and Flimsy 24: Circular</u> - Flimsy 23: Circular Chapters 1, 2, and 4 - Number of changes suggested and incorporated - Flimsy 24: Circular Chapter 3 - Outdated version of CRM safety assessment included - Latest CRM safety assessment to be provided and incorporated into draft Circular <u>Actions</u> - Project Team 6 to provide fully updated version of the Circular to the SASP Secretary by end-of June 2015 - All SASP Members to review fully updated draft Circular at or before SASP-WG/27 - MSG to continue work required on 20 NM <u>WP/9</u> - aircraft speeds - MSG comments to be incorporated into future efforts
SASP-WG/27	<u>Flimsy 20: Circular 343</u> - Some input provided and incorporated by Meeting's final review - SASP Secretary to process Circular 343 for publication
SASP-WG/28	–

Appendix E RGCSP, SASP and NAT meetings

Appendix E.1 Introduction

For this document two ICAO Panels are relevant, namely the Review of the General Concept of Separation Panel (RGCSP) and the Separation and Airspace Safety Panel (SASP). The RGCSP was established in 1973 and SASP, established in 2000. The SASP can be considered the successor to the RGCSP.

The panels work in between and at its semi-annual (two-week) meetings through the preparation and discussion of pertinent *working papers*, *information papers*, and *flimsies*. Working papers contain specific proposals for action. Each working paper is normally limited to one specific work programme or agenda item. Information papers comprise content that the originator wishes to bring to the attention of the panel. Typically, the only action required in an information paper will be an invitation to note the contents of the paper. Flimsies are very short papers, generally only one page, containing, for example, suggested text for the panel report. Flimsies are usually initiated and distributed at panel meetings and, where interpretation is provided, copies must be given to the interpreters. After each panel meeting, a meeting report is produced which is submitted to the ANC and shared with other panels.

A panel can be subdivided into working groups for specific topic. A rapporteur of a working group leads the working group and reports to the panel on the progress of the working group as required. In preparation for the Panel meetings of RGCSP and SAPS, meetings of working groups were held. RGCSP had two main working groups (Working Group A "Lateral" (WG/A) and Working Group B "Vertical" (WG/B)). Besides separate meetings for WG/A and WG/B, also joint meetings (WG/A&B) and meetings of the working group of the whole (WG/WHL) were held.

In the subsections below an overview of the RGCSP and SAPS panel and working group meetings is provided together with the documentation available at NLR. It is indicated with a [P] if the documentation is only available on paper.

For each of the meeting several documentations are produced. This can be:

- Individual decision papers, working papers, information papers, flimsies and general information on the meeting. In some cases the agenda and the report of the meeting were labelled as a working papers.
- Documentation: one document containing all material which is distributed before the meeting. This generally consists of the working papers and information papers;
- Report of the meeting: containing a history of the meeting and the main conclusions and action items. In some cases the report of the meeting was labelled as a working paper.

During the RGCSP-WG/A&B meeting in Toulouse, France from 12 to 23 October 1998 a **Mathematicians Sub-Group (MSG)** was established as a subgroup of WG/B. Geert Moek was rapporteur of this subgroup¹⁵³. The MSG continued its working during the SAPS meetings.

¹⁵³ The last meeting in NLR's archive in which Geert Moek was the rapporteur of the MSG is SASP-WG/WHL-20 (May 2012 meeting in Montreal).

Prior to 1998, NLR's archive contains two ad-hoc meetings which refer to a Mathematicians Sub-Group, namely:

- Mathematicians Sub-Groups meeting of RGCSP Working Group B (vertical) Paris, 20-22 July 1987
- Mathematicians- and Report Drafting Sub-Groups meeting of the RGCSP-WG/B, Amsterdam, 11-14 January 1988

The latter meeting was held at NLR in Amsterdam. For both meetings individual working papers and other information on the meeting are available at the archive of NLR.

The meetings (and available documentation in NLR's archive) of the RGCSP are presented in Appendix E.2 and of the SASP in Appendix E.3.

In Appendix E.4, the available reports in NLR's archive of the meetings of the North Atlantic Systems Planning Group (NAT SPG) are presented.

Appendix E.2 RGCSP meetings

Within the RGCSP the following meetings were held:

- Panel meetings (RGCSP/1, ..., RGCSP/10) (underlined)
- Working Group A "Lateral" (WG/A) and
- Working Group B "Vertical" (WG/B).
- Meetings of WG/A and WG/B (WG/A&B)
- Working Group of the Whole (WG/WHL)

RGCSP/1 - First Meeting of the RGCSP, ??

no information available at NLR.

RGCSP/2 – Second Meeting of the RGCSP, Montreal, 2-19 October 1973

no information available at NLR.

RGCSP/3 – Third meeting of the RGCSP, Montreal, 18 Augustus – 5 September 1975

- ICAO, Review of the General Concept of Separation (RGCS) Panel, Third meeting, Montreal 18 Augustus – 5 September 1975. RGCSP/3, DOCUMENTATION. [P]

RGCSP/4 – Fourth meeting of the RGCSP, Montreal, 18-29 August 1980

- ICAO, Review of the General Concept of Separation Panel, Fourth meeting, Montreal, 18-29 August 1980. REPORT. ICAO Doc 9352, RGCSP/4 (1980). [P]

RGCSP – WG B ("Vertical") Meeting 9-13 December 1985 in Brussel

- First meeting of WG/B.
- Individual decision papers, working papers, information papers, flimsies and general information on the meeting;
- Report of RGCSP Working Group "B" December 9-13, 1985, Brussels, Belgium

RGCS/5 - Fifth meeting of the RGCS, Montreal, 6-17 May 1985

- ICAO, Review of the General Concept of Separation (RGCS) Panel, Fifth meeting, Montreal 6-17 May 1985. RGCS/5, DOCUMENTATION. [P]
- ICAO, Review of the General Concept of Separation (RGCS) Panel, Fifth meeting, Montreal 6-17 May 1985. RGCS/5, REPORT FOLDER. [P]
- ICAO, Review of the General Concept of Separation Panel, Fifth meeting, Montreal 6-17 May 1985. Doc 9465, RGCS/5, Montreal, 1985. [P]

RGCS-WG/B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS). WORKING GROUP "B" (VERTICAL) Second Meeting Montreal, 19 to 30 January 1987

- Second meeting of the WG/B.
- Individual working papers, flimsies and general information on the meeting;
- Report of the Meeting (WP/64)
- During the meeting a Mathematicians subgroup was formed.

RGCS-WG/WHL/7 - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS) SEVENTH MEETING OF THE WORKING GROUP OF THE WHOLE Montreal, 18 - 29 April 1988

- 7th meeting of the whole.
- Individual working papers and other information on the meeting;

RGCS/6 – Sixth meeting of the RGCS, Montreal, 28 November–15 December 1988

- Individual decision papers, working papers, information papers, flimsies and general information on the meeting;
- ICAO, Review of the General Concept of Separation (RGCS) Panel, Sixth meeting, Montreal 28 November - 15 December 1988. RGCS/6, REPORT FOLDER. [P]
- Report of the Sixth Meeting. (Doc 9536) Montreal, 28 November–15 December 1988. [P]
- ICAO, Review of the General Concept of Separation Panel, Sixth meeting, Montreal, 28 November – 15 December 1988, Report Volume 2, Doc 9536, RGCS/6, Volume 2, Montreal 1988. [P]
- *Missing: ICAO, Review of the General Concept of Separation Panel, Sixth meeting, Montreal, 28 November – 15 December 1988, Report Volume 1, Doc 9636.*

RGCS-WG/B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS) WORKING GROUP 'B' MEETING Paris, 12 - 20 June 1989

- Individual working papers and other information on the meeting;

RGCS-WG/B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS) WORKING GROUP 'B' MEETING, Moscow, 11-20 September 1989.

- Individual working papers and other information on the meeting;
- WP/1, WP/2, WP/3 & Mathematicians Subgroup.

RGCSWP-WG/WHL/8 - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) EIGHTH MEETING OF THE WORKING GROUP OF THE WHOLE, Montreal, 24 January to 13 February 1990.

- Eighth (8th) meeting of the working group of the whole.
- Individual working papers and other information on the meeting;
- Summary of discussions and conclusions (WP/32)

RGCSWP-WG/B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP B (VERTICALS) MEETING, Annapolis. Maryland, 30 April - 8 May 1990

- Individual working papers and other information on the meeting;
- MEETING REPORT

RGCSWP/7 – Seventh meeting of the RGCSWP, Montreal, 30 October – 20 November 1990

- Individual decision papers, working papers, information papers, flimsies and general information on the meeting;
- Report of the Seventh Meeting of the Review of the General Concept of Separation Panel (RGCSWP) 1990 (WP-201);
- ICAO, Review of the General Concept of Separation (RGCS) Panel, Seventh meeting, Montreal 30 October – 20 November 1990. RGCSWP/7, DOCUMENTATION. [P]

RGCSWP/8 - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) EIGHTH MEETING Montreal, 17 March - 2 April 1993

- Individual working papers (WP/01 – WP/45);
- Report of the Eighth Meeting of the Review of the General Concept of Separation Panel (RGCSWP) 1993 (WP/45).

RGCSWP-WG/A - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A MEETING Seattle 7 to 17 September 1993

- Individual working papers, information papers, flimsies and general information on the meeting;
- Summary of Discussion and Conclusions (WP/21)

RGCSWP-WG/A (7th meeting) - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A MEETING SINGAPORE 26 APRIL TO 6 MAY 1994

- Individual working papers, flimsies and general information on the meeting;
- Summary of Discussion and Conclusions (WP/34)

RGCSWP-WG/A - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A MEETING Shizuoka, 13 - 23 September 1994

- Individual working papers, flimsies and general information on the meeting;
- Summary of Discussion and Conclusions (WP/26)

RGCSWP-WG/A (9th meeting) - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A MEETING Brussels, 2-12 May 1995

- The 9th meeting of WG/A
- Individual working papers, information papers, flimsies and general information on the meeting;
- Summary of Discussion and Conclusions (WP/??)

RGCSWP-WG/A (10th meeting)- REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A MEETING Gold Coast, Australia 9-20 October 1995

- Individual working papers, information papers, flimsies and general information on the meeting;
- Summary of Discussion and Conclusions (WP/30)

RGCSWP/9 - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) NINTH MEETING, Montreal, 6-17 May 1996

- Working paper 04 (WP/04) and 05 (WP/05).

RGCSWP-WG/A&B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A & B MEETING Annapolis, Maryland, United States 1 – 3 October 1996

- Working Group A: Summary of Discussion and Conclusions (WG/A-WP/36)
- Working Group B: Summary of Discussion and Conclusions (WG/B-WP/37)

RGCSWP-WG/A&B – Review of the General Concept of Separation Panel (RGCSWP) Working Groups A & B meeting, Singapore, 7 – 17 April 1997.

- The twelfth (12th) meeting of Working Group A
- The Working Group A meeting was held from 7 to 14 April 1997. The Working Group B (WG/B) meeting followed on from the WG/A meeting and was held from 14 to 17 April 1997.
- Individual working papers, information papers, flimsies and general information on the meeting;
- Working Group A: Summary of discussions and conclusions (WG/A-WP/24)
- Working Group B: Summary of discussions and conclusions (WG/B-WP/14)

RGCSWP-WG/A&B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) COMBINED MEETING OF WORKING GROUPS A AND B Brussels, 6 to 17 October 1997

- The thirteenth (13th) meeting of Working Group A of the Review of the General Concept of Separation Panel (RGCSWP-WG/A) was held in Brussels, Belgium from 6 to 13 October 1997.
- Individual working papers, information papers, flimsies and general information on the meeting;
- Working Group A: Summary of discussions and conclusions (WG/A-WP/29)
- Working Group B: Summary of discussions and conclusions: missing

RGCSWP-WG/A&B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCSWP) WORKING GROUP A&B MEETING Gold Coast, 27 April to 8 May 1998

- The fourteenth (14th) meeting of Working Group A of the Review of the General Concept of Separation Panel (RGCSWP-WG/A) was held in Gold Coast, Australia from 27 April to 5 May 1998. The

Working Group B (WG/B) meeting of the Review of the General Concept of Separation Panel (RGCS-P-WG/B) followed on from the WG/A meeting and was held in the Gold Coast from 5 to 8 May 1998.

- Individual working papers, information papers, flimsies and general information on the meeting;
- Working Group A: Summary of discussions and conclusions (WG/A-WP/28)
- Working Group B: Summary of discussions and conclusions: (WG/B-WP/16)

RGCS-P-WG/A&B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS-P) WORKING GROUP A&B MEETING Toulouse, France, 12-23 October 1998

- The fifteenth (15th) meeting of Working Group A of the Review of the General Concept of Separation Panel (RGCS-P-WG/A) was held in Toulouse, France from 12 to 19 October 1998. The Working Group B meeting of the Review of the General Concept of Separation Panel (RGCS-P-WG/B) was held in Toulouse, France from 19 to 23 October 1998.
- *During this meeting a Mathematicians Sub-Group (MSG) was established as a subgroup of WG/B.*
- Individual working papers, information papers, flimsies and general information on the meeting;
- Working Group A: Summary of discussions and conclusions (WG/A-WP/14)
- Working Group B: Summary of discussions and conclusions: (WG/B-WP/11)

RGCS-P-WG/A&B - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS-P) WORKING GROUP A&B MEETING St. Petersburg, Russian Federation, 17 - 28 May 1999

- The sixteenth (16th) meeting of Working Group A of the Review of the General Concept of Separation Panel (RGCS-P-WG/A) was held in St. Petersburg, Russian Federation from 17 to 24 May 1999. The Working Group B meeting of the Review of the General Concept of Separation Panel (RGCS-P-WG/B) was held in St. Petersburg, Russian Federation from 26 to 28 May 1999.
- Individual working papers, information papers, flimsies and general information on the meeting;
- Working Group A: Summary of discussions and conclusions (WG/A-WP/24)
- Working Group B: Summary of discussions and conclusions: (WG/B-WP/15)

RGCS-P-WG/WHL/9 - REVIEW OF THE GENERAL CONCEPT OF SEPARATION PANEL (RGCS-P) Ninth Meeting of the Working Group of the Whole, Montreal, 15 to 26 November 1999

- 9th meeting of the working group of the whole
- Individual decision papers, working papers, information papers, flimsies and general information on the meeting

RGCS-P/10 - REVIEW OF THE GENERAL CONCEPT OF SEPARATION (RGCS) PANEL TENTH MEETING Montreal, 8-19 May 2000

- Individual decision papers, working papers, information papers, flimsies and general information on the meeting;
- Review Of The General Concept Of Separation (RGCP) Panel Tenth Meeting Montreal, 8-19 May 2000, DOCUMENTATION [P]
- Review Of The General Concept of Separation (RGCS) Panel Tenth Meeting Montreal, 8-19 May 2000, REPORT FOLDER [P]

RGCSP-WG/A - Review of the General Concept of Separation Panel (RGCSP) Working Group A Meeting Annapolis, Maryland, USA, 6-17 November, 2000

- IP/05, WP/04, WP/06 WP/11, WP/12;

A state letter (SP 28/4-01/1, dated 26 January 2001) was sent informing that the Air Navigation Commission (ANC) reviewed the report of the tenth meeting of the Review of the General Concept of Separation Panel (RGCSP/10) which was held in Montreal from 8 to 19 May 2000 and agreed to change the name of the panel to the Separation and Airspace Safety Panel (SASP).

Appendix E.3 SASP meetings

Within the SASP the following meetings were held:

- One panel meeting (SASP/1 in 2016)
- Two Working Group A (WG/A) meetings (SASP-WGA/1 and SASP-WGA/2)
- 20 Working Group of the Whole (WG/WHL) meetings (SASP-WG/WHL/1, ... , SASP-WG/WHL/20)
- One Meeting of the Working Group (SASP-WG/1 in 2011)

SASP-WGA/1 – SEPARATION AND AIRSPACE SAFETY PANEL (SASP) FIRST MEETING OF WORKING GROUP A Madrid, Spain, 7 to 18 May 2001

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WGA/1-SD)

SASP-WGA/2 – SEPARATION AND AIRSPACE SAFETY PANEL (SASP) SECOND MEETING OF WORKING GROUP A Montreal, Canada, 29 October to 9 November 2001

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WGA/2-SD)

SASP-WG/WHL/1 – SEPARATION AND AIRSPACE SAFETY PANEL (SASP) FIRST MEETING OF THE WORKING GROUP OF THE WHOLE Canberra, 2 – 13 May 2002

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/1-SD)

SASP-WG/WHL/2 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) SECOND MEETING OF THE WORKING GROUP OF THE WHOLE Montreal, Canada, 28 October to 8 November 2002

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/2-SD)

SASP-WG/WHL/3 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) THIRD MEETING OF THE WORKING GROUP OF THE WHOLE London, England, 12 – 23 May 2003

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/3-SD)

SASP-WG/WHL/4 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) FOURTH MEETING OF THE WORKING GROUP OF THE WHOLE Honolulu, USA, 10 to 21 November 2003

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/4-SD)

SASP-WG/WHL/5 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) FIFTH MEETING OF THE WORKING GROUP OF THE WHOLE Tokyo, Japan, 17 to 28 May 2004

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/5-SD)

SASP-WG/WHL/6 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) SIXTH MEETING OF THE WORKING GROUP OF THE WHOLE Washington, US, 1-12 November 2004

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/6-SD)

SASP-WG/WHL/7 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) SEVENTH MEETING OF THE WORKING GROUP OF THE WHOLE Montreal, Canada 9 to 20 May 2005

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/7-SD)

SASP-WG/WHL/8 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) EIGHTH MEETING OF THE WORKING GROUP OF THE WHOLE Rio de Janeiro, Brazil, November 7 – 18, 2005

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/8-SD)

SASP-WG/WHL/9 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE NINTH MEETING Montréal, 22 May to 2 June 2006

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/9-SD)

SASP-WG/WHL/10 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) TENTH MEETING OF THE WORKING GROUP OF THE WHOLE Gold Coast, Australia, 27 November – 8 December 2006

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP-WG/WHL/10-SD)

SASP-WG/WHL/11 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE ELEVENTH MEETING Montréal, 21 May to 1 June 2007

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/WHL/11-SD)

SASP-WG/WHL/12 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE TWELFTH MEETING Santiago de Chile, 5 to 16 November 2007

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/WHL/12-SD)

SASP-WG/WHL/13 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE THIRTEENTH MEETING Montreal, Canada, 12 to 23 May, 2008

- Individual Working Papers, Information Papers, Flimsies and Operational Requirements (OR)
- Summary of Discussions and Conclusions (SASP-WG/WHL/13-SD)

SASP-WG/WHL/14 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE FOURTEENTH MEETING Paris, France, 13 to 24 October 2008

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/WHL/14-SD)

SASP-WG/WHL/15 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE FIFTEENTH MEETING Montreal, Canada, 25 May to 5 June 2009

- Individual Working Papers, Information Papers, Flimsies and Operational Requirements (OR)
- Summary of Discussions and Conclusions (SASP-WG/WHL/15-SD)

SASP-WG/WHL/16 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE SIXTEENTH MEETING, Auckland, New Zealand, 9 to 20 November, 2009

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/WHL/16-SD)

SASP-WG/WHL/17 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE SEVENTEENTH MEETING, Montreal, Canada, 10 to 21 May, 2010

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/WHL/17-SD)

SASP-WG/WHL/18 - SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE EIGHTEENTH MEETING Brussels, Belgium 8 to 19 November, 2010

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (*missing*)

SASP-WG/WHL/19 SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP OF THE WHOLE NINETEENTH MEETING Montreal, Canada, 23 May to 2 June, 2011

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/WHL/19-SD)

SASP-WG/1 – SEPARATION AND AIRSPACE SAFETY PANEL (SASP) MEETING OF THE WORKING GROUP FIRST MEETING Cairns, Australia, 7 to 18 November, 2011

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions and Conclusions (SASP-WG/1-SD)

SASP-WG/WHL/20 – TWENTIETH MEETING OF THE SEPARATION AND AIRSPACE SAFETY PANEL WORKING GROUP OF THE WHOLE, Montréal, Canada, 14 – 25 May 2012

- Individual Working Papers, Information Papers, Flimsies
- Summary of Discussions (SASP/WG/WHL/20)

SASP/1 SEPARATION AND AIRSPACE SAFETY PANEL (SASP) FIRST MEETING Montreal, 7 to 18 November 2016

- First Full Panel meeting of the Separation and Airspace Safety Panel (SASP/1).
- Final report

Appendix E.4 NAT SPG meetings

The North Atlantic Systems Planning Group (NAT SPG) was established by the Council of ICAO in 1965. Below a list of reports of the NAT SPG meetings is given that are available in NLR's archive are given¹⁵⁴. In this document the reports of the first meeting (NAT SPG/1) until fifty-fifth meeting (NAT SPG/55) are referred to explicitly. In NLR's archive also contains reports of the fifty-sixth meeting (NAT SPG/56), fifty-seventh meeting (NAT SPG/57) and fifty-eighth meeting (NAT SPG/58). These reports are listed below in italics. The meetings were mostly held in Paris, except for NAT SPG/7 (1971) which was held in Dublin, NAT SPG/23 (1986) which was held in Lisbon, NAT SPG/34 (1998) which was held in Brussels, NAT SPG/56 (2020) and NAT SPG/57 (2021) were virtual meetings.

- NAT SPG/1 - Summary of Discussions and Conclusions of the First Meeting of the North Atlantic Systems Planning Group, Paris, 19-21 October 1965.
- NAT SPG/2 - Summary of Discussions and Conclusions of the Second Meeting of the North Atlantic Systems Planning Group, Paris, 21 November – 5 December 1966.
- NAT SPG/3 – Summary of Discussions of the Third Meeting of the NAT Systems Planning Group, Paris, 17 – 28 April 1967.
- NAT SPG/4 – Summary of Discussions of the Fourth Meeting of the NAT Systems Planning Group, Paris, 17 – 28 June 1968.
- NAT SPG/5 – Summary of Discussions of the Fifth Meeting of the NAT Systems Planning Group, Paris, 4 – 8 December 1968. (Part I & Part II)
- NAT SPG/6 – Summary of Discussions of the Sixth Meeting of the NAT Systems Planning Group, Paris, 4 – 16 September 1969.
- NAT SPG/7 – Summary of Discussions of the Seventh Meeting of the NAT Systems Planning Group, Dublin, 17 February – 1 March 1971.
- NAT SPG/8 – Summary of Discussions of the Eighth Meeting of the NAT Systems Planning Group, Paris, 15 – 21 February 1972.
- NAT SPG/9 – Summary of Discussions of the Ninth Meeting of the NAT Systems Planning Group, Paris, 28 May – 6 June 1973.
- NAT SPG/10 – Summary of Discussions and Conclusions of the Tenth Meeting of the NAT Systems Planning Group, Paris, 10 – 20 June 1974.
- NAT SPG/11 – Summary of Discussions and Conclusions of the Eleventh Meeting of the NAT Systems Planning Group, Paris, 6 – 15 May 1975.
- NAT SPG/12 – Summary of Discussions and Conclusions of the Twelfth Meeting of the NAT Systems Planning Group, Paris, 31 May – 11 June 1976.
- NAT SPG/13 – Summary of Discussions and Conclusions of the Thirteenth Meeting of the NAT Systems Planning Group, Paris, 12 – 22 September 1977.
- NAT SPG/14 – Summary of Discussions and Conclusions of the Fourteenth Meeting of the NAT Systems Planning Group, Paris, 17 – 28 April 1978.
- NAT SPG/15 – Summary of Discussions and Conclusions of the Fifteenth Meeting of the NAT Systems Planning Group, Paris, 19 -28 February 1979.
- NAT SPG/16 – Summary of Discussions and Conclusions of the Sixteenth Meeting of the NAT Systems Planning Group, Paris, 1-10 October 1979.
- NAT SPG/17 – Summary of Discussions and Conclusions of the Seventeenth Meeting of the NAT Systems Planning Group, Paris, 10-21 March 1980.

¹⁵⁴ These documents can also be obtained from <https://www.icao.int/EURNAT/Pages/EURNAT-Meetings-NATSPG.aspx>.

- Summary of the Proceedings at the Special Co-ordination Meeting of the NAT Systems Planning Group (NAT/SPG), Montreal, 2-3 September 1980.
- NAT SPG/18 – Summary of Discussions and Conclusions of the Eighteenth Meeting of the NAT Systems Planning Group, Paris, 30 March – 10 April 1981.
- NAT SPG/19 – Summary of Discussions and Conclusions of the Nineteenth Meeting of the NAT Systems Planning Group, Paris, 19 – 30 April 1982.
- NAT SPG/20 – Summary of Discussions and Conclusions of the Twentieth Meeting of the NAT Systems Planning Group, Paris, 14 – 25 March 1983.
- NAT SPG/21 – Summary of Discussions and Conclusions of the Twenty-First Meeting of the NAT Systems Planning Group, Paris, 2 – 13 April 1984.
- NAT SPG/22 – Summary of Discussions and Conclusions of the Twenty-Second Meeting of the NAT Systems Planning Group, Paris, 15-26 April 1985.
- NAT SPG/23 – Summary of Discussions and Conclusions of the Twenty-Third Meeting of the NAT Systems Planning Group, Lisbon, 5 – 16 May 1986.
- NAT SPG/24 – Summary of Discussions and Conclusions of the Twenty-Fourth Meeting of the NAT Systems Planning Group, Paris, 4 – 15 May 1987.
- NAT SPG/25 – Summary of Discussions and Conclusions of the Twenty-Fifth Meeting of the NAT Systems Planning Group, Paris, 19 – 29 September 1988.
- NAT SPG/26 – Summary of Discussions and Conclusions of the Twenty-Sixth Meeting of the NAT Systems Planning Group, Paris, 21 May – 1 June 1990.
- NAT SPG/27 – Summary of Discussions and Conclusions of the Twenty-Seventh Meeting of the North Atlantic Systems Planning Group, Paris, 10 – 21 June 1991.
- NAT SPG/28 – Summary of Discussions and Conclusions of the Twenty-Eighth Meeting of the North Atlantic Systems Planning Group, Paris, 18 – 29 May 1992.
- NAT SPG/SPECIAL - Summary of Discussions of the Special North Atlantic Systems Planning Group Meeting, Paris, 17 – 18 January 1994.
- NAT SPG/29 – Summary of Discussions and Conclusions of the Twenty-Ninth Meeting of the North Atlantic Systems Planning Group, Paris, 7 – 16 June 1993.
- NAT SPG/HLM – Report of the North Atlantic Systems Planning Group Meeting of High Level Managers, Paris, 20 – 21 January 1994.
- NAT SPG/30 – Summary of Discussions and Conclusions of the Thirtieth Meeting of the North Atlantic Systems Planning Group, Paris, 6 – 17 June 1994.
- NAT SPG/31 – Summary of Discussions and Conclusions of the Thirty-First Meeting of the North Atlantic Systems Planning Group, Paris, 12 – 16 June 1995. (also NAT SPG/31 – WP/29 available)
- NAT SPG/32 – Summary of Discussions and Conclusions of the Thirty-Second Meeting of the North Atlantic Systems Planning Group, Paris, 16 – 20 September 1996.
- NAT SPG/33 – Summary of Discussions and Conclusions of the Thirty-Third Meeting of the North Atlantic Systems Planning Group, Paris, 9 – 13 June 1997.
- NAT SPG/34 – Summary of Discussions and Conclusions of the Thirty-Fourth Meeting of the North Atlantic Systems Planning Group, Brussels, 8 to 12 June 1998.
- NAT SPG/35 – Summary of Discussions and Conclusions of the Thirty-Fifth Meeting of the North Atlantic Systems Planning Group, Paris, 14 to 17 June 1999.
- NAT SPG/36 – Summary of Discussions and Conclusions of the Thirty-Sixth Meeting of the North Atlantic Systems Planning Group, Paris, 6 to 8 June 2000.
- NAT SPG/37 – Summary of Discussions and Conclusions of the Thirty-Seventh Meeting of the North Atlantic Systems Planning Group, Paris, 12 to 14 June 2001.

- NAT SPG/38 – Summary of Discussions and Conclusions of the Thirty-Eighth Meeting of the North Atlantic Systems Planning Group, Paris, 11 to 13 June 2002.
- NAT SPG/39 – Summary of Discussions and Conclusions of the Thirty-Ninth Meeting of the North Atlantic Systems Planning Group, Paris, 17 to 19 June 2003.
- NAT SPG/40 – Summary of Discussions and Conclusions of the Fortieth Meeting of the North Atlantic Systems Planning Group, Paris, 22 to 24 June 2004.
- NAT SPG/41 – Summary of Discussions and Conclusions of the Forty-First Meeting of the North Atlantic Systems Planning Group, Paris, 21 to 23 June 2005.
- NAT SPG/42 – Summary of Discussions and Conclusions of the Forty-Second Meeting of the North Atlantic Systems Planning Group, Paris, 13 to 16 June 2006.
- NAT SPG/43 – Summary of Discussions and Conclusions of the Forty-Third Meeting of the North Atlantic Systems Planning Group, Paris, 12 to 15 June 2007.
- NAT SPG/44 – Summary of Discussions and Conclusions of the Forty-Fourth Meeting of the North Atlantic Systems Planning Group, Paris, 17 to 20 June 2008.
- NAT SPG/SYMP/08 – Summary of Discussions of the North Atlantic Systems Planning Group, Symposium on Structure and Working Methods, Paris, 3 to 5 November 2008.
- NAT SPG/TF RCP 2008 – Summary of Discussions and Conclusions of the The North Atlantic Systems Planning Group Technical Task Force on Data Link Applications Communications Requirements, Paris, 20 to 22 February 2008.
- NAT SPG/45 – Summary of Discussions and Conclusions of the Forty-Fifth Meeting of the North Atlantic Systems Planning Group, Paris, 23 to 26 June 2009.
- NAT SPG/46 – Summary of Discussions and Conclusions of the Forty-Sixth Meeting of the North Atlantic Systems Planning Group, Paris, 22 to 25 June 2010.
- NAT SPG/47 – Summary of Discussions and Conclusions of the Forty-Seventh Meeting of the North Atlantic Systems Planning Group, Paris, 13 to 16 June 2011.
- NAT SPG/48 – Summary of Discussions and Conclusions of the Forty-Eighth Meeting of the North Atlantic Systems Planning Group, Paris, 12 to 15 June 2012. *(also Appendix Q is available as a separate document).*
- NAT SPG/49 – Summary of Discussions and Conclusions of the Forty-Ninth Meeting of the North Atlantic Systems Planning Group, Paris, 12 to 15 June 2012. *(also Appendix E is available as a separate document).*
- NAT SPG/50 – Summary of Discussions and Conclusions of the Fiftieth Meeting of the North Atlantic Systems Planning Group, Paris, 23 to 27 June 2014. *(also Appendix P is available as a separate document).*
- NAT SPG SYM/15 – Summary of Discussions of the North Atlantic Systems Planning Group Symposium 2015, Paris, 23 to 24 February 2015.
- NAT SPG/51 – Summary of Discussions and Conclusions of the Fifty-First Meeting of the North Atlantic Systems Planning Group, Paris, 22 to 26 June 2015.
- NAT SPG/52 – Summary of Discussions and Conclusions of the Fifty-Second Meeting of the North Atlantic Systems Planning Group, Paris, 27 to 30 June 2016.
- NAT SPG/53 – Summary of Discussions and Conclusions of the Fifty-Third Meeting of the North Atlantic Systems Planning Group, Paris, 26 to 29 June 2017.
- NAT SPG/54 – Summary of Discussions and Conclusions of the XX Meeting of the North Atlantic Systems Planning Group, Paris, 25 to 28 June 2018.
- NAT SPG/55 - Summary of Discussions and Conclusions of the Fifty-fifth Meeting of the North Atlantic Systems Planning Group Paris, 24 to 27 June 2019.

NAT SPG/56 Summary of Discussions and Conclusions of the Fifty-sixth Meeting of the North Atlantic Systems Planning Group, Virtual Meeting, 24 to 25 June 2020.

NAT SPG/56-2 – Summary of Discussions and Conclusions of the Fifth-sixth Meeting of the North Atlantic Systems Planning Group, 2nd Session, Virtual Meeting, 26 to 27 January 2021

NAT SPG/57 - Summary of Discussions and Conclusions of the Fifth-seventh Meeting of the North Atlantic Systems Planning Group, Virtual Meeting, 21 to 24 June 2021.

NAT SPG/58 - Summary of Discussions and Conclusions of the Fifth-eighth Meeting of the North Atlantic Systems Planning Group, Paris, France, 28 to 30 June 2022.



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