**Nationaal Lucht- en Ruimtevaartlaboratorium**
National Aerospace Laboratory NLR

NLR-TP-2002-170

# Free Flight with Airborne Separation Assurance

## An executive summary of: NLR-TP-2001-313 "Designing for Safety: the Free Flight Air Traffic Management concept"

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# Summary

The Air Traffic Management System, as it is used today, is a centrally organised system. One controller, sometimes assisted by a planner, is responsible for maintaining the separation between all aircraft in his/her sector. Pilots merely follow the directions received from the controller and have no active role in the separation assurance. To maintain an orderly traffic pattern, airways are used to structure the traffic flow and flight levels are used as layers to separate aircraft. This often inhibits a more optimal direct route at the optimal altitude. The need for maintaining situational awareness also limits the number of aircraft a controller can handle. This is a limiting factor for airspace capacity and contributes to delays.

The study described in this report investigates a revolutionary alternative for this system, called the Free Flight concept. In Free Flight Airspace, aircraft fly their own preferred route at their preferred altitude. They only need to deviate from this route if it conflicts with the route of another aircraft. The aircraft transmit their position via a data link. These data are presented on the traffic display in the cockpit. Maintaining separation now becomes the responsibility of the cockpit crew assisted by an Airborne Separation Assurance System (ASAS) that alerts and advises the crew.

When this study started in 1996 the area of Free Flight was practically unexplored. In general, it was thought to be a dangerous idea. The initial goal was to explore the human factors issues in the cockpit, which result from moving the separation task to the cockpit. However, since hardly any Free Flight research was available to build upon, the study first had to incorporate designing a feasible operational concept. The operational concept describes in what way the Free Flight concept should be implemented. What is the role of the pilot? What is the role of the systems? What procedures should be used? What should be the rules-of-the-sky? Consequently, the study became broader and investigated the feasibility of the operational concept based on the Free Flight idea.

In addition to literature surveys and analysis, two experimental methods have been used to investigate the feasibility: off-line traffic simulations, using a tool developed especially for this study, called the Traffic Manager, and human-in-the-loop simulations with airline pilots in NLR's Research Flight Simulator.

Using the operational concept designed, several issues have been investigated: acceptability and workload resulting from adding the separation task to the flying task and navigation task; the effect of lack of a global picture and central co-ordination on the traffic pattern and the effect on the capacity of a sector.

Evidence has been found that Free Flight is not only a promising concept for airspace with a relatively low traffic density, but that it is also capable of handling much higher traffic densities than today’s centrally organised ATM system. Because of this study, Free Flight has become more acceptable to the aeronautical research community. Several other studies since then have found results that confirm the conclusions of this study. The study also presents a direction in which future Free Flight research and implementation efforts should be heading. The results indicate that the introduction of Free Flight potentially offers economic, capacity and safety benefits. The author is using these results to play an active role in the decision process that is ongoing in several organisations.

# Contents

(45 pages in total)

## Abbreviations

| | |
|---|---|
| ADS-B | Automatic Dependent Surveillance - Broadcast |
| ASAS | Airborne Separation Assurance System |
| ATC | Air traffic Control |
| ATM | Air Traffic Management |
| CDTI | Cockpit Display of Traffic Information |
| FAA | Federal Aviation Administration |
| FMS | Flight Management System |
| FF | Free Flight |
| HMI | Human Machine Interface |
| IAS | Indicated Air Speed |
| ICAO | International Civil Aviation Organisation |
| IFR | Instrument Flight Rules |
| LNAV | Lateral NAVigation mode = autopilot FMS coupled mode |
| NASA | National Aeronautics and Space Administration |
| NLR | Dutch National Aerospace Laboratory |
| PASAS | Predictive ASAS |
| RLD | Rijks Luchtvaart Dienst |
| RSME | Rating Scale of Mental Effort |
| RTCA | Radio Technical Commission for Aeronautics |
| TCAS | Traffic Collision Avoidance System |
| TIS-B | Traffic Information Service Broadcast |
| TLS | Target Level of Safety |
| TOPAZ | Traffic Organization and Perturbation AnalyZer |
| VFR | Visual Flight Rules |
| VNAV | Vertical NAVigation mode = autopilot FMS coupled mode |

## Definitions

| | |
|---|---|
| **Separation Minima** | The prescribed minimum distances between two aircraft, in general specified as combination of a horizontal minimum distance and a vertical minimum distance |
| **Separation Assurance** | The act of assuring that the separation minima will not be violated |
| **Loss of separation** | The situation where the distance between two aircraft is less than the separation minima |

| | |
|---|---|
| **Conflict** | A predicted loss of separation |
| **Conflict Detection** | The act of or module for predicting conflicts |
| **Conflict Resolution** | Manoeuvring in a way that the predicted loss of separation disappears |
| **Conflict Prevention** | Avoiding manoeuvring into a conflict |
| **Recovery Manoeuvre** | The manoeuvre that resumes the original route after the conflict has been resolved |
| **Own ship** | The own or active aircraft in discussions on conflicting pairs of aircraft |
| **Intruder** | The other or passive aircraft in discussions on conflicting pairs of aircraft |
| **Lookahead time** | Time that is used as prediction window for conflict detection and resolution |
| **Protected Zone** | Area around aircraft determined by the separation minima, which should not be intruded by other aircraft. |
| **Alert Zone** | In the RTCA concept aircraft in this area are a reason to alert the crew. The concept in this study does not use an alert zone. It does use a slightly bigger protected zone for the conflict detection & resolution than the actual separation minima. |
| **Explicit co-ordination** | Co-ordinate via communication how to resolve a conflict to avoid counter-acting manoeuvres |
| **Implicit co-ordination** | Use common rules to avoid counter-acting manoeuvres |
| **Intent** | The intended trajectory of an aircraft (the flight plan) |
| **Priority Rules** | Traffic rules to determine which vehicle should manoeuvre to solve the conflict |
| **Rules-of-the-sky** | Traffic rules for air transport, analogue to rules-of-the-road |

# 1 Introduction

In 1997 NLR started working on an Air Traffic Management (ATM) concept called 'Free Flight' in co-operation with NASA and the RLD (the Dutch Civil Aviation Authority). In the Free Flight concept, all aircraft are allowed to fly their optimal route ('direct routing') and the task of traffic separation is moved from Air Traffic Control (ATC) to the cockpit ('airborne separation'). The concept therefore represents more than simply a new procedure or the use of a new tool. It is a revolutionary change of a nowadays centrally controlled ATM system to a distributed system.

The NLR study originally only focused on the human factors of airborne separation in a Free Flight environment. Because of a lack of a detailed definition of the Free Flight concept, the study evaluated several concepts derived from literature and designed a concept for Free Flight.

This concept has since then been studied in several simulations, using both human-in-the-loop simulations and off-line simulations. These simulations have resulted in several adjustments of the concept and related systems, mainly driven by human factors and safety.

The result is a robust concept that has been demonstrated in flight simulator trials to be able to cope with extremely high traffic densities in a safe and acceptable way. When designed with the humans in mind, the concept seems to be a rare case in which there are both financial benefits as well as safety benefits.

The study started in 1997 and consisted of the following sub-studies in chronological order:
- Conceptual Design
- Off-line validations
- Airborne Separation Assurance System Design
- Safety Analysis
- First Flight Simulator experiment
- Economics of conflict resolution
- Avionics requirements study
- Critical conflict geometry study
- Predictive ASAS development
- Mixed Equipage procedure study
- Second Flight Simulator experiment

The resulting conceptual design of Free Flight (and related systems), as well as a selection of the validating studies, will be described in the following sections. A complete overview can be found in original document NLR TP 2001-313 "Designing for Safety: the Free Flight Air Traffic Management Concept".

## 2 What is Free Flight?

### 2.1 Today's situation: ground controlled separation

Currently commercial aircraft continuously fly under a set of rules called IFR (Instrument Flight Rules). These rules allow the aircraft to fly even when the visibility is low. It also means the flight is controlled by Air Traffic Control (ATC) from gate to gate. The complete route, including the slot times at the airports for take-off and landing, is requested before the flight. These data are sent out via the Aeronautical Telecommunications Network to all controllers that will have the aircraft in their sector during the flight.

When there is a need for a route change this has to be requested during the flight and, if the traffic and weather situation permits, the aircraft will receive a clearance for this route change. Further, any altitude change (e.g. to climb to a higher, more economic flight level) requires a clearance from ATC. Therefore, there is no freedom for the crew to change their route to a more optimal route without negotiation with the ground.

Apart from the requests for a route or altitude change, there are several other procedures requiring communication with the ground: when crossing a sector boundary, the controller of the former sector 'hands off' the aircraft to the next controller. This requires a new position and/or route report to the new controller as a confirmation or log-on to the sector. Maintaining the separation of all traffic under his/her control is the responsibility of the controller of the sector.

Since World War II, radar has been used to monitor the traffic situation. At first only around the airport, but with the increasing amount of air traffic, also en-route traffic is monitored via the radar. Aircraft today are also equipped with a transponder that broadcasts extra information to the radar such as an identification code (squawk) and the altitude (mode C) for the air traffic controller. The result is a complete overview of the three-dimensional traffic situation. Trailing blips even provide an impression of the direction and magnitude of the ground speed. Using the mode C transponder ensures an accurate vertical position estimate while the angular nature of the radar might not provide a very accurate horizontal position estimate especially at larger distances. Typical separation minima in these circumstances are 5 nautical mile horizontally and 1000 feet vertically.

In areas, where there is no radar surveillance (e.g. large areas of Africa and Asia) the procedural separation replaces the radar-controlled separation. Procedural separation means that every aircraft reports its position and by issuing the appropriate clearances, the separation is ensured by ATC. The situational awareness of the controller is clearly less in this situation compared to radar surveillance. The result is the use of larger margins and therefore less optimal flights and also an inherently more dangerous situation.

A special form of procedural separation takes place over the ocean. Here tracks work similar to a railway system: aircraft are positioned separated at the beginning of a track and will arrive at the end of that same track. So route changes are inhibited over the ocean. These tracks are changed regularly based on the weather situation and labelled for reference. The distance between the tracks is one-degree latitude, meaning 60 nautical miles. The vertical separation used to be 2000 ft but has recently been reduced to 1000 ft over the Atlantic Ocean due the increased traffic density between Europe and North America. This enormous difference between the vertical and horizontal separation is due to possible (different) navigation errors caused by the inertial navigation system during the long flight over the ocean, while the altitude is determined via the same reference (air pressure) ensuring a very accurate estimation of the relative vertical position. Using satellite navigation to enhance and replace inertial navigation might improve the relative lateral navigation and provide a way to reduce the distances between the tracks.

Under radar coverage, traffic flows are normally structured into airways. Airways originally consisted of routes flying from one beacon to the next one. In the old days, this was the easiest way to navigate under IFR. Although today’s navigation equipment no longer requires flying from one beacon to the next, the airways are still in place. One reason for this is that it structures the traffic pattern, enabling one controller to monitor a complete sector. Possible separation problems are limited to intersections and aircraft changing altitude or overtaking each other on an airway. Apart from this benefit there are clearly some drawbacks as well: (1) the airways might not be the most optimal or direct route, (2) the local traffic density is artificially increased by concentrating the traffic on lines instead of using the full airspace, (3) flying on the same route might inhibit flying the optimal flight level or speed as a result from the traffic concentration on the airway.

When the traffic density is low (e.g. during the night) aircraft are often cleared for direct flights to a waypoint further along the route.

The air traffic controller’s highest priority is safety. Most of the time actions are based on preventing conflicts far before they could become imminent. For instance keeping two aircraft that are flying on the same airway in the same direction on a different altitude (always a value rounded to a multiple 1000 feet) even while they won’t overtake each other, ensures he/she will not have to monitor for a possible conflict between those two aircraft. In this way, he/she is able to keep workload at an acceptable level during high-density traffic situations. Though safe, it is not the most optimal way of flying. When the traffic situation allows it, the controller will allow the traffic to optimise their flight based on their requests. Airlines would prefer a more optimal way of flying with respect of fuel and time within the safety margins. Self-optimisation might provide a more optimal, while still safe, traffic pattern. This idea forms the basis of Free Flight.

Free Flight could also provide a more efficient airspace usage for instance over the ocean or areas without radar coverage and maybe even in the radar controlled areas. The reason for this is that in general (except the terminal area around airports) the separation assurance method, and not the airspace volume itself, is the limiting factor on capacity.

## 2.2 Tomorrow’s situation: Free Flight?

In Free Flight, the separation task is moved to the cockpit. By using a system that broadcasts identification and altitude but also the position, velocity and maybe even a part of the intended route, every aircraft could use this to ensure the separation. Such a system is available: ADS-B (Airborne Dependent Surveillance – Broadcast). The effect is that all aircraft receive the data broadcast by all other aircraft in the area. The data of the other aircraft are processed by an on-board system and displayed on the Cockpit Display of Traffic Information (CDTI). Several display formats are currently being developed to present the traffic situation to the crew in an optimal way.

This set-up could potentially be used to perform airborne separation, the essential element of the Free Flight concept. However, several design choices need to be made regarding how the concept should be implemented.

During the conceptual design phase of this study several choices have been made that formed the basis for the definition of Free Flight in the remainder of the study:

### 2.2.1 No ground based separation

Though there would likely be a lot of transition phases in which the separation responsibility would not be completely transferred to the cockpit, a mature form of Free Flight has been studied in this study: no ground controlled separation. The only role for the ground in this case would be a very long term strategic one: ensuring that traffic density will not exceed the capacity of airspace, exit/entry points of the Free Flight area and runways of the origin and destination airports. This is referred to as “Traffic Flow Management” by the RTCA report on Free Flight[1]. It is also referred to as autonomous aircraft, which will be able to maintain separation even over areas without radar coverage. This Freedom of Flight would allow true real-time self-optimisation.

### 2.2.2 Tools: ASAS & CDTI

Several tools will be required to assist the crew in the separation task: an Airborne Separation Assurance System or ASAS will detect predicted loss of separation (conflict). This is often referred to as conflict detection, though it does not actually detect conflicts but only predicts the possibility of a conflict within a certain time-span, the so-called look-ahead time. A conflict resolution module inside the ASAS calculates a recommended manoeuvre to avoid loss of separation. The information of the system is presented on the CDTI integrated with the traffic symbology.

### 2.2.3 Current Separation Minima

In the study, the separation minima which define a conflict have been set at today’s ATC separation minima: 5 nautical miles and 1000 feet vertically (thought often still 2000 ft is being used). This does not mean that these values are also be required in a Free Flight environment but it does provide a way to compare the results of the study with today’s situation.

### 2.2.4 Direct routing horizontally and vertically

True self-optimisation has been applied both in the horizontal plane and in the vertical plane. This allows direct routing but also flying at the most optimal altitude, even at values in between the multiples of 1000 ft. Most aircraft will be climbing slowly during the cruise (cruise climb) because the lower weight (caused by the fuel consumption) continuously increases the optimal altitude.

### 2.2.5 High traffic density scenarios

The first application of Free Flight will probably be in low traffic density areas. However, off-line traffic simulations in this study clearly indicated that conflicts are very rare in a direct routing environment, in which each aircraft flies at its optimal altitude with today’s traffic density. By using the current separation minima with today’s busy traffic over Western Europe, under nominal conditions in the upper airspace a loss of separation would be predicted typically once per hour per aircraft. This would not be a predicted collision but merely that one aircraft would come closer than 5 nautical miles (9 kilometres) within the altitude of 1000 ft (300 m). In

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[1] RTCA Board of Directors’ Select Committee on Free Flight

a man-in-the-loop simulation aimed at providing human factors data, this low conflict rate is a problem from an experimental point of view. By using artificially high traffic densities (triple the average Western European traffic density) and an even higher conflict rate (tripled again, so nine times per hour) the NLR team hoped to provide the crew with a challenging task that might provide insight into some interesting cockpit human factors issues of airborne separation.

# 3 Airborne Separation Assurance System

## 3.1 Introduction

The design of the ASAS system formed a critical part of the project. Several options, with respect to conflict detection, conflict resolution, display symbology and parameters of the systems, have been studied in literature and by using off-line and on-line simulation. An essential part of the study was the design of the conflict detection and conflict resolution and the Human Machine Interface (HMI). After the first human-in-the-loop trials, it was found that a conflict prevention module was also required. This resulted in the development of the predictive ASAS (PASAS).

## 3.2 Conflict Detection

### 3.2.1 General approach

It could very well be that the crew is able to predict conflicts by monitoring a well designed traffic display (CDTI) based on showing only the aircraft symbols. However, this might not be an optimal situation because the crew also has to control the aircraft and systems. During the climb and descent, the workload might be too high, whereas it might be too low during the cruise phase. The process of conflict detection is also mainly one of calculation, which is a task with which the automation might provide valuable help.

The result of the conflict detection module should be an alert to the crew as well as some information on the conflict, such as identification of the conflicting aircraft, time to loss of separation and other geometrical information. These data are used to display the conflict to the pilots and to supply input to the conflict resolution module.

To predict a conflict the trajectory of the “ownship” and the surrounding traffic needs to be predicted. There are several approaches possible depending largely on the look-ahead time. The most important issue is which level of intent information to use (and how):

1. No intent (just position and extrapolate with velocity)
2. Mode control panel intent (autopilot info)
3. The next trajectory change point
4. Complete flight plan as stored in the flight management system (FMS) of the aircraft

Except for bullet 1, all other information supplies some form of future state, which could be altered by the human crew at any time. Therefore, confirmation of this future state will become necessary with all levels of intent except bullet 1. The future trajectory of the aircraft might not always be the route as stored in the FMS and the selected altitude value in the mode control panel might merely be a reminder to switch from IAS climb to Mach climb or some other action. So using more intent information not only enhances the prediction, it also excludes a number of predictions. Using only position and velocity information is only useful with limited look-ahead times and depends on the route structure. In a direct route environment, this will often match the future trajectory, in an airway-like route structure more turns might limit the useful look-ahead time based on state information alone. An overview of some of the advantages and drawbacks of each method is given in the table below.

| Intent level | Pro | Con |
|---|---|---|
| None | • Simple, thus easy to implement (retrofit)<br>• Transparent to the crew<br>• Low bandwidth<br>• High update rate<br>• No requirements to change avionics infrastructure | • Will miss conflicts due to short term turning into traffic or leaving or arriving at a level (without extra precautions)<br>• Not accurate for longer look-ahead times |
| Mode control panel (autopilot) | • Relatively simple compared to FMS | • Enhancement compared with no intent might be limited when in LNAV or VNAV (without extra precautions) |
| First trajectory change point | • Compared to full route limited bandwidth requirements | • Will miss conflicts when not flying in LNAV or VNAV without extra precautions<br>• Accuracy with relation to look-ahead time might vary depending on distance to next trajectory change point |
| Route | • Will be able to use long look-ahead time<br>• Provides an accurate prediction in LNAV and VNAV, which are often used during the cruise phase | • Only works in LNAV and VNAV mode without extra precautions<br>• Complex systems<br>• Requires priority rules due to discontinuous resolution<br>• Hard to understand (not transparent)<br>• Lowest update rate<br>• Compatibility problems between different brands of FMS |

From the table it is clear there are some drawbacks to every method. Using extra information adds complexity and also introduces some problems. The route information in the FMS is only accurate when flying in the FMS controlled autopilot modes (LNAV & VNAV).

The most complex solution has the strongest advantages and disadvantages. NLR has studied both extremes of the intent spectrum: no intent and using route intent. Initially the no intent option has been explored. Note that in the table both approaches require ‘extra precautions’. In case of using intent it might mean you also use the state based system as an add-on and in case of the state based system, a system like predictive ASAS (PASAS) might seal the leak caused by not using intent information. Both options also have their specific problems in the conflict resolution module.

### 3.2.2 First step: How far can you get without intent?

As previously mentioned, the ‘no intent’ option has been explored most extensively in the study. Adding features, which add to the complexity, should only be done when required. Using no intent was thought to be the best way to find out how intent might be required to improve the system. If it is possible to fly safely without exchanging intent information, this has huge benefits (see preceding table) in terms of:

- Low complexity
- No negotiation required
- Conflict alerts transparent to crew
- No compatibility problems
- Faster than route which requires more time to be transmitted
- Lower risk of instability due to shorter look-ahead time
- Implementation of ADS-B with low bandwidth (likely) will still allow realisation of concept

To prevent the obvious missed alerts and false alarms due to turning aircraft an additional system has been added: predictive ASAS (see PASAS section for details).

For state based conflict detection, vector calculations are sufficient. The conflict detection algorithm in the NLR state based system contains the following steps:

1. Use smooth state data of traffic, extrapolated when necessary.
2. Skip aircraft for which a head-on closure speed is not sufficient for a conflict given the look-ahead time
3. Calculate the interval of loss-of-separation horizontally
4. Calculate the interval of loss-of-separation vertically

5. Is there an overlap within the look-ahead time? If so, then store conflict together with conflict data
6. Filter conflicts to prevent alerts due to manoeuvring aircraft

The resulting conflicts are stored in the conflict database. These data are, per conflict:

- Time of loss of separation (intrusion time)
- Time of closest point of approach (minimum distance time 3D)
- Position of ownship at minimum distance point (incl. altitude)
- Speed of ownship at minimum distance point (incl. track)
- Identification of intruder (incl. altitude)
- Position of intruder at minimum distance point
- Speed of intruder at minimum distance point

The horizontal minimum distance point (closest point of approach) horizontally is calculated using the following formula:

$$t_{\min\, dist} = -\frac{\underline{dv} \cdot \underline{dx}}{\underline{dv} \cdot \underline{dv}}$$

This might not be in the vertical interval where loss of separation is. When required it is therefore mapped on to the 3-dimensional interval of loss of separation.

Since the separation has been defined as the horizontal and vertical distance between two aircraft, multiple-aircraft conflicts do not exist mathematically speaking. As a result of the conflict detection algorithm they are merely a collection of two-aircraft conflicts. This is also the way they are stored in the conflict database. The conflict resolution algorithm should be able to cope with several conflicts at the same time.

These data are sufficient for the state-based version of the conflict resolution module in the system. In the intent version of the conflict detection module, extra data has been added to determine the positions on the conflicting legs of the ownship and intruder.

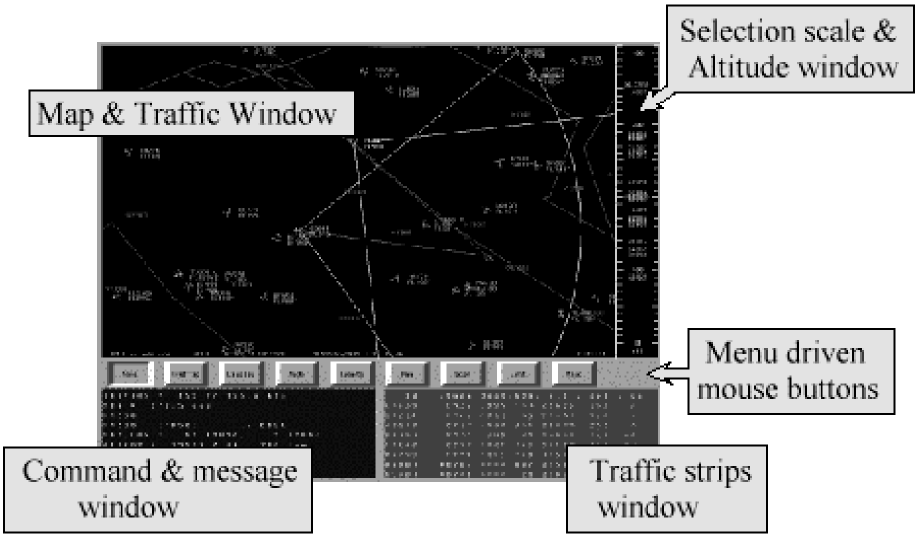

*Fig. 3.1 Traffic manager*

The conflict detection module has been developed and tested on a tool called the traffic manager. The traffic manager program has been developed within this study to analyse and simulate traffic situations of up to 400 aircraft simultaneously. This tool is able to generate traffic controlled by pilot models, autopilot modules, flight management system and includes performance characteristics of over 200 aircraft types. It is controlled using a graphical user interface as shown the figure above. It is used for off-line (optionally fast-time) simulation, scenario editing, environment simulation (for the flight simulator(s)), experiment console, data logging and data analysis. It also hosts the ASAS systems for all simulators connected to the traffic manager program. The program is able to interface with external consoles, ATC stations and several flight simulators. Current developments include an internet game domain like features to host web based experiments. The program runs on a graphical workstation but also on a common personal computer.

Reference data from Eurocontrol and the PHARE study average Western-European traffic densities have been used for the off-line simulations. An off-line simulation of a direct route environment has been created with these data. One surprising result was the low conflict rate that occurred. Using these scenarios a conflict was detected on average only once per hour (when the aircraft were not in the terminal area of an airport). A set of critical geometries for conflict detection and resolution have been tested and used to debug the conflict detection and resolution system.

From initial trials for a look-ahead time, a value of five minutes proved to be most effective with the state-based system. A longer look-ahead time did not add much to the effectiveness and could potentially lead to unnecessary manoeuvring. The lower limit while maintaining an acceptable level of passenger comfort with a horizontal manoeuvre was in the order of three minutes for worst case: exactly head-on with today's cruise speeds. Therefore the look-ahead time has been set at five minutes for the remainder of the study.

### 3.3 Conflict Resolution

A resolution advisory module is part of the Airborne Separation Assurance System (ASAS) system design. The conflict database and the traffic information are the input for the module. The module calculates one or more manoeuvres which would solve the conflict(s). It could very well be possible by designing the conflict symbology, which show all the aspects that the resolution algorithm uses, that the actual conflict resolution might be performed by the crew. The actual calculation of the shape or magnitude of the resolution manoeuvre does typically involve some calculation, which is where automation is able to provide valuable help. The actual decision of which manoeuvre to execute might involve strategies only known to the crew. In keeping with the generally held notion of "human-centred automation", the role of such automation should be limited to advising, rather than actual selection and implementation of alternative actions.

This consideration of the role of the resolution module formed the basis of the following main requirements of the module:

- Calculate manoeuvre/route change that resolves the conflict effectively
- Resolution module should be efficient in terms of time, fuel and route
- Should allow insight in the resolution generation process via the HMI
- Preferably generate more than one resolution to allow the crew to choose the most optimal one considering the complete situation
- Be able to handle multiple-aircraft conflicts
- Provide fail-safe or back-up options to increase the safety
- Prevent counteractive manoeuvring by two or more conflicting aircraft
- Resolution module should be fair (in terms of manoeuvre/economic costs) to the aircraft involved
- Module should not result in unstable, catastrophic traffic patterns

### 3.3.1 Conflict resolution algorithm

Based on earlier studies and available literature, several options were considered:

1. Vertical manoeuvres (TCAS-like)
2. Genetic algorithms
3. Extended VFR rules (as developed by Eurocontrol)
4. Cross product algorithm
5. Force field algorithms (Voltage potential)
6. Modified voltage potential (Eby)

Several of these methods were implemented in the traffic manager and validated. The final choice was a variant of an algorithm which is based on the force field or voltage potential analogy.

#### 3.3.1.1 Force field algorithm (voltage potential)

The voltage potential is an analogy, which compares traffic with electrically charged particles. Suppose all aircraft would be regarded as positively charged particles and their respective destinations as negatively charged. Summing all the repulsive forces of the traffic and the attracting force of the destination is a way to determine a vector, which maintains separation with other aircraft and will bring the aircraft to its destination. The figure below show a schematic representation of this principle.

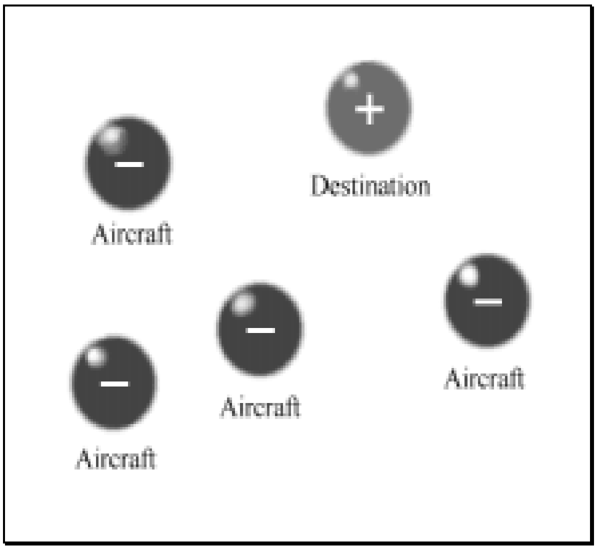

*Fig. 3.2 Simplistic view of voltage potential*

This resolution method is much too simplistic to be used in free flight. For example no minimum separation is guaranteed and attraction to destination varies with distance to destination. It is also quite impractical to sum the repulsive forces of all aircraft (including the ones with which no conflict is predicted).

#### 3.3.1.2 Modified voltage potential (Eby method)

At the Lincoln Laboratory (MIT, Massachusetts, USA) an algorithm has been developed which retains the basic repulsion feature of the voltage potential, but has a more pragmatic approach to solving conflicts (see figure below).

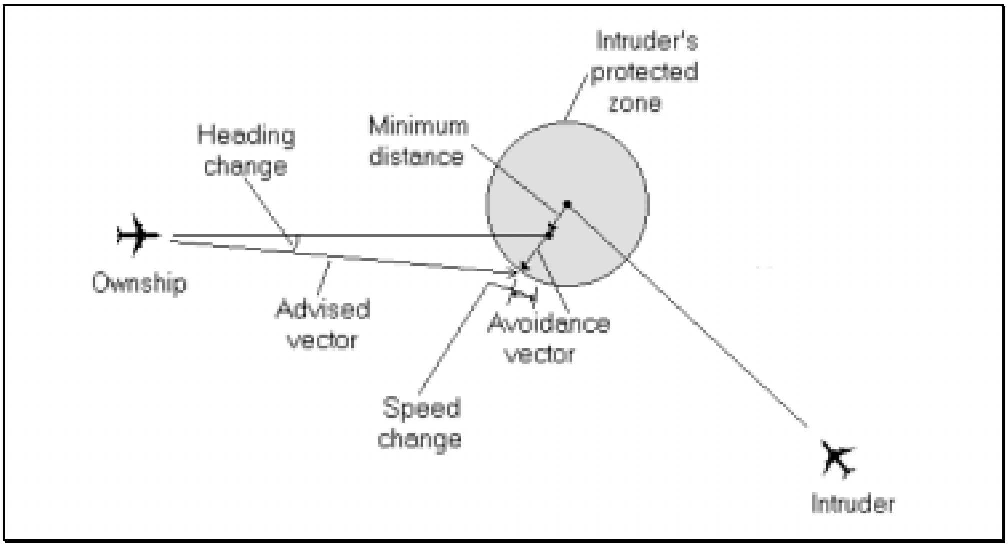

*Fig. 3.3 Geometry of resolution method*

This method has been slightly modified for use in the resolution module in the NLR study.

When a conflict with traffic has been detected by the conflict detection module, the resolution module uses the predicted future position of both ownship and the obstacle aircraft (will be called intruder) at the moment of minimum distance. The minimum distance vector is the vector from the predicted position of the intruder to the predicted position of the own ship. The avoidance vector is calculated as the vector starting at the future position of the ownship and ending at the edge of the intruder's protected zone, in the direction of the minimum distance vector. The length of the avoidance vector is the amount of intrusion of the own ship in the intruder's protected zone and reflects the severity of our conflict. It is also the shortest way out of the protected zone. Therefore the ownship should try to accomplish this displacement in the time left till the conflict. Dividing the avoidance vector by the time left yields a speed vector which should be summed to the current speed vector to determine the advised speed vector. The result is an advised track and ground speed. Using the three-dimensional vector also yields an advised vertical speed. In case of multiple conflicts within the look-ahead time, the avoidance vectors are summed.

Each geometrical resolution method has its singularities in which the avoidance vector becomes zero or the sign cannot be determined. Though this could be regarded as a theoretical problem, since in reality noise will prevent these singularities from lasting very long, numerical techniques like integer calculations or limited resolution in numbers could make it happen. This resolution method is no exception to the rule and several provisions are made to solve the singularities. For example, in case of an exact head-on collision course on the same altitude with no vertical speed, both aircraft will be advised to turn right.

This resolution method assumes the intruder does not manoeuvre to avoid the conflict. This is part of the fail safe principle of the concept. Normally the intruder will also manoeuvre. Using the same principle will always result in an avoidance vector in the opposite direction because of the geometry of the conflict (compare the future positions with the charged particles). Therefore an effective co-operation is achieved without negotiation or additional communication. This also means the initially calculated advised heading and/or speed changes will normally not be required. As soon as the conflict disappears, the current heading, speed and/or vertical speed can be maintained. This means both aircraft 'suffer' equally due to the conflict.
Both aircraft can choose whether they solve the conflict horizontally or vertically and they initially calculate the resolution advisory as if the other aircraft will take no evasive action. This means a total of four manoeuvres are available, which all are able to solve the conflict independently. Performance limits, weather and restricted airspace will sometimes inhibit one or two manoeuvres but rarely or almost never all four. If this were to happen, the backup modes like TCAS could become critical or the crew monitoring the situation could via R/T negotiate an acceptable solution. Using a look-ahead time of five minutes ensures there is sufficient time available to identify the problem and solve it.

#### 3.3.1.3 Final choice: modified voltage potential (Eby method)

In the off-line study using the traffic manager several methods for traffic resolution have been implemented: the TCAS like altitude step, a cross product of speed vectors and two different implementations of the voltage potential (one specially modified to manoeuvre without speed changes). Several were implemented and proved to be effective. Looking at route efficiency, time efficiency, fuel efficiency and other practical aspects related to displaying and executing the resolutions, the modified voltage potential method as described by Martin Eby[2] was chosen for the man-in-the-loop experiment. One modification to the description of Eby is that the

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[2] ‘A Self-Organizational Approach for resolving Air Traffic Conflicts, the Lincoln Laboratory Journal Vol. 7, Nr. 2, 1994

intended route is no longer used to predict a conflict, but rather the currently expected track is used (based on current trend information).

## 3.4 Conflict Prevention: Predictive ASAS

### 3.4.1 What is Predictive ASAS?

After the first year of simulator trials with the state-based conflict resolution and detection, one of the conclusions was that turning aircraft or aircraft levelling off could indeed lead to short term conflict alerts. As a result, some radio communication often took place to verify intentions. This was a clear indication some intent information or communication was required. However, another option was considered which might be able to enhance the state-based system without involving the intent information. The net effect might even be to solve all the problems resulting from not exchanging the intent information and at the same time maintaining all the advantages of the state-based system. This was the so-called predictive ASAS or PASAS.

The PASAS concept is based on preventing conflicts due to turning (either horizontally or vertically) aircraft. This causes the very dangerous short-term conflict alerts. In the beginning of the study a system was considered on which the pilot could pre-select autopilot actions to verify whether the manoeuvre would lead to a conflict alert. This was not thought to be acceptable. It would require extra crew action (pre-select and activate?). It would also mean a very drastic change in the infrastructure of the avionics, making a retrofit virtually impossible, an important consideration with the lifespan of today’s aircraft.

A more elegant way would be to let the display system show the result of all possible selected values on the navigation and primary flight display similar to the bands used in the TCAS symbology. The start and end of these bands could even be calculated mathematically without the iterative process of simulating all possible selections, reducing the required computing power significantly.

For example, for the vertical speed band this would be calculated by first computing the conflicts within the look-ahead time in the two-dimensional flat horizontal plane. Of course, most of these conflicts would never happen because the aircraft will not be at the same altitude during the predicted two-dimensional conflict. By calculating between which vertical speeds this would result in a conflict, a ‘forbidden’ band of vertical speeds can be calculated and displayed to the crew. Performing this calculation in all three combinations of two dimensions results in bands for vertical speed, track angle and ground speed. This calculation yields no bands on the altitude scale. When interpreted as ‘what if this altitude was selected with the default vertical speed', one could perhaps calculate useful altitude bands as well. This has not been implemented in the NLR system.

One could argue that 'conditional ASAS' is a better name for this system. However a conflict alert is now often preceded by one or more of the bands growing towards the current value for speed, track or vertical speed. By turning towards an aircraft for example coming from the right a conflict would be within the look-ahead time, while for straight ahead it is not yet within the look-ahead time. In this case the bands would start to the right and slowly move and/or grow towards the current track angle. Adding a margin to the look-ahead time as used in PASAS makes sure this is also true for the one case which normally does not yield this effect: an exact head-on conflict. This predictive effect (hence the name predictive ASAS) allowed airline crews in the flight simulator experiments to prevent not only actual conflicts but also conflict alerts. How these bands, the conflict detection and resolution algorithm translate in an understandable symbology on the display is explained in the human factors section.

### 3.4.2 What is the relation between this system and the need for intent?

At the start of this section it is suggested the PASAS system might even take away the need for the use of intent information. By enhancing the ASAS system with the PASAS system, the following rule-of-the-sky can be applied: "It is forbidden to manoeuvre (i.e. change the direction or magnitude of the speed vector) in such way that this causes a conflict within the look-ahead time with another aircraft." This rule is a way to relieve the need for exchanging intent information. It is no longer necessary to know whether an aircraft will turn, because it will not if that causes a conflict. An aircraft levelling off just below the ownship will also have to adjust the vertical speed or track angle because it is not allowed to aim its speed vector at the ownship. In this way it removes both the missed alerts and false alarms (by moving the burden to the manoeuvring aircraft) caused incidentally without exchanging the intent information. The resulting band could be interpreted as false alarms themselves if the intention is to level off before the actual conflict. However, the interpretation should be: 'The bands indicate where the speed vectors, which would cause a short-term conflict, are aiming at'. Even if an aircraft is levelling off below the ownship it might still be relevant for the crew to know about the undesirable situation of their speed vector aiming at a short-term conflict.

The simulator trials indicate the PASAS system can be used to establish a safe mode of operation without exchanging intent information. This does not mean that exchanging intent information should not be investigated. It might still be useful for some more optimal mode of operation. However, for a short or medium term solution the state-based system is still the only available solution to avoid complicated issues like bandwidth, compatibility, retrofit, etc.

# 4 Human Machine Interface

## 4.1 Design philosphy

The human machine interface as evaluated in the flight simulator trials of NLR's airborne separation assurance system (ASAS) consists of:

- Display symbology for the navigation and primary flight display
- Aural alerts
- Conflict indicator light in primary field of view
- Selection of autopilot controlled resolution manoeuvres (studied as an option)

The design of the ASAS system and its human machine interface (HMI) is according to the guidelines for human centred design as they are stated in the ICAO circular 249-AN/149:

1. The human must be in command
2. To command effectively, the human must be involved
3. To be involved the human must be informed
4. Functions must be automated only if there is a good reason for doing so
5. The human must be able to monitor the automated system
6. Automated systems must, therefore, be predictable
7. Automated systems must be able to monitor the human operator
8. Each element of the system must have knowledge of the other's intent
9. Automation must be designed to be simple to learn and operate

These principles form the guidelines for the conflict detection, resolution and display. From the sections on conflict detection and resolution it is clear the system is simple (see 5, 6, 9), only calculations have been automated and decision making is left to the human (see 1, 2). The display symbology is based on the same figure as is used to explain the conflict resolution algorithm for transparency reasons (see 2, 3, 5, 6, 9).

## 4.2 Display

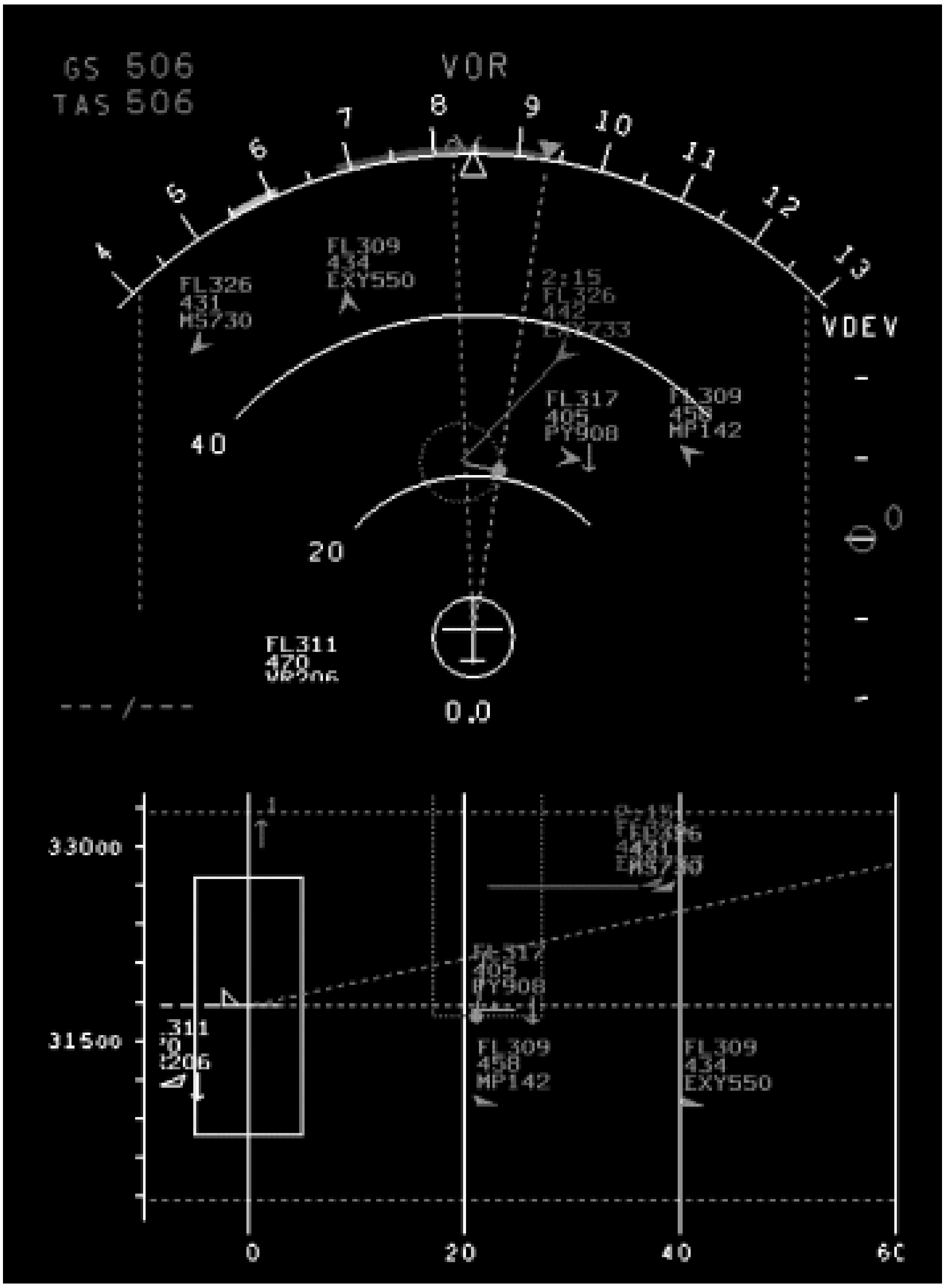

*Fig. 4.1 Cockpit display of traffic with conflict detection symbology (red)*

The part transferring most of the ASAS information to the human is the display. The considerations, that led to the current display design, include the following:

- No extra display with dedicated traffic & conflict function (retrofit, integrate info)
- Absolute co-ordinates (latitude, longitude) frame for conflicts to avoid a separate mode on navigation display
- Colours should indicate urgency based on time to loss of separation
- Traffic symbols should present as much information as possible without clutter (led to directional aircraft symbols instead of track vectors)
- Symbology should be transparent

The conflict resolution of the modified voltage potential is based on the geometry of the conflict. The figure that has been used to explain this algorithm also formed the start for the symbology. The display, showing a conflict, is depicted in the figure above.

The symbology is presented on the map mode of the navigation display. Nominally the crew would select the ‘centre mode’ as well that places the ownship symbol in the centre of the display. Based on average cruise speeds and the look-ahead time of five minutes a range setting of about 100 nautical mile would be recommended.

This example picture shows a high-density traffic situation. For de-cluttering the display there are several options. Every line of the text label can be switched off. The vertical range setting of the vertical display also determines the block of air that is viewed on the horizontal display. So zooming in on the vertical scale will reduce the number of aircraft shown on the horizontal display. Any aircraft above or below the altitudes on the vertical scale will not be shown unless it is a conflicting aircraft. In the same way the vertical display can be de-cluttered by reducing the horizontal scale. By only viewing this selected block of air, an airspace that would look extremely crowded on a radar screen could still be monitored on the CDTI. During climb or descent larger vertical scale selections might be required and extra measures should be added to the current display to avoid clutter in future situations with an extremely high traffic density. A vertical offset of the aircraft symbol on the vertical display would reduce the clutter on the horizontal display in this situation.

The conflict symbology shows the protected zone of the intruder at the closest point of approach. The cylinder is shown as a circle on the horizontal display and a rectangle on the vertical display. Depending on the horizontal and vertical scale the crew has selected, the height of the rectangle is in general quite exaggerated: the actual width to height ratio is 30 to 1, when using the current separation minima. These dimensions are also the reason the vertical solution is in most cases the preferred manoeuvre. Therefore including the vertical dimension is very important for a CDTI that is used for conflict resolution.

Red conflict symbology means the separation minima will be violated within 3 minutes, amber means within 5 minutes but more than 3 minutes. Sometimes conflicts would disappear for a short time and appear again despite the filters. In this case it often refers to aircraft which are predicted to skim the protected zone. In the display the conflicting aircraft would still be coloured amber or red for while to indicate which aircraft the conflict concerned.

The predictive ASAS bands mean: do not select a value (i.e. place the blue selection marker for heading, vertical speed or speed) in these bands or it will trigger a conflict alert. Filters prevent conflict alerts when passing through the bands to a selected value beyond the PASAS bands.

### 4.3 Aural alerts

Two aural alerts are used to differentiate the urgency of the conflict. A conflict within 3 minutes (red conflict) uses a more imminent sounding alert than a 5 minute conflict (amber conflict). Both sounds are distinctive from other sounds in a civil cockpit. The ‘threat’ sounds of a military cockpit have been used. For amber the ‘painted’ sound is used and for red the ‘painted and locked’ sound of an F-18 Hornet cockpit.

## 5 Human-in-the-loop experiments

### 5.1 Phase I flight simulator trials

Two simulator studies have been performed within the study. The first experiment used 18 subject airline pilots. The experiment matrix consisted of three traffic densities x three autopilot resolution modes x nominal/non-nominal. Every subject crew flew the concept in two days including half a day of training. The second experiment used the predictive ASAS system and investigated mixed equipage procedures. ATC controllers were also subjects in this study controlling the non ASAS equipped aircraft.

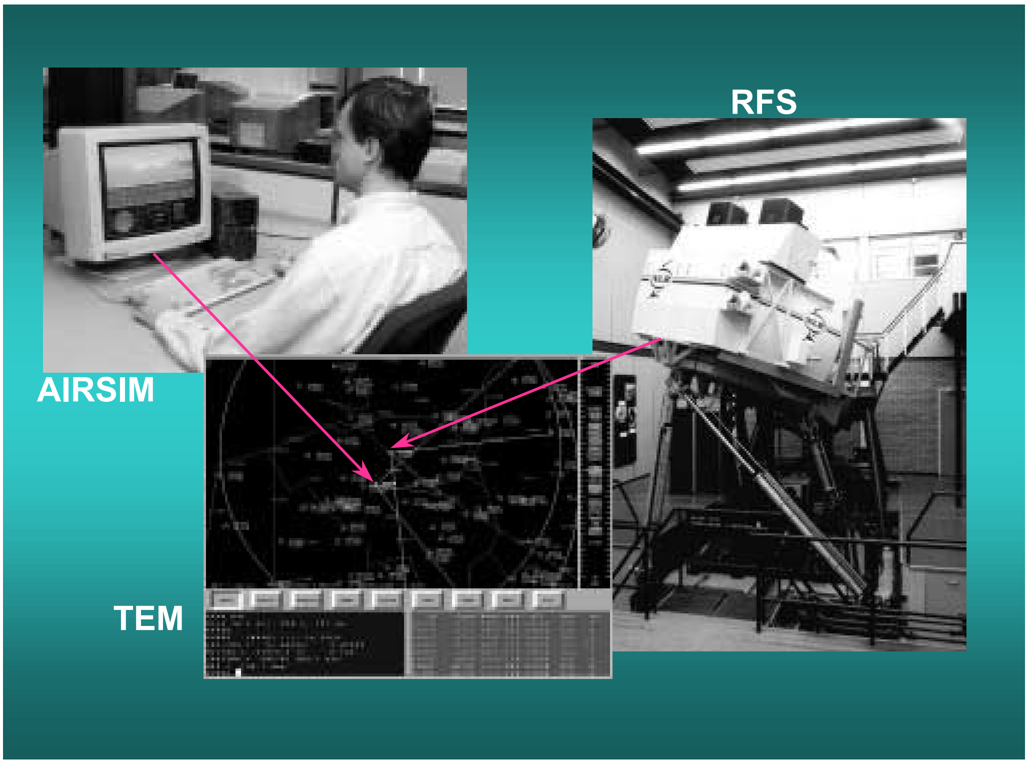

*Fig. 5.1 Simulation configuration for human-in-the-loop trials*

The first flight simulator experiments were set-up to introduce human factors problems in the cockpit by using a very high traffic density and an extremely high conflict rate. The idea behind this set-up was to demonstrate human factors issues under this excessive workload situation. This result was not obtained. The first reaction of the first crew that came out of the simulator cockpit after flying in triple Western European traffic density and nine times the amount of conflicts was: ‘It’s a fine system but what if it gets busy?’. And this was while using the Mark 1 ASAS system without the predictive ASAS, which greatly enhances the situational awareness. Because of the display design they were only monitoring a part of the airspace and their only focus was their own aircraft, in contrast to an air traffic controller who has to monitor the complete sector and control all aircraft. So apparently what is extremely busy for an air traffic controller is not perceived as such by a cockpit crew flying in a Free Flight airspace. Apart from objective data logging also a lot of questionnaires have been used during the experiments. Some of the most striking results have been found in the questionnaires on workload, subjective safety and acceptability. They are shown in the figures below.

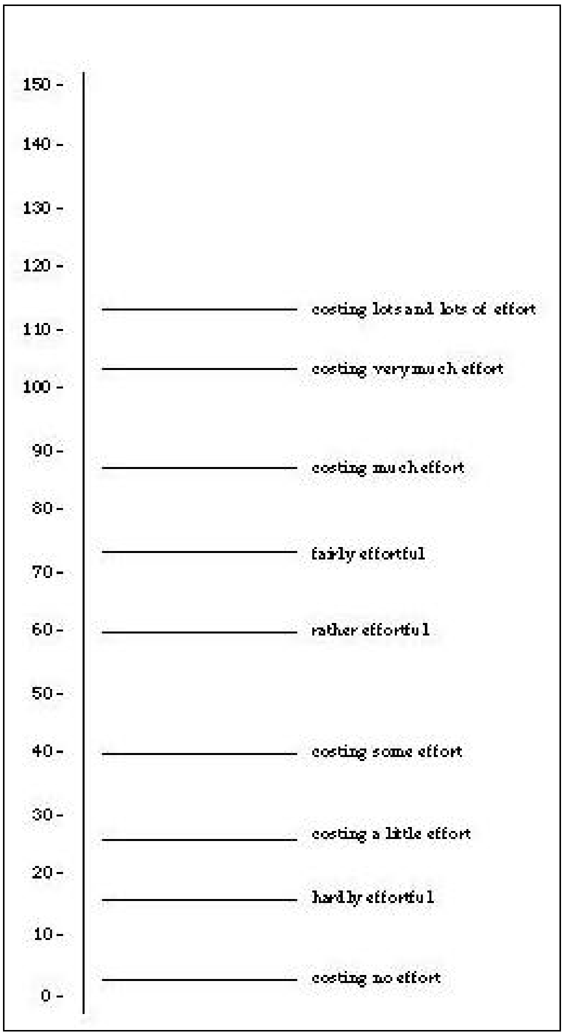

*Fig. 5.2 Subjective workload scale used in the study*

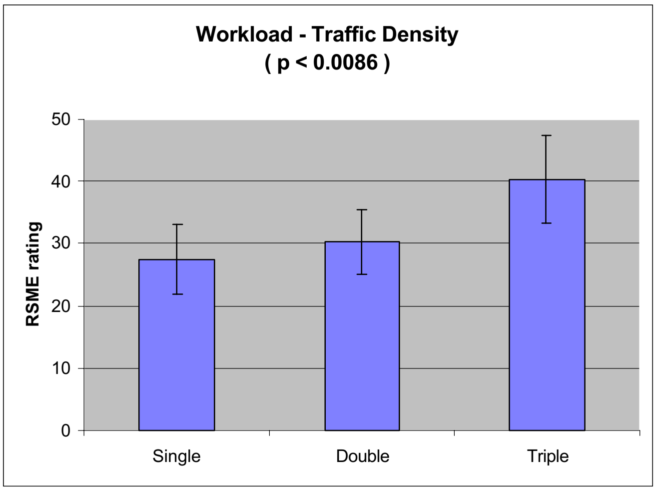

*Fig. 5.3 Workload rating as function of traffic density.*
*Compare with ATC reference value 27 for single density !*

The workload has been rated on a Rating Scale of Mental Effort (RSME) of 0 –150. The figure above shows the effect of resolution execution on workload, the largest effect observed. The rating of 27 was also observed in earlier experiments during the cruise under normal ATC operations. The sessions on the last half-day of the two day experiment also averaged this value independent of resolution execution method. This means no increase in workload was indicated even while the task of separation was added to the cockpit tasks. When confronted with this result the subject pilots were not surprised. They commented that the traffic display relieves them from maintaining a mental picture of the traffic situation based on the radio messages, which is what they do today. In some areas of the world without radar coverage this is essential in ensuring a safe operation. So by adding the ASAS system and the traffic display with the separation task this does appear to have both an increasing and decreasing effect on workload which causes an average observed value that is the same for airborne separation and ground controlled separation.

The subjective acceptability was rated using a scale of 1 to 5:

1. = Completely Unacceptable
2. = Undesirable
3. = Acceptable
4. = Favourable
5. = Perfect in every way

The acceptability ratings for the flights show an effect of traffic density (see figure below).

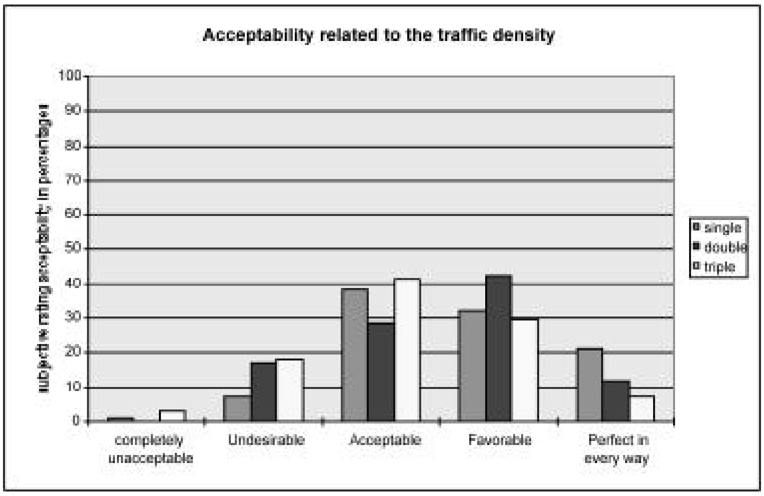

*Figure 5.4 Traffic density effect on acceptability rating*

The total variation in the acceptability, though statistically significant, does hardly change due to the increasing density. Even in triple density (with a nine times as high conflict rate) the concept was still rated on average above 3 (between favourable and acceptable).

The subjective safety rating also uses a scale of 1-5 to compare the impression of safety to today's controlled flights:

1. = ATC much safer
2. = ATC safer
3. = same as ATC
4. = FF safer than ATC
5. = FF much safer than ATC

The largest effect on subjective safety seen was traffic density.

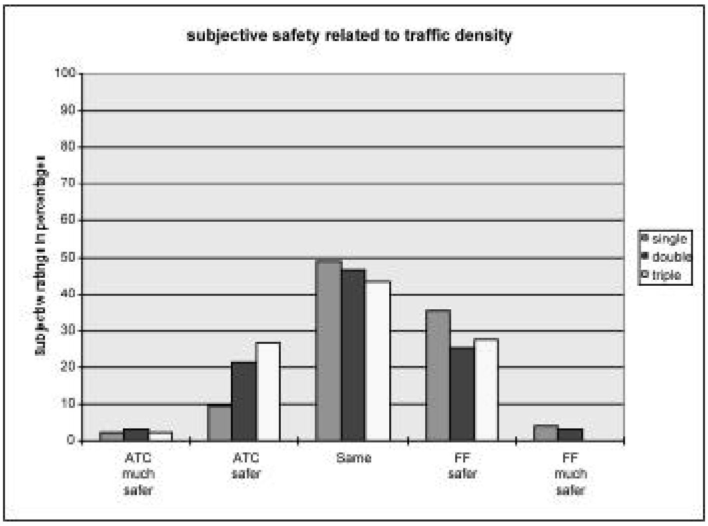

*Fig. 5.5   Traffic density effect on subjective relative safety*

The subjective safety was rated the same as normal ATC for current traffic densities. For the same traffic density the safety was rated a bit higher, while for triple densities the average rating was just (not statistically significant) below today's ATC with today's density.

## 5.2 Phase II flight simulator trials

The two main research questions for the phase II trials were:

- What would the effect of the conflict prevention system PASAS be?
- Which mixed equipage concept that has implicit benefits for equipage seems feasible from a human factors perspective?

Now also an air traffic controller's station was part of the simulation configuration with a number of controllers as subjects.

A striking result of the second set of simulator trials was that the crews now had a much better situational awareness as a result of the PASAS bands. The PASAS system also often allowed them to prevent not just conflicts but also conflict alerts.

The following three mixed equipage concepts were tested. For all it was assumed that the unequipped aircraft will be visible to the equipped aircraft by means of a TIS-B ground station.

### 5.2.1 Concept F: Flight Level Split

In this condition, the airspace above a certain altitude (the “Lower Free Flight level”) is reserved for equipped aircraft only. A transition layer just above the Lower Free Flight level is used as a buffer zone for aircraft transitioning to and from Free Flight, see figure 5.6.

*Fig. 5.6 Flight level split ATM procedure*

This buffer zone is used to avoid predicted conflicts and possible intrusions of protected zones between free flying and controlled aircraft, which would occur if only a single Free Flight Level were to be used. Flying high has a clear economic advantage for cruising aircraft. Another advantage of this method is that it allows a gradual transition to free flight by lowering the altitude limit, similar to the National Route Program in the US (FAA, 1992 & FAA, 1994). This gradual transition could increase the acceptability of the introduction of Free Flight.

### 5.2.2 Concept A: Protected Airways ATM concept

In this concept, the airspace structure remains largely intact. Airways are still present for controlled, unequipped aircraft. The ASAS equipped aircraft, however, have the right to leave the airways for direct shortcuts to their destinations, whereas the controlled aircraft have to stay within the airways.Free Flying aircraft have the right to cross an airway but only if they ensure conflict-free passage (as unequipped aircraft are visible on the display).

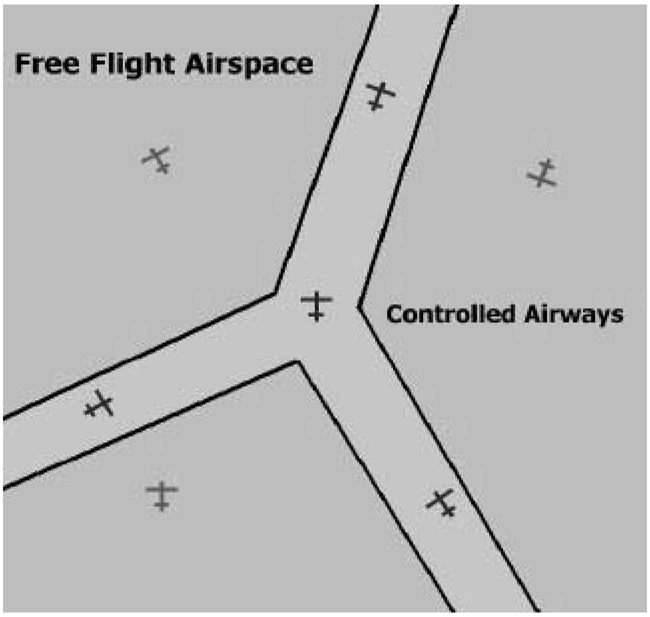

*Fig. 5.7 Protected airways ATM procedure*

### 5.2.3 Concept M: Fully Mixed

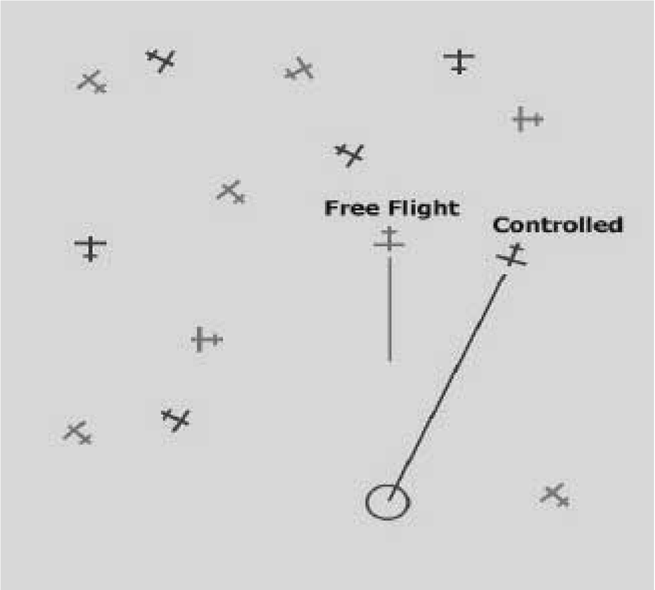

*Fig. 5.8 Fully mixed ATM concept: longer lookahead times for controlled flights*

In this case, all aircraft are able to fly direct routing. The controlled aircraft are monitored by the ground (ATC) using the same conflict detection module as is used in the airborne ASAS. ATC performs the conflict resolution task for the unequipped aircraft. By using a substantially longer look-ahead time for the conflict probing for the unequipped aircraft, these aircraft will always avoid ASAS equipped aircraft without a need for the equipped aircraft to manoeuvre. In the experiment the ground tools used a lookahead time of 8 minutes while in the air 5 minutes lookahead time was used. If all works as intended, the equipped aircraft will never detect a conflict with an unequipped aircraft because this will be resolved before it will be in the look-ahead time of the ASAS equipped aircraft. The equipped aircraft have effectively right-of-way and will not even get a conflict alert.

This is the most beneficial concept for the unequipped aircraft and therefore provides the lowest benefits for equipage. The drawback of this approach is the high controller workload in busy areas with a low equipage ratio because of the direct routing.

From the pilot workload results, the fully mixed was the most desirable. See figure 5.9.

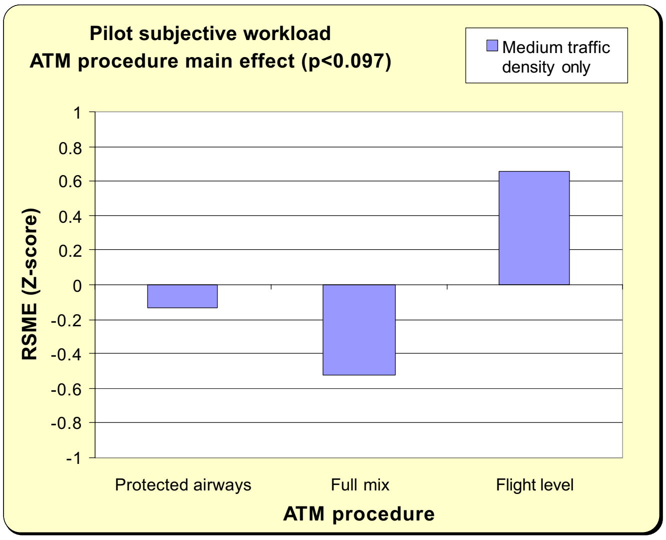

*Fig. 5.9 Pilot workload results for different concepts reach only 90% significance but show fully mixed concept has lowest workload*

For the Air Traffic Controllers the reverse trend was found: the full mix received the highest workload ratings. It seems the problem is moved back and forth depending on the concept choice. There was no clear indication for one best concept.

# 6 Distributed systems vs. centrally controlled systems

## 6.1 Introduction

As mentioned in the introduction, Free Flight is more than merely the introduction of a new procedure or a new tool. It is a fundamental change in the structure of the ATM system. The fact that the control becomes distributed causes a lot of distrust in the system. This may have more to do with the way we think than with the distributed aspect itself. Because the system becomes a collection of active agents it is in fact comparable to parallel processing: many conflicts can be handled at the same time. All these actions are caused by the interaction via the geometry. The parallel, geometrical and interactive aspects make it hard to mentally simulate or imagine the course of events in a distributed system. It is therefore less easily trusted than a centrally controlled system, which is more predictable. There is a fear of chaos as a result of the distributed effect. One could say: rather a safe chaos, than a dangerous order. Still examples like deadlocks and trapping multi-aircraft conflicts seem to require a central controlling element. These situations however could only cause problems in an airspace so full of aircraft that a centrally controlled system would never have been able to handle it in the first place, because of the overload of the central node. The real relevant effects of changing a system from centrally organised to a distributed are the robustness of the system and the immense increase in capacity.

The apparent chaos is also not real chaos: the same resolution algorithm governs the whole system. This means there is some order, which is able to cause large scale orderly patterns, comparable with waves consisting of interactions of molecules.

## 6.2 Robustness

The robustness of the Free Flight concept became evident when setting up the flight simulator experiment. One set of runs was used to explore the human factors of non-nominal cases like failures, delays, counteracting crews, etc. Just failing the conflict detection module did not yield a very interesting event: because the other aircraft’s crew initially assumes the conflicting aircraft does not manoeuvre the conflict was still solved, only this time completely by the other aircraft. The crew would not notice the situation and no dangerous situation requiring them to notice would occur. To cause problems the other aircraft’s conflict detection would also have to be failed. So two aircraft with a failing system are required for a real danger due to conflict detection failure. And of all combinations of all the aircraft in the free flight sector, these two should be the ones, which will have a conflict. Compared to the centrally organised system: this would just require a failure of the radar screen or update to cause a globally dangerous situation for any combination of conflicting aircraft.

## 6.3 Capacity

An air traffic controller is managing his/her workload most of the time by preventing conflicts long before they would happen. He is indeed separating traffic instead of solving conflicts. If he would not do this, he might be trapped in a situation requiring more than one action at a time to prevent conflicts. Because of the limits of the human controller and the radiotelephony, parallel processing is not possible. This is also a limiting factor for the capacity of the airspace. One controller has a limit to the number of aircraft in his sector. With increasing air traffic this means the sector size should be decreased, maybe even depending on the local traffic density. This causes two problems (1) we could end up with ‘stamp-sized’ sectors (2) workload might actually increase due to greater inter-sector co-ordination demands.

The difference with a distributed system is clear: with every aircraft entering the free flight sector, two potential controllers (in case of a standard two man crew) are added to the situation as well. A lot of conflicts can be solved at the same time without any stress by the cockpit crew because everyone is taking care of only his own conflicts. In the flight simulator, traffic densities have been simulated over ten times the current day traffic density (though not yet in a real experiment with 18 subject pilots). In these extremely high density scenarios the ASAS system (without using intent but with PASAS) and in a worst case mixed equippage scenario (airway-like route structures etc.) it was still manageable without an unacceptably high workload. In the same set-up with the same sector size during experiments, air traffic controllers gave up when the traffic density was higher than doubled compared to today.

## 6.4 Bottleneck conflicts

The notion that Free Flight is not feasible because it is dangerous to distribute control is often illustrated by examples of bottleneck scenarios. As an analogy for these situations, some conflict geometries have been constructed. These situations will in general give the impression that some form of central co-ordination is required to solve them. However, if they do solve very efficiently (with minor deviations from the original track) without central control then it is an illustration of how counter-intuitive the effect of distributed control can be. It is the experience of the author that the examples described in this chapter are very persuasive concerning the feasibility of separation assurance without central control.

Two types of conflicts that were regarded as very critical are described in this chapter:

- “super-conflicts” - circular conflicts, which require a high number of parallel actions to solve efficiently
- “the wall” - one wall of aircraft already separated at minimum distance where one aircraft needs to go through

In both examples, the vertical solution has been disabled to make it more constraint.

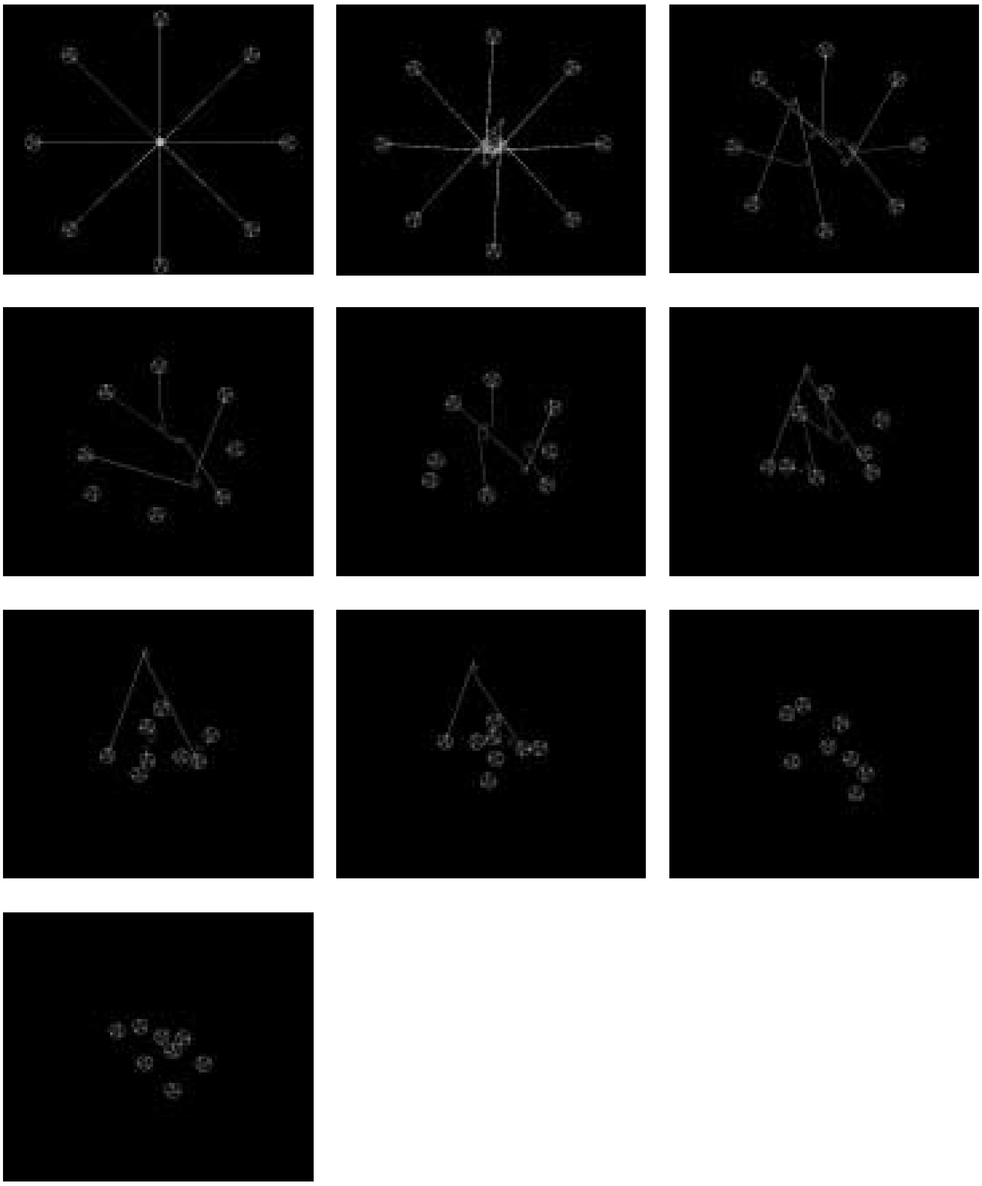

*Fig. 6.1 Superconflict with 8 aircraft with the vertical resolution disabled (Note the circles have a radius of 2.5 nm so touching circles mean the separation is still 5 nm)*

Even with a superconflict of 16 aircraft, the superconflicts are solved without intrusions.

In the wall scenario the centre aircraft opposing the wall creates a wave through the wall which causes the wall to ripple and thus make space for the aircraft to go through.

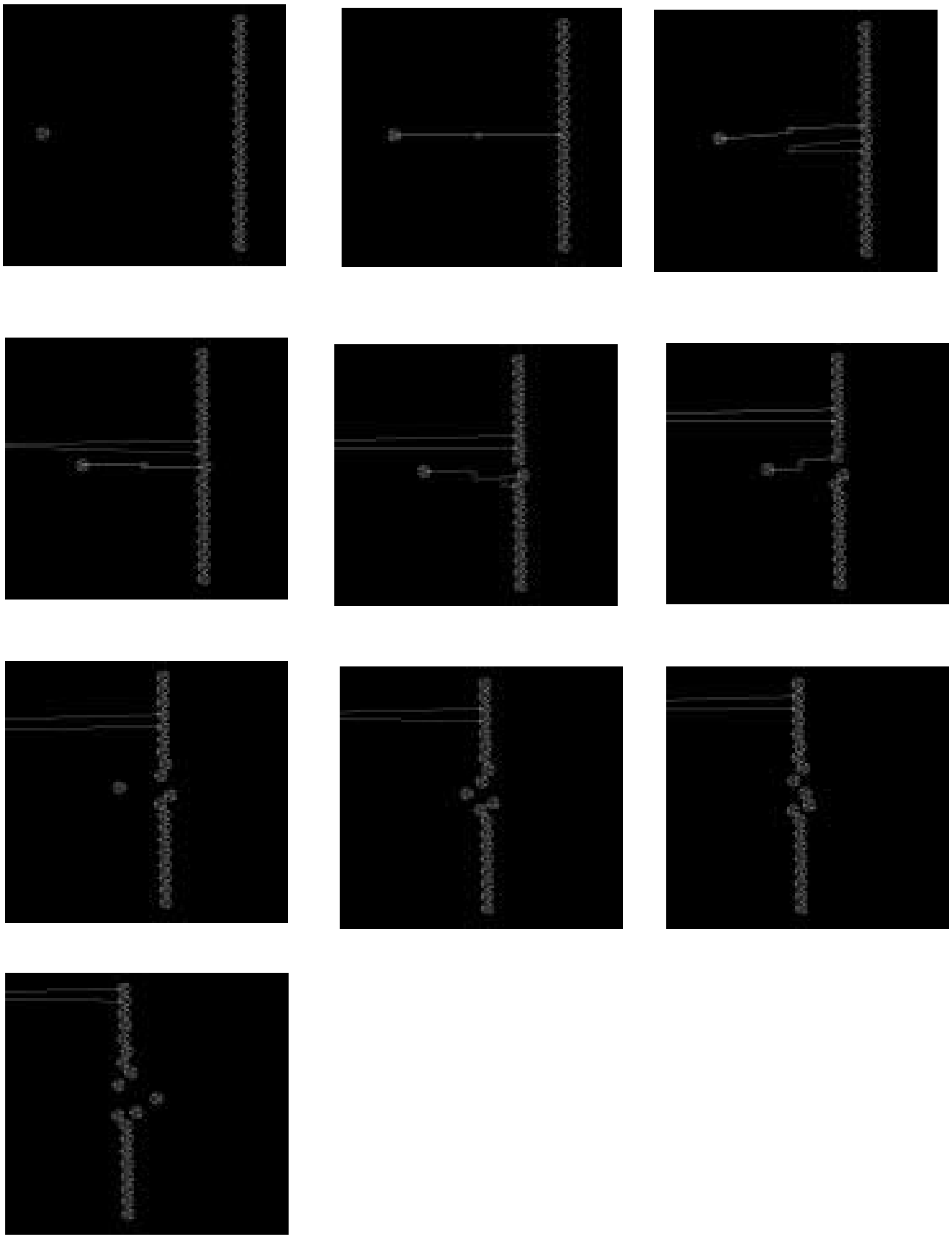

*Fig. 6.2 One aircraft heading at a 'wall' of traffic at minimum separation distance. The initial conflict causes a wave in the wall creating a hole for the opposing aircraft*

# 7 Conclusion

## 7.1 Feasibility

Based on the results and discussion in the previous section, the most important result of this study is that the feasibility of Free Flight, the combination of direct routing and airborne separation assurance, in upper airspace could not be refuted. Even in high traffic densities Free Flight proved capable of maintaining the separation minima in a direct routing concept better than today's ATM system. This result is supported by the results of flight simulator experiments using airline pilots in simulated en-route, high traffic density airspace, by off-line traffic simulations and by analysis.

## 7.2 Operational Concept

This study proposes an operational concept for Free Flight in upper airspace for further research and implementation efforts. The concept requires a state-based conflict detection, resolution and prevention system and implicit co-ordination using only two straightforward, common rules-of-the-sky:

1. As soon as a state-based conflict is predicted within the specified lookahead time, an aircraft should not manoeuvre so as to decrease the distance at the predicted closest point of approach, but resolve the conflict if possible.
2. It is not allowed to initiate a manoeuvre that will result in a state that triggers a state-based conflict alert within the specified lookahead time.

Exceptions to these rules are situations where a higher priority threat, such as terrain or a more urgent conflict, can not be solved without violating these rules. This basically leaves solving this lower priority threat to the other aircraft involved. In the rules the word state refers to only the three-dimensional position and three-dimensional velocity vector.

The lookahead time is dependent on the airspace, flight phase and separation minima. For en-route traffic and the current separation minima, five minutes proved to be an acceptable value in this study.

## 7.3 Capacity Benefits

In a direct routing environment the airspace is used more efficiently than in a concept where aircraft have to follow one-dimensional airways. Free Flight proved to be able to handle higher traffic densities than today's centralised ATM system. Under simulated traffic loads that exceed the capacity of today's ATM system, very low pilot workload has been found and pilot acceptability was found to be high. By system analysis indications have been found that a distributed ATM system, like Free Flight, has a structural capacity advantage over any centrally organised ATM concept. Together with the observation that the majority of today's European ATC-related delays are caused by en-route congestion (Eurocontrol PRC, 1999), this means Free Flight could provide the solution for the current delay problem in Europe.

### 7.4 Economic Benefits

Free Flight is a potential enabler of direct routing. Direct routing has been the Holy Grail in ATM research for a long time. The economic benefits of direct routing will be substantial compared to past efforts to increase the efficiency of the ATM system. Reducing delays is another economic benefit. The costs to upgrade the avionics will (and should) be much less than the potential benefits. The main reason why cockpit technology is expensive is because of the certification costs. By using a simple system as proposed in this study, these costs should allow to build a long-term business case for Free Flight. This long-term vision is crucial for the survival of the air transport sector and future work should focus on this.

### 7.5 Safety Benefits

The actual safety of Free Flight is hard to determine because of the number of open issues. Especially the specifications of the technology that will be available are still largely unknown. However, the fundamental change from a centrally organised system to a distributed system is potentially beneficial for the safety. This may be understood by comparing it with a simple example. How would collisions be better avoided? By having a number of blind-folded people walking in an area communicating with one monitoring controller or by taking the blindfolds away and allowing the people to walk and watch out by themselves? Another way to look at this fundamental change is to compare the situational awareness of one controller with the collective situational awareness of all pilots in a Free Flight airspace.

The de-centralisation and the inherent redundancy of the distributed system with implicit co-ordination contribute to the potential increase in safety.

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