Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-98252

Conceptual design of Free Flight with airborne separation assurance

J.M. Hoekstra, R.N.H.W. van Gent and R.C.J. Ruigrok

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-98252

Conceptual design of Free Flight with airborne separation assurance

J.M. Hoekstra, R.N.H.W. van Gent and R.C.J. Ruigrok

This investigation has been carried out partly under a contract awarded by the Netherlands Department of Civil Aviation (RLD), contract number OV/RLD-690. The RLD has granted NLR permission to publish this report.

This report is based on a presentation to be held on the AIAA "Guidance, Navigation and Control Conference", Boston, U.S.A., 7-13 August 1998.

Division:	Flight
Issued:	June 1998
Classification of title:	unclassified

Abstract

The study described in this paper originally aimed at studying the human factors problems of airborne separation in a Free Flight environment. However, to define the Free Flight environment with sufficient detail, an overall concept was also designed at NLR. This concept includes rules-of-the-sky, conflict detection, a conflict resolution algorithm, cockpit displays, system specification as well as an assessment of operational implications. The feasibility of the concept has been evaluated in three sub-studies: (i) off-line traffic simulations with very high traffic densities and a total of up to 300 aircraft in the incinity, (ii) a safety analysis comparing the resolution method with current day ATC and (iii) a man-in-the-loop simulator experiment with line pilots in traffic densities up to three times the average West-European traffic density in the particular airspace.

None of these studies could refute the feasibility of the achieved Free Flight conceptual design.

Contents

15 Figures

(29 pages in total)

Abbreviations

ACFT	Aircraft
AIRSIM	Avionics Integration Research SIMulator
ADS-B	Automatic Dependent Surveillance - Broadcast
AP	Auto Pilot
AOC	Airline Operations Center
AT	Auto Throttle
BADA	Base of Aircraft DAta
CGI	Computer Generated Image
EFIS	Electronic Flight Instument System
EICAS	Engine Indicating and Crew Alerting System
EPOG	Eye Point Of Gaze
FMS	Flight Management System
GPWS	Ground Proximity Warning System
IFR	Instrument Flight Rules
MCP	Mode Control Panel
MMI	Man Machine Interface
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
RFS	Research Flight Simulator
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
R/T	Radio Telephony
SGI	Silicon Graphics
SUA	Special Use Airspace
TCAS	Traffic alert and Collision Avoidance System
TEM	Traffic and Experiment Manager
TFM	Traffic Flow Management
TOPAZ	Traffic Organization and Perturbation AnalyZer
TTI	Time To Intrusion
VFR	Visual Flight Rules

1. Introduction

1.1 General

The following definition (italics) is taken directly from the Report of the Radio Technical Commission for Aeronautics (RTCA) Board of Directors' Select Committee on Free Flight (Ref 1).

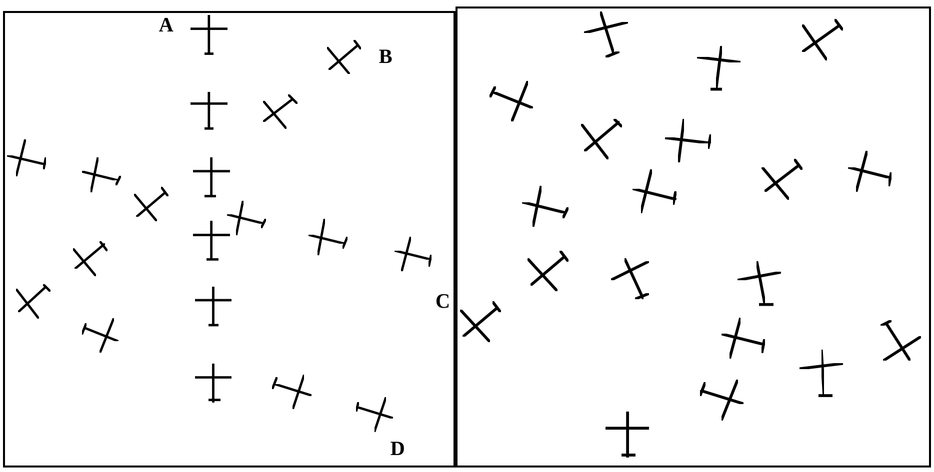
"Free Flight" is defined as :

A safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move towards free flight.

Sometimes the words "Free Flight" are used for concepts, which include direct routing but no airborne separation. The last sentence of the cursive section is the focus of this study: Free Flight with Airborne Separation Assurance.

1.2 Airborne Separation Assurance

With present day ATC, traffic is organized in a way that the air traffic controller can easily see where problems might occur. Figures 1 and 2 show this in a schematic way.



1. Airways *2.* No airways

Fig. 1 and 2: Schematic representation of how airways aid organization of traffic

Using the airways A, B, C and D and imposing altitude restrictions to the different airways a large amount of traffic can be controlled by a single air traffic controller. These airways and altitude restrictions aid the controller in maintaining a mental model of the situation. However, these airways and altitude restrictions deny the aircraft the possibility of flying their optimal route. If each aircraft would fly their optimal route the picture would look more like figure 2.

Figure 2 shows a much less structured global overview and it is expected that ensuring separation of all traffic could become problematic for a single controller. This is because the controller has to identify and resolve for each aircraft the potential conflicts. He then has to solve all problems without creating new ones. Additionally, he has to do all of this within a short time span.

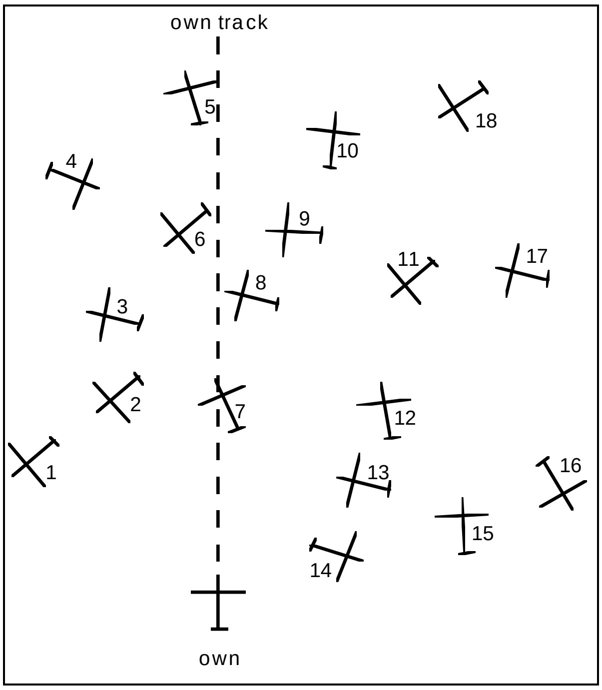


Fig. 3 The airborne perspective

The same picture shown from the perspective of an aircraft seems less problematic because it only has to be deconflicted for the “own” aircraft.

Figure 3 shows the problem as seen from the aircraft named "own" . The first assumption is that all aircraft can "see" all other aircraft. This means that all aircraft are equipped (e.g. ADS-B and EFIS traffic display).

When analyzing the picture one can see that out of the 18 aircraft seen in the picture only 4 aircraft might pose a problem in the near future. Only the aircraft numbers 13, 11, 17 and 18 might cross our track at a time that our own aircraft could be in the vicinity (assuming all aircraft in this example fly in the same speed range as 'own'). The problem of solving a problem with 4 aircraft is far less than that of solving a situation with 19 aircraft as the air traffic controller must do when confronted with the overall picture. Not only are there less conflicts there is also only ‘one’ degree of freedom: the intended position of 'own', whereas the air traffic controller has to 'control' all aircraft in the scenario. When provided with conflict detection tools the problem should be even less complex. Again it is assumed that all aircraft are equipped with conflict detection and resolution tools. It is assumed that at all times enough space is available to solve all potentially conflicting traffic. This is based on the fact that airports and their runway capacity are the limiting factor and that therefore Traffic Flow Management (TFM) will have to provide a Required Time of Arrival (RTA) for specific points (e.g. metering fixes of CTAS) to ensure optimal airspace usage and traffic flow. Thus operators can optimize their flight plans with TFM before and during the flight, but separation responsibility lies with the aircraft. This makes the long term strategic planning a centrally controlling element integrating all the necessary information and the short term conflict resolution a distributed controlled element.

This paper will describe the design of the concept of detecting and resolving conflicts during cruise flight using only airborne systems. Chapter two will discuss the design process itself and the choices made during the initial design. With off-line computer simulations the different concepts were tested. During these off-line simulations several different airborne concepts were tested and the design was frozen. Chapter three describes the design choices made based on these off-line traffic simulations, especially the chosen resolution algorithm.
Chapter four describes an initial safety study performed on the base-line concept using NLR's TOPAZ (Traffic Organization and Perturbation AnalyZer) system. Chapter five describes the follow-on Man-in-the-Loop simulation experiments, in which the human factors issues were investigated. Finally the overall conclusions and recommendations are described in chapter six.

2. Initial design

The Free Flight definition used by RTCA only loosely defines the concept. To study a Free Flight airborne concept a more detailed design was needed. Remaining issues after applying the RTCA definition are: what is the role & responsibility of ATC, how is an alert zone and protected zone defined and perhaps most important of all: which resolution method could be used to ensure a safe and efficient airborne separation. Based on the goal of this study and the available literature on Free Flight studies the following choices and assumptions were made:

1) NO ATC
An extreme form of Free Flight was chosen with no air traffic controller on the ground. The idea behind this concept is to probe the limits of the concept. By first shifting all tasks to the cockpit to where problems might occur, it will also show where ATC might be needed.

2) ALL AIRCRAFT FULLY EQUIPPED
All aircraft in the scenario are assumed to be fully equipped with ADS-B transmitter & -receiver and conflict detection & resolution advisory modules. The transmitter sends the aircraft's position and other information needed by the conflict detection, maybe even intent knowledge, to all other aircraft. The ADS-B receiver collects all the information of the traffic within a certain range in the free flight sector.
The scenarios of mixed equipage basically represent the transition to Free Flight and pose specific problems, which will be addressed in the second phase of the study planned for 1998. (See also chapter six). For the feasibility of the concept the far(?) future is studied in which the transition has taken place.

3) DIRECT ROUTING (horizontally & vertically)
All aircraft use direct routing and cruise climb without steps. So both horizontally and vertically the flight is 'free'. Considerations for this choice are similar to the NO ATC choice: probing the limits. It is also one of the benefits of applying Free Flight.

4) UPPER AIRSPACE ONLY
In the first phase the experiment is limited to the upper air space to focus on general conceptual problems. Somewhere in the descent a transition to controlled flight is foreseen. Where and how that transition should be implemented is not addressed in the first phase of the study. Highest gains for direct routing through applying Free Flight are expected in upper airspace, so the feasibility for this airspace is a worthy result in itself.

5) PROTECTED ZONE
A conflict is defined as an intrusion of the protected zone. The protected zone will be dimensioned using current ATC standards to be able to relate to existing traffic densities, even though there are indications the protected zone could be smaller. The definition of protected

zone & alert zone, as it is used in this concept differs from the RTCA definition mentioned in chapter 1. The protected zone is the zone never to be entered by any other aircraft. In this conceptual design the alert zone does not exist in a purely spatial from. There are two aspects of the alert zone: interrogation & alerting. The interrogation is limited to a (large) maximum number of aircraft and within a certain (large) range. These limits are rarely limiting the airborne separation function when chosen large enough. (Limits used in this study are: a range of 100 - 200 nautical mile, maximum number 300 aircraft for system, 100 aircraft for traffic display) The alerting of a detected conflict is limited by the look-ahead time. This look-ahead time is the maximum time-to-intrusion for which a conflict is detected. This look-ahead time could be regarded as a time-based implementation of the alert zone and has been determined in the off-line traffic simulations.

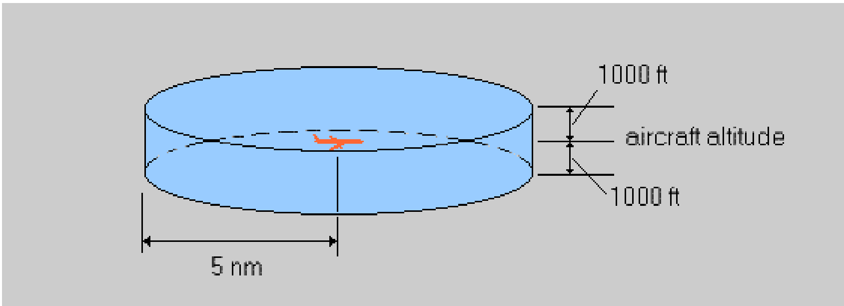


Fig. 4 Protected zone dimensions (vertical scale exaggerated)

The task of the conflict detection module is to predict an intrusion of the protected zone. This protected zone was chosen to reflect current ATC separation standards: 5 nautical mile radius and a height of 2000 feet (altitude-1000ft to altitude+1000 ft, see also fig. 4) This means the ratio diameter to height is about 30 to 1. This zone is often referred to as the "hockey puck" but the shape is actually flatter than most coins.

6) RULES-OF-THE-SKY & CONFLICT RESOLUTION ADVISORIES

From the start in this study it was assumed a resolution advisory system, comparable to TCAS, is necessary for two reasons: implementing the rules-of-the-sky in the system forms a common element in the system, which aids a consistent overall system behavior, and to ensure the workload of the crew stays within acceptable limits.
This is a feature sometimes not foreseen in the concept of airborne separation.
This obviously has a great impact on the workload introduced in the cockpit and therefore is seen as critical by the author for the acceptability of the concept by the pilots community.
For the rules-of-the-sky no clear choice had been made yet. A thorough study of other free flight studies and ATM studies yielded a number of possibilities for the resolution method (Ref. 9, 10). No clear indication was found of the relative value of these methods. Therefore it was concluded that off-line traffic simulations were needed to compare the different resolution methods for the experiment.

3. Off-line traffic simulations

3.1 Traffic & Experiment manager (TEM)

From earlier experiments a rudimentary real-time, six degrees-of-freedom traffic simulator was available. This traffic simulator could simulate 10 aircraft following prescribed instructions. It was used to simulate traffic around the Research Flight Simulator (RFS). For this study this traffic simulator was enhanced with a graphical user interface, optimized to be able to simulate 400 aircraft simultaneously, enhanced with BADA performance models (Ref. 6) and fitted with pilot models able to follow a flight plan and detect and resolve conflicts. The program includes the European navigation data and airports. Scheduling take-offs at airports and airspace entries at the border of the area enables automatic generation of realistic Free Flight traffic patterns over Europe.
This program has also been used for the man-in-the-loop simulator experiments to simulate a realistic traffic environment and control the experiment scenario. (see chapter five)

The traffic manager program has a modular structure. A collection of modules are driven by commands derived from an internal command stack. This command stack is supplied with commands from various sources: the command edit window, a playback file and mouse buttons. Next to the event driven part of the program there is a time scheduled part: the aircraft models, pilot models, automatic scenario generation functions and conflict detection.

The recording option enables the recording of commands to generate the scenario playback files. These scenario files were used for both the off-line comparison of the different resolution methods as well as for the man-in-the-loop simulator experiments.

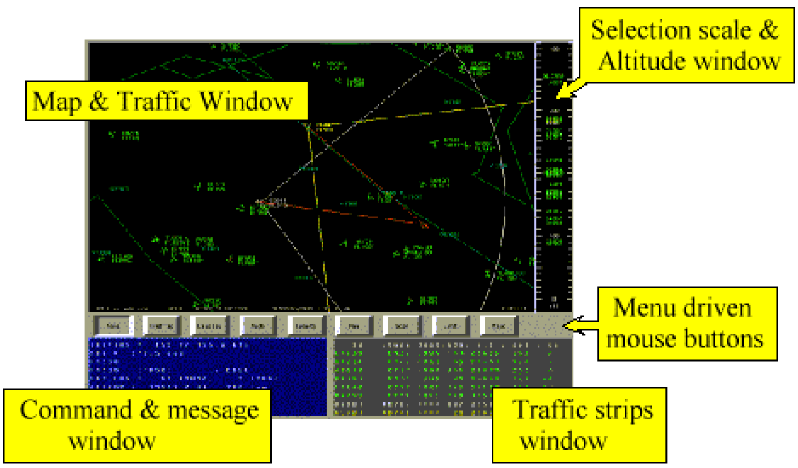


Fig. 5 Traffic & Experiment Manager

The scenario files provided the research flight simulator crew with traffic backgrounds of up to three times the Western-European traffic densities, as well as preprogrammed conflicting traffic on their route to increase the number of conflicts met during the twenty minute flight with another factor of at least three.

See also chapter 5 on the man-in-the-loop simulations for a description of the fidelity of the models and on-line application of the traffic & experiment manager

3.2 Conflict detection

For the conflict detection three levels of intent were foreseen: (i) no intent information (ii) mode control panel (tactical) information (iii) route information.
However due to the more efficient usage of the sky when flying direct routes and optimal altitude the number of conflicts (defined as an intrusion of protected zone, not a mid-air collision) already was very low when no conflict avoiding action was undertaken. Therefore the required avoidance maneuvers are so rare, that most flights are very predictable using current trend information alone. The accuracy of the prediction rarely changes when using track angle (no intent) instead of using route information (destination or next waypoint), because basically most of the times the intended route is the current track when flying direct routes. Especially with a typical look-ahead time of five minutes, increasing the level of intent hardly improves the quality of the predictions. This notion was confirmed by the first off-line traffic simulation trials where the conflict detection & resolution already proved to be very effective without using any intent information. This of course would be different in the current ATC controlled situation where the airways might introduce sudden turns when passing a waypoint or where an altitude clearance introduces a sudden climb or descent.

To drop the requirement for intent information has huge advantages: conflict detection becomes more transparent to the pilots, reduced bandwidth of required communication, no need to solve issues concerning source and validity of intent information (FMS, MCP, separate devices), less modifications to the cockpit. Therefore it was concluded it would be interesting to try whether the concept was feasible without using intent knowledge in the conflict detection module.

The conflict detection module now only has to look at the current state (position and altitude) and trend vector (ground speed, track, and vertical speed) to predict a conflict. Using vector calculations the predicted minimum distance with other traffic is calculated. When less than the required separation and if the time of intrusion is within the look-ahead time, it is stored in the conflict database, together with time of intrusion, predicted positions of both own and other aircraft. This information is presented to the crew on the navigation display graphically, triggers an aural alert and is also passed on to the resolution module.
Note that when an airborne conflict detection module performs the conflict detection, each future conflict is detected twice (by both aircraft) and this means the conflict will still be detected when one of the conflict detection modules fails.

A conflict is defined as a minimum distance in time-space, which is less than the required minimum separation distance. The conflict detection module only detects conflicts with aircraft for which the intrusion of the protected zone takes place in the near future. After several simulations with varying traffic densities this so-called look-ahead time was set at five minutes.

3.3 Resolution methods

In the off-line study using the traffic manager, several methods for traffic resolution have been considered: (i) altitude step, (ii) a cross product of speed vectors (iii) extended VFR rules (iv)variations on TCAS maneuvers and (v) different implementations of the so-called voltage potential.

(i) ALTITUDE STEP & (iv) TCAS MANEUVERS

The altitude step calculates a required altitude to arrive on before the conflict occurs. By climbing or descending the conflict is resolved. Via automatic negotiation it is resolved which aircraft maneuvers in which direction. This is similar to the TCAS III maneuvers. Advantages of these methods are the effective maneuver, because of the shape of the protected zone (see chapter two). It also prevents large deviations from the route. Disadvantages of this method are the need for communication, which also requires extra hardware or sharing the same device as the TCAS module, and extra bandwidth. On top of that there is a clear lack of transparency: the pilot is out of the loop, event thought the look-ahead time of several minutes permits active decision making by the crew. The vertical maneuver may also not always be the most cost/time effective maneuver.

(ii) CROSS PRODUCT OF SPEED VECTORS

This resolution method is based on the cross product of the two vectors i.e. aircraft speed vectors. The resolution method uses the non-commutative property of a cross-product combined with the result of the product to establish the direction of the adjustment in the aircraft's speed vector. Considering two speed-vectors for aircraft A and B respectively v_a and v_b, the non-commutative property is the following: ($v_a \times v_b = -(v_a \times v_b)$). The effect of this is that both aircraft will maneuver co-operatively to prevent the conflict. The result of the cross product is a vector perpendicular to the plane defined by the aircraft's speed-vectors. This ensures an effective and clear resolution for all vertical and horizontal characteristics of the geometry of a predicted conflict. Of course there are singularities, where the cross product becomes zero: the exact head-on or exact head-tail conflict, which were covered separately to ensure an opposite sign of the avoidance maneuver for the aircraft involved.

The magnitude of the heading, vertical speed and /or speed adjustments depends on the distances from the aircraft to the predicted point of conflict, the size of the protected zones and the current airspeeds and not on the result of the cross product.

An advantage of this method is the co-operative maneuver and the transparency to the pilot. A disadvantage is that it does not always yield the most cost-effective solution to a conflict.

(iv) EXTENDED VFR RULES

These rules basically use VFR-like system to judge, who has right of way. Eurocontrol Experiment Center has looked in to this set of rules and constructed some variations, which does not only take into account the direction the other aircraft is coming from but also the current flight phase (climb, final climb, cruise, initial descent, descent) to judge which aircraft has right of way. There still is a certain freedom to choose the maneuver to avoid the aircraft. This complicates the automatic calculation of a resolution advisory. It needs an extra algorithm to decide upon the resolution maneuver. Therefore it was concluded this method could not be used on its own in an automatic resolution advisory system. Another disadvantage of the system is the concept of only one aircraft maneuvering to avoid the conflict A typical human response of the crew who has right of way, is to still avoid the conflict instead of waiting for the other aircraft to maneuver. This is similar to behavior of car traffic in cases where the right-of-way rule is not very obvious.

(v) VOLTAGE POTENTIAL LIKE

The voltage potential is an analogy, which compares traffic with electrically charged particles. Suppose all aircraft would be regarded as positively charged particles and the destination would be 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. See figure 6.

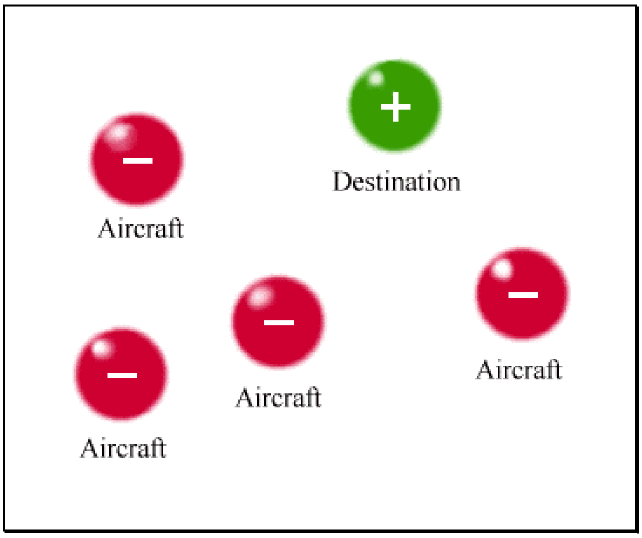


Fig. 6 Simplistic view of voltage potential

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 even the ones with which no conflict currently is predicted.

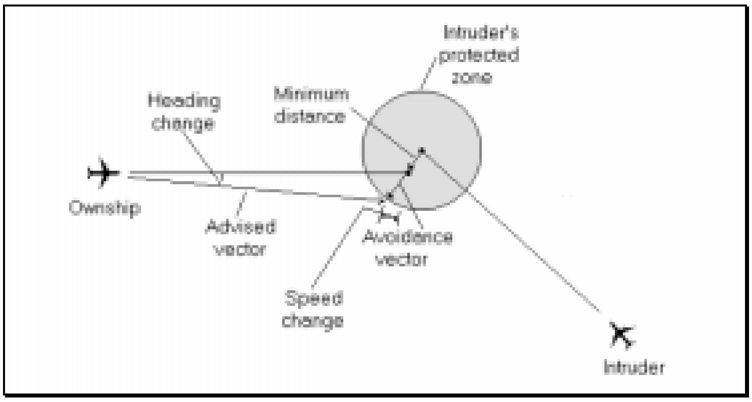


Fig. 7 Geometry of resolution method

At the Lincoln Laboratory (MIT, MA, 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 fig. 7). This method has been slightly modified for use in the resolution module.

When a predicted conflict with traffic has been detected by the conflict detection module, the resolution module uses the predicted future position of both aircraft (will be called ownship) and the traffic or 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 own ship 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 own ship 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 a ground speed. Using the three-dimensional vector also an advised vertical speed is calculated. In case of multiple conflicts within the look-ahead time, the avoidance vectors are summed.
Each resolution method has its singularities in which the avoidance vector becomes zero or the sign can not be determined. Though this could be regarded as a theoretical problem, since in reality noise will prevent these singularities to last 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 maneuver to avoid the conflict. This is part of the fail safe principle of the concept. Normally the intruder will also maneuver. 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 does not avoid the conflict. This means a total of four maneuvers are available, which all are able to solve the conflict independently. Performance limits, weather, restricted airspace will sometimes inhibit one or two maneuvers but rarely or almost never all four. When this would 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 time enough to identify the problem and solve it.

FINAL CHOICE: MODIFIED VOLTAGE POTENTIAL
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 maneuver 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 (Ref. 3) was chosen for the man-in-the-loop experiment. One modification on the description of Eby is that no longer the intended route is used to predict a conflict but rather the currently expected track based on current trend information.

3.4 System aspects
In figure 8 an overview of the involved airborne systems is shown. When the conflicting traffic is also fully equipped this means two independent decision-making loops exist to solve the conflict. Therefore the ADS-B transmitter and receiver should be completely independent to separate the two decision-making loops.

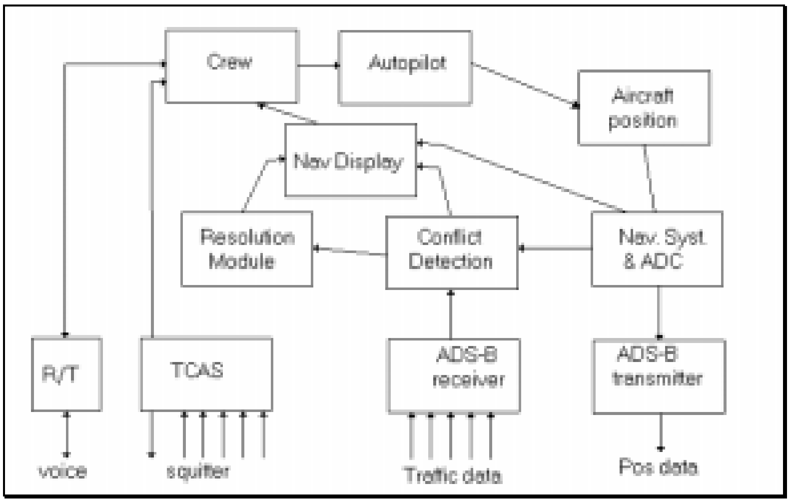


Fig. 8 System lay-out of conflict detection and resolution

Apart from all the fail-safe aspects of conflict detection and resolution, TCAS is assumed to be present as a last minute backup. Also an inter-traffic R/T frequency is available, which can serve to identify possible problems.

Because all aircraft initially maneuver as if the other aircraft will not avoid the conflict, it is tempting to stay at the route and optimal altitude and let the other aircraft solve all conflicts. Therefore an arbitration function is foreseen using a ground based monitoring system, which signals abnormal behavior in conflict solving. A fining or sanction system could be used to prevent this non-co-operative behavior.

4. Safety analysis

NLR's ATM department has performed an ATM safety analysis of the Free Flight concept, as described in the conceptual design sections two and three. The analysis concerns collision risk calculation for aircraft that follow parallel tracks of opposite direction.

The scenario considered, consists of two parallel routes of opposite direction and at a single flight level. Obviously using user preferred routing (horizontally and vertically) would decrease the collision risk significantly from the onset (Ref. 8).

Further assumptions made were:
- TCAS and voice R/T not operational
- In all circumstances, the aircraft will try to follow the resolution advisory provided by the system.
- Only conflicts of two aircraft are considered
- Weather is good
- Level of maintenance is always good
- ADS-B reception and transmission are independent
- ADS-B, global is always functioning
- No vertical resolution maneuvers were considered

Sources for non-nominal conditions were:
- Aircraft flight-plan differs from route
- Aircraft system failures
- Aircraft navigation support failures.

Broadly speaking, two steps were taken during the safety analysis of this scenario.

Firstly scenarios that comprise safety critical events were identified and their probability of occurrence was determined. This included a Hazard Identification brainstorm session, held at NLR. Also a high-level probabilistic model of the ATM scenario was developed. This model includes the occurrence of the identified events that compromise safety (e.g. ADS-B equipment not working) and the aircraft trajectories (including conflict resolution and stochastic deviations from the intended flight path).

Secondly the model was evaluated with respect to collision risk. This was done through the use of NLR's TOPAZ (Traffic Organization and Perturbation AnalyZer) (Ref. 7), a purpose-built platform that supports Monte Carlo simulations and numerical analysis of the previously developed model, for the evaluation of the frequency of occurrence of the identified scenarios and for the assessment of the corresponding collision risks.

Collision risk was calculated for each scenario, giving a clearer view of the impact of the concept on ATM safety. How does this compare with present day ATC? Drawing the resulting collision risk line for Free Flight in the same figure for ATC results in the figure below.

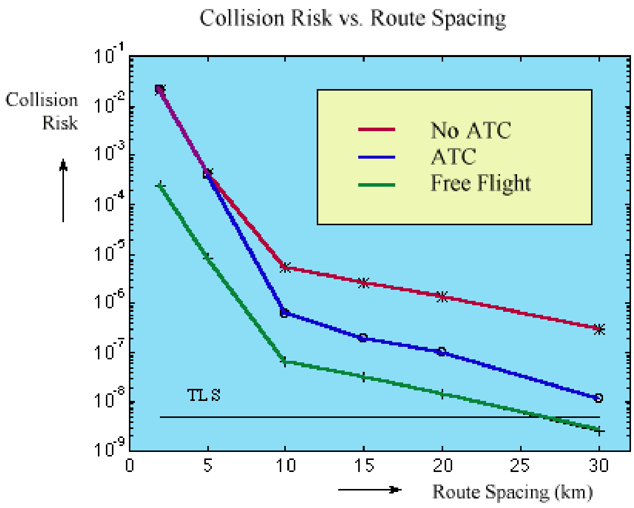


Fig. 9 Comparison safety of scenario for Free Flight and present day ATC

The horizontal line (TLS) shows a target level of safety as set for reference for the year 2000 by ICAO.

From these analyses the following conclusions can be drawn under the model assumptions made:

-The largest safety benefit will be achieved by dealing with the nominal/non-nominal contribution.

-Free Flight with airborne separation assurance is feasible in comparison to STCA based ATC (Ref. 4)..

5. Man-in-the-loop experiment

Finally Man-in-the-Loop simulation experiments were conducted. The purpose was to identify the human factor issues concerned with the above-mentioned concept.

5.1 Simulation facilities

The Free Flight experiments were conducted using three main components: NLR's Traffic and Experiment Manager (TEM), NLR's Research Flight Simulator (RFS) and NLR's Avionics Integration Research SIMulator (AIRSIM).

5.1.1 Traffic and Experiment Manager (TEM)

The Traffic and Experiment Manager (TEM) has already been mentioned in chapter 2, in the section on the off-line traffic simulations. It was also developed for simulating traffic around the RFS in a Free Flight scenario. Both automatic and interactively controlled traffic can be generated by the TEM. This traffic around the RFS is simulated using 6 degree of freedom aircraft models (using BADA, ref. 6) containing autopilot and auto throttle functionality, flight planning functionality and a pilot model. The Traffic and Experiment Manager contains all conflict detection and resolution algorithms as described in chapter 2, for all aircraft in the TEM, including the RFS.

The pilot model includes delayed reaction to conflict resolution advisories and delayed resuming navigation to the aircraft's destination once a conflict is solved. The resolution advisories from the conflict detection and resolution algorithms are taken over by the pilot models, thus controlling the autopilot to resolve the conflict.

During the experiment the TEM was connected to the Research Flight Simulator (RFS) which was one of the aircraft in the TEM. The TEM was also connected to AIRSIM (a workstation based desktop simulator). AIRSIM could take over control of any aircraft in the Free Flight scenario and give back control of the aircraft to the TEM. Events in the experiment were generated from the TEM.
Radio communication was also simulated during the experiment, thus providing R/T background consistent with the traffic situation.

5.1.2 Research Flight Simulator (RFS)

The Research Flight Simulator (RFS) consists of a side-by-side transport cockpit, based on a 4 degrees-of-freedom, low friction motion system. The cockpit of the Research Flight Simulator is a full glass cockpit with a layout common for modern aircraft, see figure 10. The Research Flight Simulator has a modular and flexible set up both in hardware and software, to be able to simulate a range of aircraft types. The simulator configuration used for the Free Flight experiments was the Boeing 747-400 configuration.

Fig. 10 NLR's Research Flight Simulator.

5.1.3 Avionics Integration Research SIMulator (AIRSIM)

Non-nominal events were necessary during the experiment. As the aircraft in the TEM were automatically controlled in the Free Flight scenario, AIRSIM was used to control the aircraft in a non-nominal way.
AIRSIM is a highly configurable and flexible desktop flight simulator with the same functionality as the RFS, using largely identical software. AIRSIM runs on one or two SGI workstations and is interactively controllable with keyboard and mouse.
(See also paper/presentation AIAA-98-4370)

5.2 Man Machine Interface (MMI) description

The MMI-adaptations in the cockpit for the Free Flight environment consisted of:

1) Modified Navigation display (incl. vertical display and traffic & conflict symbology)

2) Aural alerting of conflicts

3) Modified EFIS Control Panel used for controlling and decluttering extra information on navigation display

4) Modifications to the Autopilot for (semi-) automatically flying the traffic resolution.

The traffic was displayed on the Navigation Display like TCAS displays traffic today. Because of the expected relative importance of vertical maneuvers a Vertical Navigation display was integrated below the normal horizontal Navigation Display. In contrast with a normal TCAS display, different symbology was used because of the extra available information.

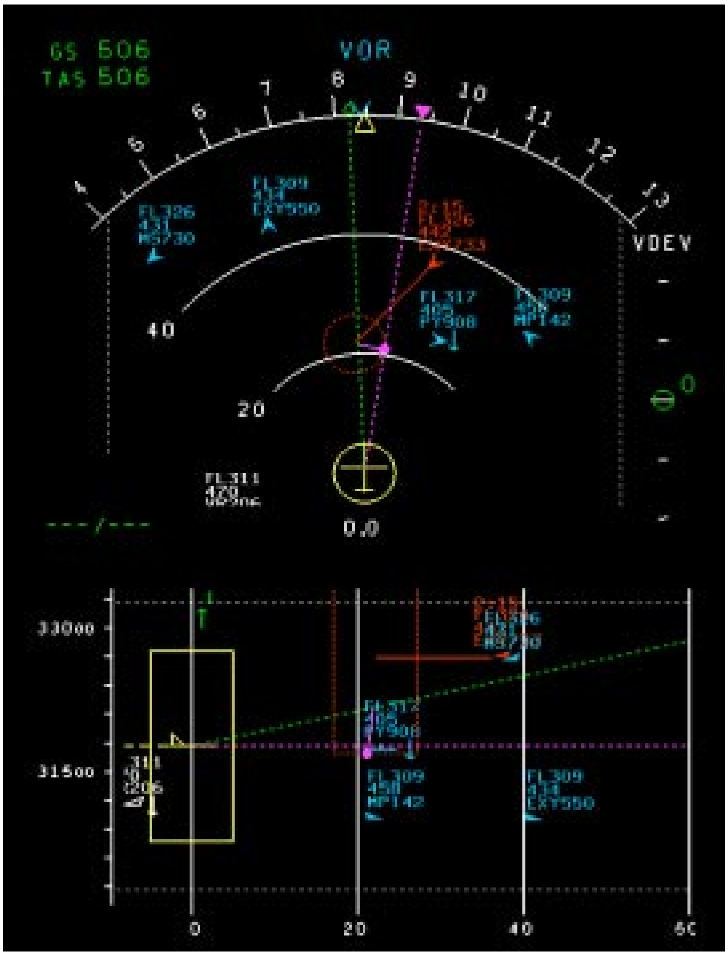


Fig. 11 Navigation display with traffic symbology

The extra information consisted of:

Traffic and own ship information:

- Traffic call sign
- Track direction
- Altitude
- Ground speed
- Vertical speed direction (arrow)
- Vertical and horizontal track of own aircraft

Conflict info

- Protected zone around predicted position of intruder at minimum distance
- Predicted track-line of the intruder, which connects the intruder with the conflict symbol indicating the predicted position of the intruder.
- Time to intrusion

Resolution to prevent intrusion by means of:

- Graphical coplanar avoidance -vector
- Steering bugs on Nav Display and PFD

When a conflict occurred with a time to intrusion of less than 5 minutes, the following sequence of display changes were shown:

1- The position of traffic (in amber);
2- The incursion of the protected zone of the traffic;
3- The traffic resolution;
4- After a conflict had been resolved the traffic symbol would remain in the conflict color (amber or red) for 10 seconds to help pilots identify the conflicting aircraft.

If during the above sequence the time to maximum intrusion became less than 3 minutes, the traffic symbols were shown in red together with a more urgent aural alerting level. Figure 11 shows the Navigation display with the traffic symbols.

5.3 Experimental scenario

It was required to have three levels of density: single, double and triple density i.e. ones, twice and three times the "normal" density in European airspace. The experimental runs would last 20 minutes and the Free Flight scenarios should be as realistic as is possible.

To have realistic scenarios, automatic scenario generation was created within the TEM, which resulted in continuously departing and arriving traffic from and to airports, using direct routes from origin to destination. Low and high altitude airports were defined. Low altitude airports simulate real airports, while high altitude generate en-route traffic leaving or entering the experiment area.
The origin of every aircraft was randomly taken from a list of 9 low and 9 high altitude airports around the experimental area and the destination of every aircraft was also taken randomly from this same list.

Fig. 12 TEM screen with typical traffic scenario

In this way eighteen realistic sets of single density scenarios were developed. By summing different single density scenarios the double and triple density scenarios were obtained. To make sure the RFS would be in conflict with other aircraft, specific conflicts were added to the scenarios. Figure 12 shows the screen of the TEM with a typical traffic scenario.

A small part of an FMS company route from Glasgow to Athens, lasting 20 minutes, was flown during each experimental run.

5.4 Experiment matrix

Eight crews were tested during four weeks in September and October 1997.
Three levels of traffic load and three levels of resolution activation were used making a total of nine experimental cells. Resolution activation was varied between three levels:

1) Manual, in which case the crew had to enter MCP entries themselves.
2) Execute separate, in which case the crew could choose to auto enter either the horizontal, or the vertical maneuver or both by pressing one or two buttons on the MCP.
3) Execute combined, in which case the crew could auto enter the complete maneuver by pressing a button on the MCP.

These nine conditions were flown in a nominal (everything works as advertised) and in a non-nominal way making a total of 18 experimental cells. The non-nominal scenarios included events in which malfunctions and distracters were simulating one out of three main mishaps:

1) Anti collision system of other aircraft fails;
2) Anti collision system of own aircraft fails;
3) Delay times of system is increased

5.5 Results

None of the experimental runs resulted in a loss of separation, except for the non-nominal runs in which loss of separation was forced upon the RFS by the TEM/AIRSIM.

5.5.1 Acceptability of Free Flight with airborne separation assurance

The subjective ratings of acceptability were scored on scales from 1 to 5 indicating respectively

5 = "Perfect in every way"
4 = "Favorable"
3 = "Acceptable"
2 = "Unacceptable"
1 = "Completely unacceptable"

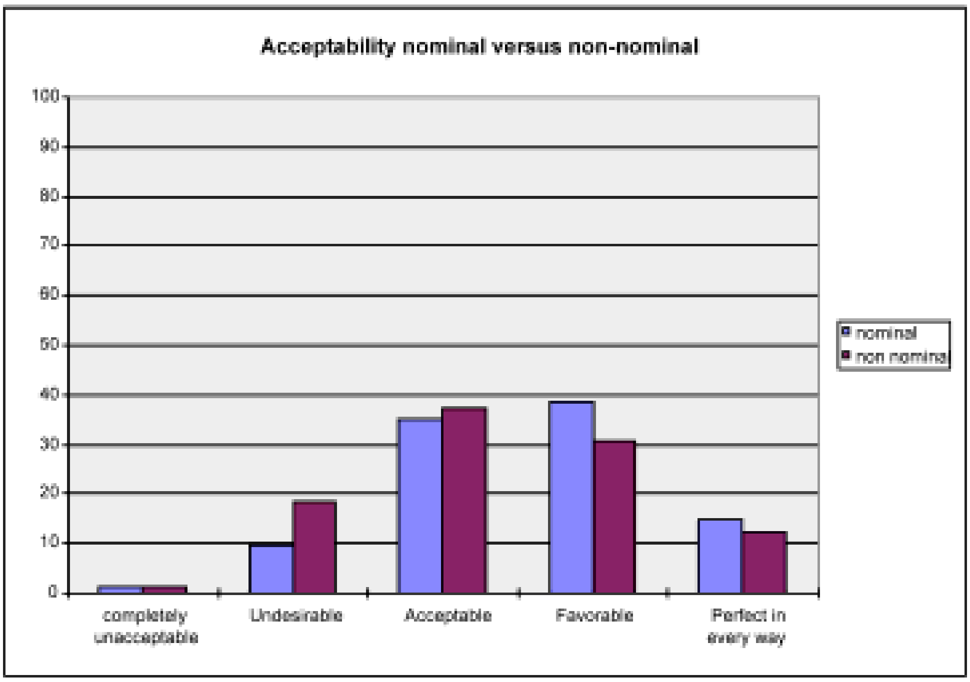


Fig. 13 Subjective acceptability rating

Figure 13 shows the acceptability rating overall, during nominal runs and during non-nominal runs. In all three cases the average rating was above 3, indicating acceptable or better.

5.5.2 Subjective Safety compared with present day ATC

The subjective ratings of safety were scored on scales from 1 to 5 indicating respectively

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

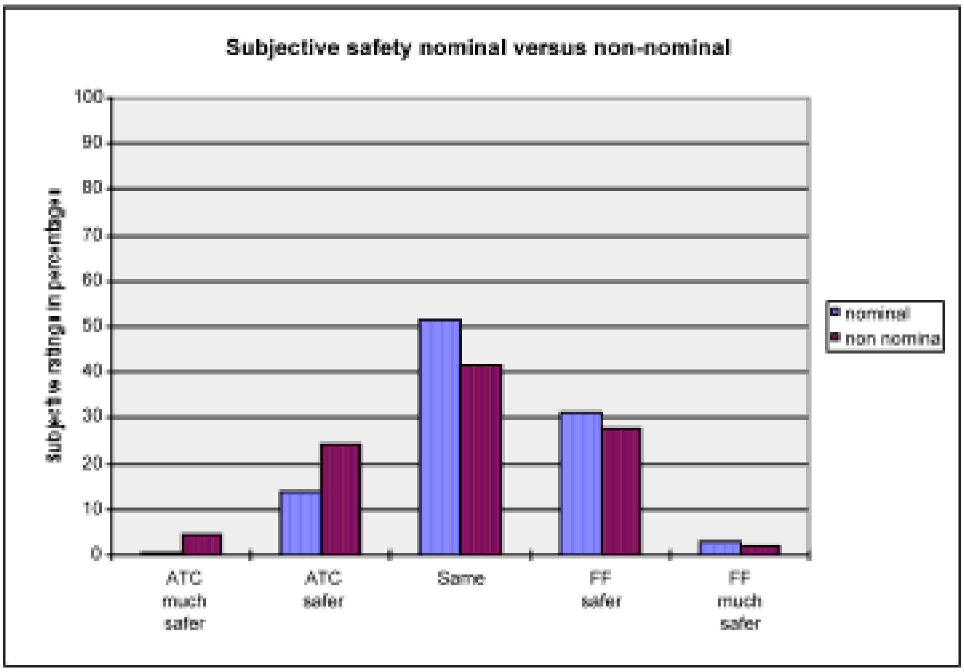


Fig. 14 Subjective safety rating

Figure 15 shows the safety rating overall, during nominal runs and during non-nominal runs. In all three cases the average rating was above 3, indicating same as ATC or better.

5.5.3 Subjective mental workload

The subjective workload ratings on a scale from 0-150 during the experiment are shown in figure 15 for single, double and triple traffic densities as well as for nominal and non nominal cases. All average ratings are at or below the 40 mark, indicating that crews rate this concept as "costing some effort" or less.

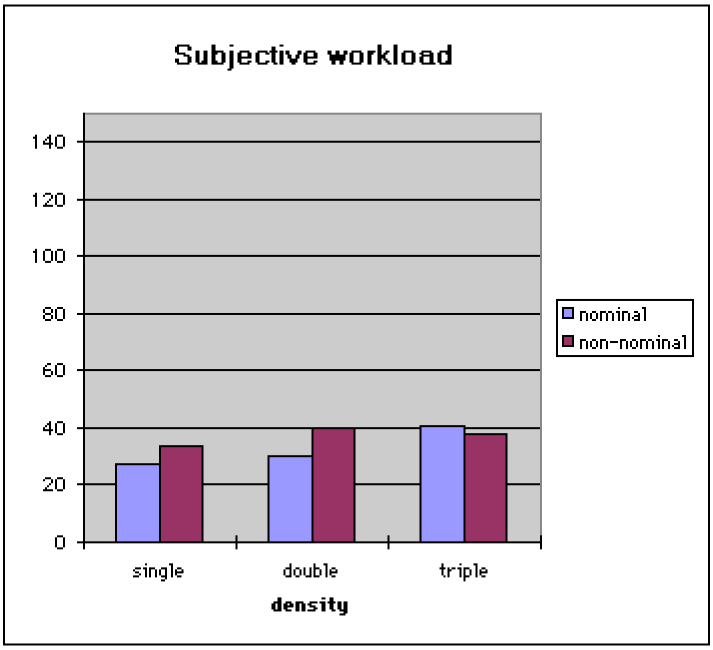


Fig. 15 Subjective workload rating

During other simulator experiments under normal cruise conditions the average rating would be 27.

6. Conclusion & remaining issues

6.1 Conclusion

None of the three sub-studies (off-line simulations, TOPAZ safety analysis, and Man-in-the-Loop experiment) could refute the feasibility of the conceptual design of Free Flight as defined in chapter two.

6.2 Issues

During the experiments comments and actions of the subject crews were noted. The major issues for improvement of the concept were derived from comments repeated consistently by all crews:

- Some form of obtaining intent information should be made available. This should NOT be used by the conflict detection module!
- Aircraft which are in trouble should be able to broadcast a signal upon which they would receive priority with conflicts.
- An extra rule forbidding large horizontal and/or vertical maneuvers resulting in conflicts less then 5 minutes away should be added. (This would require a form of prediction capability of the conflict detection module in relation to possible future maneuvers)
- Passenger comfort is a major issue, which has to be resolved in relation to vertical maneuvers.
- At cruise altitudes the limited speed regime of most aircraft excludes large speed changes as a resolution possibility.

7. References

1) RTCA, Report of the Radio Technical Commission for Aeronautics (RTCA) Board of Directors' Select Committee on Free Flight).
2) Hoekstra, Van Gent, Ruigrok., Off-line Validation of a Conceptual Design for Free Flight in Cruise. NLR Contract Report, 1997.
3) Eby, Martin S. , A Self-Organizational Approach for Resolving Air Traffic Conflicts, The Lincoln Laboratory Journal Vol. 7, Nr. 2, 1994.
4) Everdij, M.H.C., Bakker, G.J., Blom, H.A.P., Blanker, P.J.G., Designing EATMS inherently safe, TOSCA II WPR/4/01, EuroControl, NLR, 1997.
5) Daams, J. et al., Safety evaluation of an initial Free Flight scenario with TOPAZ (Traffic Organization and Perturbation AnalyZer), Draft version, NLR, 1997.
6) Bos, A., User Manual for the Base of Aircraft Data (BADA) Revision 2.5, EEC Note 1/97, Eurocontrol, 1997.
7) Everdij, M.H.C., Klompstra, M. B., Blom, H.A.P., Development of mathematical techniques for ATM safety analysis, MUFTIS WPR .3.2 Final Report part 2, European Union DG VII, NLR, 1995
8) Blom, H.A.P., Bakker, G.J., "A macroscopic assessment of the target safety gain for different en route airspace structures within SUATMS", Working paper for the ATLAS study of the commission of European Communities, NLR CR 93364 L
9) Zeghal K. “Vers une théorie de la coordination d’actions” Ph.D. Thesis, Université Paris, December 1994
10) Kuchar J.K., Yang, L.C. “ Survey of Conflict Detection & Resolution Modelling Methods”, AIAA GN&C conference 1997