Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-98286

Free Flight with airborne separation assurance

A man-in-the-loop simulation study

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Summary

This paper describes the Man-in-the-Loop part of a study looking at a concept of detecting and resolving conflicts during cruise flight by means of airborne systems. The overall study included fast-time simulations to define a base-line concept, a safety analysis, and a Man-in-the-Loop experiment to investigate human factors issues. Based on the results of the three sub-studies, the feasibility of an Airborne Separation Assurance concept for a future Free Flight environment as defined in this study, could not be refuted.

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1 Introduction

The following (italics) is taken directly from the Report of the Radio Technical Commission for Aeronautics (RTCA) Board of Directors' Select Committee on Free Flight (Ref. 8).
"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.

Free flight in its mature state is intended to provide aviation users visual flight rules (VFR) flexibility while maintaining the traditional protection afforded under IFR by using advanced technology. Intervention is limited to four situations: Tactical (short term) conflict resolution, traffic flow management (TFM) to the runway's end, unauthorized special use airspace (SUA) entry, and safety of flight.

In the free flight system, a flight plan will be available to the air traffic service provider to assist flow management, but will no longer be the basis for separation. It is possible, and highly desirable, to shift from a concept of strategic (flight path based) separation to one of tactical (position and velocity vector based) separation. There even may be instances included in the system's design where separation assurance shifts to the cockpit.

The last sentence of the cursive section is the focus of this study: Free Flight with Airborne Separation Assurance.

2 Method

Free Flight Situation

Because the Free Flight (FF) concept is still in its infancy, a lot of effort was devoted to specifying a potentially workable Airborne Separation Assurance System (ASAS). As a baseline, the RTCA concept of an Alert and a Protected zone was used. As indicated by the RTCA, each aircraft will be surrounded by two zones:

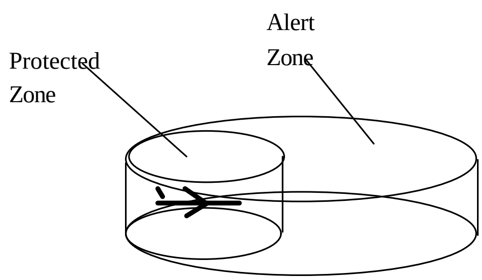

Fig. 1 Protected and Alert Zones

As soon as traffic enters the alert zone an interrogation of the aircraft's position information will take place by data link. A possible conflict is shown on a display and the crew will have to react according to predefined “rules of the road”. Previous studies (Ref 1, 6, 9) have shown that resolving a potential conflict is not always optimally performed by the crew. Therefore it was decided that a Resolution Advisory (RA) would be part of the concept. This RA had to fulfil the following requirements:

- As safe as possible, also in non-nominal conditions.
- Transparent to the crew.
- Effective, especially with multiple encounters.

For the initial experimental design several choices were made regarding the concept and first phase experiment:

- To emphasize the Man Machine Interface (MMI) aspects an extreme form of Free Flight was chosen with no Air Traffic Control (ATC).
- Direct routing & optimal cruise altitude for all aircraft. All aircraft used direct routing and cruise climb without steps.
- The experiment was limited to the cruise flight phase, however the scenario included climbing and descending traffic.
- All aircraft in the scenario were fully equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) transmitter & receiver. Conflict detection & resolution advisory

modules were integrated in the cockpit. The transmitter broadcasts the aircraft's position and other information needed for conflict detection, to all other aircraft. The ADS-B receiver collects the information of all traffic within a certain range in the free flight sector.
- A conflict was defined as an intrusion of the protected zone. The protected zone was dimensioned using current ATC standards to be able to relate to existing traffic densities.

Several resolution algorithms were tested during off-line computer simulations with the Traffic and Experiment Manager (TEM) (detailed in a later section). These simulations showed the Voltage Potential algorithms (Ref. 3) as most effective. This method has been slightly modified for use in the resolution module (see Fig. 2).

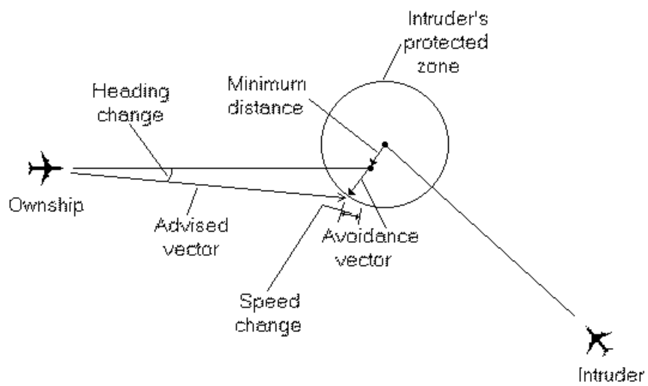

Fig. 2 Geometry of Resolution Method

When a predicted conflict with traffic has been detected by the conflict detection module, the resolution module uses the predicted future position of own aircraft (will be called own ship) and of 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 the 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 a three-dimensional vector also allows an advised vertical speed to be calculated. In case of multiple conflicts within the look-ahead time, the avoidance vectors are summed. This method fulfilled the earlier mentioned requirements:

- Safe, because initially both aircraft manoeuvre to avoid the other as if the other will not react. The safety of the concept was further investigated in an evaluation using NLR's Traffic Organization and Perturbation AnalyZer (TOPAZ), showing it to be feasible compared to STCA based ATC (Ref. 2).
- - Transparent, because the geometry of the conflict, if shown on a display, leads indubitably to the Resolution Algorithm.
- Effective with multiple encounters. Both the trails on the TEM and reference 3 show very promising results with (very) high levels of density.

A possible drawback of the algorithm is that, because the RA aims at the border, the protected zone is sometimes grazed, leading to incursions of that zone by lateral distances of up to half a mile laterally and up to 100 ft vertically.

3 Apparatus

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). Figure 3 shows the experimental set-up.

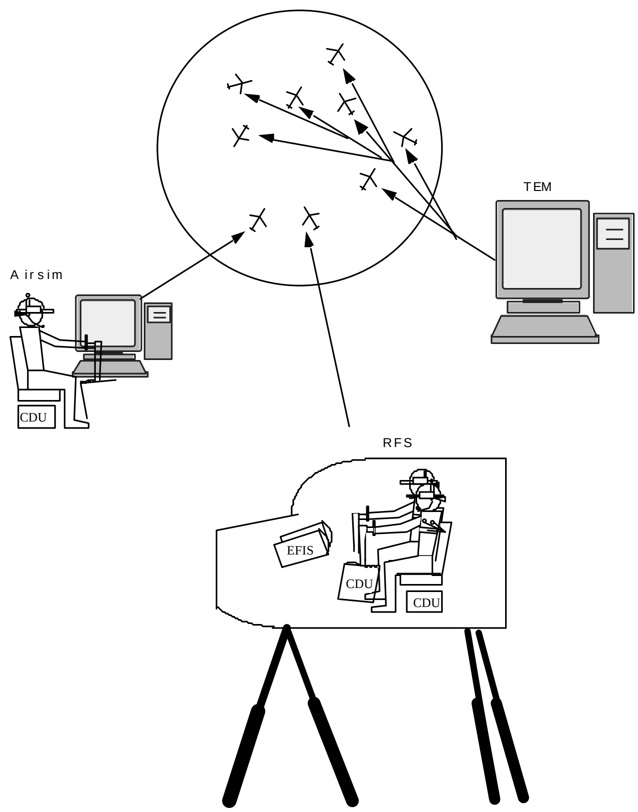

Fig. 3 Free Flight experimental set-up, enabling multiple "manual" aircraft

3.1 Traffic and Experiment Manager (TEM)

The Traffic and Experiment Manager (TEM) was especially 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 containing autopilot, auto throttle functionality, flight planning functionality and including a pilot model. The Traffic and Experiment Manager contains all conflict detection and resolution algorithms, for all aircraft in the TEM, including the RFS.

During the experiment, the TEM was connected to the Research Flight Simulator (RFS) which was one of the manned aircraft in the TEM. The TEM was also connected to AIRSIM (a workstation based aircraft simulator). AIRSIM allows manual control of any of the aircraft in the Free Flight scenario. Thus the TEM served as the experiment and aircraft behaviour controller. Conflicts in the experiment were generated from the TEM scenario and the surrounding RFS

traffic could also be controlled interactively to generate specially challenging conflicts in the Free Flight experiment.
Radio communication was also simulated during the experiment, thus providing Radio/Telephony (R/T) background, consistent with the traffic situation. Figure 4 shows the TEM screen lay-out.

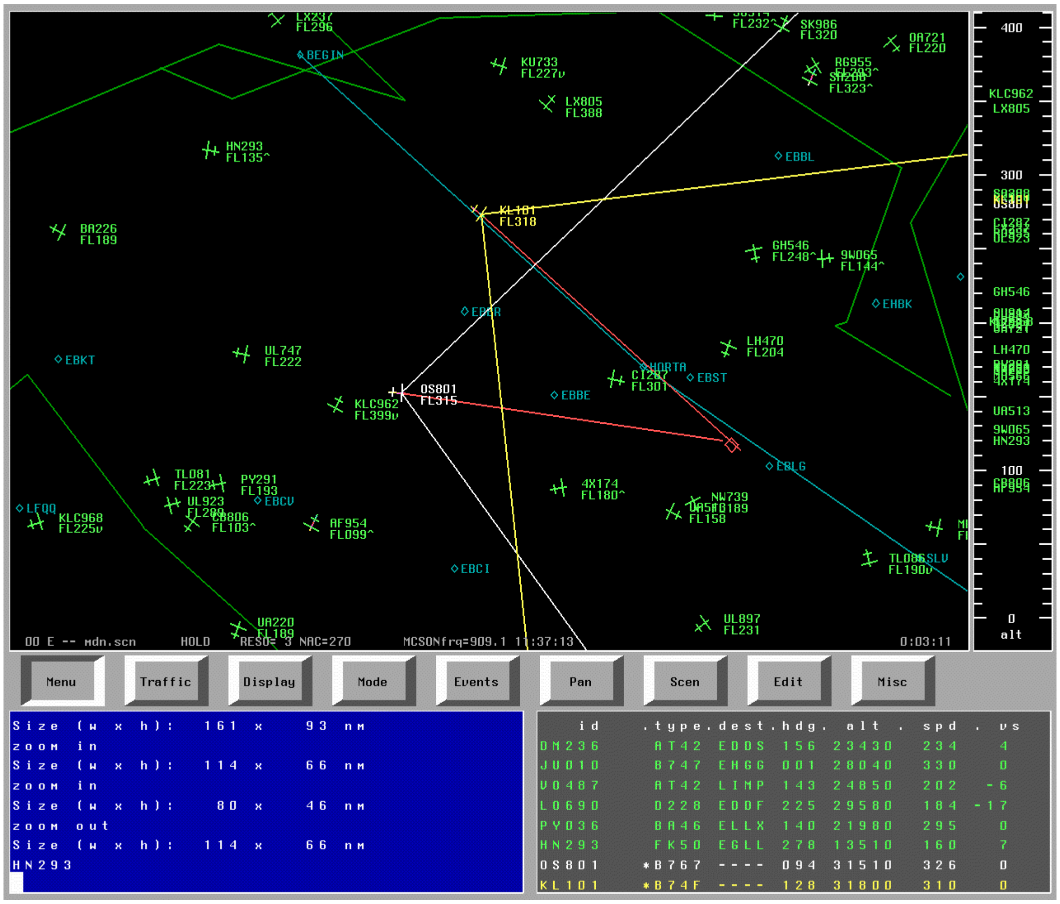

Fig. 4 Traffic and Experiment Manager (TEM) screen lay-out. The predicted conflict is shown between KL101 and OS801

3.2 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 5.

Fig. 5 NLR's Research Flight Simulator.

Avionics software was adapted for this Free Flight experiment. The vision system was adapted to allow traffic visualization in the outside view and Traffic alert and Collision Avoidance System (TCAS) software was installed in the RFS. The autopilot system was extended with automatic gating of resolution advisories. Chapter 4 described the adaptions of the Human Machine Interface (HMI) in more detail.

3.3 Avionics Integration Research SIMulator (AIRSIM)

Non-nominal events were included in 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.

4 Human Machine Interface (HMI)

The HMI-adaptations in the cockpit for the Free Flight environment consisted of modifications to the navigation display, the aural alerting, the Electronic Flight Instrument System (EFIS) control panel and the autopilot.

4.1 FF Nav display

The traffic was displayed on the Navigation Display. A Vertical Navigation display was integrated below the normal horizontal Navigation Display to facilitate vertical manoeuvres. Modified symbology was used because of the extra available information. The extra information consisted of:

<u>Traffic and own ship info</u>

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

<u>Conflict info</u>

- Protected zone around predicted position of intruder at minimum distance.
- Predicted track-line of the intruder, which connects the traffic symbol with the conflict symbol indicating the predicted position of the intruder.
- Time to intrusion.
- Resolution to prevent intrusion by means of:
  - graphical co-planar avoidance -vector on Navigation Display (Nav).
  - steering bugs on Nav and Primary Flight Display (PFD).

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

- The position of traffic (highlighted in amber).
- The incursion of the protected zone of the traffic.
- The traffic resolution.

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 (using three tones repetitively instead of one). After a conflict had been resolved the traffic symbol would remain in the conflict color (amber or red) for 10 seconds as a memory aid for the crew.

Figure 6 shows the Navigation display with the traffic symbols.

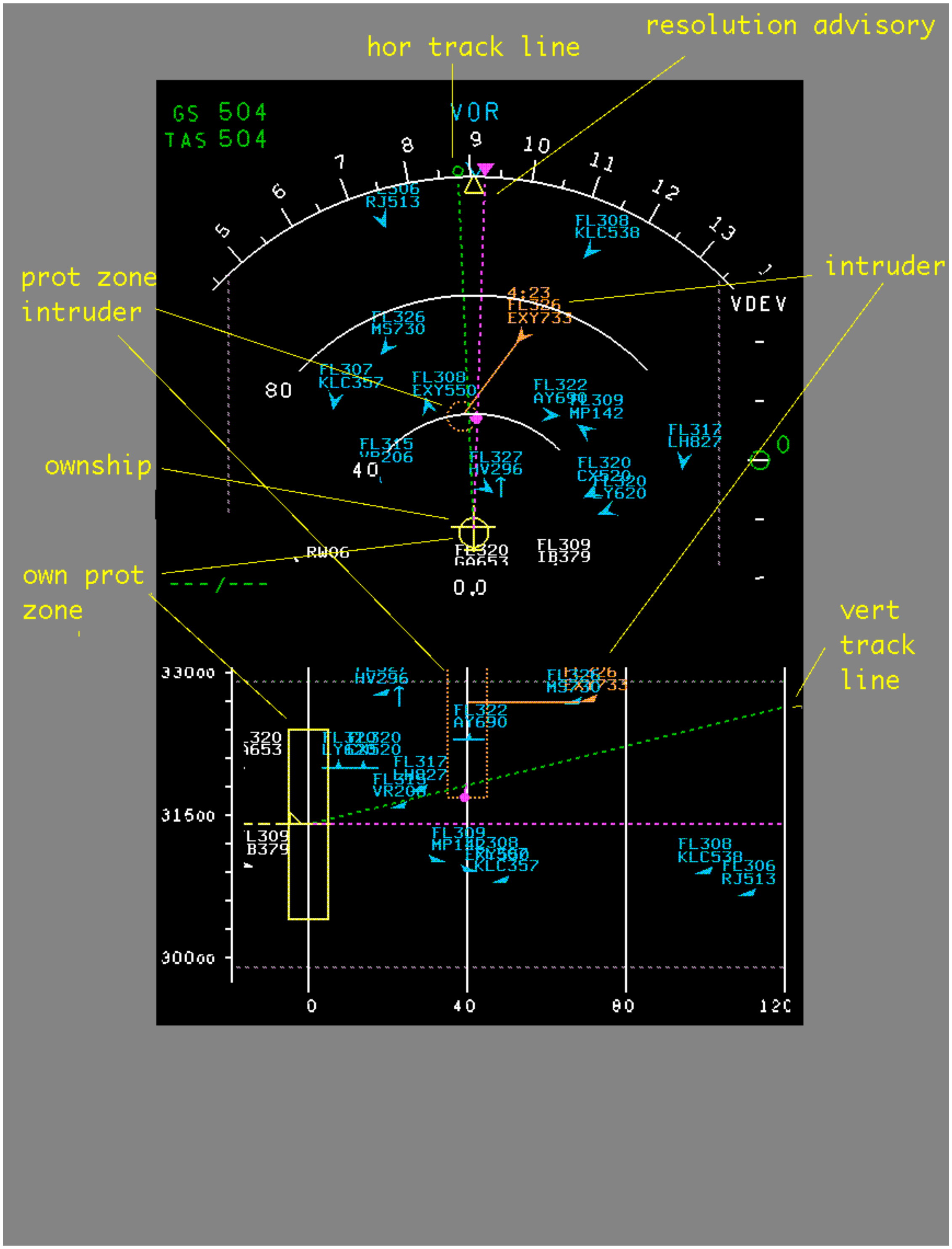

Fig. 6 Navigation display with traffic symbology

4.2 Aural alerting

Two aural alerts were added as “attention getters” in case of an amber or a red alert.

4.3 EFIS Control Panel

Modifications included:

- Toggle call sign display .
- Modifying clipping range on vertical display.
- Toggle speed info display.
- Toggle altitude info display.
- Toggle time-to-intrusion display.
- Toggle performance limit lines on horizontal and vertical display.

4.4 Autopilot

The Autopilot was modified for (semi-) automatically flying the traffic resolution. This depends on the experimental condition (See also chapter on experimental scenarios).

5 Experimental setup

5.1 Scenarios

Three levels of traffic load and three levels of resolution execution were used making a total of nine experimental cells. The three levels of density used were: single, double and triple density as compared to the average density in European airspace. Resolution execution was possible by:

- Manual, in which case the crew entered Mode Control Panel (MCP) entries themselves.
- Execute separate, in which case the crew could choose to auto-enter either the horizontal, or the vertical manoeuvre or both, by pressing one or two buttons on the MCP.
- Execute combined, in which case the crew could auto enter the complete manoeuvre by pressing a button on the MCP.

These nine conditions were flown in a nominal (everything works as advertised) and in a non-nominal scenario. The non-nominal scenarios included events such as:

- Anti collision system of other aircraft fails.
- Separation assurance system of own aircraft fails.
- Delay times of system is increased.
- Unexpected manoeuvres such as emergency descents.

The experimental runs would last 20 minutes.

5.2 Experimental Participants

Eight crews were tested consisting of professional commercial European airline pilots. The flight experience of the pilots varied between 490 and 20000 hours, with an average of 5500 hours.

5.3 Procedure

Pilots were asked to participate on two consecutive days. Pilots received instruction and practice during the morning of the first day. Testing would take place during the second half of the first day and during the second day.

5.4 Measures

Head and eye-tracking measures were taken from both subject pilots in the RFS, by means of Eye-Point-Of-Gaze (EPOG) measuring systems.

All operations on the Flight Management System (FMS) Control and Display Units (CDU), all operations on the Mode Control Panel (MCP), all conflicts in the Free Flight scenario, the scenario data itself and the RFS aircraft state variables were recorded for performance measures.

Questionnaires were taken from both subject pilots probing for mental workload, acceptability of various items and perceived safety.

Finally videotapes were taken from the TEM display and one combined display with Pilot Flying Flight Instruments and a cockpit overview from a video camera from the RFS cockpit.

6 Results

6.1 Loss of separation

Next to the non-nominal runs in which loss of separation was forced upon the RFS as dictated by the scenario, 11 incursions of the protected zone occurred. Eight incursions occurred with one crew. The maximum incursion measured was .45 nmi laterally and 86 ft vertically, leaving a minimum separation of 4.55 nmi laterally and 914 ft vertically.

6.2 Conflict times

Figure 7 shows the average times that the RFS was in a predicted conflict situation, across the nominal and non-nominal conditions, which was the largest effect seen.

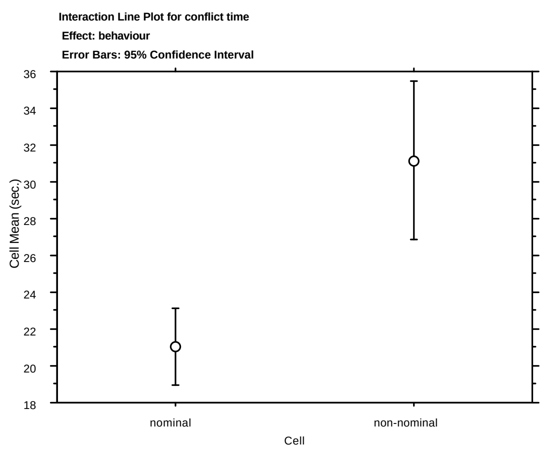

Fig. 7 Mean conflict times measured from the first indication of a predicted intrusion till the moment of “free of conflict”

6.3 Manoeuvres

Table 1 shows the average percentages of control parameters used during the avoidance manoeuvres across the three levels of resolution control. During the manual condition (which shows crew preference best) “heading” was used 57.9 %, altitude 41.4 % and speed 15.4 %, including combined types of manoeuvres.

Table 1 Average percentages of control parameters used during the avoidance manoeuvres

	Manual	Execute separately	Execute combined
Heading	57,9	83.0	72.0
Speed	15,4	57,9	47,5
Altitude	41,4	28,8	75,9

6.4 Eye Point of Gaze

Table 2 shows the average percentage of dwell time on the navigation display and primary flight display for the pilot flying and pilot not flying.

Table 2 Average percentages of dwell time on the Navigation Display and the Primary Flight Display during the experimental runs for the Pilot Flying (PF) and Pilot Not Flying (PNF)

	PF	PNF
Nav	46.6	47.8
PFD	8.9	6.9

6.5 Subjective Acceptability

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

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

Figure 8 shows the averaged acceptability ratings across the three density levels used, which was the largest effect seen. In all cases the average rating was above 3, indicating acceptable or better.

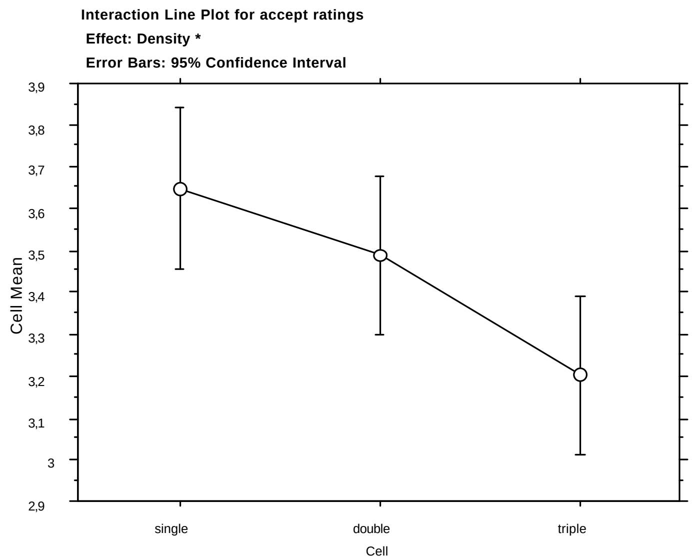

Fig. 8 Subjective acceptability rating as a function of traffic density

6.6 Subjective Safety perception

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

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

Figure 9 shows the average safety rating across the three density levels used, which was the largest effect seen.

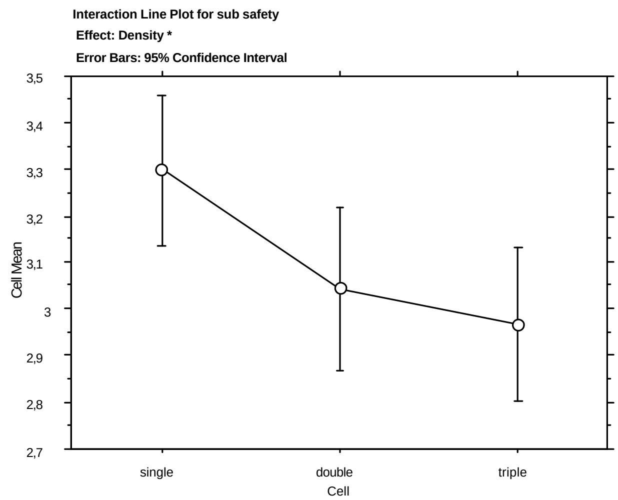

Fig. 9 Subjective safety rating

6.7 Rating Scale Mental Effort (RSME)

The subjective workload ratings on a scale from 0-150 during the experiment are shown in Figure 10 for the three levels of resolution control, which was the largest effect seen. All average ratings are at or below the 40 mark, indicating that crews rate this concept as "costing some effort" or less.

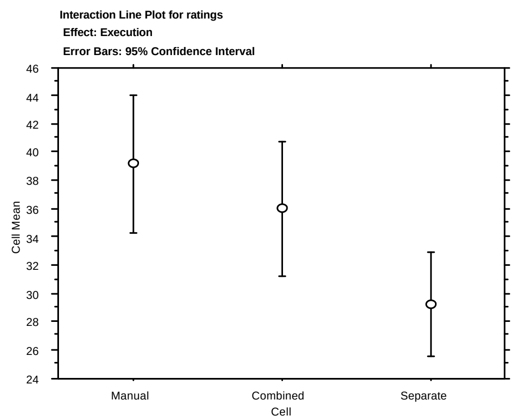

Fig. 10 Subjective workload rating on a scale ranging from 0-150.

7 Discussion and conclusions

7.1 Discussion

An enumeration of the intrusions of the protected zone, which were not prescribed by the scenario was given in the previous section. The intrusions are mainly grazes of the protected zone, either vertically or horizontally. This is caused by the resolution algorithm which aims at the exact border of the protected zone. However, as soon as “clear of conflict” is detected by the system the aircraft is again free to go back to the original course. If this happens close to the intruder, a graze of the protected zone can occur. Such grazes could be prevented by an improvement to the algorithm ensuring getting back on course without triggering a second conflict and/or grazing the protected zone of the intruder. It is also noteworthy that eight of the 11 grazings were caused by one crew. This could be explained by the fact that this crew received significantly less training due to the late arrival of one of the crewmembers.

The overall average of the conflict times, defined as the time from conflict detection till the moment of clear of conflict, was 26.2 seconds. A similar study (Ref. 6) done at NASA shows an average of 58 seconds from detection till initiation of the manoeuvre. One important reason for more than halving the time shown by the NASA study could be that no priority rules are required by the NLR concept and the inclusion of a resolution advisory. Because no priority rules are used, both will manoeuvre halving the overall manoeuvre time. In the NASA study much of the time was spent by negotiating with datalink which of both aircraft was in the best position to manoeuvre while during the NLR study a resolution is shown almost immediately when a conflict is detected, which leads to faster reaction times.

Table 1 shows that even though using heading manoeuvres would give the aircraft an offset of up to 5nmi versus 1000 ft vertically pilots preferred the horizontal manoeuvre. When asked why in the debriefing, they would answer that using flight level changes to avoid manoeuvres would not be acceptable in terms of passenger comfort and economy. Few subject pilots would use the vertical velocity mode of the MCP, with which a conflict could be resolved by a vertical speed of 200 ft/min or less!

Table 2 shows a relative large percentage of EPOG dwell time of both crewmembers on the Nav compared to the PFD. One could argue that this is due to the novelty of the display format but no effect of time was found. The percentages remained the same during the course of the experiment.

Because crewmembers were given the extra task of traffic separation assurance, in a very busy environment with newly developed MMI, it was expected that they would react in a negative manner. Therefore it was expected that the concept would be rated below acceptable, the subjective safety would be rated less safe as present day ATC and that the workload would increase with a considerable amount.

Figure 8 to Figure 10 however show opposite results. Even in sessions with triple the normal traffic density, still 78.8 percent thought the free flight concept was acceptable or better. Regarding the perceived safety, 71.3 percent of the subject pilots rated the free flight concept as being as safe or safer as present day western European ATC. During the experiment the mean

RSME rating during the third set of sessions was 29. This is very comparable to the average rating of 27.2 with other experiments done at the NLR during cruise-phase under normal routine conditions (Ref. 4).

7.2 Conclusion

The Man-in-the-Loop experiment could not refute the feasibility of an Airborne Separation Assurance concept for a future Free Flight environment as defined in this study.

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