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Free Flight in a Crowded Airspace?

J.M. Hoekstra (hoekstra@nlr.nl)
R.C.J. Ruigrok (ruigrok@nlr.nl),
R.N.H.W. van Gent (rvgent@nlr.nl)
National Aerospace Laboratory NLR,
Amsterdam,
Netherlands

Abstract

In the report of the RTCA Free Flight Task Force, Free Flight is presented as a range of concepts, allowing self-optimisation of the routes by the airlines. The document also describes a mechanism for airborne separation as a part of the Free Flight concept. Whether airborne separation is allowed depends on, among other things, the so-called “dynamic density”. This dynamic density is a measure of the density and the complexity of the traffic pattern.
According to the original airborne Free Flight concept as described in the RTCA document, when the dynamic density is too high, less freedom will be allowed and separation will remain on the ground. This is based on the assumption that central co-ordination is required in these cases.
However, this paper will try to demonstrate via analysis and simulation results, why it is precisely high density situations that require the power of a distributed system. It describes the concept as designed in the NLR study as an example of the implementation of the Free Flight concept. The lessons learned apply to most airborne separation concepts. The effect of a distributed ATM system will be illustrated by looking at some sample scenarios, the robustness and the conflict rates.

Biography of authors

J.M. Hoekstra graduated in 1991 at the Technical University of Delft at the Faculty of Aerospace Engineering. He joined NLR at the Flight Simulation and Handling Qualities department. He worked on model development, display design, handling qualities, human factors studies and accident analysis. Topics include Head-Up Displays, Flight Control Systems, Flight Management Systems, Controller Pilot Data Link and Free Flight. In the beginning of 1998, he transferred to the human factors department and is now project manager of the NLR/NASA Free Flight project.
Rob Ruigrok graduated in 1992 at the Delft University of Technology, Faculty of Aerospace Engineering. He has been working at NLR's Flight Simulation department, on Flight Management Systems, Controller-Pilot Datalink, Take Off Performance Monitoring Systems, Windshear detection systems, Traffic Alert and Collision Avoidance Systems and Free Flight. Since two years he has been working in NLR's Flight Mechanics department on Free Flight and the integration of warning systems (terrain, traffic, weather) in the cockpit. He holds a Private Pilot Licence.
Ronald van Gent has studied aeronautical engineering at the Delft University of Technology where he received his MSc in 1987. After that he has been working in the area of Human Factors, first at TNO in Soesterberg, later in Amsterdam at the NLR. Main projects he was involved in were pilot-controller datalink studies and the Free Flight studies. In 1999 he has become the Human Factors department head at the NLR.

Free Flight

The Free Flight concept was designed to allow free routing. Self-optimisation by the airlines was thought to be more effective than a global optimisation by a controller [1]. One airline might give a higher priority to fuel instead of time depending on the schedule, company strategy or other factors only known to the airline and crew. Instead of flying along airways, it is clearly beneficial to fly direct only to divert from the great circle routes to take advantage of tailwinds. The resulting traffic pattern is chaotic. See figure below.

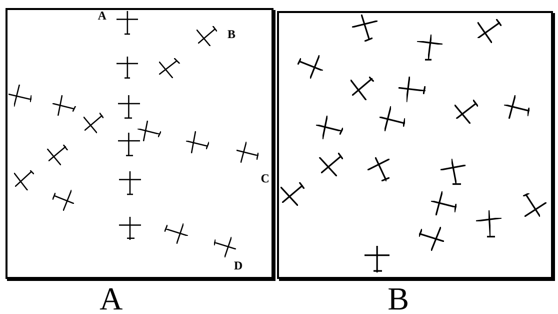


Figure 1 Schematic representation of how airways aid organization of traffic (A=airways, B=direct routing)

The lack of structure in the traffic pattern impedes ground-controlled separation when the traffic density is high. Especially when the aircraft also are free to fly at any altitude in between the normally rounded flight level values. This, together with the drive towards self-optimisation, formed the idea of airborne separation. The combined concept of free routing and airborne separation is now commonly referred to as “Free Flight”. Though a beautiful name for the concept, the freedom for the crew was in fact never the goal. Economic benefits because of more efficient flying were the main goal of Free Flight.

Air Traffic growth

Air traffic growth is predicted to grow exponentially with 5 to 6 percent per year[2]. Using the average density of upper airspace over Western Europe of 13 aircraft per area of 100 nm x 100 nm[3,4], the following table indicates the effect of this annual growth (using the conservative 5 percent). The number also is an indication of the number of aircraft under control of an en-route sector with this size, which is not uncommon.

Year	Number of ac per 100 x 100 nm	Experiment name
1997	13	'Single'
2000	15	
2005	19	
2010	25	'Double'
2015	31	
2020	40	'Triple'
2025	51	
2030	65	

If Free Flight would only be applicable for relatively low densities, it would hardly be worth the effort. After all, what we now call 'low density' airspace will become very scarce in the coming years.

Currently 75% of the delays in Europe are caused by en-route ATM problems. The year before it was only 30% of the delays. While traffic has only grown 5% over Europe, the delays have grown 40% [5]. This indicates the current en-route ATM system is saturated. This requires revolutionary measures. Introducing Free Flight is a such revolutionary measure. A gradual introduction of Free Flight might provide an evolutionary path to the mature Free Flight concept.

NLR Free Flight study

NLR has investigated the Free Flight concept in collaboration with NASA, the FAA and the RLD (Dutch Civil Aviation Authorities). The study started in 1997 and consisted of a number of substudies listed below:

- Conceptual Design
- Safety Analysis
- Scenario analysis and generation
- Man-in-the-loop experiment phase I
- Avionics requirements and reliability
- Critical conflict geometries
- Man-in-the-loop experiment phase II

Issues that have been addressed in these studies are:

- Conflict Detection & Resolution Methods
- Complex Conflict Geometries
- Pilot Workload
- Pilot Acceptability
- Display Symbology
- Safety (Both Objective & Subjective)
- Mixed Equipage Procedures

For the conflict detection and resolution module a state-based solution has been implemented. This means no flight plan data is used. The state-based conflict detection algorithm uses a look-ahead time of five minutes. The resolution algorithm uses the geometry of the closest point of approach instead of negotiation to prevent counter-acting manoeuvres. Both aircraft manoeuvre co-operatively. The calculated positions at the closest point 'repel' each other, similar to the way charged particles repel each other. This is why the method is often referred to as 'voltage potential'. The 'repelling force' is converted to a displacement of this predicted position in such a way that the minimum distance will be equal to the required separation. This avoidance vector is converted into advised heading and speed changes. The same principal is used on the vertical situation, resulting in an advised vertical speed. Initially no action of the other aircraft is assumed. This introduces a fail-safe element. Normally the conflict symbology will disappear halfway through the manoeuvre, indicating that no further avoiding action is required. The resulting manoeuvres are in the order a few degrees heading change or 200 feet per minute vertical. Passenger comfort is not affected by these shallow manoeuvres. This is very different from the traffic collision avoidance system TCAS, which uses a look-ahead time of only 45 seconds, resulting in drastic evasive manoeuvres.

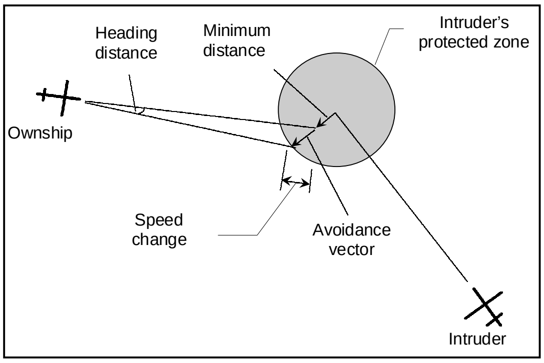


figure 2 Resolution advisory is based on geometry of Closest Point of Approach

Off-line traffic simulations comprising up to 400 aircraft simultaneously were used to validate several methods for conflict detection and resolution. This simulated traffic densities up to ten times today's average Western European density. The resolution method that proved to be most effective was based on a publication of Martin Eby [6]. Additionally, complex geometries and restrictions were used to test the robustness of the method.

This method has been developed further into an Airborne Separation Assurance System. This ASAS includes a human-machine interface that has been tested in several flight simulator trials. Airline pilots have been exposed to scenarios replicating current densities (‘single’) up to three times the Western European (‘triple’) density. It is worth noting that both density and conflicts were tripled resulting in a 9-fold increase in conflict rate. Training only lasted a few hours. No significant increase in workload has been found during the cruise phase. The acceptability was surprisingly high and, further, the subjective safety was equal or better than today’s situation.[7] (see figures below)

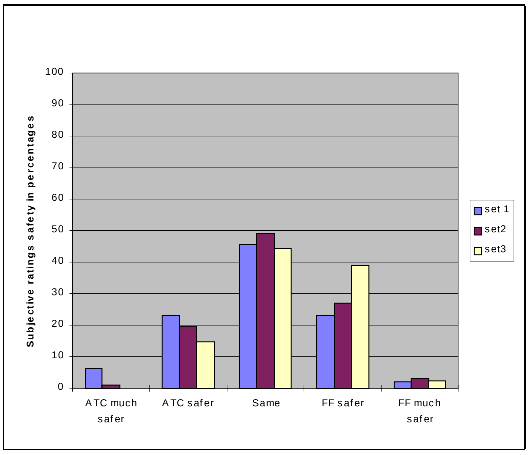


figure 3 Rating of safety by subject pilots in comparison with ATC for each set (1,2 or 3) of 6 runs in the experiment

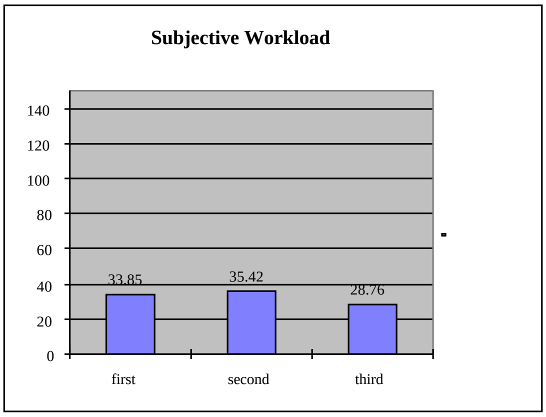


figure 4 Rating of workload on scale 0-130. The third sesion shows a workload rating very close to the '27' found for a comparable ATC situation

These results were obtained using a resolution method based on using position and velocity information only. No flight plan information, co-ordination procedures, priority rules nor ground based systems were used. An extra system called “Predictive ASAS” has been developed alleviating the need for exchanging flight plan information. Because of the simplicity of the architecture and the resolution method, the system was transparent to the crew, allowing a display design as shown in the figure. The display shows both a horizontal and vertical resolution advisory to the pilot, and he is free to choose one.

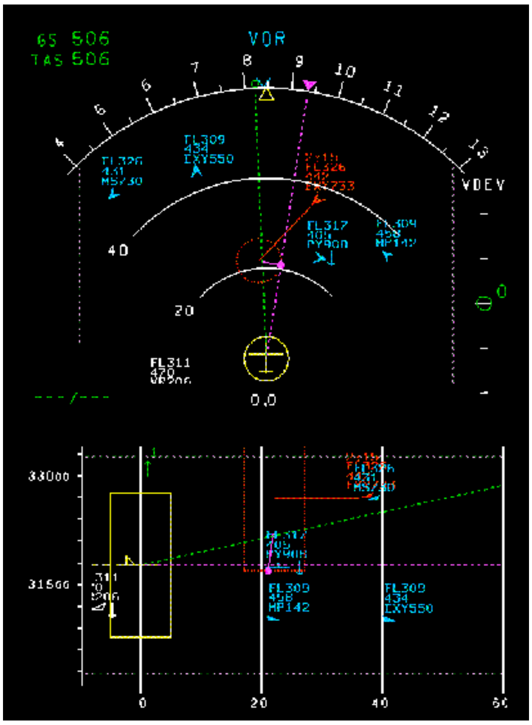


figure 5 Co-planar traffic display as used in the study. The symbology indicates a conflict (red) and the resolution advisory (magenta)

In summary, none of the sub-studies could refute the feasibility of airborne separation, even under extremely dense and constrained traffic situations.

Distrust in distributed system

When people, experts or not, are confronted with the Free Flight concept, the first reaction often is that it sounds like a dangerous idea. This probably is a result of the way human nature reacts to the chaotic nature of the traffic flow. Chaos is usually associated with danger. Throughout the NLR study the making of conflicts proved much harder than avoiding conflicts. In other words: a random, chaotic scenario, even using existing route structures was unlikely to have a lot of conflicts. In today’s traffic density, applying direct routing (horizontally and vertically) will result in a conflict rate of about once per 50 minutes per aircraft. A carefully, precisely constructed scenario was required to develop problems of the order of complex geometries like ‘the wall’ or the ‘super-conflict’ (see section on conflict geometries). These scenarios are much more orderly but also much more dangerous. The concentration of traffic at airways is also artificially increasing the local traffic density. Even though this increases the collision probability, this orderly pattern is reassuring to the human observer.

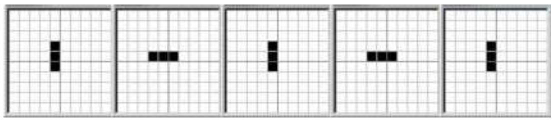
What is the reason for this distrust in chaos? This needs to be understood. The acceptance by aviation authorities, pilots, air traffic controllers and the public is required before the concept can further developed and gradually introduced. Apart from the conditioned negative association of chaos, there is a reason behind this reaction. The main reason is probably the unpredictability of a distributed system with this high level of interaction.

(Un)Predictability of a Distributed System

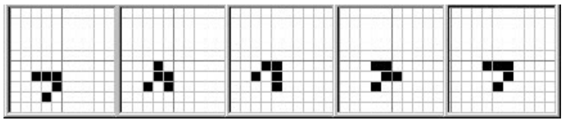
A one-on-one encounter can be analysed with some calculation and the manoeuvres as advised by the resolution algorithm can be derived and understood. To check all one-on-one situations already becomes harder since there are quite a lot of different possibilities with respect to the three dimensional position and three dimensional velocity of the aircraft. Still by sampling several initial conditions, it can be analysed with some accuracy.

However, the stability of a high-density traffic scenario really is a problem that is of a different order. This touches the field of mathematics called cellular automata [7], which deals with the maths of interacting units. A famous example of cellular automata is ‘Conway’s Life’[9]. This is a simulation in which every state is derived from the previous one with a fairly simple, discrete rule. It uses a two-dimensional matrix field consisting of cells. A cell is either dead or alive. By counting the number of living cells in the 8 neighbouring cells, the state of the cell in the next state is determined. If the total is 0 or 1, then the cells dies of ‘starvation’. If the number of living cells equals 2, the state of the cells remains the same (‘stable’). If the total is 3, then a new cell originates independent of the previous state (‘growth’) and the total higher, thus 4 to 8, results in the death of the cell due to being ‘overcrowded’. This rule is much simpler than a geometrical conflict resolution rule. However it yields some surprising higher order effects. Some examples are shown in the figures in the next column.

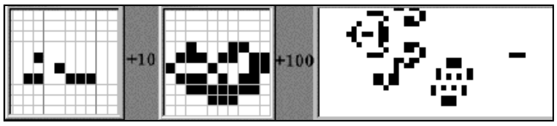
The ‘windmill’ of three cells is easy to understand. The ‘floater’ of only 5 cells moves one cell up and one cell left in five steps. This is something that is already a consequence not easily seen from the simple rule above. In fact, most patterns have been discovered in random patterns instead of being designed. The ‘acorn’ illustrates the effect of a structure of only seven cells after ten and after another hundred iterations.



‘Windmill’



‘Floater’



‘Acorn’

figure 6 Examples of Life patterns and their evolution: the flipping 'Windmill', still quite predictable, the ‘Floater’, that moves up and left in four steps, and the 'Acorn', showing an explosive growth and complexity from a relative simple starting pattern

This Life program that was often used as a screen saver in the old days of computing, is an analogy of how an extremely simple mathematical formula or law of nature can result in fantastic unforeseen effects. It has some philosophical aspects, which are not relevant here. But the behaviour of these patterns has puzzled mathematicians for decades and still there is no theory available that describes the phenomena shown above. Even logical AND, OR and NOT ports have been built (or discovered) in Life. This means at a large Life-field a complete computer can be built using these cells, while at the low level the simple rule still applies. It is a dramatic illustration of the magnitude of the challenge to analyse the behaviour of a distributed system.

A traffic pattern using a Free Flight conflict resolution algorithm is not a discrete, but a continuous system, with a geometric interaction as well as scheduling and reaction time effects. The traffic patterns are therefore much more complex than the already complex discrete Life example. Consequently , it is right now and will be for a long time impossible to guarantee the stability or risk associated with the behaviour of a large number of aircraft in any configuration. The characteristics of an aggregation level below the behaviour of the pattern, for example a pre-scripted one-on-one conflict is more predictable. The large-scale effects of traffic patterns can only be studied using simulations. The risks of introducing a distributed system can only be analysed by comparing the effect of the change in structure between a centrally controlled system and a distributed system.

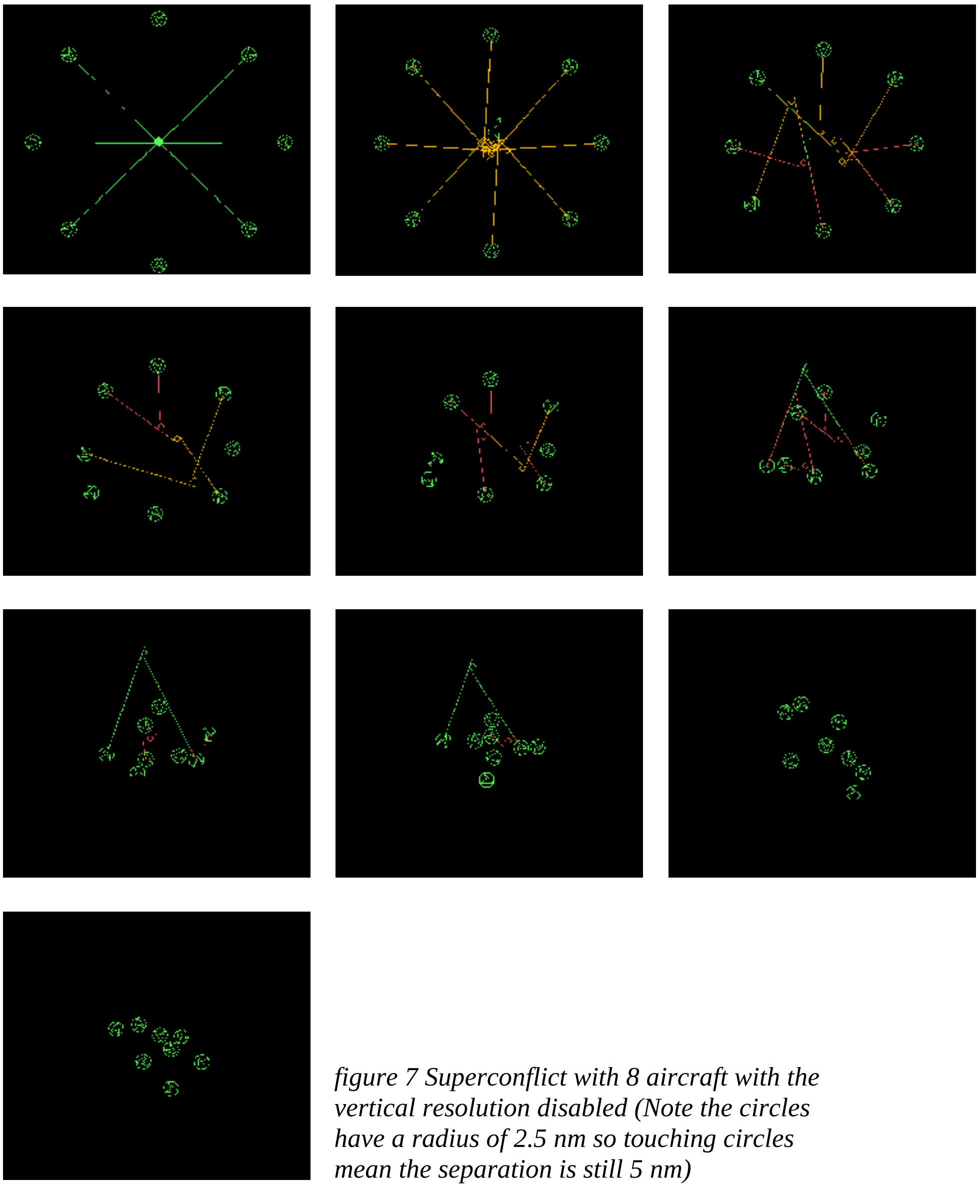


figure 7 Superconflict with 8 aircraft with the vertical resolution disabled (Note the circles have a radius of 2.5 nm so touching circles mean the separation is still 5 nm)

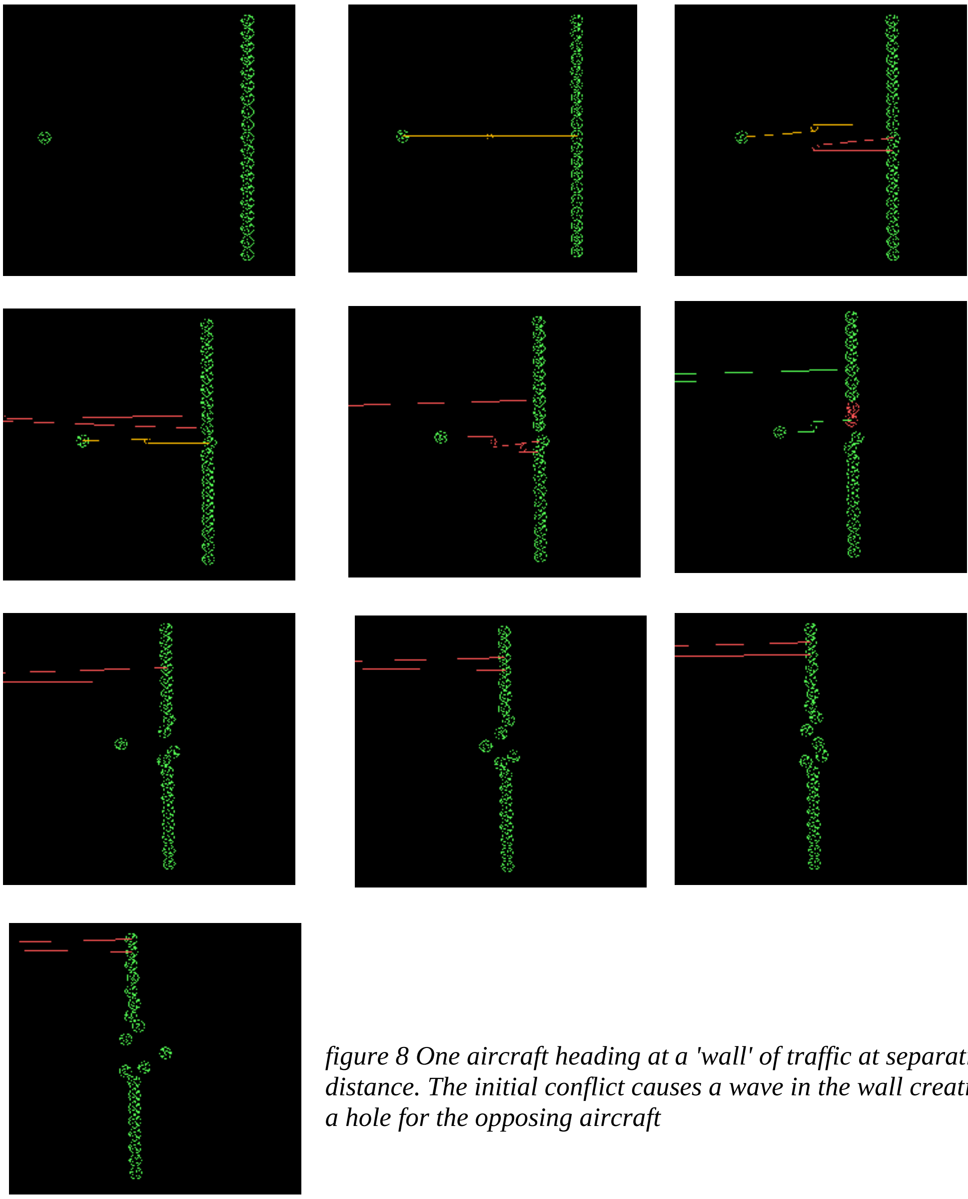


figure 8 One aircraft heading at a 'wall' of traffic at separation distance. The initial conflict causes a wave in the wall creating a hole for the opposing aircraft

Complex Geometry Examples

To investigate the robustness of the system several critical scenarios have been developed using the off-line traffic simulator (‘Traffic Manager’). This program is able to simulate up to 400 aircraft simultaneously on a PC or workstation. A demo version is downloadable from internet at the NLR Free Flight Website [10]. The aircraft models contain performance models of more than 200 types, a flight management system, pilot models and airborne separation assurance systems (ASAS). It is possible to view the overall situation on a map, but it is also possible to watch a traffic display of one aircraft with all the navigation data and resolution advisories. With this program, critical conflict geometries have been tested. The algorithms already contained the exception handlers required for singularities like the exact head-on collision, as well as filters preventing conflict alerts from turning aircraft far away. However, the effect of large-scale pattern can only be investigated with simulation. Two examples are shown in the figure 7 and figure 8. The aircraft symbols are circles with a diameter of 2½ nautical miles, equal to half the required separation. This means the circles are allowed to touch but not overlap.

The ‘super conflict of order eight’ consists of eight aircraft all flying at the same flight level, with the same speed towards the same point in space and time. Normally this type of conflict is resolved with a vertical manoeuvre, which is quick and efficient. In this case we have disabled that possibility in the pilot models and forced the pilot models to stay at the same altitude. After some initial conflict alerts the situation solves itself very quickly. It is a clear illustration of the power of a parallel system: the overall picture contains several conflicts at the same time. Per aircraft, the number of conflict is quite low. All actions take place at the same time in a way that could never result from one central controlling node.

In the ‘horizontal wall’ scenario, again vertical resolutions are inhibited. Though every aircraft follows its resolution advisories, a global solution to the problem arises. Some aircraft decelerate slightly while others accelerate. This will yield space to the left and right to manoeuvre. The wall wrinkles to make a hole in the centre for the opposing aircraft to pass through. A similar effect is seen in the three-dimensional version of this scenario. However, when switching on the noise models (including ‘noise’ in the pilot models), causes different variants of the scenarios, the same principles appear in every scenario.

A variety of these scenarios have been tested to investigate the robustness. Most can be viewed as analogies of extremely limited airspace. One of the striking results was that the ‘voltage potential’ algorithm divides the available airspace equally among the aircraft. If this means that there is no space for 5.0 nautical mile separation, it will become 4.9 nautical mile for all aircraft. This graceful degradation is preferable over an algorithm that would just ‘give up’ and display an ‘Unable to maintain separation’ message.

The densities required for the several phenomena seen in the critical geometries study, such as the wall, are unrealistically high. Even in scenarios with ten times the current densities, excessive number of traffic encounters were not observed.

Robustness & Redundancy of a Distributed System

The conceptual design of the NLR Free Flight concept uses an algorithm, which initially assumes the other aircraft does not manoeuvre but is based on co-operative manoeuvring in the end. Instead of using priority rules or risky negotiation cycles, the geometry ensures a co-operative conflict resolution. For this concept to fail, two conflict detection and resolution modules need to fail and not just any two, but two of aircraft that will have a conflict. For the reliability, this means failure rates are squared. There are two effects:

1. **Higher robustness than a central system** – compared to a central system where only one failure of the central node (e.g. the ATC computer) is a problem for any conflict of any two aircraft in the sector (macro effect robustness)
2. **Higher reliability** – The failure probability is squared as result of the co-operative manoeuvring. This means that when the airborne equipment is just as accurate and reliable as the ground equipment, and there is no reason why it should not be, the collision probability is squared (so it becomes for example 10^{-18} instead of 10^{-9}). This also means the ASAS should receive and transmit independently, to have completely separated decision loops. (micro effect robustness)

When both the transmitting and receiving function of the data fail, the aircraft becomes blind and invisible at the same time. There are several safety nets, which could take over. First of all, the transmitting and receiving functions should be separated completely, even for the power supply or battery. On top of that, this system becomes critical and should be made redundant by using two or three systems. If they all fail, there still is the voice radiotelephony to broadcast the global position while exiting the Free Flight airspace. If there is a ground station with a TIS-B (Traffic Information System – Broadcast) available, it could transmit the radar data to make sure the aircraft is visible on the traffic displays of the other aircraft. While leaving the Free Flight airspace, the last received position and velocity vectors of the aircraft could be extrapolated on the display to enhance the situational awareness for this short time. And if all this fails, the TCAS collision avoidance system, which is independent of the ASAS, could prevent collision and maintain a certain separation.

Effective Conflict Rate for Air and Ground

The higher capacity of Free Flight compared to the current en-route ATC system can be shown when looking at a direct routing scenario. Suppose the probability of two aircraft having a conflict when flying a direct route in a sector is p_2. This is independent of traffic density and whether the separation task is on the ground or in the air. The global conflict probability as a function of the number of aircraft N in a sector can be calculated assuming p_2 is known. It is the product of the number of combinations of two aircraft times the probability of conflict between two aircraft:

$$p_{c_{ground}} = \binom{N}{2} p_2 = \frac{N!}{(N-2)!\,2!} p_2 = \tfrac{1}{2} N(N-1) p_2 = \tfrac{1}{2} N^2 p_2 - \tfrac{1}{2} N p_2$$

When N increases, as traffic grows, the probability, and therefore the effective conflict rate as experienced by the controller, increases quadratically with the number of aircraft in the sector.

For the airborne conflict probability this is different: it is simply the product of the number of aircraft with the probability of meeting that aircraft. The number of other aircraft is $(N - \mathbf{1})$ so the formula becomes:

$$p_{c_{air}} = (N-1) p_2 = N\, p_2 - p_2$$

This probability and the perceived conflict rate increase linearly. The probabilities are equal for $N=2$, in this case any conflict is also perceived by all (both) aircraft.

For the European airspace the conflict rate for single density (N=13, see table) proved to be once per 50 minutes per aircraft. This yields an example p_2:

$$p_{c_{air}} = (13-1)\, p_2 = \tfrac{1}{50}\ \ {}^{1}\!/_{\min} \quad \Rightarrow \quad p_2 = \tfrac{1}{600}\ \ {}^{1}\!/_{\min} = 0.1\, {}^{1}\!/_{hour}$$

The difference between the curves is shown in the figure below. Compare the number on the x-axis with the table of the traffic growth to see the effect of time.

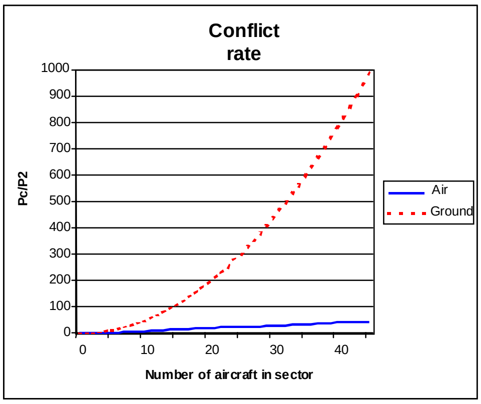


figure 9 Relation number of aircraft N in a sector and perceived conflict rate for air (pilots) and ground (controller)

From this figure, one can observe the effect of the increasing traffic on the central and the distributed system. Traffic growth probably will make Free Flight more acceptable over time. Other measures as improving the ATC user interface or decreasing sector size will only change the slope of the curve but not the quadratic nature.

Conclusion

The traffic growth is responsible for a dramatic increase of delays. Recent numbers indicate 75% of these delays are caused by en-route ATC. Radical measures are required. Free Flight could provide a solution by changing the structure of the system from a centrally controlled system to a distributed system.

For any change, stronger arguments are required next to the fact that a possibility could not be refuted. When faced with the concept of Free Flight, confidence with respect to safety is required. The nature of a distributed system with the high amount of geometric interaction, may need the application of innovative safety case building and safety management techniques. Also sample cases with complex conflict geometries can be studied by simulation. Because the change is more fundamental than an equipment change, this is only a partial answer. Comparing the structure and the nature of the ATM system is equally, if not more, important.

These comparisons indicate that when the technology in the air is equally reliable as on the ground, the distributed Free Flight ATM concept features a safety and airspace capacity that is magnitudes higher than the current en-route ATM system in spite of the apparent chaotic traffic pattern. In other words: better a safe chaos, than a dangerous order.

Abbreviations

ADS-B	Automatic Dependent Surveillance Broadcast
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATM	Air Traffic Management
FAA	Federal Aviation Administration
FMS	Flight Management System
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NLR	National Aerospace Laboratory (Dutch)
RTCA	Radio Technical Commission for Aeronautics
TCAS	Traffic Collision Avoidance System
TIS-B	Traffic Information System - Broadcast

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