Initial Results of Investigation into Autonomous Aircraft Concept (FREER−1)

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Vu N. Duong, Eric Hoffman, Jean−Pierre Nicolaon

EUROCONTROL Experimental Centre

BP 15, F.91222 Bretigny−sur−Orge, France

Abstract

Recent advances in air traffic Communication Navigation and Surveillance (CNS) have encouraged investigations into the concept following which Air Traffic Control functions can be delegated to the flight deck, allowing more freedom of movement to airspace users. In late 1995, an initiative, known under the project name FREER, for Free−Route Experimental Encounter Resolution, was introduced at EUROCONTROL to investigate the feasibility of this concept.

In this paper, we present the initial results obtained from the Autonomous Aircraft Operations study (FREER−1) that targets full delegation of ATC to aircraft operating in low−density airspace. Specific issues of Autonomous Aircraft Operations (AAO) supporting free−route, free flight and user−preferred routing are discussed. A description of the current prototype illustrating the Airborne Interactive Conflict Resolution Advisory service is included.

1.Background

Recent developments in Satellite−based Communication Navigation and Surveillance (CNS) have revealed high potential of the Automatic Dependent Surveillance Broadcast (ADS−B) technology. The combination of the capability of ADS−B and data link technology provides the technological support for pursuing research and developments into future Air Traffic Management system.

In late 1995, an initiative, known under the project name FREER, for **F**ree−**R**oute **E**xperimental **E**ncounter **R**esolution, was introduced at the EUROCONTROL Experimental Centre (EEC) to investigate the feasibility of the concept following which ATC functions could be delegated to the flight deck to:

- Allow more freedom of movement to airspace users,
- Support the implementation of Free Flight, Free−Route and User−Preferred Route concepts, and to
- Involve airspace users in the ATM loop.

It was assumed that such a concept could allow airlines to reduce operating costs; to increase efficiency; and that could enable higher capacity, as well as greater safety in poorly controlled airspace. This concept can potentially respond to the future growth in air traffic demand, and can be one of the promising options for the implementation of the ICAO Global Navigation Plan for CNS/ATM [3], and of the European EATMS [1].

Background

Based on the spectrum of autonomy that can be granted to airspace users, FREER considers three generic operational modes as shown in Figure 1:

- Ground−based Centralised Control,
- Ground−Air Co−ordinated Control, and
- Airborne Autonomous Control.

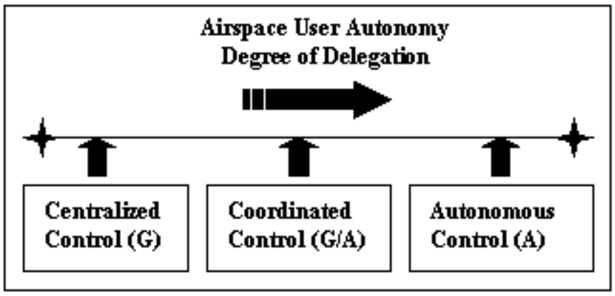

Figure 1 − Generic Operational Modes considered in FREER

Given these three generic modes, the objective of the FREER project is to investigate the feasibility of the:

1. *Airborne Autonomous Control mode* — ATC and Trajectory Management functions are <u>fully</u> delegated to the flight deck for operations in low−density airspace (**FREER−1**),

1. *Transition from the Centralised Control mode to the Ground−Air Coordinated Control mode*. In this mode, ATM activities are only <u>partially</u> delegated to the FREER−1 capable aircraft to operate in high−density airspace (**FREER−2**).

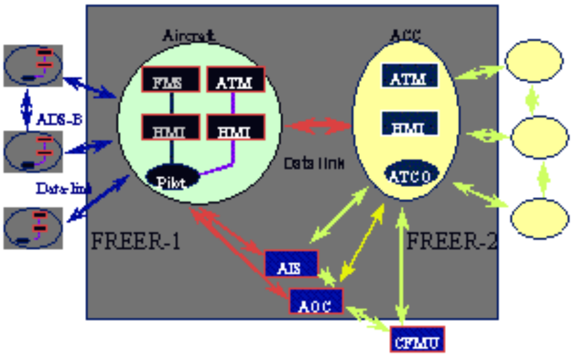

Figure 2 − Overview of FREER Objectives

The expected results of the FREER study include industrial requirements for a CSN/ATM system that satisfies the operational requirements of ICAO CNS/ATM [3]; of IATA Future Air Navigation System [4]; and of the EATMS OCD targets [1], *i.e.*, the capability to:

- Maintain and, where possible, enhance safety in future traffic growth.
- Allow maximum freedom of movement to airspace users.
- Provide users with a high degree of flexibility for flight operations.
- Fulfil the IATA Human−Centred Automation requirements [4],

In this paper we will only discuss the initial results of our investigation into the Aircraft Autonomous Control mode within the frame of the FREER−1 study.

2. The Autonomous Aircraft Concept

The Autonomous Aircraft concept was first introduced in 1993 by the European Union’s ATLAS study [2]. It is assumed that this concept allows maximum freedom of movement to airspace users. As a consequence, within the airspace where the autonomous control is granted, airspace users are responsible for the safety of flight while ATC service providers are only responsible for providing infrastructure, traffic information, contingency procedures, and search and rescue. In FREER, the term *Autonomous Aircraft Operations* (AAO) is used to represent the Airborne Autonomous Control mode, and the so−called Autonomous Aircraft concept.

The five operational components of the generic operational modes, *i.e*., Airspace Regime (AR), Flight Management (FM), Separation Assurance (SA), Demand Capacity Balancing (DCB), Airspace Allocation (AA) are shown in Table 1.

	AR	**FM**	**SA**	**DCB**	**AA**
Centralised (Ground)	Fixed−Route	ExternallyManaged	Centralised	Global	Strategic
Coordinated (Ground/Air)	User−Preferred	Distribut−ed G/A	Cooperated	Global	Strategic & Tactical
Autonomous (Air)	Free− Route	Self−Managed	Airborne + EFR	Local	Tactical

Table 1: Component Scenarios for the three Generic Operational Modes.

In FREER, the scenarios for the five operational components considered for Autonomous Aircraft operations (FREER−1) are as follows:

1. Airspace Regime: FREER−1 will be operating in low−density airspace or where ground infrastructure is not, or only partially, available. In the ECAC core airspace, FREER−1 operates in the Free−Flight Airspace (FFA) of the EATMS airspace regimes [1], as shown in Figure 3.

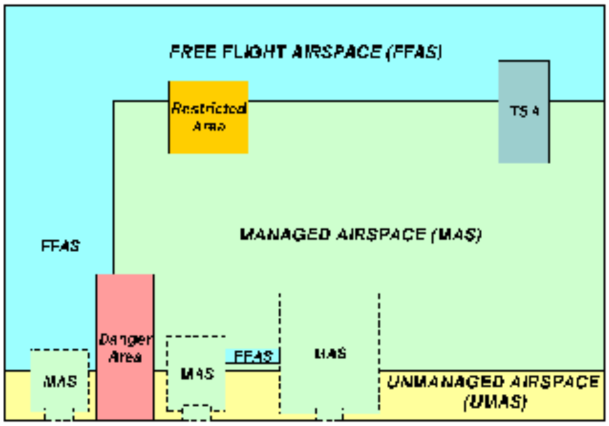

Figure 3 − EATMS OCD Airspace Regimes

2. Flight Management: the management of the trajectory or flight path of a single aircraft remains under the control of airspace user under the flight rules applied to autonomous aircraft operations [2]. In this scenario, the aircrew is responsible for the selection, implementation and monitoring of the trajectory. However, in terminal areas (TMAs), it is unlikely that trajectory management can be performed without clearance from ground ATC. The responsibility for managing the transition to such TMAs and to the airspace of adjacent States would remain with the aircrew who would have to obtain and observe the necessary clearance. (This point is covered by FREER−2 and is consistent with the airspace regimes considered since most TMAs are in the Managed Airpace.) In this scenario, the transition to the Managed Airspace is considered.

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[1] EATMS Airspace Regimes [1]: Managed Airspace (MAS) assumes (a) known traffic environment, (b) 2D / 3D / 4D networked− or free−route, (c) separation responsibility on the ground. Free Flight Airspace (FFA) assumes (a) known traffic environment, (b) free−routing and autonomous operations, (c) separation responsibility in the air. Unmanaged Airspace is similar the today’s uncontrolled airspace.

[2] Flight Rules for Autonomous Aircraft operations, namely Extended Flight Rules (EFR) will be discussed in Section 3.2.

3. Separation Assurance: In Autonomous Aircraft operations, the aircrew is responsible for separation assurance activities according to the flight rules associated with the airspace regime mentioned in point (1). The key distinction between the Autonomous Aircraft and the current VFR rules is in the sotisphication of the systems and procedures used to ensure separation minima are not infringed. In term of procedures, we proposed the *Extended Flight Rules* (EFR) to be applied to encounter resolution in the autonomous or Free Flight airspace regime (FFA). In terms of systems, there would be a stringent Minimum Aircraft System Performance (MASP) that could dictate the requirements for aircraft flying in autonomous control mode. Such a system is often referred to as an *Airborne Separation Assurance System* (ASAS).

These two topics will be discussed as part of the initial results obtained from the FREER−1 study.

4. Demand Capacity Balancing: The users would also be responsible for the adaptation of demand to capacity. An onboard system, which could be different from the Airborne Separation Assurance System (ASAS), would be needed to provide the users with forecasts of:

- capacity and demand,
- ratio of capacity to demand for the critical resources such as airspace, airport runways, *etc*.

This system, in FREER−1, is part of the *Situation Assessment System* (SAS), an optional advisory system that will be discussed elsewhere. The input to SAS includes the intent information that can be obtained via ADS−B and/or Data Link.

5. Airspace Allocation: In normal operations, the Airline Operating Centres (AOC) would allocate the flight profile in advance so as to fit with the slots and airspace allocated by the flow management unit. This pre−allocation would probably be adjusted just before take−off to take into account dynamic information such as weather and, if necessary, change in airspace regime and/or active military airspace. Successive iterations would be carried out during the flight to adapt to the actual situation and to deliver airspace which is conflict−free, at least for the following few minutes. Airspace allocation within the context of autonomous aircraft operations can be seen as a tactical adjustment of flight profile, made by the airspace users *i.e.,* Airline Opearting Centres and aircrew. This operation can be performed upon the information about the current and expected airspace regime, external factors such as weather, expected traffic density *e.g.*, congested airspace, active military airsapce, and an assessment of the current situation.

This point is also part of the Situation Assessment System.

In summary, the Autonomous Aircraft Operations in FREER−1 are placed in a context where:

- The airspace regime is the EATMS Free Flight Airspace (FFA) [1] or similar, with associated rules of the air called Extended Flight Rules (EFR) [8].
- Changes in trajectory or flight path are managed by airspace users in accordance with the EFR and procedures. This point is discussed in Section 3.2.
- Responsibility for separation assurance lies with the pilots, obeying EFR and procedures [3]. An Airborne Separation Assurance System (ASAS) is required for aircraft flying autonomously in a delegated airspace regime. This point is discussed in Section 3.3.
- Demand capacity balancing and airspace allocation are tactical operations, handled by the aircrew with the assistance of its AOC. A Situation Assessment System (SAS) is optional, but recommended.

[3] Note that inter aircraft coordination would be very complex in case of encounters involving more than 2 aircraft, and in case of large clusters. Flight Rules should cover the coordination.

In timewise order, Autonomous Aircraft operations in FREER are placed in a safety net in which the last layer is TCAS/ACAS. The ASAS component will be acting with 6 to 8 minutes ahead of TCAS and is independent from TCAS. The ground−air coordinated part (FREER−2) will be handling encounters with a 15 to 20 minute look−ahead time. On top of FREER−2 there will be tactical flow control, aiming at precluding exececessive traffic density.

In terms of complexity handling, this safety net will operate as successive filters: The tactical flow control will take care of congested airspace; FREER−2 will deal with encounters involving large number of aircraft (5 to 10 or more); the airborne side (FREER−1) with the Demand Capacity Balancing and Airspace Allocation scenarios will assist in avoiding overly complex encounters. Only encounters involving up to 4 aircraft will be handled by the ASAS. TCAS will be triggered when a conflict is unsolved less than 1 minutes to loss of separation. Figure 4 shows the operational scenarios envisioned in FREER:

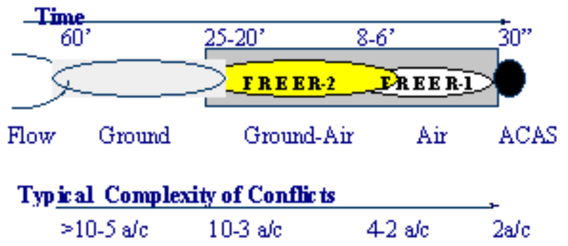


Figure 4 The Safety Net establishing operational scenario components for Autonomous Aircraft and Ground-Air Co-ordinated Operations. Time order for Separation Assurance, and Filters of Complexity of Conflicts (DCB and Airspace Allocation).

3. Initial Results of FREER−1

The main focus of FREER−1 during the first phase was on:

1. The technical feasibility of *ADS−B and Data Link* technologies for Autonomous Aircraft Operations.
2. The rules of the air as well as the procedures to be applied in Autonomous Aircraft airspace regimes. We call these rules *Extended Flight Rules* (EFR).
3. The *Airborne Separation Assurance System* (ASAS).

In the following sections, we discuss the initial results.

3.1 CNS Requirements for AAO

The challenge of the FREER project is to make the right assumptions about the future CNS technology and to use these assumptions as the constraints to satisfy user requirements for free−routing and/or user−preferred routing with human decision−makers.

Tightly dependent on ADS−B and data−link technological constraints, the project is developed with the following assumptions:

3.1.1 ADS−B and Data Link for EFR

The rules of the air to be applied in Autonomous Aircraft Operations require the exchange of information as a means to:

- coordinate actions between aircraft,
- apply the procedures when changing trajectory,

Two types of broadcast message are required:

1. Broadcast of intention of change,
2. Identified constraints on the current trajectory (*e.g.*, encounters, congested areas, *etc.*),

Two types of data link message are required:

1. Acknowledgement of reception and priority,
2. Free text.

3.1.2 ADS−B and Data Link for ASAS

The surveillance data input to FREER come principally from ADS−B messages. The project assumes that ADS−B range is about 120−150 NM from the emission aircraft.

With respect to the level of equipment, the project assumes that *tactical information* (of the RTCA MASPS for ADS−B [6]) is required for all aircraft. In other words, the following data types are assumed to be included in ADS−B messages:

A/C IDENTIFICATION	CALL SIGN CATEGORY ADDRESS
STATE VECTOR	POSITION ALTITUDE SOURCE OF ALT. (GNSS, BARO) POSITION UNCERTAINTY CAT. VELOCITY VECTOR
TACTICAL PARAMETERS	TRAJECTORY CHANGE POINT TURN RATE TARGET ALTITUDE EMERGENCY/PRIORITY STATUS

The Velocity Vector includes:

- Horizontal Velocity Vector
- Vertical rate
- Velocity Uncertainty Category (VUC)

Trajectory Change Point (TCP) may or may not correspond to a flight plan way−point, and includes:

- Three− dimensional position,
- Horizontal velocity vector outbound from the TCP,
- Target altitude (of the change),

Following RTCA MASPS for ADS−B [6], an aircraft issues TCP data at least 2 minutes prior to commencing a trajectory change. In the event of an immediate trajectory change, TCP data is issued immediately. If a subsequent TCP will occur in fewer than 2 minutes, a Next +1 TCP data set is also issued with the initial TCP.

The data link allows additional trajectory information *i.e.*, all TCP in a range of 150NM, to be made available to other aircraft upon automatic triggering.

Data link messages will be triggered or not depending on the trajectory information contained in ADS−B tactical parameters. Three cases are identified:

1. The next TCP of an intruder aircraft is at a distance greater than 150NM from its position when it enters the 150NM useful radius of the ADS−B receiver of an aircraft: No data link necessary.
2. The next TCP of an intruder aircraft is at a distance between 75NM and 150NM from its position when it enters the 150NM useful radius of ADS−B receiver of the aircraft: address data−link request must be made automatically to other aircraft to obtain further TCP so that the trajectory can be reconstructed for at least 150 NM ahead.
3. The next TCP of an intruder aircraft is at a distance of less than 75NM from its position when it enters the 150NM useful radius of ADS−B receiver of the aircraft: Data−link is not mandatory but can be invoked if necessary (decision to be made by Pilot).

Our initial assessment with simulated current Europe core area traffic running on our Airborne Separation Assurance System (ASAS) prototype shows that:

Background

a) ADS−B range of 120−150 NM is largely sufficient. ADS−B useful radius of 90 NM shall be the minimum requirement.

b) With VHF−based ADS−B [12], it is possible to include the *tactical parameters* as well as the additional TCPs for the next 120−150NM. It is likely that the normal update rate of broadcast of ADS−B tactical parameters is every 2 minutes if no change in trajectory occurs. The two minute update rate allows optimal prediction of future positions.

c) Data Link messages in VDL mode−4 can allow upto 63 ASCII characters in free−text mode. This point−to−point data link can transport upto 4 unencoded TCPs. An assessment of Manchester airspace showed that for 10 minutes look ahead time, an average of 6 TCPs is needed for short flights (under 60 minutes) in fixed−route.

3.2 Extended Flight Rules

3.2.1 Objectives and Requirements

The ultimate purpose of the Extended Flight Rules (EFR) is to assign the priority to aircraft in encounters during autonomous aircraft operations, *i.e.*, to identify which aircraft should give way or manoeuvre to avoid a separation infringement; how (*i.e*., by which procedure) and when a manoeuvre should be executed.

In this context, pilots are responsible for the resolution, which must solve the encounter, and are given the freedom to select the trajectory that best fits with the economics of the flight while maintaining the required safety level.

The background requirements, which underlie the EFR supporting on−board autonomous encounter resolution, are:

1. **Complexity Handling**: EFR shall be able to identify priority to manoeuvre for encounters involving more than two aircraft. It is necessary to employ a strategic view to minimise the knock−on effects on multiple encounters. Current safety levels must be maintained or enhanced in all cases.
2. **Economy**: EFR shall not contradict economics of flight operation, *i.e.*, the rules shall offer the best economy for all aircraft concerned. Following the free flight and free−route concepts, and in order to allow modern aircraft to achieve their optimal economy, it is necessary to allow them to fly at their preferred flight level and to perform avoidance manoeuvres in their preferred manner. It is necessary to employ a strategic view to avoid short terms solutions, which can be costly in fuel, and/or in deviation time.
3. **Clearness**: EFR shall be developed with parameters that are simple, clear and concise to the airspace users. All rules shall be consistent with the others, and exceptions shall be minimised if not avoidable. EFR shall be an extension to current VFR; therefore EFR shall accommodate VFR as much as possible.
4. **Capacity**: Application of EFR to encounters shall not imply a decrease in capacity, *i.e*., it shall favour application of Reduced Separation Minimum Standards.
5. **Best use of Communication Technology**: Communication amongst the aircraft will be part of the decision making process. It will also be used for acknowledgement and/or confirmation of the actions to be taken. Inter−aircraft communication shall not be abused, *i.e*., it shall be used when and only when necessary.

3.2.2 The EFR Rules & Procedures

A review of the Visual Flight Rules (VFR) and the ATLAS Autonomous Flight Rules (AFR) can be found in [8]. The Extended Flight Rules proposed herein are an extension of VFR and AFR. EFR take advantage of the surveillance data available in the flight deck to better consider the economics of flight operation as well as the freedom of the pilots to manoeuvres which avoid separation infringements.

EFR cover the procedures to be applied in airspace regimes for autonomous aircraft operations, and defines the priority of aircraft involved in an encounter without dictating how an aircraft shall manoeuvre to avoid the encounter.

EFR procedures consist in defining how a change in trajectory shall be made. Basically:

Proc.1 An intention of change in trajectory shall be broadcast at least 30 seconds prior to the manoeuvre.
Proc. 2 A new trajectory shall be conflict−free within the useful radius of ADS−B, i.e., about 120 to 150 NM.
Proc. 3 When an encounter occurs, the following procedure shall be engaged:
3.1 Encounter must be acknowledged at the latest at 7 minutes to encounter (first point of loss of separation minima).
3.2 The execution of the EFR rules will assign priorities to aircraft involved in the encounter. The identified priority must be acknowledged at the latest at 6 minutes to encounter.

3.3 Once the priorities are identified, intention to change trajectory, *i.e.*, *new trajectory information must be broadcast at the latest at 4 minutes to encounter.*

3.4 Effective manoeuvre can only be engaged 30 seconds after the broadcast of the new trajectory. (Cf. Procedure 1). The strategy of EFR for priority assignment is to consider:

1. the **manoeuvrability** [4] of each aircraft involved in the encounter, then
2. the **availability** [5] of each aircraft in its current flight phase, then
3. the **distance to the encounter** [6] of each aircraft

The weights of the manoeuvrability and the availability are defined according to the phase/sub−phase of flight under which the aircraft is operating. The details of these factors are described in [8].

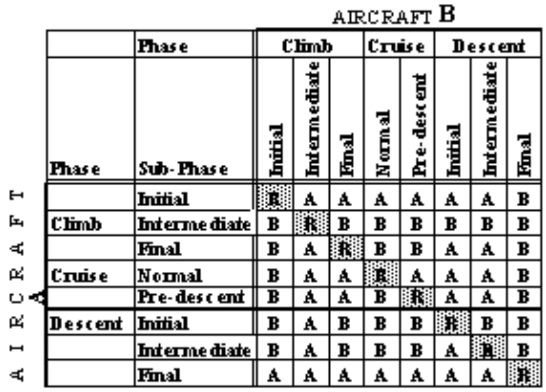
It is believed that this strategy allows the application of the same rules to encounters involving more than two aircraft.

The EFR set consists of the following rules:

Rule 1 When an encounter occurs between aircraft in normal operation, and which are in the same phase and sub−phase of flight, the aircraft furthest from the first point of loss of separation must give way to the one closer.

If the distances to the first point of loss of separation are equal for aircraft involved in the encounter, priority is calculated from the addresses of the aircraft transponders. The algorithm to calculate the priority is to be defined and approved by ICAO.

Rule 2 When an encounter occurs between two aircraft in normal operation, and which are in different phases of flight, priority is assigned according to the following table:



AIRCRAFT B

		Phase	Climb			Cruise		Descent		
	Phase	**Sub-Phase**	**Initial**	**Intermediate**	**Final**	**Normal**	**Pre-descent**	**Initial**	**Intermediate**	**Final**
AIRCRAFT A		**Initial**	R	A	A	A	A	A	A	B
	Climb	**Intermediate**	B	R	B	B	B	B	B	B
		Final	B	A	R	B	B	A	A	B
	Cruise	**Normal**	B	A	A	R	A	A	A	B
		Pre-descent	B	A	A	B	R	A	A	B
	Descent	**Initial**	B	A	B	B	B	R	B	B
		Intermediate	B	A	B	B	B	A	R	B
		Final	A	A	A	A	A	A	A	R

Table 2: Priority Assignment Lookup Table summarising the calculation of priority using the weights of the manoeuvrability and availability associated to flight phases. A and B means the priority is given to A or B respectively. R means the distance-to-encounter rule (Rule 1) must be applied.

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[4] The manoeuvrability of an aircraft is its ability to manoeuvre laterally with respect to the phase/sub−phase of flight.

[5] The availability of an aircraft represents the navigational constraints associated with its trajectory in the flight phase.

[6] The distance to the encounter is the distance from the current position to its position at the time at which separation minima are infringed.

[7] In other words, the aircraft that has higher speed must give way to the slower which is consistent with VFR.

Rule 3 For encounters involving more than 2 aircraft, the priority can be calculated as follows:

3.1. The aircraft that has higher manoeuvrability should give way to that which has lower manoeuvrability.

3.2. If the manoeuvrability of all aircraft are equal, then the aircraft that has higher availability should give way to the one(s) that has (have) lower availability.

3.3. If all aircraft involved in the encounter are flying at the same phase of flight, Rule 1 applies, *i.e.*, priority is given to the ones that are closer to the encounter.

Rule 4 When a lower category of operation encounters a flight of higher priority of operation, it would give way to that flight. The categories of operations as well as the associated priorities are listed in the Table 3, in decreasing order of priority:

3.3 Freer−1 ASAS Prototype

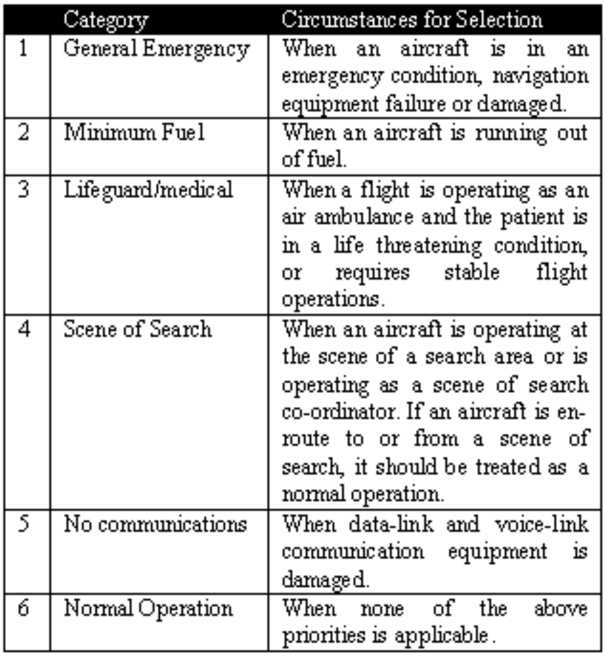
So far, a prototype of FREER−1 airborne separation assurance system has been developed on a cockpit simulator, integrated with an experimental Flight Management System to illustrate the concept.

On this prototype, a Cockpit Display of Traffic Information (CDTI) capability and a Traffic Situation Display (TSD) capability were developed and integrated into the aircraft Navigation Display. Conflicting scenarios were developed to illustrate the appropriateness of the concept.

FREER−1's approach to ASAS in Autonomous Aircraft airspace regimes is:

- Human−Centred Automation:

=>The users are the masters of the situation, not the system.



	Category	Circumstances for Selection
1	General Emergency	When an aircraft is in an emergency condition, navigation equipment failure or damaged.
2	Minimum Fuel	When an aircraft is running out of fuel.
3	Lifeguard/medical	When a flight is operating as an air ambulance and the patient is in a life threatening condition, or requires stable flight operations.
4	Scene of Search	When an aircraft is operating at the scene of a search area or is operating as a scene of search co-ordinator. If an aircraft is en-route to or from a scene of search, it should be treated as a normal operation.
5	No communications	When data-link and voice-link communication equipment is damaged.
6	Normal Operation	When none of the above priorities is applicable.

=>The system should advise the users with what−not−to−do, not with what to do.

- Free Flight, Free−Route, User−Preferred Route (UPR) Interoperability:

=> Possibility to change trajectory at any time,
=> Self−Optimisation enabled,
=> High level human−system interactivity.

The basic bricks in FREER−1 ASAS are:

1. **Conflict Detection Advisories** allowing pilots to visualise traffic situations as well as potential conflicts between their own aircraft and surrounding ones.
2. **Conflict Solving Advisories** allowing pilots to resolve conflicts in three different modes (to be decided by the pilots depending on the circumstances): manual, semiautomatic, and automatic. Appropriate automated search for *optimal solution* is triggered if the pilots request semiautomatic or automatic resolution
3. **Situation Assessment Capability** allowing pilots to maintain awareness during encounter resolution as well as to support tactical Airspace Allocation and local Capacity Demand Balancing activities.

The user interfaces:

- ***Cockpit Display of Traffic Information*** (CDTI) showing identity and status of aircraft flying in the surrounding areas together with their trails, and intents. Levels of detail of information are displayed upon pilot’s request.
- ***Traffic Situation Display*** (TSD) showing conflicting zones that shall be avoided, and potential conflict zones to prevent domino effects resulting from solving one conflict and getting into another. Situational information such as airspace allocations, constraints and restriction *e.g.*, terrain, active military airspace, turbulence areas are displayed in the same principle.

With regard to trajectory management, our approach assumes that aircraft trajectories can be exchanged via ADS−B and VHF data−link. The problem raised by this assumption is the limitation of the ADS−B and data−link bandwidth. From the ATM point of view, following the free routing and free flight concept, the trajectory of an aircraft cannot simply be predicted by just an approximation of the speed vector and the heading to a waypoint. There is a need to define a model of aircraft motion that is adequate for conflict detection and resolution, which is simple enough to be included in data−link messages allowing reconstruction of trajectory on board, or on the ground. Figure 5 shows the difference between traditional trajectory prediction, and that considered in FREER.

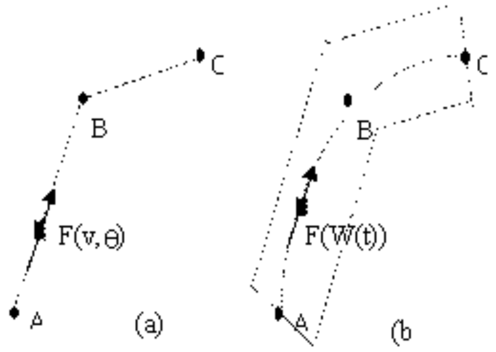


Figure 5 − Instead of interpolating the point, as in current practice (a),
flexible−routing concept requires physical model representing the movement of aircraft differently (b).

The approach taken was to investigate a parametric model that can capture the motion equations that physically model the aircraft dynamics and movements. Existing models of motion equations are analysed; a simple model is described in [10]. Hermit Polynomials were used to capture trajectory information for the purpose of transmission.

3.3.1 Conflict Prediction in FREER−1

Given the trajectories of two or more aircraft, the conflict detection problem is defined as the process of detecting the portions of the trajectories during which the distance between aircraft violates a separation standard. Traditionally, this is not a problem since in most cases, the speed of the aircraft is assumed to be constant, the current positions, and the trajectories are known. In realistic scenarios, there are several factors that can influence the prediction of a conflict. Among these factors are the effect of the wind, and the uncertainty associated with aircraft navigation. The predicted trajectory is not necessarily 100% accurate. There is the question of uncertainty handling in trajectory prediction and thus has impact on conflict detection. In fact, inaccurate conflict detection leads to large number of false−alarms that certainly influence the credibility of any automatic conflict detection system.

Most of existing work on conflict detection considers uncertainty approximately. In HIPS [9], conflict detection considers a number of straight−lines from a 4−D point modelling the possible flight paths (Figure 5a). These straight−lines are defined in an arbitrary way by taking into account the possible headings. On top of this pair−wise conflict detection, HIPS also suggests the use of 4−D geometric projection of the intersections of all surrounding aircraft with a 4−D cone representing all possible headings of own aircraft. The main advantage of this approach is that it is capable to represent eventual domino effects of heading changes through "no−go" zones.

The current FREER−1 prototype uses the 4−D geometric projection in HIPS.

Besides the use of HIPS approach, FREER−1 addresses the issue of uncertainty handling by considering a geometrically deformable volume defined from a position of an aircraft, and from the aircraft type (different dynamics and levels of equipment). The distances from the aircraft to the surfaces of the volume are used to represent the uncertainties associated with the trajectory and flight phases. For example, wind is at the right wing pushing the en−route aircraft to the left. The distance from the aircraft to the left surface could be larger than that on the right during a certain period of time. Actually, the initial idea for this representation is to associate a Gaussian distribution to a trajectory. The likelihood can be then calculated from the integral of the intersection (sum) of the Gaussian's of two trajectories. Extending this idea to cover parallel lateral and vertical contacts led to the idea of investigating the depicted deformable volume.

In this approach, a constrained minimisation algorithm for computing conflict using an interval Newton method on physically−based trajectories of objects was chosen: Using the contact constraints, a minimisation algorithm for computing collision between the two bodies is executed. For computing the collision, this algorithm takes into account the inclusion functions for the collision equality constraint, and the inclusion function for the incoming constraint representing the motion of two approaching bodies.

In this algorithm, the collision detection depends on the inclusion functions for the time−varying surfaces and their various derivatives. Note that the equality constraint involves derivatives of the time−varying surface mapping.

3.3.2 Conflict Resolution in FREER−1

Conflict resolution is often seen as the problem of finding a trajectory for an aircraft to avoid a potential conflict. If conflicts are represented by a set of forbidden zones, or no−go zones as in Figure 6, the problem consists of finding a path for the aircraft to avoid those zones, laterally, vertically, or longitudinally.

In FREER−1, in accordance to the principle of human−centred automation, and considering the economics of flight, the conflict resolution is seen as the problem of finding optimal trajectories avoiding the forbidden zones, with or without human interactions. Finding an optimal trajectory involves minimising the extra−cost associated with a deviation of a trajectory that avoids conflicts. Three major issues appear from this concept:

1. How to model the cost associated with a trajectory — a simplistic way of minimising cost is to minimise the length of the deviated path. But is this realistic? Can a vertical separation cost more in terms of fuel consumption but be less expensive in terms of overall cost, taking into account the non−fuel costs?
1. What is an optimal deviation — supposing that the system can suggest an optimal path, it is possible that the optimisation criteria that the system is using are not the same as those the pilots have in mind. So, how can pilots enter their optimisation criteria?
1. Human−centred decision — we wanted to achieve a scenario in which, to avoid a conflict, the pilot only needs to specify:

- *What* should be done, for instance "lateral separation."
- *How* the separation should be performed, for instance "don't waste energy" or "minimise time to arrival."

To tackle the issues depicted above, we first took into consideration the simplest form of optimal trajectory: shortest distance in lateral separation. From this view, shortest distance means minimum deviation time thus minimum non−fuel cost, and lateral separation is assumed to provide minimum fuel−cost with respect to vertical separation.

The point is that the set of forbidden zones to avoid can contain those generated by the current trajectory. That means that there exist simultaneous changes for the forbidden zones as soon as the trajectory deviates. There obviously exists a differential relation between a forbidden zone and a trajectory as shown in Figure 6. This differential problem was manually handled in our early prototype where an action from a human−user dragging a trajectory makes change to the form of the forbidden zones. But what if human interaction is minimised to just conceptual level as stated in point (3)? Clearly, differential analysis is of interest.

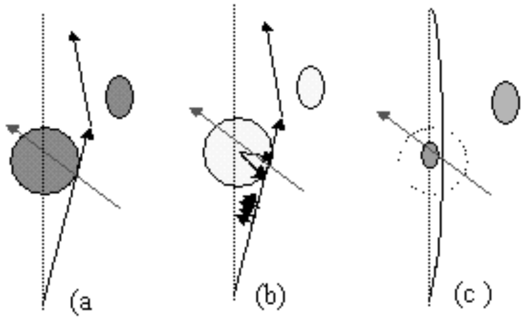


Figure 6: Non optimal conflict avoidance trajectory (a) can be optimised by establishing differential relations such as force fields (b) from trajectory to stick to forbidden zones and from forbidden zones to push trajectory out. The Equilibrium State is an optimal trajectory avoiding the minimised forbidden zone (c).

FREER−1 adopts two parallel approaches for these specific issues:

- Integrating pilots' interactive solving support on−board, via CDTI /TSD and FMS control display plus touch−pad control, and
- Investigating dynamic models for airborne conflict solving.

The integration of interactive functions into the flight deck was conducted with the assistance of a pilot from Air France. The results were demonstrated to be tractable, and can fulfil ASAS general requirements in low−density airspace. (See Figures 7 to 9)

The dynamic models for airborne autonomous conflict resolution is described in [7]. Basically, an algorithm that associates the motion equations of the aircraft with a number of constrained forces to be minimised is being developed. The forces includes the artificial potential field forces from the environment, *i.e.* forbidden zones in our case, and from the aircraft, and finally those specified by the users. The Equilibrium State of the sum of these forces subject to constrained minimisation is the solution suggested.

Should other requirements, such as (1) and (2) mentioned above, be taken into account, the problem of conflict resolution is somehow more complex. Indeed, we wanted to consider human interaction at high level specifications, and cost minimisation. Let's start with cost minimisation and the question of optimal solution with respect to fuel and non−fuel costs. Mathematically, conflict resolution in this case can be expressed as the problem of minimisation of a cost function subject to navigational and aircraft dynamic constraints. This is basically a non−linear optimisation problem for which numerical solution in real−time is not guaranteed. Human interaction with the system is yet another dimension. Controversially, human input can, in certain configurations, help accelerating the convergence thus achieving the desired state. But at the same time, high level specifications can be interpreted at the system level as differential equations dynamically input into the system, thus making the overall model over−constrained so that no solution can be delivered. The trade−off between under− and over−constrained model for minimisation are being analysed as well as the trade−off between analytical accuracy and the complexity of the computations.

Our approach to automatic conflict resolution is yet to be refined with real−time simulations and trials on experimental and commercial aircraft. At the current stage, only the interactive solving approach is integrated into our MCS cockpit simulator [11].

3.3.3 Interactive Conflict Resolution Advisory

An interactive conflict resolution advisory service has been developed to illustrate the autonomous aircraft concept operating in low−traffic density airspace. This advisory service is currently integrated in the EEC Multi−aircraft Cockpit Simulator (MCS) [1] environment.

The approaches depicted in the previous sections are used in the implementation of the FREER−1 Interactive Conflict Resolution Advisory. It is foreseen that automatic resolution advisories will also be integrated to the prototype demonstrator at end 1997.

At the current stage (June 97), the interactive resolution advisory service is capable of:

1. Capturing surveillance data from ADS−B and data−link to provide Cockpit Display of Traffic Information (CDTI). Figure 7 shows an example of CDTI service in which surrounding aircraft are displayed on the Navigation Display in the flight decks.

Each surrounding aircraft is represented by its call−sign, flight level, velocity vector, and climb or descent rate. Trajectories of aircraft are only displayed whenever they are involved in a potential encounter with the own aircraft.

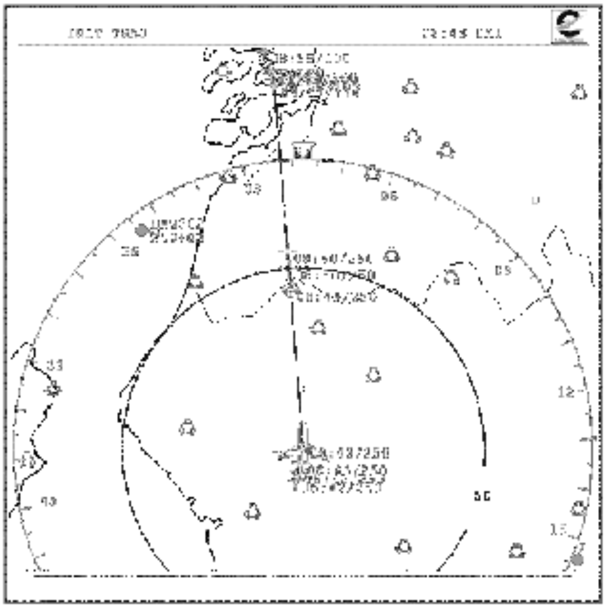


Figure 7 Example of Cockpit Display of Traffic Information (CDTI) service. Surveillance information is displayed. The example shows British Airways flight (BAW362) captured by ADS−B and an unknown at the right bottom.

2. Detecting conflicts and providing Traffic Situation Display (TSD) service. Figure 8 shows an example of TSD service in which a detected conflict is displayed by a conflict zone representing the space and time at which a standard separation is violated. The current TSD service offers vertical and horizontal conflicts.

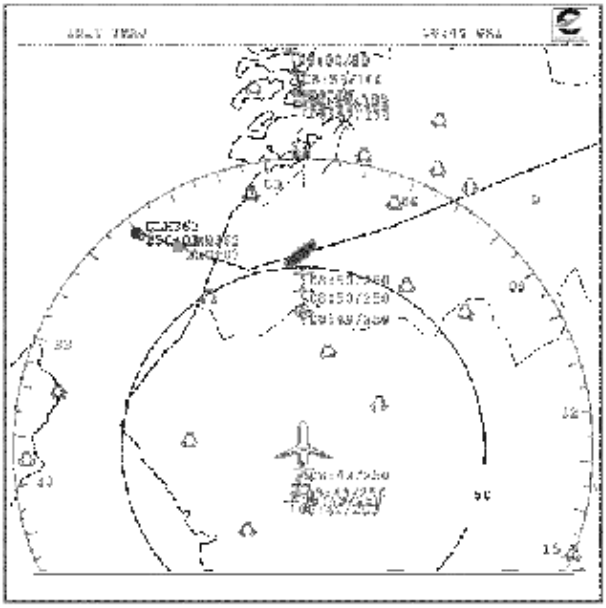


Figure 8 Example of Traffic Situation Display (TSD) in horizontal NavDisplay. In this scenario, a Lufthansa flight is entering into conflict with own aircraft and is highlighted. Its trajectory and conflict zone is displayed, showing the cause, and the space and time areas at which horizontal separation minimum is violated. The same principle is used for vertical display.

3. Detecting potential conflicts caused by a change in headings. As previously discussed, a 4D geometric projection is computed to provide the "No−Go" zones, *i.e.*, the space and time at which violations of separation standards with other

aircraft can occur when making a change in trajectory. Figure 9 illustrate a case where the British Airway’s BAW326 trajectory imposes a "No−Go" zone alerting the pilot to avoid that zone if she/he doesn’t want to get into another conflict when solving the current one. This is an efficient way to resolve the domino effects in free−route and/or free flight context.

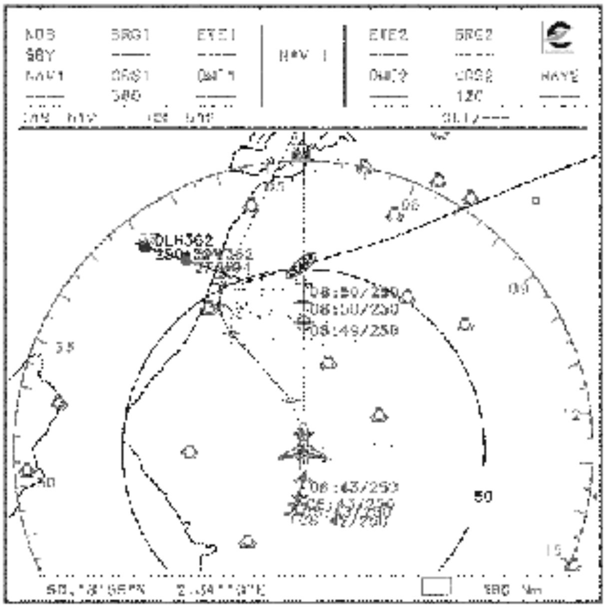


Figure 9 Example of Interactive Conflict Resolution service. In this case, pilot user enters constraints to modify current trajectory. Note that the aircraft to take the evasive action is to be identified from the Extended Flight Rules [8]

4. interactively resolving the conflicts by adding constraints to trajectories via:

- The Flight Management System (FMS) through its CDU (Control Display Unit).
- Direct manipulation of displayed trajectory on the flight deck’s Navigation Display through a pointing device (under development).
- Acceptance or modifications of constraints up−link from ground ATC.

4. Conclusion

A set of Extended Flight Rules (EFR) has been identified, and an interactive conflict resolution advisory service has been developed. Both are demonstrated to the airspace user community to acquire more specific requirements. An automatic and a semiautomatic resolution service are under development. These services will include optimisation strategy from airspace users in conflict solving.

At this stage, enhancements are in progress. The results obtained so far are encouraging and do not preclude the feasibility of autonomous aircraft operations supporting free flight, free−route. Means to achieve operational efficiency are also addressed.

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Acronyms

AA	Airspace Allocation
AAO	Autonomous Aircraft Operations
ADS−B	Automatic Dependent Surveillance Broadcast
ACAS	Airborne Collision Avoidance System
AFR	Autonomous Flight Rules
AIS	Air Traffic Information Service
AOC	Airline Operating Center
AR	Airspace Regimes
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATM	Air Traffic Management
CDTI	Cockpit Display of Traffic Information
CDU	Control Display Unit

CFMU Central Flow Management Unit
CNS Communication Navigation Surveillance
DCB Demand Capacity Balancing
ECAC European Conference on Civil Aviation
EATMS European ATM System
EFMS Experimental Flight Management System
EFR Extended Flight Rules
FFA Free Flight Airspace
FM Flight Management
FMS Flight Management System
IATA International Air Transport Association
ICAO International Civil Aviation Organization
MAS Managed Airspace
MASP Minimum Aircraft System Performance
MASPS Minimum Aviation System Performance Standard
OCD Operational Concept Development
PUC Position Uncertainty Category
SAS Situation Assessment System
TCAS Traffic Collision Avoidance System
TCP Trajectory Change Point
TSD Traffic Situation Display
UMAS Unmanaged Airspace
UPR User−Preferred Route
VFR Visual Flight Rules
VUC Velocity Uncertainty Category