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The impact of Human Factors on Airborne Separation Assurance Systems (ASAS)

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Abstract
The 3FMS project, co-funded by the General Directorate for RTD of the European Commission, aims at evaluating the consequences at the airborne level of some ASAS applications such as full Free Flight and Station keeping. This on-going project already arose an important number of issues, in particular at the human factors level which, in turn, would dramatically impact the airborne and ground functions and systems. These issues, presented in this paper, are the result of an important number of discussions and evaluations with airlines, certification, instruction and test pilots. The early findings, that are awaiting confirmation in adequate simulation settings, highlight the need to provide the crew with functionalities that enable them to carry out their new ASAS related tasks with the suitable efficiency. Indeed, though the concept of CDTI (Cockpit Display of Traffic Information) can enhance the situation awareness, it is not sufficient in itself to insure that crews will be able to efficiently and safely achieve ASAS related tasks. The most important issue comes from the need to basically *not increase* the crew workload compared to actual operations. This, in conjunction with the evidence that future ASAS applications shall run routinely with widely accepted procedures and regular crews, has strong impacts on airborne and ground ASAS functionalities, and on the shared air-to-air procedures (rules of flight in particular).

Biography
D. FERRO graduated in 1983 in Aeronautics at the Ecole Nationale Supérieure d'Ingénieurs de Constructions Aéronautiques in Toulouse. Since, he has been working on HMI design/evaluation for many projects and programs such as validation of A320 fly-by-wire and Electronic Instruments Systems, pre-development of Hermes spacecraft HMI for Guidance and Navigation, development of new A340 FMS crew functions, and other subjects related to future Airbus cockpits. He is the co-ordinator of the EEC co-funded project DIVA [1] and in charge since 1996 of ASAS studies applied to Airbus cockpit functions.

Introduction
For several years, the traffic in civil aviation has been increasing by about 5% every year. As a consequence, many ATC sectors in the world are saturated with diverse consequences like increasing delays on aircraft departures and arrivals.

On one side, with the current technologies, the continuous increase of air traffic density will create an ATM bottleneck in the medium term. And on the other side, the availability of new Communication, Navigation and Surveillance technologies provides the basis to move towards advanced Air Traffic Management (ATM) concepts like the ASAS (Airborne Separation Assurance System). The main aim of ASAS is that the ATC partially or totally delegates to the aircraft the traffic separation assurance in some airspaces to reduce effective separation between aircraft.

The ASAS concept has benefited from an important development work through many international committees, working groups and panels which mainly focused on ADS-B aspects and, among them, its functionalities and the feasibility of their implementation (media, associated equipment, …).

It is worth noting that economical justification was not demonstrated and therefore, in addition to a technical proof of the concept, sensible cost/benefit analyses are also needed to justify the payback for airlines and Air Traffic Controllers / Managers.

Because the ASAS concept might impact the airborne Flight Management System (FMS) by introducing new operational services at different flight time horizons, three of those services (Free-Flight, Station Keeping in Descent and Taxi operations) are being studied by the 3FMS project, co-funded by the General Directorate for RTD of the EEC. This project involves Sextant (co-ordinator), Aerospatiale Matra Airbus, National Aerospace Laboratory, the Netherlands, Defence Evaluation and Research Agency, Smiths Industries, Skysoft and Eurotelematik GmbH, started in early 1998 and is expected to end by late 2001. It aims at preparing an early functional definition of the European Flight Management System for ASAS applications and, for this purpose, impacts also the definition of Communication, Taxi Navigation and HMI functions.

The consortium includes a major airframer (AM Airbus), in charge of the Airbus cockpits development. In the project, one of the earliest roles of AM Airbus was to propose the operational concepts that define the crew involvement, with the aim to:

- take into account the Human Factors (HF) early in the design process

[1] Design of Human/Machine Interfaces and their Validation in Aeronautics

- define, discuss and justify the choices made, particularly in the task allocation between the crew and the systems
- assess the impacts on crew qualification and training
- assess the constraints on the definition of the procedures (protocols) that will exist between any concerned aircraft and its environment (ATC, AOC, other A/C)

Some of the concepts and findings that will be presented hereafter come from a structured process applied at several levels of the design: at the top requirements level, at the crew role level, at the airborne functions level and at the HMI definition/evaluation level. At the crew levels, the requirements were elicited through a continuous involvement of both designers and pilots of various origins (test, training, certification, and airline).

It is to be mentioned that the consortium managed to define all the sets of requirements and constraints (at the A/C level, at the crew level and at the environment level [ATC, AOC, and other A/C]) compatible with each other and together with an operational scenario. This definition eventually was the result of numerous loops in the overall design, but from the beginning it was sustained by a formalised and documented top-down process.

An important contribution to the findings come from one formal evaluation campaign of the HMI led by NLR with the participation of 7 pilots, together with evaluations held within AM Airbus on early prototypes with the help of 5 test and training pilots.

The top requirements, as described in the operational scenario, mainly include the hypothesis that two applications named Free-Flight in En-Route and Station Keeping in Descent can be carried out upon ATC decision in determined conditions.

The leading constraints on ASAS operations at the crew role level are to be:
- safe
- acceptable for crews : harmonized with the general cockpit philosophy enabling (in particular) the crew to select the level of automation which is appropriate to the situation (workload, tireness, failures, weather, …)
- efficient (time, fuel) for airline acceptability
- comfortable for passengers

Free -Flight in En Route

For this application, envisaged in the ATM2000+ step 3, two main flight time horizons are defined:

- The tactical flight time horizon lies between 30s and 10min ahead current situation. The airborne separation with traffic, terrain and adverse weather will be introduced in this time horizon as a tactical function.

The strategic flight time horizon is beyond 10min ahead current situation. The weather data fusion, the en route in flight replanning and the trajectory negotiation are in this time horizon. These functions are closely linked to the corresponding Airline Operational Centre (AOC) capabilities and it would be more appropriate to include the weather data fusion and the en route in flight replanning in it.

The organisation of the associated future flight management system can be synthesised in the following scheme:

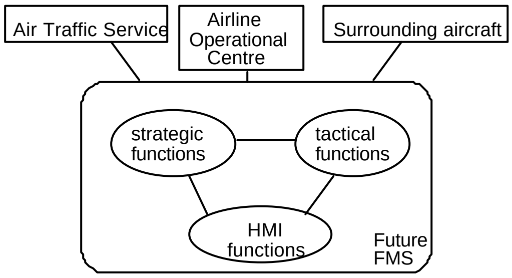

Figure 1: flight management organisation

The new, critical, on-board parameters are function of the flight phase, the type of airspace and the type of encountered situation.

Globally these parameters can be shared in function of their flight time horizon, and their topic as it is described in the following table.

Time horizon	Traffic/Weather/Terrain/SUA	Performance
Strategic management	Medium term Flight plan revision	Preferred trajectory
Tactical management	Short term Flight plan revision	Allowed trajectory
Real-time safety nets	avoidance manoeuvre	flight envelope

The crew role is:
- to manage the entry in the Free-Flight Airspace (FFAS) through A/C <-> ATC clearances
- to manage the activation of the onboard ASAS functions (they should not engage without crew validation)
- to check/modify the ASAS-related Navigation and Surveillance parameters : Required Navigation Performance / Estimated Position Error, conflict detection criteria (especially if specified by ATC), Required/Estimated Time of Arrival at FFAS exit point, conflict resolution criteria
- to monitor the Active Flight Plan in addition to the automatic conflict detection so as to insure that it is :
    - traffic safe
    - weather safe
    - terrain safe
    - SUA (Special Use Airspace) safe
- to manage the definition of the Route of Preference in absence of conflicts. The suitability of the Flight Plan shall be assessed regarding winds, geography (politics, fees…), turbulence, ETA/RTA and fuel considerations.
- to manage the conflicts with either traffic or weather (this will be more developed further) and ensuring that the new route (if any) is clear regarding terrain and SUA

- to manage the exit from FFAS zone
- to manage the deactivation of onboard ASAS functions

In FFAS (Free Flight Airspace), in addition to the theoretical capability to fly more optimised routes, the biggest innovation will consist in managing the conflicts with traffic and with weather. Probably also the hardest constraints on functions and systems will come from the need to insure that those new operations are compatible with HF aspects.

Indeed, the constraints are :

- since the conflicts may happen several times a flight, the detection and the resolution shall be considered as routinely (since ATC will nominally <u>not</u> intervene)
- since the resolution is to be considered routinely, it shall not demand exceptional skills from crews, a particular level of arousal or a better physical form than for today operations. It has to be mentioned that, today, many crews are really happy to rely on efficient and safe automation during the last of 3 or 4 medium-haul flights in a single day.

Those considerations entail that:

- the resolution shall be very low workload demanding and not consist on long nor hard tasks (not "video games")
- the communications between the crews of different A/C involved in a traffic conflict should basically not be necessary
- the computation of the resolution shall basically not request crew implication, neither to decide the priority (in case it is decided that only one A/C changes its trajectory), nor to define the resolution trajectories
- all ASAS equipped A/C implicated in a conflict must enable the crews to be aware of the conflict
- since it is acceptable (and likely in early stages of this application) that in some circumstances crews want to communicate with each other about a given conflict, those crews must be aware of a detected conflict <u>at the same time</u> to avoid discussions based on different references
- the detection of any conflict must implicitly or explicitly be agreed between A/C without crew involvement, before (simultaneous) display to all the crews.
- all the A/C of a given conflict must automatically find a consensus on the resolution (priorities, trajectory modifications
- the resolution shall be computed in a very short interval so as to avoid unnecessary crews conjectures
- the resolution shall not trigger any new conflict (traffic or weather) in the prescribed time frame
- the resolution shall be free of ACAS alerts
- the crews of all A/C involved in a conflict must be able to know the common resolution <u>at the same time</u> to avoid discussions based on different references
- the display of the conflict resolution must enable each crew to <u>instantaneously</u> understand the consequences of the resolution at the traffic/weather separation level, as well as at the overall flight plan level (lateral navigation, ETA/RTA, fuel consumption in particular); this important requirement led, in the basic procedure, to the concept of Resolution Flight Plan to enable the crew anticipate the resolution trajectory
- the crew of any conflicting A/C must nominally accept the resolution ; however, they also shall have the capability to check the resolution against the relevant raw data (ex : weather, traffic position and predictions).

Figure 2 : example of conflict resolution (ownship has not priority)

- several solutions (Resolution Flight Plans) may exist to solve a conflict ; the best shall be presented to the crew ; but when only one A/C must change its trajectory, it is acceptable that its crew is given the possibility to check another one (automatically computed)
- the <u>only</u> needed task of the crew in the A/C which change their trajectories is to validate the Resolution Flight Plan, after having checked that it :
  - clears the conflict without triggering any new one
  - is compatible with the rest of the flight
- this validation must be possible in a time frame that enables the crew to acknowledge and understand the conflict, understand the consequences of the resolution, communicate with the other A/C if really necessary, possibly refine the proposed solution for instance by disregarding a weather phenomenon and validate the trajectory change, all of this without triggering any contingency procedure (see below)

It is anticipated that the systems that will carry out on-board 3FMS functions will have dependability similar to that of the actual FMS. Therefore, it is also necessary to account for failures and contingency procedures. In the 3FMS scenario, those procedures are foreseen for situations such as:

- the conflict was lately detected by the system
- the conflict was not detected in time by the systems, and was detected by the crew of one A/C
- the crew of the "Moving" A/C has not activated the resolution on time

Contingency functions and procedures were not defined in the frame of 3FMS. Nevertheless, the trials on simulator will put some crews in contingency situations with the aim to ask the crews their opinion and make them imagine some ways to solve the situation, like new procedures, new specific functions, ACAS, ATC/ATM intervention or a combination of some of them.

After having listed the constraints at the airborne functions level, it is now time to briefly depict the duties of the crew, specific to FFAS operations. Those were defined in the frame of the project so as to limit as much as possible the open points that could unnecessarily constrain the systems.

Particularly concerning the FFAS operations, and in addition to already cited monitoring / acknowledgement / validation tasks, the crew is requested to:

- fly the A/C in full FMS managed mode, preferably with the autopilot engaged, so as to insure that the A/C flies the intended trajectory, broadcasted by the ADS-B function (otherwise, if the actual trajectory deviated significantly from the intended one, the ADS-B would generate a new one based on the velocity vector, and the stability of the FFAS would dramatically decrease as regarding conflicts)
  This new procedure is compliant with the current Airbus philosophy in which the cruise operating procedures recommend the full automatic managed mode
- respect the conflict resolutions because they aim at replace the ATC clearances ; one possible solution could be that not respecting the conflict resolution would (if no appropriate justification is given) entail a penalty for the airline and, then, most probably for the crew

A major conclusion is that to carry out the FFAS application:

- a new concept of operations will be defined
- new systems will be certified in that purpose
- adequate, certified procedures will be defined
- the crews will undergo adequate training and qualification

At the airspace level, the systems shall behave in a fully co-ordinated way among aircraft, which entails a same knowledge of the environment (traffic, weather, and terrain, SUA) for all A/C involved in the same conflict.

The corresponding two key functions of traffic conflict detection and resolution are described below.

In free-flight airspace, the most critical obstacle to manage is obviously the traffic due to its speed and the difficulty to know accurately its predicted trajectory. Also without assistance the crew is not able to safely analyse the traffic situation. The ADS-B is a communication technology enabling an operational answer to these issues. With an increased range, it should allow knowing the surrounding aircraft predicted trajectories far enough in advance and on a sufficient distance for a quiet and safe onboard traffic conflict management and an enhanced traffic situation display to the crew. This is composed of traffic conflict detection, a traffic conflict resolution and a traffic situation display.

The definitions associated to the traffic conflict detection are illustrated in the following figure. Two closest points of approach (CPA) basically define a traffic conflict: one for the ownship and one for the other aircraft concerned by the conflict. A CPA is the 4D-point of an aircraft trajectory that is the closest point to the 4D-trajectory of a defined aircraft. The closest distance between these two aircraft is the distance between their corresponding CPAs. If, for instance, both aircraft are cruising at the same level and are potentially violating the vertical separation standard and if, in the horizontal plan, their closest distance is lower than the applicable horizontal separation standard, these two aircraft are in a traffic conflict situation. The conflict duration is the period of violation of the both separation standards. For the ownship it begins at the LOS (Loss of separation) point and finishes at the GOS (Gain of separation) point.

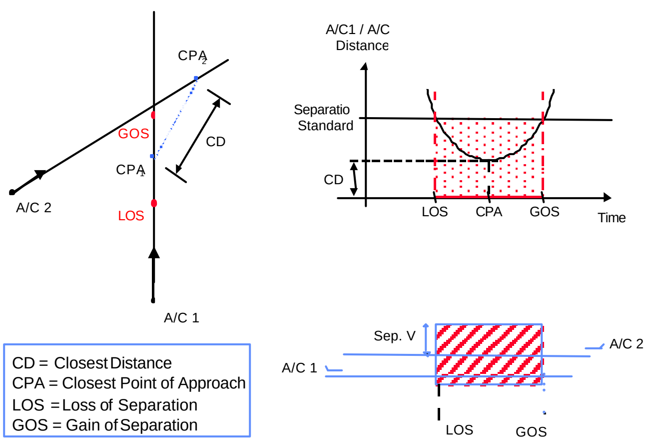

Figure 3 : Traffic conflict parameters

In case of traffic conflict, priority rules (Electronic Flight Rules (EFR)) are applied and within 3FMS project only one aircraft is moving. An automatic decision making process is performed by both aircraft through air-air data-link.

The resolution manoeuvre begins at the SOM point (Start Of Manoeuvre) which is a trajectory 4D-point, a time ahead the current time. The SOM time should be far enough from the detection time in order to allow the

crew to take a wise decision. However, this time should also have a limit before reaching the LOS in order to allow the aircraft to perform a smooth and safe resolution manœuvre.
The resolution manoeuvre finishes at the EOM point (End Of Manoeuvre). This point is conservatively taken as the Managed Airspace entry point. Practically, the preliminary end of manoeuvre (PEOM) could be a point symmetrical of the SOM relatively to the Resolved closest point of approach (RCPA).
Two exclusive types of resolution manoeuvres are envisaged: the horizontal manoeuvre and the vertical one.
The horizontal one is maintaining the closest distance equal to the separation standard through lateral changes of the moving aircraft trajectory. It introduces a new waypoint, which is close to the new CPA of the moving aircraft relatively to the non-moving aircraft trajectory.
The vertical manoeuvre of the moving aircraft is generating a combination of a step climb and a step descent allowing respecting the vertical separation with the non-moving aircraft. This manoeuvre is expected to be particularly interesting when a step was already planned in the next few minutes for performance reason.
This manœuvre could also solve some horizontal cornercases like the very slow convergence of two aircraft in the same horizontal plan and cruising at the same speed.

These two types of manoeuvre are illustrated in the following figure:

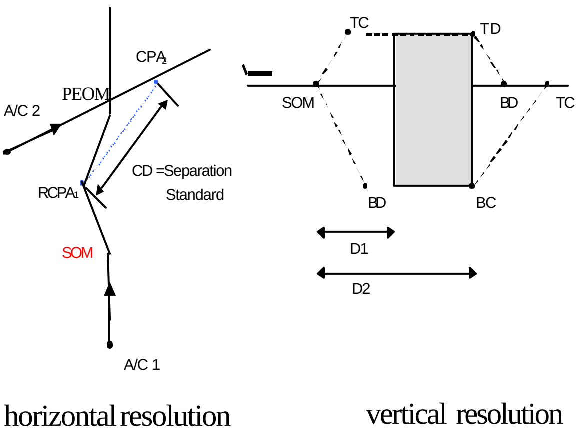

Figure 4 : types of conflict resolution

The weather and terrain (if relevant in enroute phase) obstacles are also checked in order to propose a complete obstacle-free resolution manoeuvre including, if required, a terrain separation manoeuvre or a weather separation manoeuvre.

Station Keeping (SK) in Descent

The consortium selected this application, for first assessment, because it is envisaged in the ATM2000+ step 2, and also because the questions it arises, are more complex than for Station Keeping in cruise. Indeed, build a train of A/C that change levels and that can have quite different performances (descent rates, descent profiles between two levels) is not obvious. Therefore it was decided to consider the following hypotheses (different hypotheses might lead to different applications):

- the application starts in Managed Airspace, when both the master (leading aircraft) and the slave (trailing aircraft) are in the same published lateral trajectory (airways / STAR) that result on similar latreal flihgt plans, as a result of either ATC clearances or of a specific ASAS application
- both A/C are given common vertical clearances (ex : through the published procedure) and common speed clearances that are compatible with the performances of both A/C
- the most novel task for the slave A/C is to fly a given lateral path with a series of vertical and speed clearances, by following a specified master A/C by a given distance, with a given tolerance

For this application, the crew role in the slave A/C is:
- to manage the SK clearance (through A/C <-> ATC communication)
- to manage the activation of the onboard ASAS functions (they should not engage without crew validation)
- in master A/C, to be informed and acknowledge the clearance.
- in slave A/C, to confirm the selection of the master, acknowledge the clearance and engage the appropriate Navigation modes
- to check/modify SK-related parameters : RNP/EPE, actual versus target distances, minimum and maximum distances
- to manage the conflicts (distance out of tolerance) automatically or manually detected, by applying a manual resolution rapidly enough so as to avoid ACAS alert
- to manage the end of the application (A/C <-> ATC communication)

To alleviate the crew workload in such a critical phase as Descent is, three main hypotheses were used in the project:
1. the starting clearance preferably should be given through CPDLC, so as to enable the crew of the slave A/C to quickly and reliably understand and acknowledge the clearance ; in particular, any confusion about the reference of the master should be avoided as much as possible

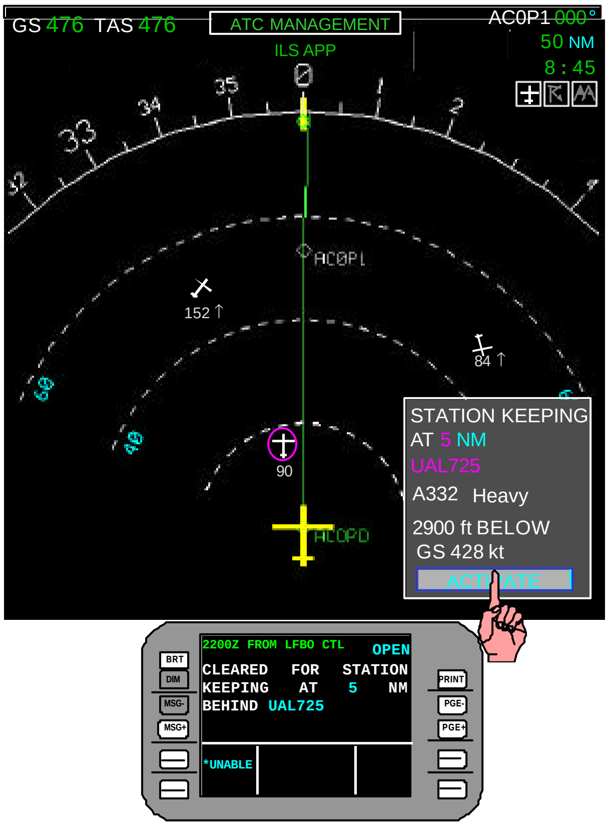

Figure 5: ATC clearance to initiate SK

2. A new AFS mode is designed, upon crew activation, to reach and maintain the distance with respect to the master by following the lateral / vertical flight plan (or the successive vertical clearances entered by the crew).

   This new mode, to be efficient, needs to be fed with the master data (position, velocity vector, ground and air speed…) at the adequate rate.

3. An automatic surveillance function monitors the actual distance versus the target. It alerts the crew when the difference exceeds a threshold, in order to apply the adequate procedure.

Conclusion

The 3FMS project deliberately based all its assumptions on the following rationale: the future ASAS functions, to be efficient and safe regarding in particular the crew involvement, need to be powerful and involve automation at the appropriate levels. Clearly, it will not be possible to rely solely on the crew with its CDTI.

If this is confirmed during the 3FMS trials planned during next year on the EPOPEE simulator at AM Airbus, with 80 flights run by 8 crews, the following conclusions apply for the future implementation of the foreseen applications.

Navigation functions will require new AFS modes, route optimisation, conflict solvers with the required level of dependability. They will find consensus with other A/C, and will use an important number of new information on surrounding traffic, weather, terrain / obstacles and SUA.

Surveillance functions will have to reliably detect any conflict with the surrounding environment, given the current ASAS application. The definition of a conflict shall be common to all A/C in FFAS.

Communication functions will have to transmit/receive many new data (traffic and weather data, specific data exchanged between A/C for conflict solving) to insure that both the pilots and the systems are able to achieve their tasks. Another important consequence lies at the ADS-B level. Indeed, to behave efficiently, the ADS-B media needs to be more powerful than envisaged today, at least to transmit the important number of Trajectory Change Points that define the Active Flight Plan.

HMI functions will have to present the relevant data to the crew under different options: from basic one (routinely situations) to the most demanding ones, during which the crew may need complementary information on the onboard ASAS parameters and/or on the environment.

A set of agreed procedures and protocols are to be defined, that allow all the A/C of a particular ASAS application and the ATC to efficiently cope with all foreseen situations, from nominal to contingency. Nevertheless, communications between crews shall be limited as much as possible.

To carry out such applications in a safe and efficient way (provided that they appear as cost effective), much work is needed to agree on and develop the relevant airborne and ground systems.

Together with other research projects, 3FMS is a good opportunity for AM Airbus to make a first assessment on the requirements that will apply to future ASAS functions.

However, numerous new CNS tools are already available with current airborne architecture which are still not being used to their design operational capability because ground systems cannot ensure the services that would enable it.

So, prior to going to further studies and research and to adding new ideas to those listed above, it is the strong opinion (fully shared by the airlines) of an aircraft manufacturer that existing tools should be exploited at their right level.

To emphasize this point, any implementation of new functions as ASAS will need a clear commitment of every party engaged.

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