Pilot-in-the-loop evaluation of cockpit assistance for autonomous operations

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ABSTRACT

The Full Aircraft Separation Transfer (FAST) study of the FREER-FLIGHT Project looks at the "autonomous aircraft" mode in the context of free flight airspace by 2015. This can be allied to free route operations and support the introduction of designated Free Flight Airspace as proposed in the EUROCONTROL ATM2000+ Strategy. While these operations are likely to be confined to low traffic density airspace, they will further enhance flight efficiency and flexibility.

New rules are needed to address the issues of communication, coordination, flight rules, separation principles and priorities among flights. For that purpose, Extended Flight Rules (EFR) procedures have been developed: encounters are treated pair-wise and a priority scheme determines which aircraft has the right of way. In addition, an Airborne Separation Assurance System (ASAS) prototype providing the pilot with the necessary assistance for conflict detection and resolution has been developed. The conflict detection provides a graphical representation of actual and potential zones of conflict, allowing straightforward conflict resolution through graphical trajectory editing. In addition, conflict resolution can be performed through system generated resolution trajectories. It is assumed that full intent information (Trajectory Change Points (TCP)) is transmitted between aircraft through Automatic Dependant Surveillance – Broadcast (ADS-B). Full Flight Management System (FMS) equipment is required.

A total of 18 pilots participated in the experiments run in a generic cockpit environment.

Pilots were observed defining their own cockpit procedures to handle separation assurance in the absence of ATC, in particular to cope with non-nominal situations. They found the two levels of automation support for separation assurance very efficient and intuitive. Furthermore, they subjectively assessed that the additional workload induced by the separation task was very low, though some concerns were raised on the possible necessity of an ATC fallback in non-nominal cases.

The zones on the display exclusively provided information on the interaction with other aircraft. The pilots expressed a need to integrate these zones on the same display with weather information, terrain and restricted airspace boundaries. A number of other enhancements to the tools were suggested by the pilots, warranting more experiments for a better understanding of the feasibility of autonomous operations.

INTRODUCTION

The major challenge facing Air Traffic Control (ATC) is to enhance air traffic capacity and flight efficiency while providing safety improvements. Research is currently under way in key Air Traffic Management (ATM) fields, such as Communication, Navigation, Surveillance (CNS), airspace and flow management, controller working methods and support tools. However, the forecasted traffic density growth in Europe and in the United States over the next fifteen years suggests that solely improving ground systems might not be sufficient to achieve the required capacity at appropriate safety levels. The development of a close cooperation between ground and airborne sides might be required to achieve
this challenge, and the delegation of separation assurance from controllers to pilots is one promising option of cooperation. The concept of delegation takes advantage of emerging CNS/ATM technologies in pre-operational state – Automatic Dependant Surveillance – Broadcast (ADS-B) [14] or Traffic Information Service – Broadcast (TIS-B) – along with additional avionics such as a Cockpit Display of Traffic Information (CDTI) providing the pilot with a picture of surrounding traffic [15]. The Operational Concept Document (OCD, [7]) of the European Air Traffic Management System (EATMS) and the ATM Strategy for 2000+ [6] proposed by EUROCONTROL envisage, within Managed Airspace (MAS), the possibility for controllers to delegate separation assurance tasks to pilots flying aircraft fitted with appropriate avionics. Fully autonomous aircraft operations are also envisaged for the new “Free Flight Airspace” (FFAS) proposed by the OCD. Similar applications are being considered under the Free Flight initiative of the United States Federal Aviation Administration. Within the European Air Traffic Management Programme, the FREER-FLIGHT project investigates operational concepts including both limited delegation [10] and extended delegation applications [3].

Various research centers in Europe (see e.g. [16] and [1]), in the United States (see e.g. [17], [12] and [2]) and industry led working groups, in particular in projects funded by the European Commission such as [13] and [5]. Under the sponsorship of EUROCONTROL Operational Development of Initial A/G Data Communications Task Force (ODIAC-TF), the terms of reference of the AIRSAW task force encompassed the Airborne Separation Assurance System (ASAS) concepts and applications [8]. Standard bodies EUROCAE WG-51 and RTCA SC-186 [14] include ASAS applications within their scope.

The Full Aircraft Separation Transfer (FAST) study of the FREER-FLIGHT Project looks at the “autonomous aircraft” mode in the context of free flight airspace by 2015. Extended Flight Rules (EFR) procedures have been proposed [4]. An ASAS prototype providing the pilot with the necessary assistance has been developed (see e.g. [3]).

The experiment described here aims at gathering more data on autonomous operations from an aircraft perspective, specifically on the acceptability of the concept by pilots, through the evaluation of a prototype interface and corresponding procedures.

This paper is organized as follows: the first section outlines the concept of autonomous operations. The next provides an overview of the simulation facility characteristics. This section is followed by a description of the experiments and finally the results are presented.

BACKGROUND

The EATMS Operational Concept Document defines FFAS characterized by operations comprising both free routing and autonomous separation. As depicted in Figure 1, FFAS will consist mainly of en-route airspace, typically so-called “upper upper airspace” and also possibly corridors over core Europe.

Aircraft operating in autonomous mode are responsible for ensuring separation from other aircraft. Flight navigation information of all aircraft is used to predict the minimum distance between aircraft. Consequently, FFAS is defined as airspace restricted to aircraft equipped with the following systems or capabilities:

- a Flight Management System (FMS) which predicts the trajectory and guides the aircraft accordingly,
- advanced surveillance capabilities (typically using ADS-B technology) which enables the aircraft to exchange flight states and trajectory intents,
- conflict detection capabilities,
- inter aircraft maneuvering coordination capabilities (implementation of EFR),
- a CDTI to display the traffic and other information related to conflict detection and resolution.

In the OCD, the role of the ground component in FFAS is limited to:

- overall supervision of the traffic situation, possibly also insuring that the traffic complexity is compatible with the on board equipment capability,
- Non-nominal operations handling, sometimes referred to as “control by exception”, including search and rescue.

Ground would be relieved of the tactical handling of the traffic. Such concept is foreseen in low-density airspace like the one encountered over Northern Scandinavia or in upper upper airspace (typically FL350 and above). One of the key issues to be tackled is the identification of the upper airspace density limit. Hence, for this reason, relatively high-density airspace was retained in the design of the experimental scenarios.
To support autonomous operations where aircraft are responsible for ensuring separation, the following tasks, normally performed on the ground by the controllers, have been transferred to the air:

- Conflict detection
- Conflict situation display
- Priority determination
- Conflict resolution

CONFLICT DETECTION - The background task to be performed by the on board system while in autonomous operation mode consists of:

- predicting the closest points of approach (CPA) between the own aircraft and each of the other aircraft within the surveillance range,
- computing the distances between the aircraft at each CPA and
- comparing each of the results with separation minima.

A conflict is detected between the own and any other aircraft for which the distance at the CPA is smaller than the separation minima. There is no known formula in the relevant International Civil Aviation Organization (ICAO) manuals to take into account airborne dependent surveillance information in the derivation of separation minima. For the purpose of the experiment, a typical ground surveillance-based minima of 6 NM has been retained.

The prediction of the CPA is using the trajectory intent information broadcast by the aircraft. Hence, any trajectory modification must be broadcast as soon as activated.

CONFLICT SITUATION DISPLAY - Conflict situations are depicted graphically by a set of forbidden zones on the navigation display. Forbidden zones are of two types:

- A conflict zone is an area corresponding to the portion of the airspace where the separation between two aircraft trajectories is infringed (see Figure 2).
- A no-go zone is an area corresponding to the portion of the airspace where the separation between two aircraft trajectories could be infringed due to a trajectory change (maneuver).

PRIORITY - In a given pair-wise encounter, one aircraft is assigned the responsibility to solve the conflict through a set of rules. A priority level is allocated to all aircraft involved in the conflict, the one with lowest value shall modify its trajectory to make it conflict free, the other has the right of way and may stay on its original trajectory.

A simplified version of the EFR [4] has been implemented and can be described through the following:

1. High priority is given to a descending aircraft,
2. Medium priority is given to an aircraft flying level,
3. Low priority is given to a climbing aircraft.
4. In case of tie, the aircraft closest to the point of loss of separation has higher priority.
5. Should everything still be equal, the unique identifier of the communication equipment is used to break the tie (e.g. lowest level of priority to first alphanumerical order).

CONFLICT Solving - The resolution task consists in re-planning the aircraft trajectory so that it is conflict free with respect to all other known aircraft trajectories, i.e. it does not intersect any forbidden zone. This requires checking the re-planned trajectory against all other known aircraft intent. As soon as activated the conflict-free trajectory is broadcast.

SIMULATION FACILITY

BASIC PLATFORM - The simulation facility used to perform the experiments is centered on a simplified cockpit simulator manned by the participants, the Multi-aircraft Cockpit Simulator (MCS). The MCS is a simple fixed base flight simulator without any external visual system. The MCS can simulate a range of aircraft types (Boeing 747, Airbus 310 and 320, Fokker 28, Swearingen Metro II). The simulator is composed of a generic cockpit mock-up allowing two-crew operation with a selection of realistic and experimental displays and controls. Advanced flight management functions,
including accurate 4D trajectory prediction and guidance, are provided through the Programme for Harmonized ATM Research in Europe (PHARE) Experimental Flight Management System (EFMS), directly coupled to the autopilot/autothrottle. Two traditional Control and Display Units (CDU), resembling a typical Boeing layout in terms of function keys and pages set can be used to control the EFMS. The MCS also includes glass cockpit functionality through in-house developed Electronic Flight Instrument System (EFIS) with CDTI capability. An alternate means to control the EFMS is supported through the graphical editing of the trajectory on the Navigational Display (ND) with Cursor Control Devices (CCD), track balls installed in the external arm rests of the pilot seats. Various hardware panels allow for the control of the display modes, autopilot/autothrottle, radios... For the purpose of this experiment, an ASAS module capable of detecting conflicts and providing the pilot with suggested solutions has been integrated in the MCS.

A traffic generator is simulating all other aircraft, in particular those shown on the CDTI. A supervision tool, the Dialog Test Facility (DialTFac) provides the experimenter with an overall control and monitoring facility of all simulation components, in particular through the ability to re-route background traffic to create conflicts (or solve them). No explicit model of ADS-B communication performance has been introduced for this experiment. Position information on all aircraft is exchanged with an update rate of at least 1-second. Trajectory intent information is exchanged every time the trajectory is updated.

CDTI - The CDTI depicts traffic information relative to the aircraft (own-ship) as an overlay on the Navigation Display (ND), using TCAS derived symbols. The information provided consists of the relative position, the track vector, the call-sign, the flight level and a vertical trend arrow indicating whether an aircraft is climbing or descending. The ADS-B useful range is assumed to be 150 NM, therefore all aircraft further away are filtered out.

CONFLICT DETECTION ALGORITHM - The conflict detection algorithm used for this experiment [11] is purely geometric and deterministic, relying on the 4D trajectory intent information from the aircraft. Detected conflicts are filtered on the basis of a look-ahead period: too long a look-ahead may lead to a too high false alarm rate while too short a look-ahead may result in inefficient conflict resolution maneuvers. Fast-time simulations over European airspace (MAICA [13]) indicated that a look-ahead time of 8 minutes should be a good trade-off between the maneuvering efficiency and the rate of false alarms.

CONFLICT ALERTS - Once detected, conflicts are conveyed to the flight crew through the following:

- an aural alert: a synthetic voice announces “Separation Loss” once immediately after detection.
- a change of color or shape of own ship symbol: the symbol is filled in yellow if the aircraft does not have the right of way and simply surrounded by a white square otherwise. The same logic applies for the other aircraft symbol.
- a display of forbidden zones.

The precise display mode of the forbidden zones depends on the priority status:
- If the own ship has to maneuver, all forbidden zones are shown: conflict zones in yellow, no-go zones in gray. The trajectory of the aircraft creating the conflict is displayed as a white dotted line
- If the own ship does not have to maneuver, only the conflict zones are displayed, in gray in this case as in the nominal case the crew does not need to take any action. The trajectory of the aircraft creating the conflict is displayed as a yellow dotted line. Should the pilot want to have a complete view of the situation, a button in the right corner of the ND allows him to switch between the default view, showing only conflict zones and resolution mode, showing all forbidden zones.

On all trajectories, tick marks at one-minute intervals indicate the remaining time before the beginning of the predicted loss of separation. The last tick mark is positioned 3 minutes before the predicted loss of separation (latest time for resolution).

CONFLICT RESOLUTION - Since FFAS is restricted to aircraft using FMS to predict their trajectories, the pilots have to modify their trajectory through the FMS.

The proposed ways of doing solving conflicts are as follows:
- Manual: the pilots insert waypoints either with the CCD on the ND or on the CDU.
- Automatic: the pilot selects with the CCD one of the system generated solutions that avoid all forbidden zones.

In both cases, conflict resolution visual feedback is provided on the ND through the change of color of the past conflict zones. After activation, all zones disappear immediately.

Either manual or automatic mode can be used to perform lateral resolutions. Manual vertical resolution, even though possible through the CDU, is out of scope of the study since no mature vertical display interface is available.
EXPERIMENT

EXPERIMENT OBJECTIVES - In the context of autonomous operation concepts, the objective of this experiment was to collect data and feedback from pilots on issues to be addressed from a cockpit crew perspective to support such concepts. More specifically, the experiment aimed at gathering information on:

1. Flight crew task sharing and procedures in autonomous operations
2. On board automation/tool support required
3. Crew expectations of the ground component (if any)

Among all the questions this experiment was seeking to help answer were the level of assistance required for solving conflicts, the suitable look-ahead time and the behavior in non-nominal situations consisting of another aircraft which did not maneuver in due time as it should have.

The potential interactions between ASAS and ACAS systems, in terms of level of surveillance, logic and data presentation, were out of the scope of this experiment. Any details in terms of explicit layout, symbology or color although they may have a strong impact on the outcome of the experiment are similarly out of scope.

SCENARIOS - In terms of airspace, the Maastricht Upper Airspace Centre with its current route structure was retained. The separation minima were assumed to be 6NM laterally and 1000 ft vertically.

The scenarios were designed so as to submit the pilots to a variety of conflict situations (crossing, head-on, converging) and to avoid learning effects. On average, there were 4 conflicts occurring per 20-minute scenario, an order of magnitude higher compared to what pilots could expect in a low-density airspace [13]. The aim was to have some indications on the maximum acceptable density and to collect more data in the available time frame on conflict handling. Pilots were faced with conflict situations where they had or yielded priority; the former case providing information on their reaction on conflict they did not have explicitly to act upon, the latter providing information on their resolution techniques. The scenarios covered the following flight phases: final climb, cruise, and early descent. Finally, all the encounters were not simple pair-wise conflicts: some were designed to include complex conflict clusters involving more aircraft at the same time, to try to approach the limits of the concept.

Pilots were instructed to solve conflicts at least three minutes before loss of separation. This margin was designed to lead to “small” trajectory deviations compatible with passenger comfort, to provide sufficient time for non-nominal cases handling either by ground or the other aircraft (i.e. an aircraft not yielding the right of way) and to insure clear separation from ACAS/TCAS.

The basic experimental plan combined the following three factors:

1. the conflict resolution mode could be :
   - manual only (pilots had to solve conflicts, using the manual insertion of waypoints only)
   - automatic only (pilots had to solve conflicts, using the solver only)
   - or both (pilots were free to choose which ever one they preferred)
2. the look-ahead time could take two values: 6 minutes or 10 minutes.
3. The situation type could be nominal or non-nominal. In a non-nominal situation, the conflict aircraft fails to take appropriate action in due time.

The direct combination of the three factors resulted in a total of 12 different scenarios. This number was reduced to 10 to meet schedule constraints, each scenario lasting between 15 and 20 minutes. The two non-nominal scenarios where the pilots were forced to use the solver were dropped.

PARTICIPANTS - A total of 18 pilots participated in the experiments, 14 coming from Europe, 4 from the US. 12 of them were captains and 6 first officers. All of them were male. They were all Air Transport rated and currently flying glass cockpits, FMS and ACAS systems. A large majority of the pilots had current Boeing ratings as: 11 of them were qualified on Boeing, 3 on Fokker (1 of them was qualified on both Boeing and Fokker), 3 on Airbus and finally one on Bombardier.

The first 4 pilots performed “pre-trial” sessions aimed at final validation of the experiment setup while the other pilots underwent the normal trial sessions.

SESSIONS - The experiment was performed over 6 sessions from March to December 1999. The same scenarios were used in all sessions. A session was divided into 3 parts: training, simulation flights and debriefing. Each session lasted 2 or 3 days, depending on the number of simultaneous participants.

Despite the fact that pilots all flew the same scenarios, they never encountered exactly the same conditions as the downstream part of any scenario depended on both the timing and the way the first conflict was solved. The sessions were carried out in two steps: Pre-trial sessions and trial sessions.

Pre-trial sessions - A pre-trial session involved 4 SAS pilots. The goal of the pre-trial sessions was to validate the experiment set-up and in particular to provide indications on interface and symbol issues that could
cause subsequent crew to focus on them rather than on the concept.
During these sessions, the pilots clearly identified that the interface was not acceptable to allow the concept evaluation. In particular they exhibited difficulties to find out who had the right of way in a conflict. In order to overcome this problem, the interface was modified as follows:

- The prioritized aircraft indication: The symbol of the aircraft yielding the right of way was changed from outlined in yellow to filled in yellow.
- Manual insertion: The logic retained was modified to be a “direct to” the last manually inserted waypoint: any waypoint too close to the inserted waypoint was automatically removed.
- Area colors: Two distinct colors (yellow for conflict zone if the own aircraft had to maneuver and gray in all other cases) were used to display conflict and no-go zones areas.
- Time before conflict: The presentation of the time before conflict was changed to tick marks spaced by 1 minute intervals from the detection time up to the remaining 3 minutes before conflict, instead of a numerical count down next to the aircraft call sign.

**Trial sessions** - Five sessions involved a total of 14 European and US pilots.

**RESULTS**

Data was collected through observations during the experiments, questionnaires and structured debriefings at the end of each session and some limited system recordings. The actual questionnaire and all the results can be found in [9]. In this section, the data is analyzed, pilots’ suggestions for enhancements are summarized and concept elements requiring further investigation are highlighted.

**ANALYSIS** - The pilots found the system very simple and very efficient to use. This sharply contrasted with their a priori opinion, due to classical pilot apprehensions for radically new concepts that may appear threatening. Such a priori negative opinions have also been observed in other similar experiments [16]. The conflict resolution interface appeared appropriately simple and easy to use despite, according to them, the complex system behind it.

Simulation facility influence - Although over 90% of pilots found that the non standardization of the simulator was not a problem for concept testing, the analysis of the comments showed that the difference in logic between standard equipment and the MCS (in particular the FMS flight plan modification, the EFIS pushbutton options and the use of TCAS symbols) was a source of problems. The pilots found the level of realism of the simulation environment very good for the task they had to perform except for the lack of weather radar display.

**Autonomous operations tasks**

Ground communication - No ground component – ATC – was simulated. Hence, no specific task was assigned to the pilots to contact ATC. This did not cause concern to the flight crew in nominal situations. However, in non-nominal cases or when facing complex conflicts, the pilots would have liked to obtain support from ATC in their decision making process. They stressed that an ATC service provision was required to handle emergency cases or non-nominal situations.

Situation Awareness - Generally, the CDTI significantly enhanced the overall situation awareness in the cockpit. However, in case of non-nominal situations, the information available about the other aircraft, in particular whether its flight crew was aware of and able to solve the conflict, was found to be insufficient; 72% of the pilots requested to be alerted. When having the right of way, 78% of the pilots got worried as soon as the conflict zone popped up. When no conflict was detected the pilots were very relaxed, having in fact very little to do. Their normal display range was most of the time set to 100NM. They appreciated very much being provided with information on the neighboring traffic even though they would have preferred a different filtering logic to prevent display clutter.

The stress level of the pilots raised significantly on oral conflict alerts in particular during the first few scenarios they flew. Two factors contributed to a reduction in stress when reacting to the conflict alerts. First, as they gained experience, they realized that the look-ahead time of either 6 or 10 minutes provided them with ample time for resolution. Secondly, they elaborated a time procedure to handle non-nominal cases. In both cases, one possible contributing factor was that they had to overcome their ACAS training that instructed them to react very quickly.

The pilots changed the range (generally down to 50NM) to see at least part of the trajectory of the conflicting aircraft, but not always the aircraft itself! In case the other aircraft was outside the displayed range, 80% of the pilots rejected an automatic change in range display (i.e. in order to have the encountered aircraft displayed on the screen).

The pilots easily identified the aircraft having to maneuver from its symbol color, in particular for the two aircraft conflicts, 71% showing no hesitation. The pilots had more difficulties, in the case of multiple encounters, to understand the exact priority status of the other aircraft because of the multiple use of the same color. In any case, through their own ship symbol color, they could immediately determine if they had to take an
action. The pilots found difficult to understand from which direction the conflicting aircraft was coming, mainly because of the other aircraft tick marks. In the case of “double conflicts”, they understood immediately through the interface that they were in conflict simultaneously with two distinct aircraft: two yellow zones appeared. However, the actual identification of the two aircraft causing the conflicts proved to be challenging, in particular if one had the right of way while the other was yielding.

When the own-ship had the right of way, no immediate action on the aircraft trajectory was performed. The pilots monitored the situation and in particular the time before loss of separation for a few minutes. Some of the pilots during this time would get prepared by displaying the automatic solution as a backup alternative. Many pilots went through an ad-hoc time-based procedure they had made up for such a case, using the well-accepted displayed tick marks (76% of the pilots) and including communication with the other aircraft. In the 10 minutes look-ahead scenario, from the conflict detection and up to 5 to 6 minutes before the conflict zone they would just monitor the situation. If after a few minutes the other aircraft had not maneuvered they would pretend to call him to know what was happening. If no answer were given within 1 minute by the other aircraft they would start to maneuver even though they had the right of way. This monitoring task induced a high level of stress to the pilots, as they are not used to passively monitor potential dangers. Within their current working procedures, they are trained to act on any danger presented to them. Consequently, with respect to conflict detection alerts, they suggested to provide alerts only when an action is required. An apparent delay by the maneuvering aircraft to handle a conflict could also be a source of major discomfort to the other aircraft flight crew, thus inducing him to prepare a back up solution. While this back up solution is elaborated, the maneuvering aircraft could very well finally solve the conflict; all forbidden zones would then disappear from the display of both aircraft, the back up solution still being displayed. In such a case, the pilots did not know any more the value of the back up solution.

Concerning the actual trajectory building process, the behavior of the pilots was strongly dependent on their experience. If they were used to lot of automatic tools they would systematically display the solver solution just to have a rough idea even though they will end with a manual solution. Others would prefer to elaborate first a mental solution then check with the solver and only then decide.

For flight plan modifications, the crew had no difficulty to use either the manual or the automatic mode, though each mode had its own domain of applicability: the pilots saw the simultaneous availability of both resolution tools as mandatory. Even the more complex situations involving several aircraft simultaneously in conflict, were solved in less than 2 minutes (and about 30s for a simple conflict). Pilots found the manual resolution very efficient. Nevertheless about 20% found it difficult to use, mainly because the insertion logic was not the one implemented on the FMS. The pointing device was very well accepted and seen as a very efficient tool for the type of task that they had to do, in the conditions of the simulator sessions. A recurrent remark from the pilots was that the manual mode should be available at all times and not only when a conflict is detected. The reason put forward was the ability to avoid with this tool other types of no-go zones like bad weather or restricted airspace in addition to those linked to conflicts. In fact, they requested to use the manual graphical resolution for any flight plan modification since it was much easier to use than the quite labor intensive MCDU flight plan modification. The pilots found that the manual solution could be time consuming and workload increasing due to the insertion of several waypoints giving a refined solution. However, time measurements showed that the manual resolution was more efficient as long as no more than three successive waypoints had to be entered. Some limitations of the solver interface could explain the difference between the pilot perception and the observations. It is highly probable that the pilots only included in their timing the span from the moment the automatic solution was displayed on the CDTI to when they accepted it. They might have omitted the time to reach this stage when comparing it with the manual solution. Over 80% of the pilots agreed on a maximum insertion waypoint number of 2, saying that the insertion of more than two forced them to concentrate too much on this task.

During the course of the trials, an indication of the difference in Estimated Time of Arrival (ETA) between the automatic solution and the original flight plan was added. Prior to this, pilots showed great difficulties to choose between solutions. The MCDU was then their sole source of information. Their lack of familiarity with the non standard page set made it difficult to find the gain or loss of time resulting from flight plan modification. For the trials where the ETA deviation from original flight plan to the modified flight plan was indicated directly on the ND, the pilots always chose the shortest solution time wise.

A crosscheck between the two-crew members was always performed before asserting that the conflict was over. Pilots had a tendency during their first few sessions to closely monitor the intruder aircraft up to the point where both flight paths appeared diverging. This ceased as they gained enough confidence in the overall system. However over 70% of the pilots requested to have means available to monitor the encountered aircraft until it has passed the crossing of the tracks. Even though, during the sessions, they did not systematically display the encountered aircraft.
Time anticipation - Both look ahead times tested, 6 and 10 minutes, were found by pilots very comfortable providing them with sufficient time for resolution in nearly all cases. The pilots expressed their preference for the 10 minutes look-ahead time. It would lead to only minor diversions from original flight plan in case the own aircraft is yielding and also because, in case the other aircraft is yielding but had not reacted within 4 minutes, the conflict could still be solved even though not in an optimal way. With the 6-minute look-ahead time even if less than 1 minute was required to modify the trajectory, pilots felt that in most cases it would result in too drastic maneuvering for the aircraft. Interestingly, currently over the denser part of Europe, the average transit time through some ATC sector is below 5 minutes, implying that air traffic controllers are routinely providing separation with a look ahead time of less than 5 minutes. However, there is no report that their clearances lead to too drastic maneuvering.

Interface evaluation - The expectation was to get feedback from the experiment on the acceptability of the interface in terms of the pertinence of displayed information, of the perception of the situation (through color change or symbols), and of the acceptability of the size and resolution of the interface (in particular in view of display clutter). From the comparison between pre-trial and trial session results, it is clear that the display modifications appropriately corrected the pre-trials shortcomings.

The symbol and text labels were easily understandable by 50% of the pre-trial pilots and by all but one of the trial pilots. Although facing similar conflict situations, only 60% of pre trial pilots compared to 100% of trial pilots found the display size/resolution adequate. The enhanced logic and color scheme seemed to allow the pilots to quickly grasp the required conflict information without having to stare at the ND, hence removing the issue of clutter. Pilots suggested differentiating surrounding aircraft with three colors depending on their altitude relative to own ship. A stricter adherence to symbol and color scheme standards (Airbus or Boeing) was strongly recommended.

From the pre trial sessions it appeared that the coloring was not adequate to identify maneuvering responsibility. The interface changes had a positive influence on the results as over 40% of the pilots found it adequate (0% for pre trial sessions).

All pre trial pilots answered that the zones did not conceal information. In fact, they meant that they did not suffer from having information masked for the conflict resolution. Although no hidden information was missing, they agreed on the fact that the transparency of the zones or the implementation of a priority order in the information could improve the conflict situation display. For both conflict and no-go zones, the pilots repeatedly pointed out that further experiments are needed to investigate potential interactions with simultaneous weather radar display. The pilots also requested that he display of conflict zones be triggered both by a certain distance/time criteria and by explicit pilot demand. The rationale is that the pilot may want to modify his trajectory even with no conflict detected and that he should be able to take into account no-go zones when doing so. The pilots’ opinions on the presentation of the conflict zones were highly dependent on the priority criteria. If the other aircraft had the right of way, the conflict zones were found to be adequately displayed in the experiment setup. But if the own aircraft had the right of way, the conflict zones were displayed using the no-go zone color coding, hence possibly misleading the pilots on their nature. They also encountered difficulties in the understanding of the forbidden zone shapes. It was not obvious, for example, that the vertical dimension in the computation could result in the truncation of the zones, despite the fact that the proposed resolutions are always lateral. Pilots also requested to be able to visualize, upon pilot request, the aircraft that create the no-go zones.

In general, there was a tendency in the displays used in the experiment to have too much information, not always de-selectable. From trial sessions, most of the comments were that “nice to know information” should not be automatically displayed by default but available on pilot demand.

The only reported missing information by 72% of the pilots was an indication of whether the other aircraft is going to maneuver or not. They suggested to be provided with an explicit priority reversal mechanism or to have the other aircraft in conflict displayed just when an action was expected from the non-maneuvering aircraft. Two of them relied on the TCAS as a back up. All pre-trial pilots (only 60% of trial pilots) requested to be alerted in case an aircraft not assigned to maneuver, starts maneuvering. The reason for this request could be due to the priority identification that was not adequate during the pre trial sessions and therefore all alerts were welcome. Trial pilots suggested that they would prefer to be alerted of the other pending trajectory modification in order to increase safety and also to minimize deviations from their original flight plan. Pilots suggested that the display on demand of the trajectory, target altitude and separation numerical value of any other aircraft would be nice to have.

From the trials, a number of shortcomings of the solver were identified:
- The available solutions were only displayed on pilot demand.
- There was a lack of a priori check on the availability of a type of solution: directional arrows were shown even if no solution in this direction existed. When two solutions were available, the crew had no
indicator of their relative performance before selection. They had to try them in sequence to conclude which one was more appropriate.

- In case where the own ship had the right of way, a SOLVE prompt was presented on the interface instead of the right and left arrows. It was not obvious to all pilots that clicking on this prompt would allow them to have access to the solver resolution (left and right arrows) and therefore to the no-go zones. The only zone shown was the conflict zone, displayed in such a case using no-go zone color. Therefore some of the pilots thought there was no other forbidden zone.

- Switching between solver mode and manual mode was found to be cumbersome. If none of the solver solutions corresponded exactly to the pilots’ expectations, they would build a solution manually from scratch even though they could have manually modified the automatic solution.

Traffic density - The pilots had the feeling that the traffic represented was roughly as dense as today over Western Europe or US East Coast. This impression was caused by the fact that the scenario used during the simulator session had been prepared with traffic files corresponding to the Maastricht area and all the traffic in between +/-10000 ft around the aircraft altitude was displayed on the CDTI.

From what the pilots had experienced during the experiments, they concluded, with a few restrictions, that the system induced workload stayed well within acceptable bounds especially in the en route phase. Should a vertical resolution mode have been available in addition to the lateral ones complex situations (converging traffic, multiple encounters would have been solved easily and restrictions would be removed.

Concept applicability - As most pilots had experience flying over Africa with no ATC management, they readily concluded that the system would be valuable in low-density areas. Pilots also noted that the majority of the conflict situations detected and presented to them were simple. They believed it quite representative of what to be expected in low-density airspace like Northern Europe or Africa. When facing simple conflicts, 80% of the pilots were confident that the solver, with the manual mode as a back up, was adequate to avoid conflict zones within the assigned time frame (at least 3 minutes before loss of separation) without ATC intervention, 40% thought that they could operate in autonomous mode in all nominal/non-nominal situations including en-route high-density areas. However, over 60% of the pilots would have preferred to have the ATC as a supervisor: the ATC role being to handle all non-nominal cases as envisaged in the time based procedures set up by most pilots in the experiment.

Responsibility - 40% of the pilots did not want to accept the responsibility of the autonomous separation assurance task in any case. 20% accepted the responsibility but only in the case an automatic solution was provided. 40% of those accepting responsibility would not require the automatic resolution to do so. But these pilots also mentioned that the definition of responsibility should not be pushed too far.

PROPOSED ENHANCEMENTS - From the analysis of the experiment results, a number of recommendations can be made for enhancements in the light of subsequent trials.

To significantly improve and extend the experiment results the following enhancements of the overall simulation context are believed to be required:

- Allow route modification with the CCD even if no conflict is detected and provide the corresponding forbidden zones.
- Clarify the role of the ground component in autonomous operations in particular with respect to non-nominal situation handling.
- Present the weather radar overlay on the same screen as the forbidden zones
- Provide vertical resolution options, including a graphical one.

Specific interface enhancements were proposed. Despite the fact that the implemented de-cluttering mechanisms led to a 60% satisfaction rate, further improvements are required. For example, only aircraft that are flying at the same level, climbing towards this level or above, descending towards this level or below should be displayed. The aircraft behind the own ship should not be shown in particular when there is clearly no risk of conflict. Additionally, pilots suggested more elaborate filtering of the surrounding traffic to further reduce display clutter. The aircraft data block/tag content could be dependent on the conflicting/ non-conflicting state.

The main pilot requests on information display are listed below:

- To be informed of conflict detection only in case they had some action to take or to have more information on what was happening on the other aircraft flight deck, in particular when having the right of way. For example the acknowledgement of the conflict priority by the yielding aircraft crew could be conveyed on the other aircraft display through a flashing symbol.
- To display precisely the remaining time before conflict zone.
- In case the own aircraft had the right of way, not to display the conflict zone as a no-go zone.
- To have the longest look ahead time (10 minutes) in order both to fly in a more optimal way and to be able to cover the non-nominal situations.
• To be able to display no-go zones in case of flight plan modification.
• To have, upon request, all information concerning the displayed traffic, although it was quite clear that pilots, in order to resolve a conflict, did not need all information concerning the aircraft being in conflict especially the other aircraft itself (no need for an automatic range).
• The content of the aircraft data tags should be pilot selectable, but it should respect the state-of-the-art logic: e.g. the flight plan data should not disappear on demand and additional information like selected altitude, selected speed, trajectory should be displayable on demand.
• Relative altitude information on the surrounding traffic could be provided through color coding: level at: color1, climbing: color2 and descending: color3

The manual waypoint insertion logic should be changed to reflect current practices. The first entered waypoint should be the direct to waypoint from the present position. The second waypoint entry should be a direct from the first waypoint entry, etc...

A proposed improvement of the automatic resolution tool would consist in letting the system systematically display with no pilot action the best solution, according to an agreed upon criteria, like minimum ETA deviation. The pilot would then have the option to activate it or to access the other solutions generated by the system or even to manually edit the proposed solution.

The need for an operational procedure can probably be traced to the proposed interface and the lack of explicit coordination mechanism. It is expected that the need for this ad-hoc voice procedure would disappear if:
• The system of the aircraft that has to maneuver was able to capture the actual state of the resolution process.
• This information was transmitted and displayed to the other aircraft flight crew.

CONCLUSION

Despite the intrinsic limitations of the experimental environment, this study provides an insight into the potential impact of the separation assurance task in autonomous operation modes on the flight crew work. Key characteristics of encounters in autonomous operations were surveyed through the use of a range of scenarios.

Pilots were observed defining their own cockpit procedures to handle separation assurance in the absence of ATC, covering in particular non-nominal cases. They found the 2 levels of automation support for separation assurance very efficient and intuitive. Furthermore, they subjectively assessed that the additional workload induced by this task was very low, though some concerns were raised on the possible necessity of ATC fallback in non-nominal cases.

The tools provided only depicted graphically the interaction with other aircraft (through no-go and conflict zones). The pilots expressed a need to integrate these zones on the same display with weather information, terrain, and restricted airspace boundaries... A number of other enhancements to the tools were suggested by the pilots, warranting more experiments to get further into the understanding of the feasibility of autonomous operations.

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REFERENCES


