ASAS – INVESTIGATIONS INTO AIRBORNE SEPARATION ASSURANCE IN A DISTRIBUTED SIMULATION ENVIRONMENT

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Abstract

With the introduction of Free Flight in dedicated airspace, investigations into collaborative as well as airborne conflict detection and resolution gain increasing importance.

For airborne conflict detection and resolution, intended flight paths of surrounding aircraft shall not only be computed through extrapolation of the present aircraft position but shall additionally include current FMS flightplan data from intruding aircraft.

Consequently, concerning threat detection and resolution, a specially designed Collision Risk Model was developed, identifying threats with regard to individual navigation performance of the conflicting aircraft. According to ICAO's RNP concept, threats are consequently defined through preset minimum level of safety adjusted dynamically to current aircraft and environment parameters.

The objective of this project is to demonstrate that well adapted resolution advisory algorithms, appropriately displayed on EFIS displays according to a Human Centered Automation Approach, can lead in the light of concepts like EATMS etc. to equally safe but more economic air traffic procedures.

In this context, a distributed simulation environment with high en-route traffic scenarios has been set up. At the Scientific Research Facility as part of the A330/A340 Full Flight Simulator, the Generic Flight Management System and its Human Machine Interface were modified in order to allow the processing and presentation of the newly developed functions and procedures.

1 General Scenario Definition

1.1 System Aspects

The project's aim was to develop an Airborne Separation Assurance System (ASAS) which may be operated in future Free Flight Airspace (FFAS) as well as in currently applied Managed Airspace (MAS) with Collaborative Decision Making (CDM). For this purpose, the Airborne ASAS consists of a suitable onboard interface which is responsible for handling the data exchange between the different systems and a conflict detection algorithm (Conflict Risk Model, CoRiM) which may be switched off during operation in MAS.

Figure 1-1 presents the system modules of ASAS together with the information to be exchanged.

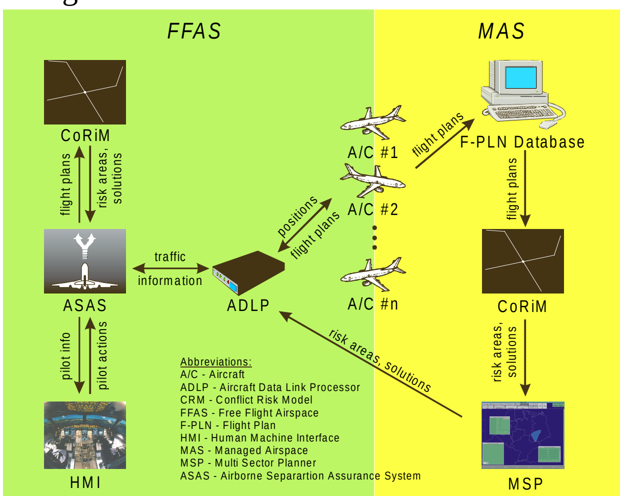

Figure 1-1 Overall System Architecture [1][3]

The ASAS core functionality is connected to an Aircraft Data Link Processor (ADLP) for data exchange with external systems such as other aircraft (A/C) or the Multi Sector Planner (MSP) in MAS. It can process conflict Resolution Proposals (RP) in the form of flight plan modifications from either an onboard CoRiM as well as the ground-based MSP.

1.2 Threat Detection

For the threat detection, a novel approach is being used which no longer refers to rigid separation minima but defines a threat in case a certain Target Level of Safety (TLS) is no longer given for the trajectories of a pair of A/C.

A quantitative assessment of the A/C collision risk (which in turn quantifies a certain Level Of Safety (LOS) at a specific location) requires obviously an estimate of the probability that an accident results in the location *P(x,y)*, this being quantified for all points of the airspace under concern. Statistical models are being developed directly from empirical probability distributions gained through international databases and technical system specifications.

The objective is to develop a statistical model of the true but unknown distribution of the accident probability locations for the different types of airspace under consideration. The model's outcome results in an analytical description of functions representing all points associated with a given risk probability (in the range of 10^{-4} to 10^{-8}). It can be shown, that these functions are of type $y = A\ e^{-Bx}$, thus describing elliptical shapes. [7].

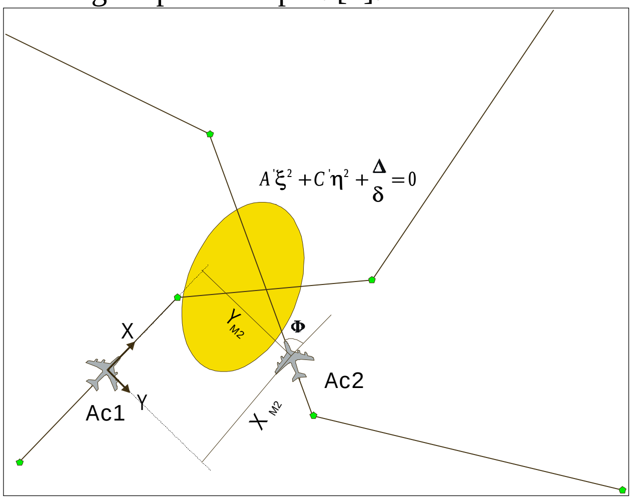

Figure 1-2 Analytical description of CRA [1]

The philosophy of this model aims at making best use of airspace while providing a preset LOS for this area with respect to Actual Navigation Capabilities (ANC) of the A/C operating within. The model not only considers a fixed navigation accuracy of a dedicated A/C but looks also at current the system status for the last position update and others. Within the evaluation phase of this project, investigations are planned with different TLS values and the associated effect of the economic burden implied to the airspace user (higher TLS values will force increasing diversions).

1.3 Resolution Method

The A/C parameters position, altitude and time plus respective derivatives like true air speed, may be modified in order to solve threats. To keep divergences small, an iterative process is searching for the minimum of necessary modifications of one or more of these parameters.

The ranking of generated RP aims at bypassing areas of a high risk level. Once, data exchange between two A/C is available, appropriate RP will be provided to modify at a time flight parameters of one A/C.

1.4 Human Machine Interface

The adaptation of the Human Machine Interface (HMI) finally follows a HCMA ensuring that the final responsibility and decision making will remain with the pilot. The modifications in the cockpit consist of:

- a modified ND with advanced display features
- visual and aural alerting of threats
- opportunities to get additional information about threats and solutions,
- opportunities for the pilots to toggle and choose among multiple solutions.

2 The experimental Environment

2.1 Air Traffic Management Simulation Network

The ATM simulation network of Technische Universität Berlin (TUB) mainly consists of four separate systems which may be operated in a common synthetic environment:

- Flow/Sector Controller Working Position
- A330/340 Full Flight Simulator (FFS)
- DC9 Instrument Flight rules (IFR) Flight Training Device
- Air Traffic Control (ATC) Experimental System

The simulation entities may be accessed either via an Integrated Services Digital Network (ISDN) router or a mountable file system (mainly used by internal applications).

The A330/A340 FFS simulation network environment consists of several IBM workstations providing all necessary functions to develop and apply user-appropriate simulation software. The research computer, called Scientific Research Facility (SRF), being identical to and independent of the training simulator computer, but provided with additional scientific research features such as direct simulator source code access, display development, testing of experimental avionic units, or audio, video and data recording, will be used for software development and validation.

All A/C parameter are organized in a so-called Common Data Base (CDB). The CDB consists of some 60.000 A/C parameter, which can be monitored, sampled and modified on-line. Due to the existence of a display development computer it is possible to process external data on any of the A/C Electronic Flight Instrument System (EFIS) displays, e.g. ATC messages, surrounding air traffic information, Collision Risk Areas (CRA) etc..

2.2 Traffic Generator

As a tool to generate virtual traffic based on flight plan information in a Distributed Interactive Simulation (DIS) scenario, the Generic Air Traffic Simulation (GATS) application "*traffic*" is used. This application is able to replicate generic traffic which can be created by editing dedicated flight plan files containing a flight plan header as well as waypoint information.

2.3 Cockpit Human Machine Interface

The A330/A340 FMS comprises two Flight Management Guidance Envelope Computers (FMGEC), one FMGEC source selector, three MCDU and one Flight Control Unit (FCU). Other crew interfaces are the thrust levers as well as the EFIS which includes the two Primary Flight and Navigation Displays, PFD and ND.

Both the MCDU and ND have been adapted accordingly in order to enable the pilots to interactively negotiate RP messages with ASAS.

The ND has been modified in order to allow for displaying messages issued by the ASAS in its upper area. In addition to an aural signal, the pilots attention may thus be drawn to process a message by this visual indication of the message. Furthermore, it is possible to display surrounding air traffic on the ND according to the project's needs. Additionally, a vertical view mode is available to display the vertical flight profile over distance.

Figure 2-2 presents both interfaces showing the major modifications implemented for RP negotiation purposes.

2.4 The Aircraft Data Link Processor

The ADLP realizes the connection between A/C avionics and the communication network. It collects and encodes the requested data derived by the Generic Flight Management System (GFMS) as well as several A/C sensors and transmits them either as uni- or broadcast message to other entities connected to this network.

The ADLP has been developed during previous projects performed in close co-operation with the Eurocontrol Experimental Centre (EEC) and was constantly updated during this research. It finally comprises the following functionality:

- Initialization function
- Open a connection to the DIS network
- Establish access to the research simulator's CDB
- Enable watch handler to detect modification of transponder code and A/C call sign

- Start additional modules as required for voice communication , Cockpit Display of Traffic Information (CDTI) functions and ASAS-specific functions
- Enable command line interface for the operator to initiate certain program actions, e.g. transmission of an acknowledgement

Position updates are computed and transmitted automatically. The watch handler also ensures the transmission of changes with A/C transponder code or call sign. All other transmissions are performed by the ASAS core module described hereafter.

2.5 ASAS Core Functionality

The purpose of an ASAS is to improve the pilots situation awareness by providing them with information about surrounding air traffic and CRA as well as to improve the airspace system capacity by supplying RP to resolve existing threats for dedicated flight phases.

For this purpose, an add-on module to the previously described ADLP was developed. It's functionality comprises the following functions:

- Initialization function
- Function to decode radio messages :
  1. threat descriptions containing information about location and temporal as well as local expanse of a threat,
  2. CRA represented by a zone type (low, medium, high risk), an altitude band (minimum, maximum), and a list of two-dimensional points (latitude, longitude) describing the area's appearance and size,
  3. RP containing a revised flight plan for either the intruder or own ASAS equipped A/C.
- Function that encodes and transmits a pair of trajectories (own and intruder A/C) from ASAS to CoRiM .
- Function that encodes and transmits a pilot initiated acknowledgement or rejection respectively as reply to a proposed resolution derived by the CoRiM
- Function that encodes and transmits the own A/C active flight plan.

2.6 Conflict Detection and Resolution Module

Taking the own active flight plan (FPLN) as means for computation, a CoRiM software module can be implemented into the A330/A340 FFS, applying the fundamental theory for position estimation to derive potential threat levels induced by intruding A/C.

The CoRiM is generating, based on the minimum separation distance predicted (Closest Approach Point [CAP]) currently three CRA representing a low, medium, and high risk level. The individual values low to high will be subject to the coming cockpit crew evaluations and certain resolution algorithm capabilities [7]. To reach a highly reliable interpolation of the trajectories to be reviewed, a Runge-Kutta algorithm of 2nd order was designed and tested against validated simulator data.

Note: The CoRiM-generated CRA are not equal to frequently discussed No Go Zones (NGZ) which move along with the insertion of resolutions for dedicated threats by the pilots leading to sometimes confusing situations [6].

2.7 Data Exchange Between the Simulation Modules

Figure 2-1 shows the data that are exchanged between the different simulation modules and interfaces.

ASAS continuously checks for A/C located within a range of 80 NM. In this case, it transmits a request for the corresponding flight plan. After having decoded the trajectory, it sends this flight plan to CoRiM together with the own trajectory for threat determination purposes. CoRiM returns a threat description containing "NULL" if no threat was detected.

If a threat occurs, CoRiM computes the corresponding CRA and sends it to ASAS, which hands it over to the HMI together with a threat description message informing the pilot about intruder call sign, CAP, start time and duration of the threat.

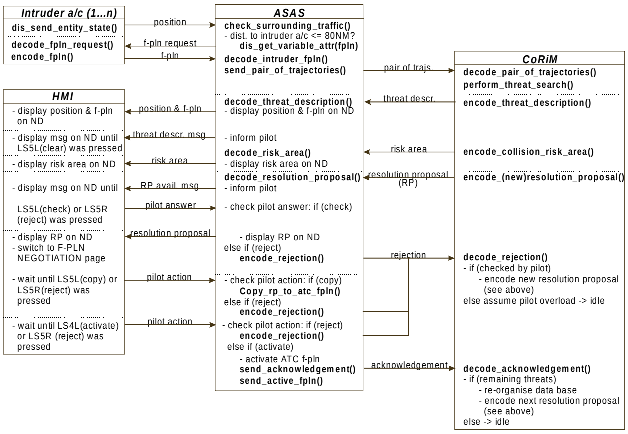

Figure 2-1 Communication Between the Different Simulation Modules

A RP is transmitted to ASAS that informs the pilot about its existence. The pilot may reject or check this proposal which results in an appropriate action by ASAS. If CoRiM receives a pilot initiated rejection message during the negotiation process, it computes a new RP which again is proposed to the pilot. The negotiation ends if the pilot activates the proposed proposal thus initiating the transmission of an acknowledgement message to CoRiM. Additionally, the new active flight plan is broadcast to surrounding traffic for update purposes.

2.8 Interactive Resolution Proposal Negotiation Process

For general, please refer to *Chapter 2.9 Operational Procedures*, for an excellent interactive demonstration, please look at:

http://visual.fb12.tu-berlin.de/ASAS

There a detailed briefing will guide you through the interactive RP negotiation process.

2.9 Operational Procedures

If the onboard conflict detection and resolution algorithm (CoRiM) identifies a threat by another A/C, it computes a threat description and corresponding CRA which are displayed on the cockpit ND. An additional message on the MCDU "DATA LINK INDEX" page – which is called automatically by ASAS – indicates the existence of a RP.

The Pilot Not Flying (PNF) – who's main task is to assist the Pilot Flying (PF) in operating the A/C – may have a first look at the proposed flight plan by selecting "CHECK" (Line Select Key 5 Left, LSK5L). This results in the presentation of the revised flight profile (magenta line) on the ND. Additionally, the MCDU switches to the "FLIGHT PLAN NEGOTIATION PAGE", which represents the available "SEC INDEX" page supplemented by flight plan negotiation capabilities.

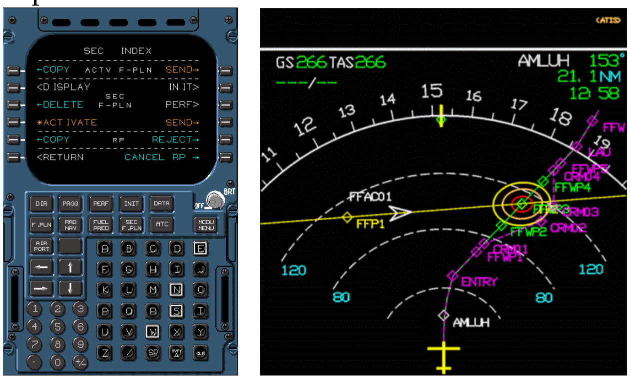

Figure 2-2 MCDU and ND During a RP Negotiation Process

The PNF now may press LSK5L again to copy the RP into the so-called "ATC flight plan". The GFMS automatically computes a corresponding 4D flight profile which may be checked by both pilots. The PNF finally accepts the RP by pressing the "ACTIVATE" button (LSK4L) on the flight plan negotiation page.

The crew may cancel a pending negotiation by pressing the "REJECT" button (LSK5R) on either the "DATA LINK INDEX" or "SEC INDEX" page. If they do so at the beginning of the process without having even checked the RP appearance, an emergency situation or pilot overload is assumed. In this case, no further RP are presented to the crew and the current threat has to be resolved manually via voice communication and/or the help of ATC. If they reject a RP later on during the process, the corresponding RP is judged "inadequate" and a new RP is provided by CoRiM. Again, if no further RP is available the current threat has to be resolved manually via voice communication and/or the help of ATC.

3 ASAS Evaluation Process

The software validation process was performed to prove the appropriate communication between the ASAS core functionality (according to figure 3) and other, peripheral systems. An overview of the corresponding systems and the information exchanged with ASAS is represented below.

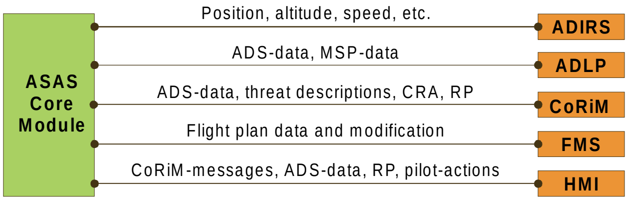

Figure 3-1 Connections between ASAS core functionality and other systems

In the next chapters, the individual functionality according to the system's concept will be summarized being subject to evaluation and validation.

3.1 Data Exchange Between ASAS Core Module and ADIRS

The Air Data Inertial Reference System (ADIRS) computes and processes among other the A/C actual:

- position
- altitude
- speed
- phi, psi, theta etc.

3.2 Data Exchange Between ASAS Core Module and ADLP

The developed software has been organized in a modular manner ensuring that different tasks are being performed in different modules. All modules may be linked together in order to allow a flexible handling of the overall functionality.

The following data are to be exchanged between ASAS core module and ADLP:

- position reports to and from other A/C
- flight plan requests via ADS-B
- flight plans
- trajectory modification message (new active flight plan)

3.3 Data Exchange Between ASAS Core Module and CoRiM

The following data are to be exchanged between ASAS core module and CoRiM:

- position reports from own and other A/C
- flight plans from own and other A/C
- threat descriptions
- CRA
- RP
- acknowledgements and rejections
- trajectory modification message (new active flight plan)

The communication with CoRiM was realized via a so-called packet server using the DIS-protocol. Both systems comprise an appropriate interface for the message exchange.

3.4 Data Exchange Between ASAS Core Module, GFMS, and HMI

Information exchanged between ASAS core module and GFMS comprise:

- position data of other A/C
- flight plan data of own and other A/C
- threat descriptions
- CRA
- RP
- pilot actions on MCDU

4 Experiments with Professional Airline Pilots in the A330/340 FFS

Before the experiment an extensive briefing took place, in which the flight task as well as the special features of the modified system were explained. In this scenario a flight from Hamburg (EDDH) to Vienna (LOWW) was realized. All needed information were supplied in the briefing material and were discussed in addition.

4.1 Airspace Considerations

For either airspace, a specific share of responsibilities between airspace user and supervising ATC unit will be defined:

- For applications within FFAS, threat detection and resolution tasks are being performed on the airborne side reducing the ground side's responsibility to traffic monitoring and short term threat alert, only. Minimum separation in FFAS is 5 NM or an equivalent LOS value with respect to the statistical threat detection algorithm. For vertical separation, Reduced Vertical Separation Minima (RVSM) can be applied.

- Within MAS, separation maintenance tasks remain on the ground side, but conceptually supported through innovative working positions like the MSP with access to a periodically updated flight plan database. The MSP will support medium term threat detection and resolution tasks and provide ASAS configured A/C with respective advisories via datalink

Only A/C with well specified navigation capabilities (according to ICAO's RNP concept) are allowed to enter the FFAS, only. During the experiments, threats will be created in FFAS, exclusively. In order to avoid contradicting resolution maneuvers, A/C operating in FFAS will be informed by any other ASAS equipped A/C, if a resolution negotiation is currently being processed (block signal).

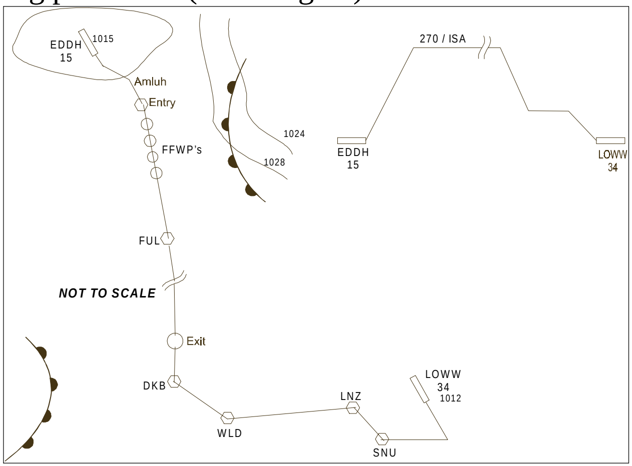

Figure 4-1 Sketch of the Flight Plan Being Applied During the Experiments

While within FFAS, the CoRiM is directly linked as additional avionics module to the ASAS to receive flight plans of surrounding A/C within a range of 80 NM [10]. (refer to Chapter *2.8 Interactive Resolution Proposal Negotiation Process*)

4.2 Participants

For the experiments 34 professional commercial airline pilots (all male) tested this system. Preferred were pilots who had Type-Ratings on Airbus A320, A330 or A340 in order to reduce or even avoid system-training effects during the test.

The average number of flight-hours figures 3753. (counted were only flight hours in glascockpit). The age of testpilots was between 25 and 60 years, mean 35,6 years.

After the experiments a detailed debriefing was done. The experiment was evaluated by an extensive discussion. Therefore a Post-Study System Usability Questionnaire (PSSUQ) [8] was filled out by the pilots. It comprises questions about the system, its interfaces and usability.

5 Results

During the experiments the data of all 34 pilots were analyzed. After the experiment evaluation ideas and remarks of pilots were quoted and together with suggestions in the PSSUQ summarized. As objective data the times of every single interactions with the MCDU were recorded, refer to next chapter *5.1 Recorded interaction times.*

5.1 Recorded interaction times

Table 5-1 gives a summary of the interaction times on the MCDU. In general these individual interactions times are the reception of a threat, the RP negotiation and the activation of the chosen one. Single results show a high scattering of interaction-times for the solving of each conflict. The average time was 116,7 sec.

Interaction on the MCDU (all times in sec)	Mean	min	max
Represents the time between the reception of a threat and the first interaction, the acknowledgement of the threat description message on the ND by pressing "CLEAR". (TD => CL)	**15,9**	3,8	52,4
Time between pressing "CLEAR" key and the next interaction pressing "CHECK" key to pre-view the Resolution Proposal on the ND. (CL/RJ => CH)	**5,8**	1,7	42,2
If the Resolution Proposal was found inadequate, this represents the time between pressing "CHECK" key and pressing "REJECT" key. **(CH=>RJ)**	**13,6**	0,9	73,1
If the Pilot inserts the Resolution Proposal into the SEC FPLN, the time between pressing "CHECK" and pressing "COPY" was calculated. **(CH=>CP)**	**12,1**	1,8	55,3
If the Pilot rejects this in the Secondary Flightplan inserted Resolution Proposal, the time between pressing "COPY" and pressing "REJECT" was calculated. **(CP=>RJ)**	**38,8**	9,4	77,8
This is the time between pressing "COPY" and pressing "ACTIVATE". This interaction will finally accept the choosen Resolution Proposal. **(CP=>AC)**	**25,4**	2,6	90,9
This is the total time of the negotiation process, from first reception of the threat and the final activation of the choosen Resolution Proposal. **(TD=>AC)**	**116,7**	16,6	326,7

Table 5-1 Interaction times for the negotiation process

The whole time for the FPLN negotiation could be as already shown in *Table 5-1* parted in several negotiation steps. Which part each single negotiation step figures could be found in*Figure 5-1*.

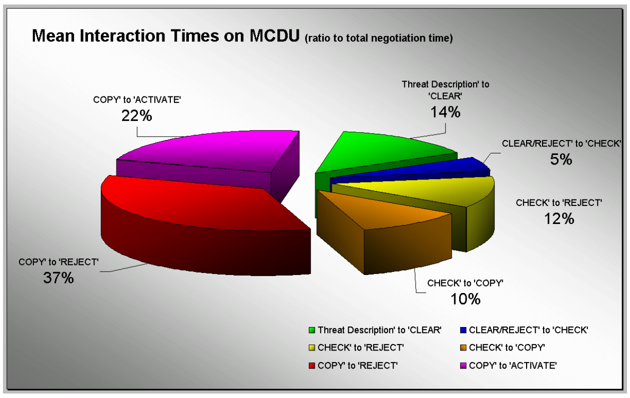

Figure 5-1 Mean interaction times on the MCDU (ratio to total negotiation time)

Please read on in chapter *6.1 Lateral & Vertical Resolution Proposals*.

5.2 The PSSUQ

Figure 5-2 shows a rating-overview of answers given by the pilots. The scale covers ratings from 1 to 7, in full steps. If answered with 1 it means "strongly agree", opposite to a 7 which stands for "strongly disagree".

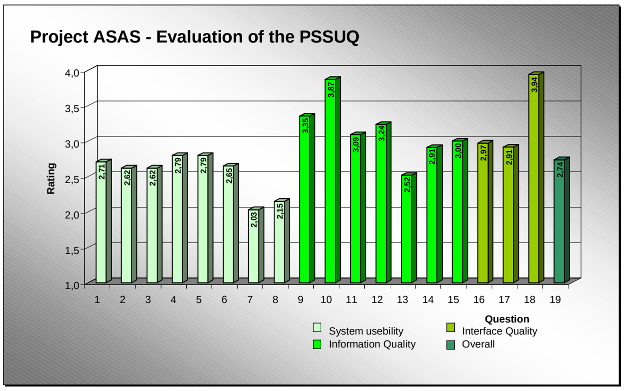

Figure 5-2 Results of the PSSUQ

- **System usability:**
  The rating for the system-usability measures between 2.03 and 2.79 (Mean 2.544).
- **Information Quality:**
  The rating here measures between 2,52 and 3,87 (mean 3,139.
- **Interface Quality:**
  Here the rating lies between 2,91 and 3,94 (3,274) and is significant worse than the rating of the complete system.
- **Overall System satisfaction:**
  The rating of question 19 "Overall, I am satisfied with the system." shows a mean of 2,735.

	Mean	Standard Error	Median
Overall System Acceptance	2,889	0,481	3
System usebility	2,544	0,292	2,5
Information Quality	3,139	0,419	3
Interface Quality	3,274	0,577	3

Table 5-2 Summary of the PSSUQ Results

Finally the collected data were examined regarding a statistical relationship. The for this kind of experiment relatively high number of participating pilots (34) make a sensible analysis possible. The following questioning was investigated:

- Is there a significant statistical relationship between system evaluation and the age of pilots or their number of Flight hours?

A correlation analysis was computed. Then a t-Test (Pearson & Hartley) was figured and evaluated [11]. The results are listed in *Table 5-3*.

This analysis judged a correlation coefficient of $r_{xy}=0.237$. A test for statistical significance showed that this correlation was significant for the pilots age. ($t(34)=1.307, p<.10$)

The conclusion is that with higher age the rating of the system becomes worse.

Project ASAS - Correlation and t-Test for PSSUQ (Mean, Overall 1-19)				
	Age (years)		Flight hours in Glascockpit	Mean, Overall 1-19
$\bar{x}$	35,65		3752,94	2,889
σ^2	- - -		- - -	0,589
r_{xy}	0,237		0,062	- - -
df	34		34	- - -
t	1,380		0,350	- - -
p	0,10	0.05	0,10	- - -
t_{crit}	1,307	1,691	1,307	- - -

Table 5-3 Project ASAS - Correlation and t-Test for PSSUQ Mean(Overall 1-19)

6 Discussion

6.1 Lateral & Vertical Resolution Proposals

The presented RP were lateral and vertical suggestions. During a discussion with the pilots in the de-briefing the following point of views were expressed:

pro	contra
+ easy to understand + presentation and meaning is clear + decision making much quicker	- deviation - costs time and fuel

pro	contra
+ no deviation + more economic, needs less time and fuel then lateral	- Engine power changes necessary - reduces passenger comfort (pitch-changes) - leaving the optimum altitude

Table 6-1 Lateral and vertical RP Arguments

The argument of a greater clearness of the lateral RP is closely connected with pilots effort for the evaluation of a RP. If vertical RP displayable as good as the lateral ones (at the moment vertical RP only evaluable on the MCDU. a better acceptance could be assumed.

Altogether 71% lateral and 29% vertical RP were accepted by the pilots. Interesting was that pilots in 54% have chosen the first provided RP by the system.

Summery: The lateral RP during a real Free Flight (A/C before conflict is on its optimum Altitude.) have a greater acceptance by most of the pilots. Looking at it from the economical point of view the lateral RP is slightly less economic from the vertical one. For the complete system and a great number of possible side-conditions within the conflict-occurrence and conflict-resolution in a FFAS the existence of lateral <u>and</u> vertical RP is essential.

6.2 Variation of look ahead-times

How long beforehand this system may be able to predict conflicts, is difficult to answer. One important aspect for how quick it could react is the duration of negotiation between pilot and system. On the other hand the quality (accuracy) of the for conflict detection available data become with greater look-ahead-time more and more inaccurate up to the moment when they are absolutely not useable for the purpose of conflict detection. It is therefore important to compromise and border the system.

Because of the results of this experiment it is necessary to express, that this introduced system has to work with a look ahead time (range) of <u>at least</u> 80NM (approx.: 600 sec). This number equals directly out of the RIT (Remaining Implementation Time) for a specific RP (typical 360 sec) and the duration of flight-plan negotiation with the system (in ASAS a maximum 326 sec occurs).

As far as possible the data of FMS of concerned A/C could be provided with a corresponding accuracy even if the distance is greater than 80 NM, the look ahead times should be increased to a measure of 120 NM (approx.: 900 sec). Necessary is this in the context to the co-ordinated resolutions (both A/C interact to avoid a conflict), which fundamentally have a higher time consume.

7 Conclusion

The major goal of this project was to show that a well adapted resolution advisory algorithm for Free Flight scenarios (provided air-air and air-ground data link capabilities) including a well adapted visualization on the EFIS displays, takes as remarkable contribution in a more economic handling of air traffic while maintaining current level of safety standard.

For the complete procedure of conflict-detection, air-air negotiation and conflict-resolution, a suitable scenario was developed based upon the one that existed already in project ASAS and was used successfully.

The developed functions were intensively tested by 34 professional airline pilots. The so obtained results were discussed in detail and explained later on. A statistical evaluation of a suitable questionnaire as well as the evaluation of interaction-times of every single pilot with the modified HMI was realized.

The gained results give a comprehensive summary of the system acceptance by the pilots as well as the necessary technical requirements in the cockpit.

To summarize participating pilots judged ASAS generally useful and helping within a future Free Flight concept. This concerns the way of conflict detection, negotiation and solution, as well as the system operation and the visualization of necessary data.

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