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COCKPIT SYSTEMS REQUIREMENTS IN A FUTURE ATM ENVIRONMENT

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Abbreviations

ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
ATS	Auto Throttle System
CDU	Control & Display Unit
CTAS	Center Tracon Automation System
DA	Descent Advisor
FAST	Final Approach Spacing Tool
FD	Flight Director
FMP	Flight Mode Panel
FMS	Flight Management System
FMt	Flight Management Concept Verification
FPA	Flight Path Angle
FPD	Flight Path Director
FPV	Flight Path Vector
IAF	Initial Approach Fix
NARSIM	NLR ATC Research Simulator
PNP	Profile Negotiation Process
RFS	Research Flight Simulator
RTA	Required Time of Arrival
SDA	Standard Descent Advisory
TMA	Traffic Management Advisor

Abstract

This paper describes an evaluation study on a number of cockpit concepts, performed at the NLR. The study was aimed at finding minimum cockpit systems requirements necessary to operate a regional aircraft efficiently and safely in a future ATM environment. Initially, a pilot experiment was performed to evaluate a number of proposed flight control and display concepts with respect to workload and situational awareness, compared to current implementations. Since future aircraft will have to operate in a busy environment with tight navigation and time constraints, this may require an improved cockpit design to compensate for the additional pilot workload. Based on the experience gained from the pilot experiment, a combined ATC-aircraft simulation evaluation was conducted utilising NLR's moving base Research Flight Simulator and ATC Research Simulator. Apart from an evaluation of the most promising cockpit concepts in a realistic environment, the study also addressed the application of two proposed 4D Air Traffic Management concepts. The latter required the use of additional FMS functionality and ATC-aircraft datalink, as well as an adapted version of the Center Tracon Automation System, used for ATC planning and control. Results of the evaluation study included subjective comments of the participating pilots.

Background

The flight simulator evaluation described in this paper is part of the "Flight Management Concept Verification" (FMt) program. The research was conducted within the "Aircraft Technology Program" (*Vliegtuig Technologie Programma*, VTP) sponsored by the Netherlands Agency for Aerospace Programs (NIVR) and carried out in cooperation with Fokker Aircraft. The knowledge obtained from this program was aimed at the development of minimum requirements for a next generation commuter aircraft.

It is anticipated that future aircraft will have to be able to operate in a busy ATM environment requiring accurate navigation in both position and time. To compensate for the higher workload of the flight crew to meet these requirements in an efficient and safe way, an improved flightdeck design may be required. The systems concerned in the study include both control systems, flight displays, FMS as well as the operational aspects related to 4D navigation and ATC datalink.

Introduction

The FMt research program started initially with a series of pilot experiments to evaluate two control and a number of display concepts aimed at improving the performance, situational awareness and workload during manual flight. An earlier fixed base simulator study(1)

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already identified a flight path vector command system being a promising concept for further development. Two (manual) control concepts were termed "manual control" and "enhanced manual control". In this study, "enhanced manual control" is used to denote the flight path vector command system providing stabilisation and control augmentation with control inputs via conventional cockpit controls (see Figure 1). "Manual control" is used to designate a conventional manual control system with only yaw damping and turn coordination provided.

The pilot experiments were conducted using the NLR moving base Research Flight Simulator (RFS) only. The initial experiment was carried out to compare the two manual control concepts and to make a selection of promising display concepts.

The following flight director displays were evaluated in combination with the manual flight control concepts:
- conventional Flight Director with cross bars (Figure 2)
- Flight Path Vector (FPV) display with Cross Flight Path Director (FPD, see Figure 3)
- Flight Path Vector display with rotating "ghost aircraft" Flight Path Director (Figure 4)

Both technical pilots and airline pilots participated each one day in the evaluations(2,3), which consisted of a series of tracking tasks to be performed for each of the six control and display modes, ie. speed, altitude and heading changes as well as configuration changes. To conclude each concept, a curved precision MLS approach was carried out to touchdown. All scenarios were flown under instrument and adverse weather conditions, ie. heavy turbulence.

The airline pilots were also subjected to a so-called double task experiment to objectively compare the workload using the two control concepts. As a primary task, the subjects were requested to fly the curved MLS approach while performing a Continuous Memory Task (CMT) as a secondary task. This CMT, listening and counting target letters received through the headset, was used to measure the spare mental capacity during the curved approach tracking. As a reference, the CMT was also conducted without flying.

Evaluation set-up

Continuing on the results from the pilot experiments, preparations were made for an combined ATC-aircraft simulation employing ATC datalink and 4D navigation. The objective was to expose the crews to a realistic operating environment involving both ATC clearances and other traffic, in order to examine the selected concepts from both aircraft as well as ATC side.

Research Aircraft

A preliminary aircraft design study, codename P370-II, of a fast short-to-medium range advanced turboprop was used as a development platform throughout the entire project. This 80 passenger commuter aircraft has a projected cruise speed of Mach 0.72/300 kts and MTOW of 30.000 kg. The aerodynamic model of the basic aircraft, covering the entire flight envelope, was derived using handbook methods. The engine performance was modeled to represent the predicted performance of the counter-rotating turboprop powerplant design as given by the engine manufacturer.

Three different flight control concepts were used which varied with respect to the level of automation in the control and stabilisation of the aircraft. Apart from manual control and enhanced manual control, the highest level of automation provided Automatic flight by means of an autopilot. Speed holding and flight envelope protection was permanently available by the autothrottle system. For the purpose of the experiments a realistic implementation of Manual, Enhanced Manual and Automatic control has been made. The manual control concepts were already verified during the pilot experiments

Conventional Manual Control. Being the baseline concept, the Manual flight control concept provides the control architecture found in most contemporary aircraft by means of conventional controls. Part of the workload is reduced by a yawdamper/turn-coordinator system as well as the autothrottle system. The Manual flight control concept consists of the following:
- conventional pitch, roll and yaw control by means of direct control of the control surfaces,
- turn coordination and Dutch roll damping is provided by a yawdamper/turn-coordinator,
- an autothrottle system for speed holding and envelope protection,
- trim by pilot operated switches on the control wheel or directly by turning the trim wheel.

The basic aircraft shows realistic steering forces and handling qualities conforming to typical Fokker flight handling requirements. This sometimes required the initial (handbook derived) aerodynamic model to be adjusted to meet these requirements. The handling qualities of the basic aircraft have been validated by a test pilot prior to the execution of the evaluations.

Enhanced Manual Control System. The objective of the Enhanced Manual flight control concept is to provide improved handling qualities relative to the conventional means of control. The handling qualities improvement is achieved by automatic stabilization around all axes, as well as relieving the pilot of trimming the stabilizer after changing the aircraft configuration or speed. Within the normal operating flight envelope the control system maintains the set flight path angle and bank angle after the pilot releases the controls. The use of the auto-throttle system is necessary for optimal operation of the Enhanced Manual flight control system, mainly due to the fact that a flight path angle controller removes the natural speed stability around the trimmed speed which is no longer the trimmed parameter.

Without pilot input, the combination of flight control system and auto-throttle system provides flight envelope protection. However, the pilot is still able to exceed the limits of this envelope by overriding through direct control. The envelope protection system is only implemented in its basic form and should be further optimised in the future. The Enhanced Manual flight control concept provides the following:

- flight path, roll and yaw control using pilot inputs through conventional input devices. The pilot commands flight path angle through the control column and roll angle via the control wheel,
- a flight control system providing automatic stabilization in all axes. The aircraft maintains commanded flight path angle and bank angle within the limits of the flight envelope after release of pilot input,
- an automatic stabilizer trim which is incorporated in the flight control system,
- a yawdamper/turn-coordinator system which is permanently engaged,
- an autothrottle system for speed holding and envelope protection.

The enhanced manual control system was implemented such that input force and displacement resemble those of the Manual control mode, although the pilot controls the airplane in a different manner, ie. provides set points to the flight path and roll angle controller.

During the pilot experiments, this control system was rated to give a great improvement in handling and a noticeable decrease in workload, especially under adverse weather conditions (ie. turbulence). The effect of automatic stabilizer trim was much appreciated by the pilots.

Automatic Control System. The autopilot shares its inner loop control laws with that of the Enhanced Manual Controller. The outer loop structure is that of the common autopilot design of the RFS(5,6), with all autopilot modes selectable through the Flight Mode Panel (FMP), including FMS controlled VNAV and LNAV navigation.

Cockpit flight displays. The RFS flight deck provides a full glass cockpit with the layout and symbology of the Primary Flight Display and Navigation Display based on that of the Fokker 100(5). Following the pilot experiments and preparations for 4D FMS navigation, the following changes were made to the PFD:

- The Flight Director presentation is based on a Flight Path Angle (FPA) presentation as opposed to the conventional pitch attitude boresight with crossbar presentation. The FPA symbol is shown as a circle with wings and tail. Compared to the FPV, the drift is removed so the symbol moves only vertically on the pitch ladder. A Flight Path Director symbol is positioned relative to the FPA symbol and provides both pitch and roll guidance, and is very similar to a conventional crossbar flight director. The FPD symbol is presented as a cross, giving the pilot a target which should be matched by the FPA symbol.
- The attitude boresight (the small square on the pitch ladder used to target the conventional crossbars and to accurately gauge pitch attitude) was removed from the display. This was done during the pilot experiments to reduce the clutter which occurred during both cruise and approach, since for this aircraft pitch and flight path angle are of the same magnitude during these flight phases.
- Speed and altitude targets from the FMS were presented as green (triangle) reference bugs on the speed and altitude tape respectively.

In the conventional Manual Control mode, the FPA symbol is positioned at the actual flight path angle, whereas, under Enhanced Manual Control, the FPA symbol indicates the commanded FPA.

The navigation display remained almost unchanged. One of the visible changes was the addition of the (curved) lateral trend vector, which is also incorporated in aircraft such as the 747-400 and MD-11. The curved trend vector gives a wind-corrected prediction of lateral flight path based on bank angle and speed, hence the path shown is ground referenced. The trend vector is shown as three consecutive circle segments with each segment representing a 30 seconds prediction, giving the pilot a 90 seconds forward look.

The central display between the left and right cockpit positions served a dual purpose (see Figure 5). The left side of the display was used as an engine display and provided an indication of the demanded (white bars) and actual (green bars) thrust produced by each engine, instead of giving an indirect measure of thrust through engine EPR or N1. This concept was adopted from extensive NASA research on the Engine Monitoring and Control System(7,8).

The right part of the display was developed to assist the crew in the 4D time management task. This display was positioned on the Engine display for reasons of available display space. The concept of the time display was to provide a graphical interface with the timing aspects of 4D navigation, indicating the Required Time of Arrival (ie. ATC constraint), Estimated Time of Arrival and both earliest and latest possible time over the required waypoint. In addition, the time display had the additional display accuracy in seconds.

Flight Management System. The Research Flight Management System (RFMS) installed in the simulator is based on the functionality of the FMS currently used in the Boeing 747-400. Towards the pilot programming and operation are similar to that of an operational FMS as installed on the aircraft. However, the internal software structure is entirely different and has been extended for other research studies. To meet the accurate time constraints along the flight path which were the subject of the study, the following enhancements were implemented in the FMS software:

- closed loop control of Required Time of Arrival per selectable waypoint
- ATC Datalink compatibility

ATC environment

The air traffic management environment (see Figure 6) in the combined aircraft-ATC evaluation is based on the following systems. The NLR ATC Research Simulator (NARSIM) provided the radar and other air traffic simulation as well as the air-ground interface within the ATM environment. All air-ground datalink messages between the RFS aircraft simulation and the ATM environment were handled by the NARSIM using the standard RTCA datalink protocol(9) with some extensions to be able to handle the negotiation processes described below.

The ATC tools, to enable 4D planning and control, were provided by an adapted version of the NASA developed Center TRACON Automation System (CTAS) (10), and tailored to the Amsterdam airspace structure. CTAS comprises an integrated set of tools to assist in efficiently managing the arriving traffic and has three major components: Traffic Management Advisor (TMA), Descent Advisor (DA) and the Final Approach Spacing Tool (FAST). The TMA assists the traffic with the sequencing and scheduling of traffic. The DA assists radar controllers in meeting the TMA's arrival schedule for the Initial Approach Fixes while maintaining separation. FAST assists approach controllers in fine-tuning the arrival flow until the final approach fix.

Traffic Management Advisor. The TMA function constitutes the planning part within CTAS and determines the most efficient sequence of traffic to the runways. This planning is already started at cruise altitude well before top-of-descent. For all arriving traffic, ie. including the RFS aircraft, a scheduled time of arrival (STA) is calculated, based on radar updates, wind profile information for the descent and aircraft performance data.

Descent Advisor. The DA, using flight plan information and calculated STA, determines a conflict free top-of-descent as well as airspeed during descent, to meet the arrival time over the Initial Approach Fix, at which point the aircraft enters the terminal area for final vectoring. Depending on equipment status of the aircraft different advisories can be generated. For 4D FMS-equipped aircraft, the Profile Negotiation Process (PNP) can be used. Other aircraft (non-FMS or 2D FMS equipped) are given a Standard Descent Advice (SDA). Both procedures were evaluated by simulating a 2D or 4D FMS equipped aircraft.

Profile Negotiation Process: Since both CTAS and the aircraft onboard FMS are able to compute their optimal vertical path, the so-called Profile Negotiation Process (PNP) is used to coordinate between the FMS and ATC (see Figure 7), to come to both a conflict free and optimum descent path. The process is initiated through datalink by ATC, which sends a proposed route including all restrictions and a required time of arrival at a given metering point, in this case the initial approach fix. This proposed profile can be loaded automatically into the FMS for verification and onboard calculation of top-of-descent and vertical profile. The on-board solution is then returned to ATC via datalink, after which CTAS verifies the FMS computed profile. In case of a conflict free solution, an ATC clearance is sent to the aircraft containing the agreed route and profile. This clearance has to be confirmed by the crew, after which the aircraft is required to adhere to the route clearance in both position and time. In case of any planning conflict, the process can be repeated until a solution is found between ATC and aircraft.

Standard Descent Advisory: In case the aircraft is not equipped with an FMS capable of vertical navigation, the process is somewhat simplified. Using the conflict free vertical profile as predicted by the Descent Advisor to meet the scheduled time of arrival, CTAS now sends a Standard Descent Advice via datalink to the aircraft. This SDA consists of a top-of-descent and airspeed during descent, ie. without required time of arrival. Only "open-loop" control of the arrival time over the metering fix is established, as opposed to the "closed-loop" control of the required time of arrival within the FMS in the PNP case.

Final Approach Spacing Tool. After an aircraft passed the metering fix, the aircraft were handed over to Schiphol Approach Control. In the terminal area, the CTAS Final Approach Spacing Tool (FAST) was used to assist the controller giving vectoring advisories to obtain an optimal line-up of the arriving traffic. The advisories were displayed on the plan view display used by the approach controller. For the purpose of this evaluation, all vectors and clearances until touchdown were issued via datalink and were to be read on the CDU in the cockpit.

Flight scenarios

All flight scenarios were based on a typical commuter flight within Europe, ie. an approximately one hour flight from Paris Charles de Gaulle to Amsterdam Airport Schiphol. The normally complicated airspace structure between Paris and Amsterdam with multiple sectors was simplified for this evaluation. This limited the amount of upper control sectors to two but did not interfere with the purpose of the experiment. The following variations could be made to the scenarios:

- two different airway routings,
- complete flights from gate-to-gate as well as flights initiated at cruise altitude halfway the route,
- no wind and conditions with wind, as well as en-route changes due to thunderstorm activity
- light or heavy traffic scenarios,
- Profile Negotiation vs. Standard Descent Advisories.

Figure 8 shows one of the routes flown during the evaluations. Figure 9 provides a monochrome screenshot of the (colour) plan view displays used by the controllers during the evaluation.

Results and conclusions

A series of evaluations were conducted to evaluate a number of concepts aimed at an improved cockpit design. Three technical and five airline pilots participated in the pilot experiments, which gave the following results:

- The Enhanced Manual Control system yielded equal or better performance compared to manual control, while both subjective as well as objective pilot workload measurements reduced. The Enhanced Manual control system shows only improved performance under high workload situations.
- Subjective ratings for the pitch and roll situational awareness improved using Enhanced Manual control.
- Workload was not significantly affected by using a Flight Director based on Flight Path Vector compared to a conventional crossbar flight director.
- The cross type Flight Path Director showed improved pitch situational awareness while providing equal accuracy compared to conventional cross bars. The display with the rotating "ghost type" flight director did not increase pitch situational awareness. Roll awareness did not seem to be affected by display type.
- Drift information was preferred not to be visible on the FPV and FPD symbols, as this gave a dynamic and asymmetric presentation of the tracking parameters during turns and crosswind. This issue has already been addressed during the development of the RAF military HUD format(4). A separate drift symbol was recommended.

Five pilots, all with an experimental flying background, participated in the full flight demonstrations. Pilots were free to select the control mode at their discretion to evaluate all aspects during flight. Apart from the training scenarios, a total of eight PNP and eight SDA scenarios were flown, during which the subjects gave their comments.

The method of issuing strategic ATC clearances, both PNP and SDA, by means of datalink was much appreciated. The pilots liked the silent flightdeck and the unambiguous communication as being big advantages over voice radiotelephony. Also the availability of ATIS information via datalink and displayed on the CDU was more convenient, less time consuming and error-free.

The tactical clearances, given via datalink in the terminal area for vectoring to the runway, were regarded as less favourable compared to voice communication. The increased workload and head-down time for the pilot not flying and the removed "party line" effect when using voice R/T were regarded as a drawback in a busy traffic environment, where the crew should be looking outside instead of typing clearances.

During the flights using the Profile Negotiation Process, it proved to take several minutes between initiation and issuing of the final PNP clearance. This may partly have been due to inexperience of the crews. The crews also cited the many keyboard entries as a drawback, the procedure appeared to be a repetition of steps. For a controller, such a time span may be unacceptably long, as he has to divide attention to other traffic as well. After the PNP clearance was given however and the FMS assumed RTA control, very accurate arrival times (within 5 sec) over the metering fix were achieved.

The Standard Descent Advisories proved easy to work with, both for the controller and the crews. A good representation of the aircraft's performance and company preferences within CTAS is essential for optimum planning. Once this is established, it is possible to arrive at an overall optimum of all traffic. A simple FMS with only LNAV is then sufficient within the aircraft.

The Enhanced Manual Control concept received high marks. Pilots cited much lower workload and more spare time for other activities while remaining in the control loop. Lack of speed stability was a concern to a few pilots. Providing the aircraft has acceptable basic handling qualities, however, the application of enhanced manual control could be limited since the aircraft will be under autopilot control most of the time.

The flight path director (FPD) presentation was well appreciated during the pilot experiments. During the gate-to-gate flight scenarios, which included take-off, it appeared that the boresight, which had been removed to reduce clutter with the FPA and FPD during flight, was badly missed during take-off and initial climb. The addition of a less-intrusive boresight is therefore recommended.

The proposed engine (thrust) display received many comments and needs a review to acquire a better understanding of its merits. During the evaluations, it became also clear that an engine display is not used intensively apart from take-off.

In addition, the time display was merely used to monitor the required time of arrival, and not used for control purposes or in assisting the negotiation process as was the initial assumption of its use.

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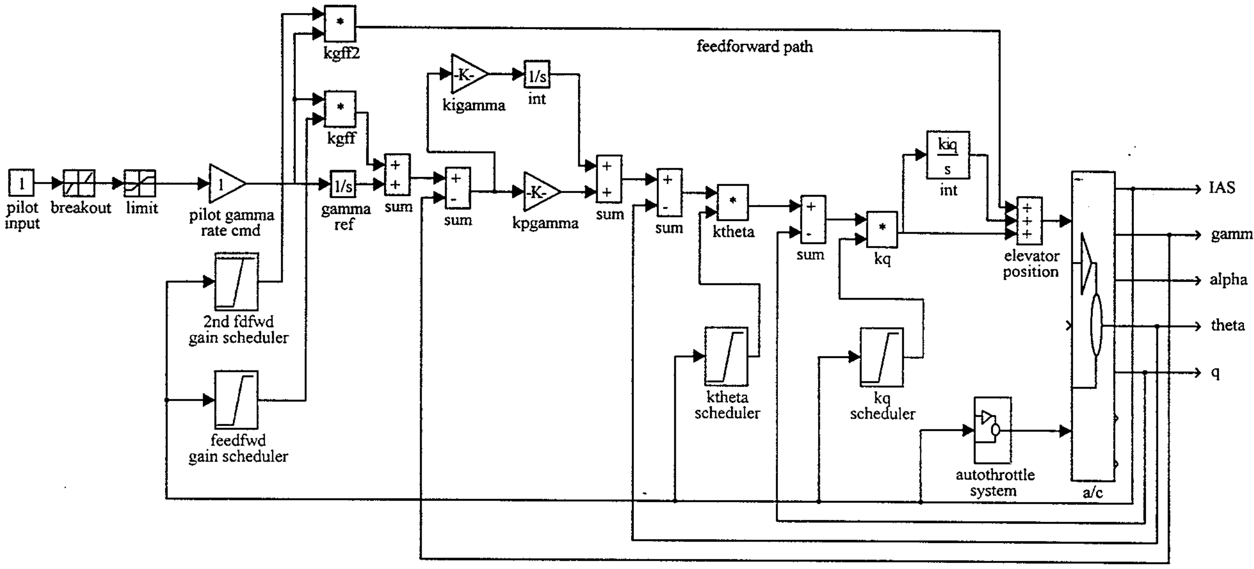

Figure 1 - Generic diagram of Enhanced manual control system, pitch axis

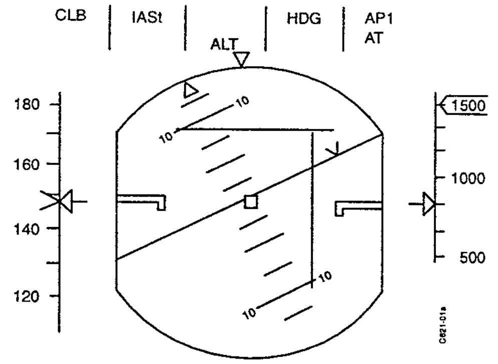

Figure 2 - Conventional Flight Director display with cross command bars

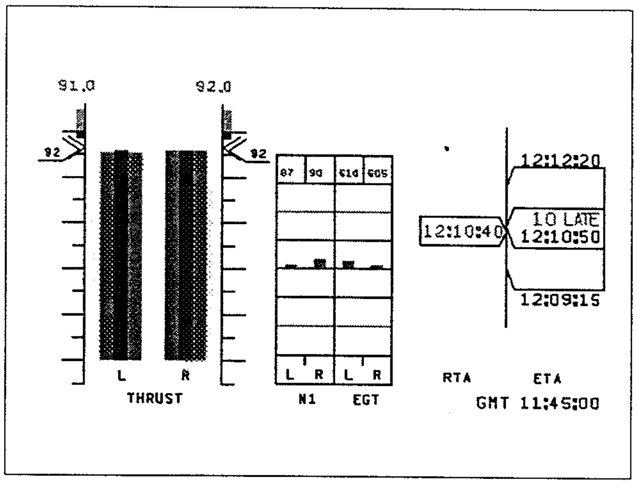

Figure 5 - Engine thrust display with Time Indicator

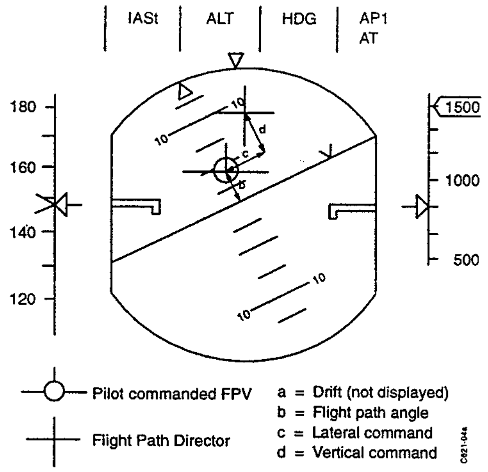

Figure 3 - Flight Path Vector (FPV) display with Cross Flight Path Director (FPD)

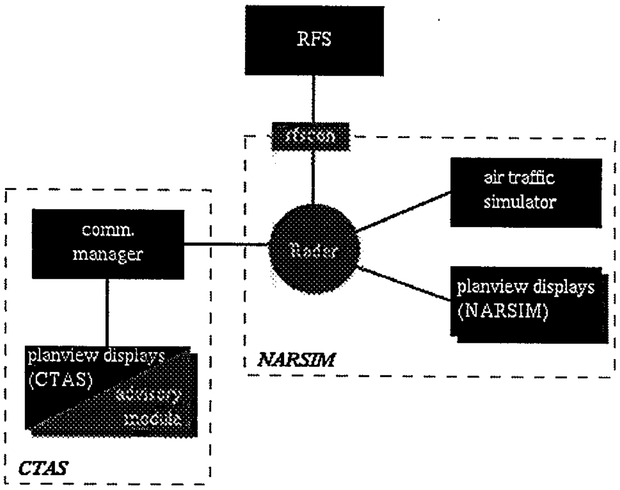

Figure 6 - ATC environment and communication with aircraft

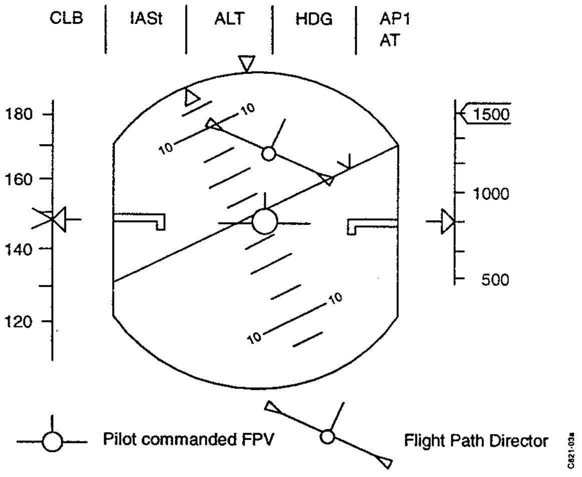

Figure 4 - Flight Path Vector display with rotating ´ghost aircraft´ Flight Path Director

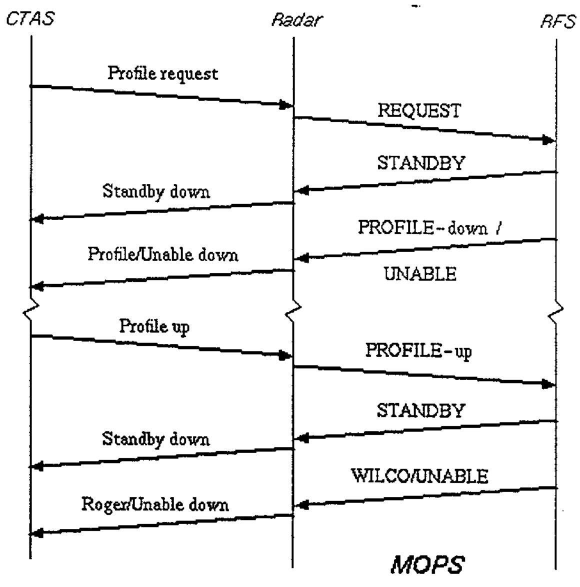

Figure 7 - Profile Negotiation Process

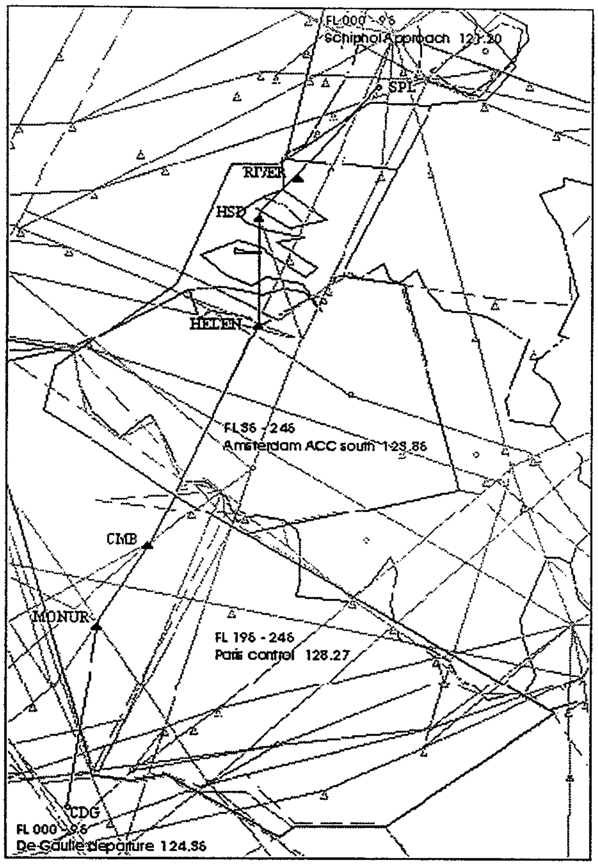

Figure 8 - ATC sectors during PNP and SDA scenarios

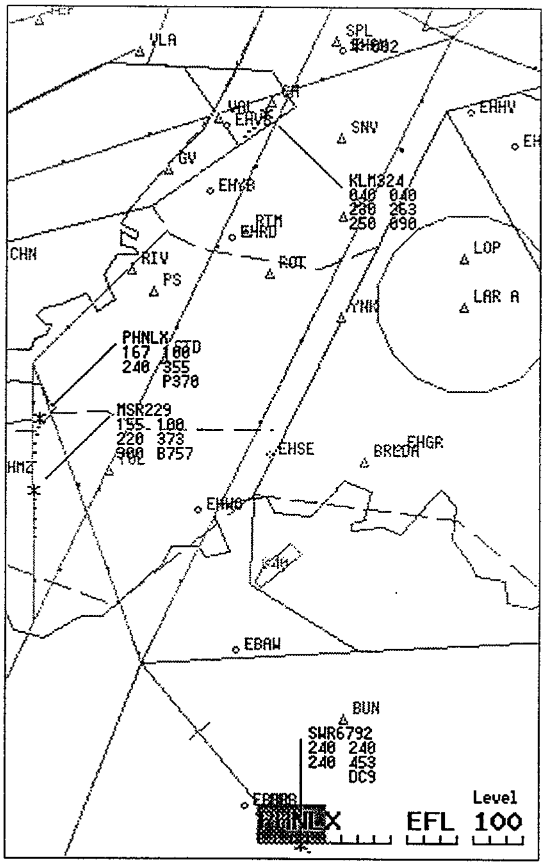

Figure 9 – Screenshot of NARSIM plan view display.