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PD/2 FINAL REPORT

Annex F

Airborne Aspects of PD/2

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1. INTRODUCTION

DLR's research aircraft ATTAS (Figure 1.1) represents the airborne side in the PD/2 demonstrations, in which it was used as live 4D-FMS equipped aircraft flying an approach route to Frankfurt from the western sector. The flight was integrated with other simulated traffic in the Air Traffic Management and Operations Simulator (ATMOS) hosted PD/2 arrival planning system and was handled by the controllers in the same way as the other simulated aircraft.

The main purpose of these flight trials was to demonstrate the ability of a 4D-FMS and datalink equipped aircraft to

- negotiate on board predicted 4D-trajectories with the PD/2 arrival planning system on the ground and then to
- fly the agreed trajectory within given tolerances fully automatically, i.e. without further intervention by the PD/2 ATC controllers working within the PD/2 simulation environment.

Aircraft control responsibility for the PD/2 demonstration part of the flight trials was allocated to the pilot seated in the ATTAS Experimental Cockpit (Figure 1.2).

Figure 1.1 DLR's ATTAS Experimental Aircraft

The PD/2 demonstration flights were performed in June 1997 following the PD/2 main phase, but allowing visitors to observe both the ground-based operation in the PD/2 and ATMOS environment as well as airborne operation of EFMS and AHMI in the ATTAS Experimental Cockpit on board the aircraft.

Preceding the live aircraft experiment trials with the ATTAS, the ATTAS Experimental Cockpit (Figure 1.2) was introduced for one simulation run in each week of the PD/2 main phase trials operating as a fixed-base cockpit simulator of DLR's ATTAS aircraft. The simulated ATTAS aircraft was handled by the controllers in the same way as the live aircraft.

Figure 1.2 ATTAS Experimental Cockpit with CDU and AHMI Display

Moreover, AHMI evaluation trials were performed with the ATTAS Experimental Cockpit in the laboratory. However, for purpose of these AHMI evaluation trials only, a Datalink Dialogue Test Facility replaced the ATMOS connection to the simulation cockpit to allow a more complete evaluation of the AHMI facilities including re-negotiation of 4D-trajectories as an essential mode of operation which was not supported by the PD/2 operational concept.

Six pilots participated in the experimental evaluation which focused on the Navigation Display layout as well as the interaction with the EFMS by means of touch-pad input as cursor control device for the Navigation Display.

2. EXPERIMENTAL AIRBORNE SYSTEM

The experimental airborne environment comprises the test aircraft, the ATTAS Experimental Cockpit which may be operated on board the aircraft or on the ground as fixed-base cockpit, the AHMI components of the experimental cockpit, the EFMS, and the telemetry system operating as datalink. These elements constitute the airborne part of DLR's experimental ATM system supporting the PHARE PD/2 demonstrations, they are described in the following chapter in detail.

2.1. TEST AIRCRAFT

The ATTAS is one of DLR's experimental aircraft. It is a twin turbofan 44 passenger transport aircraft of type VFW 614 (see Figure 1.1). The aircraft is equipped with an experimental duplex Fly-by-Wire (FbW) flight control system and a versatile airborne computer and sensor system comprising a duplicate set of inertial sensor systems (IRS), air data systems (DADC) and navigation receivers (DME, VOR, ILS and D-GPS). Two of the airborne computers are of particular interest to experimenters, since they can run software which is specific to the experiment. During the PD/2 demonstration flights software packages were implemented which provide high precision navigation data and actual wind data. An experimental Automatic Flight Control System (AFCS) comprising auto-pilot and auto-throttle functions was also implemented.

The navigation software provides a very precise position reference for 4D-guidance. Calculations are performed by means of a Kalman filter which determines aircraft position from simultaneous analysis of range measurements from up to 5 DME stations. The result is applied to support position measurement from the IRS. The degree of position accuracy which can consequently be obtained is of the order of 50 metres. Position data measured by Differential-GPS is also available, which increases the position accuracy to less than 10 metres.

The sensor systems allow in-flight measurement of wind speed and wind direction by simultaneous analysis of sensor data from the air data system and the inertial system. A corrective calculation is performed in order to reduce errors arising in manoeuvring flight. Measured signals are filtered then since only the low frequency components of horizontal air movement are of interest.

The experimental AFCS provides standard auto-pilot and auto-throttle functions. Due to the design of the control system as a coupled multi-variable system with dynamic feed-forward control of control variables, it is possible to adhere very precisely to commanded airspeed and altitude as well as to the commanded horizontal route with low control activity.

The aircraft is equipped with a data recording system which records experimental parameters for subsequent analysis. Automatic exchange of data between aircraft and ground is provided by a VHF telemetry system with a high bandwidth (see chapter 2.5 on datalink).

2.2. ATTAS EXPERIMENTAL COCKPIT

The ATTAS can be flown in a basic mode from the right hand seat in the front cockpit by means of the conventional mechanical controls, or in a FbW-mode from the left hand seat in the front cockpit via side stick control. A further simulation mode allows to fly the ATTAS under instrument flight rules (IFR) from the ATTAS Experimental Cockpit which is installed in the former passenger cabin directly behind the (primary) cockpit. The ATTAS Experimental Cockpit represents the right hand side of a modern transport aircraft cockpit.

However, the ATTAS Experimental Cockpit may also be operated as a fixed-base cockpit in a simulation environment. This configuration was utilised for AHMI evaluation trials.

The PD/2 flight trials have been performed from the ATTAS Experimental Cockpit incorporating pilot I/O-device hardware (refer to Figure 2.1 for details) such as the

- Flight Control Unit (FCU) located in the glareshield panel for mode control of the experimental AFCS,
- standard 5-inch A310 EFIS displays serving as Primary Flight Display (PFD), Horizontal Situation Indicator (HSI) and Engine Display, respectively, the displays being connected to programmable symbol-generators,
- the touch screen CDU of the Experimental Flight Management System (EFMS) located in front of the pilot, and the
- interactive Navigation Display (ND) realised on a 13-inch LCD display located in the central instrument panel above the centre pedestal, connected to a workstation representing the display generator, and a touch-pad input device driving the cursor on the display.

The software of the latter two has been developed within the PHARE EFMS and AHMI projects, respectively. The integration of the EFMS-based CDU and the interactive ND could not be solved in a perfect way, i.e. under particular conditions a pilot CDU input may corrupt another pilot input by means of the interactive ND. For the trials, the CDU was used for pre-flight initialisation, only, whereas the interactive ND served as primary I/O device when in-flight. The touch-pad device was mounted on a board which was fastened on the right hand knee of the experimental pilot.

A third set of NAV and COM equipment allows the pilot in the experimental cockpit to configure the navigation and communication system as required. Side-stick, thrust and flap levers are also available.

Pilot input recording was realised on the AHMI display generator workstation but was activated and used with the ground-based AHMI evaluation, only.

Figure 2.1 *ATTAS Experimental Cockpit with Pilot operating the Touch-pad Input Device (with his right hand)*

2.3. EXPERIMENTAL FLIGHT MANAGEMENT SYSTEM (EFMS)

The EFMS developed within PHARE is configured as a flexible research tool which can readily be adapted to specific experimental requirements. It was not intended to achieve a complete simulation of an operational FMS but only to develop and to implement such functions as are relevant to the execution of planned experimental investigations and demonstrations. And it will certainly be noted that many standard functions of present-day operational FMS are missing. However, several innovative functions required for the PHARE demonstrations are available such as:

- Planning of flight trajectories taking account of a wide range of constraints affecting the vertical profile as well as the arrival time at certain way-pointway-points.
- Precise guidance of the aircraft along a 4D-trajectory or within a 4D-tube which provides the aircraft a specific manoeuvre margin along the trajectory. Accordingly, the 4D-tube represents the air traffic control clearance given to the aircraft by air traffic control.
- Negotiation of trajectories and constraints with a ground-based air traffic control planning computer, via an automatic datalink.

- Transmission of meteorological data measured on board the aircraft to a ground-based dynamic meteorological database.
- Sampling of route-related meteorological data from this meteorological database for purposes of airborne flight planning.

The software used for the PD/2 trials was based on the EFMS software Phase 1b, Release 6.3.

The hardware used for the flight trials was the EFMS target system (Motorola 68040 VME board) coupled via ARINC 429 interface to the ATTAS onboard computer system, whereas the ground-based trials were performed by means of the EFMS host system, a Sun Sparc workstation. The CDU was emulated on a PC with a touch screen overlay connected via RS 232 to the EFMS computer system. The CDU was installed in front of the pilot seat in the ATTAS Experimental Cockpit (Figure 2.1). The Supervisor Terminal of the EFMS computer was a flat panel LCD display with a touch screen overlay. EFMS input and output parameters were recorded on streamer tape for the purpose of post flight evaluation.

Tape recordings of EFMS parameters were used as the major means to check-out and debug prediction and guidance software on the target system. For that purpose recording comprised all relevant prediction data (event recording) as well as all relevant periodic data in every guidance cycle, i.e. incoming sensor data, internal guidance data, and guidance commands sent to the AFCS.

2.3.1. Trajectory Prediction

A major function of the EFMS was to predict a flyable trajectory which meets ATC imposed constraints. To do this the EFMS generated the trajectory conforming to the route and altitude constraints by means of a simulation of aircraft motion using aerodynamic, engine, wind and air temperature data as well as performance parameters and relevant aircraft operational procedures. The meteorological data used by the trajectory predictor during airborne operation was a blend of the meteorological forecast for the future path of the aircraft and the actual data measured on-board the aircraft at its current position.

The lateral route was made up of great-circle sections between the way-pointway-points and arcs with a fixed radius at the way-pointway-points. The vertical profile consisted of a sequence of quasi-optimised flight phases. The climb was predicted at high power setting and a quasi optimised Calibrated Airspeed (CAS) schedule whilst the descent was planned at near idle power setting. Airspeed and altitude profiles were planned and modified iteratively such that all altitude and time constraints were fulfilled wherever possible. In order to adhere to required arrival times at specific way-pointway-points the CAS profile was modified accordingly. In the final phase of the flight from Metering Fix to Approach Gate within the TMA the flight path length was also suitably modified, i.e. trombone or fan type path stretching is applied.

The accuracy of the models and data employed were of vital importance for the accuracy of the predicted trajectory. However, since the data and models would always be imperfect there was a functionality built in which updated the trajectory depending on certain events. Examples are, for instance, reaching a certain phase of flight (end of climb, end of level flight) or the deviation from the trajectory exceeding an allowed tolerance value.

2.3.2. Guidance

EFMS guidance was a continuous control process which provided updated guidance commands every 150 ms to the AFCS. Lateral guidance steered the aircraft along the route via a bank angle demand which was a function of the present cross track deviation and present track angle deviation. A prediction of bank angle required during the turn was included as a feed-forward term.

Vertical guidance comprises several guidance options for climb, cruise and descent, which could be selected via parameter file depending on operational requirements.

With regard to an economical climb at high power setting with minimal thermal cycling it was decided to fly an open climb at constant thrust and CAS schedule as is common practice in transport aircraft operation, i.e. altitude and time are not controlled. The aircraft was in fact operated at the same thrust setting and CAS schedule applied for the prediction of the climb profile. This lead normally to deviations from the predicted altitude and time profile which depended on the quality of meteorological forecast (wind and air temperature) and aircraft performance data (aerodynamic drag, engine thrust, aircraft weight) used for trajectory prediction. However, If there are no strict ATC constraints which require a more precise tracking of the altitude and time profile during climb there is no reason to apply a higher control effort.

Full 4D-control commenced at the Top of Climb (TOC) and was employed throughout cruise and descent. A simple algorithm calculated an incremental CAS command according to the prevailing time deviation. During cruise, altitude was controlled on elevator and CAS was controlled on throttle.

CAS control in the descent was achieved through the elevator whilst total energy was controlled on thrust by an algorithm which was part of the experimental AFCS. In order to provide some margin for reducing thrust the descent was normally planned at a small value of thrust, rather than being at flight idle setting.

2.4. AIRBORNE HUMAN MACHINE INTERFACE (AHMI)

4D-trajectory generation and negotiation capabilities call for efficient I/O-devices that ease pilot interaction regarding flight management. Support of immediate pilot action within new cockpit procedures while maintaining the safety standards for aircraft operation is the main goal of the PHARE AHMI project.

The layout details of the concept are described by two PHARE documents on AHMI (see References). Summaries of the general concept, the essential operational modes and advanced features are given below.

2.4.1. AHMI Concept

To approach the main AHMI goal graphical representations of the constraint list, 4D-trajectory, and 4D-tube on the screen, combined with object-related input capabilities, have been chosen and implemented. The Navigation Display (ND) was enhanced by a touch-pad input device and graphical display objects which the pilot may act on directly. The AHMI concept does not replace the CDU in favour of an advanced EFIS ND. In fact, the EFIS ND command set provides mode selection, the setting of display characteristics, trajectory generation and negotiation commands, and constraint list editing capabilities which refer to particular display objects and display characteristics, whereas alpha-numeric input as well as alpha-numeric representations of constraint list and trajectory still require a CDU as an I/O-device. Thus, the EFIS ND command set is a subset of the CDU command set

The advanced Navigation Display incorporated the Horizontal Display (HD) and the Vertical Display (VD). Display and input capabilities applied to both HD and VD. The general display layout is illustrated by Figure 2.2 to Figure 2.5. Regarding the essential information the HD conformed with the conventional EFIS ND layout, whereas the VD represented a completely new development.

The ND was operated through two separate display modes. The PLAN mode supported flight planning and enabled the pilot to initialise and edit the constraint list representing the basis for any 4D-trajectory prediction. The MONITOR mode supported the pilot in monitoring flight progress with respect to the active 4D-trajectory and the 4D-tube representing the ATC clearance and contract between aircraft and ATC.

As addressed above, four different function sets were to be applied to the ND: Basic display parameters, such as the display range select sub-menu (Figure 2.4), constraint list edit functions, trajectory generation and negotiation, and - last but not least - auxiliary functions, referring to mode and display selection. Each of the function sets was placed on one border of the display. Buttons for ‘undo’ and ‘acknowledge’ were placed in the left and right lower edges of the screen.

Sub-menus open in the central display area aside the corresponding button. A sub-menu would disappear at once when the pilot selects a sub-menu button, or would be closed after the specified time of five seconds if no further pilot action was received.

The touch-pad cursor control device characteristics corresponded to the characteristics of a conventional computer mouse, or laptop touch-pad. A 'hot spot' activation of buttons located at the borders of the display was not implemented because a separation of 'hot spot' areas and areas of conventional cursor control was required. The results of the experiment were expected to support a detailed specification.

In case the cursor hit a button or was located in a specified area around a display-object this would be highlighted. Activation of a button or selection of a display object was performed either by tapping the touch sensitive surface or by using the hardware key of the touch-pad.

2.4.2. PLAN Mode

In the PLAN mode the HD was oriented north up like a geographical map (Figure 2.2). This mode was intended to support constraint list modification, i.e. planning of the flight. The EDIT menu was available in PLAN mode only, i.e. pressing the EDIT button would automatically result in a change to PLAN mode.

The function set provided for editing the constraint list included insertion, deletion, and modification of all types of constraints. Therefore, PLAN mode supported stepping forward and backward along the constraint list to edit and modify a selected constraint which was centred on the display. This was done either by utilising the '+' (forward to destination) and '-' (backward to start or departure) buttons or by direct selection of a way-point. Then, the way-point could be modified, deleted, or another way-point could be inserted after the selected one. The MOVE command deleted the actual way-point and inserted a new way-point modifying the name. The name was derived from the name of the actual way-point. Then, the way-point could be moved to a new location.

The function set included an ATTR (attribute) command that initiated a change to the VD for acting on altitude and time constraints corresponding to the current way-point, an MDEL (multiple delete) for deleting a complete sequence of way-pointway-points by specifying the first and last way-point to be deleted, and the COPY command.

As no other constraint list than the one residing in the 'pilot constraint list buffer' could be modified, the pilot would have to copy a particular constraint list into that buffer. Figure 2.6 (page 18) shows the bottom part of the HD with the COPY sub-menu opened. The pilot could access an alternative constraint list (ALT), a ground constraint list (GRD), and the constraint lists corresponding to the generated (GEN), negotiated (NEG), and activated (ACT) trajectory.

As already addressed above, the actual or current reference way-point was centred in the middle of the display. In PLAN mode the actual position of the aircraft could be within or external to the selected display range. Thus, the aircraft symbol could be out of the displayed area. However, by increasing the display range the aircraft symbol would appear on the screen.

The VD showed the vertical flight profile versus distance with the reference way-point centred on the screen (Figure 2.3). The distances between constraint list way-pointway-points conformed to those of the HD due to identical display ranges. Altitude scaling was performed automatically depending on altitude range within the selected range distance. However, a mere constraint list did not include a vertical profile unless a trajectory had been generated.

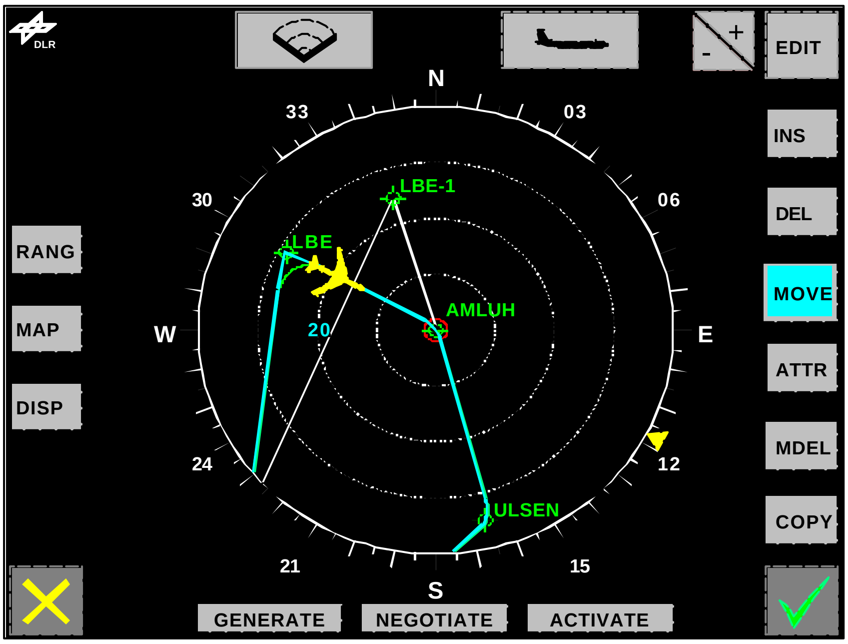

Figure 2.2 ND - Horizontal Display, PLAN Mode

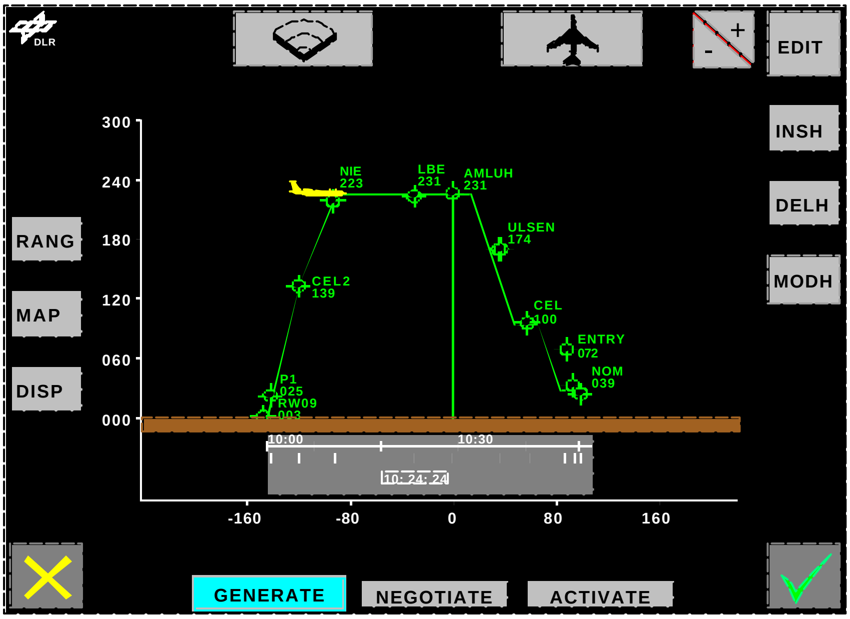

Figure 2.3 ND - Vertical Display, PLAN Mode

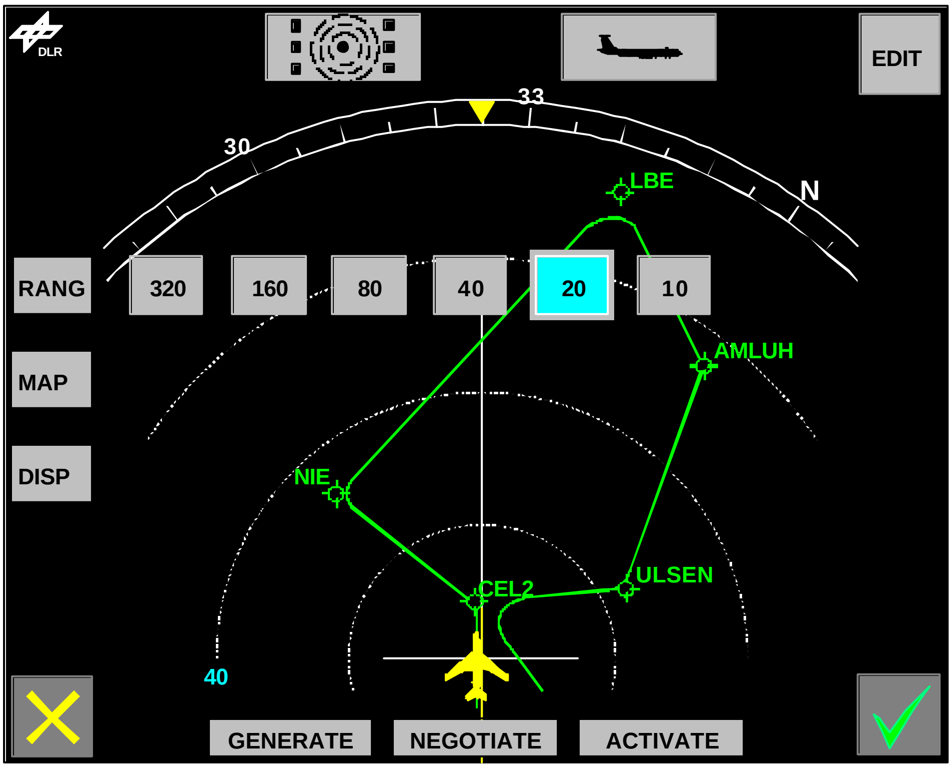

Figure 2.4 *ND - Horizontal Display, MONITOR Mode, RANGE Select Sub-Menu activated*

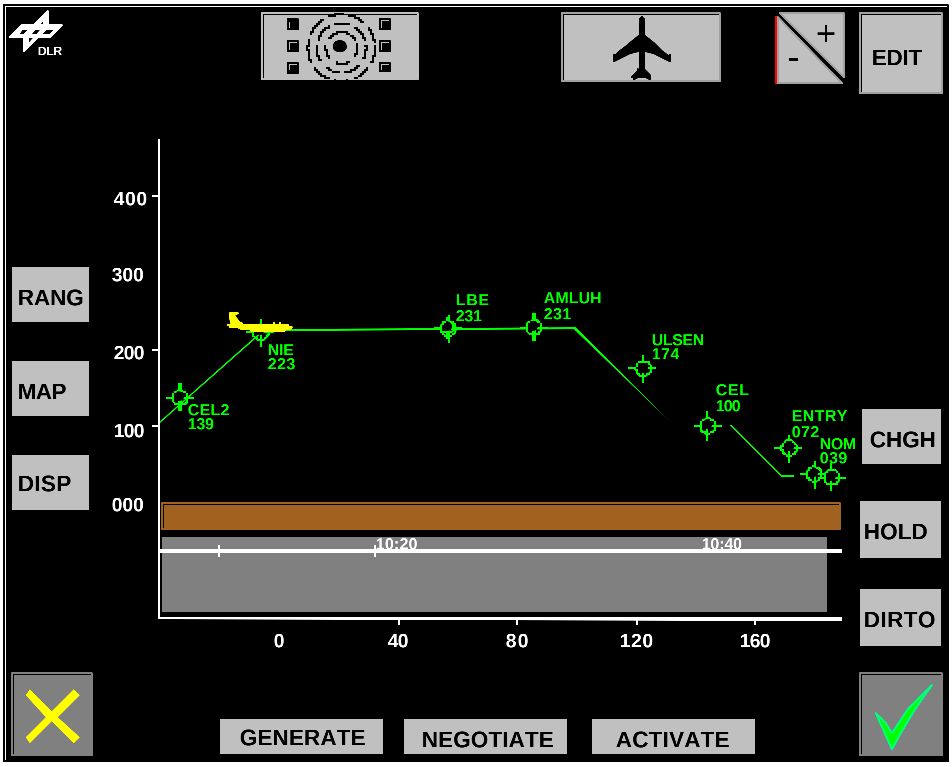

Figure 2.5 *ND - Vertical Display, MONITOR Mode*

Altitude and time constraint attributes were indicated by chevrons with reference to the particular way-point. Detailed information on predicted time is available in the area between ground symbol and distance axis.

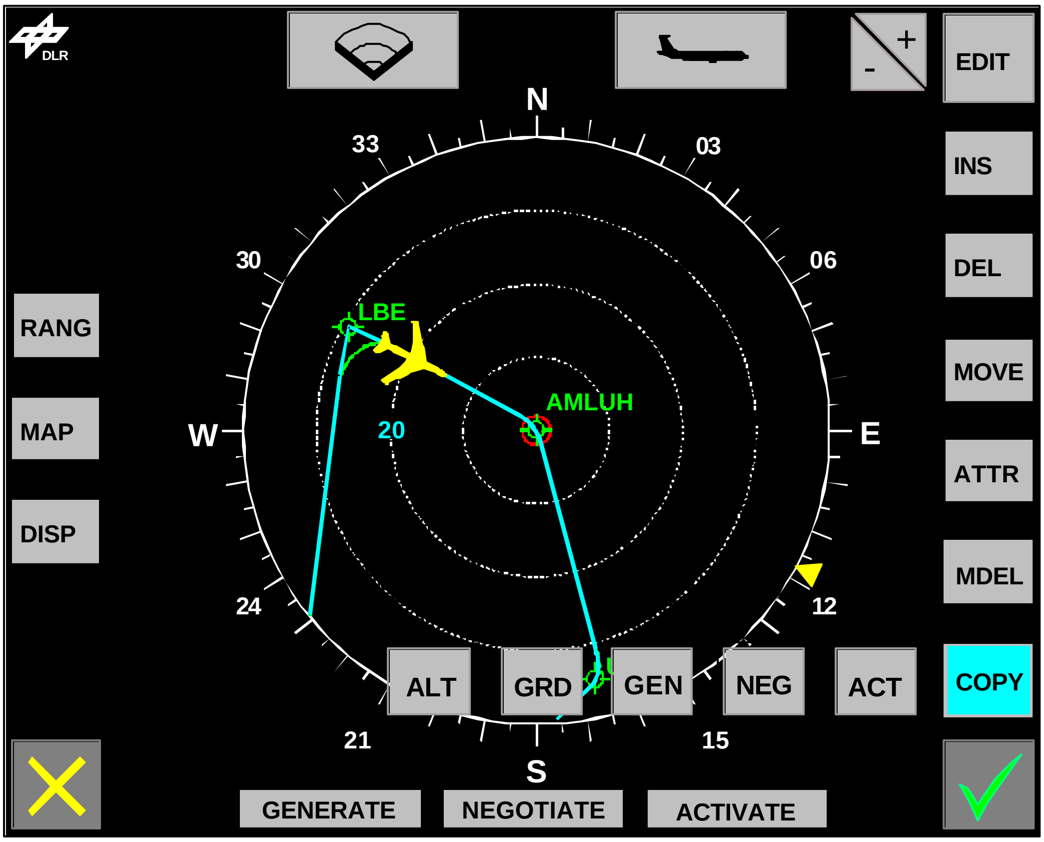

Figure 2.6 Bottom Part of ND in PLAN Mode with COPY Sub-Menu opened

2.4.3. MONITOR Mode

In the HD MONITOR mode the aircraft symbol wass fixed near the bottom of the screen. The display represented the area in front of the aircraft in an angular range of approximately 150 degrees (Figure 2.4) which corresponds to the standard EFIS ND representation.

On the VD the aircraft position was fixed near the vertical scale. The display showed the predicted vertical profile (Figure 2.5). Altitude scaling was performed automatically by the system depending on altitude range within the selected range in distance.

Moreover, the MONITOR mode allowed tactical ATC advisories to be followed by software buttons for ‘Direct-To’, ‘Hold’ (to insert a holding pattern at a specified way-point), and ‘CHGH’ for immediate change of the altitude.

2.4.4. Alert Message Window

On demand of ATC, or initiated by EFMS or AHMI error messages the AHMI process generated a message window which popped up in the upper display area (see Figure 2.7). In this window the corresponding messages, system status or general information was displayed. The boundary line colours indicated the alert status, i.e. „red“ for a warning, such as the existence of ATC constraints, and „white“ for process status or general information. The window size was configured depending on the length of the message. Acknowledgement of the message could be performed either by clicking on the acknowledgement button or on the alert window. In case of a low-priority message no acknowledgement was required, the window would automatically close after a specified time interval.

The alert window background was transparent to avoid hiding essential information on the covered display area underneath.

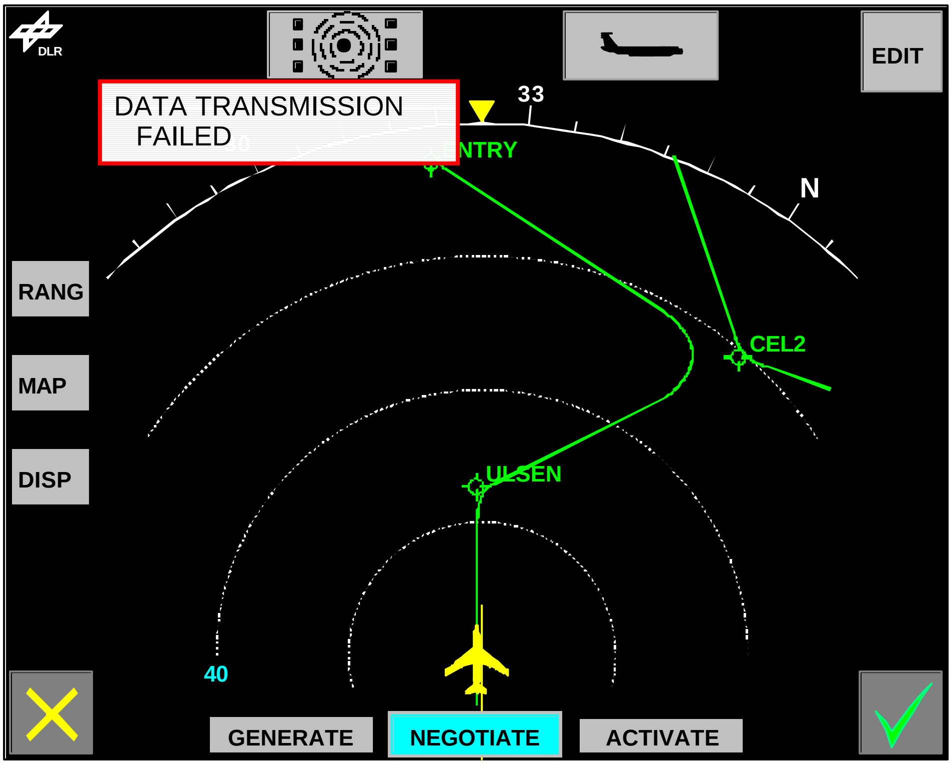

Figure 2.7 Alert Window on ND

2.5. DATALINK

For purposes of data transmission between the onboard EFMS and the ground-based PD/2 arrival planning system a telemetry datalink was employed. It operated in the S-band for downlink and in the L-band for uplink. Up to 500 kbit/s could be transmitted in the downlink direction and up to 250 kbit/s in the uplink direction. This exceeded by far the transmission capacity that was expected for a future operational datalink such as a satellite datalink or the Mode S datalink.

The EFMS target system was connected to the onboard telemetry hardware via the ATTAS computer system. The telemetry ground station computer was connected via a local area network (LAN) with the PD/2 ground system.

Three basic types of messages were employed by the emulated ATC datalink:

- position reporting
- trajectory related data
- message acknowledgements

Aircraft position was transmitted every 4 seconds to the ground. This position data was transformed to conform to the ATC ground simulation requirements of the aircraft appearing to fly in the extended TMA of Frankfurt whereas the aircraft actually flew a route in the local Hannover/Braunschweig area (Bremen FIR) in northern Germany. This transformation was implemented in a computer on the ground, thus enabling the display of real aircraft position on a map display on the ground as well as the display of transformed aircraft position on the PD/2 radar display.

3. TRIALS PROCEDURES

The PD/2 trials were conducted on the Air Traffic Management and Operations Simulator ATMOS of DLR. The airborne demonstration included the experimental cockpit and DLR's experimental aircraft ATTAS. This section provides an overview of the airborne facilities and their configurations for the trials as well as a brief summary of the underlying negotiation procedure.

Figure 3.1 summarises the PD/2 trials configuration with inclusion of the real ATTAS aircraft and the Experimental Cockpit fixed-base aircraft simulation.

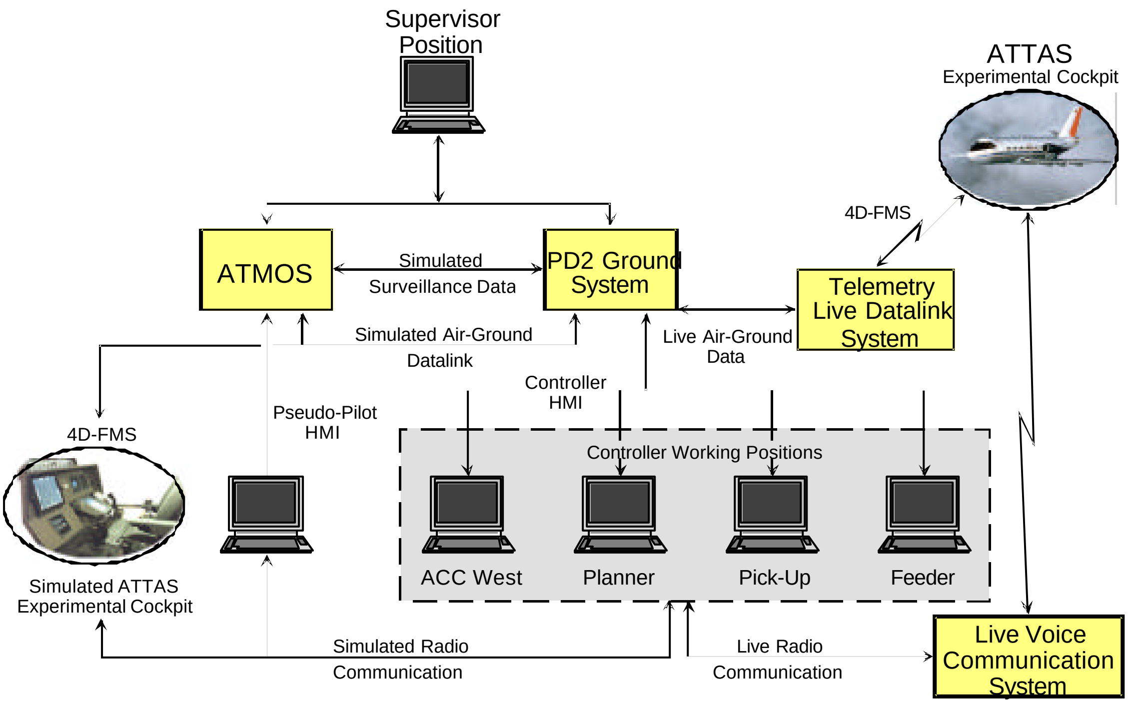

Figure 3.1 PD/2 Trials Configuration incorporating ATTAS and ATTAS Flight Simulator

3.1. AIR/GROUND NEGOTIATION OF TRAJECTORIES IN PD/2

The concept of air/ground trajectory negotiation in PD/2 was based on a concept commonly developed in PHARE. Cockpit procedures and pilot operation within the flight trials and AHMI evaluation in particular did not only depend on this concept but represented an essential part within the evaluation process. Therefore, the trajectory negotiation procedure will be described in this chapter in some detail. (For a more detailed view, refer to PHARE Document 97-70-14 on 'Trajectory Negotiation in a Multi-Sector Environment'.)

Stage 1 - The aircraft initially planned a trajectory from its current position to the Approach Gate taking account of all known constraints . This 'user-preferred' trajectory which could be regarded as ideal with respect to the criteria selected by the pilot was then transmitted by datalink to the PD/2 arrival planning system on the ground. It was checked there for conflicts with other previously-planned trajectories.

Stage 2 - The PD/2 arrival planning system incorporated the downlinked trajectory data and provided an optimum insertion of the aircraft into the approach sequence in accordance with the predicted time of arrival at the Approach Gate. It then determined flyover altitudes at Metering Fix and Approach Gate as well as the required arrival time at the Approach Gate. It also indicated the runway to be used. This set of constraints that guaranteed a safe spatial separation between the aircraft and other 4D-trajectories was transmitted to the EFMS.

Stage 3 - The aircraft then planned a 4D-trajectory on the basis of the received ground constraint list and transmitted the updated trajectory to the PD/2 arrival planning system.

Stage 4 - If the 4D-trajectory did not satisfy the constraints imposed by the PD/2 arrival planning system a specific strategy was followed to establish a fresh set of constraints which was transmitted to the aircraft. This process was repeated until a conflict-free trajectory was defined. When this was the case the planning computers on the ground transmitted a clearance to the aircraft.

Stage 5 - The EFMS guided the aircraft along the 4D-trajectory. Adherence to trajectory tolerances was permanently monitored by the EFMS as well as by the PD/2 Flight Path Monitor on the ground and corrective action was taken as necessary.

However, during the PD/2 demonstration flights the ATTAS trajectory always received higher priority than the trajectories of other simulated aircraft, i.e. ATTAS always received a clearance for its downlinked 4D-trajectory thus avoiding the need for re-negotiation.

The AHMI evaluation trials were based on an identical procedure. However, generation and negotiation of a new trajectory after having followed tactical advisories from ATC via R/T was part of the evaluation. Deviations from the pre-planned trajectory were also simulated which resulted in a re-negotiation including revised time and altitude constraints.

3.2. INTEGRATION OF AIRCRAFT WITH PD/2

The simulated airspace of the PD/2 ATM scenarios was represented by an extended TMA which was based on the present TMA Frankfurt with its surrounding ACC sectors. The approach routes within the ACC sectors were modelled as they exist today. Inside the TMA the approach routes were modified to enable RNAV procedures as well as fan and trombone type path stretching manoeuvres for precise time of arrival control.

In addition to a certain number of simulated aircraft of various performance categories and navigation capabilities ATTAS was incorporated as a live aircraft in specific scenario runs (ORG2, medium traffic, 30% 4D-FMS equipped aircraft). Accordingly, a simulation of a traffic mix of 4D-FMS equipped aircraft was obtained which can fly time accurate autonomously. Non-4D-equipped aircraft were controlled by pseudo-pilots in accordance with ATMOS air traffic controllers' advisories.

In these scenario runs ATTAS was following an approach route within the western ACC sector via Nattenheim (NTM) to Metering Fix Rüdesheim (RUD) and further on along a northern trombone path defined by way-points FWF, DPN, FPWN, PNOM to the Approach Gate GATER situated on the extended centreline of runway 25R at Frankfurt airport. Two altitude constraints at RUD and GATER and one time constraint at the Approach Gate - the end point of the 4D-approach - were applied in the demonstration flights. After passing the Approach Gate the aircraft intercepted the ILS glideslope to runway 25R.

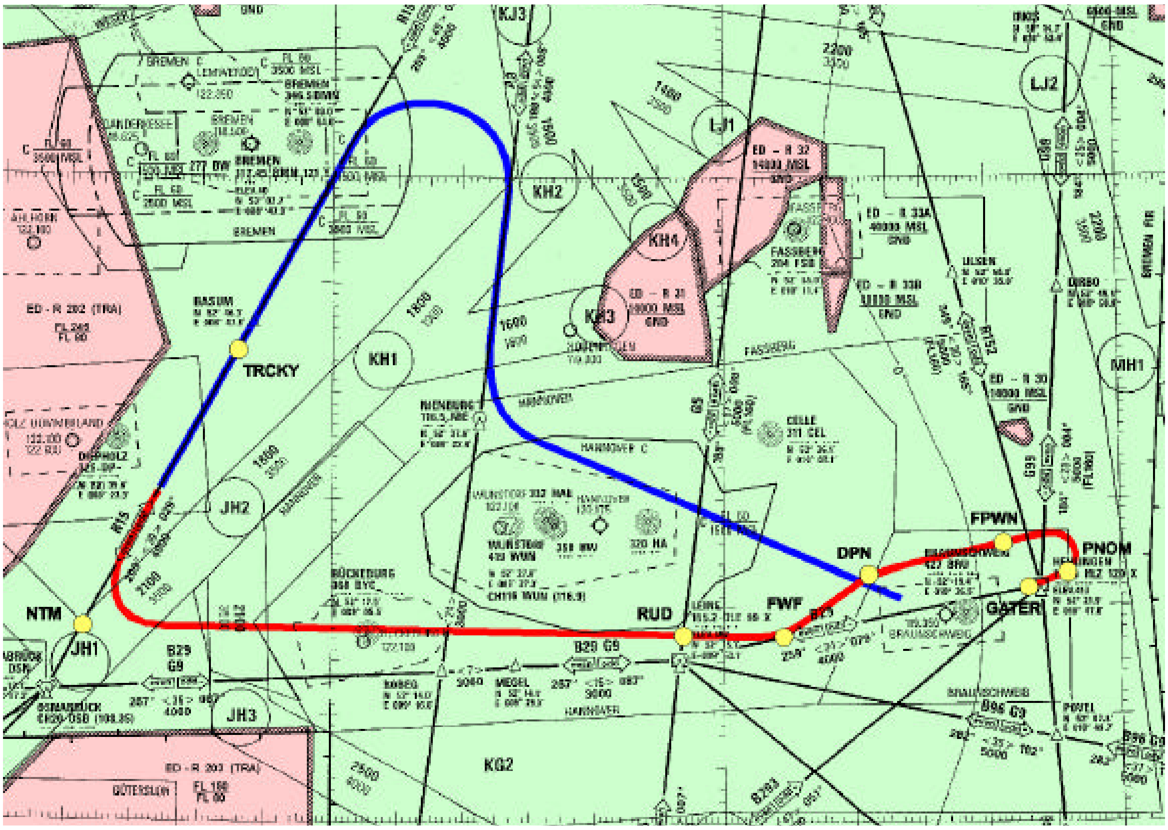

Figure 3.2 ATTAS Route in the Real World

For experimental reasons the approach route to runway 25R and the ILS 25R were emulated in the local Braunschweig/Hannover area of Bremen FIR to enable the operation of the aircraft in an airspace with less demanding constraints from real ATC. The flight test route was designed to take into account the airspace and en-route airway structure of Bremen FIR as well as the coverage range of DLR's telemetry datalink and DLR's Differential-GPS reference ground stations installed at Braunschweig airport. Therefore, in reality all demonstration flights began and ended at the airport of Braunschweig. The demonstration flights followed a route from Braunschweig to VOR NIE along airway A9 inbound to VOR LBE and after a left hand turn along airway R15 inbound to VOR OSB (Figure 3.2). Way-point TRCKY was defined as the entry point to the simulated PD/2 airspace (see Figure 3.2).

The EFMS controlled flight began inbound to VOR NIE along an in-flight predicted trajectory for the whole route from present position to the Approach Gate. After reaching cruise altitude FL 200 the trajectory was generated again. Trajectory negotiation with the PD/2 ground system began before starting the turn inbound to TRCKY. At the end of the turn the 4D-trajectory complying with the uplinked constraints was generated and downlinked for approval by the PD/2 ground system that in turn led to the uplinking of the clearance.

3.3. TRIALS PROCEDURE FOR AHMI EVALUATION

For the ground-based evaluation each of the participating pilots was requested to perform up to eight simulated approach flights as described before, each of them lasting approximately 20 to 25 minutes. With inclusion of briefing and de-briefing sessions as well as breaks a total amount of time of app. 6 hours for a one pilot was estimated. This amount of time seemed to be reasonable as no pilot could offer more than a one-day participation.

The first two trials of each pilot were meant to get familiar with the experimental environment. The pilots had to understand the PHARE ATM environment and the corresponding trajectory negotiation procedures as well as component characteristics such as AHMI command set and menu organisation, and how to operate the touch-pad when performing the particular task. The very first trial was not a flight but the cockpit procedure for pre-flight planning on the ground. This condition was established to avoid time pressure on the pilot when getting familiar with the experimental environment.

In the following trials the approach constraint list, e.g. as part of a company route, was available already. The pilot was instructed that the pre-flight planning activities had been performed adequately. As already addressed in chapter 2.2, the EFMS CDU device was not usable in combination with the interactive ND.

The general experimental conditions to be investigated by the AHMI evaluation include

- generation and negotiation of a pilot-preferred trajectory,
- cockpit procedures on ATC imposed constraints, and

- a set of operational failure conditions.

In co-operation with a test pilot DLR research engineers and psychologists designed an experiment plan which resulted in a detailed definition of eight trials each specifying the particular pilot tasks and flight conditions (see

Table 3.1). The categories covered by the experiment set-up included familiarisation with the environment (two trials), standard PHARE trajectory negotiation procedures (three trials), and failure conditions (three trials). The failure conditions were included to demonstrate that the advanced equipment was compatible with both the PHARE ATM environment and with current ATC procedures/practices, and that the pilots would benefit from an advanced AHMI under both conditions.

Trial	Characteristics	Detailed Pilot Tasks
1	Familiarisation, On-ground Flight Planning	Change Mode, Range, Display Contents, Edit Constraint List, i.e. Insert, Delete, Move of way-pointway-points on HD and Insert, Delete, Modify Altitude and Time Constraints on VD Generate, Negotiate Trajectory Examine different Constraint Lists
2	Familiarisation, In-flight	Change Mode, Range, Display Contents, Edit Constraint List, i.e. Insert, Delete, Move of way-pointway-points on HD and Insert, Delete, Modify Altitude and Time Constraints on VD Generate, Negotiate Trajectory
3	Pilot Implemented Strategic Constraints, In-flight	same as trials 1 and 2
4	ATC Imposed Strategic Constraints (way-pointway-points), In-flight	same as trials 1 and 2 plus Trajectory Generation and Negotiation based on Ground Constraint List (HD)
5	ATC Imposed Strategic Time Constraints (Path-Stretching), In-flight	same as trials 1 and 2 plus Trajectory Generation and Negotiation based on Ground Constraint List (HD and VD)
6	Tactical ATC advisories (R/T), Re-Planning of 4D-Trajectory, In-flight	same as trials 1 and 2 plus Disconnect EFMS Guidance and follow ATC advisories, Planning of new trajectory: Generation, Negotiation, Activation
7	Aircraft Deviation from active Trajectory, In-flight	same as trials 1 and 2 plus Planning of modified trajectory: Generation, Negotiation, Activation
8	Interrupt of D/L, In-flight	same as trials 1 and 2 plus Input of strategic ATC advisories (Altitude and Time Constraints), Generation, Negotiation and Activation of modified Trajectory

Table 3.1 Trials Configuration for AHMI Evaluation

Pilot performance data were recorded by the AHMI system covering button presses, object select actions, and duration of the particular event. These data did not allow application of statistics but were intended to support pilot's comments e.g. through identification of input sequences containing erroneous input or through details on procedures applied by the pilot. Input sequences were provided on the screen for use in the de-brief session.

Data collection regarding pilot acceptance was carried out by means of a structured interview. Essential topics of the interview are presented by the following list of items:

- **display layout**,

covering details of distinct display objects such as colour, basic display organisation, button realisation, menu and sub-menu organisation as well as constraint list, trajectory, and clearance representation,

- **input characteristics**,

referring in detail to button activation and display object selection including the relation to touch-pad size and location,

- **input philosophy**,

object- or function-oriented operation, as well as pilot action demanded either by ATC data-link or system generated messages,

- **operational aspects**

referring in detail to conventional CDU input strategy compared to proposed ND input sequences as well as display requirements, and the

- **PHARE trajectory negotiation concept**

referring to strategic trajectory negotiation procedures within an advanced ATM environment as well as aircraft operation under ATC tactical command.

4. GUIDANCE RESULTS

Two examples from flight trials (Test Run #60 and Test Run #59) have been selected to show the climb, cruise and descent performance achieved in PD/2 demonstration flights with ATTAS. Both test runs were conducted along the same test route (see Figure 3.2) with way-pointway-points NIE, LBE, NTM, RUD, FWF, DPN, FPWN, PNOM, GATER applying the following constraints:

- upper altitude constraint (FL 90) at Metering Fix RUD
- upper altitude constraint (A30) at Approach Gate GATER
- time constraint at Approach Gate GATER

The difference between the two test runs results from different meteorological conditions (air temperature and wind) and from different time constraints defined by the PD/2 Arrival Manager.

4.1. GUIDANCE PERFORMANCE IN CLIMB AND CRUISE

Figure 4.1 shows a typical 3D-climb and 4D-cruise performance. The predicted trajectory starts at altitude 6000 ft and CAS 180 kts. The climb is performed as an open climb; i.e. maximum climb thrust is commanded and predicted CAS is flown on elevator.

The first part of the climb to FL 100 followed nearly exactly the predicted altitude and CAS profile. The aircraft started at FL 100 to accelerate to 200 kts in an energy sharing sub-phase and then resumed climbing at constant CAS. The actual weather data (wind and air temperature) was nearly the same as the forecast data used for trajectory prediction. This resulted in only minor deviations from the altitude and time profile in climb. The time deviation at the end of climb was about 3 seconds and the altitude deviation during climb reaches about 400 ft. It was compensated for with an automatic trajectory update at the end of climb.

After the Top of Climb (TOC) at a distance of about 50 NM the trajectory was generated again and then downlinked to the PD/2 ground system.

At a distance of about 80 NM the 4D-trajectory complying with the uplinked constraints was generated, i.e. the time profile is updated and cruise CAS is revised. The cruise is performed under 4D-guidance leading to a minor CAS reduction of about 3 kts. Time deviation in cruise is about 1 to 2 seconds. Altitude deviation in cruise is less than 20 ft. The cross track deviation (not shown) is less than 20 metres on straight legs and less than 50 metres during the turns.

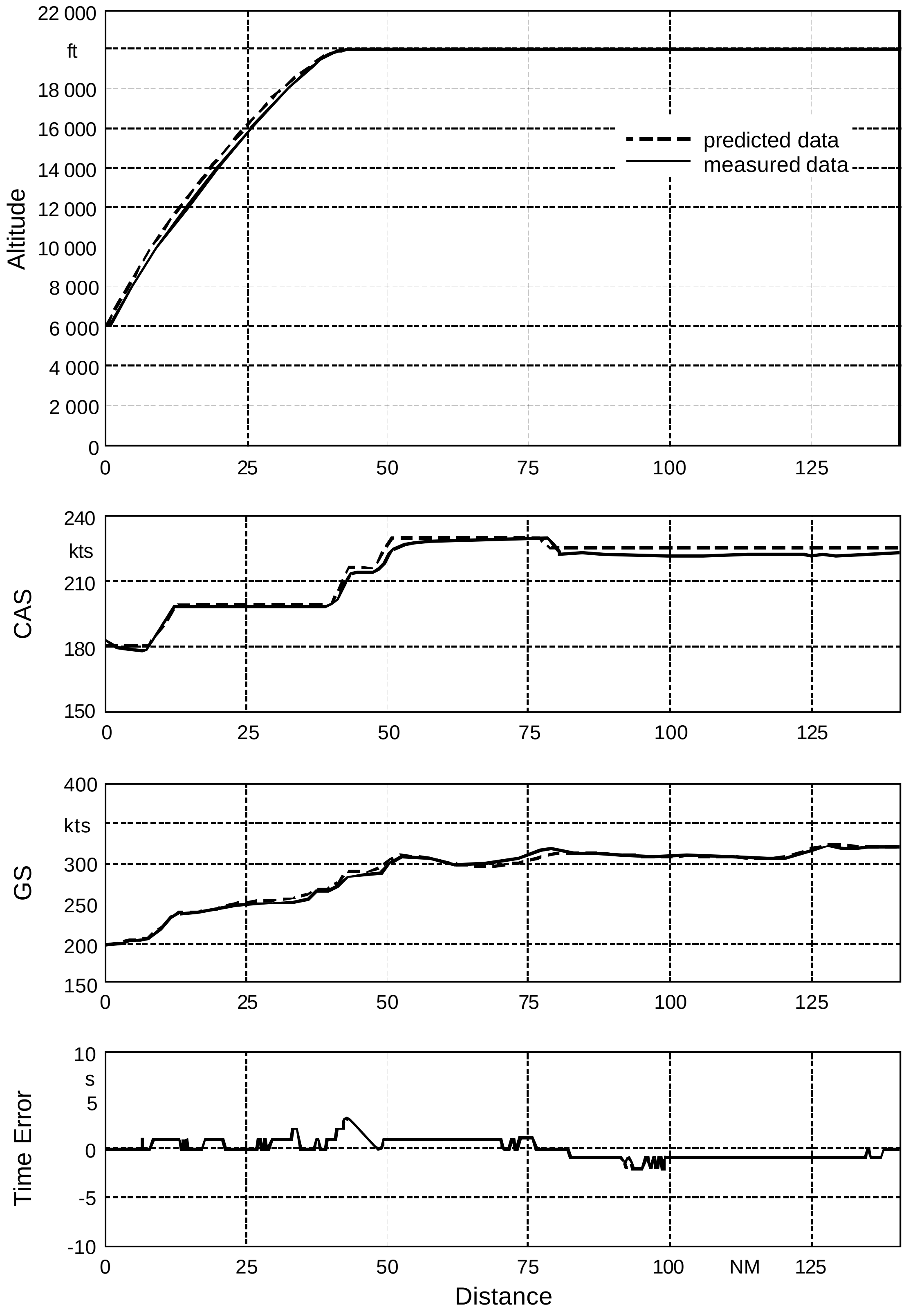

Figure 4.1 *Guidance Performance in Climb and Cruise*

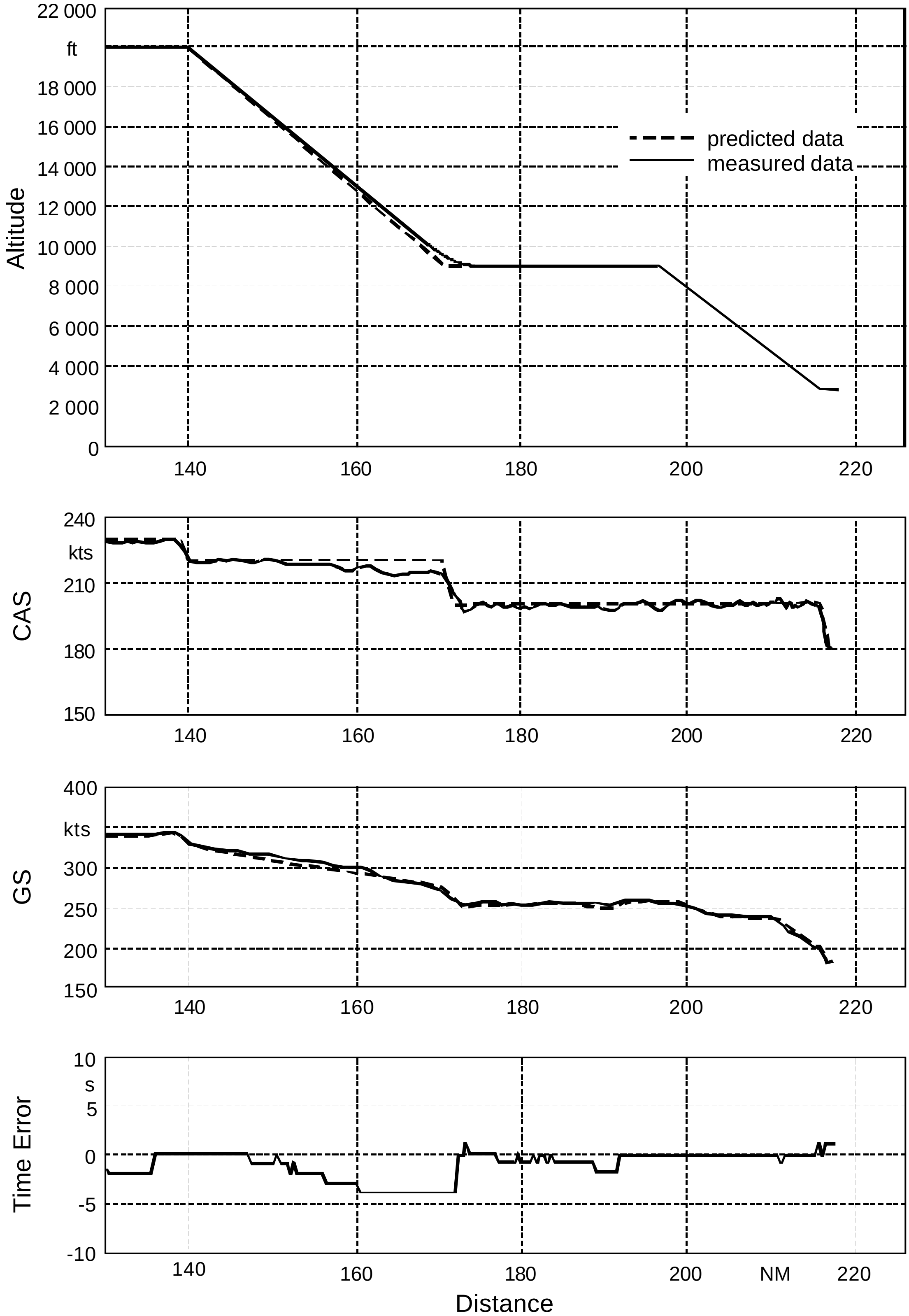

Figure 4.2 *Guidance Performance in Descent*

4.2. GUIDANCE PERFORMANCE IN DESCENT

Descent performance is shown in Figure 4.2. Shortly before reaching the Top of Descent (TOD) the 4D-trajectory was updated to compensate for any prevailing time error and to take account of the latest wind and air temperature data measured on-board for the prediction of the revised descent profile. The update of the descent profile prior to the TOD was an essential prerequisite for the accurate tracking of the descent profile, since the descent was predicted at near idle power setting, there was only a minor thrust margin available to compensate for excess energy.

The descent was initiated by reducing the thrust to near idle setting, whilst elevator maintains airspeed. After establishing the descent, thrust controls total energy.

Actual CAS was following demanded CAS, which was calculated from predicted CAS and an incremental CAS command provided for the compensation of any prevailing time error. Due to an increasing tailwind component in en-route descent the ground speed increases by about 10 kts which leads to an increase in time deviation up to -4 sec (early). The increase in time deviation lead to a CAS reduction which in turn yielded an altitude deviation since thrust had reached the idle power limit and air brakes were not applied. The altitude deviation was about 400 ft at the end of the en-route descent.

At FL 90 a level flight sub-phase was entered due to an altitude constraint at the Metering Fix. A trajectory update was performed which compensated the time deviation of -4 sec by path stretching, i.e. the length of the remaining flight path to the Approach Gate was appropriately modified.

Before starting the next descent phase the trajectory was updated again and the prevailing time deviation of -2 sec was nullified. The descent from FL 90 to 3000 ft followed the altitude profile with only minor deviations (less than 70 ft). A final trajectory update was performed at the entry way-point FPWN of the path stretching area. Time deviation in TMA descent was less than 1 sec, leading to an arrival time deviation of 1 sec (late) at the Approach Gate.

The guidance accuracy shown in these two example flights can be regarded representative for the case in which the meteorological forecast is in agreement with actual wind and air temperature. In fact all flight trials with ATTAS performed in May and June 1997 showed similar results (see Table 4.1). However, much more flights under different meteorological conditions are required to get a more comprehensive picture of guidance accuracy, as regards altitude and time deviations in climb, cruise and descent.

4.3. ARRIVAL TIME DEVIATIONS ACHIEVED

In the course of preparation and execution of PD/2 demonstration flights 12 complete test runs along the test route shown in Figure 3.2 were performed in May and June 1997. Test runs # 53/1 to # 56 served for the preparation and checkout of the onboard system as well as the ground system. Training of personal including pilots, experimenters and PD/2 ATC controllers was also an important aspect of these flights. Test runs # 58 to # 63 were the actual demonstration flights.

The table summarises the maximum positive and negative arrival time errors (in seconds) observed in four major phases of each test run, i.e. climb to FL 200, cruise at FL 200, en-route descent to Metering Fix altitude and level flight at FL 90 as well as TMA descent to 3000 ft (see Table 4.1). The last column of the table gives the final arrival time error at the Approach Gate.

Test Run #	Remarks	Climb to FL 200	Cruise at FL 200	Descent to FL 90	Descent to A 30	App-Gate
53/1		0/+8	-3/+3	-3/+1	-3/0	**-2**
53/2		-7/+3	-1/+5	-2/0	-2/+1	**-2**
54/1	wind 10 to 35 kts, no weather forecast data available	-2/+5	-24/+5	-1/+5	-7/+5	**-7**
54/2		0/+4	-12/+13	-2/+5	-3/+5	**-3**
55	no datalink	0/+3	-2/+6	-1/+5	-1/+5	**Class B**
56	wind 5 to18 kts, no weather forecast data available	-7/+8	-7/+8	-6/+5	0/+3	**+1**
58	demonstration flight	-3/0	-5/+1	-2/+1	0/+1	**+1**
59	demonstration flight	-2/+1	-2/+4	-4/+1	-1/+1	**+1**
60	demonstration flight	0/+3	-2/0	Class B	Class B	**Class B**
61	demonstration flight	0/+4	-2/+4	-1/+1	-2/0	**-1**
62	demonstration flight	0/+4	-1/+2	-5/0	-5/0	**0**
63	demonstration flight	0/+5	-5/+2	-5/1	+1/0	**-1**

Table 4.1 Time Accuracy achieved in Climb, Cruise and Descent

In 3 of 12 test runs there was no meteorological forecast (wind and air temperature) available, and all trajectory predictions performed in flight were based on the blend of measured data at the aircraft's current position and zero wind from the EFMS's meteorological data base as well as standard air temperature. This resulted in a major discrepancy between predicted meteorological data and actual data, which in turn led to altitude and time deviations from the predicted 4D-trajectory and subsequent more frequent trajectory updates.

In two of the test runs tactical advisories were given either by real ATC or by PD/2 ATC controllers, , and the aircraft was then treated as a Class B aircraft.

A discrepancy in meteorological data resulted typically in a major altitude deviation and a minor time error in 3D-climb. The column entitled ‘Climb to FL 200’ indicates the spread of actual time errors observed during climb. This spread never exceeded the set time error tolerance of +/- 10 sec. Trajectory updates in climb were mainly caused by altitude deviations exceeding the set altitude error tolerance of +/- 750 ft.

During 4D-cruise the time error was normally also within +/- 10 sec., but in case of missing meteorological forecast data, the time error exceeded this bound (see column ‘Cruise at FL 200), which caused further trajectory updates.

During en-route descent the time deviation was always within the set time error tolerance of +/- 10 sec. (see column ‘Descent to FL 90). In TMA descent the set time error tolerance was +/- 5 sec., which led to additional trajectory updates (see column ‘Descent to A 30’).

The last column ‘App-Gate’ indicates that the final delivery time error at the Approach Gate, the aim point of the 4D-approach, is within the aspired target tolerance of +/- 5 sec. in most of the test runs.

The guidance results achieved so far indicate, that the guidance concept is valid. However, more flight data under different meteorological conditions are required.

5. RESULTS OF THE AHMI EVALUATION

Six pilots, including two airline pilots, participated in the AHMI experimental evaluation. All pilots had experience with FMS-based flight planning.

Due to long briefing and familiarisation sessions which lasted considerably longer than planned, none of the participating pilots was able to perform all eight planned trial runs. The maximum number of runs which were performed was seven, the minimum four. However, each of the pilots performed at least one familiarisation trial, two trials concerning standard PHARE trajectory negotiation, and one of the failure condition trials. The reason for the increased duration of the initial sessions was the advanced ATM and AHMI environment which caused numerous detailed technical and operational pilot questions on datalink/ATN, incorporation of the Airline Operation Control Centres (AOCC), and work distribution between crew, ATC/ATM facilities and AOCC.

As addressed in chapter 3.3 on the experimental set-up, data collection regarding pilot acceptance was performed by means of a structured interview. The essential results regarding the different interview topics are presented for each topic separately, but addressed only once although the particular pilot comments were often related to more than just one topic.

In general, the overall concept was favoured by all pilots after having experienced the system. All comments were related to increased efficiency and enhanced operational capabilities of the system.

The display technology caused major concerns with respect to bright daylight conditions. However, it was noted by all pilots that display technology would progress most probably to a high-contrast display in the time frame of 5 to 10 years which then can be operated in the cockpit.

Display Layout

The basic display organisation incorporating a horizontal and vertical display for both Plan and Monitor mode was appreciated by all pilots. The ‘display page hierarchy’ was rated very efficient and easy to adapt. In addition, button realisation, menu and sub-menu organisation as well as constraint list, trajectory, and clearance or tube representation were generally appreciated.

The display size and resolution was rated adequate. It was noted by all pilots that the AHMI display concept required display sizes of more than 10 inch, and would not get acceptance at all if attempted on display sizes below 8 inch. The range in-between requires adaptation, e.g. a decreased number of buttons, to be operable in the cockpit.

Numerous suggestions and proposals referred to colour selection of distinct display objects, line widths and abbreviations. It was decided to implement the pilot’s suggestions and preferences immediately to avoid possible reasons for confusion.

Input Characteristics -

Before having operated the touch-pad the majority of pilots suggested an increased size could ease operation. However, after the familiarisation trials some of the pilots rated the size adequate and easy to operate regarding cursor control. The cursor dynamics were accepted by all pilots, but a slightly more conspicuous shape of the cursor would improve the handling. Nevertheless, it was noted that highlighting of a display object either way-point or button when being touched by the cursor supports operational handling considerably.

Two of the pilots requested 'hot-spot' activation at least for those function buttons located in the edges of the display area.

The location of the touch-pad resulted in several proposals for improvement. For the experiment it was mounted on a board which is meant to be fastened on the pilot's knee. Mounting it at the end of the armrest of the chair or beside the stick, both solutions without affecting stick operation, were proposed.

Input Philosophy -

The function-oriented display operation as well as pilot action demands initiated by either ATC datalink or system generated messages were generally favoured. However, details were criticised.

The experimental system did not support direct specification of a new way-point location by the pilot because there were no means to input alphanumerics, i.e. a way-point name. To insert a newly specified way-point in the experimental set-up required the insertion of any other existing way-point which then may be moved, thus avoiding the naming problem. This procedure was not appreciated.

Two of the pilots requested system support for SID, STAR selection by means of the advanced ND.

Operational Aspects -

The missing CDU was regarded the essential operational deficiency. Pilots experienced in operating a Flight Management System requested the CDU display. In particular, they required the alphanumeric list of way-points including Top of Climb (TOC), Top of Descent (TOD) as well as 'Distance to Go'/'Time to Go' and requested airspeed indication (CAS). This comprehensive alphanumeric list supporting identification of the next actions to be performed by FMS and aircraft was regarded as the advanced ND provides the information on two different 'display pages', i.e. the horizontal and vertical profile view. This attitude could change if vertical information such as TOC and TOD indications were included in the HD, as noted by two of the pilots.

Moreover, several incompatibilities between conventional CDU input strategy and ND input sequences were revealed by the pilots. One of these issues referred to the generate function available on the ND. Conventional systems as already in use do not require a ‘generate’ button at all because they perform an automatic generate after each input of the pilot. Other issues referred to parallel operation of ND and CDU. If the pilot changes to PLAN mode on the ND in order to modify the constraint list, the CDU could follow automatically, and vice versa.

The detailed analysis of the required inputs for planning a flight revealed that there was no need for an ‘attribute’ button that switches to VD only. This could be done by pressing the corresponding button directly. Synonymous buttons were not required. The same concept could be applied to the MDEL (‘Multi Delete’) button as the ‘delete’ function could cover such action extension.

The most frequent comments referred to the COPY function in the PLAN mode. Although identified as being somewhat necessary, it was rated very difficult. In a normal sequence the pilot would assemble a constraint list, generate the trajectory, negotiate it with ATC and after getting the clearance activate the trajectory. When performing this sequence, after each pilot action the corresponding constraint list was stored by the system. However, there was no indication at all that under standard operational conditions, all stored constraint lists were identical. In the case of ‘what-if’ modelling which was appreciated as an option, this could lead to confusion. After generation of the trajectory in a ‘what-if’, the pilot constraint list and the corresponding constraint list buffer are identical but they differ from the constraint lists related to the previously negotiated and activated trajectory. Therefore, the pilot must keep in mind the status of the different constraint list buffers. Moreover, the availability of a ground constraint list will cause additional confusion. All pilots rejected a requirement to keep in mind system buffer status.

Additionally, all pilots stated that if a ground constraint list was available the system must be capable of indicating the differences between a constraint list related to the downlinked trajectory and the uplinked ground constraint list. The pilots all rejected the requirement to detect the differences between constraint lists, i.e. to identify the ATC imposed constraints.

Although no solution could be identified, the pilots noted that such requirements must be fulfilled by future systems.

Another operational aspect referred to pilot initiated planning in-flight. The planning or modification had to be performed by means of PLAN mode. The gap between current position of the aircraft and the first way-point of the modified constraint list required the ‘direct to’ function of the MONITOR mode. This was thought to be inconsistent by the majority of the pilots. A solution for this problem could not be identified, but advanced systems must avoid such inconsistencies that increase operational load.

PHARE Trajectory Negotiation Concept -

The strategic trajectory negotiation procedures were accepted by all pilots. It was agreed that efficiency will increase with utilisation of datalink and advanced flight planning systems. However, concern was expressed regarding the co-ordination between the different controllers and regarding integration of AOCCs.

All pilots noted that under such conditions an Airborne Collision Avoidance System (ACAS) could improve pilot confidence and safety considerably.

6. SUMMARY

The results obtained from the PD/2 flight trials show that the air/ground negotiation of trajectories in the approach phase is feasible. However, crucial factors are the number of trajectories to be negotiated, the response time of the arrival planning system, and the capacity of the datalink.

A delivery accuracy of 10 seconds at a Metering Fix and of 5 seconds at an Approach Gate seems to be achievable by fully automatic approaches if realistic meteorological forecast data are available. However, more flight data under different meteorological conditions are required to support this result.

Although the comments on certain deficiencies of the layout received from the evaluation pilots indicated that additional effort should be spent in improving the layout of the system. The AHMI evaluation trials revealed appreciation of the cockpit concept. The advanced Navigation Display provides efficient means for the crew to operate the FMS in a future ATC/ATM environment.

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7. GLOSSARY

3D	three dimensional (latitude, longitude, altitude)
4D	four dimensional (latitude, longitude, altitude, time)
ACC	Area Control Centre
AFCS	Automatic Flight Control System
AHMI	Airborne Human-Machine Interface
AOCC	Airline Operation Control Centre
ATC	Air Traffic Control
ATM	Air Traffic Management
ATMOS	Air Traffic Management and Operations Simulator
ATN	Aeronautical Telecommunication Network
ATTAS	Advanced Technologies Testing Aircraft System
CAS	Calibrated Airspeed
CDU	Control and Display Unit
DADC	Digital Air Data Computer
D-GPS	Differential Global Positioning System
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DME	Distance Measurement Equipment
EFIS	Electronic Flight Instrument System
EFMS	Experimental Flight Management System
FbW	Fly-by-Wire
FCU	Flight Control Unit
FIR	Flight Information Region
FMS	Flight Management System
FL	Flight Level
GPS	Global Positioning System
GS	Ground Speed
HD	Horizontal Display
HMI	Human Machine Interface
HSI	Horizontal Situation Indicator
IFR	Instrument Flight Rules
ILS	Instrument Landing System
I/O	Input and Output
IRS	Inertial Reference System
LAN	Local Area Network
LCD	Liquid Crystal Display
ND	Navigation Display
PD/2	PHARE Demonstration 2
PFD	Primary Flight Display
PHARE	Programme for Harmonised ATM Research in EUROCONTROL
RNAV	Area Navigation
R/T	Radio / Telephony
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route

TMA	Terminal Control Area
TOC	Top of Climb
TOD	Top of Descent
VD	Vertical Display
VFW	Vereinigte Flugtechnische Werke
VHF	Very High Frequency
VME	Virtual Memory Environment
VOR	VHF Omnidirectional Range

8. REFERENCES

In PHARE numerous documents have been produced in preparation of the PHARE Demonstration 2 representing sources for the final report and its annexes. The general list is available in the reference chapter of the PD/2 Final Report Vol. 1. The list below represents additional documentation addressing the airborne system.

- EFMS Phase 1b User Requirements Document,
  Part 1: Functional Requirements,
  EUROCONTROL DOC 94-70-12, Version 2, June 1994.

- EFMS Phase 1b User Requirements Document,
  Part 2: Description of Initial CDU Page Layouts,
  EUROCONTROL DOC 94-70-25, Version 1, June 1994.

- EFMS Phase 1b Technical Reference Document,
  EUROCONTROL DOC 96-70-15, Version 1, July 1996.

- EFMS Phase 1b Air/Ground Datalink Communication for PD/1 and PD/2,
  EUROCONTROL DOC 96-70-28, Draft Version 2.2, November 1996.

- AHMI - Initial Display Format Proposals,
  EUROCONTROL DOC 94-70-26, 1994.

- AHMI Display Format Prototypes and Initial Evaluation Results,
  EUROCONTROL DOC 95-70-08, 1995.

- PHARE Trajectory Negotiation in a Multi-Sector Environment,
  EUROCONTROL DOC 97-70-14, 1997.

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