PROGRAMME FOR
HARMONISED AIR TRAFFIC
MANAGEMENT RESEARCH
IN EUROCONTROL

PHARE

EUROPEAN ORGANISATION FOR THE SAFETY OF AIR NAVIGATION EUROCONTROL

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PD/1 FINAL REPORT
Annex E
Airborne Aspects of PD/1

PHARE/NATS/PD1-10.2/SSR;1.1

EUROCONTROL

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1. INTRODUCTION

The DRA BAC 1-11 Civil Avionic trials aircraft XX105, shown in Figure 1-1, was the airborne element of the PD/1 demonstration in which a real aircraft, apparently passing through NERC sectors 10 and 11 while on the en-route climb out of Amsterdam, was integrated with other simulated traffic within a ground simulation showing typical traffic in conflict situations.

From the airborne aspect, the main purpose of the demonstration was to show the ability to negotiate trajectories with the air traffic controllers in the PD/1 ground simulation and then to fly within continuous 4-D constraints structured around the agreed trajectory. An on-board ATC simulator was available for demonstration during the periods when the aircraft was not actively involved in the ground simulation exercise. Although not part of the PD/1 demonstration, an electronic taxi map was available when the aircraft was on the ground.

Figure 1-1 - Photo of BAC 1-11

2. EXPERIMENTAL AIRBORNE SYSTEMS

The airborne elements of the PD/1 integrated air/ground system are shown in Figure 2-1. A brief description of the most important features is given below.

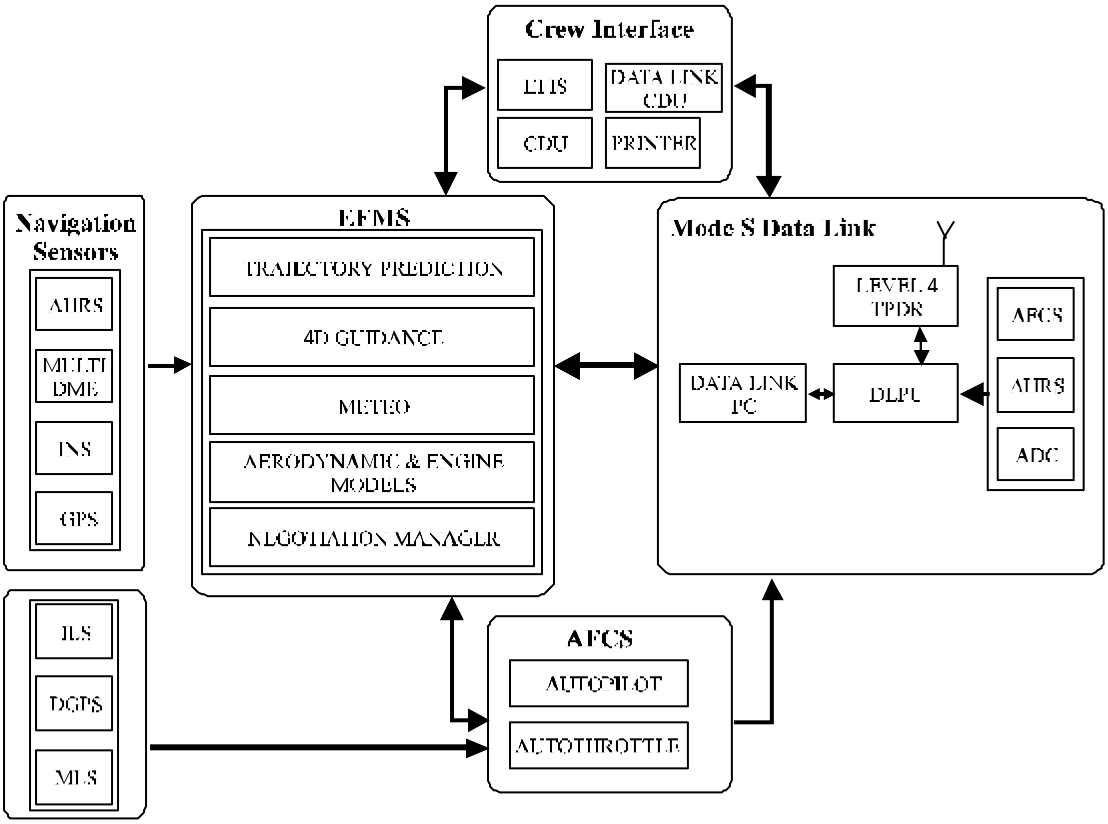


Figure 2-1 - The Airborne Systems

2.1 EFMS

The Experimental Flight Management System (EFMS) is the essential airborne element of an integrated air/ground system designed to enable research into air traffic management. It is characterised by the following features:

- Generic design - the EFMS can readily be adapted to a wide variety of applications, whether to dedicated research aircraft or to ground-based simulation;
- 4-D trajectory predictor - a realistic model of the aircraft and the environment in which it flies enables accurate trajectory predictions to be made for the complete flight profile;
- Trajectory modification - the predictor can revise trajectories to ensure 4-D constraints are met;
- Negotiation with ATC - proposed trajectories can be downlinked, while constraints and clearances can be received;
- Flying the clearance - the aircraft follows the trajectory, flying within continuous 4-D constraints, i.e the ‘tube in space’.

The current EFMS is Phase 1b: later versions of the EFMS will offer increased functionality, such as the ability to downlink meteorological data as well as being able to use updates of meteorological forecasts from the ground. It is expected that the guidance algorithm will change fundamentally, from being a continuous tracking of the trajectory to being the more efficient method of flying at constant parameter values (eg throttle setting) until predictions suggest the aircraft is liable to infringe a tube boundary.

The EFMS is housed in a 19 inch VME cabinet and uses a single MVME 167 card for all processing functions. An ARINC 429 interface card has an 8 channel input, 4 channel output capability, while an MVME 712 card serves as the interface for serial and ethernet communications.

The EFMS supervisor accesses the system through a portable PC, through which he can download the software, monitor status and performance and collect the recorded flight data. The supervisor’s PC can also be used as the airborne ATC simulator, providing - as far as the EFMS is concerned - constraint lists identical to those which would be received from ATC on the ground.

2.1.1 Trajectory Prediction

A fundamental feature of the EFMS is the ability to produce 4D trajectories which the aircraft can follow and which, if necessary, can be modified to satisfy ATC constraints.

The pilot initiates the process by using the CDU to call-up and edit as required, one of the routes stored in a database. A 4-D trajectory is generated by the EFMS and, if approved by the pilot, is downlinked over the datalink to the ATC ground simulator. While a complete - i.e. take off to destination airport approach gate - flight description can be made, partial trajectories can also be generated inflight to terminate for example, at the metering fix.

The meteorological data used by the trajectory predictor during airborne operation is a blend of the meteorological forecast for the future path of the aircraft and the measured winds and temperature for the aircraft’s current position; it will be referred to as ‘predicted’ data. Automatic trajectory re-generation is available, which takes account of updated meteorological data and therefore offers improved target values to form the basis of the guidance commands. The re-generations can be activated at significant points e.g. the top of climb or when some altitude or time deviation threshold from the trajectory is exceeded.

The aircraft performance characteristics are defined within aerodynamic and engine modules which have standard interfaces, while the flexibility of the trajectory predictor is enhanced further by the use of generic parameters such as the Energy Sharing Index, or ESI. The parameter specifies the proportioning of prevailing excess energy between along-flight path acceleration (expressed in terms of computed airspeed rate i.e. CAS rate) and vertical speed. The parameter Thrust Index or TI, defines the required thrust in terms of the proportion of the prevailing thrust range available i.e within the range 0 to 1.0. Finally, engine thrust demand is expressed in terms of the Engine Control Parameter or ECP, which is converted to the appropriate demand within the aircraft-specific area of the guidance system: in the case of the BAC 1-11 the climb is described in terms of the engine high pressure spool rpm i.e. N1, while the descent makes use of throttle position i.e CASC.

The negotiation manager schedules the data communication with ATC, who may apply constraints to the proposed trajectory: these can be route waypoints, altitude restrictions and time constraints at specific points along the route. The Constraint List is uplinked to the aircraft and once endorsed by the pilot, is input to the trajectory predictor. As long as the aircraft's performance envelope is not exceeded, a revised trajectory is produced to satisfy the constraints.

If ATC endorse the revised trajectory they will transmit a clearance 'tube' up the datalink. This is a 4-D envelope, within which the aircraft will be committed to remain. The tube may not necessarily extend to the end of the full origin to destination trajectory, i.e. a partial clearance may be given.

The pilot can activate a proposed trajectory forthwith, without invoking the full tube negotiation process; an action which is often used under trials conditions.

2.1.2 4-D Guidance

EFMS Phase 1 makes use of continuous guidance commands to control the adherence of the aircraft to the trajectory. The control gains within the guidance algorithms are quite low, to ensure a reasonable compromise between performance and control activity.

In view of the desirability of flying the climb under high power settings and with minimal thermal cycling, it was decided that time control would not be attempted in the climb. Instead the aircraft is operated at the power settings used during the trajectory prediction, while the climb profile is tracked through variation of the airspeed (CAS or Mach) command. Later guidance developments will address 4-D climb operation. 4-D control is, however, currently available throughout any level flight segments which may be imposed within the overall climb phase.

Although time control is open-loop in the climb, the accumulated time error at the top of climb is smaller than might be expected. This is because the change of airspeed required to correct for the effects of unpredicted along-track winds on altitude performance produces a partially self-compensating effect, through the associated change in groundspeed.

Apart from wind variation, the other factor influencing the climb is the effect of static temperature prediction errors on thrust: even a 1 deg error in the forecast can have a discernible effect on climb rate.

Full 4-D control commences at the Top of Climb and is employed throughout the cruise and descent. A simple algorithm calculates an incremental CAS command according to the prevailing time error.

Airspeed control in the descent is obtained through changes in aircraft pitch, in an identical manner to the climb, while altitude is regulated by change of thrust. In order to provide some margin for reducing thrust, the descent is normally planned at a small value of Thrust Index e.g. around 0.05, rather than being at flight idle settings. However, if winds are significantly different from those predicted, the pilot may still be required to deploy the airbrakes in order to dissipate energy.

Lateral control generates a continuous bank demand to null the current cross track error. A low gain integrator is used to remove residual offsets. A feedforward bank demand is produced to improve turn performance. This includes a wind compensation term: wind data measured immediately prior to the turn is used to predict the bank angle required to compensate for the changing cross track wind which will be encountered as the aircraft progresses round the turn.

2.2 NAVIGATION SENSORS

The BAC 1-11 trials aircraft has a variety of navigation data sources including Multi DME, INS and GPS, the data from which can be amalgamated to provide highly accurate position estimation.

Figure 2-2 - Photo of Flight Deck

2.3 AIRBORNE HMI INTERFACE

The Airborne Human Machine Interface (AHMI) aspects of integrated air/ground ATM systems are an important part of the PHARE research programme, and are being developed jointly by DLR (Braunschweig), DRA (Bedford) and NLR (Amsterdam). For PD/1 airborne operation, two EFMS interfaces were available to the pilot, namely the CDU and the EFIS displays as shown in Figure 2-1. (The Data Link CDU and the Printer only interface with the Mode S Data Link system, and played no part in the PD/1 demonstrations). A view of the BAC 1-11 flight deck is given in Figure 2-2, showing the EFMS CDU positioned at the front of the centre pedestal and the EFIS Navigation Display situated alongside the Primary Flight Display on the left instrument panel.

2.3.1 EFIS

The EFIS displays consist of a Primary Flight Display (PFD) and a Navigation Display (ND). For the PD/1 demonstrations, EFMS information was fed to the ND to give the pilot a graphical map presentation of the route being flown and the clearance issued by ATC. Repeater displays were provided at the port observers’ station and at the rear of the aircraft’s cabin. The map software ran on a Silicon Graphics Iris workstation, and was developed as part of the AHMI project within PHARE.

Two display presentations could be selected on the ND, one giving a lateral map display similar to those available in modern civil transport aircraft, and the other a totally new presentation showing the aircraft’s position relative to the planned vertical profile. Both the lateral and vertical presentations could be selected by the pilot to be either a planning mode or a monitoring mode, and the main features of each of these display formats are described below.

2.3.1.1 Lateral Planning Display

A typical example of the lateral planning display is shown in Figure 2-3. An orange cursor symbol was drawn at the centre of the screen with two green range circles around it. The inner range circle was labelled, in n.miles, according to the pilot-selected map range (using a rotary switch mounted immediately below the ND), and the map was always in a north-up orientation as indicated at the top of the outer range circle. TAS and ground speed were shown in the top left corner of the screen (labels in blue, data in white), and the name, distance-to-go and ETA of the next waypoint were shown in the top right corner (all in white). Wind velocity was displayed in the bottom left corner, and UTC time in the bottom right corner (labels in blue, data in white). An orange aircraft symbol was drawn, with correct heading orientation, at the appropriate aircraft position, if this was within the displayed map area. The exact aircraft position was indicated by where the wings cross the fuselage on the aircraft symbol.

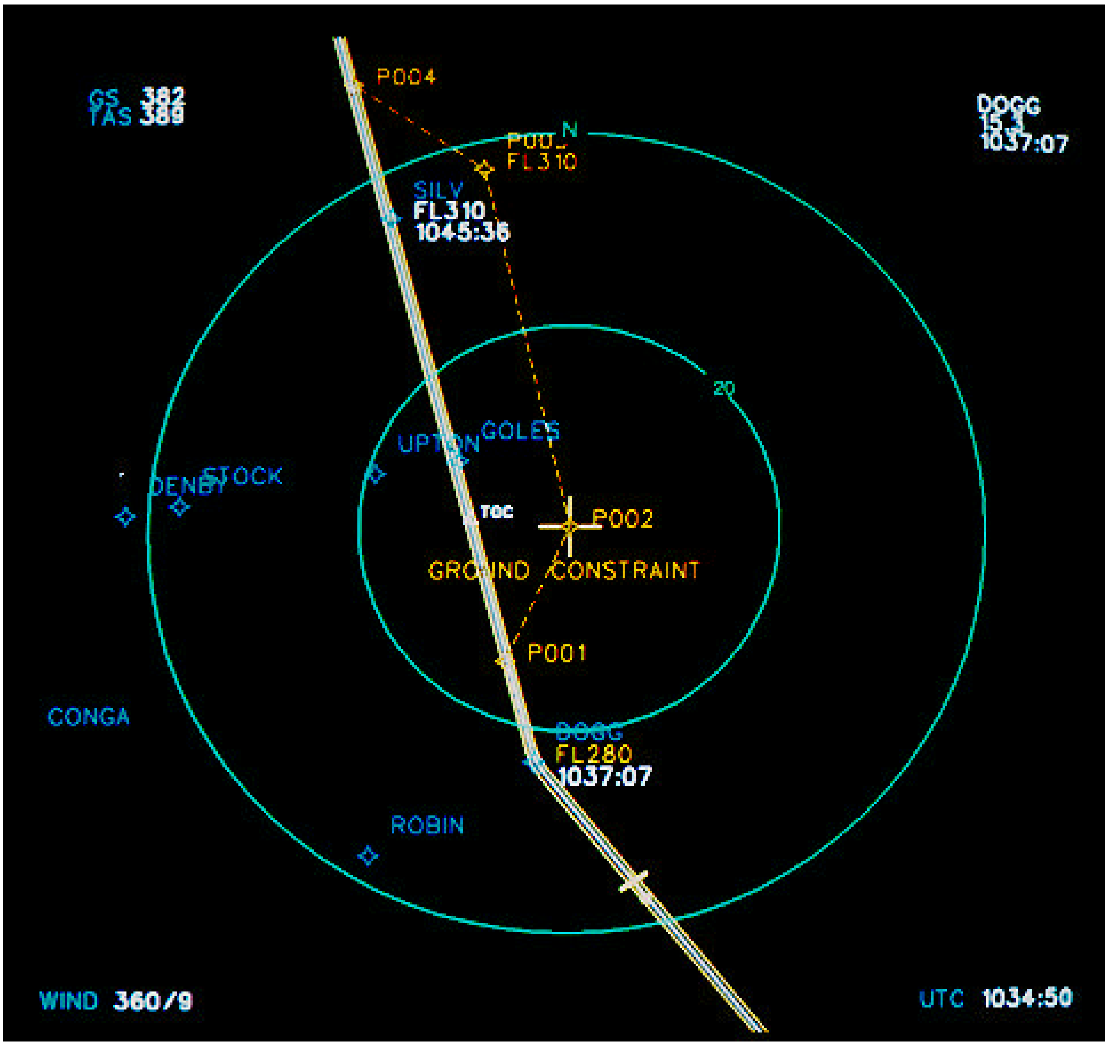


Figure 2-3 - Lateral Planning Display

The following EFMS items were drawn (in accordance with the automatic display logic described in Section 2.3.1.6 below):

- Pilot Constraint List - waypoint symbols annotated with name and any existing altitude and time constraint values (all in cyan). Dashed track line (also cyan) joining the waypoints.
- Ground Constraint List - the same presentation as for the Pilot Constraint List but coloured brown. This was only displayed when manually selected by the pilot, but an alert message “Ground Constraints” was shown in the top half of the screen when a ground constraint list was uplinked. The message was removed as soon as the pilot copied the ground constraint list into the pilot constraint list.
- Proposed trajectory - waypoint symbols annotated with name, predicted altitude and ETA (all in cyan). Solid cyan line joining the waypoints with circular arcs of the correct radius drawn at turning points.
- Active trajectory - the same presentation as for the pilot trajectory, but with all symbols, annotations and the trajectory line coloured white.
- Proposed tube - dashed amber lines showing the lateral tube limit each side of the trajectory, with circular arcs of the correct radius drawn at turning points.

- Active tube - the same presentation as for the proposed tube, but drawn with solid amber lines. (The proposed tube became active when the pilot activated the contract with ATC).

In this planning mode the map was initially centred on the first waypoint of the route being displayed. The pilot was able to step forwards and backwards along the route one waypoint at a time using push-buttons on the instrument panel immediately below the ND. By this means he was able to inspect the entire route in terms of constraints, trajectory and tube, and could expand the map scale at any point along the route to look in detail at any of the features. A "Home" button was also provided which immediately re-centred the map at the beginning of the route, to avoid having to step back one waypoint at a time.

2.3.1.2 Vertical Planning Display

A typical example of the vertical planning display is shown in Figure 2-4.

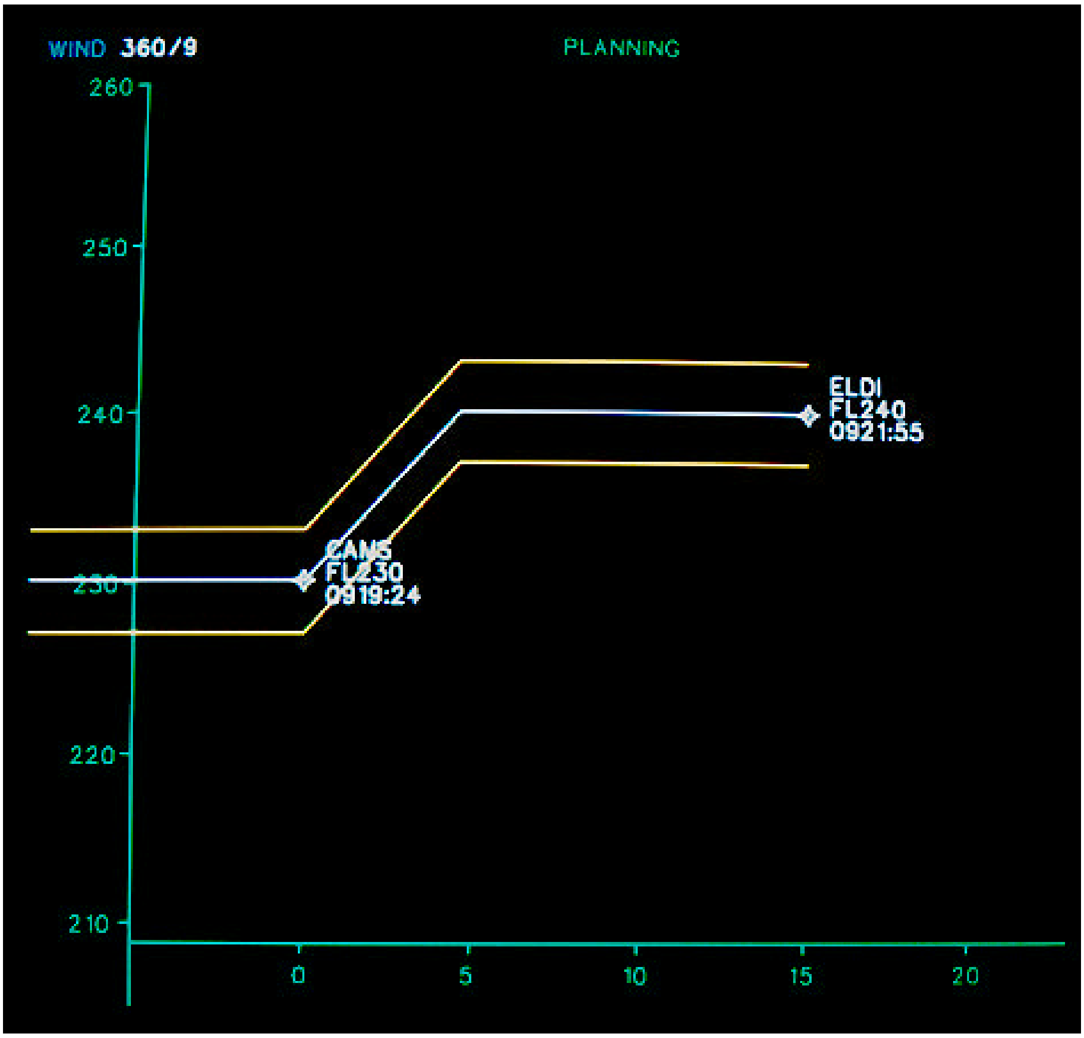


Figure 2-4 - Vertical Planning Display

A height scale was drawn on the left side of the screen and a distance scale along the bottom of the screen. The scales and their labels were in green. The range of the height scale was automatically selected so that the full screen size was always used to display the waypoints currently on the screen. This was achieved by using the altitude of the waypoint off-screen to the left to define the minimum value of the height scale, and the altitude of the waypoint off-screen to the right to define the maximum value. (This applied to a climbing situation - for a descent, the waypoints defining the maximum and minimum values were reversed). In level flight situations (e.g. cruise flight), and for initial climb and final approach situations, the height scaling was not allowed to reduce below 5,000 feet.

The range scaling along the bottom of the screen was determined by the pilot using the same rotary switch as for the lateral display. The zero range point was always positioned towards the left side of the screen, and this was the datum position for whichever waypoint the pilot selected for positioning the display around. He could step forwards and backwards along the route in just the same way as on the lateral planning display, using the same push-buttons mounted immediately beneath the ND.

A “PLANNING” title was written at the top of the screen to avoid possible confusion with the vertical monitoring display, which had a very similar appearance. This title was mainly for the benefit of visitors attending flight demonstrations, rather than for the pilot, who knew which mode he had selected. (The planning push-button illuminated when selected.)

Wind velocity was displayed in the top left corner of the screen, in the same format as on the lateral display. An orange triangular symbol was drawn at the appropriate height and distance along the route if the aircraft’s present position was within the display area. The exact aircraft position was indicated by the apex of the triangle.

The following EFMS items were drawn (in accordance with the automatic display logic described in Section 2.3.1.6 below):

- Pilot constraint list - waypoint symbols annotated with name and any existing height and time constraints (all in cyan) drawn at the appropriate distance along the route. Waypoints with no height constraint were drawn at the lowest point on the height scale. (The point was positioned slightly above the distance scale to avoid overwriting problems). Waypoints having a height constraint were drawn at the appropriate height together with magenta chevron symbols above and below the waypoint symbol, showing the maximum and minimum values of the height constraint window. No lines were drawn between the waypoints, as this would have no significance, and could be misleading, prior to trajectory generation.
- Ground Constraint List - the same presentation as for the Pilot Constraint List but coloured brown. This was only displayed when manually selected by the pilot, but an alert message “Ground Constraints” was shown in the centre of the screen when a ground constraint list was uplinked. The message was removed as soon as the pilot copied the ground constraint list into the pilot constraint list.
- Proposed trajectory - waypoints and additional trajectory points annotated with name, predicted altitude and predicted time (all in cyan), joined by a solid cyan line.
- Active trajectory - same as the pilot trajectory but all symbols, annotations and lines in white.
- Proposed tube - dashed amber lines above and below the trajectory showing the proposed upper and lower altitude boundaries.
- Active tube - same as the proposed tube but with solid amber lines showing the upper and lower altitude boundaries of the activated contract with ATC.

2.3.1.3 Lateral Monitoring Display

A typical example of the lateral monitoring display is shown in Figure 2-5. The lateral monitoring display shows the aircraft position in relation to the route being flown and in relation to any contract (tube) with ATC. An orange aircraft symbol was positioned two thirds down the screen at the centre of an inner range circle and an outer range arc (both coloured green). The inner range circle was annotated with the pilot selected range value in n.miles, while the outer arc included a compass heading scale marked at 5 degree intervals and annotated with 2 digit values every 10 degrees. Aircraft heading was indicated by an orange line in the centre of the scale, with a white digital readout of the heading value drawn in a white box immediately above the line. A green triangle just above the heading arc showed the aircraft track angle, and a symbol made up of two magenta squares was used to indicate Selected Heading (which the autopilot would control to in the event of EFMS disengagement). If the Selected Heading value was not on the displayed heading arc, then the symbol was parked at the appropriate end of the scale with a digital readout of the selected value.

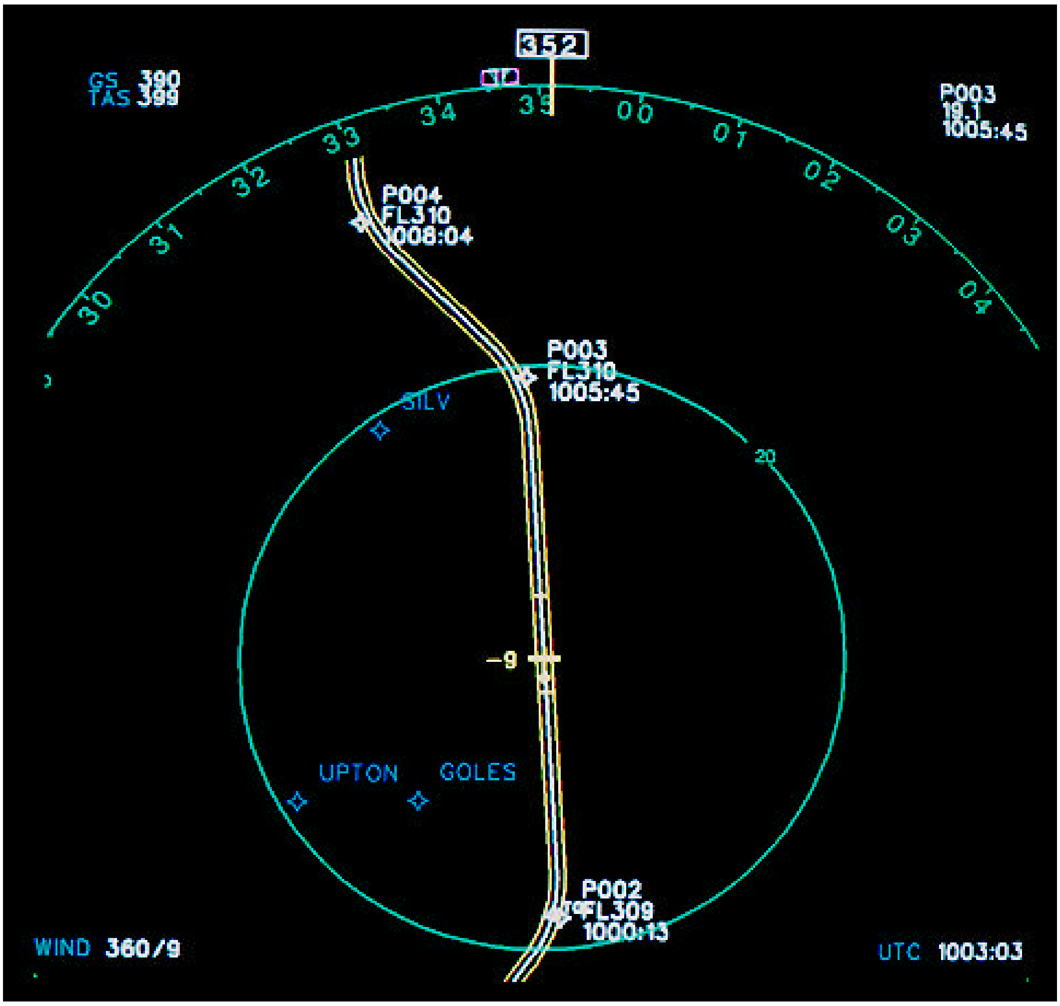


Figure 2-5 - Lateral Monitoring Display

Data displayed in the four corners of the screen was identical to that on the lateral planning display.

EFMS constraint lists, trajectories and tubes were displayed in the same way as on the lateral planning display. Also shown was the time element of the 4-D tube, with amber lines drawn at the early and late position limits of the time tube (with the time window converted into distance

using the planned speed as in the trajectory negotiated with ATC). The pilot could therefore see a plan view of the bubble of airspace the aircraft was contracted to stay within. Any time error relative to the centre of this bubble was written in digits alongside the aircraft symbol (a positive value meaning early and a negative value meaning late).

2.3.1.4 Vertical Monitoring Display

A typical example of the vertical monitoring display is shown in Figure 2-6. The display presentation is very similar to the vertical planning display, but with the aircraft symbol always positioned above the zero of the range scale. The vertical position of the aircraft symbol was automatically adjusted in order to utilise the full screen, and to provide the pilot with the maximum view of the vertical profile ahead of the aircraft whether it was climbing, descending or in level flight. In a climbing situation the aircraft symbol was positioned towards the bottom left of the screen. In a descending situation the symbol was positioned towards the top left, and in level flight situations the symbol was positioned half-way up and towards the left of the screen. Automatic height scaling was used as on the vertical planning display, with a minimum scaling of 2,500 feet applied to the initial climb and final landing phases of flight.

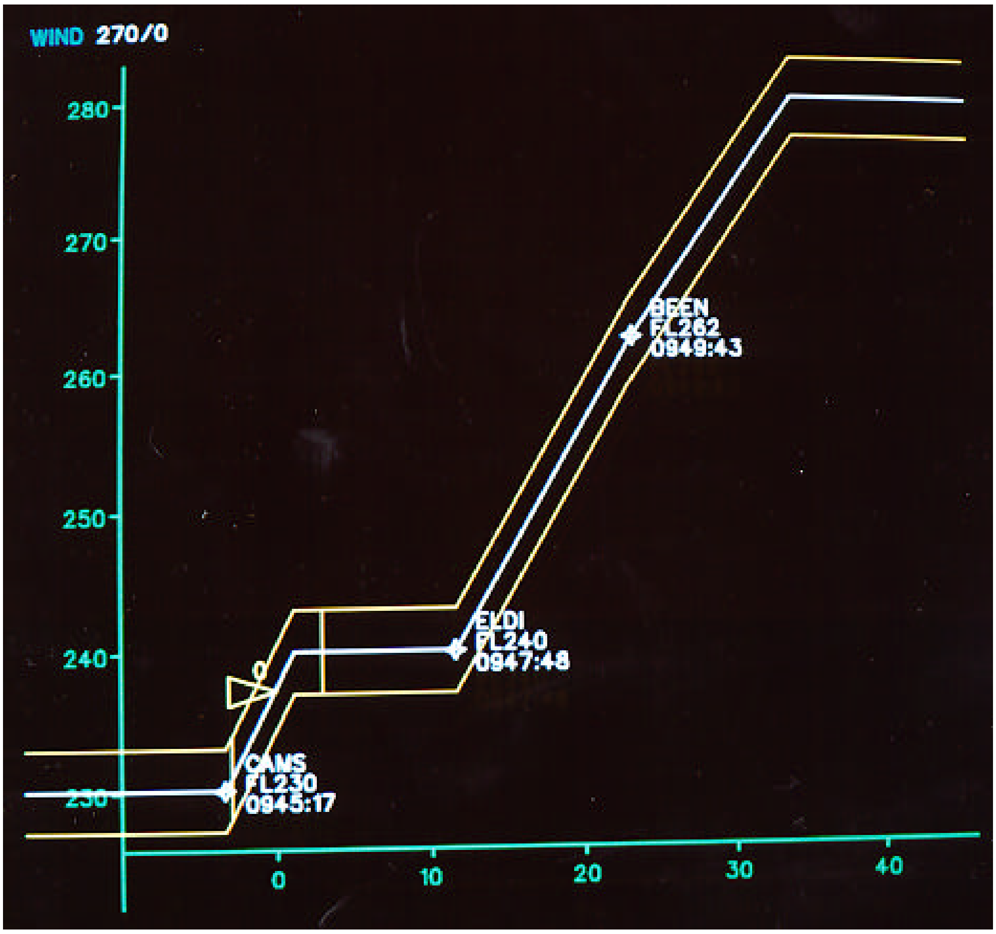


Figure 2-6 - Vertical Monitoring Display

EFMS constraint lists, trajectories and tubes were displayed in the same way as on the vertical planning display. The time element of the 4-D tube was shown in the same way as on the lateral monitoring display, so that the pilot could see a side-on view of the bubble of airspace the aircraft was contracted to stay within. As on the lateral monitoring display, a digital display of time error was written immediately above the aircraft symbol.

2.3.1.5 Additional Lateral Map Features

In addition to the EFMS constraint lists, trajectories and tubes displayed on the lateral planning and monitoring displays, the pilot could at any time choose to display any combination of navigation aids, airports and waypoints within the area displayed on the screen. Navigation aids were shown as a dot within a small square annotated with the 3 letter identifier (all coloured light pink). Airports were shown as small circles with short lines at each 90 degree point, annotated with the 4 letter ICAO airport identifier (all coloured light green). Waypoints were shown as a four-pointed star annotated with the 5 letter ICAO identifier (all coloured blue).

Ideally, the data base information used to draw the navigation aids, airports and waypoints should have been provided directly from EFMS, to ensure that exactly the same information was used within constraint lists. However, at the time of the PD/1 flights no provision had been made to pass data base information from EFMS to the EFIS displays computer, and therefore a separate data base was maintained within the EFIS computer.

2.3.1.6 Automatic Display of EFMS Data

In order to minimise the need for manual selection of the EFMS data the pilot required to view at any given time, logic was developed that automatically displayed the relevant constraint lists, trajectories and tubes during normal negotiation and re-negotiation sequences with ATC. Initially the pilot constraint list was displayed while he constructed his required route. The proposed trajectory was drawn immediately it was generated by the EFMS. If this was activated by the pilot, then the proposed trajectory became the active trajectory on the displays. After downlinking a trajectory to ATC, the pilot would see the ATC response on the displays. If ATC uplinked a proposed tube, this was shown as dashed lines around the trajectory, changing to the solid lines of the active tube as soon as the pilot accepted the contract. If ATC uplinked a ground constraint list, then a “GROUND CONSTRAINTS” alert message was written across the centre of the displays. The display of these ground constraints was not automatic - the pilot selected them on to the screen when required. The alert message was automatically removed as soon as the pilot copied the ground constraints into the pilot constraint list.

When ATC extended the contract, by uplinking a 4-D proposed tube for the route beyond the existing active tube, this was displayed as dotted lines around the active trajectory, but these immediately became solid lines because the EFMS automatically activated the contract extension with no pilot action being required (a relevant message appeared on the CDU).

If the pilot constructed a new constraint list or generated a new proposed trajectory then these were displayed in addition to the current active information. If activated by the pilot, the new active lists replaced the previous ones.

The pilot could override the automatic display logic if necessary. He could display the pilot constraint list and/or the ground constraint list at any time. He could also inhibit the display of the active lists if required (this was helpful as a short-term de-clutter facility in circumstances where a new pilot list or ground list remained close to or even overlaid the current active information).

2.3.1.7 Displays Control Panel

All pilot selection of map display modes, range scales, additional features etc., was carried out using electro-mechanical switches and selector buttons mounted on the instrument panel immediately below the ND. The Lateral, Vertical or Taxi Map presentation was selected on to the ND using a three-position rotary switch. Six range scales, from a minimum of 10nm up to a maximum of 320nm, were selectable on a second rotary switch. The planning mode of the lateral and vertical displays was selected using a push-to-latch-unlatch switch, and the forward/backward/home selections when in the planning mode were operated using non-latching push buttons. Push-to-latch-unlatch switches were used to select the pilot and ground constraint lists, to inhibit the active lists, and also to select the display of navigation aids, airports and waypoints.

All except the rotary switches were internally illuminated when selected, so that the pilot could easily identify all selections made. Under normal route monitoring circumstances the displays panel would have no lights showing. Any switch illuminated showed that the pilot had selected planning mode, or additional data for display, or had overridden the automatic display logic.

Two rotary knobs were also provided on the panel, allowing the pilot to control the brightness and contrast of the map display.

2.3.1.8 Taxi Map Display

When the aircraft was on the ground an airfield taxi map could be selected on to the ND, as shown in Figure 2-7. This map showed the principal features of the airfield, such as runways, taxiways and terminal buildings, and was designed to assist the pilot in manoeuvring between the stand and the runway when operating in restricted visibility conditions and at unfamiliar airfields. An aircraft symbol showed the current aircraft position, which was provided by GPS using real-time differential corrections passed over a data link from a GPS base station. Position errors should be less than 5 metres in this mode of operation. The Birmingham airfield map was drawn using WGS 84 coordinates provided by Eurocontrol.

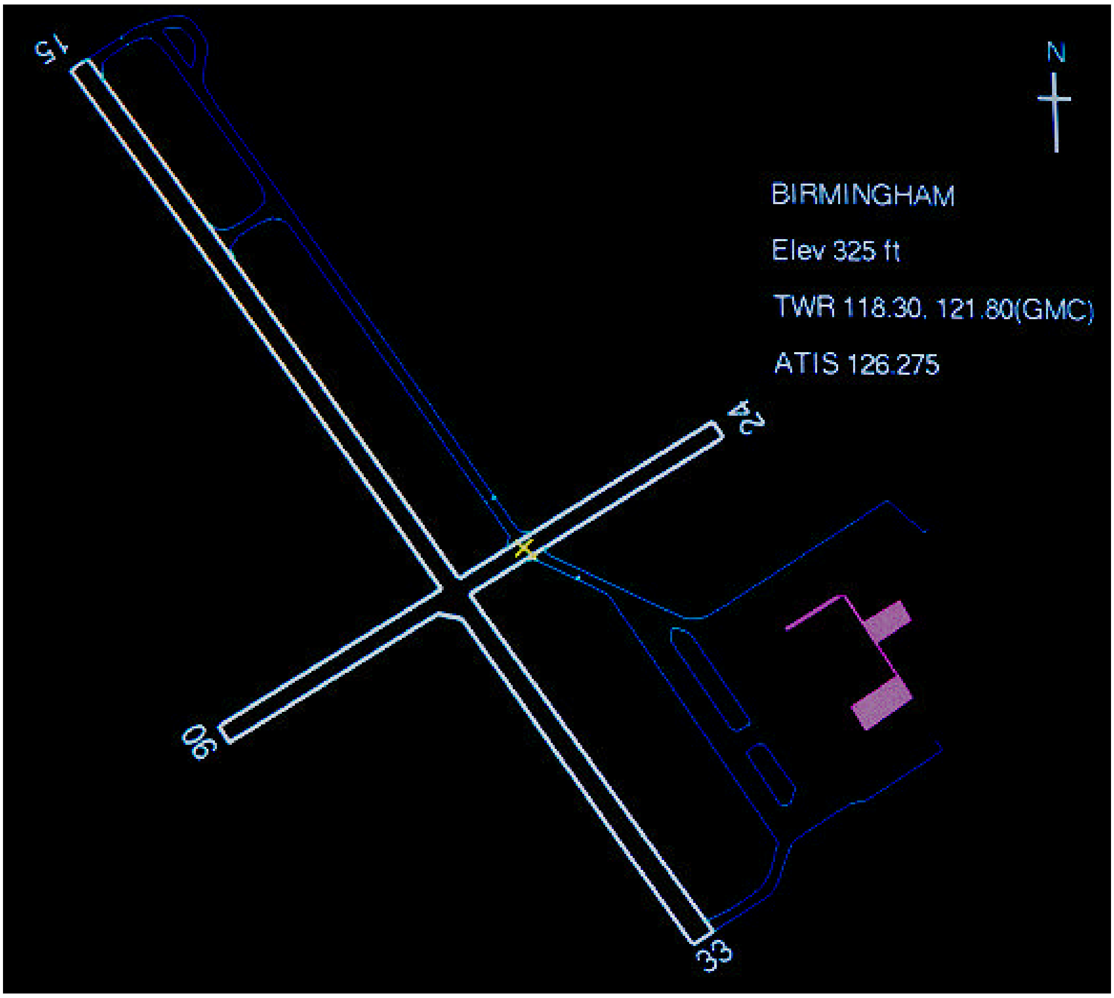


Figure 2-7 - Airfield Taxi Map

2.3.2 CDU

The EFMS Control and Display Unit (CDU) consists of a colour, liquid-crystal display (LCD) with a touch-sensitive screen and a computer to program the display format. The CDU is mounted in the centre pedestal between the pilots, while a repeater unit is mounted at the left-hand observer's console in the main cabin.

The function of the CDU is to provide the communication interface between the pilot and the EFMS: at that time the EFIS could not interact with the EFMS. The pilot used the CDU to:

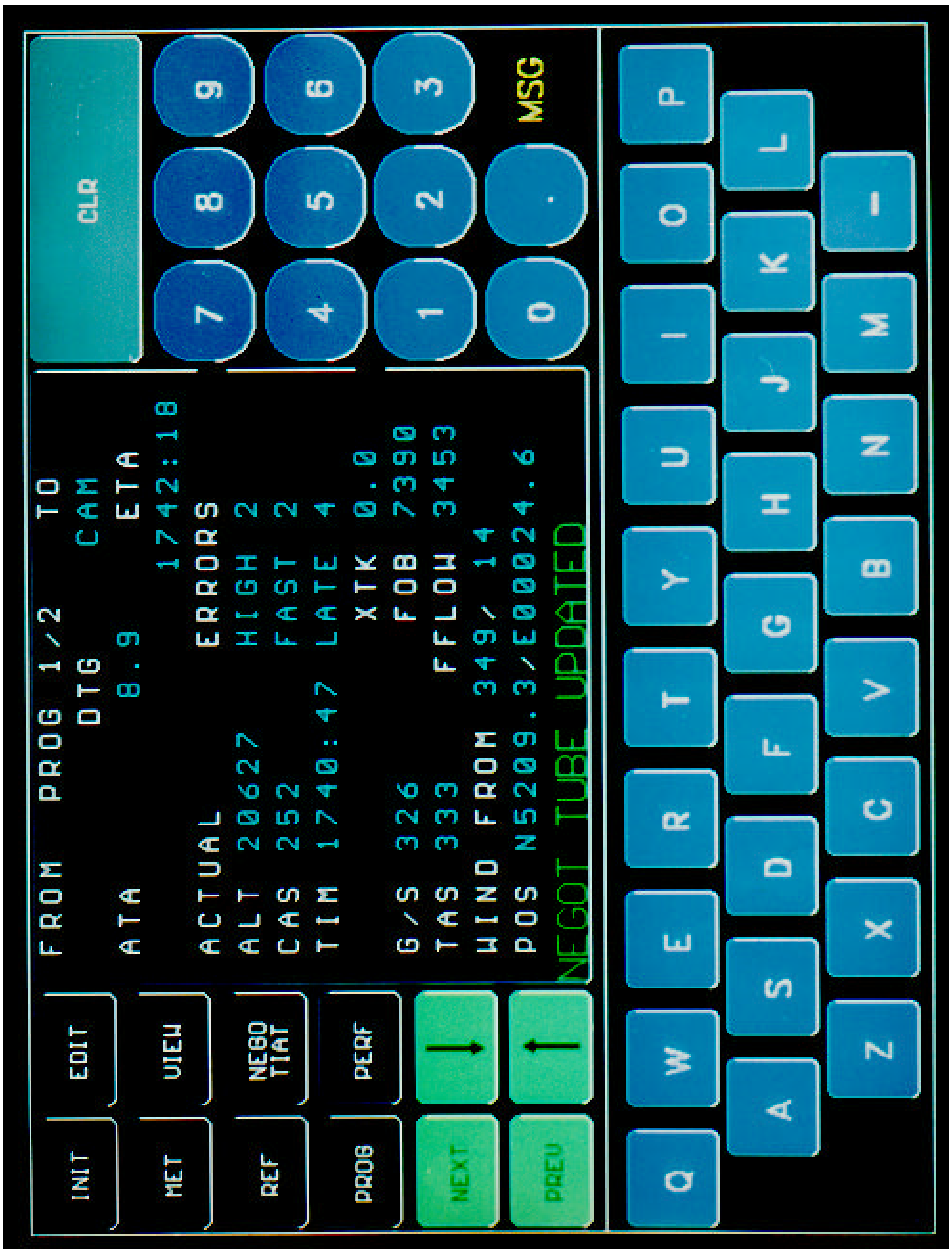
- edit constraint lists, generally to carry out 'go directs' to the next waypoint;
- generate trajectories;
- transmit trajectories to ATC;
- activate trajectories/contracts;
- monitor the aircraft's progress along the trajectory.

Prior to take-off, the pilot initialised the EFMS via the 'Init' pages on the CDU, by inserting the company route name, the cruise flight level, the zero fuel weight of the aircraft, the fuel load and the estimated take-off time. The only other occasion the Init pages were used occurred when the time synchronisation with the PD/1 simulation was made, requiring the pilot to change the value of UTC Time.

In flight, the pilot used mainly the Edit pages, the Negotiation page and the Progress pages. The functions of the Reference and Performance pages were not generally required for the PD/1 demonstrations. The View pages were used to confirm the data within the ground constraint lists that were received from the ground, as well as the predicted meteorological data for each waypoint, which the pilot was able to edit. Finally the Meteo Function, which would enable access to the weather database, was inactive in this software release.

The Edit and Negotiation pages were the features used by the pilot most heavily. The Edit pages provided the means for handling the constraint lists and the 'go direct' function, while the Negotiation page enabled trajectory generation and downlink and activation of trajectories and contracts.

An example of a CDU page is shown in Figure 2-8.



```
FROM   PROG 1/2   TO
        DTG       CAM
ATA     8.9       ETA
              1742:18
ACTUAL     ERRORS
ALT 20627  HIGH 2
CAS 252    FAST 2
TIM 1740:47 LATE 4
            XTK 0.0
G/S 326     FOB 7390
TAS 333   FFLOW 3453
WIND FROM 349/ 14
POS N5209.3/E0024.6
NEGOT TUBE UPDATED
```

Figure 2-8 - Photo of CDU

2.4 DATALINK

The Mode S datalink was chosen for the PD/1 demonstrations, earlier trials having established the performance and reliability of the system. There was also the logistical advantage of the ground station at DRA Malvern being on the same site as PD/1.

The onboard data link hardware consists of the Data link Processor Unit (DLPU) which provides the bi-directional interface between the aircraft systems and the transponder. The data link PC is an intelligent interface between experimental equipment such as the EFMS, and the DLPU.

Three basic types of message are employed by the Mode S system:

- ADS position reporting;
- message acknowledgements;
- trajectory-related data.

Aircraft position was reported at regular intervals through ADS messages from which the Ground Initiated Comm B (GICB) data was extracted by the ground system. It should be noted that the aircraft position data was in fact transformed, to conform to the ATC ground simulation requirements of the aircraft appearing to fly through NERC sectors 11 and 10 whereas, as explained in Section 3, operational considerations dictated that the aircraft actually flew a route over Eastern England. This transformation was mechanised within the EFMS output interface. Each ADS message was then transmitted to the ground coded into two GICB messages. The ground system detected these and reassembled the original ADS data before sending it to the PD/1 simulation.

The message acknowledgements were used to confirm the transmitting system had detected that the message had arrived at its intended destination. They consisted of short messages, of up to 224 bits in length.

The final message type was used to relay the trajectories, constraint lists and clearances between the air and ground systems and had a capacity of 1280 bits. Limitations on the amount of data that could be transferred in one aerial rotation - of 6 seconds duration - necessitated that full trajectory descriptions were split over two downlink blocks of data and transmitted over two rotations.

2.5 AFCS

The Digital Autopilot (DAP) is a vital component of the airborne system being able, in its coupled mode, to control the aircraft to the EFMS outer loop commands. The DAP software is developed in-house, which means that the autopilot can be enhanced as necessary to continue to support any change in the EFMS guidance mode philosophy.

The DAP can be used over the aircraft’s flight envelope, down to 50 ft VMC or to Decision Height in IMC under a coupled approach using multi-mode receiver ILS-type deviation signals or in an augmented EFMS mode, using MLS for position updates.

3 TRIALS PROCEDURES

3.1 GENERAL

Essentially, the airborne aspect of the demonstration was divided into three parts:

- after take-off, the airborne ATC simulator was used to generate a route out to Cambridge, to position the aircraft for the main demonstration;
- after initialisation, the aircraft was integrated into the PD/1 simulation exercise;
- the airborne ATC simulator was used on the return leg, as further demonstration of the system's capabilities.

The ATC ground simulation required the aircraft to appear to have departed Amsterdam with the intention of using airway UB5 to fly en-route towards Newcastle, climbing to cruise at FL 310. The demonstration would show the aircraft being cleared through NERC sector 11, followed by NERC sector 10. Data passed to and from the aircraft therefore had to be transposed so that the aircraft appeared to be flying along airway UB5 although, in reality, the aircraft was operating over eastern England.

The reasons for not flying the aircraft along UB5 were twofold: first it would be difficult to get clearance from the real ATC to operate there without conflicting with other civil traffic, secondly the Mode S data link coverage did not extend far enough east (the Mode S ground station being based at Malvern). Software was therefore incorporated into the EFMS, to allow position data - both constraint and trajectory related - to be transformed between the airborne and ground reference systems. The Mode S radar coverage also dictated the use of FL 310 for the final part of the cruise.

A default tube was used during the PD/1 demonstrations, using altitude limits of ±300 ft, lateral limits of ±0.5 nm and time limits of ±30 sec.

Figure 3-1 shows the PD/1 route, both the outbound leg to Newcastle and the return leg. This particular map reflects the VIP demonstration flights made from Birmingham Airport over the period 4 January 1996 to 19 January 1996 and therefore shows tracks to and from Birmingham.

The following summary of the airborne trials procedure is supplemented by a more detailed account in Appendix A.

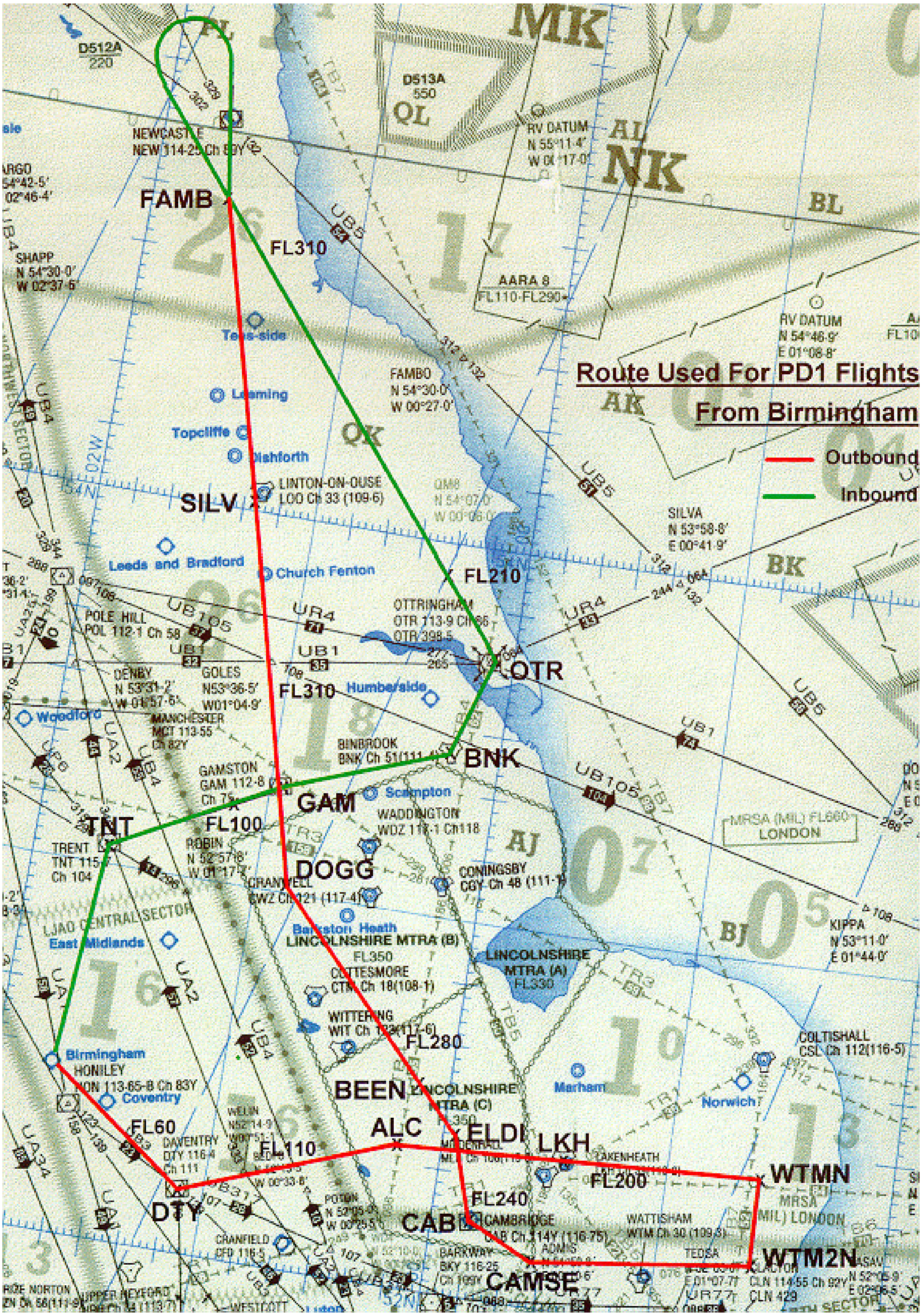


Figure 3-1 - Map

3.2 INTEGRATION WITH PD/1

Since the PD/1 simulation exercise was based on a 1700 UTC air traffic environment for time, even though the actual time of the flight could be different, the EFMS time reference had to be initialised accordingly and a revised trajectory activated. This was done before reaching CAMSE, while the Mode S data link was also activated. A trajectory through to Newcastle was generated, downlinked and upon receipt of the clearance the trajectory and contract were activated.

The aircraft entered NERC sector 11 at FL 240, when ATC gave clearance through sector 11 and the existing 4-D tube was amended accordingly. The climb to FL 280 commenced at ELDI, following which a constraint list was received from the ground. This enforced a lateral offset as well as a time constraint at waypoint DOGG and at the end of the route, at NEW1.

The new trajectory was passed to ATC and a subsequent clearance through sector 10 was received. The activated trajectory included the final partial climb, to FL 310. The ground simulation exercise terminated once the aircraft departed sector 10.

3.3 AIRBORNE ATC SIMULATION

The EFMS was reset as the aircraft was repositioned around Newcastle for the return leg and the airborne ATC simulator re-connected. A short clearance was activated, following which the planned descent profile was modified by an altitude constraint of FL 210. A revised trajectory was produced and clearance given.

A further ground constraint list was sent to the EFMS once FL 210 was reached, requiring the aircraft to be at FL 100 about 20nm before waypoint TNT. A trajectory and an appropriate 4-D clearance were generated.

4 RESULTS

4.1 GUIDANCE

The nature of the demonstration enforced frequent trajectory regenerations, a policy not conducive to identifying definitive 4-D guidance performance trends. This would have been of much less significance had the revised trajectory been a continuous extension to the previous one. In fact the new trajectory is referenced to the aircraft's current position so that errors from the trajectory are initialised to zero.

The implications are particularly significant to time control which has a low bandpass filter, requiring long uninterrupted runs to collect performance data. The bandpass of height control in the climb and descent was much wider, but the enroute climb profile was interrupted by the insertion of several levels between FL 110, where negotiations commenced, and the cruise at FL 310.

The guidance results should therefore be viewed on this basis.

Examples of a typical climb and descent will be shown, followed by consolidated results from the later flights where a baselined guidance description applied.

4.1.1 Climb

Figure 4-1 shows a typical climb profile, from near the end of the initial level flight at FL 110 to the cruise at FL 310. The initial enroute climb to FL 200 is followed by an extended level flight segment, where clearance to resume the climb is being negotiated. The activation of the revised trajectory occurs near the end of the level flight segment. Trajectory negotiations continue during the short level flight at FL 240 and the rather longer one at FL 280. A trajectory regeneration occurs part-way along the FL 280 level segment.

The aircraft tracks the climb profile particularly well, remaining within a tolerance band of some ±150 ft, while not requiring excessively large air speed (CAS) deviations. The performance is indicative of an accurate weather prediction and this is confirmed by inspection of the along track wind error and static temperature error.

Frequent regenerations were made during the climb portion, often reducing the duration of the run to the point where performance assessment becomes inconclusive. Elimination of these runs has reduced the available data appreciably.

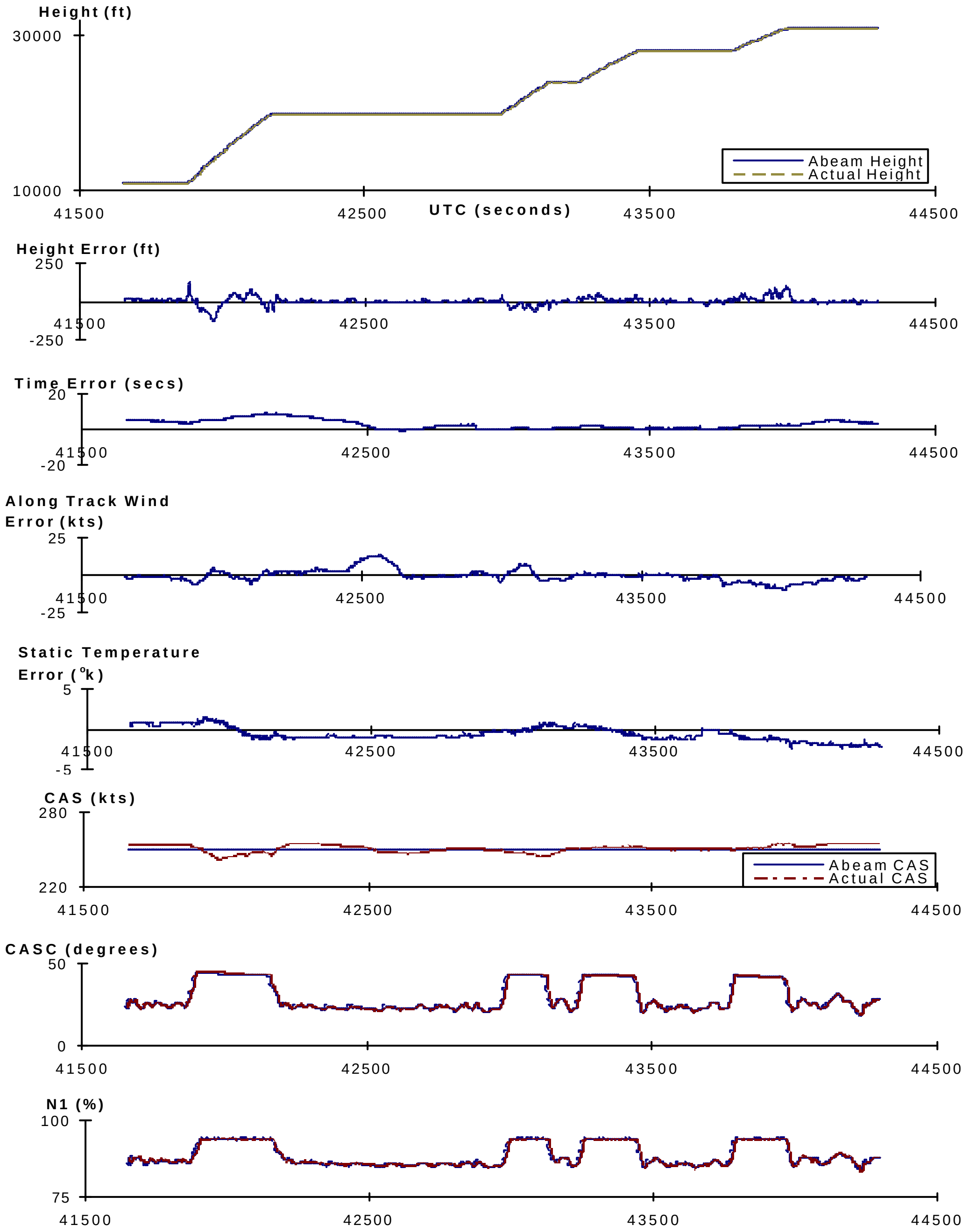


Figure 4-1 - Typical Climb Profile

Figure 4-2 shows the time errors for the various runs (identified in terms of trials flight number), for the local TOC at the start of the level flight segment at FL 200 which interrupts the climb from FL 110. This partial climb is chosen because it is of longer duration than the others. Since a regeneration occurred shortly before the start of the climb, the accumulated time error relates solely to the 3-D climb. Figure 4-3 shows the time errors plotted against the mean value of the along-track wind error over the preceding climb.

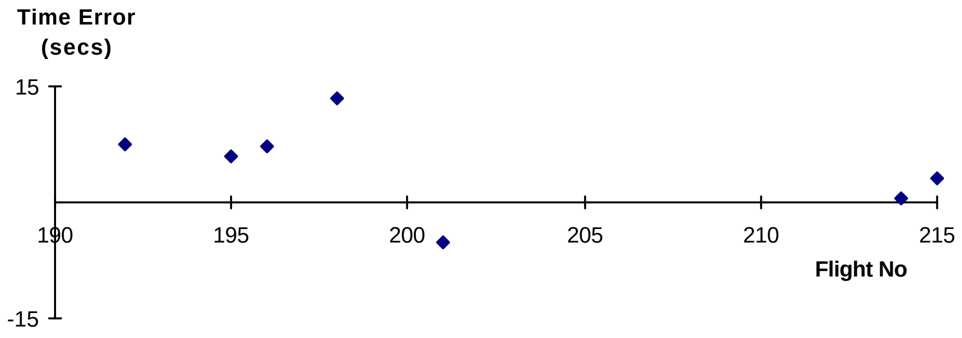


Figure 4-2 - Time Errors at TOC, FL200

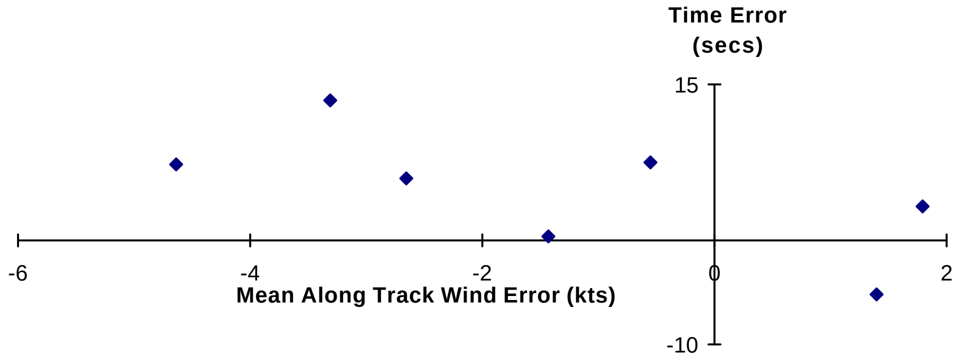


Figure 4-3 - Time Errors at TOC versus Mean Along Track Wind Error

Figure 4-4 shows the mean and 2 sigma values for altitude error, calculated for the partial climb to FL 200. The results indicate good control to the climb profile: the 95% containment figure (2 sigma) is about 120ft.

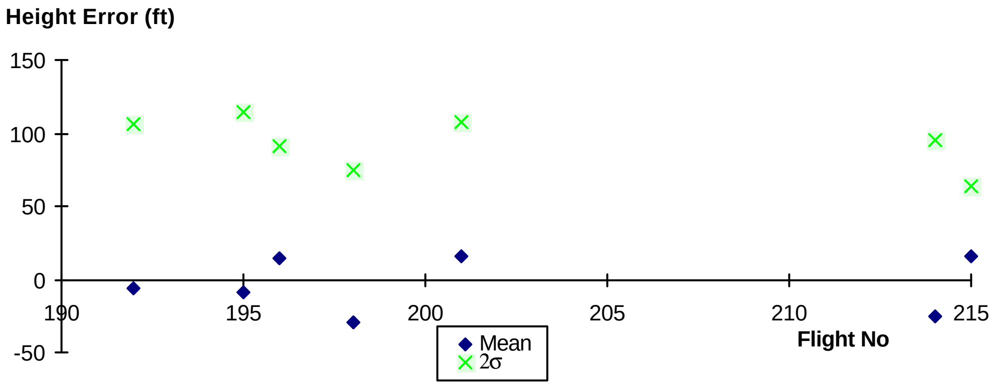


Figure 4-4 - Height Error Mean and 2s for Climb to FL200

A measure of the control activity required to achieve this performance is given by the variation of CAS about the planned value for the trajectory (Abeam CAS). The 2 sigma values for CAS deviation are shown in Figure 4-5, plotted against height error 2 sigma. The 95% containment values are within 6.5 kt, which - at least for the BAC 1-11 aircraft - implies an insignificant performance penalty arising from off-datum operation.

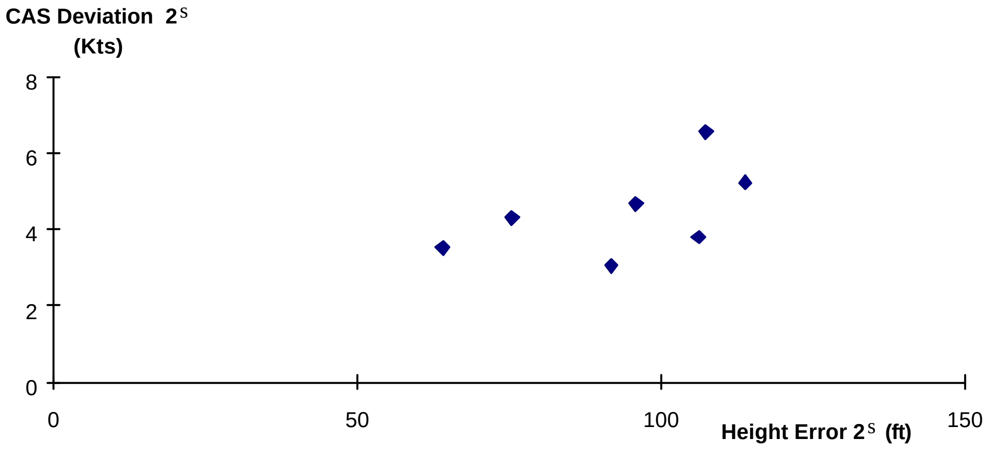


Figure 4-5 - CAS Deviation 2s versus Height Error 2s in Climb

4.1.2 Cruise

The cruise at FL 310 was fragmented by the need to reset the system for the return leg, centred around Newcastle. The durations are too short to draw any statistical conclusions: Figure 4-6 shows the prevailing time errors at the Top of Descent (at FL 310) for the return leg. The error never exceeds 10 sec and generally is well within that value.

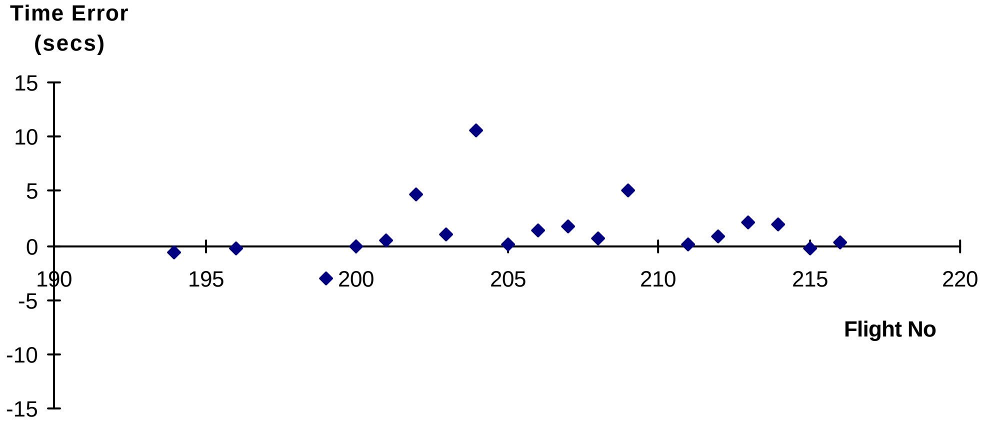


Figure 4-6 - Time Errors at TOD

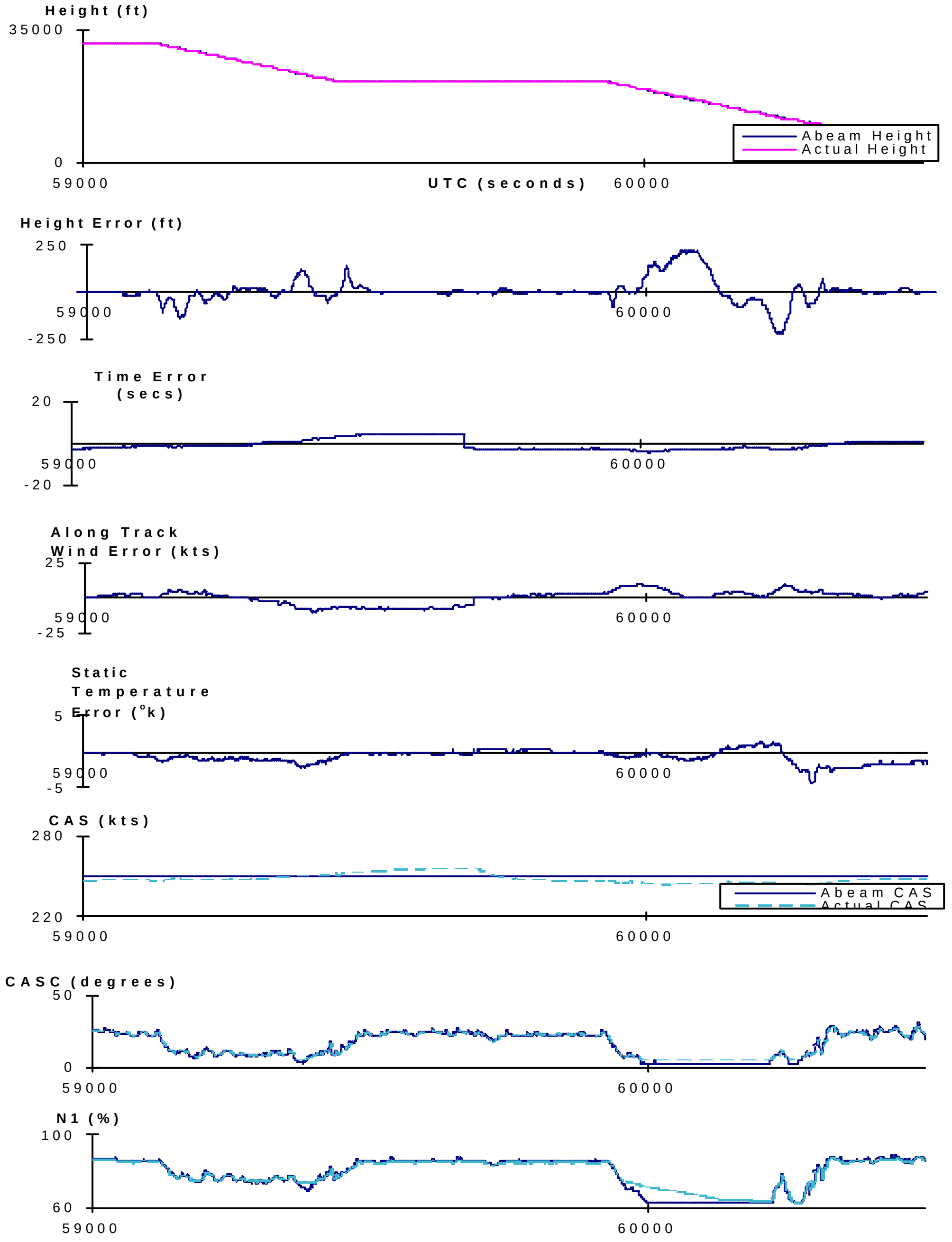


Figure 4-7 - Typical Descent Profile

4.1.3 Descent

The descent from the cruise FL to the metering fix at FL 100 was interrupted by a level segment inserted at FL 210, where negotiations for clearance to continue the descent were conducted.

Figure 4-7 shows a generally typical descent profile, but chosen to illustrate the effects of the throttles reaching flight idle (at around time 60000 sec, during the second stage of the descent). Note the re-generation which occurs at around 59700 sec, leading to a step change in the time error.

Results for altitude and time performance are presented for the two stages of the descent. Since the same time control mechanism is used both during descent and level flight, the full interval between re-generations was used for the analysis of time error, in order to realise the longest possible sampling period.

Figure 4-8 shows the mean and 2 sigma values for height error over the established part of the first descent, to FL 210. The average of the mean height error is very small; the positive value probably reflects the limited control authority available to the reduce throttle setting where (as shown in Figure 4-7) the flight idle stop may be encountered. The 2 sigma values are contained within a band of some 200 ft.

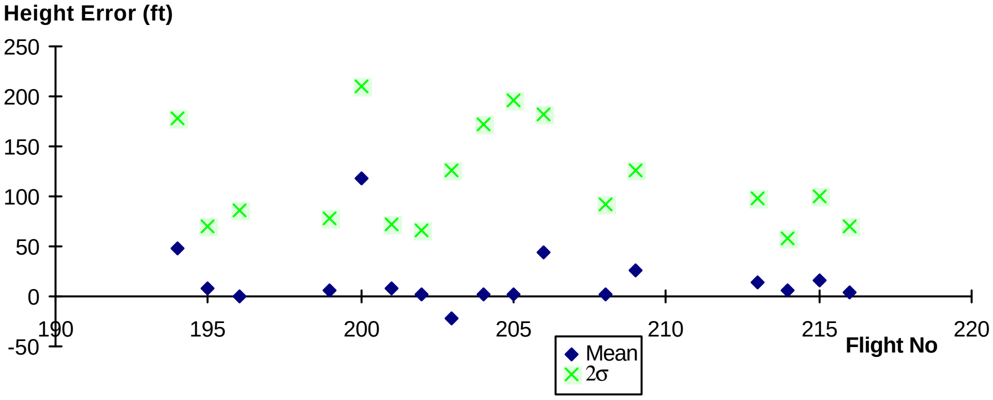


Figure 4-8 - Height Error Mean and 2s for First Stage Descent

Figure 4-9 shows the corresponding mean and 2 sigma values for time error. The spread of the mean values suggests no significant bias influences. The 2 sigma values are contained within a band of around 7 sec.

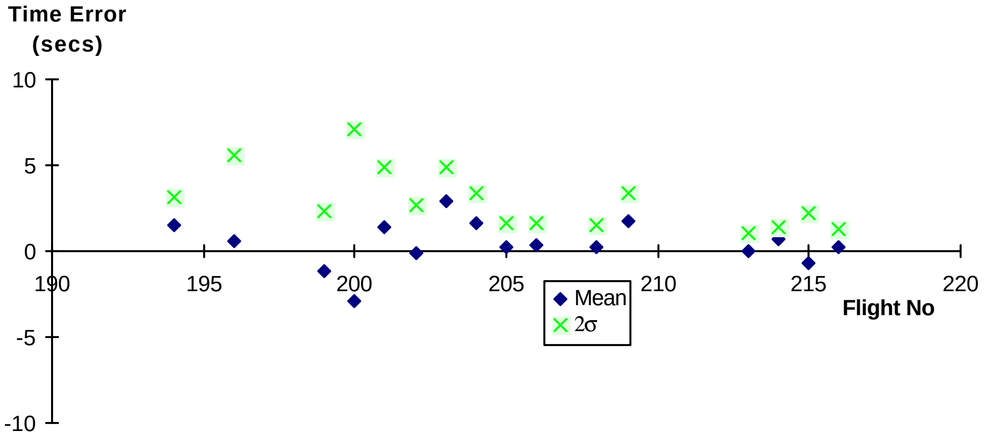


Figure 4-9 - Time Error mean and 2s for First Stage Descent

The height and time error means and 2 sigma for the second stage descent to FL 100, are shown in Figures 4-10 and 411. The results reinforce those pertaining to the first stage descent.

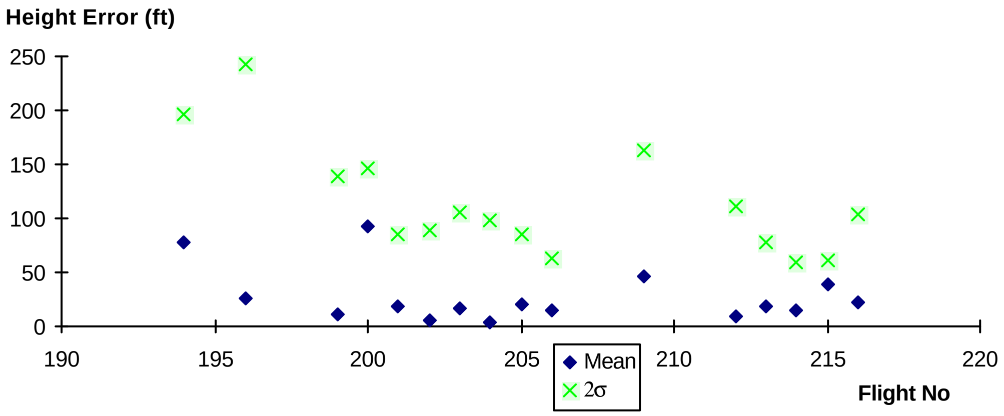


Figure 4-10 - Height Error Mean and 2s for Second Stage Descent

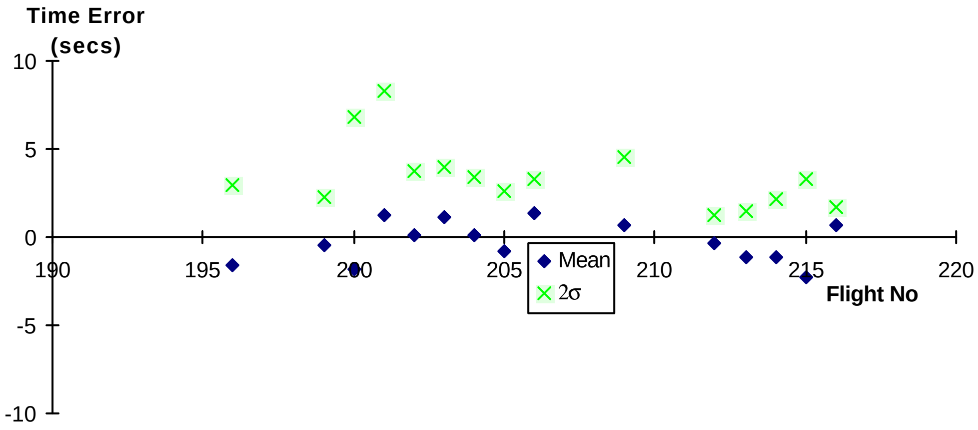


Figure *4-11 - Time Error Mean and 2s for Second Stage Descent*

The correlation between time error and wind forecast errors is emphasised in Figure 4-12, which shows the mean time error plotted against mean along-track wind error for the second stage descent and in Figure 4-13, which shows the corresponding 2 sigma values.

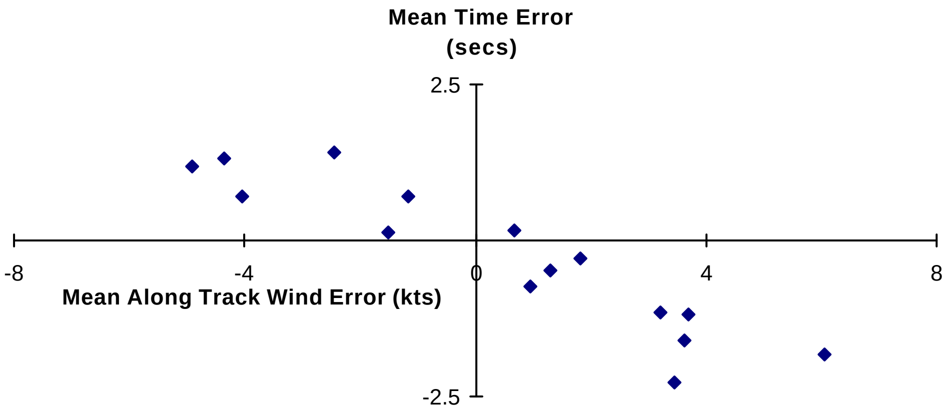


Figure 4-12 - Mean Time Error versus Mean Along Track Wind Error in Descent

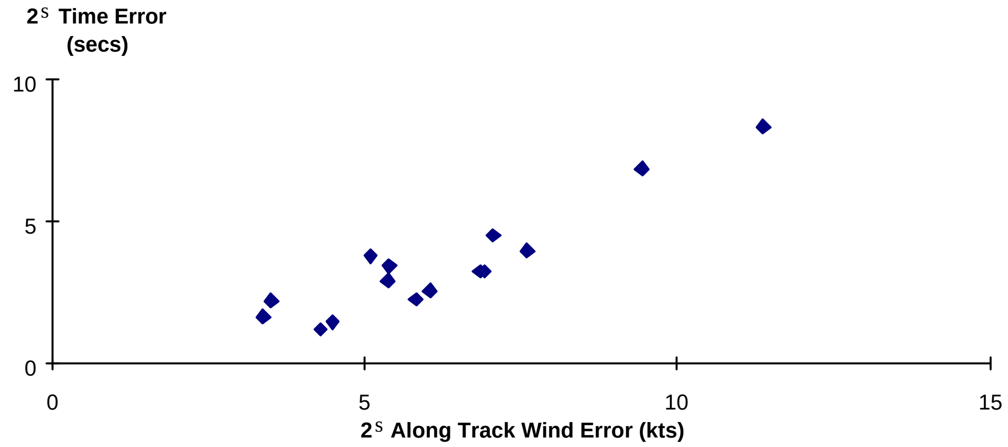


Figure 4-13 - Time Error 2s versus Along Track Wind Error 2s in Descent

The time error prevailing as the aircraft enters the TMA - through the metering fix - is of considerable significance. The results are shown in Figure 4-14, the metering fix being taken as the point of flare-out at FL 100 as the aircraft levelled from the descent. The time errors measured during the PD/1 demonstration flights are encouragingly small, within a band of some ±5 seconds, whilst no significant bias is apparent.

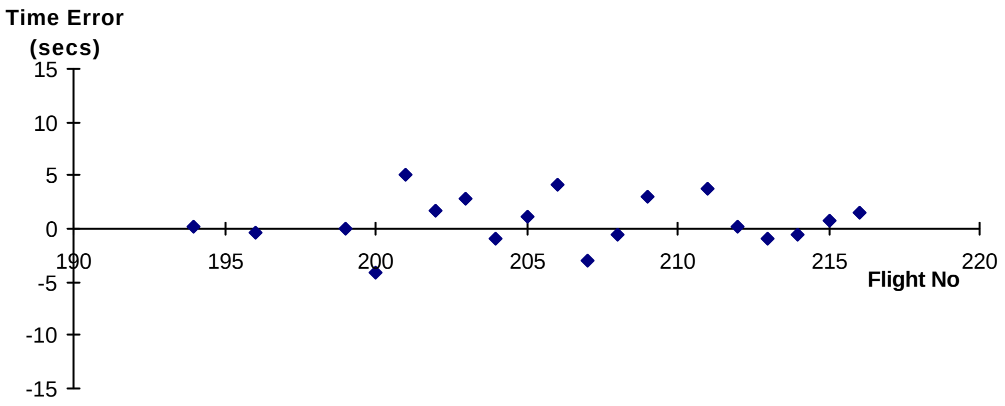


Figure 4-14 - Time Errors at Metering Fix

4.1.4 Lateral Performance

Figure 4-15 shows an example of lateral performance obtained during the outbound leg where large track angle changes are made. This particular run is chosen because the winds encountered were at considerable variance from those predicted, giving lateral guidance a bigger task for turns with large track changes where the cross track wind component can change significantly.

The maximum cross track error never exceeds 0.05 nm, even during the reciprocal heading turn - actually two 90 deg turns separated by a small straight - which occurs at around time 42500 secs, where the error in cross track wind prediction varies by some 30 kt.

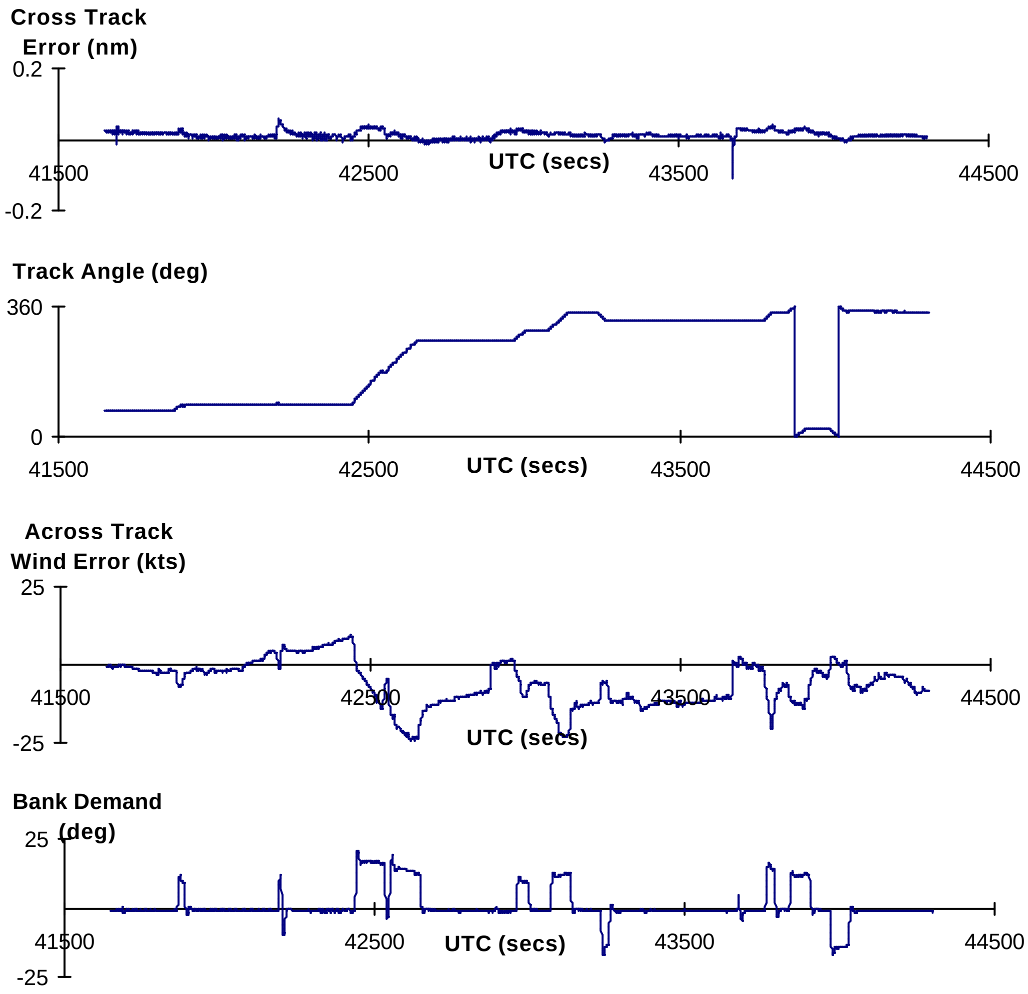


Figure 4-15 - Example of Lateral Performance

Analysis of the lateral data suggests a 2 sigma value of around 0.04 nm, while there is evidence of a small but consistent bias of around 0.015 nm. Detailed inspection indicates the offset does reduce over a long period, presumably under the effect of the bias-removing integrator within the guidance algorithm. The magnitude of the residual bank angle leads to the conclusion that the aircraft has some small lateral asymmetry.

4.1.5 Meteorological Data

Wind and temperature errors are taken as the difference between measured and predicted values, where the predicted data is the ‘best estimate’ and is a blend between the forecast data and that currently measured by the aircraft systems at the moment of trajectory generation. The weighting function biases the predicted meteorological from the measured data towards the forecast as the trajectory points become further remote from the current aircraft position.

While a detailed inspection of the meteorological data has yet to be made, preliminary analysis suggests a 2 sigma value of about 8.5 kts for wind estimation error and a 2 sigma value of about 1.3 deg K for static temperature.

4.2 DATALINK

All flights consisted of seven separate message transactions. An opening trajectory downlink initiated the exchanges, followed by uplink clearances across the ‘feeder’ sector[1] and then the first NERC sector. A constraint list was then uplinked, changing the route through the second NERC sector. This was followed by a downlink trajectory for the new route. Uplink clearances were then issued across the second sector and the final feeder sector.

Data acquisition was generally straightforward, although the clearance through the final feeder sector was not issued during two of the flights. It was also noticed that on two occasions uplink messages issued by the PD/1 ground system did not arrive at the EFMS. The table below shows average times for data communication, both for the time for the message to reach its destination and for the time from the pilot pressing the send button on the CDU to receiving a confirmation message on the CDU.

Message type	Average time to destination (seconds)	Average time to reception of acknowledgement (seconds)
1st trajectory (2 blocks) 16 messages	19.6	24.2
2nd trajectory (1 block) 16 messages	14.6	19.9
Clearance uplinks 62 messages	4.53	14.8
Constraint list uplinks 16 messages	7.06	16.5

Table 4-1 - Summary of message transmission times

On one occasion, for unknown reasons the trajectory downlink time was 125 seconds. This was excluded from the calculation of the averages.

4.3 AIRBORNE HMI EVALUATION RESULTS

The BAC 1-11 aircraft was flown by DRA pilots throughout the PD/1 demonstration period, which in terms of AHMI aspects included the pilot phase, the main phase and also the flight demonstrations carried out from Birmingham International airport. A number of civil airline pilots flew as passengers during the flights from Birmingham and had the opportunity to observe the detailed operation of the EFMS and EFIS while flying within the PD/1 negotiated 4-D clearance scenario. These civil pilots spent approximately 30 minutes in the cockpit, and the remainder of the two hour flight time observing the EFIS displays on monitor screens in the passenger cabin. All were very complimentary about the displays and felt that all necessary

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[1] In the ground simulator, feeder sectors surround the two measured NERC sectors so that the handover of traffic to and from those NERC sectors can be properly simulated.

information was clearly and effectively presented during all phases of flight. However, with such a short exposure to the displays and the operational environment, and no hands-on experience, it was not possible to obtain a detailed appraisal of the human-machine interfacing from the civil pilots. Therefore the EFIS displays assessment presented in the sections below represents the overall opinions of those DRA pilots who participated in PD/1 flights. A total of 7 pilots were involved, although the majority of hands-on operation was shared between only 3 of these pilots. The opinions of all 3 were very consistent with regard to all aspects of EFIS facilities, information presentation and system operation, and it is their answers to the questionnaire (presented in Appendix C) filled in after completion of the demonstration flights at Birmingham Airport, that are referred to in the sections below.

4.3.1 Aspects Common to Lateral and Vertical Planning Displays

The planning modes of the lateral and vertical displays were considered to be essential additions to the monitoring modes (rated 1 on the scale given in Appendix C, Section 1.1.3). The overall screen layout of both the lateral and vertical planning displays were rated towards the lower end of satisfactory (both rated 3 on the scales given in Appendix C, Sections 1.1.1 and 1.1.2), but no significant specific deficiencies or problems were identified, other than the need for a more positive indication of the state of progress during a negotiation sequence (this criticism applied equally to the monitoring displays). Pilots found that they could forget whether a trajectory had been downlinked if they were distracted before receiving a clearance or constraint list from ATC (distractions were frequent during the PD/1 demonstrations, with the pilot describing his actions and responding to questions from visitors in the cockpit). A message on the screen such as “Awaiting ATC” would probably be sufficient.

The presentation of constraint lists, trajectories and tubes, including symbology, annotation, colour coding and font size, was considered to be good. The automatic display of all relevant constraint lists, trajectories and tubes during the normal negotiation process was particularly appreciated, and the pilots emphasised that they considered this automation to be essential. The “GROUND CONSTRAINTS” alert message appearing in the centre of the screen was found to be effective, but the pilots would like to have an audio alert in addition, for situations when they are not looking at the displays. They would also prefer the ground constraints to be automatically displayed at the same time as the alert message, rather than having to manually select them.

The ability to step forwards and backwards along the route in order to inspect the detail of planned trajectories and ATC clearances was much appreciated, and was found to be a simple and natural process using the push buttons provided. The provision of a “HOME” button was well liked, but the pilots would prefer the map datum to return to aircraft present position, or to the next waypoint ahead of the aircraft, rather than to the beginning of the route. (With the EFMS/EFIS implementation then existing there was no list pointer to identify how far the aircraft had progressed along the route, and therefore this requirement could not easily be provided.)

4.3.2 Lateral Planning Display Aspects

The lateral planning display was used during selection and editing of routes, to inspect lateral and time constraints uplinked from ATC, and to check the lateral component of trajectories and tubes prior to activation.

The North-up orientation was considered to be natural, and also consistent with the “Plan” mode of current EFIS displays fitted to many modern civil airliners. The presentation of data in the corners of the display was considered to be good. Essential information was provided without obscuring the main map presentation. An improvement to the wind velocity display format (a digital readout giving wind direction and speed) was considered to be highly desirable. Wind direction, and its effect on the aircraft, would be more readily apparent to the pilot if it could be shown as an arrow symbol pointing in the appropriate direction, and positioned immediately above the digital readout.

4.3.3 Vertical Planning Display Aspects

The vertical planning display was used during selection and editing of routes, to inspect height and time constraints uplinked from ATC, and to check the vertical component of trajectories and tubes prior to activation.

The automatic height scaling was considered to be good. The positioning of waypoints with no height constraint along the bottom of the screen made it very easy to identify any with height constraints. The use of chevron symbols to show the maximum and minimum values of the height constraint windows was satisfactory (the same default window was used throughout the PD/1 exercise, and therefore the pilots had no opportunity to fully assess this feature).

4.3.4 Aspects Common to Lateral and Vertical Monitoring Displays

The overall screen layout of both the lateral and vertical monitoring displays was rated very highly (between 1 and 2 on the scales given in Appendix C, Sections 1.2.1 and 1.2.2). As would be expected, the presentation of constraint lists, trajectories and tubes was the same as on the planning displays, as also was the automatic presentation of these items during normal negotiation processes. The pilots considered all of this to be good.

The time error presentation next to the aircraft symbol was considered to be entirely satisfactory, including the use of a negative value to represent the aircraft being late.

4.3.5 Lateral Monitoring Display Aspects

The lateral monitoring display was used to monitor the EFMS operation and the aircraft's progress relative to the lateral and time components of the active trajectory and the ATC clearance (tube).

The heading scale, digital readout, track pointer and selected heading symbol were all considered to be satisfactory. The positioning of the aircraft symbol (approximately 1/3 up the screen) was found to be good, providing information behind the aircraft, which improved pilot awareness of progress along the route. The information behind the aircraft was also useful when flying within TMA's, where the routing often involved flying away from the runway before joining the final approach path. In these circumstances the pilot could easily maintain orientation with respect to the runway.

The screen update rate of 1 Hz was found to be adequate for all monitoring purposes under all flight conditions. However, purely for aesthetic reasons, pilots would prefer a higher update rate (in the region of 5-10 Hz) to avoid the "stepping" effect that occurs during turns.

4.3.6 Vertical Monitoring Display Aspects

The vertical monitoring display was used to monitor the EFMS operation and the aircraft's progress relative to the vertical and time components of the active trajectory and ATC clearance (tube).

The triangular aircraft symbol was found to be satisfactory, giving a clear and unambiguous indication of aircraft position relative to the trajectory and tube. The same automatic height scaling was used as on the vertical planning display and was found to be equally as good. The smooth transition of the aircraft symbol up and down the screen to always give the optimum view of the profile ahead of the aircraft whether climbing, descending or in level flight, was found to be very effective and totally natural in operation.

As well as the wind velocity data presented on the vertical display, the pilots would prefer to have the other data that is presented in the corners of the lateral display. The digital readout of wind velocity was perfectly acceptable on the vertical display.

4.3.7 General Display Aspects

The ability to select waypoints, navigation aids and airports on to the lateral displays at any time required was found by the pilots to be extremely helpful, especially when re-routed by ATC, and for pilot planning of alternative routes and diversions.

The pilots consider that there will eventually be a need to establish international standards in terms of the symbology and colour coding to be used on EFIS displays for operation within a "4-D negotiation" ATM scenario.

No requirement was identified during the PD/1 exercise for a "Time" planning display to provide a clear picture of how the time component of the tube narrows/broadens along the route (as provided for the lateral and vertical components of the tube). However, a fixed default value of ± 30 seconds was used on all PD/1 flights, and therefore the pilots had no experience of ATC clearances with variations in the size of time tube along the route.

4.3.8 Displays Control Panel

The Displays Control Panel proved to be entirely satisfactory, providing easy and rapid selection of modes and facilities, and a clear indication of pilot current selections at all times.

4.3.9 Taxi Map Display Aspects

The taxi map was rated at the highest level (1 on the scale given in Appendix C, Section 2), with the pilots fully appreciating the clear and precise indication of aircraft position on the airfield. Presentation of the required taxi route (passed over data link from ATC) on the display was considered to be a highly desirable future development.

4.3.10 Possible Future Developments

The pilots were extremely enthusiastic about proposals to provide a rollerball-driven cursor on the map display to enable route modifications and negotiation to be carried out without having to use the EFMS CDU. They were cautious with regard to selecting map modes and display facilities, and any other EFMS functions with the cursor, because of possible display clutter resulting from the provision of any necessary soft keys on the screen. (Even with an 8×8 inch ND, a satisfactory map presentation uses most of the available display area).

They would also like to see TCAS information integrated into the displays, with the ability to select/deselect the information as required.

With the introduction of route editing capability through the map display, there will be a requirement for close linking between the map display and the CDU page selection process in order to automatically maintain a consistent presentation of information to the pilot irrespective of whether he edits/selects through the CDU or through the map display.

4.3.11 Overall Summary of Airborne HMI Evaluation Results

4.3.11.1 EFIS Evaluation Results

The opinions of the 3 pilots who carried out the majority of the PD/1 flying were remarkably consistent with regard to all aspects of EFIS facilities, information presentation and system operation. They were fully able to monitor EFMS operation and the aircraft's progress relative to the active trajectory and the ATC clearance (tube), and gave very high ratings to both lateral and vertical displays. Suggestions for detailed improvement to a few display items, and for improved indication of the negotiation status, were put forward, but no aspect of the displays was assessed as less than satisfactory. Those DRA and civil airline pilots who had only limited exposure to the displays were also very consistent in their opinions, and although not able to comment on detailed aspects of the displays and system operation, all of them considered that the right information was always presented at the appropriate time, and in a clear and easily understood way.

A great deal of enthusiasm was expressed for the proposed implementation of route editing and negotiation facilities using a rollerball-driven cursor symbol on the map display, as an alternative to using the CDU.

4.3.11.2 EFMS CDU Evaluation Results

Following a training process, the pilots found use of the main features of the CDU to be relatively straightforward. There were some functions however, which were not well identified and were cumbersome to use. An example is the 'go direct' to the next waypoint function, within the Edit pages, which the pilots found confusing and requiring a number of key actions to enable. Civil Avionics has since modified the EFMS CDU layout to provide a more convenient operation.

The touch screen mechanism sometimes gave problems in that following function selection or editing of a parameter, remnants of the yellow highlight block - which surround the area to indicate the CDU has detected the selection - remained, and could hide the data. This could oblige the pilot to reselect the current page in order to verify the data.

Finally, the Negotiation page received comment. Although a single page provided all the trajectory generation, ATC downlink and trajectory/contract activation functions, the pilots found that if they were distracted they could lose track of the current status of the negotiation process. The pilots also felt that phraseology used on some of the pages could be improved to advantage.

5 SUMMARY

The PD/1 airborne demonstration programme was extremely successful, confirming as a matter of routine the ability of an aircraft to agree conflict-free trajectories with ATC and to fly them, while operating within continuous 4-D constraints. Specifically, the demonstration flights confirmed that

- A digital datalink enabled detailed information on proposed trajectories and imposed 4-D constraints to be transmitted between the aircraft and ATC;
- The airborne system was sufficiently flexible to realise revised trajectories to satisfy ATC short term conflict avoidance requirements;
- The aircraft followed the trajectory successfully, operating within a continuous 4-D envelope;
- The EFMS demonstrated the ability to function in a demanding trials environment;
- Accurate weather forecasting and engine performance models are essential if the aircraft is to fly close to its optimal performance parameters;
- 4-D control was remarkably accurate: in summary, the results suggest the predicted number of occurrences of height deviations greater than 300 ft or time errors greater than 10 sec would be of the order of 0.5 per hour.[2]

Finally, the flights provided a convincing demonstration to the aviation community of the direction of ATM research, enabling them to visualise the environment of the silent cockpit.

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[2] This is a prediction, based on the measured results. Strictly it applies only to this particular aircraft under the conditions prevailing, but it gives a good idea of the typical performance that might be obtained from most aircraft types.

6 GLOSSARY

2σ	95% containment figure
4-D	four dimensional (latitude, longitude, altitude and time)
ADC	air data computer
ADS	automatic dependent surveillance
AFCS	automatic flight control system
AHMI	airborne human machine interface
AHRS	attitude and heading reference system
ARINC	Aeronautical Radio, Inc (USA)
ATC	air traffic control
ATM	air traffic management
BAC 1-11	DRA Civil Avionics trials aircraft XX105
CAA	Civil Aviation Authority
CAS	computed airspeed
CASC	throttle position of BAC 1-11
CDU	control and display unit
DAP	digital autopilot
DGPS	differential global positioning system
DLPU	datalink processor unit
DLR	Deutsche Forschungsanstalt fur Luft- und Raumfahrt
DRA	Defence Research Agency
ECP	engine control parameter
EFIS	electronic flight instrument system
EFMS	experimental flight management system
ESI	energy sharing index
ETA	estimated time of arrival
FL	flight level
GICB	ground initiated comm B
GPS	global positioning system
HMI	human machine interface
ICAO	International Civil Aviation Organisation
ILS	instrument landing system
IMC	instrument meteorological conditions
INS	inertial navigation system
LCD	liquid crystal display

MLS	microwave landing system
Mode S	secondary surveillance radar
Multi-DME	distance measuring equipment
MVME	Motorola VME
N1	engine high pressure spool rpm of BAC 1-11
NATS	UK National Air Traffic Services Ltd
ND	navigation display
NERC	New En-Route Centre
NLR	Nederlands Nationaal Lucht-en Ruimtevaartlaboratorium
PC	personal computer
PD/1	PHARE Demonstration 1
PFD	primary flight display
PHARE	Programme for Harmonised Air Traffic Management Research in EUROCONTROL
rpm	revolutions per minute
TAS	true airspeed
TI	thrust index
TMA	terminal manoeuvering area
TOC	top of climb
TOD	top of descent
TPDR	transponder
VIP	very important person
VMC	visual meteorological conditions
VME	virtual memory environment
UTC	universal time co-ordinated

APPENDIX A

A.1 INTEGRATION WITH PD/1

The ATC ground demonstration was based on a typical air traffic environment occurring in the late afternoon, around 1700 Zulu. Therefore the time reference within the EFMS had to be synchronised with the ground system: once level at FL 200, the pilot made radio contact with the PD/1 systems operator, enabling him to insert the revised time through the initialisation page on the EFMS CDU. In view of the implications on time control, the EFMS profile guidance was disengaged from the autopilot prior to the time offset insertion although the EFMS lateral control was left engaged.

The pilot regenerated the trajectory to the revised time reference while on the leg towards waypoint WTMN. The trajectory was passed to the onboard ATC simulator, which returned a clearance to waypoint CAMSE. Having agreed the contract, the pilot activated the new trajectory and re-engaged EFMS profile guidance through the autopilot. The ATC communications link from the EFMS was also switched from the onboard simulator to the Mode S data link system in readiness for the initiation of data communications with PD/1.

The pilot used the EFMS CDU to append to the current trajectory (which terminated at CAMSE), the additional segment to Newcastle. Having identified the aircraft as a new contact, PD/1 used a ground-based predictor to generate the appropriate trajectory. Since it was unable to handle the smaller turn radii required at the waypoints WTMN and WTM2N, the call enabling the ground system to be primed to accept the BAC 1-11 into the simulation could not be made until the aircraft had passed the second waypoint. Once the ground system had managed to predict a trajectory, they confirmed it had been ‘radar identified’. The pilot then used the EFMS to determine a trajectory direct to CAMSE and thereon to Newcastle. This was transmitted via the Mode S data link to the PD/1 ground system and, about a minute later, a clearance to waypoint ELDI (the start of sector 11) was received. The trajectory and contract were then activated.

The aircraft climbed to FL 240 as it approached Cambridge, to conform to the ground simulation requirements for entry into sector 11. Concurrently, the PD/1 system confirmed onward clearance through sector 11, to the start of sector 10 at waypoint DOGG and the EFMS automatically activated this extension to the existing 4-D tube.

The aircraft commenced a climb to FL 280 at waypoint ELDI. A ground constraint list was received from PD/1 at that level, on the leg between waypoints BEEN and DOGG. This contained a lateral offset in the route around waypoint SILV, as well as a time constraint at the first and last waypoints (DOGG and NEW1 respectively). The names of the waypoints also changed to reflect those on the airway UB5 in the ground simulation, for example DOGG became DOGGA. The lateral offset, around 10 nm to the right of SILV, was enforced by ATC resolution of a possible conflict with other air traffic. The time constraints offered a 45 second time window. This ground constraint list was used by the EFMS to generate a trajectory which was transmitted to the ground ATC simulation: subsequently a clearance to the end of Sector 10 (a point on the route close to Tees-side) was transmitted back. The pilot then activated the trajectory and contract and the aircraft followed the lateral offset route and the new time profile. In the process of flying this trajectory, the aircraft climbed to its final cruise altitude of FL310 after passing waypoint DOGG. Clearance to Newcastle was received from Malvern during the course of the lateral offset and was activated automatically by the EFMS.

The ground ATC demonstration involving the BAC 1-11 terminated after the aircraft had departed sector 10, but EFMS guidance remained engaged until the aircraft reached waypoint FAMB, when the aircraft was repositioned for the return route.

A.2 AIRBORNE ATC SIMULATION

The EFMS was reset while the aircraft was repositioned around Newcastle because the position transformation software required during the ground simulation exercise was no longer relevant. The return route was carried out with the airborne ATC simulator performing all the trajectory negotiation aspects. The route was south-east from Newcastle to Otringham, then south-west over Binbrook followed by a leg to TNT (Trent) which represented the metering fix and the end point of the route.

The pilot initially used the EFMS to predict a trajectory for this route based on a cruise at FL 310, with a continuous descent in order to be level at FL100 at waypoint TNT. The ATC simulator then passed a short clearance to a point part way along the leg between FAMB and OTR and this was activated and flown. Subsequently, a ground constraint list was sent from the ATC simulator which restricted the height profile so as to be at FL 210, 10 nm before waypoint OTR. The EFMS was used to predict a new trajectory and a clearance to waypoint BNK was negotiated. A further ground constraint list was sent to the EFMS once FL 210 was reached. This involved another height restriction, requiring the aircraft to be level at FL 100 about 20nm before waypoint TNT. The pilot was able to generate a trajectory before reaching waypoint OTR and a clearance to waypoint TNT was agreed.

The height restrictions were in fact imposed out of operational necessity, in order to satisfy the ATC requirements that the aircraft be level when crossing airway B1 (at Otringham) and below the airway B4 (prior to Trent). The aircraft remained under continuous EFMS guidance until reaching waypoint TNT.

APPENDIX B

B.1 GUIDANCE PERFORMANCE IN CLIMB

Figure 4-1 shows a typical climb profile, from FL 110 to the final cruise at FL 310. The climb is interrupted by several level segments, where negotiations with ATC are taking place. The climb was planned at 250 kt; apparent is the variation in CAS required to track the trajectory, for time control in level flight and for altitude control during the climb segments.

The time error increases by about 5 sec during the climb to FL 200, due mainly to the lower than predicted CAS required to track the climb. CAS increases above 250kt once the aircraft has levelled and the time error is contained. A constant N1 of 93.9% - the prediction value - is used during the climb segments. This is a reduction from the standard 94.2% max continous, and was enforced by the need to restore the Turbine Gas Temperature (TGT) readings on one engine back within limits.

The climb segments are too short over the latter part of the climb to allow any meaningful time error trends to be identified.

The altitude error does not exceed 150 ft throughout the climbing segments, generally remaining within some ±60 ft. This level of performance suggests an accurate meteorological forecast and this is borne out by inspection of the along track wind error i.e the difference between the predicted and actual component of wind along the current track, and of the static temperature error, i.e. the difference between predicted and measured static temperature. The wind remains within 5 kt of the prediction while the temperature deviation does not exceed about 1 deg Kelvin.

CAS reduces to some 8= kt below the trajectory target value during the initial part of the climb, to correct the aircraft onto the trajectory. The tendency to deviate below the profile may be a result of an increasing tailwind effect, along with temperatures slightly higher than predicted. From then on, wind changes are smaller but more favourable, while the temperature reduces to below the prediction so that by the time the aircraft approached the local TOC, the CAS has been restored virtually to the target value.

B.2 GUIDANCE PERFORMANCE IN DESCENT

Figure 4-7 shows a typical descent, but characterised by the throttles reaching the flight idle stop during a significant portion of the descent from FL 210 to FL 100. The pilot would have extended the airbrakes had the deviation increased further, effectively causing the throttles to re-datum to a higher thrust setting: judicious use of airbrake can contain altitude errors within very small limits if so required.

The profile tracking performance over the first stage descent is extremely good with altitude deviations contained to within ±150 ft. Inspection of the throttle position indicates this was not achieved at the expense of large throttle activity. It is apparent once again, that the forecast winds were predicted accurately, the wind error being negligible until the latter stage of the descent when an increasing headwind of up to some 9 kts enforces a time error which reaches a maximum of some 5 sec.

The aircraft drifts above the profile during the second stage of the descent even though the throttles are on the idle stop. Certainly, the greater than predicted tailwind component encountered during the early part of the descent will make a transient contribution; subsequently the altitude error reduces as the wind subsides towards that predicted. It is probable however, that an underlying contribution arises from engine modelling errors. Firstly, the flight idle throttle positions differ slightly between the engines while more significantly, the N1 idle schedules versus altitude are at considerable variance, the port engine idling fast at altitudes above about 12000 ft. This trait was recognised during the development trials, when the original N1 idle schedule within the engine model in the EFMS trajectory predictor was revised to represent more closely the approximate average value for both engines.

APPENDIX C

C.1 EFIS ASSESSMENT DURING PD/1 FLIGHTS

Questionnaire For Participating Pilots

Please circle the appropriate number where relevant, to indicate your reply.

1 Presentation of Information

1.1 Planning Mode (To select/edit routes, and check trajectories/tubes prior to activation)

1.1.1 Lateral Planning Display

	Very satisfactory					Unsatisfactory
Was the overall Screen Layout satisfactory?	1	2	3	4	5	6

Please comment as necessary on any of the following features:

North Up orientation

Number of Range Circles (two) and Range Circle labels (10, 20, etc.)

Heading orientated A/C symbol at Present Position (if on screen)

Constraint List (symbol + name, joined with dotted line)

Trajectory (symbol, name, FL, ETA (in hrs, mins, secs), joined with solid line)

Proposed Lateral and Time Tube (dotted lines)

Active Lateral and Time Tube (solid lines)

Data in corners of screen (Top Left - TAS, Ground Speed) (Top Right - Next Wpt name, Distance to go, ETA) (Bottom Left - Wind speed and direction) (Bottom Right - UTC)

Other Comments/Suggestions on the Lateral Planning Display

1.1.2 Vertical Planning Display

	Very Satisfactory					Unsatisfactory
Was the overall Screen Layout satisfactory?	1	2	3	4	5	6

Please comment as necessary on any of the following features:

Height/Distance scales and automatic height scaling

Constraint List (symbol, name, constraint altitude + chevrons for max/min altitude limits)

Trajectory (symbol, name, FL, joined with solid line, no flare path to level flight)

Proposed Vertical and Time Tube (dotted lines)

Active Vertical and Time Tube (solid lines)

A/C symbol at Present Position if on screen

Other Comments/Suggestions on the Vertical Planning Display

1.1.3 Features common to Lateral and Vertical Planning Displays

	Essential					Unnecessary
How necessary is it to have a Planning Mode in addition to the Monitoring Mode?	1	2	3	4	5	6

Please comment as necessary on the following items:

Stepping along the Route (forwards and backwards one Waypoint at a time, Home button to re-position to beginning of Waypoint List)

Is there a requirement for a “Time” Planning Display to provide a clear picture of how the Time Tube narrows/broadens along the route, in the same way that the Lateral and Vertical Tubes are presented?

1.2 Monitoring Mode (To monitor aircraft progress/performance relative to 4-D contract)

1.2.1 Lateral Monitoring Display

Very satisfactory Unsatisfactory

Was the overall Screen Layout satisfactory? 1 2 3 4 5 6

Please comment as necessary on the following items:

Heading Scale (Labelled every 10° and marks every 5°, Digital readout above heading marker)

Selected Heading (symbol only if on scale, symbol (+ digital value) parked on appropriate side if off the scale)

Aircraft symbol and position (approx. 1/3 up the screen)

Number of Range Circles (two) and Range Circle labels (10, 20, etc.)

Constraint List, Trajectory and Tube (all presented as on Lateral Planning Display)

Time Error (digital value in seconds on left side of A/C symbol, +ve = early, -ve = late)

Other Comments on the Lateral Monitoring Display

1.2.2 Vertical Monitoring Display

Very satisfactory Unsatisfactory

Was the overall Screen Layout satisfactory? 1 2 3 4 5 6

Please comment as necessary on the following items:

Height/Distance Scales (automatic height scaling to always utilise the full screen)

Aircraft Symbol (triangle)

Position of Aircraft symbol (bottom left of screen for climb, centre left for level flight, top left for descent, with a smooth transition from one position to another)

Constraint List, Trajectory and Tube (all presented as on Vertical Planning Display)

Time Error (digital value in seconds above the A/C symbol, + ve = early, -ve = late)

Lack of data in corners compared to Lateral Display

Other Comments/Suggestions on the Vertical Monitoring Display

1.2.3 Features common to Lateral and Vertical Monitoring Displays

Is there a requirement for a “Time” Monitoring Display to check how the Time Tube narrows/broadens ahead of the aircraft?

Comments/Suggestions on common Lateral and Vertical Display features

1.3 General Features common to all the Displays

Please comment as necessary on the following items:

Symbology

Colour Coding

Font Size

Screen updating rate

Automatic presentation of Constraints, Trajectories, Tubes during Negotiation sequence

Alerting of Uplink of Ground Constraint List

Awareness of current status of Negotiation

Manual selection/control of displayed information:

Lateral/Vertical Display selection

Planning/Monitoring Mode selection

Forward/Backward stepping along Route and Home selection

Range Scale selection

Additional Data selection (Pilot, Ground, Active Lists)

Panel Layout

Switch and Selector sizes, annotation, lighting, etc.

Compatibility with Primary Flight Display

Compatibility with EFMS CDU

2. Taxi Map Display

	Very satisfactory					Unsatisfactory
Was the overall presentation satisfactory?	1	2	3	4	5	6

Please comment as necessary on any of the following features:

Aircraft symbol

Scale changing

North-up orientation

Taxiway/Runway colour coding

Presentation of ATC taxi clearances (Boscombe Down map only)

3. Any other comments/suggestions (on any human factors aspects)

Name: (optional)

Date: **Number of Flights during PD/1:**

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