Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-99068

A PHARE concept in support of a European ATM Programme

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Summary

In May and June 1998, the feasibility of a negotiation process between air and ground was demonstrated in real-time ATM simulations at NLR. New simulations have demonstrated recently en-route and arrival control of an operational ATM concept based on air-ground integration. This operational concept comprises all phases of flight from departure to arrival and focuses on ATM in the core area of Europe. The concept encompasses, at an airborne level, 4D functionality to provide services for prediction, monitoring and guidance, and on the ground, functionality to support an extended and layered planning process, assisted by advanced software tools and an advanced HMI, using windows and graphics. A prototype of an ATN provides the required datalink services.

The demonstrations are organised in the context of PHARE (Programme for Harmonised ATM Research in Eurocontrol), a research programme conducted by Eurocontrol, in collaboration with R&D establishments from France, Germany, UK and the Netherlands. The concept developed is expected to give benefits by optimised use of available airport and runway capacity, by improved use of airspace, and by reduction of human workload to control the traffic.

This paper gives an overview of the operational concept, the solutions selected for implementation, critical issues and topics for further research, as well as, in short, the scope of the executed demonstrations.

Contents

(31 pages in total)

Abbreviations

ADS-B	Automatic Dependent Surveillance – Broadcast
ACC	Area Control Centre
AOC	Airline Operations Centre
APD	Activity Predictor
AM	Arrival Manager
ArrSP	Arrival Sequence Planner
ARTAS	ATC suRveillance Tracker And Server
ASM	Air Space Management
ATCO	Air Traffic Controller
ATD	Actual Time of Departure
ATFM	Air Traffic Flow Management
ATMS	Air Traffic Management System
ATN	Aeronautical Telecommunication Network
CDA	Continuous Descent Approach
CDU	Control and Display Unit
CFMU	Central Flow Management Unit
CP	Conflict Probe
CPDLC	Controller Pilot Data Link Communications
CT	Cooperative Tools
CWP	Controller Working Position
DAP	Down-link Aircraft Parameters (datalink application)
DM	Departure Manager
EATMP	European ATM Programme
EFIS	Electronic Flight Instrument System
EFMS	Experimental Flight Management System (of PHARE)
ETD	Estimated Time of Departure
FIR	Flight Information Region
FMS	Flight Management System
FPM	Flight Path Monitor
HIPS	Highly Interactive Problem Solver
HMI	Human Machine Interface
ICAO	International Civil Aviation Organization
LAD	Look Ahead Display
LAN	Local Area Network
MIW	Message In Window
MOW	Message Out Window

MSP	Multi-Sector Planner
NARSIM	NLR ATC Research Simulator
NLR	Nationaal Lucht- en Ruimtevaart laboratorium, National Aerospace Laboratory NLR
NM	Negotiation Manager
OCD	Operational Concepts Document
PATs	PHARE Advanced Tools
PC	Planner Controller
PD/3	PHARE Demonstration 3
PFD	Primary Flight Display
PHARE	Programme for Harmonized Air Traffic Management Research in Eurocontrol
PR	Position Reporting (datalink application)
PS	Problem Solver
RPVD	Radar Plan View Display
SEL	Sector Exit List
SID	Standard Instrument Departure
SIL	Sector Inbound List
STA	Sequenced Time of Arrival
TC	Tactical Controller
TLS	Tactical Load Smoother
TMA	Terminal Manoeuvring Area
TN	Trajectory Negotiation (datalink application)
TP	Trajectory Predictor
WAN	Wide Area Network
4D	4 Dimensional, 3D + time

PHARE concept for ATM

Demonstrations

In May and June 1998, the feasibility of a negotiation process between air and ground was demonstrated in real-time simulations by exchanging 4-dimensional trajectory information between a live aircraft flying in the Amsterdam TMA and a ground ATM real time simulation. These demonstrations were part of the 3rd series of demonstrations of PHARE, PD/3.

PHARE is a EUROCONTROL Research and Development programme, conducted in collaboration with the leading research establishments of:

- France: CENA (*Centre d'Etude de la Navigation Aérienne*),
- Germany: DLR (D*eutsches Zentrum für Luft und Raumfahrt*),
- The Netherlands: NLR (*Nationaal Lucht- en Ruimtevaartlaboratorium*), and
- UK: NATS (*National Air Traffic Services*).

The programme of PHARE is concerned with the entire air/ground ATM system to support the expected increase in demand for air traffic by 2015 [Ref. 3].

The feasibility of an air-ground 4D negotiation process is one of the key elements of the PHARE advanced ATM concept in which extended prediction and guidance capability in the air is coupled to an adapted and extended concept for planning and control on the ground. An extra planning layer was added over all phases of flight from departure to arrival, and new and/or improved tools were developed. A new Human Machine Interface (HMI) between ATM system and controllers was designed in order to support a fundamental change in operational procedures. The close co-operation between air and ground is the basis of this concept and is deeply embedded in the design of all air and ground based elements of this concept.

An experimental version of the implementation of the required airborne equipment has been demonstrated, including the use of a prototype of an Aeronautical Telecommunication Network (ATN). The ground-based part of the concept was designed, implemented and tested. Initial demonstrations have been completed successfully. Further ground system demonstrations were prepared and have been completed recently. First results suggest significant benefits due to a shift of workload from tactical control to planning. Moreover, an extended, layered planning concept and a tight coupling of airborne and ground-based planning, guidance and control are expected to contribute to flight efficiency and economy. Efficient planning should provide an increase of the capacity of used airspace and improved use of available runway and airport capacity.

The PHARE concept, as well as its experimental implementations, are still under development and even if demonstrated to their full extent would require considerable R&D effort to bring them to operational maturity. Nevertheless, the demonstrations have focused on one of the most important issues of the concept, namely the feasibility of pilots and controllers to perform their tasks of flight execution and ATC in an advanced 4D ATM environment.

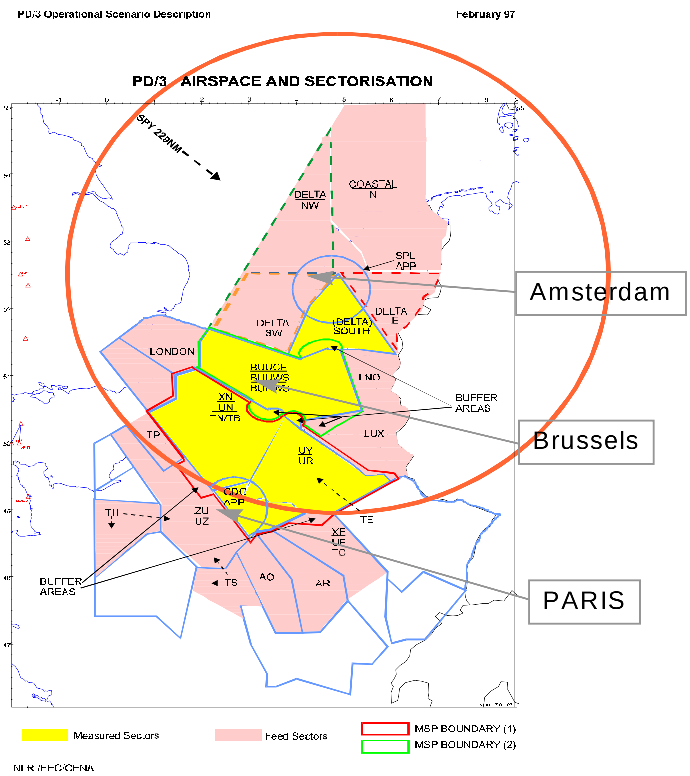

Fig. 1 The demonstration area of PD/3

The operational environment of this ATM concept is simulated as realistically as possible in the real-time simulations. The pilot's involvement was experienced through the participation of real research aircraft flying 'within' the demonstration scenarios. The PD/3 demonstrations were planned to cover several sectors within the European core area, simulating parts of the airspace between Paris, Charles-de-Gaulle and Amsterdam, Schiphol (**Figure 1**). The amount of controlled traffic in the traffic sample for the simulated sectors was set at a maximum of approximately twice the present peak traffic for the current sectors. The simulations also attempted to address questions on transition problems and support of mixed equipage by simulating traffic with different equipment levels.

The PHARE Operational Concept

Scope and the European ATMS

PHARE is a research programme into candidate options for a future European ATM System (ATMS) [Ref. 1 and 2]. As expressed in the Operational Concepts Document (OCD) of the European ATMS [Ref. 1], there is a need to provide additional capacity to meet the increased demand in the congested traffic areas, and at airports in terms of ATM related operations. Also, an increase of flight efficiency is required by supporting more flexible operations and by providing freedom, whenever possible, to select user-preferred routes, which are optimal to serve the needs of airspace users.

The European target ATMS provides the basis for an Operational Concept for an overall ATM system for Europe, and for provision of gate-to-gate services for all phases of flight. It aims to provide services to all users in all types of airspace, based on Air Space Management (ASM) in a sector organised airspace. At the same time, these services should support a smooth and seamless process from flight preparation to flight execution. This process will encompass flight planning and control services which are convergent in space and time. Capacity and demand management in an early stage of strategic flow management, in collaboration with airspace users and airport operators, are the means to control the traffic density and the workload of ATC during the airborne phases of flight. On the one hand flow management regulates the traffic loads, at the other hand in this way the declared capacity in the controlled sectors are setting the limits of the amount of traffic to be handled.

The scope of PHARE and PD/3 was limited to the airborne phases of flight and on IFR operations in controlled airspace. The aim of the PHARE Operational Concept is to integrate the air and ground systems into one System providing the means to improve the operational productivity of ATM, and in this way to provide additional capacity, whilst keeping the workload at an acceptable level [Ref. 4 and 5]. This is achieved by proposed improvements on the decision making process, by changing procedures and roles in the air as well as on the ground, and by making full use of new enabling technologies.

PD/3 makes use of a conventional airspace organisation based on sectors and with fixed routes. However, this does not imply that an advanced operational concept will not require changes on sector and route structures. Indeed, the simulations performed at NLR and some simulations at EEC made use of direct routed, user preferred trajectories. A future optimal route structure could comprise a complete city-pair connecting network instead of the conventional beacon oriented network. It is currently assumed that traffic organisation and flow planning should be based on planning flights along a pre-defined known route network, whilst free routing during flight execution might be an option. Good reasons for such requirements are the pragmatic feasibility of the flow planning process as such, and the early elimination of conflicts reached by a traffic organisation, using fixed routing. E.g. by applying one-way routes and agreed crossing levels classes of conflicts are eliminated a priori.

Improvement of the decision making process is essential to achieve increased capacity. One of the aims of PD/3 was to provide additional capacity by more efficient use of airspace and by optimised use of available runway capacity. Optimised use of airspace and runway capacity is possible only by taking early decisions, based on accurate and consistent information. The key elements of the PD/3 Operational Concept are therefore:

- Information sharing by all parties involved in decision making: The best information on the proposed flightpath, being the 4D trajectory, becomes available to all parties.
- Decision making in an early stage: An extended planning process is supported over all airborne phases of flight. Trajectory prediction and extended planning are applied, and a new concept of multi-sector planning is developed.
- Air-ground integration: Decision making is improved by combining the best available knowledge on flight trajectories generated to meet constraints imposed by ATC and environmental conditions.
- A human centred approach: The human is kept in the loop by introducing new tools to assist the pilot and the controller in their planning, monitoring and controlling tasks.

The essential justification of a concept of extended planning is the precision and reliability of the prediction on which the planning process depends. The prediction becomes reliable as the quality of prediction is sufficient and because the prediction is input to the guidance processes. The quality ensures that the flight can be executed efficiently and economically within the aircraft’s flight envelope. The guidance processes, performed by the aircraft or by the ground, will ensure conformance of flight performance with the planning.
Therefore, a reliable planning makes use of airborne predicted data, and the planning process has to be completed by agreement between air and ground on the predicted trajectory to be flown. However, in order to make best use of the concept a significant part of the traffic should be equipped with an advanced 4D FMS and with the required air-ground data communication capabilities.
At the same time, flexibility and adaptability of the planning process are required. Re-planning is unavoidable for all kinds of reasons. Economical factors may justify re-planning on request of AOC, or revised weather predictions may change the estimated arrival times. Therefore, refinement, convergence and re-negotiation in the planning process are the essential features ensuring not only safe, but also efficient and expeditious control services.

PD/3 offers a planning-based concept where benefits are expected from automation support and air-ground integration. The concept is the result of a synthesis and extension of concepts development of earlier PHARE demonstrations (PD/1 and PD/2).

Operational Roles and Tasks

Overview

The most important elements and features of the concept will be discussed briefly. **Figure 2** gives a high level overview of the concept.

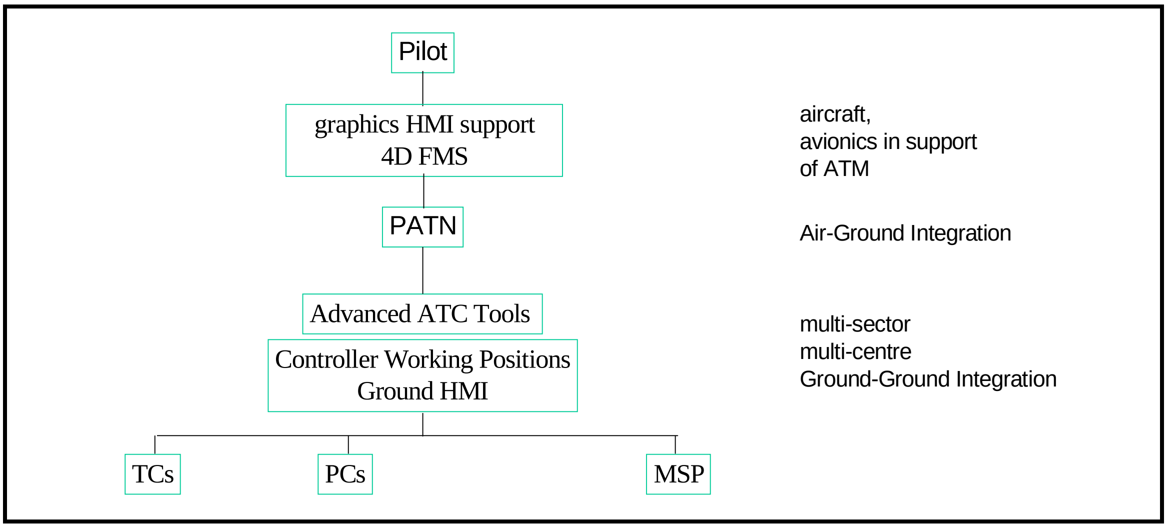

Fig. 2 Concept overview

To be realistic, it is assumed that a mixed traffic environment of equipped and unequipped aircraft is present, but to be able to demonstrate the expected benefits, that a significant part of the traffic is equipped with advanced datalink and 4D FMS. To address the essentials of the concept, only advanced equipped aircraft are discussed here.

The datalink communication services are performed by a prototype of a future datalink network, an ATN, applicable to the concept for air-ground as well as ground-ground communication. The most important air-ground application is 4D Trajectory Negotiation, but some complementary applications are needed also.

The ground system, operational in controlled airspace, consists of a multi-centre, multi-sector environment. The ground system makes use of datalink communication, to achieve information distribution to all controllers involved. The information exchange ensures transparent availability of surveillance and planning information, including trajectory prediction information. Moreover, datalink communication is applicable for silent coordination between controllers of different sectors.

The ground system is characterised by an organisation of different planning and controlling ATCO roles, and specific tasks are designated to each role, performing part of the planning and control process in en-route, ACC and TMA airspace. The controller roles are supported by a Controller Working Position (CWP), using 2kx2k rasterscan displays, and all operations are performed in a stripless environment. One universal CWP was developed to support all controller roles, based on windows oriented, interactive operations. This CWP design is configurable and modular, which permits to configure for each ATCO role a specific working environment.

Each ATCO was assisted by automation support tools. A set of PHARE Advanced Tools (PATs) has been developed, consisting of some generally applicable tools and some tools with more specific use, tuned to specific controller tasks. Access to these tools is provided via the different windows supported by the HMI.

Role of aircraft and pilot

The pilot of a 4D equipped aircraft is expected to initiate the trajectory negotiation process in the pre-departure phase selecting the preferred trajectory to be negotiated with ATC. This trajectory will be derived from the available flightplan, the Air Traffic Flow Management (ATFM) assigned departure and arrival slots and a pre-departure clearance, specifying at least the runway and SID. Re-negotiation of an altered contracted trajectory is always possible afterwards. A regular initiative to re-negotiation could occur as result of sector planning activities by ATC, but also the pilot may take the initiative and re-negotiate if flight performance is less than optimal or for other reasons such as flight efficiency or economy.

The pilot is committed to fly the contracted trajectory, down-linked during the trajectory negotiation process with the Planning Controller (PC). The Tactical Controller (TC) will control the aircraft along that part of the trajectory which goes through his sector to ensure separation. The TC may also uplink trajectory changes as a ‘Formalised Clearance’, an abbreviated form of trajectory negotiation.

The pilot has access to a 4D FMS via a Control and Display Unit (CDU) and a navigation interface, the Electronic Flight Information System (EFIS) on which the trajectory was graphically displayed in plan or elevation views. The pilot is able to select and verify graphically the preferred trajectory, and to down-link this trajectory to the ground and/or to activate this trajectory to be flown by the FMS. If the ground uplinks constraints, the pilot is able to select the adapted trajectory generated by the FMS, as far as possible fulfilling the constraints (see **illustration 1**).

Illustration 1: The navigation interface on the EFIS display, used by the pilot as an interface with the 4D Flight Management System of PHARE

Planning and Control, Departure

Departure planning creates a problem for an extended planning concept, because of the effect of an essential uncertainty of the actual departure time on other planning processes. Unfortunately, European core area traffic consists for a very significant part of short-haul flights and the planning of departure traffic plays an important role in extended planning of en-route and arrival traffic. Improved accuracy of departure planning is therefore an essential element of an extended planning concept.

The aim of Departure Management is to perform medium-term departure planning, up to 30 minutes ahead, in such a way as to predict Estimated Times of Departure (ETDs) of most traffic with an uncertainty of at most 30 seconds and to allow smooth integration into en-route capacity flow planning. Departure Management will initially be based on ATFM planning and assigned departure and arrival slots by the Central Flow Management Unit (CFMU), and will take into account airport planning and ground operations. On requesting ‘push-back’ the pilot would be given departure clearance, specifying precise push-back time, runway, take-off time and SID. These would be sent as a trajectory update in the form of a ‘Formalised Clearance’.

Before departure, the departure planning will be consolidated, as far as 4D equipped traffic is concerned, by an initial trajectory negotiation process, giving the best estimate of the preferred trajectory to be flown. After take-off the planned trajectory will be updated with the Actual Time of Departure (ATD).

Planning and Control, En-route

Planning in en-route airspace is extended with an extra planning process, i.e. multi-sector planning. The benefits expected from an extra planning layer are:

- To be able to take planning decisions with a larger scope than a single sector. This may be beneficial to the efficiency and economy of flight;
- To reduce the workload of the sectors by reducing, shifting and redistributing workload;
- To offer the pilot of the 4D equipped aircraft the opportunity to select and negotiate a trajectory at an early stage. This enables ATC to take into account the pilot’s preferences in their process of flight planning.

The span of control of the Multi-Sector Planner (MSP) in PD/3 was to control several sectors within a FIR or a centre. The number of sectors may range from 2 to 5, depending on complexity, size and type of sectors. The planning period is from 30 to 10 minutes before entering the first sector of the MSP area. There is no overlap in a sector between MSP planning and sector planning.

The planning tasks are mainly focused on en-route decision making with the objectives:

- to balance the traffic load over sectors;
- to reduce traffic complexity, and to separate flows;
- to solve traffic problems in support of safe, efficient and expeditious ATC services;

The sector Planner Controller (PC) takes over the planning process from an MSP about 10 minutes before the aircraft enters the PC’s sector. This planning period is based on an average sector transit time of 10 minutes. The PC performs planning as a refinement of the MSP planning, supporting the required convergence in space and time of planning and control. The planning of the PC is based on trajectories and exceeds therefore significantly the precision of present-day planning.

The TC assumes control of an aircraft as it enters the sector, and is expected to ensure that the aircraft complies with the trajectory planned by the PC. His role is also to monitor the traffic situation, to resolve any outstanding problems and to cope with unexpected situations. For aircraft without a 4D FMS the TC will also pass commands to ensure that the planned trajectory is followed.

The consequence of the definitions of roles of MSP, PC, and TC is a shift of workload from tactical decision making to early planning. At the same time, the role of the TC becomes more a monitoring than an executive decision making role, and this requires new tools and HMI to assist him adequately. Moreover, the TC has to be able to understand the traffic situation and planning, which requires tools to assist the TC in providing situational awareness. Advanced tools and electronic communication facilities enforce the role of the PC to support the TC in his executive task.

The PC has planning authority and implements the planning via datalink. The TC has control authority and implements control mainly using R/T unless there is time to use datalink or request replanning by the PC.

Planning and control is performed on mixed traffic. 4D equipped flights are expected to be the natural candidates for early planning, and therefore for MSP planning activities. The reliability of their 4D predictions justifies early planning. The trajectory negotiation process will enforce the stability and reliability of the planning. It is therefore not only the interest of the pilot, but also of ATC to reach a ‘contract’ on a planned trajectory. Because the PC is tasked to achieve conflict-free planning, he is expected to confirm his planning by a ‘contract’. The PC performs the trajectory negotiation process with the pilot over datalink. The TC of the previous sector, however, still controlling the aircraft, has the authority and the possibility to interrupt the negotiation process and to give a clearance instruction via R/T or, time permitting, with a Formalised Clearance via datalink, whenever this is required (see the explanation below).

The results of planning of an MSP are uplinked as additional constraints to those sent by the negotiating PC. The MSP does not negotiate directly for several reasons:

- To avoid confusion for the pilot and to allow one ATCO at a time to perform a negotiation process;
- To avoid frequent and repeatedly re-negotiations, initiated by ATC;
- To avoid work overload of the MSP given the amount of traffic to be handled.

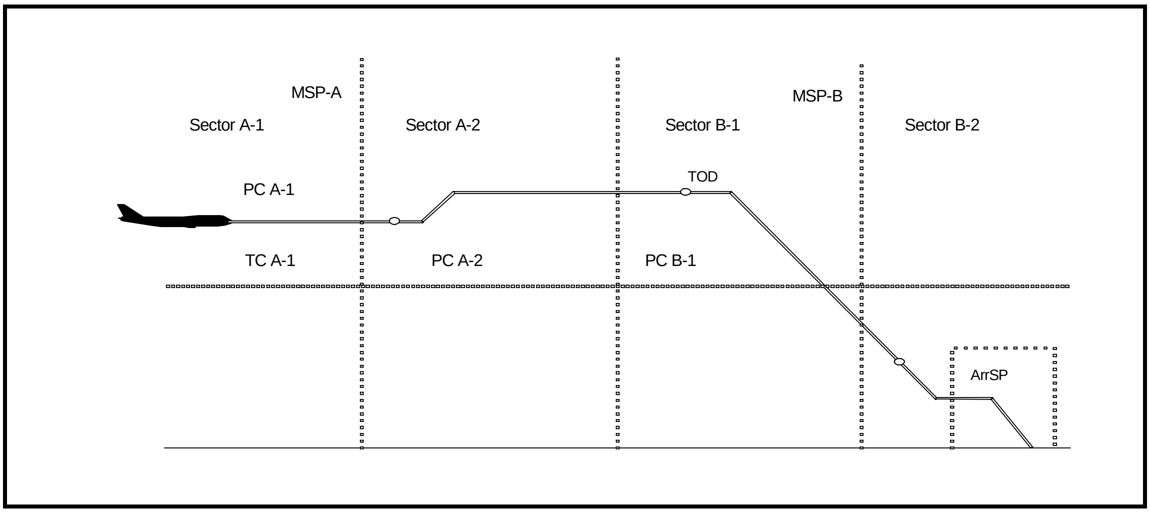

Fig. 3 Planning and control, en-route

Figure 3 illustrates the process of en-route planning and control by several ATCOs controlling several sectors and MSP areas at a time. TC (A-1) has control authority over the aircraft in his sector (A1); PC (A-2) has planning authority, and is authorised to negotiate with the pilot on the trajectory planning for his sector (A-2), and MSP-B in the next MSP area (B) is doing an early capacity planning on the arrival flow to the destination airport.

Planning and Control, Arrival

Arrival Management, metering and sequencing in the arrival phase, is an area of planning and control were benefits are expected from extended planning. Automation assistance tools to optimise the process of planning and control in the arrival phase are experienced already under operational conditions e.g. by CTAS [Ref. 10 and 11]. The aim is efficient use of the available runway capacity, and it is achieved by early control instructions (vectoring and speed adjustments).

Arrival Management in a 4D environment may demonstrate improvements by making use of the 4D guidance capabilities of equipped aircraft, even if in a mixed traffic environment part of the traffic has to be controlled manually. The expected benefits are:

- flight efficiency by early accurate planning of the arrival time and arrival sequence;
- workload reduction, because 4D guidance by the aircraft reduces the need for controller's attention and control activity in all sectors involved;
- possible options to implement favourable descent procedures with respect to noise abatement regulation (Continuous Descent Approaches, CDAs);
- increased punctuality;
- automated balancing of the load on multiple runways;
- allocation of certain aircraft types to particular runways.

The requirements on ground assistance tools comprise amongst others:

- an arrival management sequencing tool, to plan the Sequenced Time of Arrivals (STAs);
- a conflict probe to detect conflicts of the planned trajectories;
- support in conflict solving by a Problem Solver (see below);
- the capability to negotiate the imposed constraints related to arrival management and deconfliction, with the aircraft.

The implementation in a core area environment imposes specific coordination issues on performance of 4D controlled arrival management. This is illustrated by **Figure 4**. The arrival constraints are imposed by the Arrival Sequence Planner (ArrSP), operating in the TMA, and deconfliction is achieved in previous sectors. The negotiation will be initiated by the ArrSP in the TMA, but will be controlled by the TC in the en-route sector. The ArrSP only intervenes if there are problems. In most cases the sequence is left as defined by the Arrival Manager tool. If the ArrSP takes any action then the effect on the current sector is usually minor to the extent that the TC would not notice unless the system told him. However, arrival constraints may result occasionally in tactical action and/or problem solving in the current sector, which requires coordination between the TC and the ArrSP.

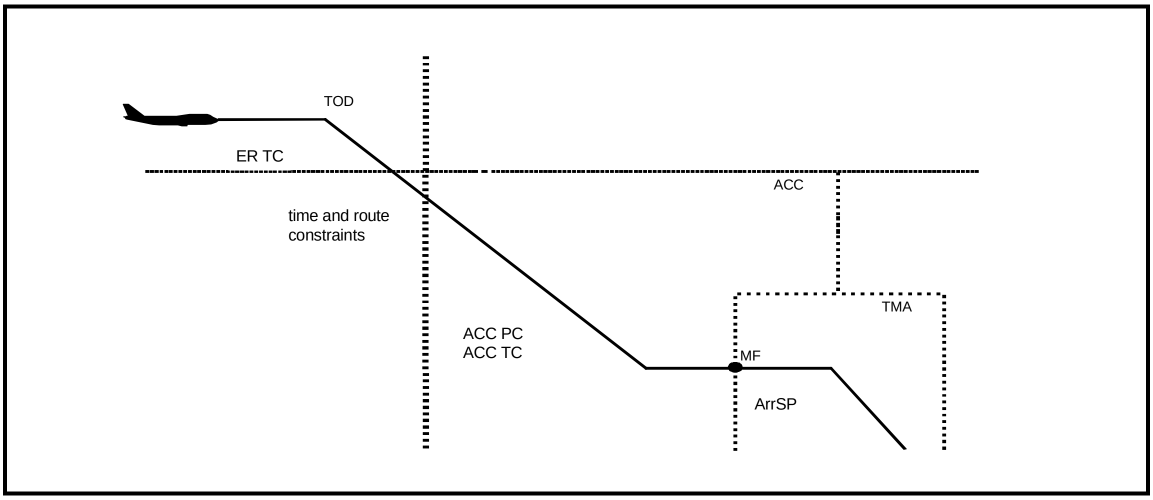

Fig. 4 Planning and Control, arrival

Communication and ATN

The essential elements of integration of planning and control on flight execution are air-ground and ground-ground data communication. An experimental prototype of an ATN has been developed in PHARE to provide the required datalink communication services. This ATN prototype supports the required datalink facilities based on extensions of the principles and architecture of the Aeronautical Tele-communication Network being defined by ICAO

(SARPs). Datalink communication in PD/3 establishes communication between the 4D FMS in the aircraft and ATC on the ground, which is provided by:

- Local Area Networks (LANs) within the different participating establishments;
- Wide Area Networks (WANs) interconnecting ground facilities of the different establishments;
- air-ground datalink subnetworks based on Satcom.

R/T and telephone communications are still available as additional means of communication. R/T is essential for short-term control instructions, and clearances via R/T can break and overrule possible negotiated contracts between air and ground. The intention is to re-negotiate a contracted trajectory afterwards.

The ATN was used for a limited set of datalink applications:

1. Trajectory Negotiation (TN)
2. Position Reporting (PR)
3. Down-link Aircraft Parameters (DAP)
4. Frequency Change (emulated)

Trajectory Negotiation is the most important application, which is replacing the limited functionality of the more traditional application of CPDLC. TN is able to exchange full 4D trajectories.

An application, to be added, and emulated in PD/3, is an application for the exchange of now-cast weather prediction data. This application would provide accurate and consistent weather data which can be input to the trajectory prediction function, both in the 4D FMS and the ATC system.

Trajectory Negotiation

Trajectory Negotiation (TN) is the key to an integrated process of planning and control. TN allows the pilot to select and negotiate his preferred trajectory before departure with support of the 4D FMS. The planned trajectory is communicated to ATC enabling ATC during all phases of flight to plan and re-negotiate the agreed execution of the flight in close co-operation with the pilot. (**Figure 5**).

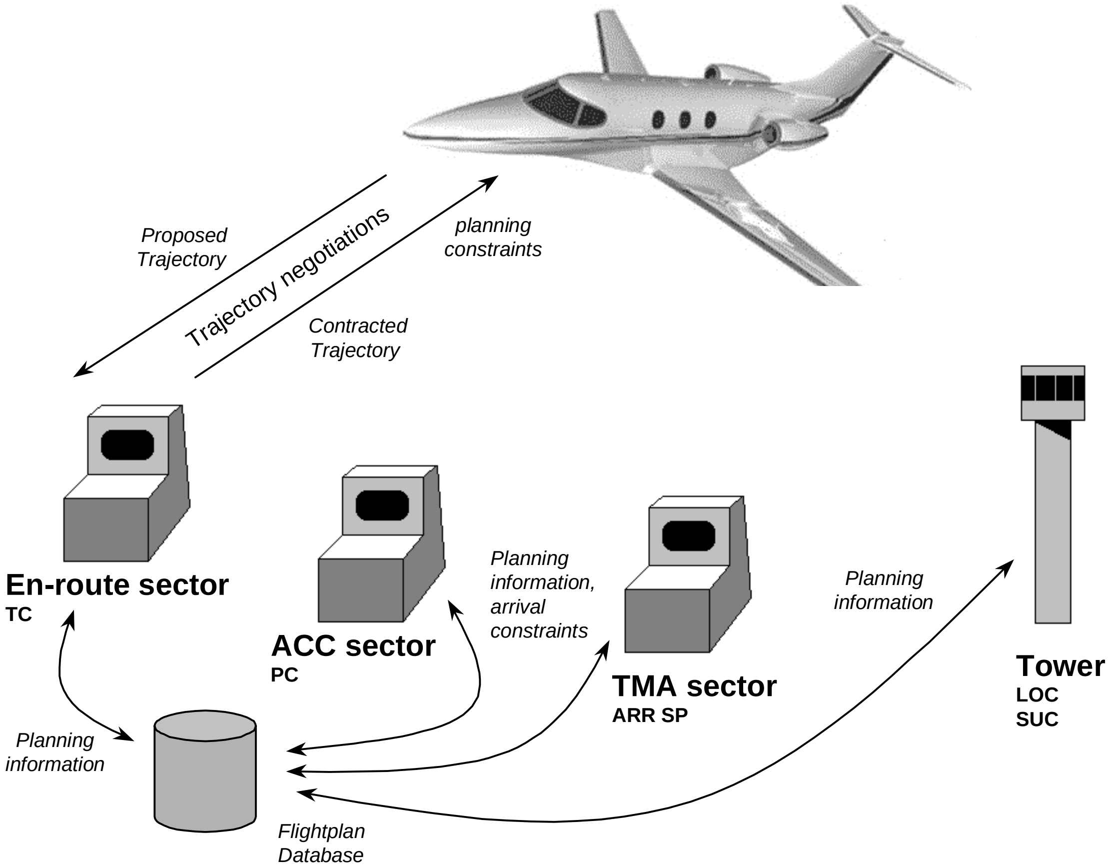

Fig. 5 Trajectory Negotiation dialogue between air and ground

The TN application may be carried out in several ways for example:

1. The aircraft down-links a proposed trajectory, the PC uplinks constraints, a proposed trajectory is downlinked to meet the constraints and then may be agreed or ‘contracted’ between the pilot and the controller. This communication agrees on the planning of a flight between ground and air, which will be conflict-free over at least the next sector.
2. A ‘Formalised Clearance’ may be uplinked as constraints to the aircraft FMS which generates, and on Pilot acknowledgement down-links and immediately starts flying, a trajectory to meet the constraints. This communication is the equivalent of a tactical clearance instruction.
3. ‘Sector Contract Approval’: Part of a trajectory through a sector is approved by ATC.

At an airborne level, selection and negotiation of an optimised trajectory are based on the scope of a full flight. A trajectory must be continuous and should be viewed in this light as a complete flight either to the destination or to the exit of the area of control. This trajectory, fulfilling all known imposed constraints, will be down-linked. Once contracted, the aircraft stores the ‘contracted’ trajectory in its FMS, and is expected to fly it, 4D compliant. If there is an exception the pilot may re-negotiate a new trajectory or take action and then re-negotiate. In these exceptional cases the aircraft may send a ‘Pre-emptive’ Negotiation consisting of the trajectory which the aircraft is now flying, to the ground system. The ground system will update its trajectory and alert the controller who will re-plan, if required.

On the ground side, planning, prediction and negotiation are based in a similar way on selecting an efficient prediction, constraining a trajectory, and negotiating a full flight. Each planner has a limited scope which is normally taken to consist of the planner’s sector plus an area of common interest in the preceding and succeeding sectors. The planner negotiating a trajectory will ensure that the flight is conflict free in these areas. In the unlikely event that the planner cannot avoid causing a conflict in an adjacent sector then the trajectory will be coordinated with the TC of the preceding, or the PC of the succeeding ‘infringed’ sector.

By definition, the ‘contract’ shall be defined as the trajectory, negotiated between air and ground, which the aircraft will fly up to the landing or to some point in the future. The ‘contract’ shall be considered on the ground as the active flightplan, describing what the aircraft is flying. The planning and control process on the ground is based on convergence of planning in time and space, and because 4D ‘contracts’ deserve confidence and because they are accurate over a long planning period, they are expected to contribute to the stability of planning.

The TC, assuming the flight, accepts the responsibility to ensure separation and to provide control service to guide the aircraft through the sector along the planned trajectory. If dealing with a contracted flight, he will issue a Sector Contract Approval, which shows the pilot the extent of TC’s control.

The result of Trajectory Negotiation is:

- Planning and control on the ground is based on a down-linked predicted 4D trajectory for flights with a ‘contract’.
- The ground and the air are working both with identical and agreed 4D trajectories for these flights.
- A ‘contracted’ trajectory will be planned conflict-free through the next sector.

System Overview

The system design, supporting the concept of PD/3, consists of three main parts (see **figure 2**): the airborne part, the ATN and the ground-based part of the system. The ATN is not discussed here in further detail.

The airborne PHARE 4D system

The airborne ATM supporting system of 4D equipped aircraft consists of an [Experimental] 4D Flight Management System (EFMS) and an airborne HMI, implemented by a CDU and an EFIS display. The 4D FMS provides the following functionality:

- a data-link interface facility allowing the exchange of trajectory planning information between aircraft and ground;
- a comprehensive navigation database facility;
- a facility to select and edit any relevant trajectory, including 4D predictions and required changes from either pilot or ground;
- an adequate graphical clearance representation;
- a 4D guidance function;
- a function to monitor flight progress against the contracted trajectory.

The ATM ground system of PHARE

The ground system simulated by PD/3 consists of a central facility for processing surveillance data, flightplan data, and data distribution to the relevant Controlling Working Positions (CWPs). The processing of the PD/3 ground system is event-driven, and controlled by client-server software. A set of advanced software tools, some as clients and some in servers, called the PHARE Advanced Tools (PATs), run in the PD/3 ground system. The functions of the PATs are accessed or initiated by the ATCOs via the ground HMI. (**Figure 6**)

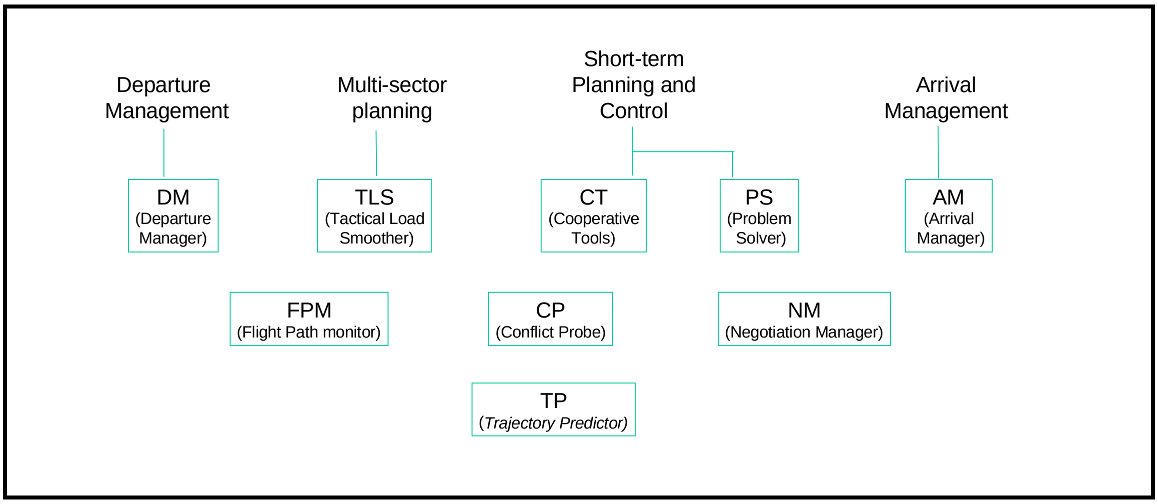

Fig. 6 Overview of PHARE Advanced Tools (PATs)

The HMI of the Controller Working Positions (CWPs) is a mouse-driven, windows-oriented graphical interface to support the ATCO with his planning and controlling tasks. The HMI is configurable for each of the different controller roles of PD/3.

The HMI was built up around a basic control window, the Radar Plan View Display (RPVD), providing overview of the traffic situation. This labelled radar display shows the traffic in 2D as well as map and routing information. General planning information is available by Sector Inbound Lists (SILs), Sector Exit Lists (SELs) and Message In/ Message Out Windows (MIWs/MOWs). (A representative picture, as used by PHARE, for en-route planning is given by **illustration 2**.)

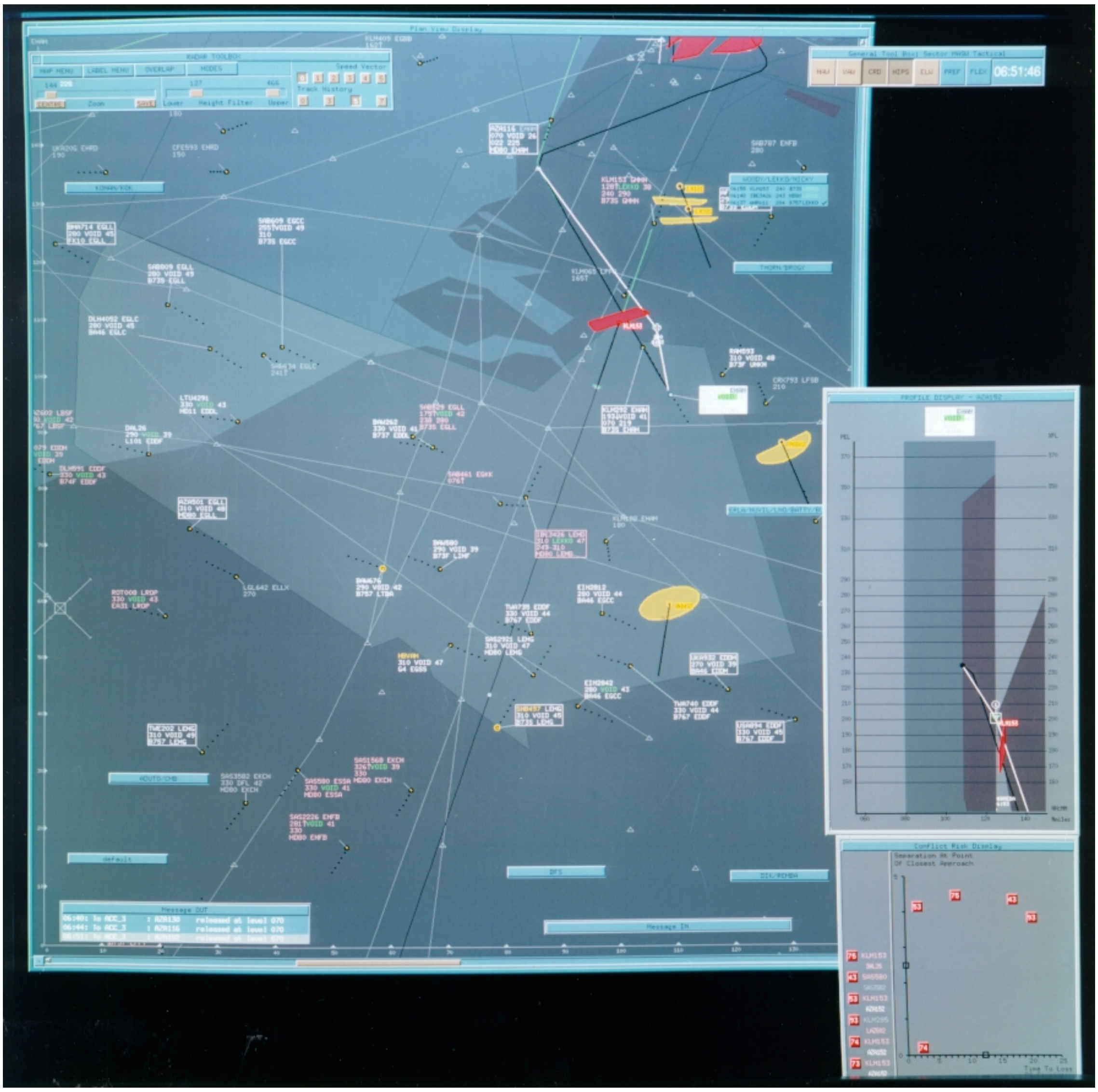

Illustration 2: An example of the display of a CWP, used in PHARE by the en-route PC

The PATs are discussed below and, where applicable, the use of specific window features is explained:

- **Trajectory Predictor (TP):**
  The TP is a 4D trajectory predictor, based on point-mass modelling. Results of trajectory prediction are used by almost all other tools. As such the TP is fundamental to the operation of the system. It is used to provide trajectories that are used by the controllers and the other tools in ‘what-if’ modelling. This trajectory is replaced by the actual trajectory downlinked from the aircraft if the aircraft is 4D and datalink equipped. In the case of non-equipped aircraft the TP generated trajectory becomes the working active trajectory.

- **Flight Path Monitor (FPM):**
  The FPM is a flightpath conformance monitor, detecting deviations between the active trajectory of the aircraft and the received position reports from other sensors such as radar or ADS-B. It is also able to make use of probabilistic data from systems such as ARTAS (although only simple radar position reports were available and tested in PD/3). Detected deviations are used to conclude to corrective speed advisories, which are presented to the ATCO. The FPM also had 2 supplementary functions, it would raise an event to other tools or HMI when the aircraft passed a significant point and track the progression of the aircraft along the trajectory marking which positions had been passed . [Ref. 12]

- **Conflict Probe (CP):**
  The CP is a geometric and probabilistic conflict detection tool, identifying losses of separation and estimating the probability of a collision between two aircraft. Conflicts are detected by using the aircraft trajectories [Ref. 13]. The detected planning conflicts are presented where applicable, e.g. in the RPVD by colouring plots and labels, but also in dedicated windows intended to present an overview of problems and/or conflicts and the priority to solve them, e.g. the Activity Predictor Display (APD).

- **Negotiation Manager (NM):**
  The NM is a tool, identifying the needs for and managing sector-to-sector coordination and air-ground trajectory negotiation. The air-ground negotiation process is discussed in one of the previous sections. The ground-ground coordination process controls required coordination due to proposed planning changes, whenever changes are such that confirmation of adjacent sector controllers is required for example if the change causes a conflict in an adjacent sector.

- **Arrival Manager (AM):**
  The AM is a tool which sequences and balances the arrival rates of the arriving aircraft on the available runway(s). A best fit for a Sequenced Time of Arrival (STA) is calculated, starting from the available predicted trajectories, using the calculated Estimated Time of Arrival (ETA). The associated HMI offers an interactive window, with vertical time bars, on which the aircraft labels are displayed allowing delays and planning conflicts to be presented, whilst preferred sequences, arrival time and runway changes can be imposed interactively by the controller dragging the aircraft labels.

- **Problem Solver (PS):**
  The PS supports Highly Interactive Problem Solving (HIPS). This comprises an advanced concept to display air situations and to give the controller a rapid and reliable means of solving conflicts between aircraft by editing or adding to the constraints on a trajectory [Ref. 14]. The PS calculates and displays ‘no-go’ zones where separation is infringed. The associated HMI supports constraint editing. The HMI is tightly coupled to the PS and makes use of PS results. (The **illustration 2** is showing the HIPS as used to edit constraints and to select a trajectory, whilst the no-go zones allow the ATCO to select an appropriate conflict-free trajectory.)

- **Cooperative Tools (CT):**
  The CT support an enforcement of team work by TC and PC for en-route control, assessing the potential risk of potential conflicts or problems and providing a filtered view of a selected subset of the ‘interfering’ aircraft involved. The HMI then presents potential conflicts in the Activity Predictor Display (APD) which is in the form of a vertical timeline with the PROblem SITuations (PROSITS) labelled on it. If the controller accesses a PROSIT the concerned interfering aircraft are highlighted on the RPVD.

- **Tactical Load Smoother (TLS):**
  The TLS determines traffic complexity for a chosen time in the future, over a certain airspace. It takes into account sector geometry, numbers of aircraft, equipment levels, numbers of aircraft changing vector (climbing, descending turning etc), particular flight conditions, and potential conflicts. From all the data the TLS produces a ‘complexity’ value which it compares to the normal value for the airspace. The TLS provides the MSP Controller with information which enables the identification and analysis of flow capacity problems. The associated HMI presents traffic complexity hot spots and traffic density histograms, whilst problem solving occurs with support of the Look-Ahead Display (LAD) (see below).

- **Departure Manager (DM):**
  The DM manages the planning of departing traffic. It balances the departure rates across runways and ensures the most efficient use of the Standard Instrument Departures (SIDs) taking into account possible conflicts on the departures and the wake turbulence separations of the departing aircraft. The associated HMI offers an interactive window with departure planning and flight status information similar to that of the Arrival Manager.

The Look Ahead Display (LAD) was an HMI function to support the MSP to look at the traffic situation as planned in the future. The LAD supported an RPVD-look-alike picture extrapolated to a future time. The intention was to allow the MSP to obtain situational awareness on the traffic situation to be planned. The HMI provided an interactive window to manipulate the reference time of the predicted view.

Planned Experiments and Demonstrations

PD/3 offered an operational concept for all phases of flight, with the intention of providing benefits from automation support and air-ground integration. One of the most critical areas where improved prediction and guidance may demonstrate its benefits, is the arrival phase. NLR has demonstrated November 1998 Arrival Management in a 4D environment. The real time demonstration simulated a core area environment around Amsterdam-Schiphol. The current FIR and sector configurations were retained requiring planning over several sectors making coordination an essential element of the demonstrations **(illustration 3)**.

The simulations used the NLR ATC Research Simulator (NARSIM) and concentrated on an integrated en-route and extended terminal area environment around the TMA of Amsterdam Airport Schiphol. Traffic was simulated in three measured sectors (TMA, ACC and Brussels West, En-route) and eight feeder sectors including Maastricht Delta high level en-route, altogether manned by fifteen ATCOs.

The objective of the simulations were, within the PHARE concept of the introduction of advanced planning, computer assitance tools and datalink, to examine the effects on controller workload, airspace capacity, quality of service and system usability of:

- Arrival management in the TMA
- The interface between TMA and en-route airspace
- Differing proportions of aircraft with 4D FMS and datalink capabilities
- Free routing of aircraft in en-route and the TMA airspace

Traffic samples have been simulated with medium and high capacity demands. High samples had a peak movement rate (inbound and outbound) of 200 aircraft per hour at Schiphol, and air traffic was 0% and 70% 4D equipped.

Illustration 3: CWP of NARSIM used for PD/3 for the demonstrations in November 1998 at NLR.

PHARE Concept Extensions and Future Work

PD/3 demonstrates an experimental system and concept. In these demonstrations so many new and advanced aspects are involved that evidently much more R&D work will be required to bring the concept to operational maturity. The concept and its implementation will have to be refined.

Important areas for future work are:

- 4D prediction and guidance
- Trajectory Negotiation (TN)
- Mixed traffic environment and transition
- Collaborative Decision Making (CDM)
- User Preferred Trajectories (Free Flight)
- Capacity and sectorisation
- Measures to be used to assess and compare ATM Systems

4D prediction and guidance

The pilot creates his preferred 4D trajectory in PD/3 with support of the 4D FMS. Once the trajectory is selected and contracted with the ground, the aircraft will use its guidance capability to follow the trajectory. Confidence in the guidance process is one of the fundamentals of implementing a concept of extended planning on the ground. Whilst it is important to have accurate guidance, attempting to be always precisely at a 4D point would be inefficient and costly. The PHARE Experimental Flight Management System (EFMS) parameterised the required guidance accuracies. In time these were as wide as +/- 30 seconds in the climb and cruise narrowing to +/- 5 seconds on approach [Ref. 15]. If these parameters were to be set to smaller values there could be an impact on flight efficiency.

The live flight trials in PHARE indicated that the EFMS values used for guidance accuracies and deviation alerts should be efficient and present no problems for the ground tools such as Conflict Probe. However, this could be an area for further research as it is possible that these values could be varied dependent on the airspace classification or on the ambient traffic levels.

Trajectory Negotiation

The PD/3 demonstrations used an implementation where a similar trajectory prediction model was used on the ground and in the air and the BADA performance model was also used by ‘air’ and ‘ground’. This proved the feasibility in simulations and also worked with live aircraft when they were trialled. However, it will be important to identify how modelling and data has to evolve towards a mature operational implementation with commercially operated aircraft.

The requirement for an operational implementation is that air and ground should both be able to make predictions for their own planning purposes, and that both, although working possibly with different models and with different modelling data, should be able to reproduce the trajectory which are in sufficient agreement. The controller requires a rapid trajectory generation system that can be used in 'what-if' modelling for problem solving, whereas the pilot requires an accurate trajectory generator for the FMS.

An option to solve this dilemma, may possibly be found by an exchange of appropriate data, defining the trajectory, and to exchange lists of waypoints, which will include the modes of flight applicable to each flight segment. Research can be spent to develop an adequate trajectory exchange protocol. Such a protocol has to be sufficient robust to be acceptable to become generally applicable and to become eventually a standard. The aircraft performance models have to be developed to communicate via this protocol for ground and air, and it has to be validated that these models are able to reproduce arbitrary flight profiles within an aircraft's flight envelope with sufficient precision.

Mixed traffic environment and transition

Another important topic for research, related to transition issues and Trajectory Negotiation, is raised by the question if it is possible in a future operational environment to work in a mixed traffic environment with different types of clearances for different classes of aircraft, depending on their equipment level. From discussions on the ATMS concepts it becomes evident that there is concern on the complexity of advanced ATM systems [Ref. 9]. It is felt that confusion may occur by providing too much data, too much status information, too much differentiation, and too many possible interactions. There might be a need to simplify the HMI, only because the risk of making failures under tension, and to return as much as possible to uniform and simplified procedures. In that context it might be an option to investigate the possibility to identify imposed constraints with planned clearances, and to use the exchange of the trajectories much more for information rather than as reliable data. The exchanged trajectories have one strict requirement only in that case, namely to be consistent with given clearances and to comply as much as possible with planned clearances.

Collaborative Decision Making (CDM)

Already in the ATMS OCD [Ref. 1], there is an increasing awareness of the importance of other actors to get an active role in ATM, given their competence, their interest and their knowledge. In this respect certain planning initiatives may be better taken by an AOC than by a pilot, and there may be good opportunities to include AOC derived preferences into the planning process.

The scope of the concept of PD/3 is limited to co-operation between ‘air’ and ‘ground’, the pilot and the controller. A future extension of the concept to an involvement of other parties can be included and might be beneficial. In projects like Collaborative Decision Making (CDM) this aspect is studied in more detail [Ref. 6]. The role of an AOC might offer a better scope to take decisions with an impact on the commercial interest of the flight and also the role of the airport might become more explicit, where it concerns links to planning and execution of ground service operations.

Free Flight

PHARE demonstrations have focused on planning and control in managed airspace despite the tools and the concept being airspace independent. However, other research projects are investigating a Free Flight concept. To link both research areas, additional work is needed:

- To transfer the TN process to an area with other planning and negotiation roles;
- To transfer the concept of contracted trajectories to an area with other rules to ensure separation;
- To integrate a concept for extended planning in managed airspace with applicable separation procedures in Free Flight airspace.

Capacity and Sectorisation

The PHARE Demonstrations have studied the PHARE concept in a present-day airspace organisation of sectors and routes. Apart from an adequate route structure, the question arises if optimal service provision requires a re-organisation of sectors. The question is complex by its organisational and institutional implications as well as by the technical and operational issues related to any possible positive result. General research work, addressing in particular the more technical and operational issues, is needed to study the optimal capacity in a specific or a representative generic airspace. Mentioning some of the typical dependencies, involved in such a study, the following list gives an indication of the complexity:

- The operational concept, and its roles and task assignments, determines the workload of the controllers and in particular the amount of traffic that can be handled by a controller.
- The traffic density, the allocation of airports and the pattern of departure and arrival flows, as well as the mutual influence of these flows on each other contribute to the complexity of the traffic and the associated workload to control it.
- The traffic mix and the expected level of advanced equipment are a contributory factor to the expected workload.
- Regular congestion and disruption, and the frequency of occurrence of such events, may contribute to stress and workload.

The demonstrations might show the feasibility of the different actors in the system, performing their appropriate roles. It is considered necessary however, to study also capacity and sectorisation aspects by combining and coupling results from real-time and fast-time simulations. The fast-time simulations will produce the data specifying the expected number of events and the characteristics of type and variation of events, while the real-time simulations will result in measuring the maximum acceptable workload, and characteristics for the required effort of handling each event.

The combined results are expected to give more reliable information on how much traffic can be handled by an advanced operational concept, applied to a configuration of sectors, which are tuned to the needs of that concept.

Conclusions

The concept for PD/3, as it has been and will be demonstrated, is a concept balancing between deterministic planning and tactical manoeuvring. The present implementation shows much of the full concept, although the whole concept can not be demonstrated yet.
Major benefits of this concept are expected from the extended and more accurate planning, combined with better control on flights and traffic in the air as well as on the ground. It is premature to draw conclusions on success of the concept, however the consistency and the level of detail of the concept justifies confidence.

NLR has performed demonstrations, demonstrating Arrival Management in a 4D environment, and simulating some of the complex sectors of a part of the European core area.
More R&D and more refinements and extensions are required in order to be able to make the concept mature and ready for operational use. Most refinements and extensions, as discussed in this paper, are focused on enforcing the flexibility and interoperability of the system. The use in PHARE of tools based on a probabilistic approach is important in that respect, because they are adaptive in the sense of being able to incorporate all available information to make a best estimate of the condition of the flight.

Many conceptual elements are closely related and mutually dependent. Extended planning processes are dependent on air-ground integration and a 4D prediction and guidance system. The tools and HMI are consistent in their functioning as an automation support system for the controller and the pilot. Therefore, in particular, air-ground integration should be considered as one integrated concept, and should be brought to operational maturity as such.
Options for refinement of air-ground integration, and a less demanding and more adaptive concept of Trajectory Negotiation were discussed. It could be beneficial to adapt the negotiation concept and to limit the need to impose constraints only to the extent, required to ensure separation. In other words to allow more free routing. Also AOC might play a role in this negotiation process.

The experience with advanced tools and HMI has led to the concern that automation assistance systems could become too complicated [Ref. 9]. New features, new options and flexibility come at the price of generating windows, input menus, and all kinds of colour and symbol status indicators. PD/3 is not the exception, and it is argued that refinements might be required, given the high risk of making failures, under stressing conditions, when the workload is high. A simple HMI and understandable tools are extremely important. An appropriate HMI will have to give straightforward transparent responses, and requires simple and limited inputs. The contradiction of a combination of complicated functionality controlled by a simple, straightforward HMI, has to be investigated in more detail.

The most important and most crucial part of the system, however, is the air-ground integrated guidance and control loop. A reliable 4D FMS, a reliable ground-based trajectory prediction function and an acceptable and consistent Trajectory Negotiation protocol have to be developed to support improved guidance and control. These form the heart of the system, and the effort to bring it to operational maturity is one of the most urgent questions to be solved.

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