PHARE Advanced Tools
Project
Final Report

PHARE/EHQ/PAT-8.2/FR;1.0

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- the DLR (Deutsches Zentrum für Luft- und Raumfahrt);
- the DFS (Deutsche Flugsicherung GmbH);
- the UK CAA (Civil Aviation Authority);
- the NATS (National Air Traffic Services);
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EXECUTIVE SUMMARY

This document is the PHARE Advanced Tools Final Report. It is the first volume of a set of 10 volumes the other volumes being the detailed final reports of each of the PHARE Advanced Tools.

In this report the PHARE concept will be discussed from the tools point of view. The individual tools are described in turn followed by the issues found in the PHARE Demonstrations and the problems found and lessons learnt.

Concepts

The objective of the PHARE programme was to demonstrate the merits of air-ground integration. The PHARE Advanced Tools exchanged trajectory data with the aircraft Flight Management System over a datalink ensuring that the trajectory data in the ground systems was identical to that in the aircraft.

In this concept the aircraft Flight Management System would have an extremely accurate guidance capability and therefore would follow the trajectory that it had sent to the ground system extremely accurately in all 4 dimensions (i.e. lateral route, altitude and time). The ground system would hold all aircraft trajectories and use them to identify if there were any conflicts to be alerted to the controller who would use the advanced software tools to amend the trajectory(ies) in the ground system. The amendment creates a deconfliction solution by adding 'constraints' to the trajectory(ies). The constraints required would then be passed to the aircraft which would generate a new trajectory and send it to the ground.

Although the aircraft guidance was expected to be accurate, the ground system would, nevertheless, monitor the progress of the aircraft on the trajectory and alert the controller should there be any deviation. As aircraft would maintain their trajectories or negotiate any change of trajectory with the ground systems, it would be possible to forecast the position of an aircraft many minutes in the future. This look ahead could be used to assess if there was any overload condition in the future in a sector. A controller with responsibility for future planning over several sectors, a "Multi-Sector Planner", could take action to amend the future trajectories and simplify and smooth the traffic flow through the sectors more than 30 minutes before the aircraft would arrive in the sector.

The ground system would also have tools for scheduling at both departure and landing airports which would schedule aircraft to the correct runways and ensure conflict and turbulence free departure and arrivals. The scheduling would be carried out by providing each aircraft with a take-off or landing time.

The PHARE Advanced Tools were defined in the PHARE Medium Term Scenario which was written in 1990. The Medium Term Scenario envisaged that the initial tools would be in operational use by the year 2000 and that there would be nearly full automation by the year 2010. It was expected that by 2010 there would be trajectory negotiation via datalink between aircraft and the ground and that there would be completely silent co-ordination and handover between controllers even between controllers on the same sector.
Tools Overview

The tools that were developed for PHARE are described in a broad overview in Section 4 of this document and in detail in the successive volumes in this series. The tools are briefly described below in an order that shows their position in the tool architecture.

**Trajectory Predictor.** The fundamental tool in the system was the Trajectory Predictor which was based on the Trajectory Predictor of the Experimental Flight Management System developed in another PHARE Project. The purpose of the tool in the ground system was to provide trajectories for the controller to try out possible deconfliction solutions in a process called 'what-if' modelling. The ground Trajectory Predictor could also be used to generate trajectories to be used by the system for aircraft which did not have datalink. In these cases the aircraft would be guided by radio command from the tactical controller. The radio commands were generated from the ground trajectory in PHARE Demonstration 1 and 2 and by the Trajectory Predictor itself in PHARE Demonstration 3.

**Conflict Probe.** The Conflict Probe operated every time a new trajectory was generated, searching the flight database to see if any other trajectory conflicted. If any conflict was found the Conflict Probe would pass the details of the conflict to the controller display or to the automated tools supporting the controller.

**Co-operative Tools.** Any conflicts would be displayed to the controller by the Co-operative Tools on an agenda of problems to solve. For each conflict the Co-operative Tools not only displayed the conflicting aircraft but also aircraft that were close enough to the conflict for the controller to consider. In this way the Co-operative Tools could be seen as a filtering tool only displaying the problem aircraft that the controller need consider for each Problem Situation. The controller could then use the Co-operative Tools functions to look ahead and assess the conflict.

**Problem Solver.** To solve the conflict the controller would use the Problem Solver which had a display that showed 'avoidance zones' as red areas on the screen. The Problem Solver display allowed the controller to use a mouse pointer to alter the trajectories of the aircraft involved on the screen by 'dragging' their constraint points until the trajectories no longer penetrated any avoidance zones. The Problem Solver then generated constraints which would be passed to the Trajectory Predictor and the deconfliction solution would be assessed.

**Negotiation Manager.** If the deconfliction was acceptable the controller would then 'register' the trajectory. This would instigate a trajectory negotiation if the aircraft was data-link equipped. This process would be managed by the Negotiation Manager which would pass the trajectory constraints by datalink to the aircraft and then check the trajectory returned by the aircraft for infringed constraints and for conflicts. The Negotiation Manager would also warn the controller if any ground-ground coordination was required as a result of the change to the trajectory. If the aircraft did not have datalink the Negotiation Manager would 'activate' the trajectory from the ground Trajectory Predictor.

**Flight Path Monitor.** The aircraft would then follow the trajectory that had been negotiated with the ground system. To ensure that there was no deviation from the conflict free trajectory the aircraft progress would be monitored by the Flight Path Monitor which would report any deviations. On a deviation the Flight Path Monitor would supply 'ground supported navigation' in the form of 'advisories' which would be displayed to the appropriate Tactical Controller to redirect the aircraft onto its deconflicted trajectory. The Flight Path Monitor would also report the progression of
the aircraft along its trajectory and signal as the aircraft passed significant points on the trajectory such as top-of-descent.

Departure Manager. The Departure Manager would operate whenever a new trajectory was generated that was departing from the Departure Manager’s airport. The ideal departure runway, route and departure time would be chosen with issues such as wake turbulence, runway load balancing conflicts on the climb out and the flow management slot time taken into consideration.

Arrival Manager. At the destination the Arrival Manager would sequence arrival traffic on receipt of a new trajectory or a change of an already scheduled trajectory. The Arrival Manager would choose the ideal arrival runway and scheduled arrival time with issues such as wake turbulence separation, runway load balancing taken into consideration. The arrival manager would also identify if an aircraft had entered a hold and generate constraints to separate holding aircraft in a stack.

Tactical Load Smoother. The trajectories generated and the associated conflicts would be assessed by the Tactical Load Smoother which would display to the Multi-Sector Planner the complexities in the various sectors. This would allow the Multi-Sector Planner to simplify the traffic patterns in the sectors. In all cases it was expected that the Multi-Sector Planner would simplify the traffic flows, the Planner Controller would deconflict the aircraft trajectories if necessary and use datalink to negotiate changes in trajectory. The Tactical Controllers, currently the busiest controllers, would have their task reduced to monitoring equipped aircraft and guiding the non-equipped aircraft.

Tool Usage

The expected course of events was that an aircraft flight plan would be processed using only the ground tools to provide an initial trajectory and departure and arrival times and runways. When the aircraft logged onto datalink it would downlink its User Preferred Trajectory to the ground system. This trajectory would replace the initial trajectory and the departure planner controller would take deconfliction action if necessary. The Departure Manager and the Arrival Manager would reschedule the runway times for the aircraft. From then on as the aircraft progressed down its trajectory the deconfliction would always be completed by the next sector planner controller before it entered the next sector, with planning authority being passed from controller to controller ahead of the aircraft.

It should be noted that the tools do not require the fixed route structure for their operation. However, almost all the PHARE Demonstrations were based on the current fixed route airspace structure. The procedures for the controllers were as far as possible retained and as such the tools were simulated in a transition environment.

PHARE Demonstrations

PHARE Demonstration 1 at DRA Malvern was an en-route simulation and involved only the Trajectory Predictor, Problem Solver, Conflict Probe and Flight Path Monitor. The simulation showed that the tools had merit and that it was possible to provide a better quality of service. However, the trial also indicated that the controller procedures needed to be reassessed and controllers needed more training in the concepts and the tools. Issues were also raised on the control of non-datalink aircraft by radio. PHARE Demonstration 1 became the first of a series testing out variations in procedures and practices. The final PHARE Demonstration 1 ++ at NATS ATMDC Hurn, largely abandoned the fixed route structure and appeared to
show that the 2015 level of traffic could be handled by half the number of controllers in a en-route scenario with PHARE Advanced Tool support, RVSM and direct routing.

PHARE Demonstration 2 at DLR Braunschweig was a simulation of the Extended Terminal Airspace and Terminal Manoeuvring Area around Frankfurt Airport. The Arrival Manager, Trajectory Predictor, Conflict Probe and Flight Path Monitor were used in the simulation. The Arrival Manager was used in a mode that made it a fully automated tool and as such no Arrival Sector Planner was involved in the advanced organisations. The demonstration was arranged with the minimum of variables purely to assess how accurately the scheduled time of arrival could be met. The tools appeared to be extremely successful with a considerable improvement in orderly handling of traffic and a reduction in controller mental workload. Aircraft flew close to continual descents and were 'higher over Frankfurt' (the airport simulated) than normal, which in practice should greatly reduce environmental impact. The accuracy of landings was also greatly improved when advanced tools were used in comparison to the baseline.

PHARE Demonstration 3 was to be carried out at CENA, EEC and NLR. However, due to system problems in development of the Ground HMI at EEC Brétigny, the Demonstrations at EEC and at NLR did not achieve measured results.

The NLR PD/3 Trial was continued in a PD/3 Continuation Trial with a Ground HMI based on a development of that for PD/1. The procedures in the Continuation Trial were adapted to suit the tools with free routing and User Preferred Trajectories being allowed for all except aircraft on the arrival routes. The NLR PD/3 Continuation trial exercised the potential of the PATs toolset in close accordance with the original operational concept for which they had been designed.

Lessons Learnt

There were several lessons learnt during the PHARE Advanced Tools Project. The primary one is that there must be full agreement on, and understanding of, the concepts involved by all parties. There should be system wide rather than project based configuration management preferably through a systems engineering function which included pilot, controller and airspace procedures as part of the Air Traffic Management System.

Metrics that equate air traffic management system capacity to controller workload, are not best suited to systems which are exception management based and where controller workload is not proportional to the number of aircraft transiting the sector. Metrics assessing controller workload can be adversely skewed by controllers maintaining their previous procedures and practices while simultaneously 'using' automated assistance tools.

Automated systems must be trusted if controllers are to use them fully. In particular poor system performance will reduce the controller trust in the system. If controllers mistrust the tools they will revert to current controller practices and instead of assisting the controller the tools can become a burden.
Summary

The PHARE Advanced Tools all individually achieved their aims. There was no demonstration in which the entire tool-set was integrated. As tool sets in the Demonstrations the tools achieved their aim of providing assistance to the controllers. The concepts of the operational procedures and of the tools needed to match for full benefit. When the concept of the operational procedures matched those of the tools, the results were extremely encouraging, indicating that such a system could support user preferred trajectories at traffic levels expected in 2015.

Further Research

There should be continued further research into procedures to make best use of the 4 dimensional approach to air traffic management. The effect of the tools should then be quantified using metrics that more directly measure their effects on the performance of the air traffic management system.
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B1. SERVICES AND EVENTS IN PROCESSING A FLIGHT

B1.1 INTRODUCTION

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1. INTRODUCTION

1.1 BACKGROUND
The objective of the Programme for Harmonised ATM Research in EUROCONTROL (PHARE) was to organise, co-ordinate and conduct studies and experiments aimed at proving and demonstrating the feasibility and merits of a future air-ground integrated air traffic management system in all phases of flight. The results of the programme aimed to refine the description of the future Air Traffic System concepts needed to satisfy demand and to provide information on the best transition from the current to the new system.

In order to perform the investigations, the ground ATM system simulators needed to be upgraded with a set of tools with advanced functionality, these tools were called the PHARE Advanced Tools or PATs.

1.2 SCOPE
This document has been produced as part of the PATS project within the PHARE program and is the final report for the PATS Project. It collates issues discussed in detail in the individual PHARE Advanced Tools reports.

1.3 DOCUMENT CONTEXT
This document is the first of the 10 volumes produced by the PHARE Advanced Tools project within the PHARE program and represents the Final Report for the Advanced Tools Project.

1.4 SUBJECT
This report details the development and usage of the PATs highlighting issues such as integration in simulation platforms and concepts of the tools as a set rather than as individual tools. It will also highlight significant issues that should be noted from individual tools. However, each of the Advanced Tools is reported separately in detail as subsequent volumes to this report.

1.5 DOCUMENT STRUCTURE
Section 2 Describes the historical operational concepts of the PATs.
Section 3. Describes the PHARE Tool concepts and requirements.
Section 4. Describes the development process of the PATs
Section 5 Describes the tools in more detail, their concepts, integration, architecture, performance, and highlights further research required
Section 6 Describes and interprets the results of PHARE Demonstrations and Internal Operational Clarification Projects (IOCPs) relative to the PATS.
Section 7 Describes tool integration issues.
Section 8 Details areas to be considered for further research.
Section 9 Describes lessons learnt during the PATs Project.
Section 10 Gives a PATs view of the PHARE Results
2. HISTORY OF PATS DEVELOPMENTS

2.1 INITIATION OF THE PATS PROJECT

2.1.1 PHARE Agreement
The Programme for Harmonised ATM in EUROCONTROL (PHARE) was based on a partnership agreement between European ATM R&D establishments and Air Traffic Service (ATS) providers in 1989.

The work was based upon a PHARE Medium Term Scenario (PMTS) which forecast the expected changes in the CNS/ATM and the perceived ATM requirements [Reference 2.]. At the same time the Partners identified requirements for tools that they had interest in researching as they could form a toolset for an advanced ATM system.

2.1.2 PHARE Advanced Tools (PATs) Project
The PATs Project started its definition phase with the PHARE agreement and the PATs Initial Requirements and Planning Document [Reference 3.] was raised in the following year. On the basis of this PATs Planning Document the PATs Agreement was signed in 1993.

The PATs Initial Requirements and Planning Document expected there to be 2 sets of tools generated:

a **PATs Set 2000.** A subset of the tools with limited automation that could be operational by the year 2000.

b **PATs Set 2010.** A fully integrated set of tools with a high degree of automation support to the controller which could be operational by 2010.

The tools in the PATs tool-sets were identified and distributed to the PATs teams based on their experience with that type of tool and to share the workload evenly between partners. However, during the course of the programme some of the tools were passed to other teams. The PATs teams were as follows:

<table>
<thead>
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<th>Tool</th>
<th>Initial Developer</th>
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<td>NATS</td>
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<tr>
<td>Conflict Probe</td>
<td>NLR</td>
<td>NLR</td>
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<td>Cooperative Tools</td>
<td>CENA</td>
<td>CENA</td>
</tr>
<tr>
<td>Departure Manager</td>
<td>DLR</td>
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</tr>
<tr>
<td>Flight Path Monitor</td>
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<td>NLR</td>
</tr>
<tr>
<td>Negotiation Manager</td>
<td>DRA Malvern</td>
<td>NATS</td>
</tr>
<tr>
<td>Problem Solver</td>
<td>EEC</td>
<td>EEC</td>
</tr>
<tr>
<td>Tactical Load Smoother</td>
<td>EEC</td>
<td>EEC</td>
</tr>
<tr>
<td>Trajectory Predictor</td>
<td>DRA Malvern</td>
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The original intention of the PHARE Programme was to develop and integrate tools in the air and on the ground. Then to carry out a series of experiments and trials to prove and demonstrate the merits of the integrated approach. During the development of the tools there would be a PHARE Demonstration (PD) of the capabilities developed to that date. The planning envisaged 4 PHARE Demonstrations of increasing complexity: PD/1 demonstrating en-route tools; PD/2 Demonstrating Arrivals; PD/3 Demonstrating Arrival, Departure and En-route at 3 different sites; and, PD/4 integrating the sites into a combined all phases of flight simulation. During the programme PD/3 and PD/4 were amalgamated into one and then, later, PD/3 was de-scoped to its original form of 3 disconnected Demonstrations but of all phases of flight.

2.1.3 Project Management

The PATs Project was set up as a distributed project with a small ‘tool team’ working on each Partner site with the PATs Project Leader working in the PHARE Management Cell at EUROCONTROL HQ. The project leader of each Partner acted as the Partner’s member of a PATs Co-ordination Group (CG) which met bi-monthly and team members were nominated to the PATs Technical Group (TG).

The intent of the PATs TG was to allow the communication and sharing of ideas and technical approaches to enable more effective research at each establishment and engender conformity and convergence in Partner programmes [Reference 3.]. This was reasonably effective initially, however, as the work for the large scale simulations increased and fault reports and integration problems began to appear, the TG became more a clearing house for production issues, configuration management and integration arbitration.
2.2 INITIAL OPERATIONAL CONCEPTS

2.2.1 PHARE Medium Term Scenario (PMTS)

The PMTS forecast concepts that were expected to be used by the year 2000 and more advanced concepts for the year 2015. The PATS were developed initially with the intention of having 2 PATS ‘Tool-sets’ as a PATS 2000 and a PATS 2010. However, this approach was dropped in favour of developing the tools to meet the requirements of the planned PHARE Demonstrations. In consequence the tools were developed around one generic operational concept that would be capable of supporting both the early transition to advanced systems and the fully advanced systems. However, in some respects PD/1 and PD/2 could be said to be based on the tools that were defined for the PATs 2000 tool sets and PD/1++ and PD/3 on those of the PATs 2010 toolset.

The PMTS did identify the PATS that were likely to be required together with a view of the expected operational concepts. On this basis the PATS Initial Requirements and Planning Document was raised [Reference 3.]. This document defined the PATS in detail and included areas that were expected to be researched in more detail. These areas are discussed both below and in the Final Reports on each tool which comprise Volumes 2–10 of this Document.

The expectations of the PMTS were that the control task would move from the tactical or executive controller to the planning controller. As it states in [Reference 3.]

a “as the quality of trajectory prediction increases, the planning function can resolve a greater proportion of the conflicts (with computer assistance), thus easing the workload on the Tactical Controller and thereby enhancing ATC capacity. As a result there should be a progressive move away from short term ad-hoc ATC measures. Ultimately one might envisage the ‘executive’ [tactical] process becoming one of monitoring the plan and reacting to disturbances from it.”

b Interaction and co-ordination between the Planner and the Tactical controller “will be silent and unidirectional, in that the Planning Controller will produce a sector transit plan which is acceptable to the Tactical Controller, which can be communicated to the Tactical Controller via the computer (eg. By a suitable display of flight information) and which generally needs no additional explanation to the Tactical Controller.”

2.3 FINAL OPERATIONAL CONCEPTS

2.3.1 Concept Summary

Around the time of PD/1 a simplified set of concept bullet points was developed that summarise what became the final PATs operational concept:

a The trajectory for an aircraft shall be chosen by the pilot and shall only be constrained by controllers when necessary for deconfliction or to follow defined procedures such as SIDs and STARs.

b The trajectory used by the ground system shall whenever possible be the trajectory generated by the aircraft systems (datalink is strongly preferred).
c Flight trajectories shall be predicted taking into account constraints for the entire flight allowing management of the flight for greatest efficiency and economy.

d Planning controllers shall take deconfliction action as far ahead as possible; tactical controllers shall ensure that the planned trajectories are complied with and be provided with deviation alerts if they are not.

e Radio workload shall be kept to a minimum and shall only be necessary for the tactical controller to give clearances to non-datalink aircraft and to handle exceptions.

f Sector to sector handovers both intra and inter-centre shall be silent (i.e. no controller to controller telephone handover necessary.)

g The 'human is kept in the loop', decision making shall not be automated to the extent that the human is out of the picture; automation shall assist not take over.

2.3.2 Conceptual Overview

The knowledge of the future 4 Dimensional (4D) trajectory [Reference 4.] of aircraft in the airspace is fundamental to the PHARE concept. If the future trajectories are known then conflicts can be identified and be deconflicted a long time in advance by advanced planning. This contrasts with the short term 'just-in-time' tactical controller deconfliction of aircraft within the same sector. As it is assumed that the workload on the tactical controller that is considered the limiting factor to current ATM systems capacity, it is expected that reduction of the tactical workload should increase ATM System capacity.

To ensure that the trajectories in the ground system match the trajectories flown, the system uses feedback loops that identify deviations and either correct the trajectories or correct the aircraft back to the agreed trajectories. In the full PHARE datalink system there are 2 feedback loops. One is internal in the 'guidance' of the aircraft Flight Management System the other is through ground system flight path monitoring which reports deviations to the controller together with advice on recovery actions.

The ideal situation is that an aircraft Flight Management System generates the aircraft trajectory and then downlinks that trajectory over datalink to the Air Traffic Management System. The ground system then compares the trajectories it holds and identifies any conflicts between them in 4 dimensions.

If a conflict is identified it is highlighted to the controller(s). When the planning controller for that sector receives planning authority for the flight the trajectory will be deconflicted [Reference 4.]. When the aircraft enters the sector the tactical controller monitors the aircraft to ensure that it follows the trajectory aided by flight path monitoring software that will highlight deviations and provide advisories in 'unequipped' dimensions for less well equipped aircraft.

PHARE did not make the assumption that the trajectory was immutable. The full datalink system would allow the aircraft to downlink changes whenever the pilot felt that this was necessary. Similarly, the controller could take deconfliction action and negotiate the trajectory change with the aircraft. When these alterations in trajectory were carried out over datalink the process was called trajectory negotiation. [Reference 4.] [Reference 18.]

This conceptual overview contains concepts that were the cause of sometimes extended debate. The issues are discussed in greater detail in Appendix A to this report.
Volume. It is recommended that the reader familiarises with them to allow greater understanding of the conceptual issues when they appear in the discussion of the individual tools and the lessons learnt.

2.3.3 Level of Automation

There is a system design axiom “just because it can be automated does not mean it should be automated”. But there are also levels of automation described by such terms as “automated assistance”, “human centred”, “highly interactive”. There is a sense in which these terms are really euphemisms used to avoid problems with ‘imposing change’ on users. However, it is important that the level of automation that they infer and the workload that they cause is understood.

The initial intent of the PATs was to fully automate some controller functions. This caused some concern that the ‘man would be outside the loop’ and it was stated that at the most the tools should provide was automated assistance.

2.3.4 Airspace Procedures

Current ATC systems are heavily influenced by the airspace structure. Controllers are only given authority over aircraft in ‘their’ sectors and transfer of aircraft between sectors is quite rigidly constrained to specified agreed points. These entry exit points are often ‘metered’ to reduce the potential flows between sectors. These concepts are systemic 3D procedures built into the airspace structure. Although an aircraft on a 4D trajectory can follow these 3D procedural routes most of the advantages of 4D control such as free routing, increased airspace capacity and reduction in conflicts are lost.

These 3D airspace concepts were sometimes written into the tools as irrevocable tenets which subsequently greatly restricted the tool capabilities and freedom of controllers. For example the Trajectory Predictor would not generate a hold anywhere except at the Metering Fix which was always taken to be the first STAR fix.

The large scale simulations that were run used the existing airspace structures and often the existing controller procedures. This was claimed to equate to a transition situation. Transition by definition cannot demonstrate the full advantage of the system and procedures being transitioned to. In fact it could be argued that a transition case is often the worst case scenario. Therefore, not surprisingly, this limited the advantage that could be gained by using the tools and restricted their use. In some cases the requirement to carry out both current operational procedures and service the tools actually increased controller workload. The only measured demonstration to make a step in this direction was one of the PHARE Demonstrations, PD/1++, where great circle routes were used and 2 sectors were combined with the traffic increased to 75% above current day, without causing unacceptable increases in workload. [Reference 14.]. A similar approach was taken in the PD/3 Continuation Trial at NLR but this trial was not measured.
2.3.5 Ground - Ground Co-ordination and Layered Planning

One of the major areas of workload in current ATC systems is co-ordination between sectors. One of the major reasons for this co-ordination is the lack of a common information base between controllers in adjacent sectors. Therefore, to simplify current co-ordination procedures, aircraft are transferred between sectors at standard 2D positions and levels. These 3D positions are normally managed using Letters-of-Agreement or Standing Agreements.

In the PHARE concept the systems’ use of the aircraft trajectories provides a common information base to all controllers. This means that controllers can see planning actions by accessing the trajectory well in advance of their sector (See Figure 1 above). The PHARE Layered Planning concept involves a temporal hierarchy of planning actions all based on the aircraft trajectory. The multi-sector planner can take action amending aircraft trajectories by adding constraints up to 30 minutes in the future without the need to co-ordinate with the Planner Controllers as the trajectory constraints will be visible to them.

Planning Authority is assumed by a Planning Controller around 10 minutes prior to the sector penetration by a flight. The Planner is warned if there is a conflict in the planner’s sector by the conflict probe and if necessary accesses the trajectory to add deconfliction constraints. There is no need however for the Planner to have explicit
co-ordination from the upstream sector as the trajectory contains all the data necessary. In the PHARE Concept the current procedures which restrict trajectories to specific entry/exit points and levels and which require explicit co-ordination should not be necessary. Linked to the ability to extend a planner controller’s planning actions into the downstream sector there is the potential to greatly reduce inter-sector co-ordination workload.

2.3.6 Aircraft Equipment

The original expectation was that all aircraft would be Flight Management System equipped to some level with increasing numbers being 4D Flight Management System and Datalink equipped towards 2015. However, to simplify the experimental design the simulations were set up around only 2 major classes of aircraft. The first class contained the fully 4D Flight Management System and datalink equipped aircraft, colloquially called 4D aircraft. The second class were called ‘unequipped’ aircraft, and did not have datalink and were called 3D aircraft. Once taken off their simulated route ‘unequipped’ aircraft were controlled within the simulations as if they were also without Flight Management Systems.

The split into the 2 aircraft classes led to 2 methods of control: datalink negotiation of trajectory with tactical control monitoring but no direct ‘control’ required for equipped aircraft; or, just-in-time commands passed by radio to the unequipped aircraft by the tactical controller based on ‘advisory’ messages either in a time sorted list (PD/1) or as a bottom line on the aircraft label (PD/2 and PD/3). The advisory messages were generated by the GHMI in PD/1, by the Arrival Manager in PD/2, and by the Trajectory Predictor in PD/3.
3. DEVELOPMENT PROCESS

3.1 INITIAL DEVELOPMENT APPROACH

3.1.1 Initial Requirements

As stated in Section 2 an initial PATs set was defined for the year 2000 and the year 2010. The 2010 tools were expected to be close to fully automated. The definition of the tools making up the tool set was very far-seeing and has stood the test of time during the PHARE programme. The tools can be considered in the form of a hierarchy with client tools ‘visible’ to the controller with dedicated HMI and server tools within the system providing the capability to the client tools.

The Client tools are:

a. Arrival Manager
b. Co-operative Tools
c. Departure Manager
d. Problem Solver
e. Tactical Load Smoother

The server tools are:

f. Conflict Probe
g. Flight Path Monitor
h. Negotiation Manager
i. Trajectory Predictor

The tool final reports (Volumes 2 to 10 of this Report) give full context of each of the tools. It is not intended in this report to repeat that detail. However, it may help to put the tools in context if the progression of processing of a flight is followed. This will show the services of each of the tools and their inter-relationships with events. In Appendix B to this report the events involved in processing a simple flight are discussed from receipt of flight plan to touch-down with the entire 2015 PATs toolset.

3.1.2 Model of Services

The PATs Model of services was developed with the PATs Initial Requirements and Planning Document [Reference 3.]. The thoughts at the time the document was developed was that the PATs would become far more automated than was the final case. This was particularly the case with problem solving. However, many of the PATs have or had the capability to be extended toward more automated systems. This will be discussed in the section on each tool.

As detailed in the tool final reports and in Appendix B, the tools provide services to each other and to the platform and HMI. Similarly the platform acts as a classic ATM set of servers to the tool-set, Airspace Server, Radar Server, Meteorological Server etc..

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1 It is conceptually easy to consider the tools in this way. Whether the client server architecture is the best system approach for the tools is discussed below and in the final reports of some of the tools.
3.2 MAIN DEVELOPMENT

3.2.1 User Requirement Documents

Each tool development team raised User Requirement Documents (URDs). These were essentially a functional description of the operation of the tools. The intention was to allow non-technical operators to understand and comment on the capability of the tools.

The URDs for each tool were initially based on the tool that was being developed locally. The documents were then reviewed and commented on both by other PATs teams and by the other PHARE development teams. As PHARE continued the URDs were updated to reflect the different requirements of the demonstrations.

3.2.2 Software Development

Software development was carried out in accordance with local methodologies. In most cases, contrary to the original intent, the teams did not have access to a working CMS compliant platform. Therefore the tools were developed in test harnesses that emulated the expected CMS interfaces.

Maintenance and development of the test harnesses was in itself a considerable task. However, it allowed testing of developments even when the tools to which it was planned to interface were not themselves ready to be tested.

In most cases tools were developed in Ada. The exception to this was the Arrival Manager developed by DLR and subsequently by NATS which was developed in C++. This entailed the provision of C++ libraries and APIs from the Ada CMS. Full discussion of the relative merits of the different languages is outside the scope of this document. There is no doubt that the strong Typing of Ada reduced some of the potential errors in the systems.

3.3 DEMONSTRATION FEEDBACK

3.3.1 Research Aims

Each of the tools started with research aims. However, as the PHARE demonstrations were based on large integrated simulations, it was sometimes difficult to identify the productivity improvements caused by a tool, or the effect of changes to the tool as these were masked by the multiplicity of variables in the demonstrations.

3.3.2 Fault reports and Configuration Management

The Partners all had their own internal configuration management systems and quality plans. However, it became apparent after PD/1 that the PATs Project itself required a similar system. Therefore, the PATs project developed its own internal Configuration Management system which was used to track faults and changes.

During PD/3 development the PATs Configuration Management system was amalgamated with the PD/3 System and held on a Web server at NLR. This allowed for a more effective means of disseminating the faults found and to some extent helped to avoid multiple reports of the same fault.
3.3.3 Functional Changes

At the time the PHARE Project started many of the planned advanced tools were novel. Perhaps one of the less obvious successes of the PHARE Programme was to bring advanced tools into the common place. This is especially true of the graphical Problem Solver which has now become almost ubiquitous. The PHARE tools were thus developed against the future requirements that had been defined in the PMTS [Reference 2.]. As research tools there were many problems in the initial work carried out by their developers and some ideas in the Initial Requirements were abandoned.

The 'Operational' definition of the demonstrations had requirements that sometimes were only partially met even though in other areas they often only used a subset of a tools capabilities. In consequence, the integration phases of demonstrations were 'learning experiences' for both the demonstration project team and for the tools teams. The result was that there were sometimes short notice changes to carry out to allow the operational scenario to work.

3.3.4 Integration Changes

The integration of a complex system is always the area of most risk. With novel tools, platform and GHMI it was also the case in PHARE. In every case the Tools teams exceeded their expected effort in integration. There were 2 main reasons for the integration problems:

a Conceptual mismatch
b Services mismatch.

Conceptual Mismatch. Conceptual mismatch both between the tools and the tools and the other projects was the underlying cause of most of the integration problems as they were only detected at a late stage of final integration when the simulation system was functional. This is discussed in more depth in Chapter 8.

Services Mismatch. There were occasions when the developers of one tool or project expected data to be provided by another where their expectations were not fulfilled. Commonly this occurred when the GHMI or platform services were involved as tools had been developed in test harnesses.

3.3.5 PHARE Tool Documentation

Although developed at different establishments with different standards, each of the PHARE Tools has been documented on similar lines. The documents developed were:

b User Guide. The User Guide documented how the tool was to be compiled and integrated into the ATM System. How the test harness could be compiled set up and run and the expected results.
c Architectural Design Document. Tool developers also provided an architectural design document or its equivalent.
d Change and Fault Report Forms. A change control procedure was put into place for the project. Variants of the forms used were subsequently taken up by PD/3 and made commonly accessible on a web site.
4. TOOL SETS AND INDIVIDUAL TOOL OVERVIEWS

4.1 OVERVIEW CONTEXT

4.1.1 PHARE Tool Final Reports

Each PATs tool project has generated a Final Report. These reports form the volumes 2 to 10 which follow this Volume 1 in the DOC 98-70-18 Series. The documents all have the same general format.

This report does not repeat information which is in each of the tool Final Reports which should be read for more technical detail of the tools, their development and their use. However, it highlights those issues which should be noted especially where these concern integration aspects, both the conceptual and technical, or areas that were found to be difficult in the PHARE Demonstrations and smaller Internal Operational Clarification Projects (IOCP) simulations.

Wherever possible the sections on the tools will follow the same general format:

a Concept(s)
b Integration
c Architectures
d Performance
e Experience in Use
f Further research (Specific to the particular tool)
4.2 TRAJECTORY PREDICTOR

4.2.1 Concepts

The knowledge of the trajectory of an aircraft is fundamental to Air Traffic Management. PHARE gives ‘ownership’ of the aircraft trajectory to the aircraft. Therefore, in PHARE the ideal is that the aircraft Flight Management System generates the trajectory to meet the ground constraints and datalinks that trajectory to the ground system which then uses the aircraft generated trajectory.

The purpose of the ground based Trajectory Predictor is then to allow the ground system to generate trajectories that are close to those that would be expected from the aircraft to allow the controller to model deconfliction and sequencing constraints before negotiating them with the aircraft. The Trajectory Predictor also allows the ground system to generate trajectories on behalf of aircraft that do not have a 4 dimensional Flight Management System or a datalink capability. In the case of these aircraft they will be directed from the ground to keep to the 4 Dimensional trajectory. The directions or ‘advisories’ as they are called are also generated by the Trajectory Predictor and linked to the trajectory.

4.2.2 Integration

The major issue with integrating the Trajectory Predictor was the need to understand how it worked and how it fitted the PHARE Concept. The tool generated trajectories which were those expected to be flown by an aircraft flying with a 4 dimensional Flight Management System. This meant that the Trajectory had a Constant Ground Radius turn of a relatively large radius. Without exception the simulators used in the PHARE Demonstrations were initially based on air radius ‘Constant Bank Angle’ turns. It was sometimes very difficult to obtain acceptance of the problems caused by this mismatch and even more so to get the simulators to change to the track and ground radius turn philosophy. This was despite the acceptance that B-RNAV required this approach and was or would be mandatory in European Airspace.

Each trajectory was expected to have a set of tubes surrounding it. [Reference 7.]. However, the Trajectory Predictor did not generate an ‘error tube’ that continually got larger as required by the philosophy of the Co-operative Tools. Aircraft were expected as a minimum to be equipped with 3 dimensional Flight Management Systems which were only inaccurate in time. The generation of error tubes was dropped for PD/3. Nevertheless, the Problem Solver and Co-operative Tools continued to use ‘error tubes’.

Advisory R/T commands, required for aircraft without datalink, had been generated by the GHMI in PD/1 and by the Arrival Manager in PD/2. After discussion it had been agreed that for PD/3 the most suitable tool to generate the advisories was the Trajectory Predictor. The way the advisories were generated however was relatively simplistic and they were all ‘just in time’ advisories which increased the workload of the Tactical Controller. The GHMI designers had expected to receive ‘Clearance’ type advisories so that the commands could be passed in advance. However, as the Trajectory Predictor had no ‘airspace knowledge’ this proved impossible to produce within the timescales. Also, adding a search for fixes to use would have reduced an already slow performance.
4.2.3 Architectures

The Trajectory Predictor in common with the other tools was embedded in the System Plan Server\(^2\) within the CMS Client-Server concept. The embedding of tools in servers means that they run ‘context free’ and cannot retain trajectory information for reuse. This meant that each time a trajectory needed to be calculated the Trajectory Predictor started from scratch even if the change was a minor change many minutes ahead on the route. The Trajectory Predictor was based on the EFMS Trajectory Predictor which of course always had access to the aircraft position therefore it was not suited to recalculation of a trajectory where the entire constraint list was present but the aircraft had progressed. The effect of calculating the entire trajectory was that the EFMS part of the Trajectory Predictor took longer than necessary and could return errors that were only valid for an aircraft in flight.\(^3\)

4.2.4 Performance

Processing Speed. The ground Trajectory Predictor was based on the EFMS Trajectory Predictor which utilised an aerodynamic model to generate accurate trajectories. Much of the processing of the Trajectory Predictor was iterative. When the Trajectory Predictor requirements for context information were added the Trajectory Predictor could take some considerable time to generate a trajectory. The iterative production of early times for example could take more than 5 seconds. PD/3 included changes to the way environmental data was stored and accessed and in some algorithms improving the response times. [Reference 29.]

Multiple Instances. The PD/3 Continuation Project at NLR ran with up to 9 instances of Trajectory Predictor to remove potential bottlenecks. This considerably improved the performance of the simulation.

4.2.5 Experience in Use

Path Stretch. A path stretch area defined on STARs in which the EFMS made use of flexibility in the 2D route to ensure that the aircraft was very accurate at the approach gate. The EFMS Trajectory Predictor was modified to make use of the Path Stretch area if there was a time constraint on both the Metering Fix and the Approach Gate or if a change in time constraint on the approach gate was made when the aircraft was inside the Metering Fix. This was the only area where the 2D route was varied to meet constraints.

Fixed Order of Flight Phases. The EFMS Trajectory Predictor was based on a fixed order of ‘Flight Phases’. The basic Phases were: Climb, Cruise, and Descent. Within these phases would be ‘Sub-Phases’. However, there were initially some relatively simplistic rules that were applied such as “it is not feasible for an aircraft to enter a descent from a climb phase”. But Climb Phase only ended when the Requested Flight Level had been reached. In PD/1 this led to the occasional aircraft refusing all attempts to make it descend. Therefore, a parameter Flight Level was used after which the Climb Phase was deemed to have ended.

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\(^2\) The System Plan Server would in other systems be called the flight database and contained all the trajectories and associated constraints in the system.

\(^3\) Errors such as ‘Geometry Error’ when given a new flight level constraint 30 minutes ahead as there was a turning point just ahead of current position and a real aircraft could not guarantee to calculate the turn in the time to the turning point.
Advisories. There were two ways of considering advisories: either they were considered to be instructions to be passed by rote without thought by the Tactical Controller, this was the approach in the PD/1 series of trials; or, they were to be used as advice to the Tactical Controller who would apply experience and knowledge to decide whether the advisory instruction should be varied, this was the approach in PD/2. There could be no guarantee that they would be applied precisely at the time that the equivalent vector change would have been carried out by a Flight Management System. This was because both the controller and the (pseudo) pilot had latency in their application. The PD/2 approach where the advisories were treated as a guide by the tactical controllers appeared to be the best approach to just-in-time advisories.

4.2.6 Further Research

Performance. There should be research into algorithms that generate trajectories accurate enough for ground modelling for deconfliction preferably within interactive response times. This would allow the use of the ground Trajectory Predictor inside the Problem Solver and remove the requirement for the ‘Validation’ step.

Advisories. Whilst the ‘just in time’ advisories were used throughout PHARE they make no use of the capabilities of modern aircraft, treating them as if they had no navigational capability. Ideally, it should be possible to generate a flight ‘clearance’ that could be passed by the Tactical Controller on assumption of control of aircraft without datalink. It should be possible to recalculate the trajectory in the less accurate terms of the advisories to be passed by R/T and adjust them to allow for the inaccuracies so that the resultant trajectory is closely similar to the datalinked one.

Route Structures. The Trajectory Predictor should not have any ‘knowledge’ of the semantics or procedures being used. This semantic close coupling, as with insistence on the provision of a STAR, reduces the flexibility of the Trajectory Predictor. The ideal Trajectory Predictor should be able to generate a trajectory given the definition of the departure runway (or current state vector and position) and the arrival runway. There should be no preconceived notion of the constraints that may be applied.

Performance Dependant Constraints. A Trajectory Predictor should be able to calculate performance dependent constraints as would be applied in the instruction “climb straight ahead when passing 5000 feet turn onto direct track for destination”.

Open and Closed loop Controller instructions. Controllers in the trials were still using headings as opposed to tracks this opened the closed gate-to-gate trajectory. The effect of a closed instruction philosophy is that the controller should always be aware of the affect of instructions on the entire trajectory.

CFIT Reduction. Controlled Flight Into Terrain can only occur when the aircrew and/or controller(s) are unaware that the aircraft trajectory passes through terrain (or would attempt to). With continual knowledge of the aircraft total gate-to-gate trajectory and a Conflict Probe that identifies 3 dimensional volumes that are to be avoided, such as terrain, it would be far more unlikely that CFIT accidents would take place.
4.3 **CONFLICT PROBE**

4.3.1 Concepts
Discussion took place on whether there should be new definitions of conflicts. The normal methods of specifying conflicts were geometric. Separation standards are based on rule-of-thumb values that although they have stood the test of time, appear to be unsupported by any valid quantification. Thus the decision that had to be made was whether to have a conflict probe that used *collision risk* rather than infringement of separation standards.

The initial Conflict Probe in PD/1 used the more common geometric approach. In development for PD/3 the probabilistic Conflict Probe was assessed [Reference 22.]. It appeared however, that controllers wanted a clear indication of infringement of the separation standards rather than probabilities of collision. With the current ATC rules probability of collision is not a useable approach.

Conflict detectors need to assume that all aircraft will follow their trajectories within a specified margin of accuracy. The PHARE concept is based on feedback loops to ensure that aircraft actually *do* follow the trajectory that they have agreed with the ATM System. This allows the Conflict Probe to operate with a long look-ahead. The limitation of the look-ahead is due to uncertainty rather than potential inaccuracy.

In PD/1 the ACOD approach to ‘nominal path’ algorithms was used. In PD/2 this was continued but with the addition of wake-vortex separation. In PD/3 there was the addition of probabilistic algorithms and the CP was extended with services to support the Departure Manager in probing for conflicts with different parameters and to support tools during what-if modelling. [Reference 22.]

4.3.2 Integration
Conflict Probe integrated well at software level. However, there were some mismatches in identification of a conflicts between the Conflict Probe and the Problem Solver and Cooperative Tools which had their own conflict detection algorithms.

The Departure Manager in PD/3 used an additional service limiting the length of probing to a parameter time. This improved performance and allowed the Departure Manager to operate without having to parse out conflicts outside the terminal airspace.

4.3.3 Architectures
The Conflict Probe was developed as a ‘Conflict Server’. The requirement was to operate on every new active trajectory and on alternate trajectories ‘sent’ to it from tools during what-if modelling.

4.3.4 Performance
The performance of the Conflict Probe was naturally affected by the size and number of the trajectories compared. Some changes were made to limit the probing carried out ‘on request’ by allowing an ‘end time’ to the probing.

4.3.5 Experience in Use
The Conflict Probe was intended to be the sole tool identifying conflicts between trajectories. However, the Co-operative Tools and Problem Solver both had conflict detection algorithms. These algorithms were different to that used by the Conflict Probe. The effect could be that the Conflict Probe could show a conflict but when the controller went into the Problem Solver the conflict did not show, or vice versa. By PD/3 the tools had been more closely matched and it was rare for conflicts in one tool not to show in the others.

4.3.6 Further Research

The consistency of conflict detection and alerting is one of the major elements of trust in the system. The ideal would be that all methods of detecting separation infringements produce the same results. One way of doing this would be to use the Conflict Probe as the basis of the Problem Solver conflict detection. The Problem Solver was required to be interactive and had its own algorithms for conflict detection. It would be useful to research the use of the Conflict Probe algorithms within the Problem Solver as one approach to removing the inconsistencies.

Separation Standards need to be researched rather than taken as immutable constraints on capacity and illogicalities caused by differing separation standards either side of virtual airspace boundaries should be removed. Separation standards could for example be replaced by acceptable levels of collision risk this would be an area for research that may allow for a more logical approach to separation than the current symmetrical geometric standards. If separations could be safely reduced airspace capacity could increase or controller workload be reduced.
4.4 CO-OPERATIVE TOOLS

4.4.1 Concepts
The major concept of the Co-operative Tools was that of filtering the information for the controller to allow rapid assimilation of the air traffic situation. The difference in approach of the Co-operative Tools was that of identifying areas of 'interactions' these were areas that would be of interest to a controller where for example there was a risk of a conflict although there was no actual loss of separation. The tool then put these 'interactions' and the conflicts into PROblem SITUations (PROSITS) which were displayed on an agenda time line with levels of seriousness indicated. This approach allows the work of the controller, or controller team, to be more efficiently managed.

The Co-operative Tools approach was geared to the 2 controllers for a sector working more as a team rather than the hard temporal split that was envisaged in the layered planning concept of the PMTS [Reference 2.].

The Co-operative Tools were to some extent self contained and had within them a problem solving system based on the ability to provide look-ahead along modified trajectories.

4.4.2 Integration
Co-operative Tools as the name suggests was actually a set of tools in its own right. Some of these could be replaced by the normal PATs.

The Co-operative Tools were very visible to the controller through the Activity Predictor Display and this required close interactive integration with the GHMI.

4.4.3 Architectures
The Co-operative Tools were a set of servers in their own right that interfaced with the central CMS servers. When moved to a non-CMS environment such as the ESCAPE platform at EEC these servers were all encapsulated within one Cooperative Tools 'object'.

4.4.4 Performance
The Co-operative Tools could run functions at the sector level or as a central server. The Interaction Detection Function (similar in function to the Conflict Probe) was run at the Sector level to improve performance.

4.4.5 Experience in Use
The Co-operative Tools were only used during the CENA PD/3 Trial. The basic concept of the Co-operative Tools was the sharing of workload whereas layered planning requires the controllers on a sector to work separated temporally. The Planner therefore had to be able to revert to current time to assist the tactical controller.

4.4.6 Further Research
There is a need to research the procedures for the use of the Co-operative Tools in particular the sharing of workload. It may be that the PMTS approach could be
feasible if the Tactical Controller was able to retrieve more information on trajectories from the system than was the case in PD/3.

As with the Problem Solver there is a need to research the use of the Co-operative Tools in the terminal airspace where algorithms to detect conflicts and interfering aircraft which work well in the en-route case are less efficient due to the manoeuvring of aircraft on approach or climb out.
4.5 PROBLEM SOLVER

4.5.1 Concepts

The Problem Solver developed in the PATs did not provide solutions independent of the controller. Instead it provided an entirely novel interactive graphical interface that allowed controllers to model deconflictions and then issue the trajectory constraints to apply them. The graphical interface allows the controller to display a trajectory graphically then amend the trajectory by dragging its constraints with a mouse pointer. Conflicts are shown as ‘avoidance zones’ on the screen and as the trajectory is interactively amended the conflicts are updated in almost real-time to show the affect on the conflicts of the amendment to the trajectory. Controllers found the use of the Problem Solver was intuitive and it rapidly became the tool by which PHARE was known. (See Figure 2)

![Figure 2: Example of Highly Interactive Problem Solver GHMI](image_url)

The amendments to the trajectory can be made in all dimensions. The 2D amendments were made on a Plan View Display (or Horizontal Aid Window). In the PD/3 variant the Problem Solver Plan View Display was overlaid on a filtered radar display. The trajectory is amended in altitude in the same way by dragging with the mouse in an elevation display (or Vertical Aid Window). In the early versions of Problem Solver, time amendments were made in a time window by dragging a
trajectory in the slow direction or the fast direction. The PD/3 version abandoned the
time window that was difficult to envisage and instead used a drop down menu for
minutes to delay or expedite. The tool is fully described in [Reference 27.] and
[Reference 19.]. Although the Problem Solver was closely integrated with the GHMI
the GHMI was not part of the tool.

The Problem Solver was a developed in PHARE as a totally new concept.
Understandably, there were some conceptual and usability issues that required more
explanation to the controllers. These were:

a Constraint Editing not Trajectory Editing. The PHARE concept is based
on the aircraft generating a trajectory which meets ground constraints. The
way those constraints are met is therefore an aircraft issue. However, the Problem Solver needs to generate a trajectory and assess it
for conflicts interactively. The early Problem Solver effectively allowed the
controller to edit the trajectory and drew straight lines between point
constraints. Whereas the Trajectory Predictor in the ground system and
EFMS would apply rules and aerodynamic performance criteria. Thus
there was a 'quick and dirty' interactive trajectory used to resolve the
conflict, followed by a call to the Trajectory Predictor for a trajectory that
was realistic for the aircraft.

b Conflict Detection Algorithm. The Problem Solver used a totally different
system for detecting and displaying conflicts. Use of parameters in the
Conflict Probe and the Problem Solver largely resolved these mismatches.

c Trajectory Validation. As stated above the Trajectory Predictor trajectory
used parameterised rules and aircraft performance to calculate a
trajectory to meet the constraints generated by the Problem Solver. In the
PD/1 version of the Problem Solver the generated trajectory occasionally
did not match the Problem Solver trajectory requiring a rework of the
solution. However, the PD/3 Problem Solver employed a simple
approximation for aircraft performance and used the same rules for
constraints and climbs/descents as the Trajectory Predictor. The result in
PD/3 Continuation at NLR was that the Problem Solver developed as an
en-route tool was useable even in the terminal area where aircraft were
manoeuvring.

d Amendments affecting Other Sectors. In current systems the sector
controllers treat the 'entry and exit conditions' of the aircraft as a formal
agreement with the adjacent sectors. This is because it is generally the
only reliable point of reference for the co-ordination and safe hand-over of
the flight. There often an area of common interest in which both sectors
work but the boundary of responsibility is firmly set. This concept was
made a Problem Solver requirement by the demonstration teams. The
consequence was that the virtual entry and exit points on the trajectory
were treated as firm 4D constraints and the Problem Solver ensured that
the controller could not operate any trajectory edits outside his sector.
This was repeatedly commented on by controllers who felt that the
limitation was unnecessary [Reference 14.]. In PD/3 this and the Problem
Solver allowed controllers to amend a trajectory anywhere. (The
Negotiation Manager checked the subsequent trajectory for
'infringements' that is changes that would affect adjacent controllers, and
suggested co-ordination with the infringed controllers.)
4.5.2 Integration

The main integration issues were conceptual in that the algorithms for conflict detection were different from those of the Conflict Probe and the Co-operative Tools. By PD/3 these tools were returning very closely similar results despite their differing algorithms.

The Problem Solver was very closely integrated with the GHMI. In PD/1 and the associated trials and in PD/3 at CENA the Problem Solver was integrated into the GHMI and almost ran as part of it. In the PD/3 at EEC and NLR the Problem Solver was linked to the GHMI by a high speed ‘pipe’. The performance of the link to the GHMI demonstrated the extreme demands that interactive tools are placing on the modern workstation displays. The Problem Solver was coupled to 2 main display types in the various PHARE Demonstrations:

a. **Highly Interactive Problem Solver.** The Highly Interactive Problem Solver (HIPS) display had a set of 3 windows, Plan View Display (Horizontal Assistance Window), Elevation Display (Vertical Assistance Window) and Time Display.

b. **Trajectory Editor and Problem Solver.** The Trajectory Editing and Problem Solver (TEPS) had an elevation display but the time and 2D window were displayed on the main radar picture Plan View Display. The name Trajectory Editor and Problem Solver indicates that the philosophy of Constraint Editing was not fully understood.

4.5.3 Architectures

As stated above the Problem Solver was closely coupled with the GHMI to the extent that in PD/1 and associated demonstrations the Problem Solver was integrated into the GHMI. The Problem Solver has a separate ‘Problem Solver Core’ that actually carries out the algorithmic processing identifying no-go areas and conflicts, and editing the constraint lists. This core part held a redundant copy of the system trajectories in Problem Solver format to allow the response time of the system to be met.

4.5.4 Performances

From the controller point of view the Problem Solver was an interactive tool. As the mouse dragged a trajectory point across the screen the Problem Solver was required to generate a new trajectory, draw it, re-identify all conflicts and redraw the appropriate no-go zones without any perceptible delays. This placed considerable demands on the GHMI. System performance bottlenecks were resolved by using multiple instances of the Trajectory Predictor and multi-threading the Negotiation Manager.

4.5.5 Experience in Use

**Highly Interactive.** The Problem Solver in its PD/1 implementation was called the Highly Interactive Problem Solver. It was found that some controllers had difficulty achieving the deconfliction of aircraft before they had entered their sector. Some of this was due to the relatively short look-ahead that was available in PD/1 which was caused by the imposition of tactical handover rules to the planner. It is important for this kind of tool for the planner to be able to identify flights that require deconfliction far enough away for the deconfliction action and associated negotiation to be completed before sector entry. PD/1 was a learning exercise in this regard.
Trajectory Editor and Problem Solver. The Trajectory Editor and Problem Solver was the name given to the implementation of the Problem Solver in the PD/3 GHMI. Instead of a separate Problem Solver PVD on which to carry out problem solving, the Trajectory Editor and Problem Solver used the main ‘radar picture’ PVD and overlaid the Problem Solver display on it.

Problem Solver and Maneuving. The Problem Solver algorithms are based on a set of parallel alternative tracks being plotted either side of the aircraft track and the conflicts with each potential track being plotted as a no-go zone [Reference 27]. These algorithms work well in relatively constant velocity flight but they become more complex in maneuvering flight. This complexity is added to in the Terminal Areas where the separation standards are varying and the ‘interfering aircraft’ are also maneuvering. Not only the algorithms were complex but also the GHMI display of no-go zones became very difficult with re-entrant maneuvers. Thus the Problem Solver was designed for use in en-route airspace. Many changes and improvements were made to the Problem Solver for PD/3, in particular the use of constraints and the aircraft performance data were amended to closely follow the Trajectory Predictor methods. This made the Problem Solver suitable for the NLR PD/3 Continuation that simulated the Schiphol TMA.

4.5.6 Further Research

Maneuvering Traffic. The Problem Solver algorithms should be developed further to be able to cater successfully with maneuvering traffic both in accurate detection of conflicts and in the GHMI methods used to display them.

Constraint Types. Currently controllers use instructions such as “clear to resume own navigation” or “no altitude restriction” these ‘open’ instructions were difficult or impossible to use on the Problem Solver GHMI which required explicit changes to the trajectory. The GHMI would need to be developed to allow a more complete repertoire of instructions from the controller including the ability to input rates of change of vector.

Suggested Deconfliction Solutions. Often when the Problem Solver was displayed to controllers they requested that the tool suggest potential solutions. Perhaps parameterized with controller preferences. Although this is an area that merits further research it should be noted how easy and intuitive the controllers found the Problem Solver to use. (Note: In the PD/2 scenario in which there was no HIPS there was a simplistic problem solver within the Arrival Manager, which ran transparently. The controllers were unaware that the trajectories had been deconflicted as the trajectory constraints were modified automatically while the aircraft was still outside the sector. Whilst this may be a philosophical issue, it did not appear to cause any problems to the controllers and was not commented on during the demonstration [Reference 11].)

Controller Techniques and Procedures. The use of a Problem Solver where the precise deconfliction is carried out for the sector well in advance of the aircraft flight through the sector, is novel. It is apparent from comments in CENA PD/3 that it is important that the information on the deconflicted trajectory, sometimes called the ‘sector transit plan’ is available to the Tactical Controller. As was found in PD/2 and PD/3 at NLR if the trajectories are marked with the vector changes then this is often enough to keep the Tactical Controller informed. The actual use of the Problem Solver is a matter of skill. The Problem Solver is easy to use, but at the same time to use it well requires some finesse. Standard Operating Procedures perhaps be identified and the controllers trained in them. This was the case in PD/3 Continuation
at NLR in which inbound sequenced aircraft were not varied in heading, to reduce impact on the sequence, whereas outbound climbing aircraft were not varied in level or restricted in climb, to reduce fuel use and engine cycling. These areas require more detailed research if good use is to be made of the Problem Solvers in future systems.
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4.6 NEGOTIATION MANAGER

4.6.1 Concepts

The Negotiation Manager manages the electronic dialogue between sectors for coordination and between the sectors and the aircraft for Trajectory Negotiation. As stated above the PMTS expected the advanced systems to be ‘silent’ with no R/T or telephone verbal exchanges necessary. However, there was some discussion on the impact of this on control procedures.

The Negotiation Manager used the concepts of ‘Planning Authority’ and ‘Control Authority’. [Reference 4.]

a Control Authority. Control Authority is passed from Tactical Controller to Tactical Controller, sector by sector successively along the aircraft trajectory. This ‘ownership’ was enforced by the Negotiation Manager.

b Planning Authority. Planning Authority was intended to be passed successively from Planner Controller to Planning Controller in the same way as control authority. The planning by Arrival Manager sequencing and Multi-Sector Planner had been allowed for by letting the Arrival Manager and the Multi-Sector Planner controller put constraints on flights at any time to be added to the constraint list for the flight. These constraints would be negotiated at the next Trajectory Negotiation or at a parameter time. However, there was considerable planning overlap between Sector Planning Controllers with the extreme being the Arrival Sector Planner who in IOCP and PD/3 trials at NLR often completed planning for arrivals before the extended TMA Planning Controller commenced planning. In view of this the Negotiation Manager did not enforce rigid ‘Planning Authority’ instead it was left to the controller procedures.

Ground-ground co-ordination is one of the major workloads on a control position. In current systems this workload is increased as sectors proliferate as their size is reduced to bring the tactical controller ‘control’ workload within acceptable limits. There is therefore a trade-off between the co-ordination workload and the control workload. The Negotiation Manager would reduce the ground-ground co-ordination workload by automating some aspects of it. However, the co-ordination requirements are different if all the controllers have access to the common information base provided by the 4 Dimensional Trajectories. The Negotiation Manager could enforce controller-controller inter-sector co-ordination if the ‘entry exit conditions were changed’ or if there was a conflict caused in another sector. To do this the Negotiation Manager made checks if a trajectory was amended to see if there was an alteration in another sector or if a conflict had been caused in another sector. If so the Negotiation Manager suggested co-ordination with the ‘infringed’ sector(s). However, controllers preferred the decision on coordination to be left to them as the ‘human-in-the-loop’. In the PD/3 Continuation Trial the checks for infringement were bypassed and the Negotiation Manager only proposed co-ordination if a trajectory amendment caused a conflict in an adjacent sector. This improved performance and caused no problems for the controllers. [Reference 15.] [Reference 10.]

The air-ground trajectory negotiation dialogue was managed by the Negotiation Manager. The Negotiation Manager initially was requested to enforce a rigid layered planning passing ‘planning authority’ successively to sectors along the route based
on time and sequence. However it was found preferable to allow the planner of any sector penetrated to plan if the aircraft was within a parameter time of the sector boundary.

There were several differing levels of Trajectory Negotiation. If the full normal Trajectory Negotiation is carried out the process is certain to take time due to the involvement of the pilot, who has to assess the trajectory generated by the Flight Management System and the Controller who would assess the response. These could be shortened by either pilot or controller with the pilot using ‘Pre-empted Negotiation’ effectively sending a datalink message to the ground system which was the trajectory actually now being flown by the aircraft. It was foreseen that Trajectory Negotiation over datalink was for the Planner Controller with the Tactical Controller carrying out changes using R/T which would be followed with datalink updates from the air or the ground. [Reference 4.] [Reference 6.]

4.6.2 Integration
As the focal point through which all trajectory update requests and aircraft negotiations take place the Negotiation Manager was an important tool to integrate. The Negotiation Manager would receive inputs from the Trajectory Predictor, Arrival Manager, Departure Manager, GHMI and the aircraft (via the PATN) and would use the Conflict Probe and platform services to check for infringements with other sectors. [Reference 26.].

The Negotiation Manager was amended in PD/3 Continuation at NLR to also drive the GHMI label states and completely automate the handover of 4D Flight Management System and Datalink equipped aircraft.

4.6.3 Architectures
The Negotiation Manager in PD/2 was a very simple tool which was only involved in Trajectory Negotiation. Even in this the tool was simplified and fitted to the particular peculiarities of the simulation set up. Nevertheless, the simplified tool was integrated into the CMS/PARADISE platform on which the PATs ran in PD/2. This was also the case in the PD/2+ exercise at NATS ATMDC.

In PD/3 the Negotiation Manager was a complete tool managing both ground-ground and air-ground negotiation and co-ordination.

4.6.4 Performances
During PD/3 it was found that single threading the Negotiation Manager could lead to delays. Multi-threading the Negotiation Manager reduced these delays and allowed the trajectory amendments to be issued without requiring the controller to await a response before continuing.

A more radical approach was adopted for the PD/3 Continuation where the Negotiation Manager only checked for, and alerted the controller to, conflicts caused by the new trajectory, all other checks were bypassed. The effect of this change was that trajectories that did not cause conflicts were automatically accepted. The performance gains were such that the numbers of aircraft in the system did not appear to have any affect on the Negotiation Manager performance. Operationally the effect was to allow the PD/3 Continuation scenario to become even more ‘free routed’. This did not appear to have a deleterious affect on the control of traffic although there were no formal measurements.
4.6.5 Experience in Use

As stated above the normal trajectory negotiation process could become prolonged. The Negotiation Manager did give controllers the option to override or ‘force’ the negotiation. Similarly the trajectory negotiation with the aircraft could be sent as a ‘Formalised Clearance’. The intention of these functions was to allow trajectory amendments when there may not be time to carry out full negotiation or co-ordination. However, given the capability controllers seemed to habitually carry out ‘Forced’ co-ordination or negotiated as a ‘Formal Clearance’ to shorten the negotiation procedure. This could indicate that there is scope to simplify the Trajectory Negotiation procedure. Nevertheless, it would be counter-productive to only provide ‘formalised clearance’ as this would be reverting to full control of aircraft rather than to the User Preferred Trajectory approach espoused in the Strategy for ATM2000+.

4.6.6 Further Research

In some respects the Negotiation Manager is central to the PHARE concepts as it is the tool that integrates the aircraft and ground system. Whilst there was trajectory negotiation in all PHARE Demonstrations, only the PD/3 Trials were run with the complete fully functional Negotiation Manager with the complete repertoire of negotiation types. There is no doubt that there should be further research in this area. The areas for further research in the Negotiation Manager should include:

a Trajectory Negotiation Procedures. The PHARE Procedures worked and kept the ‘human in the loop’. Other candidate solutions should be trialled and assessed. This must be in a global context and this could lead to a less sophisticated but globally achievable approach.

b Crossing Negotiations. Negotiations ‘cross’ when both the aircraft and the ground initiate a negotiation simultaneously. Whatever system is used for trajectory negotiation there are bound to be instances of crossing negotiations. It is not a complex issue and similar problems occur in all data communications but rules will need to be agreed to handle these instances.

c Ground-Ground Co-ordination. It was initially envisaged by the PATs tools that this co-ordination aspect would be reduced to a minimum as downstream planning controllers had all the information required for planning provided by the aircraft trajectories. When co-ordination is required with a free-route trajectory it should be far easier to present it graphically to the other controller for assessment. This area needs further study quantifying the differences with more formal entry / exit condition coordination.

d Planning Authority and Overlap. There are times when more than one controller wishes to plan or amend a trajectory. This may be the arrival planner setting an arrival time constraint, the multi-sector planner adding a ‘flow’ constraint 30 minutes in the future, or even sector planners where the aircraft trajectory penetrates several sectors within a short time4. The sequential or otherwise transfer of planning authority was not enforced in PD/3.

4 This often results in sector ‘skipping’ in practice with controllers passing traffic to the sector beyond the next sector. It would probably be unwise for automation to attempt to enforce this aspect.
e Missed Approach Negotiation. It was argued that missed approach negotiation could be considered as a pre-empted negotiation from the aircraft. However, there are aspects of the control of missed approaches such as resequencing for the next approach that require negotiation from the Tactical controller within the sector rather than to the planner that make it a special case.
4.7 FLIGHT PATH MONITOR

4.7.1 Concepts
The Flight Path Monitor could automatically trigger a new trajectory if there was a significant deviation. However, the controller might want the aircraft to return to the original trajectory. The ‘human centred approach’ would mean that the controller or pilot should be the one to decide if a trajectory was to be updated. In consequence it was decided to drop the requirement for the FPM to automatically trigger a new trajectory.

Progression. The FPM when monitoring the progress of a flight, could mark the trajectory points passed as a progression marker on the trajectory. If there was no deviation this was actually redundant as the point on the trajectory corresponding to present time was the current progression point. If the aircraft was deviating it would be unsafe to guess where the aircraft was progressed. Except perhaps to mark points that had been overflown within capture distance. However, this is not a simple matter as when an aircraft is manoeuvring identification of whether the aircraft is cutting the corner on a turn (ahead) or deviating (behind) depends on knowledge of the future trajectory. In PD/2 it was often noted that aircraft could show a continually increasing ‘late’ deviation which suddenly became an ‘early’ deviation as the apex of the turn being cut short was crossed.

Progression of Constraints. The progression of constraints on the trajectory was not a simple matter as constraints could be applied at one point and be valid for the entire trajectory whereas others were limited to only the position they were implied. (for example: “Climb to and maintain FL240” is a closed constraint that does not need to be progressed. “pass <fixname> at FL240 by” is a constraint that can be progressed). Many of these issues display the great flexibility that there is in the current R/T procedures.

4.7.2 Integration
The Flight Path Monitor had no specific integration problems. The Flight Path Monitor integration with the GHMI was the difficulty in displaying unambiguously what the deviation was. When Ground Supported Navigation initiated on a deviation there was a need to show the controller that the advisories were from the Flight Path Monitor and not standard Trajectory Predictor advisories. These problem areas were not researched in detail and remains an area that could be further researched.

4.7.3 Architectures
The Flight Path Monitor was integrated as a ‘Progression and Significant Point Server’ within the CMS System.

The Flight Path Monitor was one of the tools that had its own ‘redundant’ copy of the system plans. This was to ensure that the performance of the tool was satisfactory.

4.7.4 Performances
The Flight Path Monitor had no performance problems even in the more complex simulations where the ‘radar server’ was passing large numbers of positions.
4.7.5 Experience in Use

The Flight Path Monitor is an important component of the closed loop concept of PHARE. If an aircraft deviates outside the contract tube then the Flight Path Monitor will raise a deviation alert. On receipt of this alert the controller can either correct the aircraft to the agreed trajectory or amend the trajectory in the ground system to match that actually being flown by the aircraft. However, despite its importance, the GHMI representation of the deviation alerts only indicated that there was a deviation. On the PVDs this normally consisted of some kind of highlight on the aircraft position symbol, on the Arrival Management Displays it consisted of an early or late indication.

4.7.6 Further Research

In PD/3, the Flight Path Monitor had a full Ground Supported Navigation facility for aircraft deviating linked to the equippage and performance of the deviating aircraft. This was capable of generating advisories to recover the aircraft to its negotiated trajectory. However, the set-up of the demonstrations was such that it was never used in any realistic way.

One of the candidate concepts in PHARE was the GARTEUR concept of allocation of large manoeuvre space to aircraft to allow the aircraft freedom to choose an optimal trajectory within that manoeuvre space. In PHARE as the aircraft was allowed to generate the optimal trajectory first and then a ‘contract’ tube was generated around it. The idea of the contract tube, or more precisely a 4 dimensional bubble, was to allow the aircraft a degree of freedom in its guidance to allow it to be smoother and more economic. Whilst the GARTEUR concept was abandoned, the initial intention was that the contract ‘bubble’ could be varied in size dependent on the phase of flight and the ambient traffic levels. The Flight Path Monitor would have been the tool adjusting the parameters. However, within PHARE this research was not carried out and the parameters were kept at default values throughout. [Reference 7.]
4.8 DEPARTURE MANAGER

4.8.1 Concepts

The Departure Manager schedules and sequences departures to balance the load on runways and improve the traffic flow in the terminal airspace. A runway is allocated and a Scheduled Time of Departure (STD) generated as soon as an initial trajectory is available. The Departure Manager not only takes safe separation into account but also the allocated CFMU slot, if any, and the surface movement constraints on the airport. The Departure Manager provides the Departure Planning Controller with optimised and conflict free trajectories.

The Departure Manager bases its initial planning on fixed Standard Departure Routes but they can be varied. The Departure Planner accesses the Departure Manager through a dedicated Departure Manager Display.

Figure 3: Departure Manager Display

4.8.2 Integration

The Departure Manager was integrated successfully with the CMS based PD/3 platform at CENA where it used the services of the Negotiation Manager and Conflict Probe. The use of the Conflict Probe was tailored to restrict the probing of what if trajectories to the boundary of the Terminal Airspace.
4.8.3 Architectures

The Departure Manager was integrated as a client tool. It interfaced with the System Plan Server, the Negotiation server and the Conflict Server.

4.8.4 Performances

The Departure Manager itself had no problems with performance. However, the Departure Manager required the Trajectory Predictor to produce many trajectories and then the Conflict Probe to check for conflicts on each of them, this sometimes caused delays in the TMA Function of the Departure Manager.

4.8.5 Experience in Use

The Departure Manager was used in PD/3 at CENA where the 2 Westbound runways were simulated. Although apparently content with the basic sequencing capabilities controllers felt that it would have been useful to be able to reallocate departure runways after pushback. This is not feasible due to the runway and taxiway layout, but it was requested nevertheless.

Controllers felt that a what-if functionality for alterations after pushback would have been useful.

4.8.6 Further Research

Departure Manager and Arrival Manager integration. There is a need to research the interaction between arrivals and departures on the same runway using the PHARE time based sequencing. The capability was in the Departure Manager and the hooks were in the Arrival Manager but these were never really exercised. In PD/3 at CENA there was no arrival manager but there was a ‘frozen’ arrival sequence that was held in the Approach Server which the Departure Manager used as a basis for its sequencing. There is also the issue of Departure Manager to Arrival Manager relationships from the departure airport to the arrival airport. This is likely to be significant in Europe where the departures are usually within an hour of arrival at take-off. A significant delay in for arrival should translate to a delay on take-off.

En-route Integration. Departing traffic should be integrated in an orderly and efficient way with the en-route traffic flows. This would entail impact on the departure sequence due to the availability of cruise levels for example. This would probably have less importance in free-route operations.

CFMU Slot Priorities. The aircraft with CFMU slots were given priority for scheduling in the CENA PD/3 exercise as it was felt that the use of the Departure Manager could increase the proportion of CFMU slots that were successfully used. However, there was the question of the prioritising of aircraft without a CFMU slot. The criteria that were used rigidly in PD/3 could lead to excessive delays.

Take-off Precision. The area of take off precision and the associated integration with surface management is one that needs considerable research. Whilst controllers accepted the premise that PD/3 was a simulation and therefore would have a level of unreality, they found the idea that aircraft would take off within 30 seconds of a Scheduled Time of Departure difficult to accept. It is certainly not the case in the
current systems. However, the PHARE concept is dependent on aircraft flying accurately on their 4D trajectory and the deconfliction of departures was also based on this accurate flight along the trajectory. The issues here are:

a **Surface Management.** Currently there is no real attempt at precision in surface management although tools are becoming available. If the Departure Manager provides push back time with ETD and STD times a suitable taxi-time period later, then the ground controller should be able to make those times. This is not required with current systems but that does not mean it is infeasible.

b **Deconfliction of Departures.** Most airports have a climb out procedure enforced by noise abatement regulations. This would normally be expected to extend around 3 – 5 miles and to about 5000ft or 1 – 2 minutes flying time. Provided that the climb area is kept clear of other traffic there should be sufficient warning to adapt any deconfliction. In fact this was the situation in PD/3 as there was limited warning to the departure tactical controller.

**Free Routing.** The Departure Manager worked using a catalogue of Standard Instrument Departures. After the initial noise abatement climb it is possible that the standard departures that normally extend to the terminal manoeuvring area boundary could be shortened and a more free routed approach taken from then on. There needs to be quantification of the effects of free routing in managed airspace and the positioning of the boundary between free and fixed routes.
4.9 ARRIVAL MANAGER

4.9.1 Concepts

The Arrival Manager is primarily a sequencing tool that balances the load on the runways. However, the major difference between the PHARE and the ‘classic’ arrival managers is that the PHARE Arrival Manager is based on the concept of a 4 dimensional trajectory. This means that aircraft are given a precise landing time and not a landing sequence. Although the effect is to sequence aircraft the implications of this approach should not be underestimated. Aircraft sequenced to a time should tend, on average, to land closer to that time as the variances of aircraft ahead will not propagate back along the arrival stream because each aircraft is aiming to land at a time rather than solely maintaining a separation from the aircraft ahead. The lack of propagation reduces the probability of conflicts being caused in the Extended TMA phase due to a delayed aircraft in the arrival stream causing all the other aircraft in the stream to delay, or be delayed, to maintain separation.

The cost of this 4D trajectory approach is that there needs to be a feedback correction to any deviations to ensure that aircraft stay within a close tolerance of their 4D trajectory. There is also a more stringent requirement on Tactical Controllers to keep aircraft without 4D Flight Management Systems on their trajectory. In the real world this should only be a matter of time correction.

The Arrival Manager controlled the sequence by setting a time constraint on the approach ‘gate’ a position around 10nm finals. This arrival constraint was added to the constraint list for the flight ensuring that the time constraint would be applied at the next trajectory negotiation. This meant that aircraft would be affected by the arrival constraint set at every trajectory negotiation. In the gate-to-gate scenario this means that before departure the arrival constraint is already being considered. This approach tends to even out peaks in traffic, it is less efficient if the constraint is only applied when the aircraft are close to the terminal airspace.

In the PD/2 exercise the Arrival Manager also included a simple automated deconfliction system. This reduced although it did not remove conflicts in the terminal airspace. In PD/3 it was decided that automated deconfliction was not in line with the ‘human in the loop’ philosophy. (Although it could be argued that sequencing is itself deconfliction.)

The current approach to sequencing in the terminal airspace is based around metering the traffic flow into the TMA to reduce the pressure on the arrival management. To this end the Trajectory Predictor had the Metering Fix Time and level constraints coded into it. However, with 4 dimensional trajectory control it is unnecessary to have a metering fix constraint. In both PD/2 and PD/3 the Arrival Manager ran without setting Metering Fix time constraints unless it required to hold the aircraft.

The Arrival Manager carried out continual sequencing and re-sequencing as the it received each trajectory change. The automated re-sequencing is frozen to present a stable sequence to the controller when the aircraft is at the planning horizon which may be flexibly set a parameter time from the top of descent or from the Metering Fix at the TMA boundary.

The initial PD/2 Arrival Manager used the Trajectory Predictor capability to provide the earliest and latest arrival times at a fix to assess the maximum expedition or delay that an aircraft could accept. This had a time penalty due to the iterative method used by the Trajectory Predictor to calculate these values. Moreover, an
aircraft expedited has less flexibility available for any en-route deconfliction. The early time achievable when the initial calculation is made is likely to be unachievable by the time any negotiation takes place while there is no limit to late times as the aircraft can hold. For this reason the Early/Late time calculation was abandoned and the ETA taken as the earliest time for the aircraft.

The Arrival Manager in PD/3 also contained a Stack Manager which calculated conflict free levels and occupancy times for use by subsequent trajectory predictions. The Trajectory Predictor would only produce a hold at the Metering Fix and the Stack Manager allocated levels in the hold to separate aircraft providing descent times.

The Arrival Manager could be linked to a Collaborative Decision Making (CDM) system if necessary.
4.9.3 Architectures
The Arrival Manager in PD/2 was split into two parts a standalone sequencer and a platform interface part this was to facilitate the interfacing to the ATMOS simulator and this architecture was continued in PD/2+. However, in PD/3 the Arrival Manager was rebuilt into a single entity.

4.9.4 Performance
The PD/3 Arrival Manager needed to be restricted in the depth to which it attempted to re-sequence and load balance the runways. Without this restriction the Arrival Manager was taking extreme times (sometimes up to minutes) to reassess sequencing in response to trajectory updates due to the large number of potential runway sequences.

The re-sequencing of many flights could cause a significant load as there is a cascade of events caused by the new trajectories in the system. This was ameliorated in NARSIM by the use of multiple instances of Conflict Probe and Trajectory Predictor.

4.9.5 Experience in Use
In PD2 the AM was run without allowing manual intervention. Although this was due to delays in the building of the operational system, it did allow more consistent measurement of the introduction of the Arrival Manager functionality without the variance caused by Arrival Planner Controller inputs. It is interesting to note that despite meaning complete automation of the arrival sequence this approach was well accepted by the controllers.

In PD/2 the inbound traffic was frozen on entry to the simulation. This was at around 80 to 90 nm from finals. In PD/2+ the experiment was repeated with a PD/1 version of the Problem Solver being used in the ETMA. The traffic was assumed to be a normal sample. This caused considerable problems as the peaks were not smoothed by trajectory control from a long way out.

In PD/3 at NLR the Arrival Manager was provided with trajectories from around 200 miles distant. The timing of the traffic was from the standard peak day traffic sample from EEC but increased to 2010-2015 levels by the addition of traffic mainly from regional airports which led to an arrival/departure rate of approximately 40 aircraft per hour per runway with 5 runways operating. The traffic was all free (direct) routed to the STARs for Schiphol. The trajectories of arrivals were 'live' from about 200 miles out allowing the time constraint of the scheduled time of arrival to be taken into account early. Unlike PD/2+ this method did not lead to unmanageable peaks of traffic nor were stacks in continuous use. This would indicate that trajectory control is more effective when considered on a gate-to-gate basis rather than as a short range solution. However, the exercise was merely a technology demonstrator and a formal measured run would be necessary to be certain of the results.

4.9.6 Further Research
Formal Measured Trials. Although PD/2 was a measured trial of arrival management it was very focused and included no exceptions and only unintentional perturbations\(^5\). The more competent systems developed for PD/3 have not been exposed to formal

\(^5\) Such as mistakes by the pseudo pilots.
trials and measurement. Lack of capacity in the terminal airspace is one of the major issues facing Air Traffic Management. It is essential that full measured trials of the advanced 4 dimensional concepts are carried out, in realistic simulations, in order to quantify what improvements, if any, can be provided in capacity, efficiency and environmental impact.

Exponential Instability. The problems of operating multiple re-sequencing Arrival Managers in a fixed route environment need to be researched. There is a potential risk that the system could become exponentially unstable. The scenario could be for example that a deconfliction action is taken in the en-route area that forces a re-sequence in one or more Arrival Managers, the re-sequencing causes changes in the en-route trajectories of several aircraft causing more conflicts, the subsequent deconfliction action causes more re-sequencing and so on. Whilst there is a similar effect in free-routed environments it is less pronounced as these environments have far less conflicts in the en-route airspace. Also generally there is not the same tendency to have streams of aircraft which tend to create 'overtaking conflicts' when there is a re-sequence.

Expedition or Requested Time of Arrival. The re-sequencing of aircraft was based on the tenet of not expediting aircraft which was compatible with the User Preferred Trajectory concept. This allowed a margin of flexibility to deconfliction as an aircraft that was running to its earliest achievable time would always force a re-sequence if deviated for some reason as it would no longer be able to make the arrival time. This could be a matter for Collaborative Decision Making where re-routes or expedition could be agreed with AOCs.

Automated Stacks. As far as the tools are concerned an aircraft in a stack is following a 4D trajectory in the same way as an en-route aircraft. The Stack Manager applies the specific stack rules and the EFMS Trajectory Predictor generates the correct number of turns and the correct rates of descent. For a controller, however, a stack is a procedure that requires cautious handling. It was sometimes difficult to sell the concept of a stack with mixed 4D and datalink traffic and 3D traffic needing advisories. The idea of aircraft commencing descent automatically in a stack, albeit on a cleared trajectory was difficult for controllers to accept. The Stack Manager was adjusted to slightly alter the descent times in that a 4D aircraft would only descend after the aircraft below it in the stack had attained a level two levels lower. In manual stacks the aircraft are cleared down as soon as the aircraft below vacates the level one lower. Putting all aircraft in the stack under 'manual' control negates all the trajectory negotiation and would be counter-productive. In the PHARE long term layered planning concept stacks should be avoided. However, they will undoubtedly occur so the control of stacks needs research to confirm that the procedures are safe and efficient.
4.10 TACTICAL LOAD SMOOTHER

4.10.1 Concepts

The Tactical Load Smoother was seen as the tool for the Multi-Sector Planner. The original concept of the Multi-Sector Planner was that the aircraft with 4 Dimensional Flight Management System and datalink would be planned over several sectors whereas less capable aircraft would be planned as currently over the smaller sectors. In the PMTS [Reference 2.] this was seen as the split between ATFM and Air Traffic Control. The intent was to allow the complexity of the traffic to be reduced as far as possible in advance to avoid the ‘ad hoc’ resolution of conflicts the tactical controller. It was foreseen that the complexity of the traffic could be reduced limiting the number of conflicts to be solved by ATC to an acceptable level. Within the PD/3 demonstrations the Multi-Sector Planner was more akin to a real time Flow Manager than a precise planner of 4D Flight Management System and Datalink equipped aircraft.

Once aircraft are airborne their trajectories may be influenced by many external factors. It is therefore possible for complexity to develop in sectors potentially overloading the controllers even after CFMU filtering of the flight plans. The Tactical Load Smoother would identify such hot-spots up to 45 minutes in advance allowing the Multi-Sector Planner to take action to simplify the ATC requirements.

The concept behind the Tactical Load Smoother was therefore to identify complexity and provide a means to the Multi-Sector Planner of reducing that complexity to a level that meant the workload in the sectors was kept at an acceptable level. The first part of this concept was achieved to some degree. The second part of allowing interaction with the traffic flows was not except by the use of the Problem Solver interface to interact with individual flights.

Complexity was assessed by amalgamating measures of several factors:

a. Number of aircraft
b. Number and complexity of conflicts and conflict probability density
c. Mix of different speeds of the aircraft
d. Mix of different rates of climb and descent
e. Number of changes of vector
f. Aircraft equipment levels
g. Proximity to sector boundary
h. The sector transit times of the aircraft.
i. The uncertainty of the aircraft actually achieving their trajectories the forecasting period ahead
These measures were then taken and converted into a coefficient of complexity (the process is given in full mathematical detail in [Reference 28.]). The complexity was then displayed as a coloured ‘contour map’ on a PVD. It was also displayed as a line graph in an adjacent window. This allowed the Multi-Sector Planner to identify peaks of certain types of workload move the display time backward or forward to the peak and assess where that peak occurred on the PVD. The Tactical Load Smoother allowed a query to the graphical interface to display the aircraft that were planned to be in the area selected at the time selected. This would allow the Multi-Sector Planner to amend the trajectories of those aircraft as necessary to reduce the complexity of the sectors.

4.10.2 Integration

The Tactical Load Smoother was successfully integrated onto trials platforms at EEC and run under an EEC IOCP [Reference 9.]. Although, it was not run during the main PD/3 Trials the Tactical Load Smoother was designed to be platform independent within a ‘client server’ environment.

4.10.3 Architectures

The Tactical Load Smoother was internally set up as a requester-server set of processes. The Core was served by Time, Airspace and Traffic Servers and output its results to a Sector Load ‘client’ and a Map ‘client’. The interface to the platform was via a ‘wrapper’ which encapsulated the Tactical Load Smoother.
4.10.4 Performances

The Tactical Load Smoother was extremely computationally loaded. Ideally it would operate each time there was a new trajectory in the system. This initially took a considerable time. The algorithm and architecture used was amended and this increased the efficiency considerably.

The ideal is a routine update of the GHMI every minute with updates on each new trajectory. Although this sounds relatively straightforward, it has not been exposed to the very large number of changes that may be occurring when a full centre with several Arrival Managers and Departure Managers are running concurrent with pilots and controllers amending trajectories. This will be an area for future research.

4.10.5 Experience in Use

The Tactical Load Smoother in the IOCPs was used with a Look Ahead Display which was more akin to a normal radar picture. The tendency was for controllers to revert to type and start solving conflicts rather than reduce complexity. It was felt generally that conflicts were given too much weight in the complexity coefficient.

From the work in the IOCP it was apparent that the techniques used by the controllers had significant impact on their own and the Sector Planners’ workload. So whereas some controllers tried to clear or simplify individual conflict areas, others would just fan or spread the traffic to reduce the complexity, which as a side effect reduced the number of conflicts.

Exception Management will only reduce the controller workload if the number of exceptions is small and less than the workload from direct control. However, by definition exceptions cannot be forecast. The Layered Planning concept with Multi-Sector Planning allows the Multi-Sector Planner to reduce the number of exceptions that a sector will have to deal with and reduce the complexity of the traffic so that exceptions that cannot be foreseen 30 minutes into the future are easier to handle. It is probable that exception management will need some kind of Multi-Sector Planner to ensure that the Sector controllers are not overloaded by peaks in complexity.

4.10.6 Further Research

Controller Procedures Techniques. If the Tactical Load Smoother is to be used it will be necessary to identify the most efficient controller procedures and techniques. As was stated above there would appear to be several approaches that could be taken. What is needed is a way of quantifying them to identify the most useful and efficient technique from the System point of view.

Complexity Coefficient Details. The measures of complexity and their conversion to the subsequent amalgamated coefficient need more research. It was thought in the IOCP that perhaps too much weight was being given to some conflicts and some other values. This led to the possibly simplistic idea of the ‘single troublesome aircraft’ that could be re-routed and all problems solved.

Multiple Edit Capability. The Tactical Load Smoother did not achieve the planned full capability which was to include an SQL-like query on an area followed by a multiple edit being applied to all flights meeting the criteria of the query. This approach could have considerably reduced the workload of the Multi-Sector Planners. However, the application of a multiple edit to a set of dissimilar trajectories would require research into the many differing implementation possibilities.

Workload Reduction by Multi-Sector Planner. The Multi-Sector Planner activity is to ensure that the workload of the Sector Controllers remains safely achievable. With
tools changing the work of the controllers to become more exception management, the workload is dependent on the traffic samples and the number of unforeseen exceptions. It will be important to demonstrate that the presence of a Multi-Sector Planner creates a safer system that is easier to manage at the Sector level. Research is needed not only into the Multi-Sector Planner procedures and controller techniques, but also into the metrics and validation methodologies.
5. USE OF TOOLS IN THE PHARE DEMONSTRATIONS

5.1 PHARE DEMONSTRATIONS (PDs)

5.1.1 PD/1

PD/1 was the first main PHARE trial and was of the en-route airspace [Reference 8.]. A limited subset of tools and the procedures used were more based on current controller procedures rather than on 'advanced' procedures. The tools used were the Trajectory Predictor, Problem Solver as HIPS, the Flight Path Monitor and the Conflict Probe. Simplified trajectory negotiation was carried out by bespoke software over a Mode-S link there were no bandwidth or delay problems as a simplified data object was sent from the EFMS to a peer EFMS process in the ground system.

PD/1 was very successful. However, it indicated that a lot of work needed to be done on the controller roles and the controller procedures and practices. The controllers were allowed to act only within their sector and this was enforced by coding in the Problem Solver. Furthermore, the Planner Controllers were only given access to plan on a flight when it was 'forced' to them by the upstream Tactical Controller. This meant that there could be insufficient time to carry out deconfliction. The effect sometimes led to planner controllers still attempting to 'plan' a flight through the sector after the flight had already entered.

a) Trajectory Predictor. The Trajectory Predictor was a wrapped version of the EFMS Trajectory Predictor.

b) Problem Solver. The Problem Solver was used in PD1 for the first time as the ‘Highly Interactive Problem Solver’. It had three windows for amending the trajectory of aircraft one of which was its own Plan View Display called the Horizontal Aid Window.

c) Flight Path Monitor. The Flight Path Monitor was used in PD/1 but as the Trajectory Predictor generated climbs did not match the Air Server generated climbs (the Flight Path Monitor treated the air server as a radar server) the Flight Path Monitor continually reported deviation in level. The display of level deviations was therefore inhibited in the GHMI, reducing the effectiveness of the Flight Path Monitor.

d) Conflict Probe. The Conflict Probe was used in its ACOD form.

e) Advisories. It should be noted that unlike PD/3, the advisories were generated by the GHMI in PD/1 and displayed in a message window rather than as part of the label.

5.1.2 PD/2

PD/2 was a trial of the Approach phase of flight. The tools were limited again to the PATs Set originally expected for the year 2000 by the PMTS, that is the Trajectory Predictor, the Flight Path Monitor, the Conflict Probe, the Negotiation Manager and the Arrival Manager. The Arrival Manager was the only 'client' tool and the only interaction with the system. In the PD/2 Project inputs through the AMD were inhibited to give a more stable picture of arrival management and this meant that the trial in the advanced phase was almost completely automated.
Another aspect of automation that was 'descoped' after much discussion was the automated recovery of a 'Class A' aircraft to its trajectory after a deviation. It had been intended that when a large deviation was identified by the Flight Path Monitor which would make the aircraft become Class B (i.e. controlled by advisories) it would trigger a trajectory negotiation to 'recover' the aircraft into a Class A status. However, the re-negotiation could also cause the arrival sequence to be adjusted. It was also felt that controller freedom would be removed as the system would always be trying to recover the aircraft if it was directed away from its trajectory for a legitimate purpose.

**Trajectory Predictor.** The Trajectory Predictor in PD/2 had to operate in the more exacting regime of the TMA, which gave little scope for changes. Some issues that arose were:

a. **Standard Descent Rate.** The Trajectory Predictor always assumed a standard almost flight idle ideal descent rate. This meant that if constraints were imposed the trajectory generated did not make good a descent through each constraint, instead it formed a series of steps. The approach procedures were modified to remove all the altitude constraints. This led to aircraft flying higher and faster in the TMA area than normal but this would lead to more efficiency and less environmental pollution. It also reduced the controller workload.

b. **Wide Ground Radius Turns.** The STARs in PD/2 were defined with constant bank-angle turns in mind. However, aircraft flying ground radius turns have a far larger radius turn.

c. **Early Late Times.** The PD/2 Arrival Manager sequencing depended on defining how early or late aircraft could be. This gave a time-period within which the aircraft could be sequenced. However, due to the very short trajectory length from the ETMA boundary to the Top of Descent it was often the case that the trajectory generation for an aircraft scheduled for its early-time would fail. To avoid this the Arrival Manager was amended not to schedule the aircraft to its early time but to a time a parameter time later.

**Flight Path Monitor.** The Flight Path Monitor was used by the Arrival Manager to identify when aircraft passed certain significant points. It was also used to display any deviation of the aircraft in time on the Arrival Management Display. One issue that was shown up by the Arrival Management Display was the effect of an aircraft cutting a corner where the delay indication suddenly became an early indication.

**Conflict Probe.** The Conflict Probe was used by the Arrival Manager for indication of conflicts in the TMA. The Conflict Probe did not filter the conflicts apart from the application of a height filter to provide differences in separation standards. The Conflict Probe expects the client tool to carry out any more intelligent filtering such as aircraft trajectories for approach to parallel runways.

**Negotiation Manager.** The Negotiation Manager in PD/2 only managed the air-ground negotiation. For simulated aircraft the Air Server used the already generated trajectories and reflected them back to the Negotiation Manager with a built in simulated delay to match that achieved in the real aircraft. However, the Negotiation
Manager coped well with the live ATTAS aircraft which flew in the trial. A direct VHF telemetry link was used and there were no bandwidth or delay problems.

**Arrival Manager.** The Arrival Manager was the only client tool in the system. Unlike the PD/3 Arrival Manager the PD/2 version as well as sequencing and load balancing also carried out deconfliction of arrival traffic. This was transparent to the controllers. Despite the simplistic approach of the deconfliction which was limited to level constraints, the high traffic sample which was difficult for the controllers to handle was almost completely deconflicted by the Arrival Manager. The PD/2 Project made the decision not to allow the Planner Controller to amend the Arrival Manager generated sequence. This reduced the risk of trajectory generation failures and also removed the variability of results that could have occurred if controllers had ‘played’ with the sequence. The declared aim of the simulation was to see how accurately aircraft could be controlled to land at their Scheduled Time of Arrival not to assess the planning capability.

**Advisories.** It should be noted that in PD/2 the **Arrival Manager** generated the advisories by parsing the trajectories in the flight server. The advisories were then displayed as a highlighted area of the Track Data Block or Label. The advisories were also marked on the trajectory if it was displayed with a highlight indicating the position of the next advisory when it was within 30 seconds.

### 5.1.3 PD/1+

PD/1+ was a rerun of the PD/1 exercise but with attention given to the controller roles. The tools and issues were the same as the PD/1 exercise although the simulation was carried out at NATS ATMDC. [Reference 12.]

### 5.1.4 PD/2+

PD/2+ was a rerun at ATMDC of the PD/2 trial. The intention of the PD/2+ trial was to make the PD/2 scenario 'more realistic'. The trial included the Problem Solver instead of the Arrival Manager based deconfliction. The Arrival Management Display was also made active to allow the Planning Controller to amend the schedule if required. The trial was also split the stack areas (stacking had not been used in PD/2) into automated stacks for 4D aircraft and those for 3D non-datalink aircraft.

Apart from the Arrival Manager which was a modified version of the PD/2 Arrival Manager the remaining tools were those that had been used in PD/1+. However, there were considerable problems. [Reference 13.]

- **Problem Solver - Trajectory Predictor Incompatibility.** The Problem Solver team had stated that the PD/1 version Problem Solver was not designed for use in the TMA. It had a simplified approach to aircraft performance. The trajectories generated by the Problem Solver were therefore almost always different to those that were generated by the Trajectory Predictor for the same constraints where aircraft were rapidly changing vector as in descent in the ETMA. Therefore it was not feasible to use the Problem Solver to carry out deconfliction.

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7 This was notable as the only trial in PHARE where a Partner carried out trials of an airport that was not in their area.
b Strategic Time Constraint. The PHARE concept is based on long look ahead and whole flight trajectories. The traffic sample input to the PD/2+ system was based on 'live' traffic into Frankfurt. The sample was given to the system for the Arrival Manager to sequence at just before the ETMA boundary. The extreme traffic peaks that are normal part of current day operations and lead to stacks to buffer the traffic and meter it into the TMA would have been smoothed before arrival at the boundary by the long look ahead concept. The PD/2 Arrival Manager could not cope with these peaks.

Thus the PD/2+ trial showed up many of the difficulties foreseen by PD/3 and some that had not been. The tools subsequently developed for the PD/3 trials took these issues into account. What was indicated strongly was the requirement to match the controller techniques and the procedures, to the tools.

5.1.5 PD/3

PD/3 was intended to be run at 3 sites; CENA, EEC and NLR. Each of these sites had differing simulator architectures. The CENA and NLR architectures were CMS type and the EEC architecture was based on a CORBA platform called ESCAPE. The approach of these platforms to tool integration was also different.

5.1.6 PD/3 at CENA

CENA PD/3 had a DAARWIN platform which was completely 'CMS compliant'. The CENA Trajectory Predictor rather than the PATs Trajectory Predictor was used.

The PHARE tools used at CENA were:

a Co-operative Tools. The PHARE Co-operative Tools were used for the first time in the CENA PD/3. The Co-operative Tools did not use the Conflict Probe for conflicts but rather its own internal conflict detection system.

b Conflict Probe. The Conflict Probe was only used to provide conflict information to the Departure Manager. There was no link to the other parts of the system. The Conflict Probe worked with no internal performance problems but the system slowed when the Departure Manager requested multiple trajectories. However, although the Departure Manager tool had knowledge of the conflicts these were not displayed to the Departure controllers until the aircraft was airborne; leading to a reactive deconfliction rather than the PHARE long term planning approach. [Reference 15.]

c Departure Manager. The Departure Manager was used for the first time in the CENA PD/3 demonstration.

d Flight Path Monitor. The Flight Path Monitor was used both for its significant point service and for deviation alerting

e Problem Solver. The Problem Solver used at CENA was a variant of the PD/1 Problem Solver. The display was also somewhat different with the altitude window displayed on a supplementary screen. However, as with all the PD/3 trials the Problem Solver was displayed as an overlay on the live radar screen and called the Trajectory Editor and Problem Solver TEPS.
f. Negotiation Manager. The Negotiation Manager was used 'wrapped' into a Negotiation Manager Server and was single threaded. To this end a special version of the Negotiation Manager had been developed for CENA.

5.1.7 PD/3 at EEC

To integrate the tools in the EEC ESCAPE platform they were modified with new EEC defined interfaces. Apart from the Departure Manager the tools were integrated successfully. The processing caused by the Arrival Manager sequencing and re-sequencing could create a significant load and sometimes overload on the ESCAPE platform. This was due to the cascade of Inter Process Messages and events. It should be noted that only one Arrival Manager was operating and there was no Departure Manager. In a real world case where there could be multiple Arrival Managers and Departure Managers the load on the system would be considerable. In any case, due to the missing GHMI no PD/3 trials were performed at EEC.

5.1.8 PD/3 at NLR

The NLR NARSIM System was developed using CMS compliant APIs and integrated the tools without significant difficulties. The PD/3 at NLR was run was as an unmeasured demonstration called the PD/3 Continuation Trial [Reference 17.]

Whilst the lack of measurement was disappointing it also meant that the tools concepts could be more literally applied than in the measured runs where the concentration was more on transitional issues, retaining current sectors and controller practices.

The delay to the trial and its organisation as a small focused sub-project, also allowed the lessons from the other PD/3 exercises and from PD/2+ to be assessed and reassessed. This led to a considerable number of improvements to the tools.

The tools used by PD/3 at NLR were:

a. Arrival Manager. The Arrival Manager was modified to reduce the 'depth' of sequencing greatly reducing the load on the system. The stack manager was integrated into it. The Arrival Manager was also integrated into a completely new Arrival Management Display allowing the TMA Planning Controller (who planned both arrivals and departures even at nearly 200 per hour) to modify arrival times and runways. The early-late time approach of PD/2 to assessing the sequencing possibilities of an aircraft was abandoned. In its place it was assumed that the Estimated Arrival Time was the earliest time of arrival, this allowed leeway to the en-route ATM systems to deviate an aircraft without necessarily forcing a re-sequence. An aircraft could be delayed by almost any amount but too much delay would cause the aircraft to enter a hold/stack at the Metering Fix.

b. Problem Solver. The Problem Solver was integrated in its TEPS form but again developed in a completely new GHMI. A considerable amount of effort was made by the Problem Solver team to match the Trajectory Predictor philosophy and use the same performance model. The result was that the trajectory created by the Problem Solver modelling and that generated by the Trajectory Predictor were almost identical.
c Negotiation Manager. The Negotiation Manager was considerably modified from that of the PD/3 trial at CENA. The main changes were:

i The Negotiation Manager was multi-threaded and thus allowed asynchronous calls to its service. This meant that the system did not slow down waiting for the Negotiation Manager to finish servicing requests. However, it also meant that the controller could be required to return to an aircraft after working on others.

ii An associated issue was the reduction in checking of the downlinked trajectory by the Negotiation Manager. The only check that was retained was that for conflicts. If a downlinked trajectory had no conflicts it was accepted by the Negotiation Manager. This was also the case for unsolicited downlinks of trajectory changes from the aircraft. The rationale was that the controller is only required to act on conflicts. This approach considerably reduced the controller workload without apparently affecting their capability to solve those conflicts that did arise.

d Flight Path Monitor. The Flight Path Monitor was integrated and provided the Significant Point service to the Arrival Manager and the Deviation service to both the controller and the Arrival Manager. The intention of the Flight Path Monitor was that it could provide advisories to the Tactical Controller of a deviating unequipped aircraft to allow the controller to recover the aircraft to its trajectory.

e Conflict Probe. The Conflict Probe was integrated normally, but to reduce a perceived performance bottleneck the Conflict Probe was integrated as multiple instances of Conflict Probe.

f Trajectory Predictor. The reduction in Trajectory Predictor size and resource requirements allowed the use of multiple instances of the Trajectory Predictor rather than one. This led to a considerable performance improvement.

5.1.9 PD/3 Concepts

The PD/3 Demonstration at CENA used the tools within the framework of current airspace structures and current controller practice and task sharing. This along with considerable system problems which reduced the information on trajectories displayed to controllers caused the controller workload to increase.

The PD/3 Continuation Trial at NLR made many procedure changes including free routing and reduction or removal of altitude constraints. Furthermore, controllers were briefed that the task of the Planner Controller was to solve conflicts whilst the Tactical Controller was to ensure that aircraft without datalink followed their conflict free trajectories. There was no requirement to ‘plan every aircraft’ nor was the Tactical Controller required to make R/T contact with 4D and datalink aircraft. The Negotiation Manager only required controller input if there was a conflict and only initiated co-ordination if there was a conflict in an adjacent sector. Whilst this is a very large conceptual change from the current controller practice, it greatly reduced controller workload and appeared to improve the quality of service to aircraft.
5.1.10 PD/1++

In the same way as the NLR PD/3 trial had amended procedures with the intention of making better use of the tools PD/1++ also altered procedures. In this measured trial the airspace and control procedures were modified with a view to making full use of the tools. The tools were updated in some respects in that the Trajectory Predictor was the PD/3 Trajectory Predictor but otherwise the PD/1 tools were re-used.

The trial design in PD/1++ was not intended to identify the advantages of the tools rather it was to look at the effect of alteration in airspace structure and aircraft routings and procedures. The simulation used several airspace and procedure variants but the same tools were always available. Therefore, it was not possible to identify the impact of using the tools from measurements in the simulation. However, combining 2 sectors, using great circle routes and increasing the traffic sample to 75% of current day, did not cause unacceptable increases in the controller workload.
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6. TOOL INTEGRATION ISSUES

6.1 INTEGRATION PLATFORM

The PATs are not standalone tools they require the services of the other PATs to work successfully. The teams therefore used test harnesses and test files ensuring that the input data matched what was thought would be coming in events from the platform and the other tools. Subsequently, it was found that the workstations were not, in any case, able to support all the tools and platform services neither was there a suitable GHMI for the client tools which were the drivers of the system. Consequently, although the workstations provided a suitable intermediary platform to confirm the tools' portability, they could not fully replace a stable platform running the entire toolset with a suitable GHMI. This meant that the first time the tool-sets could be fully integrated was on implementation on the demonstration platforms.

6.2 TOOL TO TOOL INTEGRATION

There were 3 levels on which tools would need to be integrated:

a) Technical Integration
b) Functional Integration
c) Conceptual Integration

The order in which the integration was considered was very much that above. As stated several times in the individual tool final reports, the conceptual integration should have been carried out prior to any work. The conceptual differences were not always apparent due to the widespread use of homonyms and synonyms.

Technical Integration. The technical integration of the tools was relatively straightforward. The CMS APIs created a common ground and method for integration.

Functional Integration. The functional integration of the tools had two aspects the actual usage of information from one tool by another, and the meaning of the data sent from one to another. The major issue was the actual usage of the information and associated assumptions. For example the Conflict Probe team assumed that the subscribing client tool would filter the conflict events as necessary. As in the case of the PD/2 Arrival Manager which had filtered out ‘conflicts’ reported on aircraft on final approach to the same runway separated by sequencing. However, initially this led to the occasional problem with other client tools of the Conflict Probe accepting conflict reports at face value. There was also the issue of functional overlap where for example the Co-operative Tools used an internal conflict detection server rather than use the Conflict Probe; or the more commonly commented Problem Solver using its own conflict algorithms rather than the Conflict Probe.

Conceptual Integration. There were conceptual mismatches which caused integration difficulties. Examples here were the Trajectory Predictor based on the concept of 4 dimensional windows or constraints through which a trajectory would be generated by the aircraft, whereas the Problem Solver was based (until PD/3 at NLR) on the idea of 4 dimensional points.
6.3 CONFIGURATION MANAGEMENT

The PATs had a configuration management system although with different teams under their own configuration management at their site the imposition of an external Configuration Management system was not always easy. However, it became very apparent during PD/3 with multi-site operations that a central configuration management system was needed for all Projects. This was eventually set up on a web site at NLR.
7. FURTHER RESEARCH

7.1 DEPARTURE AND ARRIVAL

7.1.1 Sequence Manager

It is possible to link the Arrival Manager and Departure Manager for a runway through a Runway or Approach Server ‘object’ which owns the runway sequence. The inter-relationship of arrival and departure managers also needs to be extended to the interaction between the Departure Manager at the departure airport to the Arrival Manager at the arrival airport. This is particularly the case in Europe where there are a large number of short haul flights where aircraft are in the arrival sequence almost as soon as they depart.

The PHARE Departure Manager used the Approach Server to hold the runway sequence. The initial intent had been that the Departure Manager and the Arrival Manager would be linked through the intermediary of the Approach Server. The Approach Server would then have been the source for the GHMI to show the sequence for the runway.

The Departure Manager would pass a rate of departure to the Approach Server which would pass a maximum arrival rate to the Arrival Manager. If there were no departures there was no restriction on the Arrival Manager. However, should a controller allocate a future departure to the runway the Arrival Manager would receive the reduction in landing rate. This would mean that any runway could be multi-mode without any software change.

Given that the arrival rate over a 15 minute period allowed for say 5 departures, then when a request for pushback was received, the Departure Manager would identify a position in the arrival sequence more than 10 minutes into the future and this would be passed to the Arrival Manager from the Approach Server. The Arrival Manager would expedite the aircraft scheduled to land before the departure by a ‘forward limit’ parameter, and retard the aircraft landing after the departure by a ‘backward limit’ parameter. Thus a departure ‘slot’ would be inserted into the arrival stream. The surface management system or ground controller would then have the task of ensuring that the departing aircraft was at the holding point as the departure slot ‘flew past’.

When the decision was made that PD/3 would not have a single multi-site gate-to-gate demonstration, but rather would be 3 separate demonstrations, the Arrival Manager to Departure Manager link was abandoned. CENA ran an unconnected Departure Manager and NLR ran a similarly unconnected Arrival Manager. However, this linkage is an area for future research as all runways are potentially multi-mode, even if only in exceptional circumstance.

7.1.2 Local Departure Manager to Remote Arrival Manager

Most flights in European airspace are of short duration with an average of 40 minutes to an hour. The arrival sequencing could often include aircraft that are not yet airborne. This would especially be the case in extreme delays. This raises problems of uncertainty of times and impact of Scheduled Time of Arrival time constraints on departure sequencing. It was plain that in the real world, the sequence of the remote Arrival Manager would need to be managed and linked in some way where close departures could interfere with already sequenced longer flights. However, the linkage was dropped as something to be considered in PHARE.
Another area for research is the interference between trajectories being amended by Arrival Managers at closely located airports and similarly those being amended by Departure Managers. It can be postulated that the entire system could become exponentially unstable\(^8\). The Arrival Manager in PHARE actually damped this instability by only negotiating changes to STA when there was a large alteration required.

The issue of Arrival Manager and Departure Manager interactions especially with multiple airports is one that must be researched further.

### 7.2 FULLY PROBABILISTIC CONFLICT PROBING

Aircraft are currently separated by 'separation criteria' that define a cylindrical volume around the aircraft (for example: 5 miles radius of the aircraft, 1000 feet above and 1000 feet below). The actual sizing of these separation criteria has not been justified; it is just "the way things have always been done". The reasoning for the criteria being larger in the en-route phase is apparently to allow for the operation of a corrective feedback loop (i.e. radar sensor - controller alert - controller action - pilot action - radar sensor). However, this would infer that conflicting aircraft were allowed to penetrate the cylinder defined by the separation criteria provided that corrective action was taking place. This is not the case. Controllers treat the cylinder described by the criteria as sacrosanct to the extent that an unofficial avoidance parameter is often added to the official\(^9\). The effect of these approaches to separation is to reduce airspace capacity.

The Conflict Probe team investigated a different approach to separation which was based on the probabilities of collision between 2 aircraft. This probabilistic approach however gave an accurate varying measure rather than a simplistic black and white answer. Unfortunately, it was felt that controllers would not accept a varying chance and instead the boolean approach based on geometric separation criteria was used.

It is important for controller trust that conflict detection is understandable. A Conflict Probe that provided a probabilistic approach combined with the simplistic geometric approach is likely to be the best method. Controllers already use the separation criteria in trail but deconflict far earlier for aircraft in a head-on conflict.

The entire area of separation and conflict/loss of separation needs to be researched. However, with the current regulations and concerns on safety there may not be the freedom to research all the areas in a scientific way.

### 7.3 TEMPORAL ISSUES – TOOLS AND LAYERED PLANNING

The guidance accuracy of the EFMS and the Flight Path Monitoring guidance allow problems and conflicts to be corrected by relatively minor changes a long period

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\(^8\) Example of this is a deconfliction action en-route delays an aircraft causing a re-sequence. The re-sequencing itself generates more than one conflict. The deconfliction action on these conflicts cause more re-sequencing etc. This fear was expressed in PD/2+ as "the Arrival Manager could be required to solve the entire system". It was for this reason that damping parameters were included to reduce the number of negotiations from the Arrival Manager.

\(^9\) This is sometimes termed the 'snitch patch' as automated systems now report the infringement of separation criteria to the ATC management.
before the problem or conflict occurs. The Tactical Load Smoother in PHARE was providing information to the Multi-Sector Planner up to 40 minutes in the future. The Planner Controllers using the Problem Solver were expected to start deconfliction action on aircraft 10 minutes prior to sector penetration, perhaps up to 30 minutes prior to the conflict. Only the Tactical Controller remained working in 'current time'. Thus there was a distinct and sometimes large temporal split between controllers.

There were 3 areas of further research into temporal issues:

a. Human Factors and task sharing.
b. Sufficient display of flight information
c. Handover of planning and control responsibility

Human Factors and Task Sharing. Controllers from some of the partners were more used to a team approach to problem solving. The explicit splitting of tasks was therefore contrary to their normal working methods to which they reverted when busy, abandoning the tools. The tools were also judged against criteria that foresaw the team approach to problem solving when some were designed to be more efficient with a layered approach.

Sufficient Display of Flight Information. The Trajectory Predictor generated trajectories and the downlinked trajectories carried a plethora of information. The constraints were also all stored in detail. However, the display of the information was often insufficient. In PD/2 and the NLR PD/3 the trajectories were marked with the vector changes so controllers could see where level changes, turns and speed changes would occur. Where this information was available the controllers did not experience any 'operational gap'. There were similar problems with the Flight Path Monitor which gave full details of deviation to the HMI and client tools, but the HMI reduced this information to a highlight of the aircraft position symbol. There needs to be some formalised research on how much information needs to be continuously displayed and what information should be available on request.

Transfer of Planning and Control Responsibility. The concepts of planning and control authority and their transference were defined. However, there were issues raised during the PHARE Demonstrations that worked well, but more due to controller flexibility than by design. Such issues as the Arrival Sector Planner having Planning Authority for sequencing before the Extended TMA Planner receiving planning authority for deconfliction. In the event, the Negotiation Manager which had been intended to enforce transfer of authority, would accept any inputs leaving the transfer of planning authority to controller practice. This gave the controllers freedom to invent their own approaches to out-of-sequence planning.

7.4 TRAJECTORY TRANSMISSION TO NON-4D AND DATALINK AIRCRAFT - ADVISORIES

The PHARE 4D Control concept is based on the accurate guidance of an aircraft along its agreed, deconflicted, 4D trajectory. An aircraft with a 4D Flight Management System and datalink will have the precise trajectory in its Flight Management System and an identical copy of the trajectory will be held in the ground system for the Flight Path Monitor and for the controller to monitor.

For an aircraft without datalink, the details of the trajectory that the ground system has deconflicted need to be transmitted to the aircraft. This was done by the Tactical Controller with control authority passed each successive vector change to the aircraft by R/T. This method of passing advisories takes no account of the potential equipage of the aircraft, which could even be equipped with a 4D Flight Management
System but without datalink. Ideally, the advisories could be collated into a 'clearance' that would then be input into the aircraft Flight Management System. Creating a clearance in terms that can be passed by R/T to the pilot is not a simple operation and the tool to carry it out needs both knowledge of the trajectory, the airspace structure and the fixes available for use (which may vary with aircraft equipment). The generation of clearances is an area that requires further research.

7.5 ADVISORIES AND CPDLC

It would be possible for the ground system to 'read' the advisories and automatically issue them over a Controller Pilot Datalink Communications (CPDLC) link to the pilot. This would reduce the controller workload and would be visible to the controller. However, it raises many issues and would require further research.

7.6 TOOL SETS

The PATs made a complete set of tools that were capable of interworking successfully. However, there were some overlaps. For example in some ways the Co-operative Tools was capable of standalone operation. Furthermore, the various trials and demonstrations ran without a full set of PATs. This would indicate that it is possible to some extent to provide automated assistance to differing levels by mixing and matching the tools.

The requirement for automated support varies considerably dependent on traffic mix and density. There should be research into the correct mixes of automated support tools or tool-sets for each type of region.

7.7 TECHNIQUES FOR USE OF AUTOMATED SUPPORT TOOLS

The use of automated support tools requires a different way of working by controllers. Put simply "Automated tools can only reduce workload if controllers let them do some of the work.". However, allowing tools to carry out some of their tasks means that controllers have to alter their normal tasks when they are using the tools. Moreover, the tools have different techniques for their successful use. Whilst the demonstration projects gave training in the use of the tools there was no iterative attempt to find the best way to use them.

There is an urgent need to identify the best way to use automated support. There are many issues to solve and the techniques can often be counter intuitive from a controller's point of view. Ideally there should be an R&D exercise measuring the quality of service and controller workload against each candidate technique so that validation with a formally quantified approach can be carried out on each suggested technique and practice.

7.8 CONTROLLER PICTURE AND AUTOMATED RESPONSES

The NLR PD/3 exercise was carried out with the Negotiation Manager providing automated acceptance of downlinks that were conflict free. The controller 'big picture' did not seem to be hindered by this although there were no measurements of the impact. However, the workload of the controller was reduced and the speed of negotiation was increased. There is some degradation of the detail of the controller picture with this approach although this did not appear in this case to cause detriment.
In the longer term perhaps responses that are conflict free but different to that expected, and unsolicited trajectory changes that are conflict free, could be highlighted to the controller in some way by GHMI so action to intervene could be taken if required.

This is another area in which there needs to be research. The need for a 'continual accurate big picture' in the controllers' heads is the major capacity restriction in the ATM System. It should not be accepted *de facto* without testing of alternate concepts.

### 7.9 MEASUREMENT AND METRICS

The major issue in the area of measurement was that the tools were being assessed against the 'airspace capacity' which in turn was being assumed to be equivalent to the 'controller workload'. Controller workload with tools that allow exception management would not appear to be a valid measure of airspace capacity. It will be influenced by the number and detail of the exceptions to be handled and with the training of the controller in the use of the tool and the controllers' trust in the tools.

There needs to be research into metrics and measurement of automated ATM systems. This ideally should include methods for isolating the affect of different tools on the capability of the ATM System.

### 7.10 SAFETY CASES AND FAULT TOLERANCE

One of the issues that was always raised by controllers was "what happens if it fails" or more often "what happens when it fails". In the simulations controllers could be told to 'suspend their disbelief' and act as if the system were 100% reliable. This was difficult, as the simulations were sometimes unstable. For a system to become operational there needs to be a full Safety Case and the design needs to be fault tolerant. With modern distributed systems this should not prove difficult but the software and hardware design and architecture needs to take fault tolerance and system recovery into account from the outset. Therefore research is required into such designs.

From an operational viewpoint, the tools provide the capability to deconflict aircraft with a long look-ahead say between 10 and 30 minutes, so called strategic deconfliction. The advantage of this is that a system failure is can be considered less dangerous than a radar failure in a radar vectoring area. However, if the automated support was degraded it is important that the controller is not left as a helpless spectator of a system that is overloaded beyond his capacity to cope. For this reason there is a need for a detailed review of degraded mode operations to ensure that procedures and recovery modes exist for all potential failures. This may cause limits to be placed on the load on the normal system operations to ensure that a failure does not become irrecoverable. This requires considerable detailed research and should be carried out *before* automated support is accepted into service.
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8. LESSONS LEARNT

8.1 TRAJECTORIES ARE FUNDAMENTAL

8.1.1 Understanding of Trajectories

Many of the misunderstandings and much of the discussion and disagreements both in tool development and in integration into simulation platforms were on trajectories and associated issues such as errors and uncertainties. These issues are certain to recur outside R&D when 4D trajectories are implemented.

Lesson Learnt. Trajectories are fundamental to ATM. Their use in PHARE indicated that accurate guidance along a 4D trajectory is far more important than accurate generation of the trajectory. It is essential that the concepts of 4D control and guidance are understood.

8.1.2 Common Definition of Trajectories

The 4D trajectories must be sent from the aircraft to the ground system and exchanged between ground tools. Trajectories are also generated in the ground system for what-if modelling. It is essential that the trajectories sent are accurate and that there is a full and unambiguous understanding of the content of the trajectory structure. In PD/3 the PATs and EFMS were required to use the CMS structures for exchange of trajectory and constraint information. Internally the Trajectory Predictor and the EFMS Trajectory Predictor used the same non-CMS structures. Translation between the structures was difficult and could lead to loss of information and inefficiency. [Reference 18.]

Lesson Learnt. Trajectories are fundamental to safe Air Traffic Management. Ideally all tools and systems that use trajectories should have precisely the same data definition and have the same understanding of the information content.

8.1.3 Handling of non-datalink aircraft

3D Aircraft have Trajectories. 3D aircraft are accurate in all but time and that all aircraft are planned with 4D trajectories even though they may not be ‘fully equipped’ with 4D EFMS with datalink. Therefore, a 3D aircraft controlled by a tactical controller using R/T need only be maintained on its 4D trajectory in time and should be trusted in other dimensions. However, this can only be done if the controller can see where that aircraft should be. In PD/2 this was done by marking the position of the aircraft on the trajectory with an “X”. Once the controllers realised that their task was to keep the aircraft in station on the X using the ‘advisory’ R/T commands generated by the system as a guide, they found that the task was less demanding. Nevertheless, work still needs to be done to assess the best way to sequence aircraft flying on internal systems with datalink with those flying under R/T control. [Reference 10.] [Reference 21.]

Advisories. The advisories were passed as just-in-time clearances which had the tendency to treat non-datalink and non-4D Flight Management System equipped aircraft as if they were being radar vectored. A full clearance taking advantage of the aircraft capabilities would be better. The PD/1 approach to this was to generate the advisories in the GHMI. The advisories were formed by parsing the trajectories. The advisories were then displayed in a message window with times to apply them, which required the tactical controllers to read and sort the window. In PD/2 the trajectory was parsed by the Arrival Manager but the advisories themselves were displayed
both on the trajectory and as a highlighted bottom line on the aircraft label. This reduced the mental load on the controller and kept their radar scan going. In PD/3 the Trajectory Predictor generated the advisories as it generated the trajectory this was a more efficient approach, the advisory display matched the advisories from PD/2.

**Lesson Learnt.** For the foreseeable future there will be non-datalink and/or aircraft without 4D Flight Management System. The generation of information on their trajectories, advisory guidance messages and their collation into clearances suitable for lesser equipped aircraft are an important, if not fundamental, part of the success of a 4D ATM System.

### 8.1.4 Larger Planning Horizon – Larger Sectors

The use of 4D trajectories with assured guidance allows longer term deconfliction planning. This was shown almost inadvertently by the controller comments in PD/1 series in which the Problem Solver limited the trajectory amendment to within the sector, where the controllers complained of being limited to trajectory amendment within their own sector. Controllers using the HIPS or TEPS were able to see if their action caused any impact in upstream and downstream sectors and would plan to reduce impacts accordingly. At the opposite extreme the sector boundaries were the existing boundaries and with sometimes short penetrations there were problems with the Negotiation Manager allocation of Planning Authority. However, the PD/1++ Demonstration explicitly explored larger sectors and the results show that there was no detriment to the workload or aircraft throughput despite halving the number of controllers for the airspace. Although larger sectors will still have aircraft that have short penetrations they should be considerably less than the short sectors. Nevertheless, the Negotiation Manager should leave choice of which controller has authority to the controller rather than to the machine.

**Lesson Learnt.** The use of the 4D tools is suited to larger sectors and allows a longer planning horizon. Controllers are better than the tools at choosing whether to alter trajectories inside or outside a sector, whether to co-ordinate with other controllers or not, and, whether and when they should start planning a particular flight. The tools should not enforce rules for planning inside or outside sectors.

### 8.2 SYSTEM TRUST

#### 8.2.1 Gaining Trust

An automated system will only be used if it can gain the controllers trust. Trust cannot be assumed it has to be 'earned' by the system. There are several areas that were found to reduce the controllers' trust in the automated support. Some of the major items are given below\(^\text{10}\).

\(^{10}\text{It appeared that controllers had differing ideas of what reduced their trust in the automation.}\)
8.2.2  Work like a controller would

The automated tools did not have the instinctive rule base that a controller has. One simple example is that with a deconfliction action a controller will always attempt to 'miss behind' and will avoid descending through the level of an aircraft in level cruise just a separation distance ahead. The Conflict Probe however assessed whether a conflict existed according to its rules which were that no conflict existed if the separation exceeded the separation criteria. However, controllers habitually allow a buffer distance in lateral separation they also apply practices such as "always miss behind". It was not uncommon to see controllers disagreeing with 'what the system had allowed' as it was against the way they would normally work and repeatedly checking the distances between aircraft that were separated, but only just [Reference 8].

Lesson Learnt. Although not strictly necessary from a mechanistic point of view, the current controller practice for some issues is usually borne out of awareness of likely problems. The tools would be accepted more easily if these controller 'practices' were assessed and those worthwhile were used in a 'rule base'. In this way tools could be more acceptable and perceived as safer.

8.2.3  Visibility of trajectory information

The Planning Controller deconflicts trajectories based on the use of the Conflict Risk Display and/or the Co-operative Tools Agenda Function. The Tactical Controller is in a different position as the exceptions that are handled almost by definition take the aircraft away from their trajectories. This means that the tactical controller needs to be able to assess rapidly what the future trajectories of aircraft are in order to handle exceptions. In PD/2 the vector change information was shown on the trajectories. Unfortunately however, some of the Simulation platforms hid this trajectory information from the controller. This is contrary to the design ideas of the PMTS and increased the workload of the Tactical Controller.

Lesson Learnt. Automation takes away some of the 'big picture' from the controller. The information must be readily available from the system when it is required.

8.3  AUTOMATED SUPPORT ISSUES

8.3.1  Automation and Procedures

There are 2 main methods of providing automation: automate the current procedures, an example would be strip printing; or automate the function as in provision of conflict detection. The PATs and EFMS were designed around the concept of a 4D trajectory. The simulations were set up to use the current airspace structures which are based on the systemic separation of 3D trajectories. This 3D separation is redundant in a 4D system. However, 4D separation procedures or 'free routing' as it was called, were only approached in a very limited way and this meant that the airspace procedures that were in place were 3D.

11 To quote a controller "that's 5 nautical miles plus one coat of paint".
12 The "snitch patch"
13 In PD/3 the GHMI design did not cater for trajectory information as in PD/2. This information was added to the trajectories in PD/3 Continuation at NLR.
Similarly there were controller procedures that were continued with despite the presence of automation that had already carried out the task. A simple example being Tactical Controllers intervening to clear perceived conflicts that the Planner Controller had already deconflicted. This was a symptom of lack of trust in the system. But automation can only reduce controller workload if the controllers let the automation do some of the work.

**Lesson Learnt.** The automated tool concepts and airspace and controller procedures must be compatible.

### 8.4 ‘HUMAN FACTORS’, PROCEDURES AND GHMI

#### 8.4.1 Deskillling or Reskilling

One of the issues raised by controllers was that the use of the automated support would de-skill them and could mean that there was a requirement for repeated simulator training to exercise skills that would otherwise be lost. Whilst this is true to some extent in such things as identification of conflicts, there was another issue and that was that the use of the tools actually required a considerable degree of finesse. A controller mishandling the automated support tools could cause many more problems than a controller mishandling the current systems. It was a credit to the GHMI and training teams that the PHARE controllers were able to learn the use of the advanced systems in less than a week. The importance of training was continually emphasised.

**Lesson Learnt.** The automated tools can simplify the controller's work but if mishandled can greatly increase problems and workload for the control team. As the tools are powerful, controllers should be trained to be able to use them efficiently and achieve the most from them.

#### 8.4.2 Automation Approaches

Automation can be used to prevent the ‘human in the loop’ from breaking system rules or to merely be available to assist the ‘human in the loop’ in carrying out functions.

**Permissive Automation.** This automation provides assistance to the controller but does not force particular action. For example PROblem SItuation displays in Co-operative Tools or Flight Path Monitor deviation alerts. [Reference 9.]

**Restrictive Automation.** This is automation that is meant to defend the system from misuse or mistake, but seen by the controller as unnecessary, and failure to ‘trust’ the controller. Examples of restrictive automation would be the forcing of co-ordination when trajectories are changed, or the limiting of controller access to trajectories for deconfliction by imposing strict planning authority rules. [Reference 9.]

In general controllers accepted permissive automation but disliked restrictive automation as it created extra work and set bounds on their activities that they felt unnecessary.
9. RESULTS FROM PATS VIEWPOINT

The demonstrations showed the merits of the ‘PHARE Concept’ of layered planning with a long look ahead and the assistance from advanced tools. These demonstrations showed the feasibility and the acceptance of controllers of modified roles and procedures whilst using the tools. The tools were all used in at least one PHARE Demonstration. Some of the tools were used in nearly all demonstrations. However, the toolset approach meant that it was not possible to carry out individual evaluation of the tools.

There is no doubt that the PHARE Demonstrations proved that the concept of air-ground integration was feasible. Indeed the later demonstrations showed that integration was feasible at 2010 or later levels of traffic.

In some cases the tools performed well where the feasibility was in doubt. For example the ability of the Arrival Manager to sequence and balance the traffic load was doubted prior to the PD/2 and PD/3 exercises.

For the detailed results for each tool see the individual Final Reports. In summary:

Trajectory Predictor. The Trajectory Predictor was used in all the PHARE Demonstrations except PD/3 at CENA. It was based on the EFMS Trajectory Predictor, as such many of the functions were those from the EFMS. The Trajectory Predictor in the ground system was possibly too accurate and because of this rather slow for the what-if modelling and generation of ground based trajectories for non-datalink and non-4D Flight Management System equipped aircraft. The Trajectory Predictor was the fundamental tool in the system generating the 4D trajectories. The advisory generation when linked to the generation of trajectories was far more efficient.

Conflict Probe. The Conflict Probe became an important research tool in conflict probing providing comprehensive output to its client tools. It proved easy to adapt and was one of the tools that was integrated and used in all the simulations.

Co-operative Tools. The Co-operative Tools assisted controllers in the en-route environment in risk assessment and tracking of problems and in task sharing.

Problem Solver. The Problem Solver in the guise of Highly Interactive Problem Solver became the best known tool in the PATs. It was the tool most used by controllers to carry out their primary deconfliction task. A substantial degree of development was carried out between the initial PD/1 Problem Solver and the PD/3 Continuation Version. The final version was usable in the TMA and was capable of handling multiple separation standards between conflicting aircraft.

Negotiation Manager. The Negotiation Manager was only fully developed for the PD/3 series of exercises. The tool was fully configurable from a high level of automation to a lower level requiring controller intervention at each step. It was found subjectively that the more restrictive controller intervention approach was less welcome than the more automated. The Negotiation Manager must be capable of multi-threaded operation allowing several coincident operations to avoid adversely affecting system performance.

14 Although it was used only in support of the Departure Manager in PD/3 at CENA.
Flight Path Monitor. The Flight Path Monitor provided a deviation, significant point and progression service to the clients. The GHMI for deviation is an area that needs further research.

Departure Manager. The Departure Manager showed that the sequencing of departures was feasible and could respond to short term operational needs. The underlying concepts were shown to be valid producing acceptable sequencing.

Arrival Manager. The Arrival Manager showed that it was possible to provide better management of arrival traffic with more precise arrival times and runway load balancing. The PD/3 Continuation at NLR demonstrated the Arrival Manager sequencing and balancing the load on three inbound runways at up to 120 movements per hour without the requirement for holding.

Tactical Load Smoother. The Tactical Load Smoother provided a graphical on-line indication of the complexity of traffic in sectors up to 40 minutes in the future. This function is expected to become important as the tools allow a move to exception management. Use of the Tactical Load Smoother showed that there was promise in the Multi-Sector Planner approach.
10. CONCLUSION AND RECOMMENDATIONS

10.1 CONCLUSION

The PATs Project produced advanced software automation and automated support tools in the ground system which integrated with, and was the peer processing to, the Experimental 4 Dimensional Flight Management Systems in the aircraft. The aim of the tools was to provide automated support which would reduce controller workload and increase the Air Traffic Management System capacity. The concept of the tools was based around the forecast capability of aircraft to follow a 4 dimensional trajectory negotiated and agreed with a high degree of accuracy. The trajectory in the ground system would be identical to the trajectory in the aircraft Flight Management System providing greater confidence in conflict detection by the Conflict Probe and deconfliction by the Problem Solver and greatly increasing flight safety. The ground system Flight Path Monitor would then monitor the aircraft flight and alert to any deviation from the trajectory.

The Departure Manager and Arrival Manager provided sequencing and runway load balancing, the Problem Solver and the Co-operative Tools aided the problem solving and deconfliction. The Negotiation Manager provided silent handover, ground-ground co-ordination and air-ground trajectory negotiation. As the trajectories were more accurately followed, the Tactical Load Smoother was able to provide the Multi-Sector Planner with information on future complexities allowing the Multi-Sector Planner to reduce complexity and thus the exceptions that the Sector Planners would need to deal with. The Sector Planner could deconflict the aircraft well before aircraft entered the sector and the Tactical Controller workload was thus reduced with the task becoming one of monitoring aircraft with 4 dimensional Flight Management System and datalink and guiding less well equipped aircraft. This approach to planning the flights where complexity is reduced to a manageable level at up to 40 minutes prior to Sector entry and deconfliction is carried out up to 10 minutes prior to sector entry, was called the 'Layered Planning Concept'.

The PHARE Demonstrations were based on a transitional case with the existing 3 dimensional airspace structures and procedures. This was both an advantage and a disadvantage. The demonstrations showed that the tools could work within the constraints of a 3 dimensional airspace structure and cater for the 'transition case'. But this approach reduced the potential advantages of the tools by restricting demonstration of their capabilities to support free routing. The final PHARE Demonstration 1++ and PHARE Demonstration 3 Continuation at NLR indicated the great potential benefits that could become available if the tools were used in a free routing environment.

The nine tools developed in PHARE supply all the functions that are required for an Air Traffic Management System. There were a limited number of overlaps which could be reduced either by greater sharing of some algorithms or redesign of some tools. Although there was no demonstration in which all the tools were integrated and running as a single toolset, the tools were used in all phases of flight in the PHARE Demonstrations. The tools were the progeny of research and development of the PHARE Partners and did not all share the same conceptual view. This led to some integration difficulties prior to the PHARE Demonstrations.
The tools were not individually measured, tools teams were therefore not able to identify the impact of their tool on the overall performance of the system. Furthermore, the metrics used were based on manual procedures and concepts which assumed a certain standard proportion of controller work per aircraft in the sector. With the potential for conflict free aircraft on 4 dimensional trajectories to transit a sector without affecting either the planning or tactical controller, such standard measures will need to be revisited to assess their validity.

Every PHARE Demonstration ran with a percentage of aircraft in the simulation that were not equipped with 4 dimensional Flight Management System and datalink. In many of the demonstrations there were intermediate 'organisations' that had no 4 dimensional equipped aircraft. Whilst the controller workload was not greatly diminished in these organisations, the ground tools alone were sufficient to improve the quality of service to the aircraft. Thus it was demonstrated that datalink is not a pre-requisite of automated support tools and that aircraft can benefit immediately without a need to equip with advanced avionics. Nevertheless, for full benefits and greater airspace capacity datalink is needed. Unfortunately, the datalink technology used within PHARE does not appear to be capable of providing the capacity and the quality of service that would be required for a trajectory negotiation environment.

The main aim of the tools was to provide automated support to the controller. Where the automation was seen as prescriptive or restrictive the controllers found it unwelcome. Where the automation assisted the controller but did not force actions or restrict actions it was accepted much more readily. Controllers need to be able to trust the automation before they are willing to abandon their current operational procedures. Trust cannot be forced on the controllers, they need to give it. Controllers will only give their trust when they are confident in the tools. Trust was destroyed if the system failed or if for example the tools gave mismatching conflict warnings or even if the tools correctly allowed something that was 'safe' mathematically but that would not normally be allowed by a controller.

To reduce the controller workload the tools have to do some of the controllers' work. This concerned some controllers who were worried about the impact of the tools on their 'skills'. It is possible that in future controllers may have to carry out training in the use of degraded systems in the same way as aircrew. However, it should also be recognised that the use of the tools also requires skills some of these are the addition of more finesse to long term deconfliction others are more based on a requirement to understand what the tool is doing such as in arrival and departure management.

The objective of PHARE was to 'demonstrate the feasibility and merits of a future air-ground integrated air traffic management system in all phases of flight'. The PHARE Advanced Tools provided the ground side of the integration and the feasibility of integrated Air Traffic Management Systems is no longer in question. More work needs to be done to quantify the merits of an integrated system, not least in the identification of metrics for exception management systems. Due to PHARE, the potential benefits to the aviation community of integrated advanced automation tools are now apparent.
10.2 RECOMMENDATIONS

The following recommendations are made:

a. Many of the problems found during the PATs implementation were due to conceptual misunderstandings. Action should be taken to ensure that the 4 dimensional air traffic management concepts are understood at all levels from developer to controller to ATS and airline management.

b. Measurements taken of the effects of the tools in airspace structured for 3 dimensional control with 3 dimensional procedures hide the benefits of the 4 dimensional tools. The effects of the advanced automation tools should be measured and quantified in a completely 4 dimensional user preferred trajectory environment.

c. PHARE was aimed at feasibility and did not attempt to provide a pre-operational system. Therefore the PHARE demonstrations had little if any exception handling. Indeed some of the 'exceptions' that were not tried would, operationally, be called normal events (e.g. runway changes). Any new simulation or quantification work must take exceptions and exception handling into account.

d. The tools provide new capability to the controllers as well as reducing their workload. Controller procedures and techniques should be developed that make best use of the capabilities of the tools.

e. Legacy computer system architectures tend to be based around database servers which mainly output or even broadcast data to the controller work positions. The advanced tools are far more interactive. Therefore, rather than being based on legacy architectures System Architectures should be investigated which can provide high performance and scalability. Ideally these should follow a complete object oriented approach to system analysis and design.

f. Automation will only be successful if the tools have matching concepts and semantics.

g. When the tool concepts are agreed and matching it becomes possible to share algorithms between the tools. Therefore, research effort should be put into the sharing of algorithms between the tools.

h. Systems Engineering approach must be taken to the development of Air Traffic Management systems with automated support. The System boundary must be set sufficiently wide to include the controller and cockpit procedures. Human-in-the-loop factors should also be taken into account in the design. This should ensure that concepts are matched throughout the ATM system.

i. Air Traffic Management Systems that depend to a greater degree on automation and decision support tools must have sufficient reliability. Therefore their design should take in the concepts of fault tolerance and rapid and consistent recovery from failures.

j. Controllers must trust the automation and will need to be able to rely on it to be correct at all times. Without this level of trust the controllers will carry on using current procedures as well as the tools and this will impose excessive workload on them. The issue of responsibility if a system failure causes an incident will need to be openly discussed and agreed before controllers will be willing to accept automated support tools into use.
## 11. ACRONYMS, DEFINITIONS AND REFERENCES

### 11.1 ACRONYMS AND DEFINITIONS

#### 11.1.1 See [Reference 1.]

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Meaning</th>
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<tbody>
<tr>
<td>3D</td>
<td>three dimensional (latitude, longitude and altitude)</td>
</tr>
<tr>
<td>4D</td>
<td>four dimensional (latitude, longitude, altitude and time)</td>
</tr>
<tr>
<td>API</td>
<td>Application Program Interface</td>
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<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
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<tr>
<td>ATS</td>
<td>Air Traffic Services</td>
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<tr>
<td>CMS</td>
<td>Common Modular Simulator</td>
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<tr>
<td>CORBA</td>
<td>Common Object Request Broker Architecture</td>
</tr>
<tr>
<td>DAARWIN</td>
<td>Distributed ATM Architecture based on RNAV Workstations Intelligent Tools and Networks</td>
</tr>
<tr>
<td>EFMS</td>
<td>Experimental Flight Management System</td>
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<tr>
<td>ETA</td>
<td>Estimated Time of Arrival</td>
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<tr>
<td>ETMA</td>
<td>Extended TMA</td>
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<tr>
<td>FMS</td>
<td>Flight Management System</td>
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<tr>
<td>GARTEUR</td>
<td>Group for Aeronautical Research and Technology in Europe</td>
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<tr>
<td>GHMI</td>
<td>Ground Human Machine Interface</td>
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<tr>
<td>HIPS</td>
<td>Highly Interactive Problem Solver</td>
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<tr>
<td>IDL</td>
<td>Interface Definition Language</td>
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<tr>
<td>IOCP</td>
<td>Internal Operational Clarification Project</td>
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<tr>
<td>NARSIM</td>
<td>NLR ATC Research Simulator</td>
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<tr>
<td>PARADISE</td>
<td>Prototype of an Adaptable and Reconfigurable ATM Demonstration and Integration Simulator Environment</td>
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<td>PHARE Demonstration &lt;number&gt;</td>
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<td>Programme for Harmonised Air Traffic Management Research in EUROCONTROL</td>
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<td>PHARE Medium Term Scenario</td>
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<td>PROblem SITUation</td>
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<td>R/T</td>
<td>Radio Telephony</td>
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<tr>
<td>RTA</td>
<td>Requested Time of Arrival</td>
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<td>Standard Instrument Departure</td>
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<tr>
<td>STAR</td>
<td>STandard Arrival Route</td>
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<tr>
<td>TEPS</td>
<td>Trajectory Editor and Problem Solver</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>TMA</td>
<td>TerMinal Manoeuvring Area</td>
</tr>
<tr>
<td>URD</td>
<td>User Requirement Document</td>
</tr>
</tbody>
</table>
11.2 REFERENCES

[Reference 1.] PHARE Glossary of Terms and Acronyms DOC 97-70-05, version 4, April 97
[Reference 2.] PHARE Medium Term Scenario dated 1 Jul 90
[Reference 3.] PHARE Advanced Tools Initial Requirements and Planning Document dated 14 Jul 92
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[Reference 7.] PHARE: Definition and Use of Tubes DOC 96-70-18 dated 15 July 1996
[Reference 8.] PHARE PD/1 Final Report DOC 96-70-24
[Reference 10.] Human Centred Approach IOCP
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[Reference 12.] PHARE PD/1+ Final Report DOC 97-70-**
[Reference 13.] PHARE PD/2+ Final Report
[Reference 14.] PHARE PD/1++ Final Report DOC 98-70-16
[Reference 17.] NLR PD/3 Final Report DOC 99-70-01 Vol 4
[Reference 19.] PHARE GHMI Final Report DOC 99-70-02
[Reference 20.] PHARE Common Modular Simulator Project Final Report DOC
[Reference 21.] PATs Arrival Manager Final Report DOC 98-70-18 Vol 2
[Reference 22.] PATs Conflict Probe Final Report DOC 98-70-18 Vol 3
[Reference 23.] PATs Cooperative Tools Final Report DOC 98-70-18 Vol 4
[Reference 24.] PATs Departure Manager Final Report DOC 98-70-18 Vol 5
[Reference 26.] PATs Negotiation Manager Final Report DOC 98-70-18 Vol 7
[Reference 27.] PATs Problem Solver Final Report DOC 98-70-18 Vol 8
[Reference 29.] PATs Trajectory Predictor Final Report DOC 98-70-18 Vol 10
[Reference 30.] PHARE Aeronautical Telecommunications Network Final Report
DOC 99-70-03
APPENDIX A TO DOC 78-70-18-VOLUME 1: CONCEPTUAL ISSUES

A1. TRAJECTORIES IN PHARE

A1.1 TRAJECTORIES CONCEPTS

The knowledge or estimation of an aircraft’s future trajectory is fundamental to safe aircraft operations and the provision of air traffic control. It is somewhat surprising therefore that the use of trajectories within PHARE exposed conceptual differences. These differences led to misconceptions that became apparent not only designing the tools but also in the integration of the tool-sets. They were further highlighted when procedures were defined for the use of the tools by the PHARE Demonstration teams.

In Air Traffic Management, aircraft are deconflicted by varying one of the 4 dimensions of their future trajectory. All aircraft have 4D trajectories that run from present position or departure point to arrival point. For an aircraft in flight these trajectories exist regardless whether they have been forecast (or predicted) and regardless of the aircraft avionic equipment level. The difficulties are in identifying, describing, transmitting and then storing the trajectory in such a way that it can be used. Then there are further difficulties and inaccuracies in the implementation of the trajectory and the monitoring of that implementation. These issues are discussed below, as they are fundamental to the conceptual understanding of several of the tools.

A1.1.1 Constraints and Trajectory Modification.

As stated above the PHARE approach was for the aircraft to generate a User Preferred Trajectory and transmit that to the ground system. The controller would if necessary for deconfliction or for ATC procedures alter the trajectory by ‘constraining’ it in one of the 4 dimensions. The constraints took the form of altitude windows times and 2D route points. The set of constraints on a trajectory was known as a ‘constraint list’ and this was transmitted back to the aircraft which would generate the most efficient trajectory (in user terms) that met the constraints. The way the aircraft met the constraints was a matter for the trajectory generation algorithms in the aircraft. Therefore, the controller imposed constraints to force a change in the trajectory and did not ‘edit’ the trajectory. This caused considerable problems both conceptually to the controllers (and the GHMI design team who continued to use the term throughout the project) and to the tools such as the PS.

Constraints are more complex than just a 4D point. Controllers normally use instructions such as “climb to and maintain Flight Level 240” This is a closed constraint as there is no time limit on the requirement to maintain flight level 240 and the aircraft must maintain that level until told otherwise. Alternatively, a controller may give the instruction “Cross KOK not below Flight Level 240”. This is an open constraint as there is no top limit neither is there a requirement to maintain flight level 240 either before or after KOK. The Trajectory Predictor would accept such constraints in the terms of Windows with top and bottom bounds and an indication whether the constraint was closed, i.e. It applied after the point at which it was first applied; or, Open, i.e. there was no restriction after the point at which the constraint applied. There were mixed constraint types open after and open before and these...
had to be paired correctly. Unfortunately, the initial Problem Solver had no concept of these constraint types. The Problem Solver in PD/3 did recognise them.

A1.1.2 Trajectory Prediction ‘Errors’

Some tools were designed in the expectation of an ‘error tube’ around the trajectory of an aircraft that widened with time. Yet the PHARE concept included feedback loops to ensure that the aircraft remained within a deviation parameter of the trajectory, known as the ‘contract tube’ [Reference 7]. Therefore, as long as the trajectory generated was flyable the aircraft would follow it within the bounds agreed either using internal or external guidance. There were 2 cases that could be considered in trajectory ‘prediction’:

a Trajectories generated by the aircraft FMS and datalinked to the ground system will be flown to the accuracy of the aircraft guidance within the contract tube. If the guidance cannot remain within the contract tube a new trajectory negotiation is instigated. There is no ‘prediction error’ as such.

b Trajectories generated by the ground system are used either for modelling trajectory amendments or for guidance of non-datalink aircraft by radio. There will be a mismatch between modelled and FMS generated trajectories as even with identical software the generations are done at different times and therefore have different starting points. However, sub-paragraph (a) above applies in this case and the actual negotiated trajectory is accurate. If the trajectory is for the guidance of a non-datalink aircraft then the tactical controller’s task is to ensure that the aircraft follows the trajectory as with an “ATC Clearance”.

A1.1.3 Statistical Trajectory Errors/Uncertainties

There is another class of ‘error’ that should be mentioned as it was considered important in the development of the Tactical Load Smoother and multi-sector planning. This was the probability that a trajectory that was forecast up to 40 minutes ahead would actually be flown. Rather than ‘error’, this is more correctly called ‘uncertainty’. As stated in above trajectory changes and exceptions are always happening. Therefore, of the trajectories generated 40 minutes in advance there will be a probability that some will not be flown. However, whilst this is true, the probability of change cannot be used in an ATM context apart from an often self evident warning to a planning controller that a trajectory is less certain (for example when the aircraft is not yet airborne).\(^\text{15}\)

A1.1.4 Accurate Transmission of Trajectory Information

The generated trajectory in the aircraft FMS needs to be transmitted to the ground. The format required to do this governs both the accuracy of the trajectory definition received by the ground and the speed of the transmission. There were 2 competing methods of transmitting the trajectory; as a simple array of 4D points with their associated attributes, or, as a constraint list and phase-table [Reference 5]. Whilst the array of points is a simple concept the size of the array can lead to problems for a long or complex flight. Reduction in the number of points on the trajectory could lead

\(^{15}\) Despite this uncertainty, in the EEC PD/3 IOCP to assess Multi-Sector Planning it was apparent that controllers using the ‘Look ahead display’ were taking relatively precise deconfliction actions on trajectories forecast 30 – 40 minutes into the future.
to extrapolation problems for flight path monitoring, conflict probing and even GHMI display.

A1.1.5 Guidance Errors

The PHARE EFMS had guidance feedback to keep the aircraft within the deviation tube around the trajectory. Should the guidance software detect a forthcoming deviation that exceeded the control authority limits of the FMS then it would raise a deviation warning to the pilot. Similarly, the Flight Path Monitor tool tracked the progress of aircraft against their active trajectories and provided deviation alerts if the aircraft deviated outside the contract or large deviation tubes [Reference 5]. Therefore, whilst there may be guidance errors, there should be no unreported deviations from the negotiated trajectory.

A1.1.6 Optimal or User Preferred

A final conceptual issue on trajectories was the distinction between 'optimal', 'initial flight plan' and 'user preferred' trajectories. Ideally, the aircraft should prepare and downlink a 'blue-sky' trajectory which has no concept of airspace restrictions. This would be a 'user preferred' trajectory. It may also be an aerodynamically optimal trajectory but that is not necessarily the case. For example, high route charge areas may mean that a more circuitous route is chosen. In the current fixed route system the flight plan will obey the restrictions of the procedures and the airline would not attempt to file either a user preferred or optimal profile. This distinction becomes important with multi-sector planning where a flight that is less than optimal can be optimised whereas a flight that is already optimal can only be de-optimised.

A1.1.7 Gate to Gate Trajectories

Initially the approach to trajectories in PHARE mirrored that of the current systems [Reference 3.] where only a short stub ahead of the aircraft perhaps to the next sector boundary was generated. However, by PD/3 it became apparent that the trajectory would need to be extended more if multi-sector planning was in use. Moreover, to ensure that aircraft could adjust their speeds early for sequencing, the Arrival Manager would need to start dynamic sequencing as soon as a trajectory was received [Reference 21.]. In consequence aircraft trajectories were generated along the same lines as those in the EFMS from aircraft current position to ILS intercept point [Reference 5.]. This had the added operational advantage of consistent handling of the aircraft through the airspace as the trajectories took into account all the constraints whenever they were generated. This also allowed constraints that were less urgent to be bundled with the next sector negotiation rather than force an immediate trajectory negotiation.

A1.1.8 Ground Track and Ground Radius Turns

Aircraft flying under flight management system control fly ground tracks and ground radius turns. The EFMS Trajectory Predictor (used in the ground TP) was based on ground tracks. Ground radius turns are variable angle of bank compared to air radius turns which are constant bank angle. The EFMS (as with commercial FMSs) had a minimum turn radius parameter of approximately 5NM (at low level) rising to more than 15NM at height and a max angle of bank parameter set to around 22 degrees. This naturally led to wider turns than would be expected with a rate 1 constant 30 degree bank angle turn. It also meant that the TMA procedures that were copied from existing procedures were deemed unflyable by the Trajectory Predictor. The
simulation teams were loath to change the procedures that were known by the controllers and actually flown current day.

Future airspace procedure design for FMS flown procedures in the TMA will need to take account of wider shallower turns.

Of more importance, in every PHARE Demonstration with the exception of PD/1++, the Aircraft Simulators that generated the tracks in the simulations were all initially set-up to fly headings and air radius constant bank angle turns. The PATs Trajectory Predictor generated a trajectory that was ground track and ground radius turn based. This was ‘negotiated’ with the simulated aircraft who returned a trajectory that was also ground track and ground radius turn based. However, the simulators then flew the aircraft as if the tracks were headings and all turns were air radius constant bank angle. The result was that the simulated 4D FMS aircraft all deviated from their negotiated trajectories if the simulation input a wind effect and always deviated in the turns. This obviously defeated the object of the exercise.

Various ‘fixes’ were used to ameliorate these problems by both sides.

a To fit the approach procedures, the PATs Trajectory Predictor parameters were set to allow rate 1 30degree bank turns and the minimum turn radii parameters were set to unrealistically tight turns.

b To reduce the deviation due to the simulators flying headings and not tracks the wind could be removed either for the entire simulation or just for the 4D aircraft in the simulation.

It should be noted that the ‘real’ live aircraft that flew within the simulations did not have this problem and did not deviate significantly from their negotiated trajectories.
APPENDIX B TO DOC 78-70-18-VOLUME 1: OVERVIEW OF TOOL SERVICES AND EVENTS

B1. SERVICES AND EVENTS IN PROCESSING A FLIGHT

B1.1 INTRODUCTION

This Appendix provides a step by step indication of the processing of a flight by the PATs. It does not replace the more detailed technical view in the individual Final Reports that make up the final volumes of this Document set. However, it intended to give a simple and example overview of the interaction of the tools.

The tools themselves subscribe to servers and other tools for the receipt of 'events'. The effect can be that there are cascades of events when certain processing completes, such as the generation of a new trajectory.

B1.2 INITIAL FLIGHT PLAN

B1.2.1 Initial Trajectory Generation

The initial trajectory is generated from the input Flight Plan a parameter time prior to the departure time of the flight. The initial flight plan from a flight is supposedly a 'blue-sky' trajectory. In actual fact it will be a trajectory that has already been constrained so that it will meet with ATC approval and so will include a minimum number of ATC constraints such as SID and STAR with any associated level and speed constraints.

When the new trajectory enters the Flight Data-base (System Plan Server or SPL Server) an event is raised that there is a new active trajectory. The new trajectory event is received by those tools that have subscribed to that event. These will be the:

Conflict Probe: The Conflict Probe checks the new trajectory against all active trajectories and any identified alternate trajectories. If a conflict is found the conflict probe issues an event providing the details of the conflict.

Problem solver: The problem solver loads the new active trajectory into its local database.

Arrival Manager: If the arrival point of the trajectory is the airport that is managed by an Arrival Manager, that Arrival Manager will load balance the runways and set the Scheduled Time of Arrival (STA). It will enter a time constraint for the arrival time and a STAR to an arrival runway. The Arrival Manager will attempt to sequence the flight at its ETA if this is not possible it will sequence it as close as possible after the ETA. The result of the processing is a set of STAR constraints added to the constraint list. The trajectory will not be displayed as it is not frozen. This process could involve several iterations of trajectory generation [Reference 21.].
**Departure Manager:** If the departure point of the trajectory is the airport that is managed by a Departure Manager and the aircraft is not yet airborne the Departure Manager will load balance the runways and set the Scheduled Time of Departure (STD). It will enter a time constraint for the departure time and choose the most appropriate SID for the departure runway, modifying the SID if necessary. The Departure Manager will attempt to sequence the flight close to its ETD within the CFMU slot, if this is not possible it will sequence it as close as possible after the ETD. The result of the processing is a set of SID constraints added to the constraint list. This process could involve several iterations of trajectory generation [Reference 24.]

**Co-operative Tools:** The Co-operative Tools loads the new trajectory into its database.

**Tactical Load Smoother:** The Tactical Load Smoother at its next iteration will take the trajectory into account in its assessment of the airspace complexity. The trajectory is still uncertain as the aircraft has not taxied, so it will be displayed in a colour to indicate that state.

**Secondary Processing.** The result of the processing is that the system has a ‘working trajectory’ or a trajectory in the planning state allowing the longer term capacity planning to be carried out. Secondary processing on subsequent events takes place. Conflict probe events and constraint list updates.

**Constraint List Updates:** The constraint list updates for initial modelling are passed to the Flight Database which then initiates the Trajectory Predictor to generate a new alternate trajectory and pass back the trajectory to the calling process.

**Conflict Probing:** The Conflict Probe operates on the alternate trajectory(ies) when called for example by the arrival or departure manager returning the any new conflict or cleared conflict detail to the calling process.

**B1.2.2 Aircraft Log on to ATN – Initial Negotiation**

The next stage starts when the aircraft systems start up and log in to the ATN. [Reference 30.] The aircraft then downlinks the ‘user preferred trajectory’ based on the flight plan and the SID and STAR information.

The downlinked trajectory replaces the planning trajectory in the ground system and the processing in now repeats the process above in B1.2.1. However, this time the trajectory is the aircraft active trajectory rather than just a planning trajectory. Therefore:

**Conflict Probe:** The Conflict Probe checks the new trajectory against all active trajectories and any identified alternate trajectories. If a conflict is found the conflict probe issues an event providing the details of the conflict if the change to the new trajectory removes a conflict then this is also raised as an event.

**Problem solver:** The problem solver loads the new active trajectory into its local database.

**Arrival Manager:** If the arrival point of the trajectory is the airport that is managed by an Arrival Manager, that Arrival Manager will load balance the runways and set the Scheduled Time of Arrival (STD) such that wake vortex and other separation standards are maintained [Reference 21.]
Departure Manager: If the departure point of the trajectory is the airport that is managed by a Departure Manager and the aircraft is not yet airborne the Departure Manager will load balance the runways and set the Scheduled Time of Departure (STD). It will enter a time constraint for the departure time and choose the most appropriate SID for the departure runway, modifying the SID if necessary. The Departure Manager will attempt to sequence the flight close to its ETD within the CFMU slot, if this is not possible it will sequence it as close as possible after the ETD. The result of the processing is a set of SID constraints added to the constraint list.

Co-operative Tools: The Co-operative Tools loads the new trajectory into its database.

Tactical Load Smoother: The Tactical Load Smoother at its next iteration will take the trajectory into account in its assessment of the airspace complexity. The trajectory is still uncertain as the aircraft has not taxied, so it will be displayed in a colour to indicate that state.

Secondary Processing. Secondary processing on subsequent events takes place. Conflict probe events and constraint list updates.

Constraint List Updates: The constraint list updates for initial modelling are passed to the Flight Database which then initiates the Trajectory Predictor to generate a new alternate trajectory and pass back the trajectory to the calling process.

Conflict Probing: The Conflict Probe operates on the alternate trajectory(ies) when called for example by the arrival or departure manager returning the any new conflict or cleared conflict detail to the calling process.

Trajectory Negotiation. The result of the processing is that the system has a live trajectory allowing the initial deconfliction planning in the departure terminal airspace to be carried out. However, this needs to be negotiated and agreed with the aircraft if it has datalink. The negotiation manager is called and passed the trajectory reference:

Datalink Equipped Aircraft. The Negotiation Manager initiates trajectory negotiation with the aircraft If the trajectory returned by the aircraft is meets the constraints the Negotiation Manager: [Reference 4.] [Reference 18.]
calls the Conflict Probe: If there is no new conflict caused by the downlinked trajectory, the Negotiation Manager ‘Activates’ the Trajectory by a call to the Flight Database Server.

If there are conflicts or the trajectory is significantly different by a <parameter> difference from the ground generated trajectory then the trajectory is referred to the controller via the HMI of the client tool.

Non-Datalink Equipped Aircraft. The Negotiation Manager immediately activates the ground generated trajectory by a call to the Flight Database Server.

On activation of the trajectory:

Problem solver: The problem solver loads the new trajectory into its local database.

16 The PD/3 Continuation Trial simplified these checks and the Negotiation Manager only checked for new conflicts.
Co-operative Tools: The Co-operative Tools loads the new trajectory into its database updating the Activity Predictor Display for new PROblem SITUations if there are any associated conflicts. This entails also selecting the all the aircraft associated with the conflict. [Reference 23.]

Tactical Load Smoother: The Tactical Load Smoother at its next iteration will take the trajectory into account in its assessment of the airspace complexity. The trajectory is still uncertain so it will still be displayed in a colour to indicate that state.

B1.2.3 At Take-Off
As the aircraft takes off it will:
- initiate a Downlink of Aircraft Parameters (DAP) giving the change of state, or,
- The ATC facility will enter a departure message indicating the change of state, or,
- The reception of radar data for the flight will trigger a change of state.

(Note that in PHARE this DAP or airborne input was assumed)
The trajectory is now updated with the ‘activation’ message with the actual departure time. If there is significant difference between the planned departure time and the actual departure this is shown by the Flight Path Monitor which will issue a deviation alert event for the flight giving detail of the deviation.
The GHMI will display the deviation alert and it is then a controller and pilot decision whether to amend the trajectory to match the actual position of the aircraft or for the aircraft to correct back to the planned 4D trajectory by expediting or by amending its route.

B1.2.4 In Flight and Approach
The subsequent processing of the flight follows the sequences above. Every alteration of the trajectory will result in a cascade of events equivalent to that in B1.2.1 except that the departure manager is no longer involved.
The Negotiation Manager using the time on the trajectory and the Significant Point service of the Flight Path Monitor [Reference 25.] can progress the planning and control authority states of the flight.

Deconfliction. As an example, assume that the Conflict Probe has operated on a new input trajectory and a new conflict is found. The Conflict Probe then raises a new conflict event. This event is transmitted by the platform system to all the system programs that have subscribed to it. The Co-operative Tools and the GHMI receive these events. The Co-operative Tools will display the conflict as a PROblem SITUation on the Activity Predictor Display and the GHMI will display the conflict on the Conflict Risk Display.
Problem Solving. The Problem Solver is initiated by the controller through the GHMI. The Problem Solver will have copies of all the active trajectories in its database. However, it does not have the conflicts from the Conflict Probe. When the Problem Solver is initiated on a flight it will create the no-go diagrams by itself checking for conflicts [Reference 27.]. The controller amends the displayed trajectory on the Problem Solver display then selects ‘Validate’ from a GHMI drop down menu. This step causes the Problem Solver to call the Trajectory Predictor with a constraint list amended by the problem solving. This is an asynchronous call and an Alternate Trajectory is returned for modelling and to confirm that the trajectory prediction rules will also return a conflict free trajectory. If the controller is content with the validated trajectory then the controller selects ‘Register’ from a GHMI drop down menu. This sends the constraint list to the flight database and an event to the Negotiation Manager to activate the flight. The sequence at 0 is then followed to negotiate, if necessary, and activate the trajectory.

Approach. As described in [Reference 21.] the Arrival Manager considers the flight in 2 phases. The initial phase starts on first receipt of a trajectory and the arrival sequence is continually reassessed as trajectory updates are received. If a new computed STA is more than a parameter time different to the ETA of the flight then a new time constraint is set in the constraint list and the Negotiation Manager is triggered [Reference 21.]17. At a parameter time prior to Top-Of-Descent that indicates the start of the planning phase the Arrival Manager will freeze automatic recomputation of the sequence.

B1.2.5 Event Cascades

When the Arrival Manager and Departure Manager are operating and re-sequencing, they may often operate on several aircraft at once. This may be on receipt of new flight plans that are coincident on ETD or ETA or it may be caused by controller input to make a large re-sequence. The impact on the system is that there are repeated calls for alternate trajectories each tool testing each runway with different departure or approach paths and potentially with the Arrival Manager repeated assessments of the load balance on the runways. Efforts were made to reduce the iterations in the tools however, if the chain of events at B1.2.1 is considered and multiplied up for say 30 or 40 flights then there can be a significant impact on the platform especially if clients such as the Problem Solvers are distributed.

17 This is a gross simplification readers are recommended to read the reference Arrival Manager Report.