PROGRAMME FOR HARMONISED AIR TRAFFIC MANAGEMENT RESEARCH IN EUROCONTROL

PHARE

EUROPEAN ORGANISATION FOR SAFETY AIR NAVIGATION, EUROCONTROL

**DOC 98-70-18**

**(Volume 10 of 10)**

# PHARE Advanced Tools Trajectory Predictor

# Final Report

PHARE/NATS/PAT-6.2.10.3.4/FR; 1.0

EUROCONTROL

EUROCONTROL
96 rue de la Fusée
B-1130 BRUXELLES

Prepared by: Ian Fairclough, NATS
David McKeever, NATS

Date: 08 February 2000

## REVISION HISTORY

| Date | Revision Number | Reason for revision |
|---|---|---|
| 08 December 1999 | 0.2 | Incorporate comments from review at PATS CG meeting held at NATS on 23/6/98. |
| 11 December 1998 | 0.3 | Incorporate comments from review with PATS Project Manager held at NATS on 05/10/98. Also, fully populate all sections to produce first full draft. |
| 22 December 1998 | 0.4 | Incorporate comments from review with PATS Project Manager held at NATS on 21/12/98 and 22/12/98. |
| 12 August 1999 | 1.0 | Publication Version |

# DOCUMENT APPROVAL

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| **AUTHOR** | Ian Fairclough, NATS | | 12 Aug 99 |
| **PATS Project Leader** | Ian Wilson, Eurocontrol | | 12 Aug 99 |
| **PHARE Programme Manager** | H. Schröter | | 12 Aug 99 |

# EXECUTIVE SUMMARY

This document is one volume within the final report produced by the PHARE Advanced Tools (PATs) project within the PHARE program. The document represents the final report for the PATS Trajectory Predictor tool that is identified within the PATS final report parent document, reference [3].

The PATS Trajectory Predictor is a ground based tool that has been developed to fit within the PHARE operational concept for a future air-ground integrated air traffic management system that is applicable to all phases of flight. The tool is intended to provide support to air traffic controllers in their manipulation of constraints, allowing them to model and assess the effect of their actions prior to the modified constraints being sent to the aircraft. For non-datalink and / or non-4D-FMS equipped aircraft, the output of the tool is used for conflict detection and flight path monitoring functions.

The PATS Trajectory Predictor utilises airspace, aircraft performance and meteorological data supplied by the other data servers within the integrated system. The tool is not reliant on any other tool within the PHARE advanced toolset. The tool provides an interface for initiating trajectory generations that is used by PHARE planning tools, such as the PATS Arrival Manager, Departure Manager, Problem Solver, Negotiation Manager etc., and as a result of tactical and planning controllers modifying aircraft trajectories.

Development of the PATS Trajectory Predictor was initially carried out for the PD1 trial by DRA at Malvern under contract to NATS. For PD2 and PD3 trials, development has been carried out by NATS at the ATMDC in Bournemouth. As development of the tool has progressed, a number of ideas and concepts have been dropped including early / late time calculation; the calculation of cost of flying a trajectory; the calculation of an error tube; and the specification of turn type.

The requirements for the PATS Trajectory Predictor have been derived from the operational concept. The tool was required to provide support to air traffic controllers and other tools within the PHARE advanced toolset. Support for controllers is provided for their manipulation of constraints, to allow them to model the likely effect of their actions prior to those constraints being sent to the aircraft. Support for other tools is provided in the areas of 4D trajectory generation; advisory generation; and contract tube computation.

The PATS Trajectory Predictor has been designed using an object orientated approach and implemented using the ADA programming language. The design of the tool has had to ensure that the implementation is capable of generating a trajectory within a reasonable timeframe. The consequence of poor performance within the tool is a significant impact on the successful operation of the integrated PHARE system, since the tool provides such a central service. During development, a number of problems have been found and solved and there are a number of unsolved problems, the majority of which warrant further research.

There have been a number of lessons learnt during development of the PATS Trajectory Predictor within the overall framework of the PHARE program. Significant lessons have been learnt from the approaches adopted for systems engineering; the system architecture adopted for integrated PHARE systems; and from the use of different platforms for different PHARE demonstrations.

The tool has been successfully integrated into a number of different host platforms

within the PHARE program. The tool can be supplied with a user guide (reference [10]) that provides a full set of details on how the tool should be integrated into a new host platform.

There are a number of objective results and subjective comments available from the PHARE trials program to evaluate the PHARE trajectory prediction operational concept.

This report proposes a number of recommendations for developing the PHARE trajectory prediction concept. Recommendations are made in the areas of further trajectory predictor research; for establishing a similar programme to PHARE; and for considering re-use of the PATS trajectory predictor.

# LIST OF CONTENTS

This page left intentionally blank

# 1. INTRODUCTION

## 1.1. SCOPE

This document has been produced as part of the PATS project within the PHARE program. The document is the final report for the PATS Trajectory Predictor tool.

## 1.2. DOCUMENT CONTEXT

This document is one volume within the final report produced by the PHARE Advanced Tools project within the PHARE program. The document represents the final report for the PATS Trajectory Predictor tool that is identified within the PATS final report parent document, reference [3].

## 1.3. SUBJECT

The PATS Trajectory Predictor is a ground based tool which generates aircraft trajectories and associated data for other tools.

The PHARE concept is based around aircraft defining their own preferred trajectory (using internal trajectory prediction software) from a set of constraints sent to the aircraft from the ground ATC system. This preferred trajectory is sent back to the ground system which ensures separation standards are maintained.

The main role of the PATS Trajectory Predictor is to support the ground controllers in their manipulation of constraints, allowing them to model and assess the effect of their actions prior to the modified constraints being sent to the aircraft. Additionally, the tool generates trajectories on behalf of 3D aircraft.

The Trajectory Predictor provides the following services to support the PATS:

- When requested, calculate an optimal 4D trajectory[1], from the current position of the aircraft to the last position on the planned route, and generate text advisories, which assist a tactical controller providing instructions to the pilot to maintain the aircraft on this trajectory. The predicted trajectory will conform to the four-dimensional constraints imposed by the controller, wherever possible within the performance capabilities of the aircraft. If it is not possible to meet all the constraints, the “best effort” trajectory[2] will be returned.
- Compute a Contract Tube[3] and Large Deviation Tube[4] when computing a trajectory. These tubes are utilised by the Flight Path Monitor, whilst checking to see if the aircraft is conforming to the agreed trajectory. The aircraft is provided with the required information concerning the contract tube, providing it with some flexibility for deviation from the agreed trajectory without unnecessarily alerting the controller.

---

[1] For definition of Optimal 4D trajectory, see section 8.2

[2] For definition of Best Effort trajectory, see section 8.2

[3] For definition of Contract Tube, see section 8.2

[4] For definition of Large Deviation Tube, see section 8.2

- In performing these services, the TP will use the flight plan, constraint information, aircraft performance data, meteo data, airspace information and the aircraft's current state vector.
- At the core of the PATS Trajectory Predictor lies the Experimental Flight Management System (EFMS). This is the air-based trajectory prediction software, which has been modified to make it suitable for use within a ground based system. The EFMS provides the core algorithms for computing an aircraft's future trajectory. For a full description see reference [4]. The TP provides the shell that encapsulates the EFMS and drives the interfaces provided by the EFMS. The TP provides an API that is suitable for use within a ground based air traffic management system.

## 1.4 REPORT STRUCTURE

Section 2 describes the operational concept of the PATS Trajectory Predictor tool.

Section 3 describes the requirements for the PATS Trajectory Predictor tool.

Section 4 describes the implementation of the PATS Trajectory Predictor tool.

Section 5 describes the usage of the PATS Trajectory Predictor tool.

Section 6 describes and interprets the results of real time trials relative to the PATS Trajectory Predictor tool.

Section 7 provides conclusions and makes recommendations for future work utilising the PATS Trajectory Predictor tool.

Section 8 provides definitions of acronyms, terms and references used throughout the document.

# 2. OPERATIONAL CONCEPTS

## 2.1 OPERATIONAL CONCEPT

The main purpose of the Trajectory Predictor is to provide the controller with a close representation of the 4D trajectory that would be calculated by an air-EFMS, as a result of the proposed constraints on it's ideal trajectory. This enables the controller (or other PATs) to manipulate the route or constraints, model the effect, and assess the impact on the aircraft's 4D trajectory before uplinking them to the aircraft. This removes the potential need for several uplink-downlink iterations before a successful solution is achieved (which could be very costly and time consuming). When a satisfactory solution is found on the ground, the latest constraint set is uplinked to the aircraft, which will then re-predict and downlink the actual trajectory that will be flown. This may differ slightly to the ground-predicted trajectory (for example, due to operator specific preferences) but should be close enough so not to require further constraint manipulation.

The Trajectory Predictor is also used to calculate 4D trajectories for non-datalink equipped aircraft that are unable to downlink the trajectory that they are flying. In this case, the ground predicted trajectory is used for conflict detection and planning purposes. The text advisories produced by the Trajectory Predictor can be used by the controller as tactical instructions to maintain the aircraft on the planned trajectory. This may be required if an aircraft goes to manual operation, or if the ground are unable to uplink the 4D constraints for an aircraft (as is the case for a non datalink equipped aircraft).

Once a suitable trajectory is available (and downlinked where appropriate), the Trajectory Predictor calculates the contract and large deviation tube, which 'encloses' the 4D route. The contract tube is uplinked to the aircraft (or the aircraft is instructed to use the default tube sizes) and defines the airspace through which the aircraft is contracted to fly. The aircraft is permitted to manoeuvre within this tube as much as necessary - for optimisation. The large deviation tube is held by the ground system and is used by the flight path monitor to alert the controller if the aircraft deviates significantly from its contracted trajectory. Both the contract and large deviation tubes can be altered in dimensions to meet the needs of the airspace (for congestion, safety etc.).

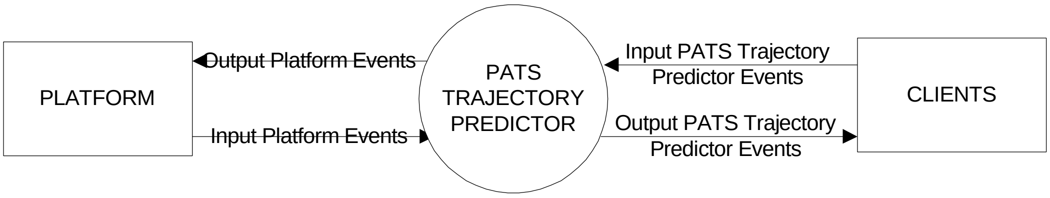
The 4D trajectory stored in the ground system can be used to display the entire route of the aircraft to the controller, using the HMI. This provides quick graphical information regarding the intended destination and route of the aircraft and will enhance the controllers situational awareness.

If the aircraft deviates from the 4D trajectory, the controller will be alerted by the flight path monitor.

## 2.2 CONTEXT DESCRIPTION

This section identifies the interactions between PHARE system components and the PATS Trajectory Predictor.

The following diagram illustrates the interactions. The central bubble represents the PATS Trajectory Predictor tool. The surrounding boxes represent each of the PHARE system components that the tool interacts with, and the connecting arrows represent the direction of communications between the system components and the tool.




The diagram identifies that the PATS Trajectory Predictor tool interfaces with facilities within the integrated platform, and other clients, and that there is two-way communication with both of these entities.

The PATS Trajectory Predictor does not utilise any historical information relating to an aircraft's previous flight profile to assist in the generation of an aircraft's future trajectory (the tool runs “context free”). The tool generates an aircraft's trajectory from it's current state (data taken as a snapshot when a prediction request is made, and includes current airspeed, heading, altitude, rate of climb / descent etc.) and attempts to meet any future 4D constraints whilst conforming to the appropriate BADA aircraft performance model for the aircraft type.

The following sections describe the PATS Trajectory Predictor tool external interfaces.

### 2.2.1 Sub-system Terminators

a) Platform

To achieve the functionality expected of the TP other data servers are accessed. The data servers accessed are:

- Airspace server
- BADA server (aircraft performance data)
- Meteorological data server

b) Clients

The tool expects to receive requests for it's services from external clients which are represented by this terminator. Examples of clients that may request the services of the tool are:

- Arrival Manager
- Departure Manager
- Problem Solver

- Co-operative Tools
- Tactical Load Smoother
- Negotiation Manager

There are other clients that may utilise the trajectories produced by the tool as a result of requests from other clients. Examples of such clients are:

- Conflict Probe
- Flight Path Monitor

### 2.2.2 Sub-system Inputs

a) Input Platform Events

The tool receives airspace, aircraft performance and meteorological data from servers within the host platform to assist in the generation of aircraft 4D trajectories.

b) Input PATS Trajectory Predictor Events

The tool receives trajectory generation requests.

A trajectory generation request contains aircraft information, aircraft state data, and the strategic constraint list which describes the aircraft's flight plan. Although the generation could be an initial generation or an update generation nothing within the supplied data identifies the type of generation that is required. The generation type is determined internally to the tool.

The tool outputs a 4D Trajectory in response to this type of request.

### 2.2.3 Sub-system Outputs

a) Output PATS Trajectory Predictor Events

The tool produces output in response to trajectory generation requests made of it. The outputs produced by the tool are as follows.

- Generation Status

  The tool produces a status that indicates the completion status of the requested trajectory generation. The status can be one of constraints met, constraints not met or generation failure.

  A status of constraints met indicates that a good generation was performed, and all of the specified input constraints are met in the computed 4D trajectory.

  A status of constraints not met indicates that a 4D trajectory was produced, however one or more of the specified input constraints are not met within the computed trajectory. In this case, the constraints not met report (described below) contains data to identify which of the input constraints are not met.

  A status of generation failure indicates that computation of a 4D trajectory was not possible. In this case, no data will be contained within the 4D trajectory, tubes or advisories.

- 4D Trajectory

  The trajectory describes the computed behaviour of an aircraft defined as a list of points, sufficient in number to allow linear interpolation between them. These points are described in terms of latitude, longitude, altitude, time and type (i.e. start of turn, end of turn, bottom of climb, top of climb, top of descent, bottom of descent or null).

- Tubes

  The tool produces a contract tube whenever it generates a trajectory. The contract tube is comprised of a series of windows at each point of the trajectory. The window provides offsets perpendicular to track, along track and in altitude.

  For unequipped (without 4D FMS capability) aircraft, the tool also produces a large deviation tube.

  Tubes are used by other tools in the determination of, for example, deviations from contracted trajectories and conflicts.

- Constraints Not Met Report

  The constraints not met report contains valid data when the TP has not been able to meet all of the specified input constraints (indicated by a status of constraints not met). When valid, the data indicates which of the constraints have not been met and identifies the amount of deviation between each of the constraints that have not been met and the computed trajectory.

- Advisories

  The tool produces advisories whenever it generates a trajectory. Advisories are text messages with time stamps, that are designed to assist controllers with guiding aircraft to ensure that they do not deviate from the generated 4D trajectory.

## 2.3. DEVELOPMENT PROCESS

### 2.3.1 History of Tool Development

The PATS Trajectory Predictor development evolved throughout a series of PHARE Demonstrations (PD): PD1 took place towards the end of 1995; PD2 took place in late 1996 and beginning of 1997; and PD3 took place in 1998. The TP as used during PD1 was designed and developed by DRA Malvern, and made use of functionality provided by the EFMS. The EFMS has a trajectory generation capability which when operating in the air would pass trajectory information to the aircraft's navigation system to maintain the aircraft on the desired track and to follow the desired vertical profile. The generation facility of the EFMS is used by the TP on the ground. In this case the trajectory is returned via the trajectory server to other clients. For a full description of the EFMS, see reference [4].

PD1 was an en-route scenario, hosted by NATS at DRA Malvern. Initial versions of the TP software were developed, and integrated with other tools within a framework called CMS. The scope of the tool developed for PD1 was restricted to en-route and descent flight phases. Time and altitude window constraints were also supported.

PD2 extended PD1 to include the TMA arrival scenario and was hosted by DLR in Germany. The TP software was enhanced to include additional aspects relevant to TMA arrival operation such as handling holds and stacks. The PD2 TP provided predictions for the phases of flight from the en-route cruise to the runway threshold at landing.

PD3 was a multi-sector scenario hosted by NLR, EEC and CENA, and included the full route of aircraft from departure at one airport through en-route control to arrival at another. For the first time the underlying EFMS supported holds and stacks. The TP functionality was extended to provide advisory information used by the GHMI and the FPM, and to provide Tubes data. For PD3 the TP was no longer provided with Tactical Constraints when calculating an update prediction, rather the TP had a new function Determine_Prediction_Type which used known parameters, such as aircraft position, heading and the position of the strategic constraints, and worked out whether the prediction request was for an initial prediction or an update prediction. An update prediction would then make use of a new capability of the EFMS, Calculate_Abeam_Point.

### 2.3.2 Why it was developed that way

The Trajectory Predictor was developed to meet the requirements of the PHARE trials. For the PD1 trial, the en-route functionality was developed (4D prediction meeting altitude and time constraints). For PD2, the TP was upgraded to handle the arrival phase of flight - for example STARS, holds, descent and final approach. For PD3, departure requirements were also incorporated.

In addition, as a result of the trials and technical/operational discussions, other modifications to the Trajectory Predictor were proposed and incorporated (such as the facility to handle update predictions if the aircraft is deviating from its planned trajectory) to enhance the services offered by the TP.

A key design decision for the TP was the decision to utilise the EFMS as the “engine” for generating aircraft trajectories. The EFMS is designed for use on-board an aircraft for computation of an aircraft’s future flight profile that meets the performance capabilities of the aircraft, and any 4D constraints derived from the flight plan and / or set by the flight crew.

During the initial design phases of the PHARE concept, there were concerns that differences between flight profile predictions within the ground system and on-board aircraft would result in the ground system predicting trajectories during what-if modelling that bear no relation to the actual performance capabilities of the aircraft. Therefore, the decision was taken to use the same trajectory computation algorithms within the ground system as those used in the aircraft, hence the EFMS was selected for the TP. The use of the EFMS introduced difficulties with performance and re-generation consistency. These are discussed within section 4 of this document. Additionally, PHARE trials, for example PD/1++, have demonstrated that the use of different prediction methods within ground and air systems does not result in significant problems.

### 2.3.3 Dropped ideas and concepts

- Early / late Time Calculation

  Calculation of early/late time at a point involved calculating the earliest and latest times an aircraft could be expected to arrive at a specified navigation point on it's route.

  The earliest and latest times were found by requesting predictions with a time constraint on a point set as very early or very late (as appropriate). The Trajectory Predictor calculated a trajectory which attempted to meet the extreme constraint as closely as possible, thus providing either the earliest or latest arrival time for a point.

  This function was removed from the TP as the time taken to produce the predictions was significant as it involved repeated, iterative calculations. It was thought that it would be sufficient for the AM to chose a time window for the arrival and only request re-calculation (and confirmation) once the sequence was determined.

- Cost Calculation

  There was an original intention to include functionality within the TP to compute the fuel cost of flying a generated trajectory. However, this was not pursued within the PHARE program.

- Error Tube Calculation

  The error tube was an estimate of the inaccuracy of the prediction expressed as a tube around the trajectory. This was considered to be of little value to the system/controller - an EFMS equipped aircraft is expected to follow a trajectory despite the inaccuracies, using it's guidance system (providing it can meet the performance requirements). If the required performance cannot be met, and the aircraft does deviate from the trajectory, the deviation tube will alert the controller and action can be taken to negotiate a new trajectory that can be flown.

- Turn Type Specification

  Following the PD/1 trial, functionality was added to the Trajectory Predictor to add the facility for the turn type to be specified. The turn type could either be a constant ground radius (CGR) or a constant bank angle (CBA) turn. This was to cater for the non-RNAV equipped aircraft, which would only be able to perform CBA turns, whilst RNAV equipped aircraft will be performing CGR turns. This was considered unnecessary as most/all aircraft in the PHARE timeframe (2010) will be RNAV equipped and therefore capable of CGR turns. Therefore, for the PD/3 trial it was decided to hard code the Trajectory Predictor to make all turns CGR turns.

# 3. REQUIREMENT DESCRIPTION [5]

## 3.1. USER REQUIREMENTS

### 3.1.1 Controller Support

The TP shall support ground controllers in their manipulation of constraints, to allow them to model the likely effect of their actions prior to those constraints being sent to the aircraft.

### 3.1.2 PATS Support

The TP shall support the PATS by providing the following capabilities:

- the calculation of a 4D trajectory from the current position of the aircraft to touchdown
- the generation of advisories which allow a controller to instruct the pilot how to maintain the aircraft on this trajectory
- the computation of a contract tube.

## 3.2. FUNCTIONAL REQUIREMENTS

### 3.2.1 Determine Prediction Type

a) Requirement

The tool shall determine whether the trajectory generation request is a request to generate an aircraft's initial trajectory or is a request to generate an update to an aircraft's trajectory.

b) Description

Since the Trajectory Predictor is no longer provided with a resume navigation point, it has to determine if a request is for an update to an aircraft's trajectory or an initial trajectory generation. It does this by looking at where the aircraft is, where it is heading and where the strategic constraints are.  If the aircraft appears to have passed the first constraint point, then the tool determines that the aircraft has already started flying along it's route, and as such the generation request is an update request.  Otherwise, the request is assumed to be for an initial generation.

### 3.2.2 Computation of a 4D trajectory

a) Requirement

The tool shall provide a ground based prediction of aircraft trajectories in the climb, en-route, descent and approach phases of flight.

[5] A formal definition of the requirements can be found in document DASR\PD3TP\URD02

b) Description

The trajectory predictor shall be able to generate trajectories for holds, stacks, missed approaches and fan and trombone path-stretching.

The trajectory predictor shall compute a trajectory only when requested. This will occur:

- following the creation of constraints derived from the aircraft's flight plan
- following the completion of constraint modification
- when a deviation is detected

For each 4D trajectory the tool shall generate advisories. These advisories will be correctly formed for conveyance by the controller.

### 3.2.3 Compliance

a) Requirement

The tool shall attempt to generate a trajectory that meets all constraints.

b) Description

Constraints should only be applied by controllers when separation is compromised - the EFMS is designed to generate an optimal trajectory for the aircraft based on relatively few constraints. Every additional constraint imposed on a trajectory de-optimises that trajectory (increasing operating costs and controller workload), reduces the performance of the EFMS and may even cause the trajectory generation to fail. Therefore, it is important that constraints are both carefully and sparingly applied.

If a trajectory is generated that fails to meet all of the specified constraints then the tool shall identify those constraints which are not met.

## 3.3. IMPLEMENTATION DEPENDENT REQUIREMENTS

### 3.3.1 Integration

a) Requirement

The tool shall be capable of being integrated into a number of different air traffic control simulation systems. These systems shall include:

- NARSIM (at NLR)
- ESCAPE (at EEC)
- NRF (at NATS)
- CMS, PARADISE (PHARE)
- DAARWIN (at CENA)

b) Description

The tool shall be developed without dependency on the platform that it is to be integrated into. Additionally, a suitable API shall be provided that ensures that the integration activity is as simple as possible.

### 3.3.2 Client / server architecture

a) Requirement

The tool shall be developed to work in a client / server architecture.

b) Description

The tool shall be developed so that it is capable of being integrated into a client / server architecture. However, the TP shall be developed to receive a request, generate a trajectory and issue the response. The TP shall not be capable of handling multiple generation requests. If generation requests are issued whilst the TP is already processing a request, the platform shall provide functions for queuing and prioritising requests as appropriate.

### 3.3.3 Platform independent

a) Requirement

The tool shall be developed in an operating system independent manner.

b) Description

The tool shall be developed so that there is no reliance on any underlying operating system (for example, UNIX). The developed software shall not make references to operating system specific functions.

This page left intentionally blank

# 4. IMPLEMENTATION

## 4.1. HOW DEVELOPED

The PATS Trajectory Predictor was originally developed by DRA at Malvern under contract to CAA/NATS for the PD1 trial. The initial deliveries of the tool were made in two phases to the PD1 project team at DRA Malvern for integration into the PD1 simulation system.

The first phase (phase 1) was a trajectory predictor of limited capability, it's purpose was to provide earliest availability of software to support PD1 system integration. It's limitations included: support for only one aircraft, no early/late time calculations and fixed (zero wind) meteo conditions. It was used to determine the degree of testing and reliability required, it was not required to operate reliably for the full range of input data.

The second phase (phase 2) was a delivery of software that had been sufficiently tested and debugged so that the PATS Trajectory Predictor achieved the required degree of reliability for PD1 simulations. The final, phase 2, delivery for PD1 included CMS interface specifications and trajectory generator software from EFMS Phase 1b version 3.1.

The final PD1 TP provided:

- en-route, cruise, and en-route descent to gate phases of flight
- BADA point mass Aircraft modelling for many aircraft types
- support for altitude and time constraints
- 4D trajectory prediction
- calculation of early / late times
- calculation of error tube
- support for constant ground radius turns only
- fan path stretching
- calculations were based on the WGS84 Earth model.

For the PD/2 trial, the PATS Trajectory Predictor tool was also developed by DRA at Malvern under contract to CAA/NATS. The tool was delivered to the PD2 project team at DLR, Braunschweig for integration in to the PD2 simulation system. The PD/2 version of the PATS Trajectory Predictor was based on EFMS phase 1b.

For PD2, the capabilities of the PD/1 Trajectory Predictor were extended to include:

- initial climb and final approach phases of flight
- support for constant bank angle turns
- trombone path stretching
- interim solution to multi-level holding
- prediction of missed approach procedures was not supported.

For the PD/2+ trial, the PATS Trajectory Predictor was developed by DASR (NATS) at Hurn. The software was delivered to the PD/2+ integration team also at Hurn. The PD/2+ version of the PATS Trajectory Predictor was based on EFMS version 2.2.

For PD3, the capabilities of the PD/2 Trajectory Predictor were extended to include:

- The EFMS now calculated trajectories to the threshold
- Calculation of a large deviation tube
- Calculation of a contract tube
- Removal of error tube calculation
- Advisory generation
- Incorporation of version 2.6 of BADA data
- Stack handling

The PD/3 version of the PATS Trajectory Predictor was based on EFMS version 2.5.

The PATS Trajectory Predictor has been developed using object orientated principles, using the Booch object orientated development method as described in reference [2].

### 4.2. TECHNICAL ENVIRONMENT

The tool is written in the ADA 83 programming language. The source code is maintained at NATS on a UNIX file server accessed from a network of SUN workstations. Modifications to the source code are managed using the RCS source code control toolset.

Executable versions have been successfully built using the VERDIX compiler / linker toolset. The tool has been successfully integrated into five different simulation platforms, the NATS Research Facility at the ATMDC in Bournemouth; NARSIM at NLR in Amsterdam; ESCAPE at EEC in Bretigny; DAARWIN at CENA; and the PHARE platform CMS, PARADISE.

### 4.3. PERFORMANCE ISSUES

Originally, there were no performance requirements specified for the TP since response time is largely dependent on EFMS and CMS performance. However, the issue of performance was raised when NLR raised a discrepancy report complaining about poor performance, where the average time to generate a prediction was 2 seconds, and could be as bad as 7 seconds under some circumstances. This was addressed by removal of .DAT files, hence decreasing the amount of I/O performed for each trajectory generation.

### 4.4. PROBLEMS FOUND AND SOLVED

There were a number of problems found and solved throughout the development of the PATS Trajectory Predictor, and these are recorded within the PHARE Problem Tracking System.

## 4.5. UNSOLVED PROBLEMS

### 4.5.1 Only CGR Turns Supported

The design separates the lateral route from the vertical profile. The lateral route is calculated before the vertical profile using constant ground radius turns. Hence only aircraft capable of flying constant ground radius turns in all conditions can be accurately modelled. However, in the real world, FMS equipped aircraft are expected to fly only constant ground radius turns.

### 4.5.2 Performance Dependent Constraints Unsupported

The EFMS does not support performance dependent constraints, all constraints being geographically based. An example of a performance dependent constraint is the definition of a turning point as dependent on reaching a specified altitude. This type of constraint is commonly used in operational SID and STAR definitions, often as part of noise abatement procedures. It is therefore not possible to model such procedures using the EFMS TP.

### 4.5.3 Fixed Order Of Flight Phases

Phases of flight are scripted to be flown in a fixed, restricted order. Extra sub-phases may be inserted automatically in order to meet constraints but the basic restrictions mean that a missed approach procedure, changing from approach into an ‘initial’ climb, as was required for PD2 onwards, cannot be modelled as one continuous prediction.

### 4.5.4 Consistency Of Trajectory Re-generation

During some of the PHARE demonstrations, particularly when aircraft on approach have been simulated, instances of inconsistent trajectory re-generation have been noted. Limited investigation has identified that when aircraft are at different stages of descent, predictions of gate arrival times are not consistent with earlier predictions, despite there being either no change in the 4D constraints, or an updated gate arrival time constraint being set that specifies an arrival time equivalent to the time that an earlier generation predicted for arrival at the gate. It may be that the simplistic, stepwise implementation within some EFMS algorithms may be the cause of some of these problems. See reference [4] for more information.

These inconsistencies have had a significant impact on increasing the workload and frustration of planning controllers, particularly the arrival sequence planners. It is vital that any future system should employ a trajectory generation technique that is capable of consistent re-generations, in order to provide an adequate level of support to the air traffic planning task.

## 4.6. LESSONS LEARNT

### 4.6.1 Context Free Operation

The PATS Trajectory Predictor has been implemented so that it executes "context free". That is, for each trajectory generation it utilises information regarding the current state of the aircraft, 4D constraints to be met, aircraft type specific performance model and weather data to generate a trajectory from the aircraft's current position to the end of it's planned route. The tool does not utilise any information regarding the past flight profile of the aircraft.

The EFMS, at the core of the PATS Trajectory Predictor, includes algorithms to determine an aircraft's current flight phase from the specified input data. This initial flight phase is used as a basis for determining the aircraft's remaining trajectory, and inaccuracies in it's determination have a significant effect on the trajectory generated. Additionally, continuity in flight profile when transferring from a current trajectory to a new predicted trajectory is critical for both equipped and unequipped aircraft. For example, if an aircraft is in a descent phase when flying the current trajectory then, assuming that there is not a new 4D constraint that requires the descent phase to be terminated, the new predicted trajectory should continue the descent without inserting even a momentary level flight phase at the start of the new trajectory. The algorithms for determining the initial flight phase are critical for ensuring continuity in flight profile between trajectory generations.

Additionally, for PD3 some functionality was added to the PATS Trajectory Predictor to determine if the prediction request for an aircraft was an initial prediction or an update. This was to ensure that the tool only considers 4D constraints that have not yet been past by the aircraft. Since the tool was running "context free", a rather complex function was added to determine if the aircraft had progressed along it's constraint list, and if the aircraft had started to progress along the constraint list then this was determined to be an update prediction, otherwise an initial prediction was assumed.

It would appear that there are benefits to be obtained from introducing some contextual awareness into the operation of the tool. This would provide additional information that could be used to reduce the complexity and increase the reliability of the algorithms that determine the initial flight phase of an aircraft, and that determine if the prediction request is for an initial or an update prediction. Improving the reliability of the algorithms will improve the continuity when transferring to a new predicted trajectory. Reducing the complexity of the algorithms should also yield some performance improvements.

### 4.6.2 Accuracy Of Generations

The trajectories generated by the PATS Trajectory Predictor, utilising the EFMS for the core generation algorithms, accurately model the precise aircraft behaviour that is required to meet the specified 4D constraints. Clearly, such a high degree of modelling is computationally intensive, and this has a significant impact on the time taken to generate a trajectory.

During the integration phases of developing systems to support real time trials within the PHARE programme, it has become apparent that the PATS Trajectory Predictor tool provides a central service to the integrated system, and is used continually and extensively throughout a simulation exercise. Performance of the tool has been identified as a critical factor in achieving adequate performance within the integrated PHARE system.

It may be that such a high degree of accuracy is not required within trajectories generated by the PHARE ground system, and that a less accurate prediction will be adequate and capable of being generated in a fraction of the time. As long as the trajectory predictor is able to provide a mechanism for modelling the ability of an aircraft to meet a revised set of 4D constraints (so that iterations of uplinking constraints to an aircraft and downlinking a trajectory that fails to meet the constraints are avoided), and produces an adequate representation of an unequipped aircraft's profile for conflict detection and flight path monitoring purposes (the trajectory of an equipped aircraft will be downlinked from the aircraft to the ground system), then there is no need to precisely model aircraft behaviour within the generated trajectory.

### 4.6.3 Approach Route Structure

The PATS Trajectory Predictor imposes a fixed structure on the approach route, requiring a metering fix and star gate to be present in the route specified within the input parameters. These fixes are highly significant to the tool and the EFMS algorithms embedded within it.

This fixed approach route structure has provided unacceptable limitations to the controllers operating the system in an approach simulation. During heavy traffic periods, it is quite routine to separate traffic laterally on entry into the TMA. This involves routing aircraft on parallel tracks that do not necessarily fly directly overhead the metering fix. Additionally, with total disregard for the desires of the controller, the EFMS insists that an altitude constraint is set at the metering fix.

For future systems, the assumptions regarding route structure and the presence of key fixes with constraint lists, should be minimised, since these assumptions are based on current day operation that may not be applicable to future systems. The tool should be as flexible as possible, and be driven by the initial aircraft flight plans and subsequent flight plan updates initiated by other automatic tools or by manual controller intervention.

### 4.6.4 Advisory Message Generation

Whilst it was technically inappropriate for the TP to generate text string messages describing the advice to be given to pilots, this function was added for PD/3. Doing so placed a requirement upon the TP to "know" the format and nature of the advisories to be given. Such knowledge does not "fit" with the expected capabilities of the TP. Rather, the TP should simply specify what is required of the aircraft to fly it's contracted flight trajectory. The business of forming the displayed text message would then be the GHMI's, which is far more appropriate.

### 4.6.5 Systems Engineering Approach

The PHARE program has been organised in such a way that development of tools, platforms and GHMIs has been carried out by different teams in different European countries. This distributed organisation has caused some communication difficulties between teams, and there has not been a central team to advise on how the integrated system should be achieved. This has resulted in the integration teams (responsible for integrating systems to support a PHARE demonstration) having to make fundamental decisions about the manner in which the different system components interact, without necessarily understanding the impact on the underlying, overall operational concept of PHARE. Additionally, it has resulted in system components being developed that do not properly interact with each other (without modification).

Future developments would benefit from central management by a systems engineering function, that has responsibility for developing and modifying the overall system concept (requirements), and partitioning the concept so that system components and interfaces are identified, and consistent requirements allocated to each. Systems engineering should be closely involved in the systems integration activity to ensure that the system components are properly linked together to provide a system that satisfies the system level PHARE concept.

Management by a central team will also provide far more opportunity for lessons learnt from one demonstration to be carried forward to the next. PHARE has not been successful at carrying forward lessons learnt into future work packages.

### 4.6.6 System Architecture

The increased processing requirements of data within the PHARE system has caused difficulties with performance within the client / server systems supporting PHARE demonstrations.

The host platforms used for supporting PHARE demonstrations have all been developed using a client / server architecture supported by different middleware at different sites. The method adopted for integrating PHARE tools into host platforms has been to “wrap” a tool within an appropriate API (which is understood by the site specific middleware), and to either create another client or server (as appropriate), or to merge the tool with an existing client / server within the host system. The client / server approach has created bottlenecks within the host platforms, most noticeably in the case of the trajectory predictor which provides prediction services used by the each of the available GHMI positions and the arrival manager.

To attempt to overcome this problem, system integrators have had to juggle with allocating clients and servers to different and enhanced processors, and to enhance network performance to improve the rates at which data is transferred between processors. In the case of the trajectory predictor, it has been necessary to add extra platform functionality to utilise multiple instances of the tool executing within the platform.

These problems bring into question the underlying client / server system architecture, and it may be that a new architecture would be more appropriate to support the processing requirements of an advanced PHARE system. Future developments should reconsider the complete system implementation, particularly in light of more recent developments in distributed object implementation using CORBA. CORBA provides the capability to implement a system as a set of distributed objects without having to corrupt an object orientated design model into a series of clients and servers prior to implementation. Therefore, an object orientated design can be implemented as designed, and the CORBA compliant middleware would manage creation of instances of objects and offer the capability for balancing object creation across the available processing resource. This provides a flexible architecture that is not constrained by static allocation of clients and servers to available processors.

#### 4.6.7 Common Platform For Demonstrations

There has also been a high degree of duplicated effort during the integration activities prior to a PHARE demonstration. The different teams carrying out these activities have had to overcome similar difficulties when integrating the PATS tools within the chosen host platform for their particular demonstration. Duplicated effort could have been avoided if a common platform had been used to support the PHARE demonstration program.

Future programs of this nature should select a host platform for trials to be used from the outset. This platform should be established and stable prior to the integration of further tools to support advanced processing. The platform will then evolve as the trials program develops, with problems found during one trial being overcome prior to the next. Additionally, the software build toolsets should be common to all developers producing software to be integrated into the host platform.

The benefit of adopting this approach was evident during the PD/1++ staged at NATS on the NRF. The PHARE system within the NRF had evolved through the staging of the PD/1, PD/1+, PD/2+ and finally PD/1++ PHARE demonstrations. In the periods between trials, NATS had the opportunity to address problems found in previous trials, and had the opportunity of ensuring continuity within the teams of engineers working on the development of the PHARE NRF system. The stability within the platform used for the final PHARE trial staged on the NRF (PD/1++) has enabled a full investigation of the trial objectives to take place.

This page left intentionally blank

# 5. USAGE OF TOOL

## 5.1. OPERATIONAL USAGE

### 5.1.1 During Trial PD/1

Extracted from the PD/1 trial report (reference [6]):

*"The trajectory predictor (TP) is a ground based version of the tool used in the EFMS to predict the trajectory of the aircraft. The ground TP uses a database of aircraft performance characteristics, the initial flight plan and trajectory constraints entered from the GHMI to generate close-to-optimal 4-D trajectories for each flight. This allows the controller to carry out accurate 'what-if' modelling with tools such as the problem solver. Although the TP is capable of forecasting an entire flight from take-off to landing, in PD/1 the forecasts were limited to the 20-30 minutes flying time for flight across the simulated airspace."*

For full details of the PD/1 trial see reference [6].

### 5.1.2 During Trial PD/1++

As trial PD/1.

For full details of the PD/1++ trial see reference [9].

### 5.1.3 During Trial PD/2

Extracted from the PD/2 trial report (reference [5]):

*"For the ground system the PATS Trajectory Predictor provided the trajectory as the new basic information entity extending the flight plan information in use today (for the airborne part a 4D FMS and datalink equipped aircraft can provide this information).*

*The Trajectory Predictor generated the trajectory information for each aircraft. In PD/2 only the arrival part of the trajectory was used, equivalent to about 30 minutes flying time including the top of descent from cruise level until the Approach Gate (10NM from runway threshold). All trajectories were generated using standard arrival routes (STARs)."*

For full details of the PD/2 trial see reference [5].

### 5.1.4 During Trial PD/2+

As trial PD/2.

For full details of the PD/2+ trial see reference [8].

### 5.1.5 During Trial PD/3 (at CENA)

The PATS Trajectory Predictor was not used during the PD/3 experiments at CENA.

For full details of the PD/3 (CENA) trial see reference [12].

### 5.1.6 During Trial PD/3 (at EEC)

Awaiting information.

For full details of the PD/3 (EEC) trial see reference [10].

### 5.1.7 During Trial PD/3 (at NLR)

As stated previously in Section 4.3, performance was an issue with the Trajectory Predictor. During preparations for the PD/3 Continuation Trial considerable work was done to reduce the resource and processing required by the Trajectory Predictor. Furthermore, to avoid queuing, multiple instances were run on the NARSIM platform and in the final trial there were 10 instances of TP running. In the trial, despite the impact of the Arrival Manager repeated sequencing activities, from the operators viewpoint there were no perceptible TP performance problems.

There were also amendments to the requirement of the TP for a Metering Fix on entry to the TMA. The final version of the TP would allow modification of the position and level of the Metering Fix allowing easier resolution of conflicts at the TMA boundary.

For full details of the PD/3 (NLR) trial see reference [11].

## 5.2. TECHNICAL USAGE

The tool is supplied as a set of ADA source files that are intended for integration into an air traffic control simulation system.

The source code is provided with a number of ADA API routines that are used by system integrators as an interface between the tool and the software that the tool is being integrated into.

The source code is delivered as a single compressed file that is created using the ‘gzip’ and ‘gtar’ gnu programs, executed under the UNIX operating system. The source code should be uncompressed using the ‘gunzip’ program and unpacked using the ‘gtar’ program using a specific set of command line options.

The tool is supplied with suitable ‘make’ files used to produce object libraries that can be subsequently linked with interface software to create an executable version of the tool. It is intended that the tool should be built using the ‘make’ utility running within the UNIX operating system.

The document DASR\PD3TP\TP_UG02.doc provides a full description of the technical usage of the software.

# 6. RESULTS

## 6.1 APPLICABLE RESULTS

The following high level objectives have been identified for the PATS Trajectory Predictor to provide a basis for determining if the results from PHARE demonstrations indicate that the operational concepts implemented by the tool have been achieved:

- OBJECTIVE: Improved Quality Of Service through:
  - Aircraft flying preferred trajectories
- OBJECTIVE: Improved Airspace Capacity through:
  - Aircraft flying preferred trajectories
- OBJECTIVE: Reduced Controller Workload through:
  - Provision of planning and guidance assistance
- OBJECTIVE: Adequate Usability through:
  - Consistency of trajectory generations (between ground system and aircraft)
  - Consistency of trajectory re-generations
  - Advisories for ‘3D’ aircraft (frequency and accuracy).

The results from the PHARE demonstrations have been reviewed to identify applicable results to support conclusions relating to the objectives identified above. Since there has been such a wide use of the PATS Trajectory Predictor tool within PHARE demonstrations, results from IOCPs and other trial runs (including PD/1+) have not been reviewed. The applicable results are reported in the following sections.

## 6.2 TRIAL PD/1

Results from the PD/1 trial staged by NATS indicate that there are potential benefits to be obtained from the introduction of advanced tools, 4D FMS and datalink in en-route airspace. The PD/1 trial concluded that “*PD/1 successfully demonstrated the integration of air and ground air traffic management, in en route airspace, through computer assistance tools, 4-D flight management systems and air-ground datalink. The evidence suggests that gains in controller workload, airspace capacity and quality of service to airlines are achievable.*”

The PD/1 trial also included demonstrations of the airborne element of the PHARE system, where the EFMS (the core of the PATS Trajectory Predictor) is used to fly an agreed (with ATC) conflict-free trajectory while operating within 4D constraints. The PD/1 trial concluded that “*The PD/1 airborne demonstration programme, with participation of the NATS funded DRA BAC 1-11, was extremely successful. The flights provided a convincing demonstration to the aviation community of the ‘silent cockpit’.*”

A full description of the PD/1 trial and results can be found in document reference [6].

### 6.3 Trial PD/1++

The results from the PD/1++ trial presented here are preliminary, and may be updated when the PD/1++ final report is published. The NATS PD/1++ project was a continuation of the previously conducted PD/1 and PD/1+ trials and was specifically designed to begin the process of exploring the introduction of PHARE tools and operational concept within alternative en-route airspace structures.

Comparison with a "no tools" baseline was not within the scope of this trial and, therefore, it is not possible to state with certainty that the ability to successfully manage the traffic within PD/1++ can be attributed to the PHARE advanced toolset alone. However, the fact that such a successful trial was run using the toolset, and specifically the PATS Trajectory Predictor as a central component, is an indication that the tools were providing the intended service and highlights successful operation of the PHARE Trajectory Predictor within an en-route scenario.

Some selected conclusions have been extracted from reference [9] and follow:

> "*The introduction of the PHARE concept alongside direct routes and larger sectors, received controller approval and warrants further, detailed investigation."*
>
> *"An environment through which direct routes are flown through larger sectors implicitly improves the service provided to aircraft and was supported by controller comments."*

A full description of the PD/1++ trial and results can be found in document reference [9].

### 6.4 Trial PD/2

Results from the PD/2 trial staged at DLR indicate that there are potential benefits to be obtained from the introduction of advanced tools, 4D FMS and datalink in an extended terminal area airspace. The PD/2 trial concluded that "*Experimental evidence suggests that the PHARE concept of trajectory-based traffic guidance provided by the advanced tools and human/machine interfaces was approved by the controllers and pilots, and that it has the potential for improving traffic throughput and quality of service, at acceptable levels of controller workload*."

Applicable results extracted from reference [5] are as follows :

- Quality Of Service
    - "*It can be concluded that a benefit of the introduction of PATs and GHMI could be observed such that particularly higher traffic demand could be handled more smoothly and efficiently. That efficiency gain was achieved without any detrimental effect on separation. There was even a positive effect on separation by the introduction of tools.*"
    - "*Significant benefits for the number of landings per hour, average flight time of aircraft, precision of delivery and separation were reported. It should be noted that the positive effects were mainly present under high traffic load.*"

- Workload
  - "*Statistical analysis of controller workload revealed, as an effect of the PD/2 PATs and GHMI introduction, some re-distribution of workload between tactical controller positions. Important to note is an observed decrease of workload at the Approach Pickup controller position which under reference baseline condition was the position with the highest workload. Furthermore, the introduction of 30% and 70% 4D FMS / Datalink aircraft in the traffic sample produced a stepwise reduction of workload for all tactical controller positions.*"

The PD/2 trial also included demonstrations of the airborne element of the PHARE system, where the EFMS (the core of the PATS Trajectory Predictor) is used to fly an agreed (with ATC) conflict-free trajectory while operating within 4D constraints. The PD/2 trial concluded that "*A PD/2 airborne demonstration programme using DLR's ATTAS Aircraft, with the ATTAS Experimental Cockpit integrated, was successfully accomplished. The ability of an aircraft to fly, in a routine manner, negotiated trajectories while operating on its inbound route down to the Approach Gate within continuous 4D constraints was convincingly demonstrated."*

### 6.5 TRIAL PD/2+

Results from the PD/2+ trial specifically related to the PATS Trajectory Predictor, primarily relate to technical problems encountered when using the tool in approach airspace. Since the main thrust of PD/2+ became to investigate the proposed PD/3 baseline, no measured exercises were completed for the advanced system. Therefore the advanced system was only explored using qualitative and subjective data. The following comments have been extracted from reference [8]:

> *"Problems were experienced relating to the use of the TP. These fell into three main categories: failure to generate reliably a trajectory; difficulty in generating adequate trajectories in certain circumstances; and the run-time performance of the TP software."*
>
> *"Significant difficulty was experienced in ensuring that the TP was able to generate trajectories in all the relevant circumstances. Further refinements to TP/EFMS algorithms may be required to ensure that fewer TP failures occur."*
>
> *"The TP is core to the operation of the advanced organisation, especially for the AM which uses the TP both for trajectory prediction and early / late time calculation. The performance of the TP is hence critical to the performance of the overall system. TP performance proved inadequate in the PD/2+ system."*

A full description of the PD/2+ trial and results can be found in document reference [8].

### 6.6 TRIAL PD/3 (AT NLR)

It is not intended to report on the originally planned PD/3 trials at NLR. Due to inadequacies in the GHMI software delivered to NLR for use in their PD/3 experiments, no advanced system validated runs were possible. NLR are continuing their efforts to demonstrate a subset of the PHARE PD/3 system under a PD/3 continuation project (see 6.9 below).

### 6.7 TRIAL PD/3 (AT CENA)

The PD/3 experiment staged at CENA did not utilise the PATS Trajectory Predictor within the validated system runs during the trial period. CENA used their own trajectory predictor tool. Therefore, the results from the experiments at CENA are not applicable to support conclusions about the PATS Trajectory Predictor and are not reported here.

A full description of the PD/3 (CENA) trial and results can be found in document reference [12].

## 6.8 TRIAL PD/3 (AT EEC)

The PD/3 experiment staged at EEC did not achieve any of its objectives within the context of PHARE due to the simulator functionality, which fell significantly short of the PD/3 design specification. However, throughout the four week trial period, controllers had sufficient exposure to the PHARE concept that a number of areas of concern regarding the concept were expressed. Nevertheless, the comments reported are not specifically related to the trajectory predictor tool and, therefore, are not reported here.

A full description of the PD/3 (EEC) trial and results can be found in document reference [10].

## 6.9 TRIAL PD/3 CONTINUATION (AT NLR)

During the PD/3 Continuation trial held at NLR, November 16th to 27th, 1998, there were no formal measured exercises performed since this period was originally planned as a pilot trial. However, the TMA working positions were closely observed and comments were canvassed from the TMA controllers with particular respect to the operational objectives of the PATS Trajectory Predictor.

It should be noted that there were a number of significant technical problems that may distort the significance of some of these comments.

- OBJECTIVE: Improved Quality Of Service through:
    - Aircraft flying preferred trajectories
        - "*Not yet planning for optimal, just resolving conflicts when replanning trajectories. Once again, the increased time available, coupled with better functionality of the system, allowed some optimal trajectory planning. This was achieved by straightening out route legs and, to a lesser extent during this simulation, by improving descent profiles by eliminating/reducing level stop-offs.*"
        - "*Suspect that all trajectories are not user preferred. Looking at some of the original trajectories (sometimes in the horizontal plane but more often in the vertical), it was clear that a significant number of trajectories were not optimal, and therefore were not likely to be user-preferred.*"

- OBJECTIVE: Improved Airspace Capacity through:
    - Aircraft flying preferred trajectories
        - "*By definition, if aircraft are flying user preferred trajectories then this must increase airspace capacity. By spreading out the traffic, the AIRSPACE certainly gained capacity, but the bottlenecks at the approach gate still could not be overcome.*"
- OBJECTIVE: Reduced Controller Workload through:
    - Provision of planning and guidance assistance
        - "*Familiarity and increased competence of the controllers operating the system, together with improved system functionality was reflected in the increasing capacity of controllers to offer help and share tasking*. "
- OBJECTIVE: Adequate Usability through:
    - Consistency of trajectory generations (between ground system and aircraft)
        - "*Did not consider that there were any significant inconsistencies*."
    - Consistency of trajectory re-generations
        - "*Having 're-planned' a particular trajectory as 'conflict-free' it was very common for the validated trajectory to come back with conflicts not previously thought to be worth a 'red'*."
    - Advisories for "3D" aircraft (frequency and accuracy)
        - No specific comment noted.

A full description of the PD/3 (NLR) trial and results can be found in document reference [11].

## 6.10. ACHIEVEMENT OF CONCEPT

This section has been partitioned to discuss each of the key operational concepts of the PATS Trajectory Predictor in turn.

### 6.10.1 Trajectory Prediction

a) Desired / expected results

Improved quality of service by aircraft flying preferred trajectories.

Improved airspace capacity by aircraft flying preferred trajectories.

Reduced controller workload as a result of using trajectory predictions within the planning process.

b) Discussion

Since the PATS trajectory predictor has provided such a central service within the integrated systems used to support the PD/1, PD/2 and PD/3 demonstrations, the mere fact that successful demonstrations have been staged is an indication that the tool has achieved, at least in part, this aspect of the operational concept.

Results from the airborne demonstrations performed within the PD/1 and PD/2 trials provide further confirmation about the accuracy of the 4D profiles generated by the EFMS software, which is used as the core of the PATS Trajectory Predictor.

Results from the PD/1 (en-route) and PD/2 (TMA) trials indicate that there is the potential for improvements to quality of service and airspace capacity (particularly under high traffic load), and a reduction in controller workload as a result of introducing the PHARE advanced toolset and GHMI. The results from the PD/1++ trial are awaited, and it is expected that they will provide further support to these conclusions.

Comments from the PD/2+ trial identify a number of technical problems associated with the PATS Trajectory Predictor, particularly with respect to reliability and performance. The performance issues are most concerning since the impact of poor performance within such a central and frequently used tool, on the overall integrated system behaviour, can be catastrophic.

Comments from the PD/3 trials (excluding the PD/3 Continuation trial) are subjective and, in the main, highlight problem areas to be considered within further research of PHARE concepts. It is difficult to identify specific comments that directly support conclusions regarding the use of the PATS Trajectory Predictor.

Comments from the PD/3 Continuation trial at NLR are subjective and may be distorted due to technical problems within the platform during the trial period. Additionally, comparative statements with a suitable baseline are not available since baseline trial runs were not performed. However, the comments do suggest that planning support was provided by the PATS Trajectory Predictor, and that a percentage of the generated trajectories were considered to be optimal (user preferred).

c) Conclusion

Trajectory prediction has been implemented, tested and integrated into PHARE systems. It is concluded that this aspect of the trajectory prediction concept is partially achieved, specifically with respect to accuracy of prediction. However, poor performance of the tool when generating each trajectory causes delays to constraint modelling requests made via the GHMI by controllers, and this can cause knock on delays within the integrated system, particularly at busy periods. Further investigation to improve performance is required before this area of the concept is fully achieved.

### 6.10.2 Advisory Generation

a) Desired / expected results

Reduced controller workload as a result of providing advisories to assist the controller with providing guidance to 3D aircraft for following registered trajectories.

Achieve adequate usability through frequency and accuracy of generated advisories.

b) Discussion

In PD/1 the advisories to the controller were generated by the GHMI from the trajectory data. In PD/2 the advisories were generated by the Arrival Manager tool from the trajectory data. However, in PD/3 it was decided that the TP would be the best source for the advisories. It was also hoped that a new class of advisories could be generated. All the advisories used prior to PD/3 were 'just in time' advisories that had to be passed at the right time to allow the (pseudo) pilot to change the vector of the aircraft and follow the trajectory. PD/3 wanted to develop a class of advisories that could be given ahead of time. However, the TP had no airspace knowledge and it was not feasible with the performance constraints for the TP to generate such complex advisories. Rather than the GHMI produce the advisories the idea was dropped.

If an aircraft is flying a simple 'ideal' trajectory there are very few advisories to give. However, every time ATC constraints are applied either for deconfliction or to follow defined procedures they cause the generation of advisories. There is a direct link between the number of advisories and the workload of the tactical controller and pilot. This becomes particularly apparent in the TMA where current fixed route STARS and SIDs may require many changes of vector.

Through all of the PHARE demonstrations, there have been many subjective comments made about the frequency of generation and accuracy of advisories. In some cases, controllers have questioned the accuracy and realism of advisories for certain aircraft types (for example, some aircraft have been asked to perform unfeasible rates of climb and descent). Additionally, controllers have often questioned the principal of having to pass messages at a very specific time to maintain the aircraft on it's planned trajectory.

The en-route trials (PD/1, PD/1+ and PD/1++) have demonstrated that it is possible for non-datalink and / or non-4D-FMS equipped aircraft to follow predicted 4D trajectories registered within the PHARE ground system. This appears to be a manageable task within the en-route PHARE concept for traffic patterns with approaching 30% unequipped aircraft.

The trials where control of aircraft within a TMA has been included (PD/2, PD/2+ and PD/3) have demonstrated that control of unequipped aircraft can be a significant problem, although PD/2 did demonstrate that it is possible for tactical controllers to get unequipped aircraft to follow their predicted trajectories. The high number of advisories generated for aircraft on approach and following complex procedures, coupled with the required precision of implementation in order to maintain the predicted trajectory, are the contributing factors to the difficulty of this task within the TMA. The PD/3 Continuation Trial simplified the departure patterns from Schiphol and the number of advisories for departures was not raised as an issue.

There have been comments made by controllers complaining of conflicting advisories being generated for individual aircraft within a very short space of time. For example, there have been occasions when an advisory has suggested a speed increase and then, a few seconds later, the system requests a speed decrease back to the original speed. This situation may be caused by the overlap in planning authority where, for example, a downstream planning controller may have requested a trajectory update to resolve, say, a downstream conflict, immediately after an upstream tactical controller was requested to pass an advisory. Since the PATS Trajectory Predictor re-generates the complete aircraft's trajectory from it's current position to the end of it's route, this may result in an immediate alteration to the aircraft's 4D profile and, in the case of unequipped aircraft, results in an advisory being generated to be passed immediately.

c) Conclusion

Advisory generation has been implemented, tested and integrated into PHARE systems. It is concluded that this aspect of the trajectory prediction concept is partially achieved, specifically with respect to accuracy of advisories in most circumstances. However, issues regarding the generation frequency of advisories, particularly for aircraft on approach, overlapping planning authority, and inaccurate advisories under some circumstances require further investigation before this area of the concept is fully achieved. It will also be necessary to investigate the generation of advance advisories which could allow the controllers to take advantage of the real capabilities of modern non-datalink aircraft.

### 6.10.3 Consistency of Trajectory Re-generation

a) Desired / expected results

Achieve adequate usability through consistency of trajectory generations (between ground system and aircraft), and consistency of trajectory re-generations.

b) Discussion

Since the PATS Trajectory Predictor has provided such a central service within the integrated systems used to support the PD/1, PD/2 and PD/3 demonstrations, the mere fact that successful demonstrations, with advanced planning, have been staged is an indication that the tool has achieved, at least in part, this aspect of the operational concept.

Throughout the PHARE trials programme, there has been good correlation between trajectories generated within the ground system, and trajectories generated by simulated 4D aircraft. Clearly, a contributing factor to this is the implementation of the 4D aircraft simulators, and that this situation may vary in the real world, where aircraft will probably use different FMS equipment from alternative suppliers.

There have been some observed problems with consistency of trajectory re-generations, particularly within approach airspace. It appears that the EFMS has problems with generating consistent arrival times when re-generation requests are submitted at different stages of descent. These problems have been evident from frustrations reported by arrival sequence planner controllers when attempting to replan aircraft in the arrivals sequence to meet a new ETA for the aircraft.

c) Conclusion

It is concluded that this aspect of the trajectory prediction concept is partially achieved, specifically with respect to the re-generation of trajectories within en-route airspace. However, re-generation inconsistencies when aircraft are on approach require further investigation before this area of the concept is fully achieved.

This page left intentionally blank

# 7. CONCLUSION AND RECOMMENDATIONS

## 7.1. CONCLUSION

The principal conclusions are as follows:

- An operational concept has been developed to support trajectory prediction within the PHARE system operational concept.
- A tool that meets a set of requirements derived from the PHARE trajectory prediction concept has been developed and tested.
- It has been demonstrated, through usage within real time trials, that the tool partially achieves the PHARE trajectory prediction concept.
- There are a number of unsolved problems that warrant further research.
- Development of operational concepts and tool requirements would have been easier if PHARE had established a central systems team, responsible for developing and partitioning the overall system operational concept.
- The client / server system architecture requires review in order to support the increased data processing requirements of the PHARE system (over current day ATC systems). An architecture based on distributed object implementation may be more appropriate.
- Duplicated system development / integration effort could have been avoided if a common platform had been used to support the PHARE demonstration program.

## 7.2. RECOMMENDATIONS

### 7.2.1 For Further Trajectory Predictor Research

- Improve Performance

It is recommended that research should investigate performance improvements for the tool. This may require a revision to the core algorithms used for the generation of a trajectory to implement a less computationally intensive approach, whilst still providing an adequate service within the ground system.

See sections 4.6.2 and 6.10.1 for more information.

- Advisory Generation

It is recommended that research should investigate improvements to advisory generation. Areas to be considered are accuracy of advisories, frequency of advisory generation (particularly within approach airspace), and overlap in planning authority. It will also be necessary to investigate the generation of advance advisories which could allow the controllers to take advantage of the real capabilities of modern non-datalink aircraft.

See section 6.10.2 for more information.

- Improve Consistency of Trajectory Re-generation

It is recommended that re-generation inconsistencies when aircraft are on approach require further investigation.

See section 6.10.3 for more information.

- Context Free Operation

It is recommended that investigation should be carried out in order to determine if some contextual awareness would benefit operation of the tool.

See section 4.6.1 for more information.

- Remove Restrictions on Route Structure

It is recommended that for future systems, assumptions regarding route structure and the presence of key fixes within constraints lists (i.e. a metering fix), should be minimised, since these assumptions may be based on current day operation that may not be applicable to future systems. Work needs to be done in order to remove the reliance on a fixed route structure within the current version of the tool, in order to provide a solution that is sufficiently flexible for use within approach airspace.

See section 4.6.3 for more information.

- Performance Dependent Constraints

It is recommended that the tool should be extended to provide support for performance dependent constraints. This would enable constraints to be defined such as a turning point which is invoked when a certain altitude is reached.

See section 4.5.2 for more information.

### 7.2.2 For Establishing A Similar Program to PHARE

- Systems engineering approach

It is recommended that future developments would benefit from central management by a systems engineering function, that has responsibility for developing and modifying the overall system concept (requirements), and partitioning the concept so that system components and interfaces are identified, and consistent requirements allocated to each.

It is also recommended that systems engineering should be closely involved in the systems integration activity to ensure that the system components are properly linked together to provide a system that satisfies the system level PHARE concept.

See section 4.6.5 for more information.

- Common platform for demonstrations

It is recommended that future programs of this nature should select a host platform for trials to be used from the outset. This platform should be established and stable prior to the integration of further tools to support advanced processing. The platform will then evolve as the trials program develops, with problems found during one trial being overcome prior to the next.

It is also recommended that the software build toolsets should be common to all developers producing software to be integrated into the host platform.

See section 4.6.7 for more information.

### 7.2.3 For Considering Re-use Of PATS Trajectory Predictor

- System architecture

It is recommended that future developments should reconsider the complete system implementation, particularly in light of more recent developments in distributed object implementation using CORBA. CORBA provides the capability to implement a system as a set of distributed objects without having to corrupt an object orientated design model into a series of clients and servers prior to implementation.

Therefore, an object orientated design can be implemented as designed, and the CORBA compliant middleware would manage creation of instances of objects and offer the capability for balancing object creation across the available processing resource. This provides a flexible architecture that is not constrained by static allocation of clients and servers to available processors.

See section 4.6.6 for more information.

- Concept Research Review

It is recommended that if the PATS trajectory predictor is to be re-used, then the list of recommendations within section 7.2.1 should be reviewed to determine if any of these should be addressed prior to re-use.

See section 7.2.1 for more information.

This page left intentionally blank

# 8. ACRONYMS, DEFINITIONS AND REFERENCES

## 8.1 ACRONYMS

| | |
|---|---|
| API | Application Programming Interface |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| ATMDC | Air Traffic Management Development Centre |
| BADA | Base of Aircraft DAta |
| CMS | Common Modular Simulator |
| CP | Conflict Probe |
| DASR | Department of ATM Systems Research |
| DLR | Deutsche Forschungsanstalt fur Luft- und Raumfahrt (Germany) |
| DERA | Defence Evaluation and Research Agency |
| DRA | Defence Research Agency |
| EEC | Eurocontrol Experimental Centre |
| EFMS | Experimental Flight Management System |
| FMS | Flight Management System |
| GHMI | Ground Human Interface |
| NARSIM | NLR ATC Research Simulator |
| NATS | National Air Traffic Services |
| NLR | Nationaal Lucht- en Ruimtevaartiaboratorium (Netherlands) |
| NM | Negotiation Manager |
| NRF | NATS Research Facility |
| OTF | Operational Task Force |
| PARADISE | Prototype Adaptable and Re-configurable ATM Demonstration and Integration Simulator Environment |
| PATS | PHARE Advanced Toolset |
| PD | PHARE Demonstration |
| PD/1 | PHARE Demonstration 1 |
| PD/2 | PHARE Demonstration 2 |
| PD/2+ | PHARE Demonstration 2+ |
| PD/3 | PHARE Demonstration 3 |
| PHARE | Program for the Harmonised Air Traffic Management Research in Eurocontrol |
| SPL | System Plan |

| | |
|---|---|
| STA | Scheduled Time of Arrival |
| STAR | Standard (Terminal) Arrival Route |
| TBD | To Be Defined |
| TEPS | Trajectory Editor and Problem Solver |
| TMA | Terminal Manouvering Area / Terminal Control Area |
| TP | Trajectory Predictor |

## 8.2 DEFINITIONS

NOTE. Definitions marked with * have been extracted from ref [1].

| | |
|---|---|
| 2D constraint | * A point specification i.e. a route point on a trajectory. |
| 3D | * 3 Dimensional - used to denote a position in space defined relative to the Earth. Can be considered as being lat., long and altitude. |
| 3D constraint | * A 2D constraint with added altitude specification. |
| 4D | * 4 Dimensional - used to denote a position in space defined relative to the Earth and time. Can be considered as being lat., long, altitude and time. |
| 4D constraint | * A 3D constraint with added time specification. |
| 4D trajectory | * A list of 4D way-points. |
| 4D way-point | * A 4 dimensional geographical point defined by latitude, longitude, altitude and time - used to denote a position in space defined relative to the earth and time. |
| Across Turn | A turn initiated prior to reaching the designated waypoint (also referred to as ‘before waypoint’ or ‘regular’). |
| Approach gate | As Star gate. |
| Arrival | An aircraft that is due to land at the airport being managed by the arrival manager tool. |
| Arrival constraints | Constraints generated by the tool defining the STAR to be flown and limiting holding pattern at the metering fix (optional); metering fix departure time (optional); and star gate arrival time. |
| Best effort trajectory | A trajectory generated by the TP that fails to meet at least one of the specified 4D constraints. |
| Constraint | * Limitations placed upon the (trajectory) prediction process in terms of pairs of altitudes and times at specified locations. |
| Contract tube | A volume of airspace around the trajectory within which the aircraft is contracted to fly. |

| | |
|---|---|
| Datalink | The communication link which allows electronic data exchange between the ground system and suitably equipped aircraft. |
| Early / late time | The earliest and latest (without holding) time of arrival at the gate that the arrival is capable of achieving from it's current position flying it's defined flight plan. |
| Equipped aircraft | Aircraft equipped with 4D-FMS and datalink. |
| Gate | As Star gate. |
| Large deviation tube | A volume of airspace around the trajectory (enclosing the contract tube) which defines the boundary of 'recoverable navigation error'. |
| Metering fix | * The TMA entry point and the first point in a STAR (derived from the definition of STAR in ref. [3]). |
| Optimal 4D trajectory | TBD |
| Overfly turn | A turn initiated at the designated waypoint (also referred to as 'wat waypoint' or 'start of turn'). |
| Star gate | * The last point in a STAR (derived from the definition of STAR in ref. [3]). |
| Trajectory | As 4D Trajectory. |
| Unequipped aircraft | Aircraft without any datalink of 4D capability. |

## 8.3 REFERENCES

[1] PHARE Glossary of Terms and Acronyms

DOC 97-70-05, version 3, March 97

[2] Software Engineering with Ada,

G Booch, 2nd edition

[3] PHARE Advanced Tools Final Report

PHARE/TBD

[4] EFMS Prediction of Optimal 4D Trajectories in the Presence of Time and Altitude Constraints

DOC 97-70-09

[5] PD/2 Final Report

DOC 97-70-13, PHARE/DLR/PD/2-10.2/SSR;1.2

[6] PD/1 Final Report

DOC 96-70-24, PHARE/NATS/PD1-10.2/SSR;1.1

[7] PD/1+ Trial Report

DOC 97-70-10, PHARE/CAA/PD3-5.2.8.4/SSR;1

[8] PD/2+ Trial Report

DOC 97-70-17, PHARE/NATS/PD2+-5.10

[9] PD/1++ Trial Report
DOC 98-70-16, PHARE/NATS/PD1++-2.10

[10] PD/3 (at EEC) Final Report
PHARE/TBD

[11] PD/3 (at NLR) Final Report
PHARE/TBD

[12] PD/3 (at CENA) Final Report
PHARE/TBD