

PROGRAMME FOR
HARMONISED AIR TRAFFIC
MANAGEMENT RESEARCH
IN EUROCONTROL



DOC 98-70-18
(Volume 8 of 10)



EUROPEAN ORGANISATION FOR THE SAFETY OF AIR NAVIGATION, EUROCONTROL



PHARE Advanced Tools Problem Solver

Final Report

PHARE/EEC/PAT-6.5/FR; 1.0



EUROCONTROL

EUROCONTROL
96 rue de la Fusée
B-1130 BRUXELLES

Prepared by: Mark Whiteley, EEC
Ian Wilson, EHQ

Date: 16 August 1999

The information contained in this report is the property of the PHARE participants.

The report or parts thereof may be published and or reproduced on the condition that due acknowledgement of authorship is made by quoting the copyright statement below. The copyright and the foregoing condition on publication and reproduction shall extend to all media in which the information may be embodied.

The information contained in this document is provided on an "as-is" basis and the PHARE Participants shall provide no express or implied warranty of any kind and shall accept no liability whatsoever for or in connection with the use of the information contained in the document.

* The PHARE Participants are:

- the EUROCONTROL Agency;
- the CENA (Centre d'études de la navigation aérienne);
- the STNA (Service technique de la navigation aérienne);
- the NLR (Nationaal Lucht- en Ruimtevaartlaboratorium);
- the RLD (Rijksluchtvaartdienst);
- the LVNL (Luchtverkeersleiding Nederland);
- 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);
- the DERA (Defence Evaluation and Research Agency)

Copyright statement:

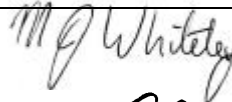


The copyright in this report vests in the European Organisation for the Safety of Air Navigation (EUROCONTROL); the CENA (Centre d'études de la navigation aérienne); the STNA (Service technique de la navigation aérienne); the NLR (Nationaal Lucht- en Ruimtevaartlaboratorium); the RLD (Rijksluchtvaartdienst); the LVNL (Luchtverkeersleiding Nederland); 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) and the DERA (Defence Evaluation and Research Agency).

All rights reserved.

REVISION HISTORY

Date	Revision Number	Reason for revision
12/11/98	0.1	First Draft
2/02/99	0.2	Final Draft
16/08/99	1.0	Publication Version

DOCUMENT APPROVAL

	NAME	SIGNATURE	DATE
AUTHOR 1	M.J. Whiteley		16 Aug 99
Project Leader	I. Wilson		16 Aug 99
PHARE Programme Manager	H. Schröter		16 Aug 99

EXECUTIVE SUMMARY

The fundamental concept in PHARE is that of the 4 dimensional trajectory running from take-off point to landing. The Conflict Probe alerts to conflicts on the trajectory, which then have to be 'solved' by the controllers. The Problem Solver displays the conflicts on the trajectory graphically as 'avoidance zones' and allows interactive graphical amendment of the trajectory constraints. As the trajectory is modified the avoidance zones showing the conflicts are also modified showing the controller the efficacy of the deconfliction action. If the modification causes new conflicts in different segments of the trajectory then new avoidance zones will be shown.

The Problem Solver algorithm involves assessing the affect of trajectories parallel to the aircraft trajectory that the aircraft could fly and displaying their penetration of the separation criteria of other aircraft. The penetration points are then drawn as the avoidance zones. As the trajectory of the subject aircraft is amended a new set of parallel trajectories is generated and the avoidance zones remapped. This process is particularly graphically intensive and requires close working or even integration with the Ground HMI.

Due to the way the avoidance zones are mapped using parallel potential trajectories, the operation of the algorithms becomes difficult with aircraft making many manoeuvres. This was due to the difficulty of modelling the trajectory fast enough for interactivity but accurately enough to be close to the trajectory that would be generated by the Trajectory Predictor for the same constraints. For this reason the initial Problem Solver was unsuitable for use within the Terminal Manoeuvring Area for this reason. However, the final version of the Problem Solver developed for PD/3 Continuation at NLR was more capable.

The Conflict Probe and Co-operative Tools reported conflicts based on algorithms that were different to the Problem Solver. This led to some inconsistency between conflicts reported by these tools. These inconsistencies were greatly reduced in the final version of the Problem Solver for PD/3.

The initial intent for the Problem Solver was that the tool should actually solve conflicts and present the solution to the controller. There was some disquiet about this and the highly interactive approach was adopted with considerable success. This approach continually displays the outcome of trajectory modifications to the controller. This initial version of the Problem Solver was known as the Highly Interactive Problem Solver (HIPS). The HIPS display was based on 3 windows that were separate from the controller PVD, with a window each for horizontal, altitude and time changes. In PD/3, to reduce 'window clutter' the horizontal display was put onto the controller PVD. This version of the Problem Solver was named the Trajectory Editor and Problem Solver.

The PHARE Problem Solver is a novel tool that allows the controller to interactively modify trajectories for deconfliction. The interactive graphical interface developed for the Problem Solver is intuitive for controllers and ideally suited to rapid problem solving of conflicts on 4 dimensional continuum trajectories with the 'controller in the loop'.

This page left intentionally blank

LIST OF CONTENTS

1. INTRODUCTION.....	9
1.1 SCOPE	9
1.2 DOCUMENT CONTEXT.....	9
1.3 OVERVIEW	9
1.4 DOCUMENT STRUCTURE.....	10
2. OPERATIONAL CONCEPTS	11
2.1 THE CURRENT CONCEPT	11
2.2 THE PHARE CONCEPT	11
2.3 PS DECONFLICTION CONCEPT.....	12
2.4 LIMITATIONS	17
3. REQUIREMENT DESCRIPTION.....	19
3.1 USER REQUIREMENTS	19
3.1.1 Overview	19
3.1.2 Display Requirements.....	19
3.1.3 Input Requirements	19
3.2 FUNCTIONAL REQUIREMENTS	20
3.3 PERFORMANCE REQUIREMENTS	20
3.4 CONTEXT REQUIREMENTS	21
3.4.1 Required Information	21
3.4.2 Generated Outputs	22
3.4.3 Events	23
3.5 IMPLEMENTATION-DEPENDENT REQUIREMENTS.....	23
4. IMPLEMENTATION	25
4.1 HOW DEVELOPED	25
4.1.1 The First Prototype	25
4.1.2 The Second Prototype.....	25
4.1.3 The PD/1 Problem Solver	26
4.1.4 Enhancements for PD/3.....	26
4.2 PERFORMANCE ISSUES	27
4.3 PROBLEMS	28
5. USAGE OF TOOL	29
5.1 THE FIRST PHARE DEMONSTRATION (PD/1)	29
5.2 THE SECOND PHARE DEMONSTRATION (PD/2)	32
5.3 THE THIRD PHARE DEMONSTRATION (PD/3).....	32
6. RESULTS	33
6.1 PHARE DEMONSTRATION RESULTS	33
6.2 ACHIEVEMENT OF CONCEPT.....	33
7. CONCLUSIONS AND RECOMMENDATIONS	35

7.1	CONCLUSIONS.....	35
7.2	RECOMMENDATIONS.....	35
8.	ABBREVIATIONS AND ACRONYMS.....	37
9.	REFERENCES.....	39

1. INTRODUCTION

1.1 SCOPE

This document has been produced as part of the PHARE Advanced Tools (PATs) Project within Programme for Harmonised Air Traffic Management Research in Eurocontrol (PHARE). The document is the Final Report for the Problem Solver (PS) tool.

This document deals primarily with the development of the PS software, which provides the functionality of the tool. The information generated by the PS software is displayed to the relevant air traffic controller¹ via the Ground Human Machine Interface (Ground HMI) (i.e. one that has a graphical user interface (GUI)). A controller can interact with the PS software only using the HMI.

Although from the controllers' view the HMI is an integral part of the PS, it is not dealt with in particular in this document as the PS HMI can be integrated with the HMIs of other systems. Nevertheless, as the PS software generates information that is to be displayed, the general form of the displays is mentioned.

The purpose of this document is:

- to describe the PS software;
- to describe the development of the PS software;
- to describe how the PS software has been integrated into other systems and how it has been used experimentally;
- to describe the results of those experiments; and
- to make recommendations for further work.

This document should be comprehensible to anyone with a basic understanding of air traffic control (ATC) systems. It is not necessary to have knowledge of the PHARE programme.

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 Problem Solver tool that is identified within the PATS final report parent document, Ref. [4].

1.3 OVERVIEW

The PS is a ground based planning and deconfliction tool. Its purpose is to allow the controller to solve conflicts by providing a graphical view of conflicts in the set of planned aircraft trajectories.

The PHARE concept views the trajectory of an aircraft as a continuum from take-off to landing therefore the traditional radar control approach to deconfliction in which aircraft are put onto short term headings is not appropriate. Instead an aircraft trajectory is considered as a whole for problem solving and deconfliction action taken at one point shows the affect on the other segments of the trajectory. This approach can be achieved graphically by showing conflicts along the entire trajectory and interactively showing the affect of trajectory changes as they are made.

¹ From now on, the term "controller" will be used in place of the term "air traffic controller".

In the context of the PS, a conflict exists either when two aircraft in flight are too close to one another (as defined by the separation rules in force) or when an aircraft in flight is found in airspace that is out-of-bounds to it. The conflict(s) is(are) then passed to the HMI that will display the subject aircraft trajectory together with the conflict(s) as coloured avoidance zones. The trajectory and its associated avoidance zones may be displayed in a horizontal, vertical or time presentation.

Despite its name the PS does not 'automatically' solve conflicts. It provides the controller with a graphical representation of the conflict(s) and interactively updates to show the effect of deconfliction actions taken by the controller. This is the reason for the more usual name of the tool which is 'Highly Interactive Problem Solver' (HIPS)². Within PHARE the intention was that in deconfliction the 'Human should remain in the loop'.

A predicted conflict constitutes a problem that has to be resolved. The only way to resolve such a problem is to modify the planned trajectory of at least one of the aircraft involved. The controller uses the HMI to alter the trajectory of the subject aircraft and as the trajectory is modified by the HMI the edits to it are passed to the PS which updates the conflict(s) allowing the HMI to update the conflict zone(s). It is possible for the controller to alter several aircraft trajectories in turn.

This is an interactive process and requires significantly fast HMI performance allowing the controller to model trajectories that are conflict free. The controller may also use the PS for what-if modelling of proposed trajectory amendments to assess them for conflicts.

The PS was designed to be part of a suite of tools that provide useful functions to a controller working at his Controller Working Position (CWP). The HMI of the PS will be integrated into the HMI of the CWP. In most of the PHARE demonstrations the PS was the main tool used for trajectory modification.

1.4 DOCUMENT STRUCTURE

This document contains nine sections.

- Section 1 is this section.
- Section 2: problem solving in the context of air traffic control systems. First, it includes a definition of a problem. Then, there is a description of how problems are resolved in current air traffic control systems, and why this will not be possible to be continued if the capacity of the airspace is to be increased as desired.
- Section 3: a description of the requirements that the PS had to meet.
- Section 4: a description of how the PS software was implemented.
- Section 5: a description of how the PS has been used in experiments such as the PHARE Demonstrations.
- Section 6: the results of the experiments mentioned in Section 5.
- Section 7: the conclusions and recommendations for future work.
- Section 8: a list of abbreviations and acronyms.
- Section 9: a list of references cited in this document.

² Note that in PD/3 the HIPS acronym was dropped by the GHMI team in favour of the name 'Trajectory Editor and Problem Solver' (TEPS)

2. OPERATIONAL CONCEPTS

2.1 THE CURRENT CONCEPT

The principle requirement of Air Traffic Management is the separation or deconfliction of aircraft in flight. Effectively, a "bubble" of airspace that must be kept free of other aircraft can be envisioned surrounding every aircraft in flight. The form and dimensions of this bubble are specified in terms of minimum separation standards.

A related function that an ATC system must perform is to ensure that no aircraft passes through airspace that is out-of-bounds to it. (Airspace can be permanently or intermittently out-of-bounds to civil aircraft.) Temporarily restricted areas (TRAs) and significant meteorological areas (SIGMETs) are examples of out-of-bounds airspace.

The current ATC systems in Europe require the controller to identify potential conflicts usually by means of flight strips or radar displays. The controller then takes action to solve the conflicts and monitors the aircraft to ensure that the deconfliction is carried out and is effective. Most deconfliction activity is carried out by the Tactical Controller (TC) using radar and is relatively short term. This is due to the inaccuracy of the trajectory models used either in the 'mental picture' in the controllers' heads or as shown by flight strips.

2.2 THE PHARE CONCEPT

In the PHARE concept the trajectory model is based on continuum 'gate-to-gate' trajectories in the aircraft FMS with feedback loops in the aircraft and in the ground systems ensuring that the actual flown trajectories and the ground trajectory model in the ATC flight database are always in agreement. This allows Planning Controllers (PC) to carry out deconfliction by adding or amending trajectory constraints long in advance of conflicts³. Thus the deconfliction workload can be largely transferred to the PC. As the TC workload was seen as the main limitation on current systems the 'system capacity' should be increased. [Reference 12]

The PC is alerted to the potential conflict in the planned sector by the output of the Conflict Probe (CP) (= Ref. [2]) which may be filtered by the Co-operative Tools (CT) (= Ref. [3]) into PROblem SITuations (PROSITS). When an aircraft involved in a conflict enters the PC's Planning Authority, normally 10 minutes prior to entering the sector, the PC opens the PS through the HMI and then amends the trajectory in any dimension to clear the conflict in the most efficient way. This could involve amending more than one aircraft trajectory. The trajectory is treated and displayed as a continuum so the PS also assesses and displays the effect(s) on existing conflicts or the creation of new conflicts from the deconfliction action.

The HMI and PS are working interactively and therefore a simplified trajectory generator is used within the PS for generating the modified trajectories and identifying the conflict zone(s). Once the controller is content that the best solution of the conflict has been found, the PS generated deconfliction constraints are sent to the Trajectory Predictor (TP) by the controller selecting 'validate' on the HMI (= Ref. [8]) and an alternate trajectory is received in response. The TP uses a rule base and aerodynamic modelling to produce a trajectory and its response time is too long for interactive use. The subsequent alternate trajectory is then loaded into the PS and the conflict zones recalculated. If the new aircraft trajectory is still deconflicted then the controller implements that trajectory.

³

In PHARE this is part of the Layered Planning concept.

The PC indicates on the HMI that the current trajectory is to be implemented or in PHARE terms 'Registered'. If the aircraft is not datalink equipped the trajectory being registered becomes the 'active' trajectory for the aircraft. The aircraft will then be guided along the trajectory by R/T 'advisories'. These advisories or ATC Instructions were generated by the HMI in PD/1 and by the TP in PD/3. If the aircraft is datalink equipped the constraints to build the conflict free trajectory are sent to the aircraft. The aircraft FMS then generates a trajectory that meets the constraints as closely as possible and on Pilot acceptance downlinks the trajectory to the ground system. (= Ref. [24])

2.3 PS DECONFLICTION CONCEPT

It would be useful if a controller could select an aircraft involved in a predicted conflict situation and then "see" all (or at least a significant number) of the possible future trajectories for that aircraft. If those trajectories that would result in a future conflict situation are removed, the controller could select one of the remaining trajectories, make that the planned trajectory for that aircraft, and know that he had resolved the problem (if the aircraft then followed that trajectory).

There are very many possible trajectories for any particular aircraft (even after considering constraints on those trajectories). Therefore, instead of indicating the trajectories that are free of conflict, it might be better to indicate the possible trajectories that would result in a conflict situation. In practice, it turns out that it is sufficient to display only those segments of the possible trajectories where a conflict situation would occur.

One of the problems with a basic radar display is that it gives a 2-dimensional view of the air traffic situation. To do his job, a controller also needs altitude information and time information. Therefore, the basic plan view display of trajectory needs augmentation with altitude information and time information. The controller uses all this information to build a mental image of the air traffic situation.

It is not obvious how to advance from the restrictions of a 2-dimensional display when a 4-dimensional display is needed. The PS uses so-called "abstracted diagrams" to present air traffic situations to the controller in a clear, graphical way and allows him to interact with the displays to develop solutions.

The implementation of the PS was based on the concept of abstracted diagrams showing no-go zones. The geometric model used in this approach is described in Ref. [15]. The abstracted diagrams attempt to provide a view of the air traffic situation from the perspective of a single aircraft in such a way that a conflict-free trajectory can be determined for that aircraft.

To derive an abstracted diagram, it is necessary to model the planned 4D trajectory of each aircraft as a tube. This tube, which encloses the planned 4D trajectory, takes account of both the errors associated with the predicted trajectory and the required minimum separations.

One aircraft is selected as the subject aircraft. Its 4D tube can be compared with the planned 4D trajectory of every other aircraft. The other aircraft are referred to as the environment aircraft. If the planned trajectory of the subject aircraft is displayed, the segments of that trajectory that are predicted to be in a conflict situation can be highlighted.

If a future point on the planned subject aircraft trajectory is selected as a point at which a turn will take place instantaneously, and a new trajectory segment is displayed, it too can be marked where there would be a conflict situation. If a series of heading changes were assumed at that point, and the corresponding future trajectory was plotted for each and marked for conflict situations, the conflict segments would merge to give the impression of an area. If there were a heading change for which there was no conflict situation with the environment aircraft, that heading change would represent a valid manoeuvre to perform to eliminate that conflict situation with those environment aircraft. All the other trajectories that passed through the conflict situation zone would imply that the corresponding heading change was not a valid manoeuvre to eliminate the conflict situation with those environmental aircraft.

The controller's task is to find a future trajectory that does not pass through the area of conflict situations. For this reason, such an area is called a no-go zone. See Figure 1.

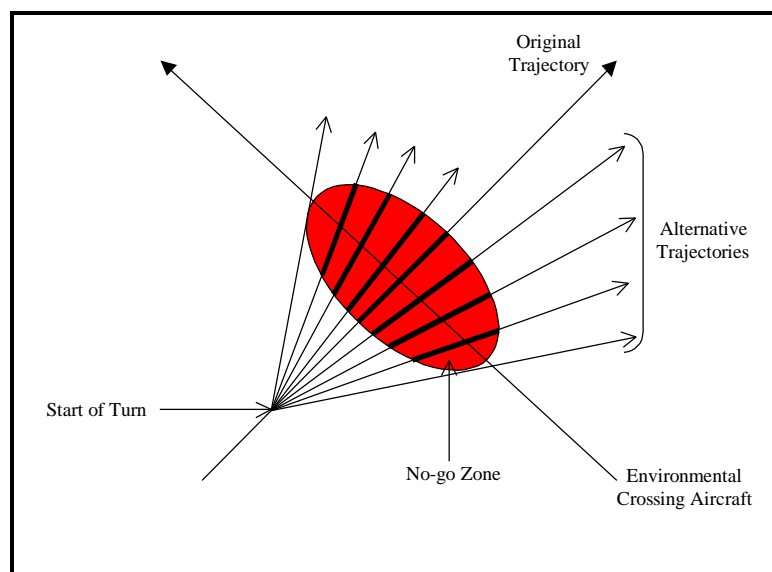


Figure 1: Constructing a no-go zone.

In practice, it is not necessary to draw every possible future trajectory from the point at which the turn would be made. The calculation of the no-go zone can be done *a priori* once the point at which the turn would be made has been specified.

Other manoeuvres can be tried as well as turn manoeuvres. The altitude profile of the subject aircraft could be modified, as could its speed profile. These three sorts of manoeuvres (route changes, altitude profile changes, and speed profile changes) are considered the most useful.

Figure 2 shows the sort of plan-view that can be displayed. This figure shows that **ABC123** is the subject aircraft. Aircraft **DEF456** is an environmental aircraft (from the point of view of **ABC123**) whose planned trajectory is predicted to be in conflict with that of **ABC123**. The relevant no-go zone is displayed for a planned turn position as indicated.

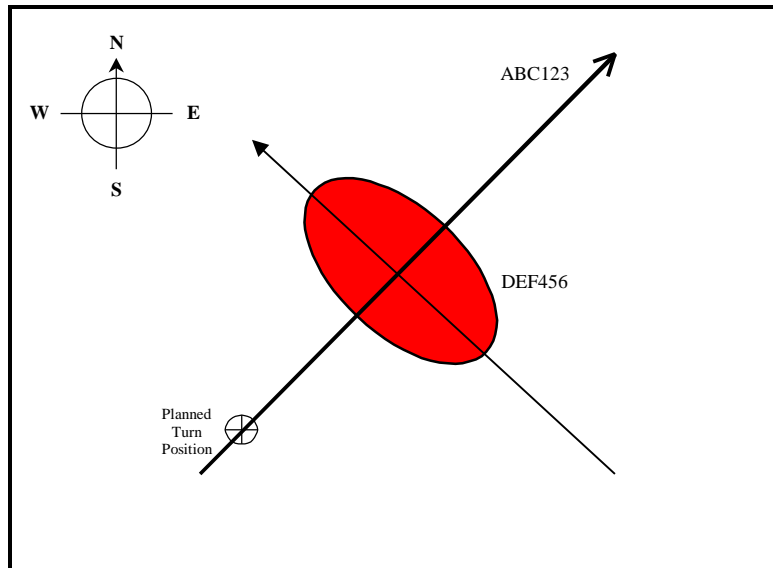


Figure 2: A plan view of a predicted conflict situation.

For the controller, a possible solution is to re-route **ABC123** so that it passes either to the north or to the south of its current planned position. The turn starts at the planned turn position. In practice, a controller would probably select to pass **ABC123** behind **DEF456** as shown in Figure 3.

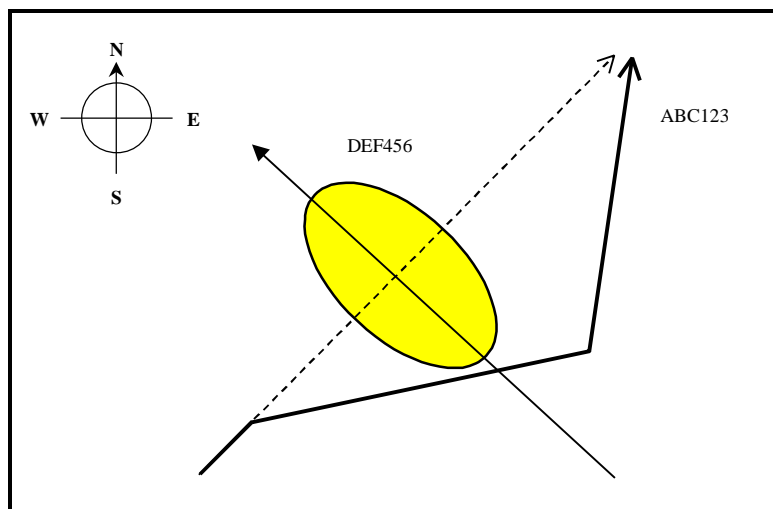


Figure 3: A plan view of a possible conflict-free trajectory for ABC123.

The no-go zone shown in Figure 6 has changed colour from red to yellow (at least in the electronic version of this document) to indicate that the new trajectory of **ABC123** is no longer in conflict with that of **DEF456**.

Figure 4 shows the sort of altitude profile that can be displayed.

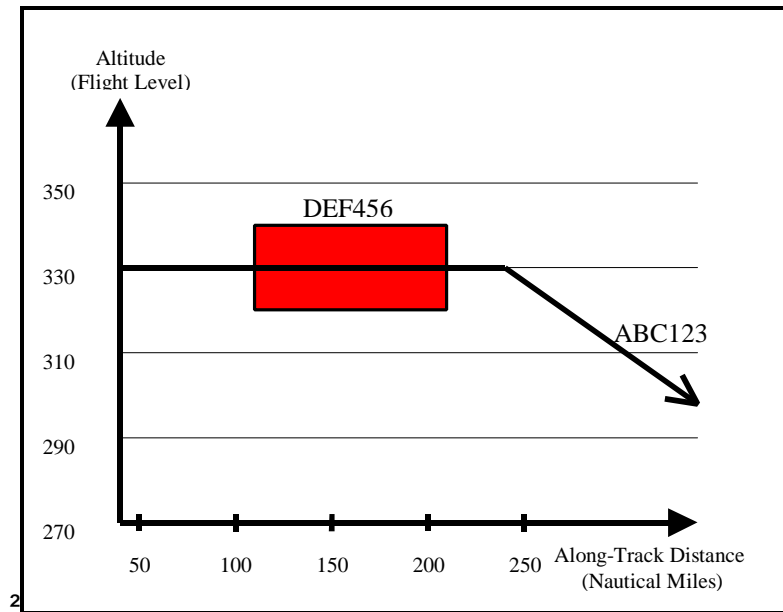


Figure 4: An altitude profile view of a predicted conflict situation.

With this situation, a possible solution is to descend **ABC123** before the predicted conflict situation arises and so pass **ABC123** under **DEF456** as indicated in Figure 5. The reports on the PD/1 and PD/3 results give for more detail of working in an integrated system with the Trajectory Predictor.

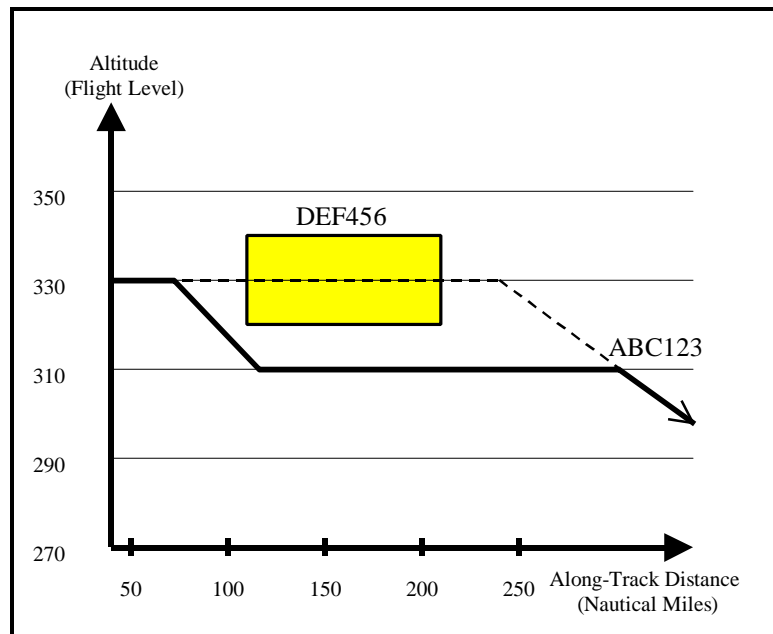


Figure 5: An altitude profile view of a possible conflict-free trajectory for ABC123.

It is also possible to delay or expedite an aircraft to clear a conflict. This can be shown graphically in a similar way to the other dimensions. Figure 6 shows the sort of speed/time profile that can be displayed. Instead of displaying the speed of the aircraft directly, this sort of diagram displays the amount of time early or late that the aircraft will arrive at a given along-track distance.

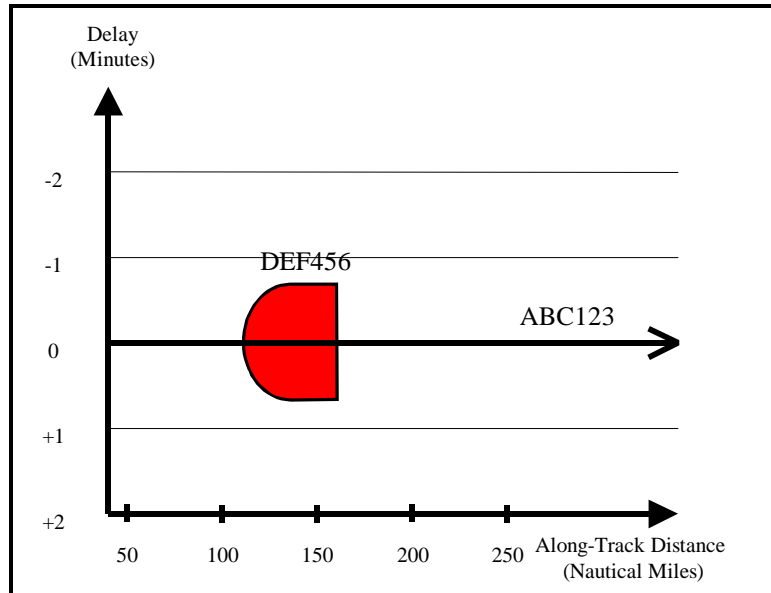


Figure 6: A speed/time profile view of a predicted conflict situation.

With a conflict such as that in Figure 6, a controller could apply a speed modification to the planned trajectory of **ABC123** so that it arrives at the particular along-track distances earlier or later than planned at the moment. See Figure 7 in which, the planned speed of **ABC123** has been reduced, resulting in the fact that the aircraft would now arrive one minute later at points further along the trajectory.

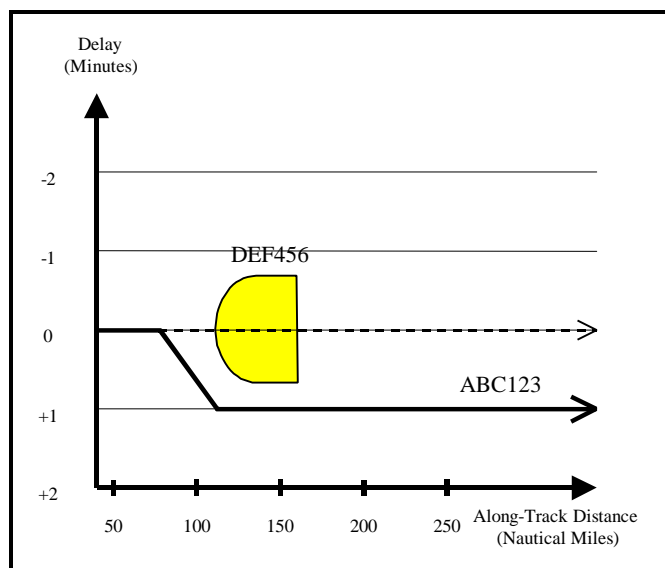


Figure 7: A speed/time profile view of a possible conflict-free trajectory for ABC123.

The graphical display allows controllers to modify a planned trajectory and see the results immediately. This allows rapid assessment of potential deconfliction actions and identification and implementation of the most efficient action.⁴

2.4 LIMITATIONS

The PS was developed primarily for en-route controllers. It was not designed for use in areas where aircraft are making many manoeuvres such as terminal airspace. There was some use made of the PS in the PD/3 Demonstration at CENA where it caused problems for departure and ETMA controllers and at NLR in the Terminal Airspace where some degree of work was required to make the system usable (see Section 5.1). It is probable that whilst a similar graphical approach could be taken a considerable effort may be needed

⁴

Note that these diagrams are simplifications and that there may be many no-go zones displayed.

This page left intentionally blank

3. REQUIREMENT DESCRIPTION

3.1 USER REQUIREMENTS

3.1.1 Overview

The intended users of the PS software are controllers with either the en-route planning or en-route tactical roles. Consequently, the PS software will be associated with every CWP. A controller will be able to interact with his CWP by means of a display and several input devices.

3.1.2 Display Requirements

The CWP must be able to display representations of:

- the 4D trajectory that each aircraft is currently planned to follow in the future;
- the constraints on the 4D trajectory that the controller would like the subject aircraft to follow in the future;
- the constraints on the 4D trajectories that the controller would like certain other aircraft to follow in the future⁵;
- the current 3D position, speed, and heading of each aircraft;
- the no-go zones for the subject aircraft;
- the performance limits of the subject aircraft; and
- the extent of out-of-bounds airspace.

3.1.3 Input Requirements

It should be possible for a controller to:

- select a particular aircraft as the subject aircraft;
- impose a new constraint on the planned future 4D trajectory of the subject aircraft;
- modify an existing constraint on the planned future 4D trajectory of the subject aircraft;
- delete an existing constraint on the planned future 4D trajectory of the subject aircraft;
- get the constraints on the planned future 4D trajectory of an aircraft checked to verify that the aircraft could actually generate a 4D trajectory that met the constraints; and
- submit an alternative set of constraints for the planned trajectory of an aircraft.

⁵

This requirement is necessary if the controller wishes to eliminate a predicted conflict situation by modifying the planned future trajectory of more than one aircraft.

3.2 FUNCTIONAL REQUIREMENTS

The information that has to be displayed dictates the functions that the PS software has to perform.

The PS software shall be capable of determining where and when the planned trajectory of the subject aircraft will be in conflict with the planned trajectory of every other aircraft.

The PS software shall be capable of determining the form of the no-go zones for the planned trajectory of the subject aircraft given the point at which a manoeuvre might be made.

The PS software shall be capable of determining where and when the alternative planned trajectory of the subject aircraft will be in conflict with the planned trajectory of every other aircraft.

The PS software shall be capable of determining the form of the no-go zones for the alternative planned trajectory of the subject aircraft given the point at which a manoeuvre might be made.

3.3 PERFORMANCE REQUIREMENTS

The display associated with a PS should be updated sufficiently rapidly after a change to the set of constraints to enable a controller to interact with it. For example, while editing a constraint, the display should show the effect of the change almost immediately so that the editing is indeed an interactive real-time process. The effect of 'dragging' a trajectory must be that not only the trajectory is dragged, without lag, by the 'pointing device'⁶, but also that the no-go zone shapes are also updated without lag.

To meet this requirement, the display should be updated *at least* once every 100 milliseconds when changes are being made to it. Consequently, the PS software must execute sufficiently quickly that it can complete all the necessary calculations in less time than this maximum display update interval. The time needed to perform the required calculations is dependent on the number of aircraft with which the planned trajectory of the subject aircraft has to be compared, as well as on the number of no-go zones generated.

These are demanding requirements for processing on both the PS and the HMI. It is essential for the 'look and feel' that they are met.⁷

⁶ All PHARE demonstrations used a mouse as the graphical input device

⁷ The performance of the graphical displays was often the limiting factor. (see lessons learnt).

3.4 CONTEXT REQUIREMENTS

The Figure 8 illustrates the interactions between PHARE system components and the PATS Problem Solver.

The central bubble represents the PATS Problem Solver 'core' tool that is the tool without HMI. The surrounding boxes represent each of the PHARE system components that the tool interacts with, and the connecting arrows represent the direction of communications. The basic purpose of the PS software is to generate information that indicates predicted conflict situations and that could be displayed to the controller.

It should be noted that the context diagram is generalised. In PD/1 the PS was closely coupled to and compiled with the HMI. In PD/3 each of the sites took a slightly different approach to integrating the PS with their platforms, Ref.[25]

3.4.1 Required Information

The Platform Servers provide:

- airspace information;
- surveillance information.
- Time information
- Active System Trajectory information

The required airspace information includes:

- The form of the airspace associated with the sector;
- The location of each navigation point and beacon that is in the sector.
- The separation criteria for the airspace

The required surveillance information is the actual (measured) current position of every aircraft at regular intervals which is used to update the PS trajectory database.

The time information is in the form of 'clock ticks'.

The required active trajectory information is the 4D trajectory of each aircraft that is planned to enter the sector.

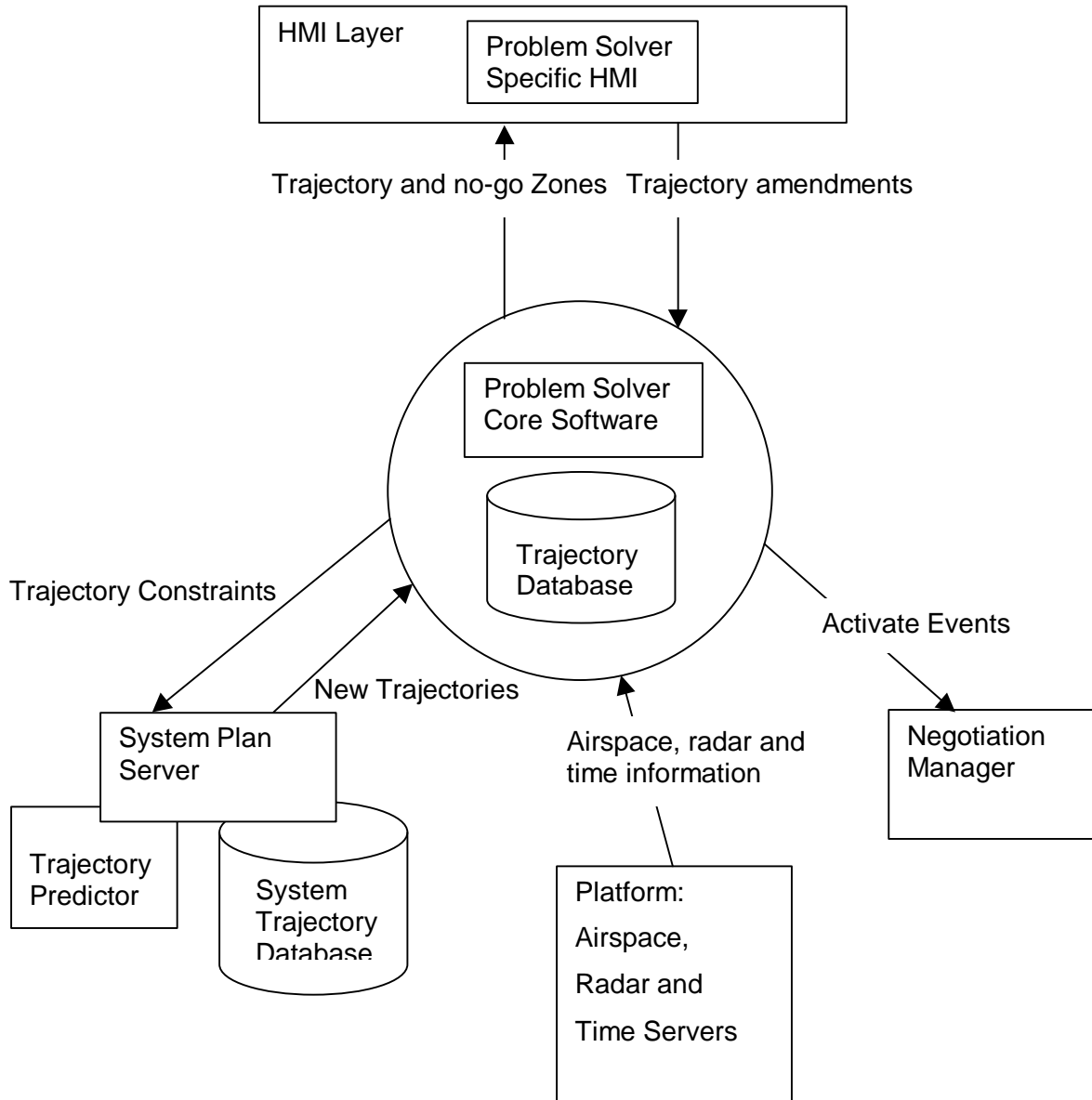


Figure 8: The context of the PS software.

3.4.2 Generated Outputs

The HMI client to generate HIPS or TEPS displays uses the information that is generated by the PS software.

When an aircraft has been selected as the subject aircraft, the PS software generates a trajectory meeting the constraints and a description of every no-go zone for the planned trajectory of that aircraft.

3.4.3 Events

The PS software needs to be informed of changes to information that it stores. The platform servers have to be able to send messages to the PS software to notify it of the occurrence of certain "events". The relevant events for the PS software are:

- the creation of a flight plan for an aircraft that is planned to enter the sector;
- the updating of a flight plan that is already known about;
- the measuring of the position of an aircraft;
- the selection of an aircraft as the subject aircraft;
- the addition, modification, or deletion of constraints on the alternative planned trajectory of the subject aircraft; and
- the forecasting of a change to the status of an area that is out-of-bounds from time to time;
- the expiry of a fixed time interval.

As new flight plans enter the System Plan database and trajectories are generated, or if a trajectory is modified, the PS loads the relevant flight plan data into its internal trajectory database.

The PS needs to be kept up-to-date with aircraft positions to ensure that the no-go zones are not displayed behind the aircraft. Consequently, it uses radar or other position reports whenever they are available

The PS software needs to be informed by the HMI:

- whenever the controller selects an(other) aircraft to be the subject aircraft.
- of changes to the alternative planned trajectory of the subject aircraft. For example when the controller adds, modifies, or deletes a constraint on that trajectory.

The PS software must be notified in advance that the status of an airspace that can temporarily be out-of-bounds is about to change.

The PS software needs to be informed of the current time at regular intervals. This is achieved by notifying the PS software of the expiry of a fixed interval of time. Once an interval of time has expired, a new interval of time starts to be counted.

3.5 IMPLEMENTATION-DEPENDENT REQUIREMENTS

The PS software has to be capable of being integrated into a number of different ATC system platforms, including:

- ESCAPE (the Eurocontrol Simulation Capability And Platform for Experimentation); and
- DAARWIN
- NARSIM (the NLR ATC Research Simulator).
- PARADISE (the Prototype of an Adaptable and Re-configurable ATM Demonstration and Integration Simulation Environment).

This page left intentionally blank

4. IMPLEMENTATION

4.1 HOW DEVELOPED

4.1.1 The First Prototype

Initially, a prototype problem solver was produced at the Eurocontrol Experimental Centre (EEC). This was known as PEPSI 1 (the first PATs' Experimental Problem Solver Implementation). It was produced:

- to see if it was feasible for predicted conflict situations to be resolved using abstracted diagrams;
- to involve HMI and operational expertise as early as possible;
- to investigate the geometric algorithms used to calculate the no-go zones; and
- to investigate the computational load attributable to the determination of the no-go zones and to the generation of the displays.

The PEPSI 1 was integrated into its own custom-built test environment. This environment was capable of generating a simple, but realistic, traffic sample where each aircraft followed its flight plan perfectly. The performance capabilities of the aircraft were greatly simplified. In addition, meteorological conditions were not taken into account.

For both the PEPSI 1 and its test environment, it was assumed that the Earth is flat. This assumption meant that a simple (X, Y, altitude) co-ordinate system could be used to specify 3D positions.

4.1.2 The Second Prototype

After the feasibility of using abstracted diagrams was shown, a second prototype was developed. The main reason why a second prototype was produced was to have a tool that was suitable for a series of preliminary trials with controllers. The second prototype was known as PEPSI 2. A lot of attention was paid to how a controller could interact with a PS.

The PEPSI 2 was integrated into the rapid prototyping system at the EEC. Both the rapid prototyping system and the PEPSI 2 had a model of the Earth that was more accurate than the model used for the PEPSI 1 demonstrations. The Earth was assumed spherical, ground positions being specified by a (latitude, longitude) co-ordinate pair. The generated aircraft trajectories were more realistic than before – all aircraft were assumed capable of performing 4D navigation from point to point following great circle arcs. However, no account was taken of varying aircraft masses; meteorological conditions were also ignored.

The test environment included independent trajectory generation and conflict detection tools. For the PEPSI 2, simple definitions of separation standards and uncertainties were assumed. There was no time uncertainty.

4.1.3 The PD/1 Problem Solver

The PS software has been used in the PHARE Demonstration 1 series, which commenced in 1995 with PD/1, then PD/1+ and PD/1++ as an en-route problem solver.

The PS was not used in PD/2, which concentrated on arrival management, but it was used in PD/2+. This was despite the warnings from the developer that the HIPS as developed for PD/1 was not suited to other than en-route use. The use of the HIPS in the extended terminal area in PD/2+ demonstrated the problems integrating the HIPS with the Trajectory Predictor and the Conflict Probe. It also showed some of the issues of using the PS in areas where the subject and environmental aircraft were manoeuvring.

A number of PATs were tested during the PD/1 experimental runs. These were:

- the PS;
- the CP;
- the FPM; and
- the TP.

The HMI for the PS was integrated into the GHMI system along with:

- the Conflict and Risk Display (CRD);
- the Conflict Zoom Window (CZW);
- the Horizontal and Vertical Assistance Windows (HAW and VAW); and
- the Communications List Window (CLW).

The PS software generates information to be displayed on three types of display. The first type of display is a plan-position display. This shows the planned route of the subject aircraft. The second type of display is the vertical profile display. This shows the planned vertical profile of the subject aircraft. The third type of display is a speed-based display. This shows the planned speed profile of the subject aircraft. In practice, the speed profile display can actually be a display of early/late times.

4.1.4 Enhancements for PD/3.

The basic HIPS techniques described above were retained for PD/3, with the following additional features. Note that the HMI implementation and operational use of these features were defined within the overall context of the PD/3 GHMI requirements. Many of these features are inseparable from the overall HMI subsystem.

- **Improved algorithms.** The algorithms for derivation and display of no-go zones and for trajectory editing were significantly improved over those used in PD/1.
- **Improved trajectory modelling.** In PD/1 it was necessary to incorporate a 'validate' step before a proposed solution could be applied. This was due to the fact that the simplified trajectory model used within HIPS was not sufficiently well integrated with the external trajectory predictor. This situation was rectified for PD/3 by improving the quality of the trajectory model used within HIPS, and by better integrating this with the external trajectory predictor. The objective was to eliminate, if possible, the requirement to 'validate' solutions.

- **Performance Guidelines.** The accuracy of the performance guidelines (background triangles) shown on the vertical and speed displays was improved by using specific aircraft type and state information rather than the default values that were used in PD/1. However, this was further adapted in PD/3 continuation at NLR.
- **Explicit display of uncertainty.** In PD/3 it became possible to explicitly display temporal uncertainty around no-go zones. In PD/1 uncertainty was assumed to be a fixed value which is combined with separation requirements to produce a simple homogeneous no-go zone. Explicit display of uncertainty allows visualisation of time-dependent uncertainty 'clouds' around each no-go zone. The size of the uncertainty depends on aircraft equipment fit, and is also time-dependent (diminishing to a near-zero value at time *now*). The controller then has a choice as to how to use uncertainty: either conservatively or not according to traffic conditions etc.
- **ETMA considerations.** The requirements for use in ETMA, in particular to handle conflicts between climbing and descending traffic and overflights. Note that significant problems were both anticipated and borne out in practice in the use of PS with aircraft in holding patterns.
- **Multi-sector capability.** The PS explicitly took into account requirements for use in multi-sector planning and deconflicting applications. Whereas, the sector boundary was a restriction to planning controllers in PD/1, in PD/3 the Planner Controller could access and change a trajectory anywhere. It was assumed that the Operational Procedures would limit the controller rather than the automated limitations of PD/1.

PD/3 PS. In 1998, an upgraded version of the PS software was made available for the three platforms that were used for the third PHARE Demonstration (PD/3). The PD/3 trial at CENA used a version of the PD/1 HIPS. The EEC Brétigny trial did not complete due to HMI Problems this also had delayed the NLR Trial.

PD/3 Continuation Developments. The NLR trial concentrated on the interface between arrival and en-route sectors a considerable amount of PS development was carried out for PD/3 Continuation Trial at NLR to clear problems found in PD/2+ and enable the use of the PS in the terminal area. (See sections 5 and 6 below and [Reference 25]).

4.2 PERFORMANCE ISSUES

The calculations of the form of the no-go zones require a significant amount of processing.

4.3 PROBLEMS

The PS software generates descriptions of the no-go zones for the planned trajectory of the subject aircraft based on the separation standards in force. In principal, the PS software could have used the PATs' CP to determine the no-go zones. However, because that it was thought that the PATs' CP would be too slow, it was decided to use a simplified CP within the PS software.

The problem with having two types of CP, one in the PS and one external to it, is that there is a risk that they will be incompatible. A possible effect of such an incompatibility is that a controller could design a trajectory that is conflict-free as far as the PS is concerned but that is not conflict free as far as the PATs' CP is concerned. A possible result of this is that an alternative planned trajectory that is deemed to be free of conflicts by the PS could be reported by the external system as being in conflict with the planned trajectory of another aircraft.

The possibility of such a problem was removed by ensuring that the separation standards used by the PS software were stricter than the separation standards used by the PATs' CP. This ensured that if the PS software indicated that a planned trajectory was free of conflicts, it was free of conflicts for the PATs' CP.

5. USAGE OF TOOL

5.1 THE FIRST PHARE DEMONSTRATION (PD/1)

PD/1 was a large-scale, real-time simulation that was run in 1995 by NATS with the support of the Defence Research Agency (now the Defence Evaluation and Research Agency (DERA)) in Malvern, England. The aims of this series of simulations were to answer a number of questions related to en-route issues [16, 17]. For PD/1, several sectors were simulated. A version of the PS software was integrated directly into the Ground HMI (GHMI) system.

The PS was used as follows: Assume that a conflict situation had been predicted to occur in the airspace of a certain sector. Such a prediction would have been based on information generated by the CP. Further information about this conflict situation (such as the identities of the aircraft involved) would have been displayed to the relevant planning controller by means of the CRD of the GHMI.

The controller selects one of the aircraft involved in the conflict situation as the subject aircraft. This could be done by clicking on a call sign. If the conflict involves several aircraft, he should try to select an aircraft that is common to all of the individual aircraft-aircraft conflicts.

The moment that the controller selects an aircraft as the subject aircraft, the PS calculates the form of the no-go zones for that aircraft and gets them displayed on the GHMI system. The controller analyses the displayed information and decides on the form of the trajectory that he would like the subject aircraft to follow so that it avoids the no-go zones. He decides on the first manoeuvre to try. The time at which the manoeuvre would start should be several minutes in the future to give enough time for any required negotiation process between the ground system and the aircraft to take place.

Starting with the constraints that are currently applicable to the future trajectory of the subject aircraft, the controller can add new constraints, remove existing constraints, or modify existing constraints. He can do this by interacting with the display. The displayed no-go zones are updated as the set of constraints is modified.

At any time, the controller can remove all modifications to get back to the original set of constraints for the planned trajectory.

Once the controller is happy with the new set of constraints for the trajectory of the subject aircraft, he can request that they be validated. The constraints on the alternative trajectory are passed to a trajectory validation system. This system tries to generate a description of the actual trajectory that the aircraft would follow given the new set of constraints. If a trajectory can be generated, a description of the proposed trajectory is sent to the FMS of the subject aircraft. The pilot can agree or disagree with the proposed trajectory.

Figure 9 shows the sort of displays that were used in PD/1 to display the information generated by the PS software.

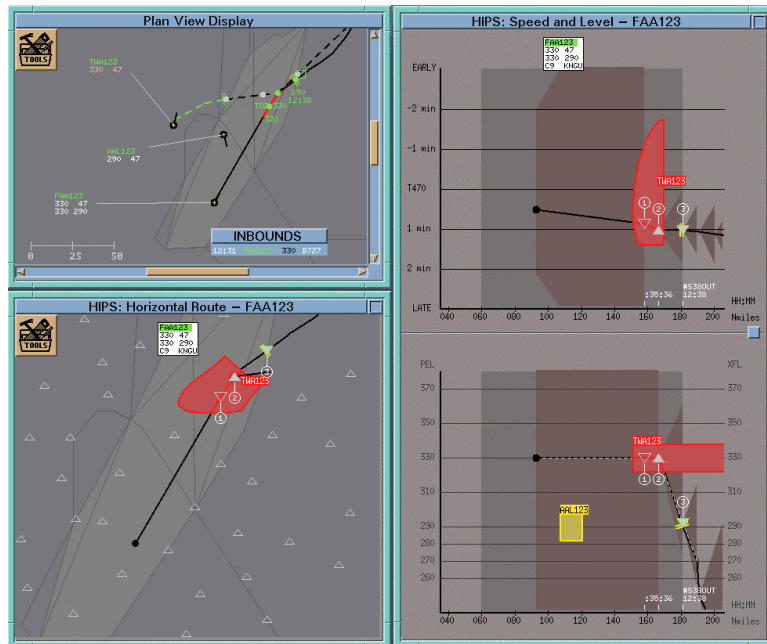


Figure 9: An example of a GHMI display.

Figure 9 contains three windows, with four displays. The three windows are the plan-view window, the HIPS horizontal route window, and the HIPS speed and vertical level window. The PS tool is sometimes referred to as the Highly Interactive Problem Solver (HIPS). This was the type of display used in the PD/1 series of demonstrations it was considerably modified for PD/3.

The contents of the HIPS Horizontal Route window are shown in more detail in Figure 10.

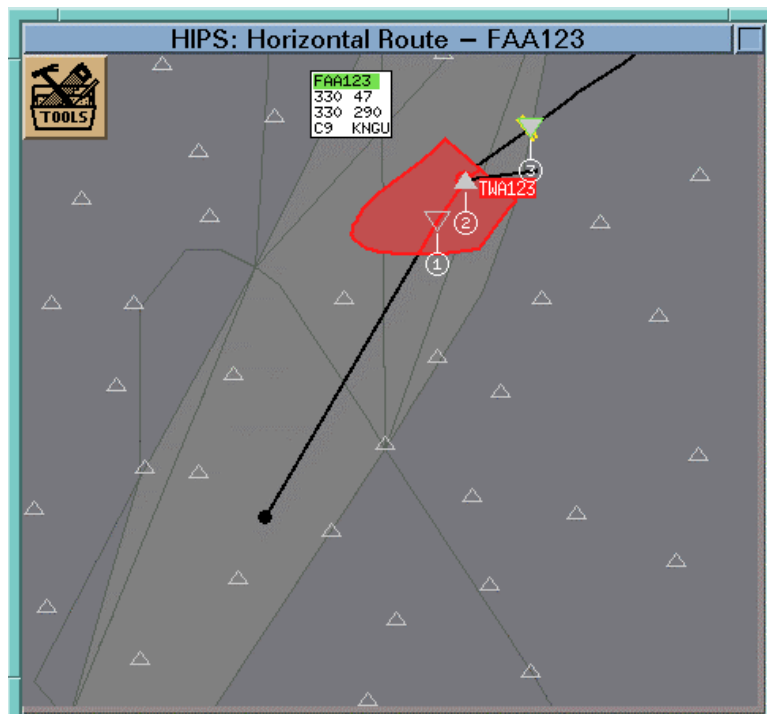


Figure 10 the HIPS Horizontal Route window.

This display shows that the planned trajectory of the aircraft FAA123 is in conflict in the horizontal plane with the planned trajectory of the aircraft TWA123.

The contents of the HIPS Speed and Level window are shown in greater detail in Figure 11.

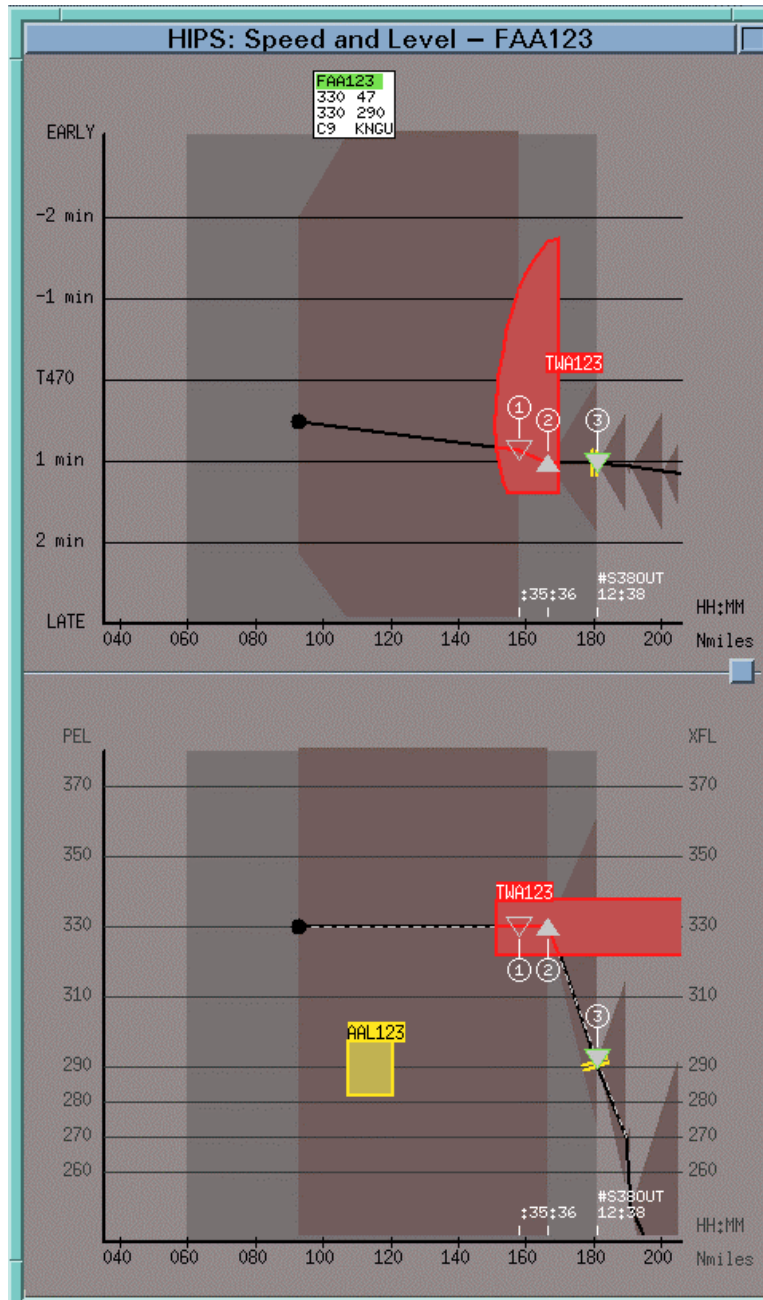


Figure 11 the HIPS Speed and Level window.

This display contains the speed profile and altitude profile windows. The altitude profile window indicates that the aircraft FAA123 will be in conflict with the aircraft TWA123. It also indicates that the aircraft AAL123 could also be a problem.

The speed profile window indicates that the predicted conflict between FAA123 and TWA123 could be avoided if FAA123 is speeded up or slowed down.

5.2 THE SECOND PHARE DEMONSTRATION (PD/2)

The second PHARE Demonstration was run in 1996 at the Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) in Braunschweig, Germany. This series of experiments addressed terminal approach issues; several sectors of an extended TMA (ETMA) were simulated (Ref.[18, 19]). A PS was not required for this demonstration.

5.3 THE THIRD PHARE DEMONSTRATION (PD/3)

The third PHARE Demonstration addressed multi-sector, en-route, and ETMA issues. It was run in 1998 on three separate sites, namely at the Centre d'Etudes de la Navigation Aérienne (CENA) in Toulouse, France, at the EEC in Brétigny-sur-Orge, France, and at the Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) in Amsterdam, the Netherlands. Each of these sites used the series of simulations to study a different aspect of the ATM problem including departure integration with en-route control, the integration of en-route and ETMA concepts, and the integration of en-route with arrivals (Ref.[13, 14, 20]).

The main aim of the experiment that was intended to be performed at the EEC was to demonstrate an air-ground integrated system in all phases of flight. PD/3 was required to show the potential for both airspace capacity and controller "productivity" improvements in a full "gate-to-gate" environment using:

- Layered planning techniques to operate at scales greater than the traditional sector scale;
- The introduction of advanced computer-based tools and associated GHMI to assist controllers with their organisation and planning tasks;
- The introduction of both an arrival- and a departure-management tool; and
- The introduction of 4D trajectory negotiation and editing.

The layered planning concept in PD/3 commenced with a multi-sector-planning controller using the Tactical Load Smoother, Ref.[7] to reduce complexity and thus the number of exceptions and conflicts up to 40 minutes in advance. The planning responsibility is given to the sector planning controllers for deconflicting any conflicts approximately 10 minutes before the aircraft were due to enter the relevant sector. The sector planning controllers were tasked with either solving any predicted conflict situations. The sector tactical controller was responsible for implementing the solutions prepared by the sector planner, solved and implemented any other problems that arose tactically, and maintained radio contact with the aircraft.

6. RESULTS

6.1 PHARE DEMONSTRATION RESULTS

The results obtained with the PS are rather subjective, being the views of the controllers that used it. Also, the PS was only visible by means of the GHMI. Thus, comments made about the PS were often comments about how the information generated by the PS was displayed.

The achievements of PD/1 are documented in Ref.[21]. The PS in PD/1 was used mainly by the sector PCs. These controllers used the PS a lot and, on the whole, thought that the PS was a relevant tool. The controllers indicated that the PS had helped to reduce their workload. There were some comments as to how best to display the information generated by the PS so as not to distract the controllers from performing other tasks.

Some comments about the information generated by the PS were a consequence of a lack of trust of computer-based tools. Such a lack of trust is, perhaps, well placed. The PS could sometimes lead a PC to safely plan an aircraft to climb in front of another aircraft. The TCs would not normally trust such a plan and, consequently, monitored these cases closely; this could result in an increase of their workload. Similarly, a trajectory planned with the help of a PS might result in an aircraft climbing later than a TC would have climbed it.

Some controllers found the speed profiles difficult to use and interpret; no doubt this was because the speed was not displayed directly.

6.2 ACHIEVEMENT OF CONCEPT

The PS is a tool that can indicate where and when a selected aircraft is predicted to be in a conflict situation with other aircraft. In addition, it also indicates where and when the trajectory of that selected aircraft should go if those predicted conflict situations are to be avoided. In this way, the PS enables a controller to design an alternative trajectory for the selected aircraft that he knows will be conflict-free. The exact form of the alternative trajectory is left to the controller to decide. The PS does not even suggest the form of the alternative trajectories.

The PS cannot be said to be a solver of problems itself. It does, however, help controllers to resolve predicted problem situations.

This page left intentionally blank

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The PATs' PS is a computer-based tool that provides certain views of the predicted air traffic situation that, combined with a means to modify planned aircraft trajectories, allows a sector planning controller to design trajectories that are conflict-free. The PS provides a view of the predicted air traffic situation from the point of view of a particular aircraft, known as the subject aircraft. The "volumes" of 4D space that the subject aircraft should not enter if it is not to be in conflict at some moment or another with another aircraft are indicated by means of a set of 2D "abstracted" displays.

The PS has been successfully used by sector planning controllers to design conflict-free trajectories when accurate descriptions of the planned trajectories are available twenty minutes or so ahead.

The PS concepts can be use in other applications. Sector tactical controllers could use a version of the PS if a way could be found to display the relevant information on the same display as the plan-position display. Another version of the PS has been developed so that its applicability to oceanic control at the Oceanic Area Control Centre at Prestwick, Scotland can be assessed, Ref. [22].

Airlines would like more control over how their aircraft go from A to B. A pilot cannot act alone, however. He must have an idea of the air traffic situation around him. A version of the PS could be used for this. The PS is particularly suited to being placed on-board an aircraft as it provides an aircraft-centred view of the predicted air traffic situation. Putting a PS in the cockpit could allow a pilot to request routing or flight level changes in the knowledge that such requests were reasonable given the air traffic situation.

As a part of the FREER (Free-Route Experimental Encounter Resolution) study, a version of the PS software has been integrated into the Cockpit Display of Traffic Information system on-board an aircraft, Ref.[23]. The aim of this study is to assess the feasibility of the autonomous aircraft separation concept.

7.2 RECOMMENDATIONS

The usefulness of the PS tool is highly dependent on the way in which the information that the PS software generates is presented to the controller. The design of HMIs is a specialist job. It requires a lot of work to design really useful displays and ways of inputting information. This work should be continued for the PS type of tools.

The algorithms that generate the no-go zone descriptions can also be improved. Novel algorithms could be developed, linked to novel ways of interacting with the PS software.

This page left intentionally blank

8. ABBREVIATIONS AND ACRONYMS

3D	3-Dimensional
4D	4-Dimensional
ATC	Air traffic Control
ATM	Air traffic Management
CENA	Centre d'Etudes de la Navigation Aérienne
CLW	Communications List Window
CP	Conflict Probe
CRD	Conflict and Risk Display
CWP	Controller Working Position
CZW	Conflict Zoom Window
DERA	Defence Evaluation and Research Agency
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
DRA	Defence Research Agency
EEC	Eurocontrol Experimental Centre
ERPC	En-Route Planning Controller
ERTC	En-Route Tactical Controller
ESCAPE	The Eurocontrol Simulation Capability And Platform for Experimentation
ETMA	Extended TMA
Eurocontrol	The European Organisation for the Safety of Air Navigation
FMS	Flight Management System
FPM	Flight-Path Monitor
FREER	Free-Route Experimental Encounter Resolution
GHMI	Ground HMI
GUI	Graphical User Interface
HAW	Horizontal Assistance Window
HIPS	Highly Interactive Problem Solver

HMI	Human-Machine Interface
NARSIM	The NLR ATC Research Simulator
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium
PARADISE	The Prototype of an Adaptable and Re-configurable ATM Demonstration and Integration Simulation Environment
PAT	PHARE Advanced Tool
PD/1	PHARE Demonstration #1
PD2	PHARE Demonstration #2
PD/3	PHARE Demonstration #3
PEPSI 1	The First PAT's Experimental Problem Solver Implementation
PEPSI 2	The Second PAT's Experimental Problem Solver Implementation
PHARE	The Programme for the Harmonised ATM Research in Eurocontrol
PS	Problem Solver
SIGMET	Significant Meteorological Area
TLS	Tactical Load Smoother
TMA	Terminal Manoeuvring Area
TP	Trajectory Predictor
TRA	Temporarily Restricted Area
VAW	Vertical Assistance Window

9. REFERENCES

1. PHARE Advanced Tools Arrival Manager Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
2. PHARE Advanced Tools Conflict Probe Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
3. PHARE Advanced Tools Co-operative Tools Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
4. PHARE Advanced Tools Departure Manager Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
5. PHARE Advanced Tools Flight-Path Monitor Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
6. PHARE Advanced Tools Negotiation Manager Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
7. PHARE Advanced Tools Tactical Load Smoother Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
8. PHARE Advanced Tools Trajectory Predictor Final Report, PHARE Document DOC 98-70-XX (Volume X of Y)
9. PHARE Advanced Tools Umbrella Document, PHARE Document DOC-98-70-XX (Volume X of Y)
10. PHARE Advanced Tools Initial Requirements and Planning Document, Version 1.1, July 1992
11. PHARE Advanced Tools: PATs IDD - Interface Document, Version 2.3, PATs/CET/GEN/IDD/2.3/94/312, September 1994
12. PHARE Medium-Term Scenario, 2000-2015, Version 1, July 1990
13. PD/3 Operational Scenarios Document (Volume 1), PHARE Document DOC 97-70-04
14. PD/3 Operational Scenarios Document (Volume 2), PHARE Document DOC 97-70-08
15. Proposed Use of Abstract Diagrams for the Problem Solver HMI, PAT/EEC/PS/WP/3/93/001, Version 1.0, July 1993
16. PD/1 Operational Specification, PHARE Document DOC 94-70-02
17. PD/1 Operational Scenarios, PHARE Document DOC 94-70-28
18. PD2 Operational Specification, PHARE Document DOC 94-70-03
19. PD2 Operational Scenarios, PHARE Document DOC 95-70-11
20. PD/3 Demonstration Operational Specification, PHARE Document DOC 95-70-02
21. PD/1 Final Report, PHARE Document DOC 96-70-24
22. Price A., Meckiff C., "HIPS and its Application to Oceanic Control", Presented at the FAA/Eurocontrol R & D Symposium, Paris, 17-20 June 1997

23. Duong V., Zeghal K., "Conflict Resolution Advisory for Autonomous Airborne Separation in Low Density Airspace", Presented at IEEE CDC'97 Conference, San Diego, 10-12 December 1997
24. Wilson I A B, "Trajectory Negotiation in a Multi-Sector Environment" PHARE DOC 70-97-14 dated January 1998.
25. PD/3 Final Report