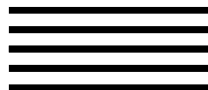
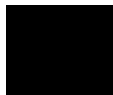


PROGRAMME FOR
HARMONISED AIR TRAFFIC
MANAGEMENT RESEARCH
IN EUROCONTROL



DOC 96-70-18



PHARE : Definition and use of Tubes



EUROCONTROL

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DOCUMENT APPROVAL

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DEFINITION AND USE OF TUBES IN PHARE

1. INTRODUCTION

- 1.1 Tubes are defined as a series of 4D windows which are used to describe airspace volumes around a trajectory. However, while tubes were seen as important within PHARE their definition and use was confused.
- 1.2 The PATs team members, together with members of the GHMI team, developed a consistent set of definitions which seem to meet the requirements of all the systems in PHARE. The paper was circulated at PHARE Review Team and PHARE Co-ordinating Committee levels for comment, agreement and amendment . These definitions are for use in PHARE and the PATS groups intend to use them in PD/2 and PD/3.
- 1.3 Unfortunately, as tubes are often given synonyms and homonyms, discussion of the topic can be difficult and confusing. Tubes are used to describe volumes of airspace around a trajectory. They are used variously to describe:
 - a. The likely error in forecasting of the trajectory predictor;
 - b. The degree of freedom given to an aircraft to maintain the trajectory;
 - c. The contracted volume of airspace that the aircraft must fly within;
 - d. The boundaries outside which deviation warnings are passed to the controller and possibly navigation assistance to the aircraft.
- 1.4 The purpose of the tubes is another area of confusion. In the 1980s a tube concept called the GARTEUR Concept was developed. The central theme of this concept was allocation of the maximum airspace to an aircraft in order to allow the aircraft to optimise its trajectory within the allotted airspace without the requirement to negotiate with the ground system. However, as PHARE is based on an *integrated air/ground ATM system* in which the aircraft generated trajectory is held in the ground system, the PHARE concept allows the aircraft to negotiate the optimum trajectory with the ground system and then the airspace is allocated around the agreed trajectory. Thus in the PHARE environment the minimum amount of airspace is allocated consistent with maintenance of the agreed optimum aircraft trajectory.

2. DEFINITION OF TUBES

- 2.1 Error Tube. The Error Tube defines the boundaries of the Trajectory Predictor forecasting error. It allows for all the inaccuracies in the variables input into the forecasting process and for the likely errors of the aircraft in trying to follow the trajectory.
- 2.2 Contract Tube. The Contract Tube defines the boundaries of a volume of airspace around the contracted trajectory along which the aircraft is 'contracted' to fly. This is called the Active Tube by EFMS and is the *only* tube of interest to the EFMS or AHMI.
- 2.3 Large Deviation Tube. The Large Deviation Tube is a tube around the Contract Tube which defines the boundary of 'recoverable navigation errors'¹ by the aircraft.

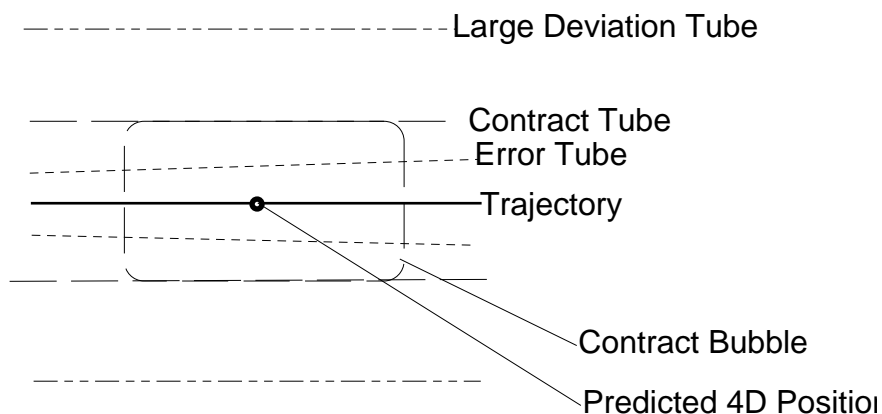


Figure 1. Diagram of Tubes

¹ A Recoverable Navigation Error can be defined as: "A Recoverable Navigation Error is a deviation from the 4D trajectory which is small enough to allow the aircraft to recover to within the contract tube by the current sector boundary and which causes no hazard to other aircraft." However, for the purposes of PHARE a standard tube size will be used throughout, regardless of airspace.

PURPOSE OF TUBES

- 3.1 **Error Tube.** The Error Tube is a tube used only by the ground systems and is not displayed to the controller. It can be used by the ground software Tools to assess the degree of inaccuracy of a trajectory. If the error tube becomes too large further trajectory prediction, conflict probing and trajectory editing may be considered nugatory. Note that inaccuracy in this instance means the difference between the ground Trajectory Predictor prediction and the air Trajectory Predictor prediction. Once a trajectory has been contracted, the only error that is of interest is the flight technical error of the aircraft following the trajectory. See 5.3 below. The error tube produced by the ground trajectory predictor identifies the likely boundary of the trajectory produced by the EFMS on the aircraft and so provides an indication of the inaccuracies between the ground and air trajectory predictors.
- 3.2 **Contract Tube.** The parameters of the Contract Tube are passed to the aircraft as the final up-link of the Trajectory Negotiation process to indicate that 'the ground' wishes to agree a contract on the trajectory. It is used by the aircraft to provide manoeuvre smoothing for recovery to the trajectory if or when the aircraft fails to follow it precisely. It also allows the aircraft limited but sufficient manoeuvre space when following the trajectory. In the aircraft the EFMS will warn the pilot as soon as it is possible to detect that with the present trends and with the authority limits assigned by the pilot to the EFMS, the aircraft will deviate from the Contract Tube. On the ground the Flight Path Monitor will provide a *medium* deviation alert to the Tactical Controller if the aircraft is detected to be flying outside the Contract Tube. If an aircraft departs the Contract Tube it is for the Tactical Controller and/or the pilot to decide if the Contract requires re-negotiation - automatic re-negotiation will not take place².
- 3.3 **Large Deviation Tube.** The Large Deviation Tube is only used by the ground Flight Path Monitor which issues a 'Large Deviation' alert if and when the aircraft flies outside it. The Large Deviation Tube is not displayed on the GHMI neither is it transmitted to the aircraft. If an aircraft flies outside its Large Deviation Tube the trajectory must be re-negotiated by ATC.

GENERATION OF TUBES

- 4.1 **Error Tube.** The Error Tube is generated by the ground Trajectory Predictor. It is calculated from the probabilistic errors in the forecasting process.
- 4.2 **Contract Tube.** The Contract Tube is generated by the ground Trajectory Predictor as a parameter size greater in all dimensions than the error tube. It consists of a series of 4D windows or constraints close enough together to allow interpolation to form a consistent tube. At the runway, at take off and landing, the contract tube should be coincident with the Error Tube. However, for the purposes of PHARE,

² An aircraft may exit the Contract Tube due to Tactical Controller action on exception events. Automatic system action to re-negotiate, enforcing extra workload on the controller and pilot at this stage, would be unwelcome and could be hazardous.

the contract tube will remain at a constant size for the entire flight. The Contract Tube will be sized such that the expected navigational errors (Flight Technical Errors) of the aircraft are less than the size of the Contract Tube thus ensuring that under normal circumstances the aircraft should remain within it. For simplicity, in PHARE this will be based on simple parameters; in an operational system the tube sizing could be linked to the known navigational capabilities of the aircraft. The Contract Tube is symmetrical about the trajectory with limits of the order of: 1 nm laterally, 200 feet vertically and 10 seconds longitudinally; either side of the contracted 4D trajectory position.

- 4.3 Large Deviation Tube. The Large Deviation Tube is generated by the ground Trajectory Predictor as a parameter size greater than the Contract Tube. At the runway, at take off and landing, the Large Deviation Tube should be coincident with the Contract Tube. However, for the purposes of PHARE, a standard tube size will be generated regardless of airspace. After the initial generation of the tube, the Conflict Probe may vary the sizing of the allocated Large Deviation Tube to take into account traffic conditions. Thus, in areas with a high traffic density the tube will be reduced.
- 4.4 It is important to note that the tubes are sized without any regard to the type of airspace or sector boundaries. Furthermore, in the PHARE environment aircraft are expected to attempt to follow the contracted trajectory. The tubes in PHARE are *not* the GARTEUR concept variably sized tubes for 'tactical freedom'.

5. TUBE USAGE

- 5.1 In this section the method of usage of the tubes is detailed. The usage made of the tubes in the air and on the ground differs because of the different requirements of the controller and the pilot. To clarify the use of tubes, the sequence of their use is described. The allocation of free airspace to flights is also highlighted. It should be noted that there is only one trajectory in use, the contracted trajectory. The ground systems and the aircraft have the same trajectory. In normal trajectory negotiation the trajectory used is the trajectory generated by the aircraft. For non-datalink equipped aircraft, the trajectory used is the trajectory generated by the ground Trajectory Predictor.
- 5.2 **Step 1 - Initial Trajectory.** The initial trajectory in the ATM system may be from the aircraft as a data-link down-link or from the ground systems trajectory predictor on behalf of the aircraft if it is not data-link equipped. The initial trajectory is an ideal 'blue sky' trajectory with no constraints other than ideal aircraft performance. Effectively, the aircraft (or the ground Trajectory Predictor as its proxy) has assumed that it has unconstrained use of the whole airspace. It is based on the CFMU response to the initial Flight Plan for the flight.

- 5.3 **Step 2 - Error Tube Generation.** The ground Trajectory Predictor, on generation of a new trajectory, produces an error tube around the prediction indicating the likely probability of error in generation of the trajectory. When the controller is carrying out 'what -if' modelling of potential trajectories prior to contract, there is a probability that although they have the same constraints, the trajectory being used in the model and the trajectory that a 4D datalink aircraft would return, will be different. In that case the error tube can be used as an indication of uncertainty by the Problem Solver. However, as the aircraft will try to fly (or be instructed to fly) the trajectory generated, the error tube is only an indication of the degree of inefficiency of the trajectory - unless the trajectory is forecast outside the flight envelope of the aircraft and is thus not flyable. An unflyable forecast trajectory is extremely unlikely, as the ground based trajectory predictor operates to the same functional requirements as the airborne trajectory predictor, with near identical data. Therefore there is little constructive operational use that can be made of the error tube. The likely manoeuvre space required by the aircraft when flying the trajectory is defined by the Contract Tube (see Below).
- 5.4 **Step 3 - Imposition of Constraints.** The trajectory proposed by (or for) the aircraft is checked by the ground system for conflicts and, if any are found, the trajectory is edited to 'solve' the conflicts. This editing is done (for example using the HIPS) by imposing constraints for use by the Trajectory Predictor, defining the limitations which the trajectory must meet to be conflict free. The constraints produced are data-linked to data-link equipped aircraft. The allocation to the aircraft of the entire FIR/UIR is therefore reduced by the constraints to a smaller volume of airspace within which the aircraft must forecast its trajectory.
- 5.5 **Step 4 - Trajectory Generation to meet Constraints.** The Trajectory Predictor in the aircraft (or the ground Trajectory Predictor on behalf of the aircraft) generates a trajectory to fly most efficiently and economically³ within the airspace defined by the constraints. If any of the constraints cannot be met, a trajectory is produced that comes as close as possible to meeting them. The generated trajectory is down-linked to the ground. Any constraints which are not met are flagged. Note that as the Trajectory Predictors attempt to produce an ideal economic trajectory, the imposition of constraints may cause changes in areas of the trajectory remote from those constraints. If it is necessary to prevent propagation of trajectory changes, then extra constraints will be needed to enforce retention of the trajectory in other areas. This could be done by passing the old contract tube as constraints.
- 5.6 **Step 5 - Trajectory Check and Contract Tube.** The downlinked trajectory is checked to ensure that it meets the constraints and that no new or unforeseen conflicts are caused. If the trajectory is acceptable then it is 'contracted' with the aircraft. However, in order to allow the aircraft a degree of manoeuvre space around the trajectory, a 'Contract Tube' is generated around the Trajectory. This Contract Tube further confines the airspace available to the aircraft but it allows minor deviations (due to such things as flight technical errors or meteo inaccuracies) to be corrected smoothly. The Large Deviation Tube is also generated at this stage. Either the Contract Tube parameters or an indication that standard parameters should be used is up-linked to the aircraft as its 'clearance'.

³ Economic Trajectory can be defined as: "The trajectory which minimises the entire operation cost of the aircraft in flying between its current position and its landing point."

Efficient Trajectory can be defined as: "The trajectory that minimises the number and severity of vector changes of an aircraft flying between its current position and its landing point."

Note: There is no current optimisation of trajectories within PHARE

5.7 **Step 6 - Pilot Acceptance**. The AHMI displays the Contract Tube to the pilot. If the pilot Accepts the Contract Tube allocated, then the aircraft down-links an 'Accept'. This completes the trajectory negotiation process.

5.8 **Step 7 - Flying the Trajectory**. The FMS in the aircraft will attempt to fly the trajectory that has been agreed. As it operates it continually rechecks to ensure that the aircraft will remain within the Contract Tube. If the FMS detects that the aircraft may shortly exit the Contract Tube, the pilot will be warned. For non-data-link aircraft, the controller will be provided with advisories to pass on R/T to keep the aircraft within its Contract Tube. The Flight Path Monitor (FPM) in the ground system checks each radar response against the contracted 4D position for the aircraft. If the aircraft is outside the Contract Tube, a Medium Deviation warning is raised. If it is outside its Large Deviation Tube, a Large deviation warning raised. In this way, the Tactical Controller is warned of any aircraft deviating.

6. **BUBBLES**

6.1 Although the word 'Tube' is used as a convenience, a tube is a 3D structure, whereas the actual airspace contracted with the aircraft is a 'Bubble'. This takes account of the longitudinal/temporal manoeuvre space given to the aircraft and can be considered a 4D structure. Thus EFMS and the FPM monitor the aircraft position in the bubble and will also provide warnings of longitudinal/temporal errors.

7 **SEPARATION MINIMA AND TUBES**

7.1 Whilst the use of tubes is simple to grasp, it does introduce some possible areas for further research. The most important of these is the philosophy of separation minima for predicted conflict detection and tubes. There are two opposing views. The first is that the aircraft is always attempting to fly the trajectory, therefore the separation should be measured from the 4D predicted position of the two aircraft. In opposition to this is the view that the aircraft could be at any 'edge' of the contract bubble and therefore the separation should be measured between the boundaries of the contract bubble. This conflict in philosophies was highlighted in PD/1 between the HIPS and the Conflict Probe.

7.2 The current separation minima do not seem to be generated from sets of parameters to allow for various errors. However, they are large compared with the likely dimensions of the Contract Tube, so it could be argued that they already take the manoeuvre space of the aircraft into account. This area requires more detailed research, as the potential benefits of reducing separation minima could be considerable for the airlines.

8. SUMMARY

- 8.1 The three types of tube used in PHARE are the Error Tube, the Contract Tube and the Large Deviation Tube. All are generated by the Trajectory Predictor on the ground and are used by the PATs on the ground. The tubes are based solely on the aircraft's ability to fly a trajectory and are not affected by airspace semantics, although the large deviation tube may be amended to take traffic density into account. The Contract Tube parameters are passed to the aircraft EFMS as the last up-link of the negotiation process. The only tube of consequence to the EFMS is the Contract Tube.

9. IMPLEMENTATION RESEARCH ISSUES

- 9.1 Operational implementation of the PHARE concepts will require more detailed research into the quality and performance issues of tube generation. Further research is also required into the required separation minima for 4D aircraft maintaining a trajectory, as there could be considerable airspace capacity benefits from their reduction. Nevertheless, the definition and use of tubes in PHARE, although limited in some places for experimental simplicity, is based on a realistic approach to implementation and provides real benefits from 4D trajectory generation and negotiation.

GLOSSARY

4D	4 Dimensional - Refers to an aircraft FMS ability to fly accurately to time as well as navigate in position and level.
AHMI	Airborne HMI
ATC	Air Traffic Control
ATM	Air Traffic Management
CFMU	Central Flow Management Unit
EFMS	Experimental Flight Management System - a 4D capable flight management system.
FIR	Flight Information Region
FMS	Flight Management System
FPM	Flight Path Monitor
GARTEUR	Group for ATM R&D Technology in Europe.
GHMI	Ground HMI
HIPS	Highly Interactive Problem Solver - an advanced tool which assists the controller to deconflict aircraft trajectories in 4D.
HMI	Human Machine Interface
nm	Nautical Mile
PATs	PHARE Advanced Tools - The advanced software tools in the ground ATC system to assist controllers in managing the 4D ATM environment.
PD/1	<u>PHARE Demonstration 1:</u> PHARE Concept demonstrated in en-route phase of flight.
PD/2	<u>PHARE Demonstration 2:</u> PHARE Concept demonstrated in TMA Arrival phase of flight.
PD/3	<u>PHARE Demonstration 3:</u> PHARE Concept demonstrated in departure, en-route and Arrival phase of flight.
PHARE	Programme for Harmonised ATM Research in Eurocontrol
R/T	Radio Telephony
TMA	Terminal Control Area
UIR	Upper Information Region