Final Report for Publication

ARAMIS

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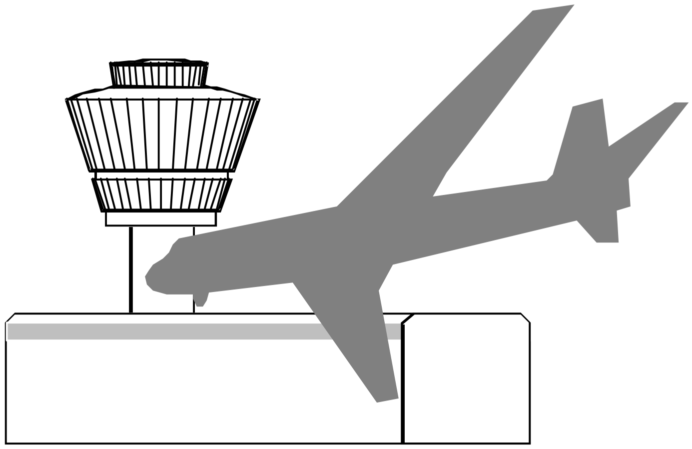

ARAMIS

Final Report

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1. Introduction

1.1. Purpose

This document presents the results of the ARAMIS project, contract AI-95-SC.301 of the ECARDA programme led by the European Commission, DG7, within the 4th Framework Programme.

The present report constitutes the deliverable D5 cited by the Technical Annex of the ARAMIS contract.

ARAMIS stands for Advanced Runway Arrivals Management to Improve airport Safety and Efficiency. The global goal of the project is to adapt and develop models and tools for 4D-planning, guidance and control, to assist Air Traffic Controllers in the sequencing and monitoring during the approach phase of flight.

1.2. Intended audience

The document is public. It can be distributed to any internal or external organisation.

DISCLAIMER: Alcatel ISR, ALENIA, Dassault Electronique, NATS, National Avionics, NLR and Sofréavia shall not be liable for any damage resulting for the application of the contents or part of the contents of this report.

1.3. Document Structure

This report is organised in three sections, plus this one. The section 2 exposes the project summary, with objectives and main results. The section 3 presents the models used in the system, resulting of the studies realised during the first year. The section 4 provides a description of the realised demonstrator: functionalities, architecture. Finally the section 5 presents briefly the results of the validation.

1.4. Abbreviations

A/C	Aircraft
ADS	Automatic Dependent Surveillance: a surveillance technique in which A/C provide data via data-link.
A/P	Airport
API	Application Programming Interface
ARAMIS	Advanced Runway Arrivals Management to Improve airport Safety & efficiency
ATC	Air Traffic Control
ATCO	Air Traffic Controller
ATIS	Automatic Terminal Information Service
CWP	Controller Working Position
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
FIR	Flight Information Region.
FM	Flight Manager (function of the ARAMIS demonstrator)
FMS	Flight Management System: on-board multi-purpose computer
FPG	Flight Plan Generator (function of the ARAMIS demonstrator)
HMI	Human-Machine Interface
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rule

LAN	Local Area Network
KT	Knot
MG	Monitoring/Guidance (function of the ARAMIS demonstrator)
MIN	Minute
NM	Nautical Mile
NWP	Numerical Weather Prediction
OMT	Object Modelling Technique
RDPS	Radar Data Processing System
SEQ	Sequencer
SID	Standard Instrument Departure: A pre-planned IFR departure procedure.
SSR	Secondary Surveillance Radar (mode S)
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival Route: a pre-planned IFR arrival procedure
TAS	True Air Speed
TF	Trajectory Forecast (function of the ARAMIS demonstrator)
TMA	Terminal Manoeuvring Area
TTA	Target Time of Arrival
TP	Trajectory Prediction
TS	Trajectory Synthesis (function of the ARAMIS demonstrator)
WP	Work Package

2. Project summary

2.1. Objective of the study

Airports and terminal control areas are behaving as bottlenecks in the capacity growth of passengers and freight transport. Existing structures are not fully exploited, so high gains in air transport capacity can be obtained by a more efficient overall traffic flow. If air traffic management is well provided by ATM systems, on the other hand, current Surface Movement Guidance and Control Systems (SMGCSs) suffer from insufficient automation and appear as bottleneck in the overall system.

The operational Sequencing and Metering tools provide the controllers with a sequence of arriving aircraft including the Schedule Time of Arrival (STA) and the amount of delay to be absorbed by each aircraft in order to meet the STA, but they present some limitations, coming from the lack of accurate 4D aircraft performance models and meteorological models.

The main objective of the ARAMIS project is to adapt and/or develop models, and develop tools for 4D-planning, guidance and control during the approach phase of flight, from initial approach fix until runway threshold. For the surface planning and guidance the controller needs to anticipate, with accuracy, the time and localisation where aircraft will land. In fact, knowing when an aircraft arrives at the runway threshold, with an error of a few seconds, allows to plan aircraft surface movement around runways.

To enhance time accuracy of aircraft landing, it is necessary to increase the prediction accuracy of flight path for the final phase of flight. This phase is very complex as aircraft fly with different throttle and flap settings. These settings depend mainly on the procedures used by the different airports and airlines, on the aircraft types, and also meteorological conditions such as wind.

The ARAMIS project thus intends to produce efficient spacing, and contribute to increase airport capacity by smoothing the controller's workload, ensuring that he does not become overloaded.

In the first stage, the ARAMIS project studied the choice and the adaptation of the existing models in the field of procedures, aircraft performance and weather, in order to select the appropriate ATC procedures, and build an aircraft performance model and a weather model to be exploited in the further phases of the project.
The second phase of the ARAMIS project deals with the definition of the users and operational requirements.

Based on the results above mentioned, the third objective of the ARAMIS project consisted in the development of a prototype, including an aircraft performance model, a weather model, a trajectory prediction, monitoring/guidance, sequencer, human-machine interface. This prototype has been completed in July 1998.

Finally the test and evaluation phase, including workshops with controllers, has been achieved in April 1999.

The project is realised by a consortium grouping Alcatel ISR (F), Alenia (I), Dassault Electronique (F), NATS (UK), National Avionics (EI), NLR (NL), and Sofreavia (F), with a contribution from the Eurocontrol Experimental Centre (EEC).

2.2. Summary of results

The study has been organised in the following steps:

- Description of procedures,

- Definition of the aircraft performance model,
- Definition of the weather model,
- Realisation of a demonstrator,
- Tests and evaluation.

All the tasks have been achieved and the corresponding deliverables, provided.

The 21 public documents are grouped in 4 groups numbered D2 to D5 (The D1 was the Project Management Manual), and describe the initial studies, requirements, specification of the ARAMIS system.

From this specification the ARAMIS software has been realised from scratch on Unix stations and is based on a CORBA architecture. It has been presented to and tried by controllers.

2.3. Main documents

The table hereafter lists the documents that constitute the output of the project. The main public document is the final report. Several reports are restricted on request expressed done by the providers of information.

The public documents can be requested to the European Commission, DG VII, or to the ARAMIS coordinator (see address below).

Title	Date
Procedures and models study	Oct 21, 1996
Current ATC Procedures at Heathrow, Charles de Gaulle, and Linate	Jun 26, 1997
Selection, adaptation and evaluation of an aircraft performance model	Jan 31, 1997
Study of a class C model	Jan 21, 1997
A Weather Model Adapted to Specific Approach Problems	Jan 3, 1997
Users requirements	Jan 31, 1997
Operational requirements	Jan 18, 1997
Specification of system functions (9 parts)	July 28, 1997
Test and Evaluation Report	April 6, 1999
Final Report	May 6, 1999

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3. Models

3.1. Description of procedures

ARAMIS performed a survey, conducted at various airports, to gather statistics on the traffic, companies operating at these airports and aircraft types. The collected data has been analysed making distinction between the engine categories (Jet, Turbopropeller; Piston) and the weight categories (Light, Small, Medium and Heavy).

The airports have been selected to cover a wide range of number of movements, airport configurations and ATC procedures.

On the basis of this survey the project selected for the three wake vortex categories: the B747-400 in the *heavy* category, the A320 and the B737-400 in the *medium* category, the ATR42 in the *small* category, as the most representative aircraft for the selected airports.

The project studied the descent procedures with the selected aircraft types, airports and individual airline policy. A generic type descent and approach plan is shown in the figure to give a broad appreciation of distances, speeds and heights from top of descent (TOD) until landing. The point at which the level flight path intercepts the glide slope on the localiser is known as the Final Approach Point (FAP).

The study addressed the procedures recommended by the different airlines during the time where the Approach Controller can exercise speed and flight-plan control over the aircraft; and the procedures specific to the different aircraft types: average landing weights, speeds for ‘clean’ and ‘approach’ configurations (‘clean’ means that the aircraft is not using flaps, brakes, landing gear).

The analysis of the responses done to the questionnaire highlighted important differences in procedures for different airlines flying the same aircraft type: landing weight, descent speed, stabilisation height, wind factor, use of speedbrakes.

From the data provided it appeared that it is necessary to model the different airlines explicitly, due to their different policies on descent speeds and point of stabilisation.

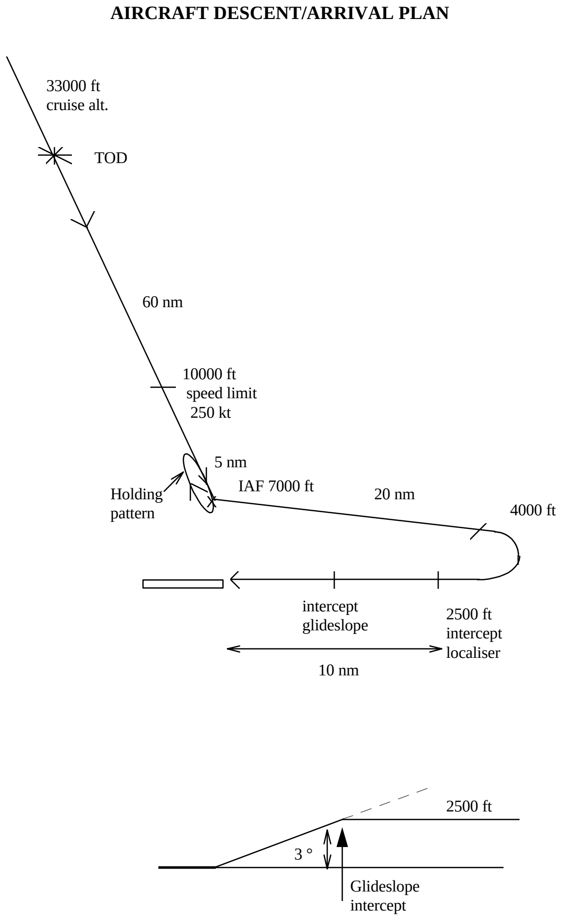

Figure 1: Typical approach procedure

3.2. Aircraft performance model

One of the main goals of ARAMIS is to analyse and adapt an aircraft performance model for use within tools for accurate 4D planning, guidance and control. The phase of flight considered in ARAMIS starts at the initial approach fix and ends at the runway threshold. One of the most important issues within this phase of flight is the complexity due to the variety in throttle and flap settings depending on procedures used by different airports, airlines, aircraft types and wind conditions.

First the requirements for such an aircraft performance model have been studied and an inventory and classification of existing aircraft performance models has been made. It was concluded that there are two classes of aircraft models which have possibilities for use within the ARAMIS project, i.e. the class of Flight Mechanical Point-Mass models (know as class B models) and the class of Parametric models (known as class C models). Both the selected aircraft performance model and its input data, i.e. the aircraft performance data, must satisfy the relevant requirements listed during the study.

The second part of this work consists of a selection, adaptation and evaluation of an aircraft performance model. In addition, some recommendations for adaptation of the existing aircraft performance data Base of Aircraft Data (BADA) are given.

One of the aims of this task was to make a selection of a model. Since both classes B and C have possibilities for use within ARAMIS, they have been investigated separately. Both classes of models have been discussed with respect to the requirements. Next, the mathematical modelling, aircraft performance (input) data and runtime consideration issues have been discussed for classes B and C.

A class B model can be described in a general way by means of mathematical equations, representing the actual motion of an aircraft, which are fed by aircraft performance input data. Due to this general mathematical description it provides better accuracy, when the aircraft performance input data are sufficiently accurate. The higher CPU load of such a model is not considered as a limiting factor. Within ARAMIS it was decided to use a class B performance model using the BADA database for the development of the trajectory generator.

Given this choice of model and model parameters, which is referred to as a baseline aircraft performance model, the aim was twofold. First to adapt qualitative aircraft performance models within this class B for flights from initial approach fix until the runway threshold. Secondly, to identify for which modelling aspects a further elaboration is worth while.

ARAMIS listed possible extensions of such a baseline aircraft performance model. These extensions include mathematical descriptions of lift and drag characteristics for different aircraft configurations, idle thrust level for jet engines and autopilot modelling.

The database BADA provides aerodynamic modelling and data, i.e. lift and drag characteristics, for various types of aircraft. However, in the release of BADA that was available at this stage of the project (version 2.5), the drag polar data for non-clean configurations such as high lift devices, speedbrakes and landing gear was not specified. These non-clean data are very characteristic for the final phase of flight, but are difficult to obtain since they often remain restricted to the manufacturer and the airlines.

An aerodynamic model for the drag coefficient has been elaborated covering the non-clean configurations and the effect of Mach number. This model is based on the drag polar as formulated within BADA and is extended with drag polar coefficients for landing and approach flap settings and a drag coefficient increase due to undercarriage and speedbrakes. For the idle thrust level a simplified linear model is elaborated, which depends on Mach number, altitude and temperature correction.

First simulations have been performed for a B747-400 approaching Charles de Gaulle runway 27 from Merue. The model has been evaluated for the influence of the aircraft performance parameters such as drag coefficients, thrust coefficients and aircraft mass.

In order to test whether or not this sixth order class B model is sufficient for the final phase of flight, another more detailed version of the aircraft model has also been used. This extended version belongs between the classes A (i.e. the Full Flight Dynamical Model) and B, and will be referred to as an A/B class model. Both the class B model and the class A/B model have been evaluated for the approach scenario as described above, in order to determine the impact of the level of detail of the model on the accuracy.

From the evaluations two important conclusions can be drawn. First, it turned out that the more extended A/B class model results in a much higher time accuracy of the trajectory predictor, when compared to the sixth order class B model. Secondly, the simulations showed that some of the parameters need more accurate assessment, than currently available in BADA. In particular these parameters are the aircraft mass at the initial approach fix and the aerodynamic parameters for non-clean configuration, since they have significant impact on the time accuracy of the trajectory predictor. Therefore further research has been required to Eurocontrol in order to extend the current BADA release with these parameters for various kind of aircraft types. With less priority, this need for extension of the current BADA release refers to the thrust parameter and derivative, which have minor impact on the time accuracy of the trajectory predictor.

The Eurocontrol Experimental Centre (EEC) contributed to the project by providing in a first time data for two aircraft types (ATR42 and A320) as an enriched version of BADA files, including data for non-clean configuration. This intermediate version of BADA (version 2.6) has been used in ARAMIS to develop and validate the trajectory prediction. Finally EEC provided in June 1998 the version 3.0 including 9 aircraft types with non-clean configuration. This version of the database has been used with the final ARAMIS demonstrator.

3.3. Weather model

ARAMIS has produced a nowcasting[1] model, derived from WAFTAGE, which can significantly reduce the errors in the numerical weather predictions (NWP) currently provided to aviation users in the terminal area. It has been shown using aircraft data that, in the terminal area, the nowcasting model derived from WAFTAGE reduces the RMS vector wind error in the NWP forecast by a substantial fraction, in some cases to produce errors close to 2 m/s.

The statistical simulation study shows that a high density of aircraft observations are required to produce good results. Ideally, observations from all arriving aircraft are needed every 1,000 feet (vertical) during the descent in the terminal area. Close to the ground (below about 3,000 feet) observations every 500 feet (vertical) would be beneficial.

The statistical simulation study further suggests that the use of independent observations could reduce the errors still further perhaps to 1 m/s or less. However, this would require a substantial financial investment to deploy a network of profilers, and possibly also one or more (clear air) scanning Doppler radars. These instruments would provide 24 hour coverage, which would be augmented by aircraft reports during the daytime. Additional sources of independent wind observations could be Doppler acoustic sounders for the boundary layer, and satellite water vapour track measurements in the upper air, but these possibilities have not been explored in this study.

In conclusion, the WAFTAGE model could be implemented in a terminal area to provide gridded nowcasts of winds (and temperatures) every 15 minutes provided an adequate source of observations becomes available either from aircraft (via an appropriate air to ground data link) or from other sensors such as a network of strategically placed profilers.

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[1] *nowcast* is a neologism meaning "very short term forecast".

4. Demonstrator

The project developed a set of computer programs which aim to demonstrate the interest of the studied models, so their usability in a ground-based tool to assist controllers. The main part of these tools is a trajectory predictor which is based on the aircraft model B and on the on-line weather nowcasts to provide accurate estimated time of arrivals.

The demonstrator supports computations of aircraft trajectories during the descent, initial approach and final approach phases. Its central part is the Trajectory Predictor. This tool calculates the aircraft trajectories as accurate as possible, taking into account the latest weather information and local ATC procedures. The Trajectory Predictor is triggered by the Sequencing Tool and the Monitoring/Guidance Tool.

4.1. Requirements

A preliminary step in the elaboration of the demonstrator consisted of establishing the users and operational requirements. These have been defined from questionnaires to the controllers, and existing documentation.

The users requirements addressed the assistance expected by the controllers (in runway sequencing, conflict detection, trajectory optimisation), the characteristics of the system (functions, workload, input/output), the performance and human-machine interface requirements.

The operational requirements concerned the applicable standards, the needed characteristics of the trajectory predictor, the generation of advisories, the human-machine interface, computer performances.

4.2. Overall scenario

The global aim of the system consists in organising the arrival sequence, in monitoring the conformance of the descent with the computed trajectory, and in adapting the trajectory automatically to maintain if possible the original target time of arrival (TTA).

The system obeys therefore the following overall scenario:

1. When a new aircraft enters in the zone of surveillance, the sequencer allocates it a runway, and adds it in the sequence. The sequencer realises this by:
    - calling the Trajectory Predictor (TP) to get an interval of possible Estimated Time of Arrival (ETA), from the type of aircraft, the STAR, the current position and speed of the flight;
    - determining the TTA by placing the flight in the sequence of the chosen runway;
    - saving the “nominal trajectory” corresponding to this TTA in the Flight Repository, to be read by the other modules (in particular, Monitoring).

2. The Monitoring compares the nominal trajectory with the actual position of the flight, when the flight is in the zone controlled by the ATCO using ARAMIS.

3. On medium deviations, the Guidance calls the Trajectory Predictor to modify the trajectory in order to maintain the TTA. It realises this task by:
    - calling the TP to get a new trajectory allowing the flight to arrive at the TTA determined by the Sequencer. The TP uses the possibilities of path stretching described on the STAR;
    - storing the new nominal trajectory in the repository;
    - presenting advisories to the ATCO to maintain the aircraft on this new trajectory.

4. On large deviations, the Guidance asks to the ATCO to move the flight in the sequence (open loop). The Sequencer/Trajectory Predictor computes a new trajectory from this new TTA.

5. The flights are removed from the system when they land.

4.3. Architecture

4.3.1. Overview

The ARAMIS demonstrator consists of a set of tools, named the ARAMIS Advanced Tools, which communicate through a local network. The main tools are:

1. Trajectory Predictor,
2. Sequencing Tool,
3. Monitoring and Guidance Tool,
4. HMI Module.

The interaction between these tools is illustrated by the data flow diagram as depicted below.

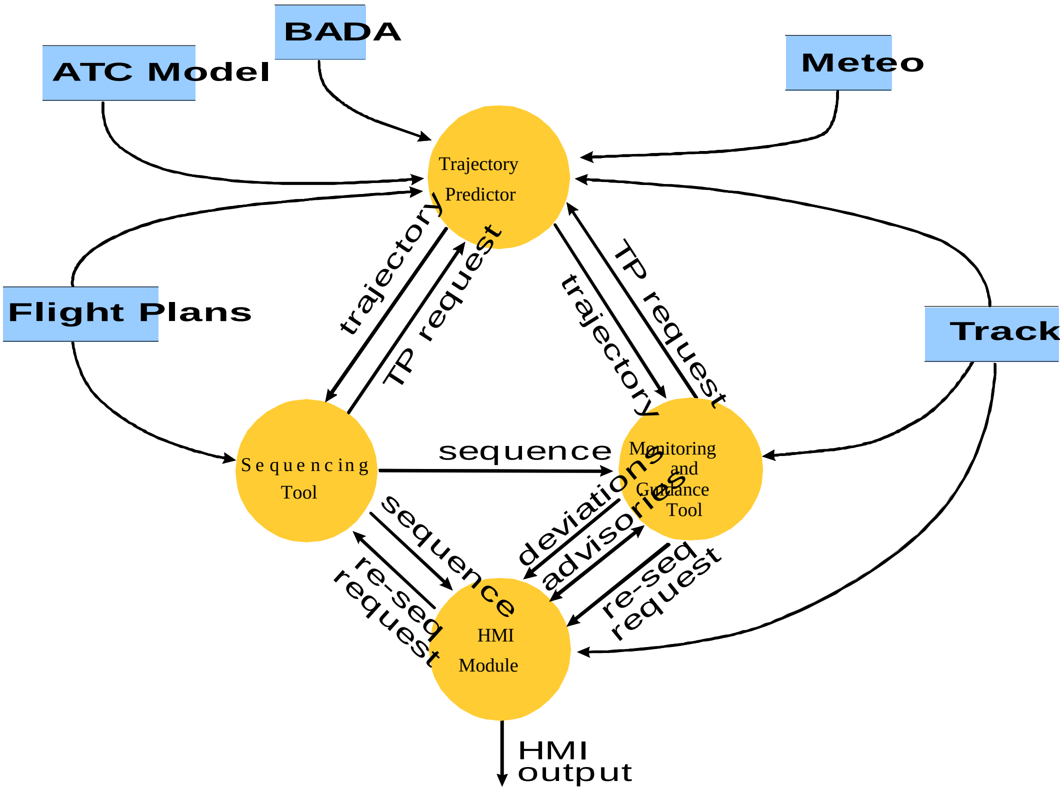

Figure 2: ARAMIS global architecture

The whole system is based on the CORBA architecture for the exchanges among the different modules. All the modules are realised in C++, and run in a Unix/X-Window environment.

4.3.2. Client/servers

The ARAMIS modules communicate conforming to the CORBA standard. They provide a public set of functionalities available for other modules.

In general each of the ARAMIS modules acts as a server for other modules, and is also client of one or several other modules. For instance the TP is considered as a server by the Sequencer and the MG, and is itself a client of the aircraft database (encapsulation of BADA) and the met server.

The figure below illustrates the main data flows among the servers.

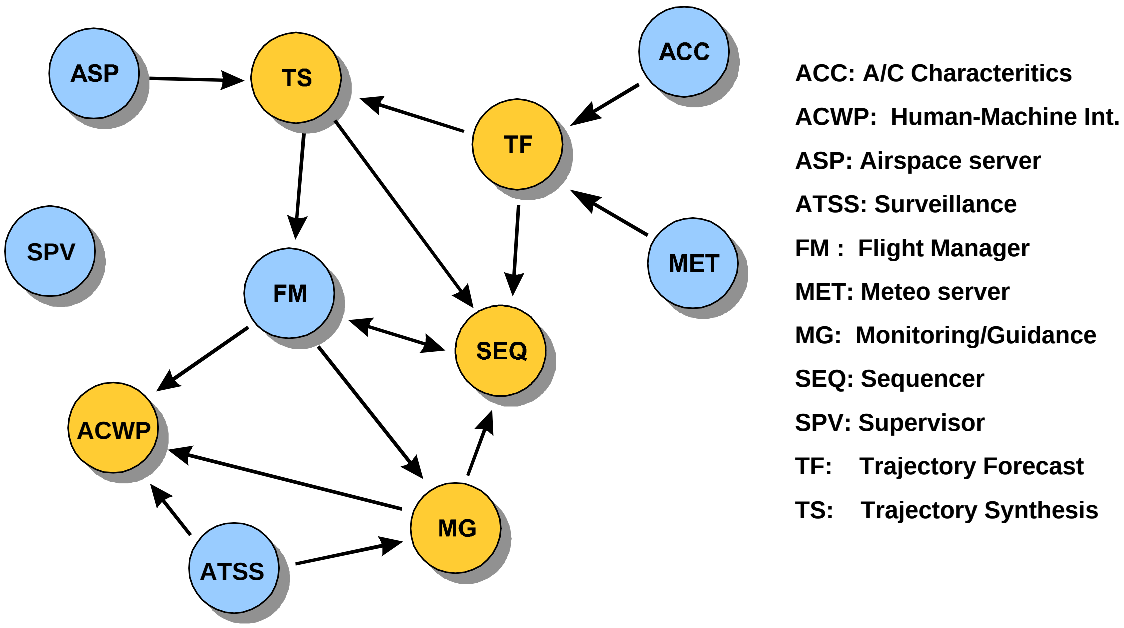

Figure 3: ARAMIS servers

A short description of the different servers is given hereafter.

The Supervisor (SPV) controls the system as a whole:

- It allows to choose the scenario used for the exercise (airport, configuration, options);
- It initializes the other modules, allows to run/stop/exit the system;
- Constitutes the reference for the scenario, the simulated time, etc.

The Airspace Server (ASP) provides static data like airports, beacons, ATC sectors, STARs, etc. The input of ASP consists in ARINC data, but also MAFF files (the data format used by MASS) for consistency with the traffic generator or for data corresponding to future configurations.

The Met server (MET) reads the weather forecasts generated by WAFTAGE every 15 minutes. It interpolates on demand this data to provide wind vectors. The Met server is used in particular by the Trajectory Predictor which allows to take into account a different wind vector for each of the intermediate points along the trajectory.

The Aircraft Characteristics (ACC) reads the BADA database (version 3.0) and provides the description of an aircraft on demand.

The Flight Manager (FM) behaves as a repository of the flights known by the system. It stores the usual flight plan information, plus the trajectories calculated by the TP, the target time of arrival, the allocated runway, etc.

The Air Traffic Situation Server (ATSS) provides the radar tracks to the other modules (sequencer, monitoring, HMI). For the simulations performed during the project, ATSS has been interfaced to the traffic generator of Eurocontrol, MASS, which includes pseudo-pilot facilities.

The Trajectory Prediction (TP) calculates the trajectories. It is constituted of the Trajectory Synthesis (TS) and the Trajectory Forecast (TF). The TF calculates the detailed 4D trajectory from a list of checkpoints and constraints. The TS is a higher level which determines the path which is used as an input by TF.

The Sequencer (SEQ) allocates the runway, in case of several possible runways used for landing, inserts the flights in the sequence, and calls the TP to get the nominal trajectory.

The Monitoring/Guidance (MG) compares the current position provided by ATSS with the nominal trajectory; if the ETA differs significantly from the TTA, the module determines a new trajectory to reach the TTA. The corresponding advisories are sent to the HMI.

Finally, the HMI server, named Arrival Control Working Position (ACWP) consists mainly in a radar window with a dedicated label management to display the advisories. The system displays the type of aircraft, the TTA and current ETA, speed/altitude/heading advisories.

Note that SPV, ASP, ATSS, FM constitute a simulation platform which could be replaced by an other one. The functionalities specific to ARAMIS, i.e., TP, SEQ, MG, ACWP, are presented a bit more in detail in the following subsections.

4.3.3. Trajectory predictor

The Trajectory Predictor server (TP), kernel of the ARAMIS system, is based on the aircraft model and the weather model cited in the section 3. The TP provides the following main services:

1. Trajectory Forecast (TF): this function constitutes from far the main part of the TP. It determines intermediate positions along a route described by 3D checkpoints and speed constraints. In ARAMIS this is used to get the trajectory from the current position until the runway. Each of the intermediate positions is characterised by a state vector (XYZ, speed, bank angle, inclination, etc.). The final position of the trajectory provides the ETA.
2. Trajectory Synthesis (TS): this function computes a trajectory complying with a given Target Time of Arrival (TTA).

4.3.3.1. Trajectory Forecast

The procedure used to compute the detailed trajectory from the route is as follows.

1. The TF gathers the input data: Flight plan info (from FM), aircraft characteristics (from ACC/BADA), used STAR, current state vector (from ATSS), meteo data.
2. The route is refined by computing the geometry of turns and decomposing the route in segments having a homogeneous attitude, called *mode*. They are 8 modes determined by the vertical, transversal and longitudinal directions. For instance mode 4 is level-turn-deceleration.
3. Calculation of the detailed trajectory consists to computes the aircraft state vector for each intermediate point: x, y, h, grounspeed, inclination, course. For each iteration, the system determines:
   - atmospheric characteristics,
   - thrust force,
   - lift coefficient and lift force,
   - drag coefficient and drag force,
   - bank angle;

   Then solves the differential equations constituting the aircraft performance model, to get the resulting inclination and speed.

The segment is terminated when the state vector matches the ‘guard functions’ which compare the state vector with the desired state at the end of the segment (in vertical, transversal, and longitudinal directions).

4.3.3.2. Trajectory Synthesis

The TS computes a trajectory for an aircraft which has to comply with a given TTA. The ARAMIS project chose to perform this by using only path stretching. We considered that speed changes were difficult to ask during the approach and focused on dynamic updates of the followed route.

The TS uses enriched STARs describing path stretching possibilities. The STAR waypoints are described as usually plus:

- Type of variant (trombone/fan),
- Characteristics: extents decreasing/increasing length of path.

The ARAMIS TS supports two types of manoeuvre: the *trombone* and the *slider*. For the trombone the provided values on a checkpoint are:

- Direction of the axis,
- Extents in distance along this direction from the waypoint.

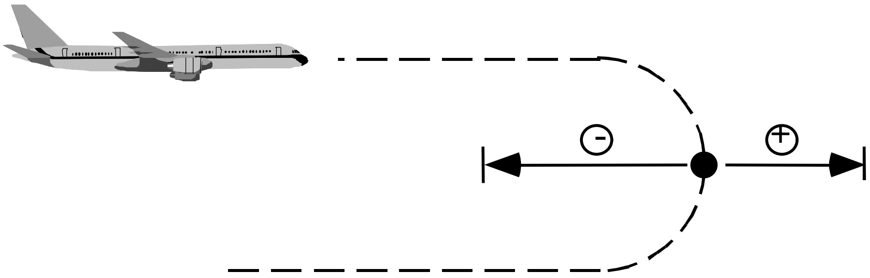

Figure 4 : Trombone path stretching

For the slider the two values provided with the waypoint (inner range and outer range) are the possible moves of the waypoint along the next segment.

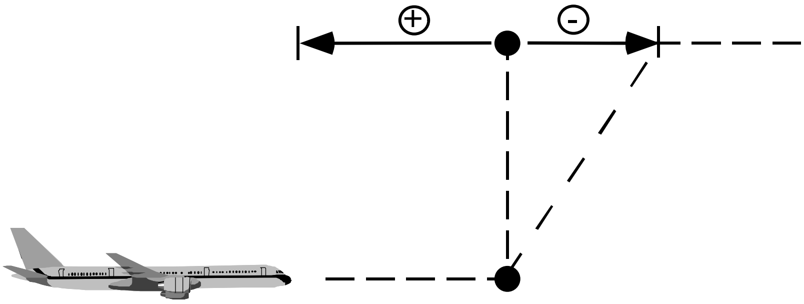

Figure 5: Slider path stretching

Note that a third type of path stretching, called *fan*, has been identified but not implemented in ARAMIS. It consists in a bundle of possible directions from a waypoint to the next segment defined by a radial.

The TS computes trajectories (thanks to calls to the TF) by varying the path stretching until the ETA is within a tolerance around the TTA. Algorithms adapted to the path stretching type allow to limit in general the calculation to 1 or 2 iterations.

The TS fails if the TTA is out the range constituted by the ETA for fastest trajectory and slowest trajectory. In this case the calling module (the Sequencer or the Guidance) seeks an other TTA or warns the user that he/she has to manage the flight. In this case the ATCO can place the flight somewhere else in the sequence manually, or to manage the flight in a classical way, without help from the system.

4.3.4. Sequencer

The Sequencer is organised in two main functions:

1. <u>Flight sequencing</u>: Each aircraft entering the area of the APP's responsibility is affected to a runway. A preliminary sequence of incoming flights is established, according to the principle First Come - First Served (FCFS), landing intervals, runway capacity. This function uses the TF module. The result of this function is a time interval in which the TTA must be placed.
2. <u>Flight scheduling</u>: It computes an accurate TTA in the time slot allocated by the previous function, to obtain the runway sequences respecting the sequencing rules. This function is based on the TS module.

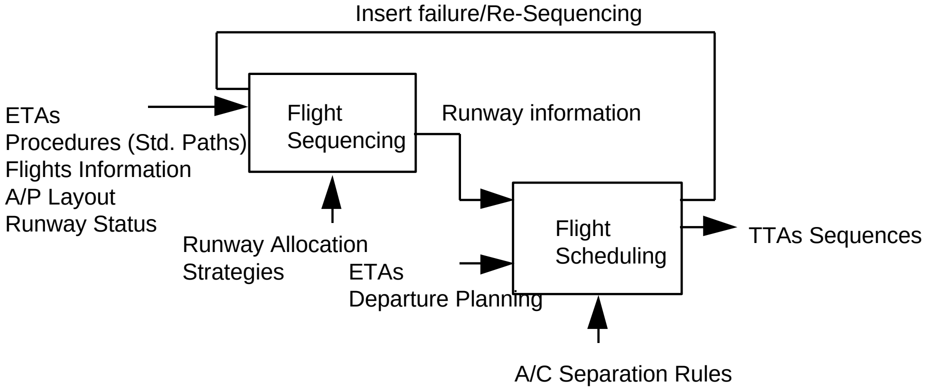

Figure 6: Functional organisation of the Sequencer

The runway allocation is performed by comparing the range of possible ETAs provided by the TS, with the corresponding load of the possible runways. The possible runways are listed for each STAR, for each configuration. The runway capacity is represented by time slices having a current already allocated load, which can include departures. The flight sequencing includes a simple algorithm which tries first to place the flight at its nominal ETA (corresponding to the nominal STAR, without path stretching), and, if the runway is already saturated for the corresponding slot, in an other slot within the ETA range.

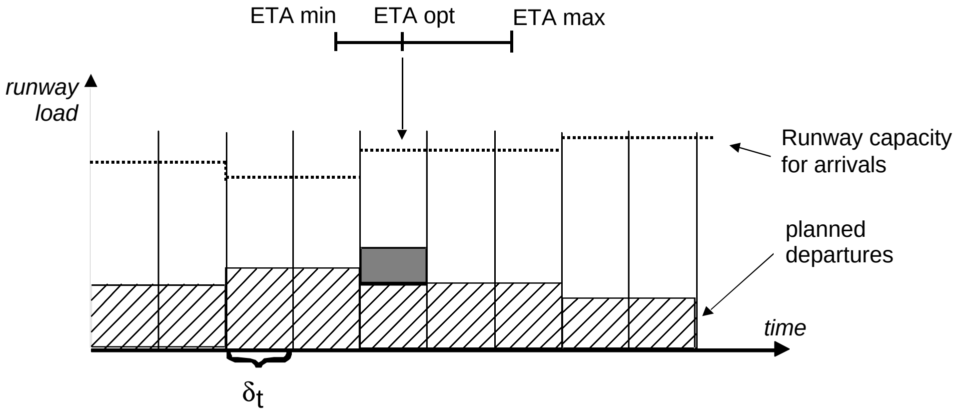

Figure 7: Principle of the runway allocation

The Flight Scheduling function consists to find an exact TTA within this time slot, respecting the separation minima between two flights.
If the TS fails to provide a trajectory for the chosen TTA, the Sequencer will re-try later to sequence the aircraft. When the flight is sequenced, the HMI displays both TTA and ETA in the label. On success, the trajectory provided by the TS function becomes the 'nominal trajectory' and is stored in the Flight Manager.

4.3.5. Monitoring/Guidance

The monitoring and Guidance are grouped in a unique module, MG. The role of this tool consists to check the conformance of the aircraft actual course with the nominal trajectory, and, if needed, to change the nominal trajectory to maintain the TTA.

Note that ARAMIS does not provide conflict alert facilities, which could nevertheless be added in the system. The project focused on models accuracy, and do not pretend to develop a complete Arrival Manager.

The Monitoring detects deviations between ETA and TTA. It calls the Trajectory Forecast (TF) function to compute an ETA from the current position of the aircraft and the nominal route. To avoid exaggerated CPU load, the TF is called only if a significant deviation between the state vector and the nominal trajectory is detected, by filters on 3D position similar to the «guard functions» of the TF.

The Guidance adjusts if necessary the trajectory to maintain the TTA, by calling the Trajectory Synthesis (TS). It translates the manœuvres needed at the ends of the segments of the route, to advisories provided to the ATCO *via* the HMI.

The modules distinguishes the *corrective guidance actions*, provided on medium deviations, which aim at adjusting the nominal trajectory; and the *pre-emptive actions*, which consist to provide an advisory on next checkpoint, corresponding to the manoeuvre to be transmitted to the pilot.

Through these advisories the system let the controller know the path chosen for each flight.

4.3.6. Human-Machine interface

The ARAMIS human-machine interface is a rather simple one, consisting mainly in a radar window. Its main role consists to display the advisories sent by Guidance.

The radar window is a refinement of the radar window realised by the ATHOS project, on a X11/Motif/IlogViews base. The HMI server, called ACWP for Arrival Control Working Position, is a client of ATSS, FM, ASP.

The advisories are displayed by explicit queries from the Guidance, and removed by a timeout communicated individually with the advisories. The advisories consist of additional fields in the label, and symbols appearing ahead the track.

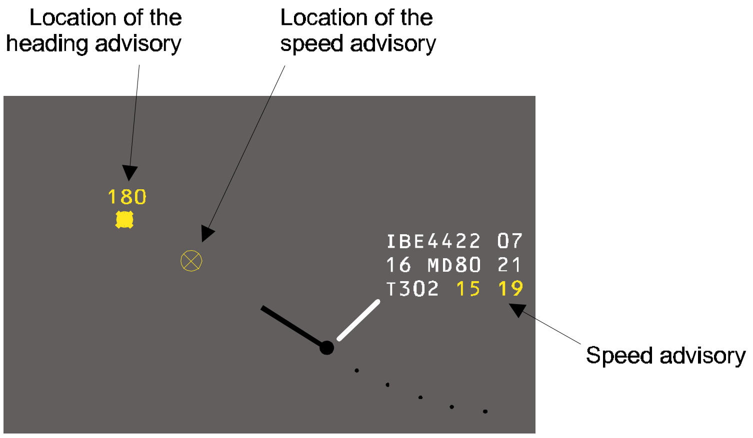

Figure 8: Advisories

5. Evaluation

The system has been tested in a simulation environment.

This section presents the performances of the demonstrator, and a summary of comments from controllers.

5.1. Tested functionalities

As described in preliminary studies (D2), an arrivals sequencing tool includes the following functions:

- Trajectory Prediction,
- Sequencing,
- Monitoring and Guidance,
- Conflict Detection and Resolution,
- HMI.

According to this decomposition, the evaluation of the ARAMIS prototype has been split in two phases: in the first one the implemented component functions are evaluated, while the global prototype is evaluated in the second phase. To implement this strategy the following constraints have to be take into account:

- some functions can not be isolated and evaluated (for instance the HMI),
- the Conflict Detection and Resolution function is not present in the developed prototype.

Consequently, the two phases have been decomposed in steps as follows:

- validation of the TP module,
- validation of the Monitoring and Guidance module,
- global validation of the system.

The first two steps have been carried out through a comparison of actual traffic data with the data computed using the ARAMIS prototype; the last step has been performed by letting ATC controllers to use the ARAMIS prototype, and using a traffic simulator to provide the scenario.

The first step, validation of the TP module, has been supported by the development of a specific software including the standard ARAMIS components:

- Trajectory Forecast (TF), including the aircraft performance model,
- Meteo Server (MET), to interpolate the wind at positions computed by TF,
- The BADA 3.0 interpretor;

and additional software developed specifically for the validation:

- generation of pseudo flight plans from recorded actual traffic,
- tools to analyse the trajectories generated by ARAMIS,
- plotting facility to compare visually the planned route with 2D trajectories, descent and speed profiles.

The second step has been supported by the whole set of ARAMIS tools, as seen in chapter 4.

5.2. Performances

The system, interfaced to the traffic generator MASS, demonstrated it was able to sequence in real time the arriving aircraft by computing their trajectories.

Each trajectory is computed by the TP module in typically 0.2 seconds on a SUN Ultra2, allowing both Sequencer and Guidance to send queries to the TP with adapted time of response.

The system showed it was possible, conforming to the requirements, to display more than 50 aircraft simultaneously, and to monitor trajectories for more than 30 aircraft simultaneously.

5.3. Accuracy

The validation of the TP modules requires a comparison of actual traffic samples from Heathrow and Charles-de-Gaulle airport with the corresponding trajectories computed by the TP for each of the flights in the samples.

5.3.1. Method

The first step of this validation was thus to analyse the traffic samples in order to detect:

- straight segments, turns;
- segments flown at constant rate of descent;
- segments flown at constant rate of deceleration.

These segments have been merged for each aircraft into a “pseudo” flight plan, composed of a list of 2D points with, for each point, an objective altitude, an objective speed and a radius of turn (possibly null) to join the point.

These pseudo flight plan have then been passed to the TF function which computed for each flight a trajectory composed of 4D points (X, Y, Z and speed) at predefined time intervals (4 seconds).

The final phase of the validation consisted in comparing the actual flight trajectories with the flight trajectories computed by the trajectory prediction. For each flight, four different kind of comparisons have been performed:

- Comparison of the actual flight time and the computed flight time; this comparison is the most essential in evaluating the accuracy of the TP module.
- Comparison of the actual horizontal path and the computed horizontal path by computing at each time step the distance between the actual flight position and the computed flight position.
- Comparison of the actual vertical path and the computed vertical path by computing at each time step the difference between the actual flight altitude and the computed flight altitude.
- Comparison of the actual speed profile and the computed speed profile by computing at each time step the difference between the actual flight speed and the computed flight speed.

5.3.2. Results

HORIZONTAL PLAN

The mean horizontal deviation between the actual trajectories and those computed by ARAMIS is shown in the figure below. The mean deviation in Nautical Miles is presented in abscissa and the number of aircraft corresponding to a deviation is shown in ordinate.

This figure clearly shows the ability of the TF function to accurately follow a 2D trajectory. This has been confirmed by plotting for each flight the actual horizontal trajectory and the computed horizontal trajectory. In general there is no visible deviation from the planned horizontal trajectory.

The analysis of the cases where the trajectories presented an horizontal deviation highlighted the following causes:

- In some cases, the problem comes from the analysis of the actual trajectory; for instance when the flight had performed long segments on which the flight heading had been constantly adjusted (in this case, it was impossible to detect straight segments in the flight path).
- In other cases, the problem comes from the trajectory prediction itself, for instance when a speed or altitude objective was reached before the end of a turn. In these cases the TF is slow in correcting this deviation.

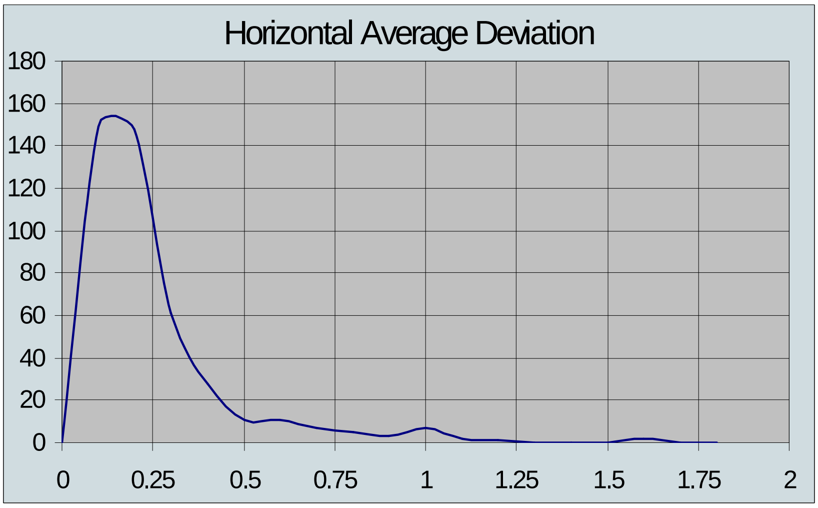

Figure 9: Distribution of horizontal average deviations

VERTICAL PLAN

The distribution of the mean deviations between the actual and the computed trajectories in the vertical plan is shown in the figure below, where the mean deviation in Feet is presented in abscissa and the number of aircraft corresponding to a deviation is shown in ordinate.

The distribution of vertical deviations is more spread than the horizontal deviation. This is mainly due to the speed profile deviations presented in the next section: when the flight flies faster (or slower) than planned, the TF will still try to reach the vertical objective on the objective point and thus will have a higher (or lower) rate of descent.

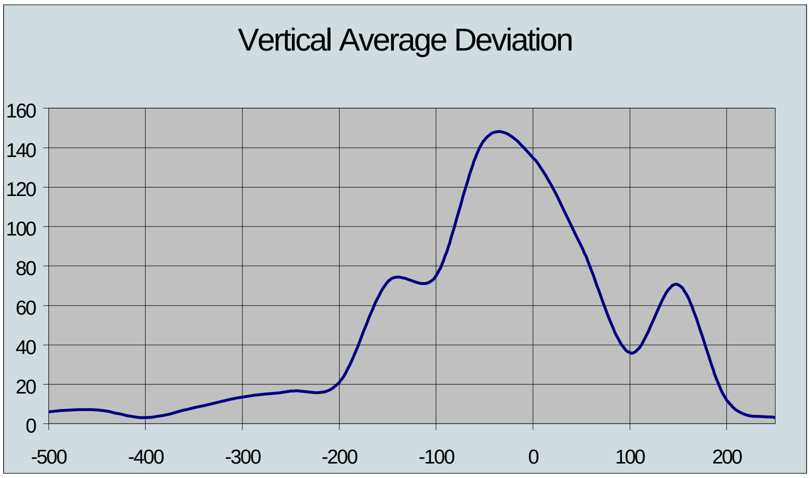

Figure 10: Distribution of vertical average deviation

As for horizontal trajectories, plots have been made for each flight presenting the actual and computed vertical trajectories. An example of such a plot is presented below; it displays the altitude of the flight versus the flown distance from the beginning of the flight.

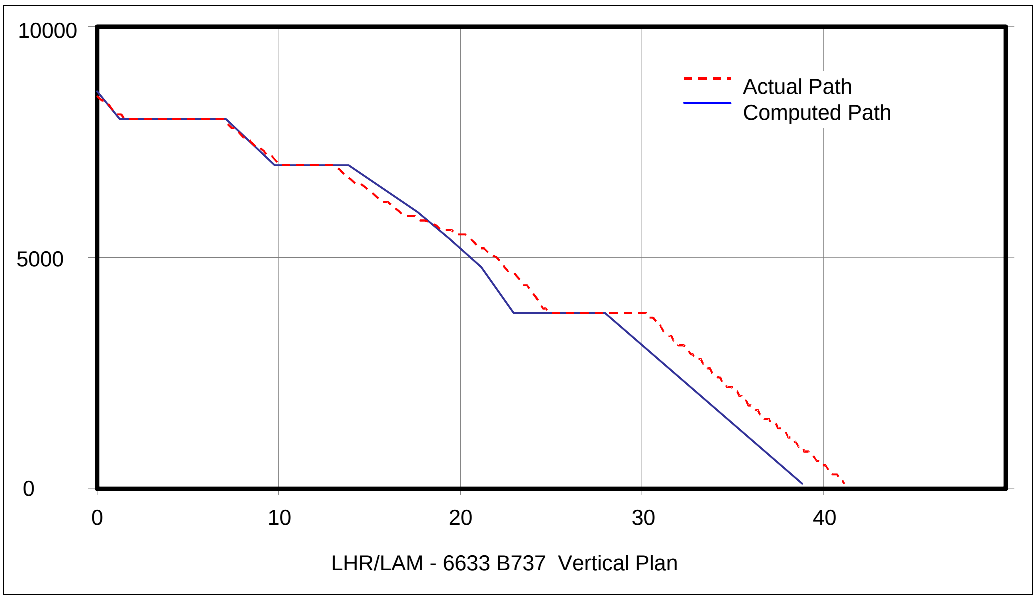

Figure 11: Example of a vertical trajectory with a deviation

SPEED PROFILE

The mean horizontal deviation between the actual and the computed trajectories has been computed for each flight and a distribution of these mean deviations is presented by the figure below. The mean deviation in Knots is presented in abscissa and the number of aircraft corresponding to a deviation is shown in ordinate.

The distribution of speed deviations is probably the factor which has the most important impact on the overall accuracy of the TF function. This deviation can be explained by the way the TF function has been designed: the aerodynamic configuration of a flight is determined in function of the current flight speed and altitude but a better approach would have been to iterate on a given segment in order to determine the aerodynamic configuration which gives the most accurate profile for the segment.

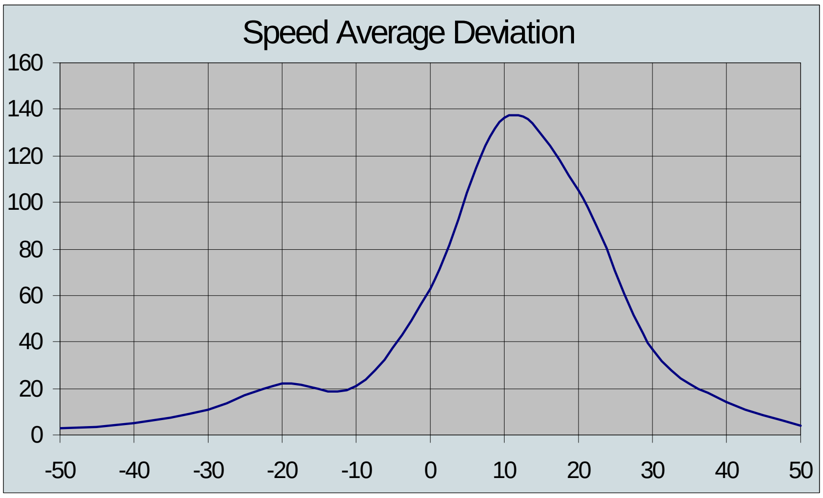

Figure 12: Distribution of speed average deviations

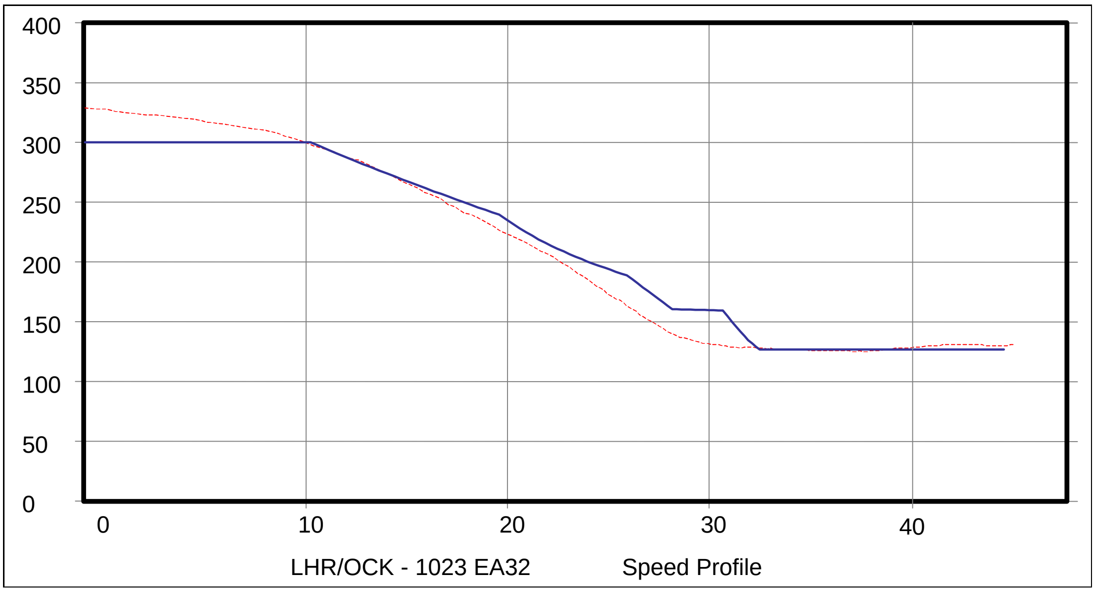

Figure 13: Example of a speed profile with a deviation

TIME DEVIATIONS

The figure below presents the distribution of the time deviations between the actual flight times and the computed flight times, with the value of the time deviation in abscissa and the number of aircraft corresponding to this deviation in ordinate. This figure distinguishes the distribution for the flights for which non-clean aircraft performance data was available and the distribution for the flights for which they were not available.

The most noticeable difference is that, for aircraft for which non-clean data are available, a clear concentration of the deviation occurs around 6 seconds whereas, for other flights, the distribution is largely spread. This shows the evidence of the importance of the non-clean data in the approach phase

The standard deviation of the distribution is 38 seconds, indicating that, although the objective of a 10 seconds accuracy has not been reached, a great improvement has been brought in the aircraft performance model by implementing the non-clean configurations. We think the final objective of 10 seconds can be reached by improving the layers of the TP module above the aircraft performance model, and continue to work in this direction.

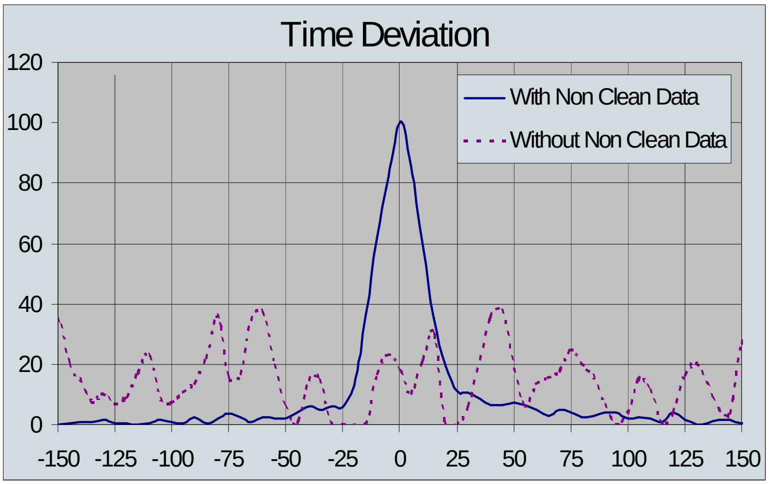

Figure 14: Distribution of time deviations

5.3.3. Comments

The analysis of the aircraft behaviour during the evaluation task led us to the following comments:

1. The most important impact on the accuracy of the ETA is the STAR description itself. Smoothing intermediate speeds or altitude can change the ETA by 1 minute. To be operational a ground-based system like ARAMIS needs to have a description of the descent profile adapted to the different aircraft types and eventually airlines. This data could be obtained by a campaign of measures along the STARs, to identify waypoints and speed/altitudes constraints for aircraft types and eventually airlines.
2. A critical problem consists in knowing when to change the drag configuration (clean / flap levels / landing gear). If the system changes this configuration some minutes later than the actual traffic, the aircraft land 20 or 30 seconds too early, due to excessive speed. When the configuration change is performed at the right moment, the difference between ATA and ETA is less than 10 seconds.
   In the existing prototype the changes in the configuration are computed in a passive way, depending on the thresholds specified by BADA 3.0 for altitude and speed. For instance, a B777 will be set in the flaps configuration "approach" when it comes under 8,000 ft and 240 kt. The algorithm used by ARAMIS, chosen for performances reasons, must be modified: instead to undergo the configuration changes, led by the aircraft current state, it shall decide them itself to fulfil the constraints of speed and altitude at the end of the segment.
3. The knowledge of the mass has a significant impact. For instance, a difference of 30 tons for a B757 introduces a final error on the ETA of 16 seconds. In ARAMIS the weight was merely calculated by a ratio between nominal mass and empty mass; a better estimation is necessary. A future study could provide data about the mass at IAF, depending on company, aircraft type, range of flight, etc. The mass could also be provided through datalink facilities by the aircraft itself.

5.4. Pertinence of proposed trajectories

The project choose to use only the path stretching to maintain the Target Time of Arrival (TTA), and to avoid to request speed changes that could not fit with the strategy of airlines concerning the fuel consumption. The tests showed that when a flight deviates from its nominal trajectory, the application of path stretching allowed to maintain the TTA in an interval of 4 seconds with required computer performance.

When systematically applying to an aircraft the advisories generated by the system, the simulated landing time was within 5 to 10 seconds of the TTA, which proved to be a good value for the accuracy of the provided advisories. Although it may seem at first sight to be a biased approach because we are working in a closed loop, it is a valid approach since the Trajectory Prediction and Guidance modules present in the ARAMIS system and in MASS (the traffic generator) are different.

5.5. Feedback from controllers

At the end of the two workshops, suggestions have been collected from the controllers. Most of them concern the guidance actions provided by the system. With reference to this, it is opportune to remember that two types of guidance actions are provided by the ARAMIS prototype: corrective and pre-emptive.

Corrective actions are given when medium deviations are communicated by the Monitoring function. The Guidance function uses the Trajectory Predictor function to compute a new target trajectory. On receipt of the new target trajectory the pre-emptive actions (advisories) resume.

The pre-emptive actions are advisories determined by interpreting the planned trajectories and giving the controller descriptions of the maneuvers that have to be transmitted to the pilots to follow those trajectories.

USABILITY

The controllers made several remarks concerning the usability of the system.

The first remark concerns the fact that the controller does not have a clear understanding of the strategy of the system by looking at the advisory on the next waypoint for a flight. A better approach would consist in displaying the complete trajectory computed by the system at various moments:

- When the flight first appears in the system;
- When a new trajectory is computed due to the detection of a large deviation between the flight actual position and the computed trajectory;
- On controller demand.

The second remark concerned the strategy for displaying advisories. The controller should rely on the complete trajectory displayed by the system to guide the aircraft and advisories should not be displayed systematically for a flight but only when a deviation between the flight actual position and the computed trajectory occurs.

The last remark concerned the content of the advisories. As implemented in the system, the advisories contain an altitude and speed objective on the next waypoint. It is difficult for the controllers to convert this information into control orders to be transmitted to the pilot and it adds to their workload rather than relieve them. A better approach would be to display the advisories at the point where they should be applied and indicate only heading or speed information to be applied depending on the type of advisory.

Concerning the type of generated advisories, it has been noted by the controllers that the speed advisories should be added into the system because they are generally a simpler way of reaching a given objective. But as we said above, for ARAMIS this strategy had been deliberately moved aside for the descent phase.

ADAPTABILITY

An Arrival Manager shall provide a mean for the ATCO to move a flight in the planned sequence, for instance in a timeline; in addition, the controllers suggested that the display of the complete flight trajectory should also offers possibilities of modifying this trajectory, by dragging the waypoints.

6. Conclusion

The global goal of ARAMIS was to adapt and develop models and tools for 4D-planning, guidance and control during the approach phase of flight, from initial approach fix until runway threshold.

These models have been studied and implemented with success in the demonstrator.

The study demonstrated that, from a technical point of view, a ground-based controller aid for the aircraft approach was realisable and works.

Nevertheless a number of points remain to be studied. For instance the implementation of trajectory synthesis made by ARAMIS is a simple one; difficulties remain in the representation of the rules to apply on complex cases:

- what priorities must be applied when several path stretching possibilities are available along the same STAR;
- how to solve conflicts with such trajectories;
- how to minimize the impact on noise when the system chooses a trajectory.

Several directions can be explored to improve the accuracy of the trajectory forecast function:

- update of the algorithm allowing to change the flap configuration,
- estimation of the aircraft mass,
- the vertical component of wind, supported by the model, was not provided by Waftage.

Operational problems remain also to be explored further, like the problems on the human-machine interface raised by a systematic use of the path stretching.