FINAL REPORT

POTRA: PARAMETRIC OPTIMISATION SOFTWARE PACKAGE FOR TRAJECTORY SHAPING UNDER CONSTRAINTS

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1. INTRODUCTION

1.1. PURPOSE

The present document is to provide the Final Report of the EEGS project. The document contains the following sections:

- Chapter 1 and chapter 2 include the introductory aspects.
- Chapter 3 provides the Executive Summary.
- Chapter 4 describes briefly the project and provides main information concerning the POTRA Consortium Partners.
- Chapter 5 provides the project results.
- Chapter 6 presents the project impacts.

1.2. SCOPE

This document has been issued in the framework of the POTRA project under the Grant Agreement 270624 with the Clean Sky Joint Undertaking.

1.3. DEFINITIONS AND ACRONYMS

1.3.1. DEFINITIONS

Concepts and terms used in this document and needing a definition are included in the following table:

Table 1-1 – Definitions

Concept / Term	Definition
GANTT	A GANTT chart is a popular type of bar chart that illustrates a project schedule.

1.3.2. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2 – Acronyms

Acronym	Definition
AD	Applicable Document
CCN	Contract Change Note
EC	European Commission
EIS	EGNOS Improvement Studies
ESA	European Space Agency
EU	European Union
EGNOS	European Geostationary Navigation Overlay System
FP	Framework Programme
FR	Final Review / Final Report
EEGS	EGNOS Extension to Eastern Europe
GAL	GALileo study
GNSS	Global Navigation Satellite System
GSA	European GNSS Supervisory Authority
IICA	Improvement of Ionosphere Coverage Area
INTDG	Interoperability Demonstration done by GMV
INTDR	Interoperability Demonstration done by RSS
INTS	Interoperability Studies
INTSD	Interoperability Studies and Demonstrations (consolidated and final version)

Acronym	Definition
IPR	Intellectual Property Rights
KOM	Kick-Off Meeting
MM	Men/Month
MoM	Minutes of Meeting
MTR	Mid Term Review
PDM	Project Dissemination Material
PDP	Project Dissemination Plan
PFER	Project Final Event Report
PMP	Project Management Plan
PO	Project Officer
POLD	POLish Demonstration
PPP	Precise Point Positioning
PPPDG	PPP Demonstration done by GMV
PPPDR	PPP Demonstration done by RSS
PPPS	PPP Studies
PPPSD	PPP Studies and Demonstrations (consolidated and final version)
PR	Progress Report
PRE	Presentations
PRAB	Progress Report to EGNOS Advisory Board
PWEB	Project WEB site
RD	Reference Document
ROMD	ROManian Demonstration
ROMS	ROManian regional Studies
RUSS	Russian regional Studies
SDCM	System for Differential Corrections and Monitoring
TBC	To Be Completed
TBD	To Be Defined
UKRD	UKRainian Demonstration
UKRS	UKRainian regional Studies
WBS	Work Breakdown Structure
WP	Work Package
WPL	Work Package Leader

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Grant Agreement or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1 – Applicable documents

Ref.	Title	Code	Version	Date
[AD.1]	-	-	-	-

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2 – Reference documents

Ref.	Title	Code	Version	Date
[RD.1]	-	-	-	-

3. EXECUTIVE SUMMARY

One of the integrated Technology Demonstrators around which the Clean Sky JTI is articulated is the Systems for Green Operations (SGO) which focuses on all-electrical aircraft equipment and systems architectures, thermal management, capabilities for **"green" trajectories and mission** and improved ground operations to give any aircraft the capability to fully exploit the benefits of SES.

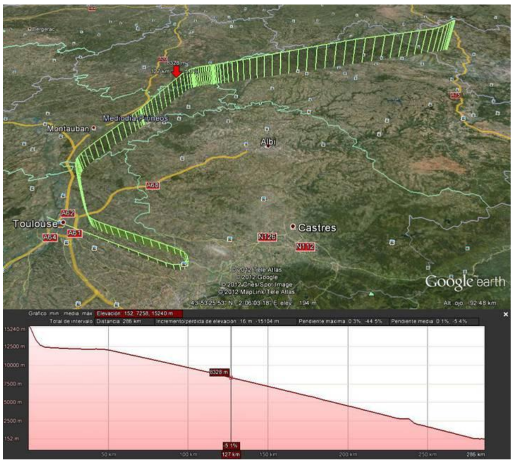
In particular, the SGO aims at defining new approaches for the Management of Trajectory and Mission for an overall optimization of the aircraft and systems by implementing the following two concepts:

Green Trajectories, based on more precise, reliable and predictable 3 dimensional flight path, optimized for minimum noise impact and low emission, including agile trajectory management, in response to meteorological hazard

A **Green Mission** from start to finish, with management of new climb, cruise and descent profiles, based on new aircraft performances database which includes noise parameter and allows multi-criteria optimization (noise, emissions, fuel, time), including management of weather conditions which could negatively impact the aircraft optimum route and results in additional fuel consumption.

The POTRA project has been devoted to analyse and develop the following points:

- Overview of the state of the art of collocation optimization techniques
- Definition of the theoretical problem to solve
- Specification of the numerical optimization techniques applicable to the problem
- Developing of a numerical optimization software package
- Define the validation methodology and perform numerical simulations



As a result of this project a tool has been developed with the following functionalities:

- 4D Trajectories (e.g. emulate CCB, FRA, CDO, point to point)
- Considered trajectory constraints
    - Aircraft dynamics and operational weights
    - Fly over fixes with altitude bands (user defined, SIDs and STARs)
    - Altitude bands at each trajectory segment between fixes
- Direct operations cost
    - Fuel consumption
    - Flight duration (CI)
    - Noise charges (noise stations)

4. PROJECT DESCRIPTION

4.1. PROJECT OVERVIEW

Traditionally the routes followed by the aircrafts were defined mainly by means of VOR/DME navaids. DME allows measuring the range from the aircraft to the navaid and VOR measurements provide bearing information with respect to the magnetic North. With these data the pilot is able to fly from navaid to navaid. The main limitation is that the routes depend strongly on the position of the navaids with the consequent decrease of the flexibility in the routes.

Due to the increase of flights during the last decades it has been necessary to define new routes and ways of flying. In order to overcome the limitations in existing procedures a new concept was envisaged, called Area Navigation (RNAV). This concept is defined by ICAO as "A method of navigation which permits aircraft operation on any desired flight path within the coverage of the station-referenced navigation aids or within the limits of the capability of self-contained aids, or a combination of these". That means that the pilot is able to fly from waypoint to waypoint if the navigation system in the aircraft is able to compute these waypoints using the navaids in the area where it is flying. With this new concept the avionics industry has developed new systems in order to adapt the aircrafts to this new way of flying. At the same time the number of routes and the flexibility of these routes have been increased.

New ATS routes, flight procedures in the terminal area, and departure, approach and arrival procedures have been defined as a consequence of the Area Navigation concept. The RNAV concept was complemented with the introduction of the Required Navigation Performance concept that defines the level of performance that should fulfill the navigation on board the aircraft to flight the RNAV procedures, and both concepts have been recently enhanced by ICAO with the new concept of Performance Based Navigation (PBN).

In spite of the fact that the Area Navigation has introduced new routes and more flexibility to the usage of the airspace, the Air Traffic Management (ATM) is still a very complex and highly regulated system. A substantial change in the current ATM paradigm is needed because this system, responsible for sustainable, efficient and safe operation in civil aviation, is reaching the limits of its capabilities. Its capacity, efficiency, environmental impact and flexibility should be improved to accommodate airspace user requirements and the forecasted demand growth.

These inefficiencies are caused by many restrictions currently in use. The need to fit aircraft trajectories to ATM system requirements makes them difficult to be optimized and, therefore, generally suboptimal flight profiles are being flown. This results in higher operational costs and higher emissions due to non-minimal fuel consumption (e.g. air traffic is responsible for 2% of CO_2 global emissions).

The SESAR program establishes that in the mid and long term the Air Navigation will be based mainly on GNSS. Those systems will allow the aircrafts to fly more accurate routes with high integrity that will be traduced into a more flexible and less restricted airspace. The need of computing and flying 4D optimal routes will be essential in order to have less fuel consumption and emissions and a more efficient airspace.

The following paragraphs analyse the current problem of route optimisation and the proposed study to be undertaken in the scope of **POTRA**.

The work done in the context of POTRA has covered the following issues:

- Definition of the problem to solve.
- Analysis of the optimisation methods, basically it will be analysed and compared the direct method with Gauss-Lobatto collocation techniques, Legendre collocation techniques (pseudospectral) and hybrid method.
- Based on the conclusions of the first analysis an optimizer will be selected.
- With the methodology and optimizer selected a software package will be developed in order to solve the optimum trajectory problem.

The problem to solve will be analysed and studied as general as possible and the implementation will done from the simplest to the most complex. This step by step implementation will be as follows (in all the steps flight envelope and weight restrictions are considered):

- Optimisation of Vertical Profile
- Optimisation of Horizontal Profile with winds

- Optimisation of 4D profile
- Optimisation of 4D profile with phases (climb, descend and stepped climb in route)
- Optimisation of 4D profile with phases and departure constrained (SID)
- Optimisation of 4D profile with phases, departure (SID) and arrival constrained (STAR)
- Optimisation of 4D profile with phases, departure, arrival and route waypoints constrained.

The following picture shows the architecture of the tool developed:

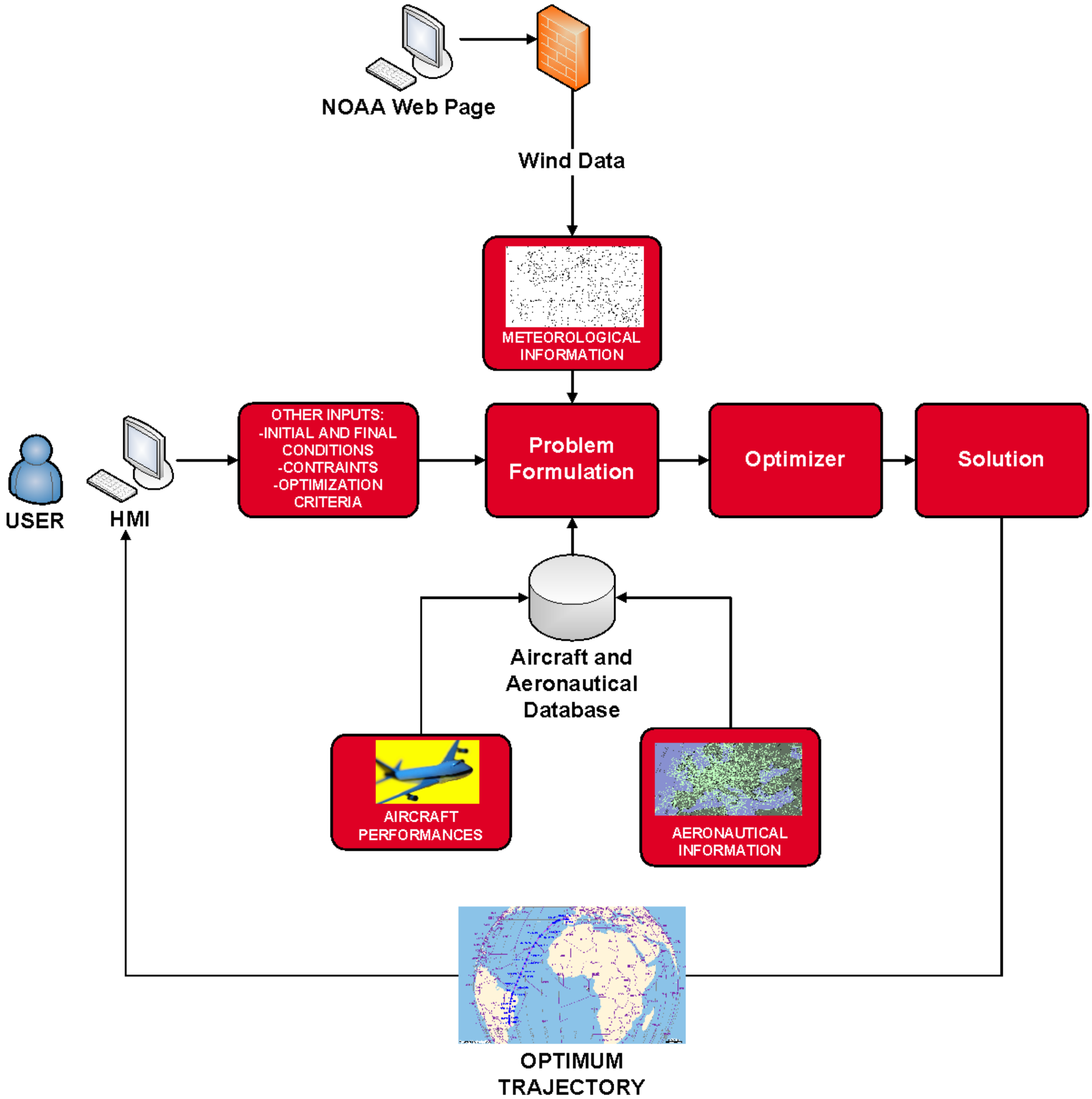


Figure 4-1 – Architecture of the tool to be developed

The user will be able to select the following data:

- Type of Aircraft (within the ones in the BADA model)
- Initial Mass (fuel and payload)
- Wind Data
- Initial Aerodrome

- Initial SID
- Final Aerodrome
- Final STAR
- Waypoints to follow during the route
- Operational Constraints(climb at constant M, constant CAS, etc)
- Cost Parameters (cost of allowance, cost of fuel, cost index)
- Optimisation Criteria (minimum overall cost, minimum emissions or both)

4.2. CONSORTIUM PRESENTATION

The consortium is composed of 3 partners, covering all the different competencies needed by the project. The following table presents the relevant information about the Consortium partners.

Table 4-1 – Partners information

Participant no.	Participant organisation name	Beneficiary short name	Country	Website
1 (Coordinator)	**GMV Aerospace and Defence SAU**	**GMVAD**	Spain	www.gmv.com
2	**GMVIS Skysoft, SA**	GMVSKY	Portugal	www.gmv.com.pt
3	**Universidad Rey Juan Carlos**	URJC	Spain	www.urjc.es

4.3. PROJECT IMPLEMENTATION

In order to be able to achieve the project final objectives, the work has been structured in five work packages (WPs), a summary of which is included in the following table:

Table 4-2 – Work Packages Overview

WP number	WP title	Description
WP0	Project Management and Quality	Project management (both programme and technical management).
WP1	Problem and Requirements Definition	The objectives of this workpackage are the following: • Definition of the problem to solve • Review of the state of the art • Specification of the software to develop • Prototyping
WP2	Library Development	The purpose of this workpackage is the development of the software that will solve the optimisation problem of an aircraft using direct methods.
WP3	Validation	This workpackage will be in charge of validating the software developed in the previous workpackage. Within this workpackage the Validation Test Plan will be defined and Tests execution will be performed.
WP4	Acceptance Phase	This workpackage will be dedicated to prepare the delivery of the software and solve the problems that may appear in the validation phase.
WP5	Dissemination	Dissemination and exploitation of project results for European awareness and also in international forums

4.4. WORK PACKAGES

The following table shows the work package list.

Table 4-3 – Work Packages List

WP no	WP Title	Type	Lead no	Lead	Person-months	Start month	End month
0	**Management and Quality**	**MGT**	**1**	**GMVAD**	**2.7**	**T0**	**T0+16M**
0.1	Management	MGT	1	GMVAD	1.35	T0	T0+16M
0.2	Quality	MGT	1	GMVAD	1.35	T0	T0+16M
1	**Problem and Requirements Definition**	**RTD**	**1**	**GMVAD**	**7.5**	**T0**	**T0+10M**
1.1	Problem Definition	RTD	1	GMVAD	1.5	T0	T0+2M
1.2	State of the Art	RTD	3	URJC	1.5	T0+2M	T0+2.5M
1.3	Specification Document	RTD	1	GMVAD	3	T0+2.5M	T0+3.5M
1.4	Prototyping	RTD	3	URJC	1.5	T0+3.5M	T0+10M
2	**Library Development**	**RTD**	**1**	**GMVAD**	**12.75**	**T0+3.5M**	**T0+10M**
2.1	Design Document	RTD	1	GMVAD	2.75	T0+3.5M	T0+4.5M
2.2	Software Development	RTD	1	GMVAD	8.5	T0+4.5M	T0+8.5M
2.3	Preparation of Software and Documentation Package	RTD	1	GMVAD	1.5	T0+8.5M	T0+10M
3	**Validation**	**RTD**	**2**	**GMVSKY**	**6**	**T0+3.5M**	**T0+8.5M**
3.1	Validation Test Plan	RTD	2	GMVSKY	3	T0+3.5M	T0+4.5M
3.2	Tests Execution in Factory	RTD	2	GMVSKY	3	T0+7.5M	T0+8.5M
4	**Acceptance Phase**	**RTD**	**1**	**GMVAD**	**7.35**	**T0+10M**	**T0+16M**
4.1	Preparation of the test environment and tests	RTD	2	GMVSKY	1.5	T0+10M	T0+12M
4.2	Problem report and model modification	RTD	2	GMVSKY	1.5	T0+12M	T0+13M
4.3	Software changes	RTD	1	GMVAD	2	T0+13M	T0+14M
4.4	Final Tests and Acceptance	RTD	2	GMVSKY	1	T0+14M	T0+15M
4.5	Final Software Release	RTD	1	GMVAD	1.35	T0+15M	T0+16M

WP no	WP Title	Type	Lead no	Lead	Person-months	Start month	End month
5	**Dissemination**	**OTHER**	**3**	**URJC**	**1.5**	**T0+3.5M**	**T0+16M**
5.1	Dissemination Plan and Presentation in Relevant Forums	OTHER	3	URJC	1.5	T0+3.5M	T0+16M
	TOTAL				**37.8**		

4.5. PROJECT PLAN

The different milestones identified for EEGS project are shown in the following table.

Table 4-4 – List of milestones

Milestone Number	Milestone	WPs involved	Expected date	Means of verification
KOM	Kick-Off	WP0	01-10-2010	Activities are authorised to be started.
D1	Problem Definition (PD)	WP1	26-11-2010	Review of the document delivered.
D2	Overview of state of the art of collocation optimisation techniques (SOA)	WP1	17-12-2010	Review of the document delivered.
D3	Optimisation technique specification document (OTS)	WP1	14-01-2011	Review of the specification checking that the requirements fulfil the expected functionalities.
D4	Software package design document (SDD)	WP 2	18-02-2011	Review that the design covers all the requirements. Inspection of the compliance matrices.
D5	Validation Test Plan (VTP)	WP 3	18-02-2011	Review that the test plan covers all the requirements specified in the specification document.
D6	Validation Test Report (VTR), Reference tests data files	WP 3	17-06-2011	Review that the Test Report follows all the test cases and the reference tests files are consistent with the executed tests.
D7	Software Package Delivery (V1)	WP 2	29-07-2011	Check that the software delivery contains all the expected packages and documentation.
D8	Acceptance Test Report (ATR)	WP 4	30-09-2011	Review of the document.

Milestone Number	Milestone	WPs involved	Expected date	Means of verification
D9	Problem report and model modification request document (PRD)	WP 4	28-10-2011	Review of the document checking that the modifications comply with the errors solve and the model changes.
D10	Software package delivery (V2)	WP 4	25-11-2011	Check that the software delivery contains all the expected packages and documentation.
D11	Final Acceptance Test Report (ATR-2)	WP 4	30-12-2011	Review of the document.
D12	Software Package Delivery (V3)	WP 4	27-01-2012	Check that the software delivery contains all the expected packages and documentation.

5. PROJECT RESULTS

The following sub-sections summary the results obtained during the course of the project.

5.1. GENERAL DESCRIPTION

The tool is divided in two main subsystems:

- Graphical interface (HMI)
- Problem configuration & solver (PSOPT+IPOPT)

MySQL is used as the interface between the two subsystems

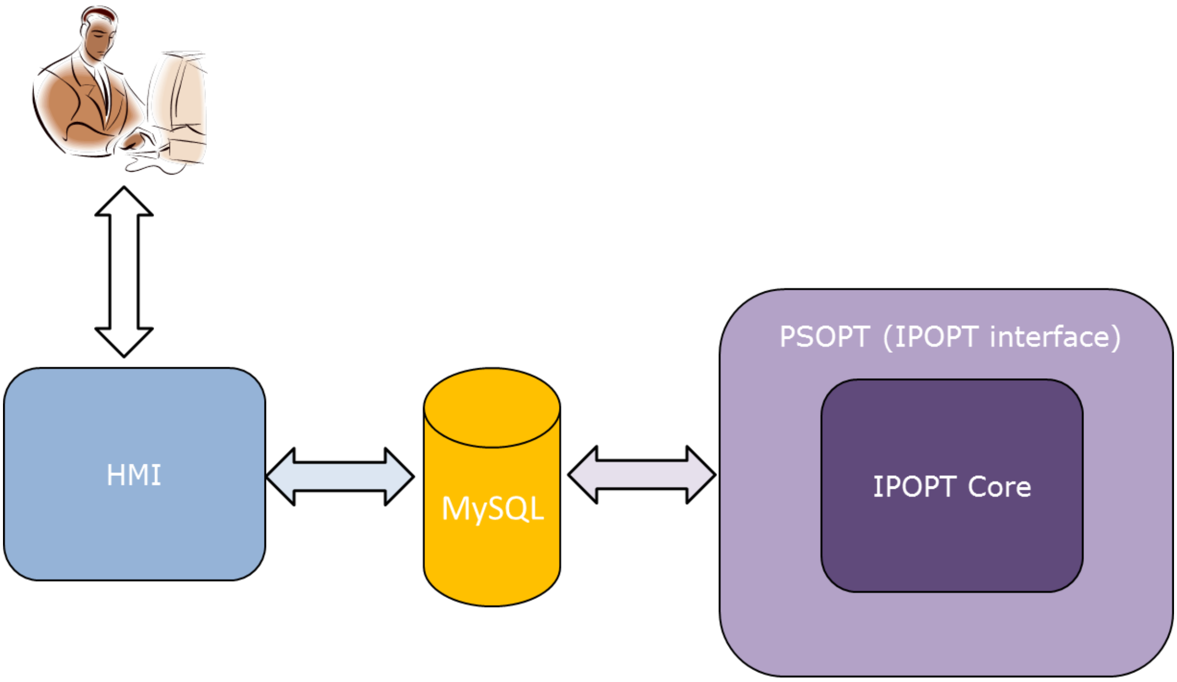


Figure 5-1 – System Description

The user will be able to select the following data:

- Type of Aircraft (within the ones in the BADA model)
- Initial Mass (fuel and payload)
- Wind Data
- Initial Aerodrome
- Initial SID
- Final Aerodrome
- Final STAR
- Cost Parameters (cost index)
- Optimisation Criteria (minimum fuel, minimum time or minimum noise)

The aeronautical information and aircraft model will be read from databases previously populated from the AIS information and the BADA model. The wind data will be read from the NOAA web page or from the files specified by the user in GRIB format.

Once the input data has been selected the software will compute the optimum trajectory in 3D dimensions together with the guidance parameters. The problem will be solved with 3 degrees of freedom that will be Thrust, the load factor and the bank angle. The user will be able to see the trajectory displayed on a map of the world using Google Earth and the graphical representation of the mentioned guidance parameters plus the variation of the rest of the parameters of the flight.

The equations to be solved are the following:

Dynamic equations:

$$\begin{aligned}
&T - D - mg\sin\gamma = m\left(\dot{V} + \dot{w}_{xm} + w_{zm}\dot{\gamma} - w_{ym}\dot{\chi}\cos\gamma\right)\\
&L\sin\mu = m\left(\dot{w}_{ym} + \left(V + w_{xm}\right)\dot{\chi}\cos\gamma + w_{zm}\dot{\chi}\sin\gamma\right)\\
&mg\cos\gamma - L\cos\mu = m\left(\dot{w}_{zm} - \left(V + w_{xm}\right)\dot{\gamma} - w_{ym}\dot{\chi}\sin\gamma\right)
\end{aligned}$$

Navigation equations:

$$\dot{\lambda} = \frac{V\cos\gamma\sin\chi + w_y}{(N+h)\cdot\cos\varphi}$$

$$\dot{\varphi} = \frac{V\cos\gamma\cos\chi + w_x}{M+h}$$

$$\dot{h} = V\sin\gamma - w_z$$

Mass variation:

$$\dot{m} + \Phi = 0$$

Since we have 7 equations (3 dynamic, 1 mass equation and 3 navigation equations) the problem has three degrees of freedom.

$$N = 10 - 7 = 3$$

Those three degrees of freedom define the control variables. Hence, there is an independent variable that is time and the dependent variables might be divided into state variables and control variables:

- 7 state variables:

$$\gamma \quad \chi \quad V \quad h \quad \lambda \quad \varphi \quad m$$

- 3 control variables:

$$\mu \quad T \quad n$$

In order to solve the problem several strategies are available. Those strategies have crystalized over the last years on several NLP solvers which have been extensively used to solve (non-linear) optimal control problems. Some of the most popular NLP solvers are LANCELOT, FILTER, SNOPT, LOQO, MINOS or IPOPT.

IPOPT (Interior Point Optimizer, pronounced IPOpt) is an open source software package for large scale nonlinear optimization. It can be used to solve general nonlinear programming problems. IPOPT implements an interior point line search filter method. Efficient optimization methods have led to the development of interior-point or barrier methods for large-scale nonlinear programming. In particular, these methods provide an attractive alternative to active set strategies in handling problems with large numbers of inequality constraints.

The problem of aircraft optimal trajectory embraces all the negative properties that one might find for solving a NLP problem: it has a very large number of variables; it is sparse; it is highly non-convex;

and it requires many constraints. For the problem to be solved, IPOPT is the most suitable solver because it handles properly large-scale, sparse, non-convex problems, with a large number of equality and inequality constraints.

5.2. ARCHITECTURE

The architecture of the tool will be basically composed by layers. The main layers will be:

- **HMI**: The Human Machine Interface will allow the user to insert the data and show the results of the optimization. This layer will store the input data selected by the user in the database and it will retrieve the results data from the database in order to present the results to the user.
- **COMPUTATION**: The computational layer will be in charge of running the optimization algorithms. This layer will read the input data, aircraft data and AIS data from the database, it will formulate the problem to solve, it will call the optimizer. The results of the optimization will be stored in the database.
- **DATABASE**: The database will contain the Aircraft, AIS, Results and Inputs data. Aircraft and AIS data could be modified by the user however they are supposed to be stable data. Inputs and Results data will be modified every time the application is run.

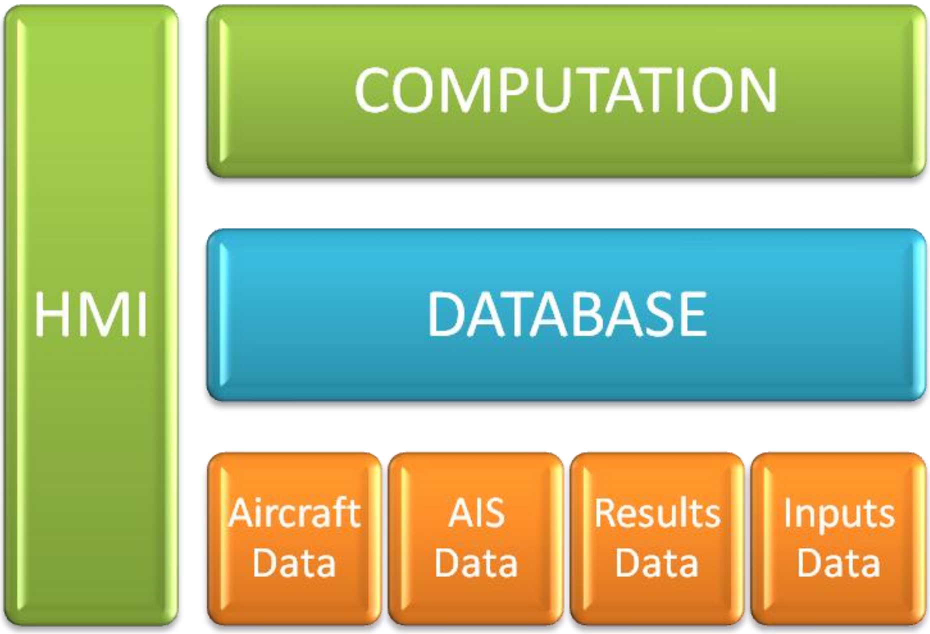


Figure 5-2 – Layer Architecture of the application

Computation and HMI layers will be totally decoupled. This architecture has several benefits:

- Easier validation approach as it can be divided into Computation layer testing and HMI testing.
- Isolation of problems and errors, as there is no interaction between the HMI layer and the Computational layer.
- Possibility of defining different HMI without changing the computational layer depending on future needs.

5.3. GRAPHICAL INTERFACE DESCRIPTION

5.3.1. MAIN FRAME

The main frame is the first one to appear when the application is started.

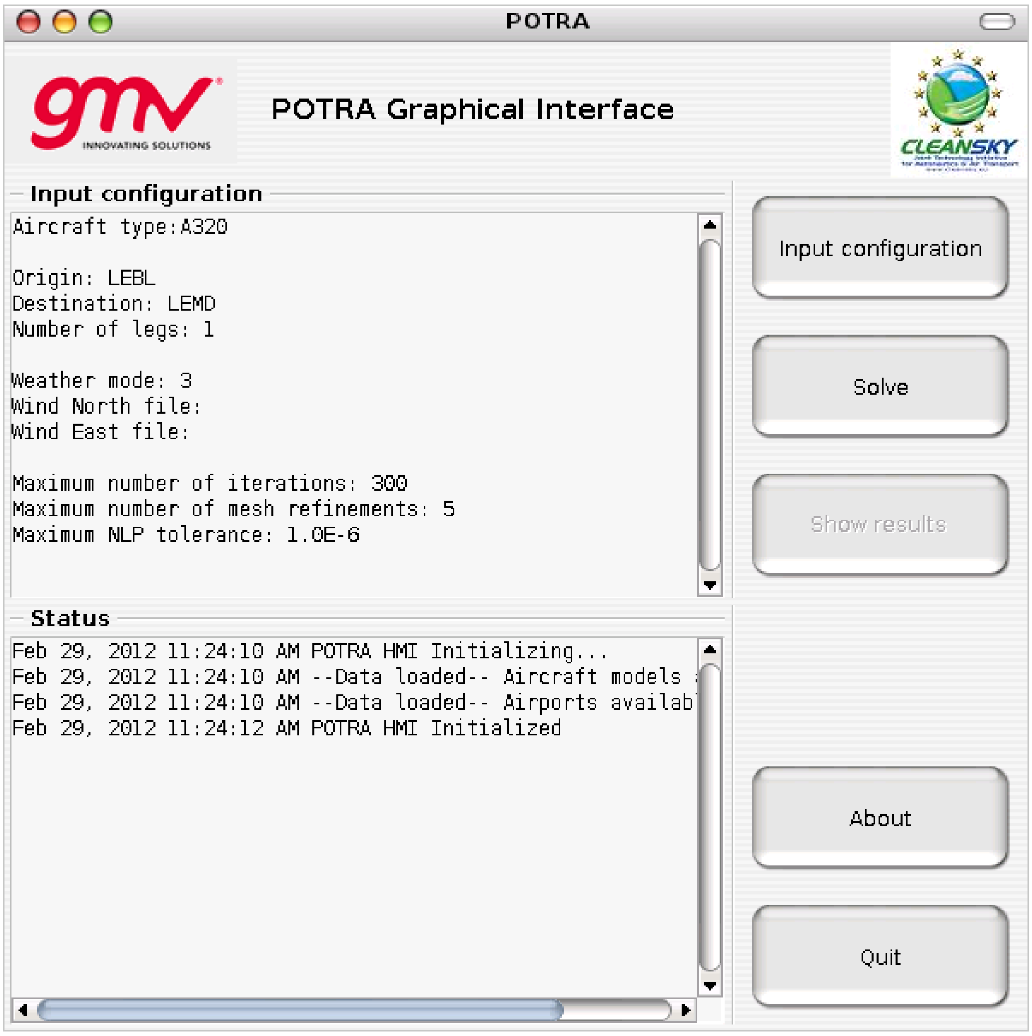


Figure 5-3: Main frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description
Input configuration area	Shows a summary of the input configuration
Status area	Shows the actions that are being done with a time caption
Input configuration button	Opens the input configuration frame
Solve button	Launches the solver with the current input configuration
Show results button	Opens the output results frame
About button	Opens the about frame
Quit button	Quits the POTRA tool

Table 5-1 – Main frame element description

5.3.2. INPUT CONFIGURATION FRAME

The input configuration frame is accessed through the main frame button "Input configuration".

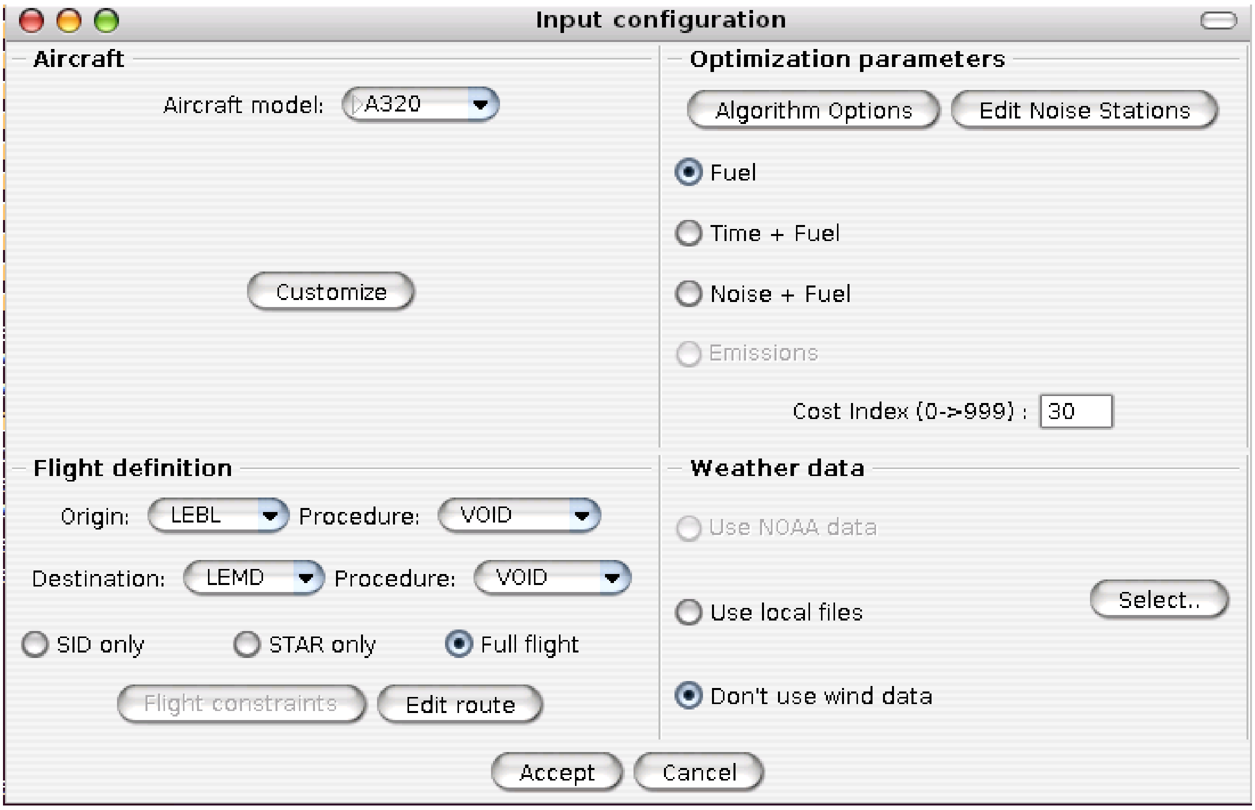


Figure 5-4: Input configuration frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description	Units and limits
Aircraft model combo box	List of selectable aircraft models available	
Customize button	Opens the customize aircraft frame	
Origin combo box	List of available departure airports	
Origin procedure combo box	List of the available SIDs at the selected origin airport	
Destination combo box	List of available arrival airports	
Destination procedure combo box	List of the available STARs at the selected destination airport	
SID only option	This option allows the user to optimize the trajectory through the SID	
STAR only option	This option allows the user to optimize the trajectory through the STAR	
Full Flight	This option allows the user to optimize the full flight.	
Edit route button	Opens the route editor frame	
Algorithm options button	Opens the algorithm options frame	
Edit noise stations button	Opens the edit noise stations frame	
Optimization parameters radio buttons	Allow the user to select the cost function of the problem	
Cost index number	Allows the user to set the cost index to be used in the cost function	Kg/s or Kg/dB (from 0 to 999)
Weather data source radio buttons	Allow the user to select the source for the wind data	
Select button	Opens a frame to access a browser to select the GRIB files for the wind	
Accept button	Saves the current input configuration and closes the	

Element	Description	Units and limits
	frame	
Cancel button	Closes the frame without saving.	

Table 5-2 – Input configuration frame element description

5.3.3. AIRCRAFT CUSTOMIZATION FRAME

The aircraft customization frame is accessed through the input configuration frame button "Customize" in the Aircraft panel.

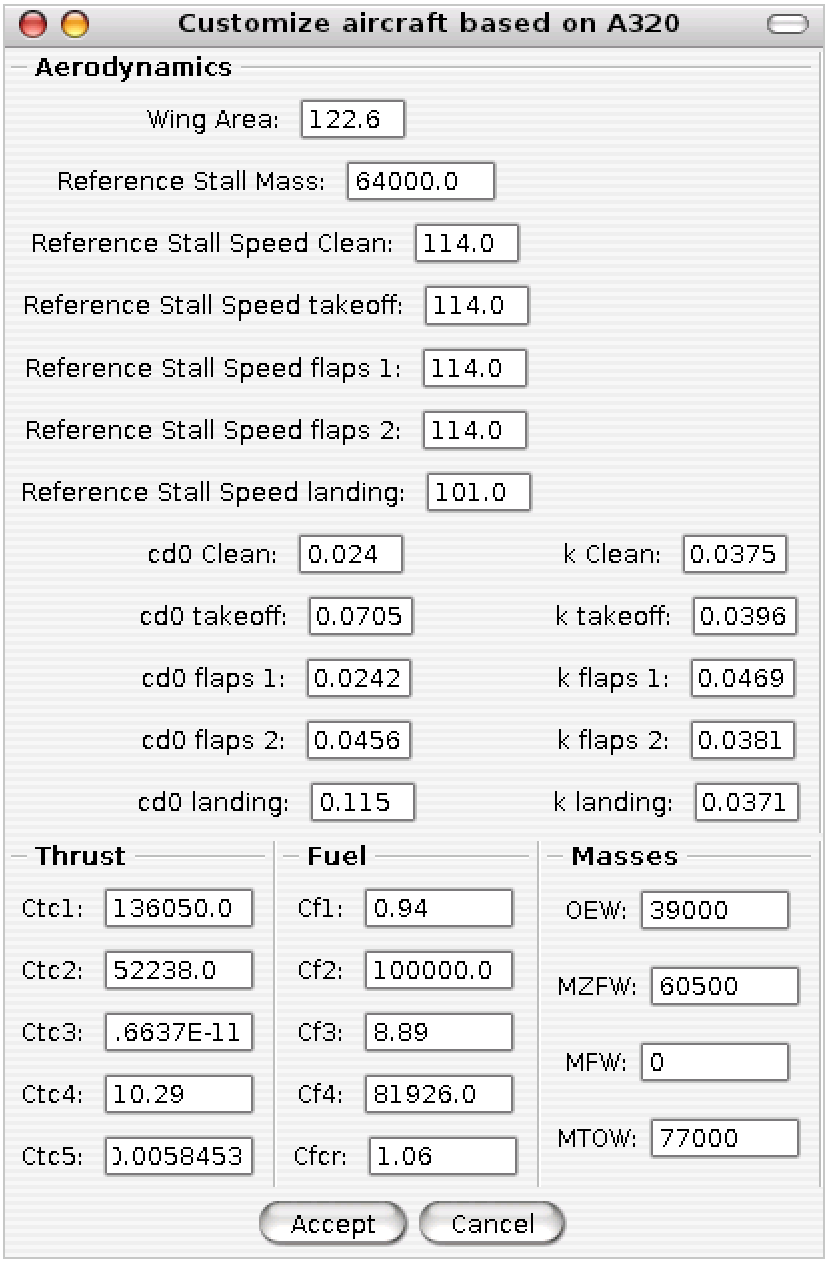


Figure 5-5: Aircraft customization frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description	Units
Aerodynamics panel	Allows the user to set the parameters to be used for the aerodynamics model	Area: square meters Mass: kg Speeds: knots Aerodynamic coefficients: dimensionless
Thrust panel	Allows the user to set the parameters to be used for the thrust model	
Fuel panel	Allows the user to set the parameters to be used for the fuel consumption model	
Masses panel	Allows the user to set the parameters to be used for the mass model	kg
Accept button	Saves the current parameters and closes the frame	
Cancel button	Closes the frame without saving	

Table 5-3 – Aircraft customization frame element description

5.3.4. ROUTE EDITOR FRAME

The route editor frame is accessed through the input configuration frame button "Edit route" in the flight definition panel.

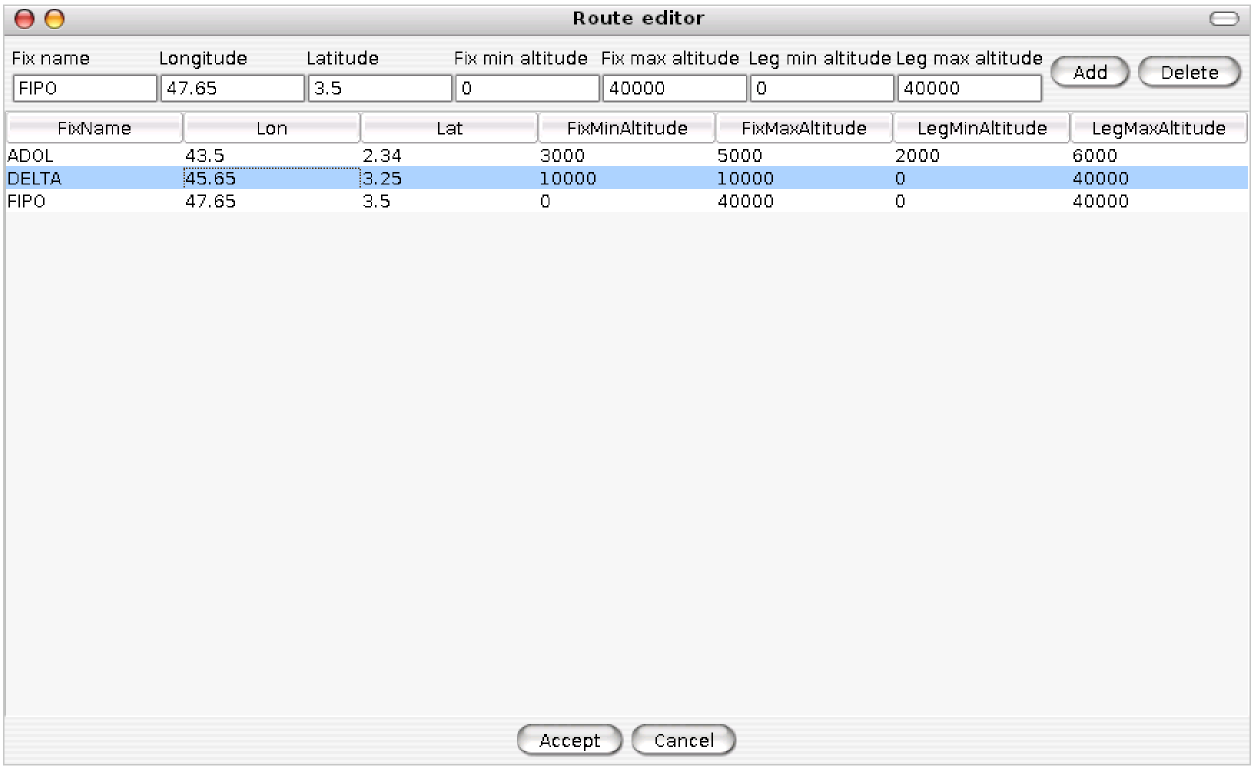


Figure 5-6: Route editor frame

In this version of the tool each waypoint should be introduced manually as there is no reference to a set of predefined waypoints in a database.

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description	Units and limits
Fix name	The name to be used for this waypoint	
Longitude	The longitude of this waypoint	Degrees (-180 to 180)
Latitude	The latitude of this waypoint	Degrees (-90 to 90)
Fix min altitude	The minimum altitude at this waypoint	Feet (0 to 50000)
Fix max altitude	The maximum altitude at this waypoint	Feet (0 to 50000)
Leg min altitude	The minimum altitude in the leg to this waypoint	Feet (0 to 50000)
Leg max altitude	The maximum altitude in the leg to this waypoint	Feet (0 to 50000)
Add button	Adds a waypoint the bottom of the list with the properties specified in the previous fields	
Delete button	Deletes the selected waypoint from the list	
Table	Shows the current list of waypoints that makes up the route between the two airports	
Accept button	Saves the current list and closes the frame	
Cancel button	Closes the frame without saving	

Table 5-4 – Route editor frame element description

5.3.5. ALGORITHM OPTIONS FRAME

The algorithm options frame is accessed through the input configuration frame button "Algorithm options" in the optimization parameters panel.

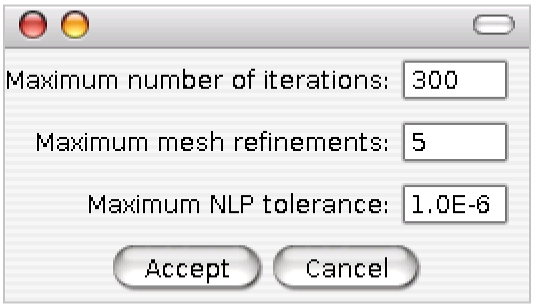


Figure 5-7: Algorithm options frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description
Maximum number of iterations	Allows the user to specify the maximum number of iterations per mesh refinement. (non zero)
Maximum mesh refinements	Allows the user to set the maximum number of mesh refinements (non zero)
Maximum NLP tolerance	Allows the user to set the maximum NLP tolerance used by the solver (non zero)
Accept button	Saves the current parameters and closes the frame
Cancel button	Closes the frame without saving

Table 5-5 – Algorithm options frame element description

The test conducted in the development phase show that apparently the SW can work with a maximum number of mesh refinements up to 10. Moreover some problems might not converge to a solution so the maximum number of iterations will be reached in those cases.

5.3.6. EDIT NOISE STATIONS FRAME

The noise stations frame is accessed through the input configuration frame button "Edit noise stations" in the optimization parameters panel.

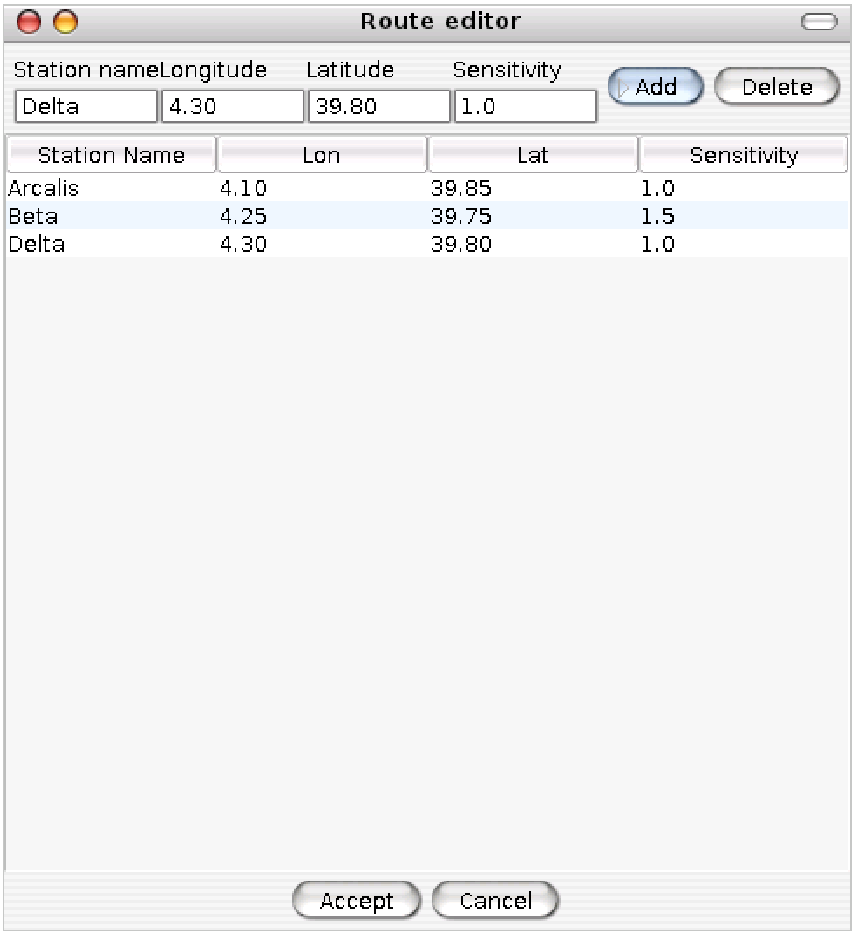


Figure 5-8: Noise stations editor

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description	Units and limits
Station name	The name of this station	
Longitude	The longitude of this station	Degrees (-180 to 180)
Latitude	The latitude of this station	Degrees (-90 to 90)
Sensitivity	The sensitivity to the noise of this station	Dimensionless (0 to 99)
Add button	Adds a station with the parameters specified to the list	
Delete button	Deletes the selected station from the list	
Table	Shows the current list of noise stations	
Accept button	Saves the list and closes the frame	
Cancel button	Closes the frame without saving	

Table 5-6 – Noise stations editor frame element description

5.3.7. OUTPUT FRAME

The output frame is accessed through the main frame button “Show results”.

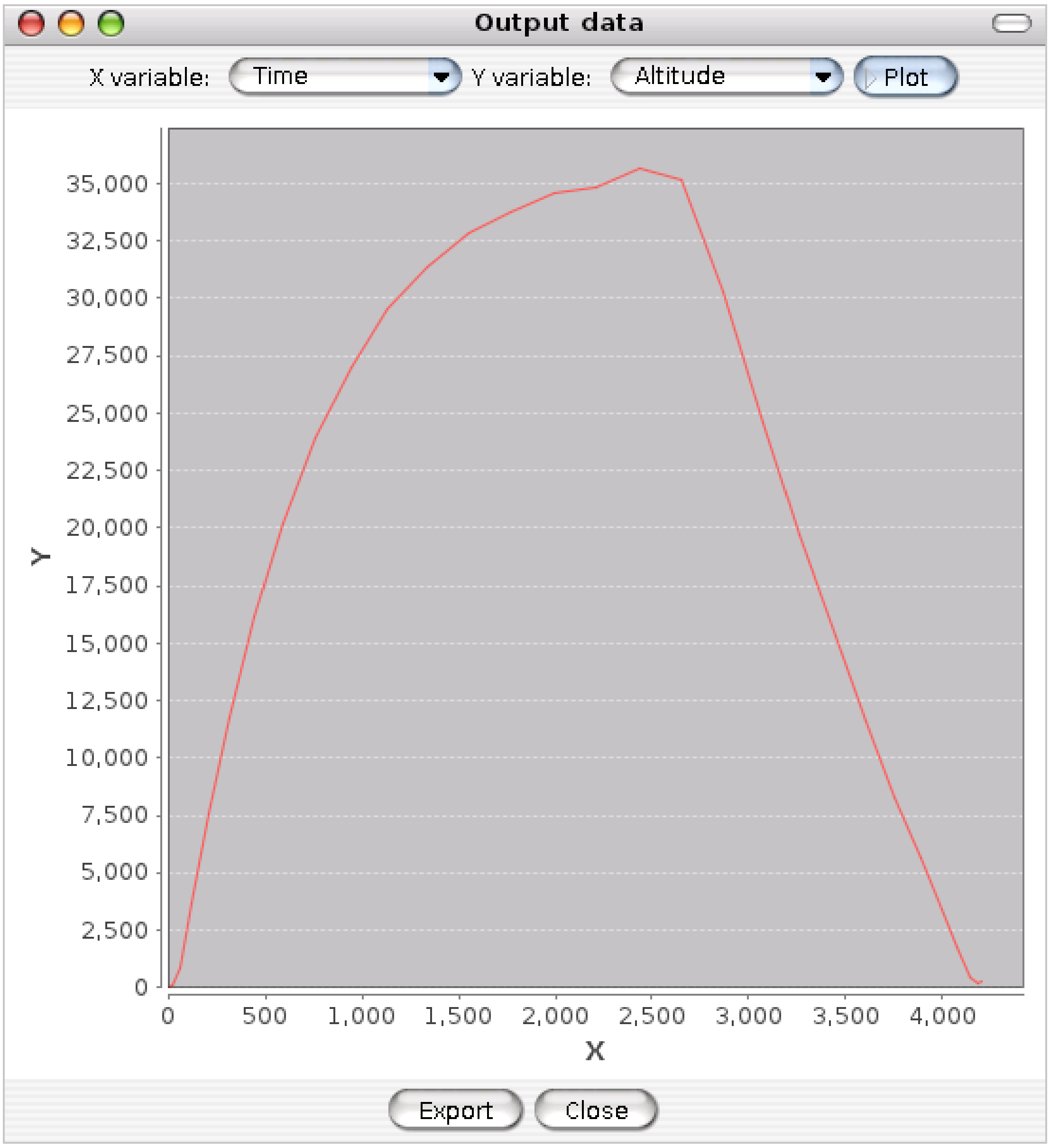


Figure 5-9: Output frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description
X variable combo list	Allows the user to select a variable to be used in the X axis of the 2D graph.
Y variable combo list	Allows the user to select a variable to be used in the Y axis of the 2D graph
Plot button	Generates the 2D graph with the variables specified
Graph area	Shows the graph generated
Export button	Opens the export results frame
Close button	Closes the output frame

Table 5-7 –Output frame element description

5.3.8. EXPORT RESULTS FRAME

The export results frame is accessed through the output frame button “Export”.

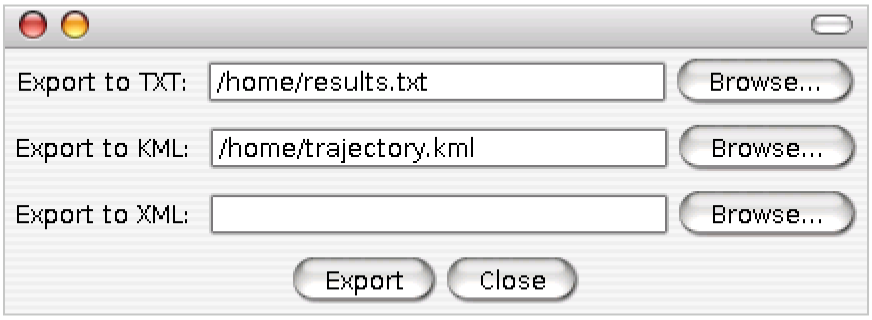


Figure 5-10: Export results frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description
TXT text line	Allows the user to specify the path and name of the TXT output file
KML text line	Allows the user to specify the path and name of the KML output file
XML text line	Allows the user to specify the path and name of the XML output file
Browse buttons	Opens a browser to select a directory and writes it to the text line
Export button	Exports the results to the specified files. If no file is specified the output is not exported.
Close button	Closes the frame

Table 5-8 – Export results frame element description

5.3.9. ABOUT FRAME

The about frame is accessed through the main frame button “About”.

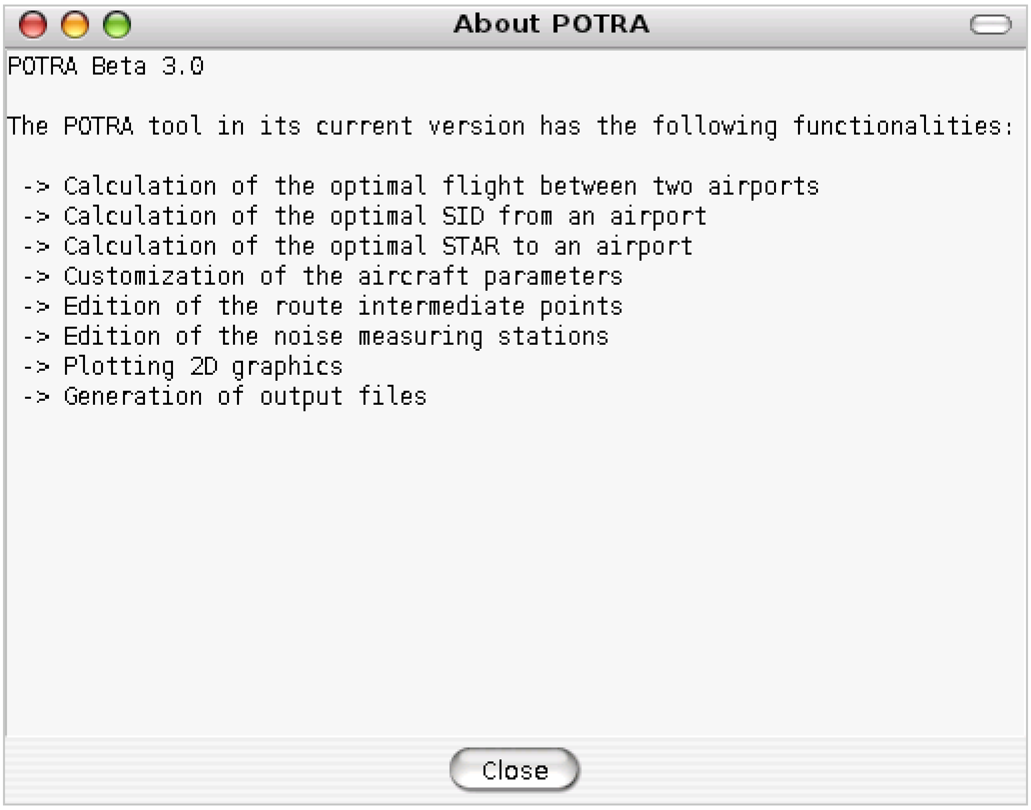


Figure 5-11: About frame

The following table describes the elements of this frame from top to bottom and from left to right.

Element	Description
Text area	Shows the current version of the tool and give additional information
Close button	Closes the frame

Table 5-9 – About frame element description

5.4. FUNCTIONALITIES

The POTRA tool in its current version has the following functionalities:

- Calculation of the optimal flight between two airports
- Calculation of the optimal command along SID from an airport
- Calculation of the optimal command along STAR to an airport
- Customization of the aircraft parameters
- Edition of the route intermediate points
- Edition of the noise measuring stations
- Plotting 2D graphics
- Generation of output files

The tool allows also the generation of output files for Google Earth and the generation of output files with control and state variables data in XML and TXT.

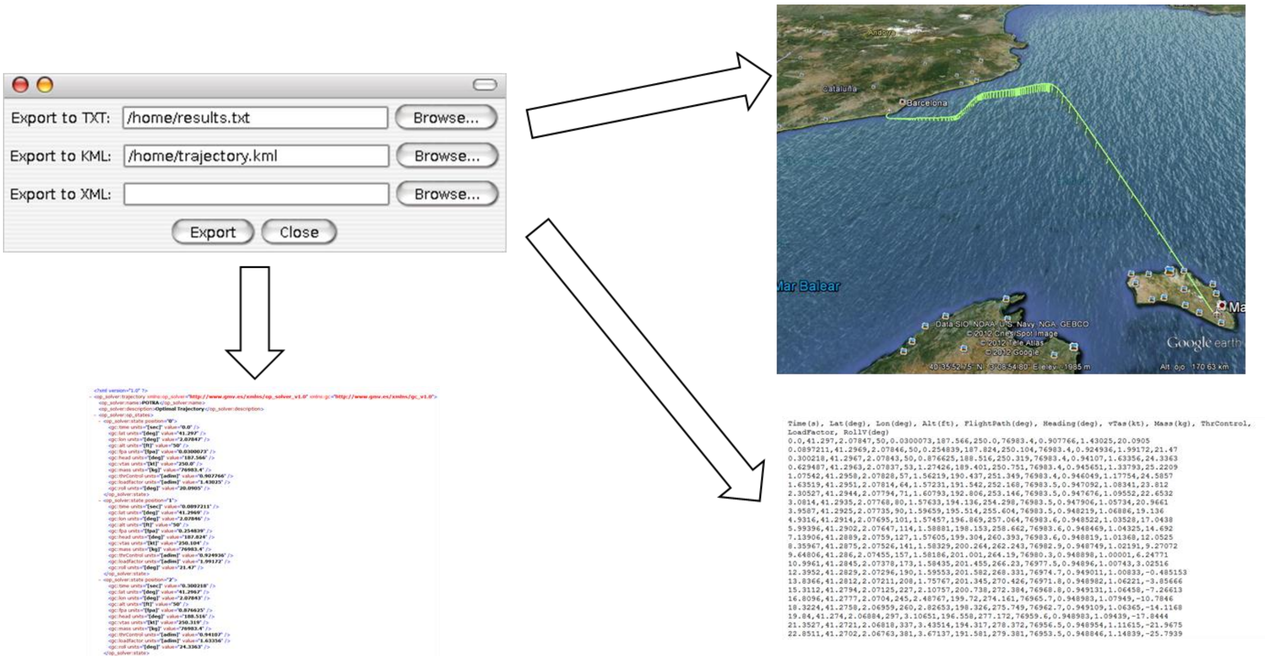


Figure 5-12: Different POTRA outputs

5.5. VALIDATION

The Test Cases defined in order to fulfill the requirements were the following:

Test ID	Test title	Test Objective
General test cases		
[POTRA-VTC-1001]	The input procedure	The objective of this test is to verify the ability of the application to provide an appropriate selection of the input options.
[POTRA-VTC-1002]	The change of Aircraft Data and flight limitations	The objective of this test is to verify the ability of the user to Change / introduce aerodynamic, propulsion and fuel consumption coefficients and to change the flight limitation of each aircraft.
[POTRA-VTC-1003]	Outputs for a SID departure in the database	The objective of this test is to verify that the database stores all the relevant outputs from the optimization for a SID departure.
[POTRA-VTC-1004]	Outputs for a STAR arrival in the database	The objective of this test is to verify that the database stores all the relevant outputs from the optimization for the phase of arrival.
[POTRA-VTC-1005]	Procedures with wind forecast files	The objective of this test is to verify that the application HMI allow to download the file with wind forecast of the day from the NOAA web page and the use of local files in the GRIB format.
[POTRA-VTC-1006]	Google Earth format outputs	The objective of this test is to verify that the optimized trajectory is saved in .kml format to be represented with Google Earth.
[POTRA-VTC-1007]	Outputs for a SID departure	The objective of this test is to verify that the output parameters for the phase of departure are saved in different file formats for further analysis.
[POTRA-VTC-1008]	Outputs for airport-to-airport	The objective of this test is to verify that the output parameters for the phase of airport-to-airport are saved in different file formats for further analysis.

Test ID	Test title	Test Objective
[POTRA-VTC-1009]	Outputs for a STAR Arrival	The objective of this test is to verify that the output parameters for the phase of arrival and landing are saved in different file formats for further analysis.
[POTRA-VTC-10010]	Verification of trajectory of Airport-to-airport, SID and STAR	The objective of this test is to verify that the tool can produce a lateral trajectory that fulfill the constraints of SID and STAR.
[POTRA-VTC-10011]	Verification of optimization parameters, methods and models consideration in optimization calculations	The objective of this test is to verify that all the optimization parameters, methods and models are considered when calculating the trajectory.
[POTRA-VTC-10012]	The relevant content of the database	The objective of this test is to verify that the database contains the coefficients of the BADA model for each type of Aircraft and AIS data: aerodromes, SID and STAR, waypoints.
[POTRA-VTC-10013]	Use of IPOPT optimizer	The objective of this test is to verify that the application uses IPOPT optimizer for calculations.
[POTRA-VTC-10014]	Graphic representation of parameters	The objective of this test is to verify the ability of the user to represent the output parameters versus time.
[POTRA-VTC-10015]	Representation of SID and STAR	The objective of this test is to verify that the application divides SID and STAR procedures in different phases and that each of these phases are considered a 2D or 3D problem.
[POTRA-VTC-10016]	Changes in Force model	The objective of this test is to verify that the changes in the Force model.
Computation test cases		
[POTRA-VTC-2001]	Correct implementation of the computational model	The objective of this test is to verify that the application performs all computations of optimal trajectory correctly.
[POTRA-VTC-2002]	Computation of optimal route	The objective of this test is to verify that the application computes the optimal route of aircrafts with defined flight plans (e.g.; commercial, business jet).

In particular test cases to check the convergence of the application were done with 940 flights with winds and 940 without winds. The results were the following without winds:

Total Number of Flights optimized	940
Total Number of Failed optimizations	164
Total Number of Failed optimizations with Maximum Number of Iterations	157
Total Number of Failed optimizations with infeasible Problem	7
Total Number of Solved optimizations	776
Percentage of Failed Cases	17.45 %
Percentage of Solved Cases	**82.55 %**
Percentage of Infeasible Problems (from Failed)	4.27 %
Percentage of Maximum Iterations (from Failed)	95.73 %

The following picture shows the solved trajectories presented with google earth.

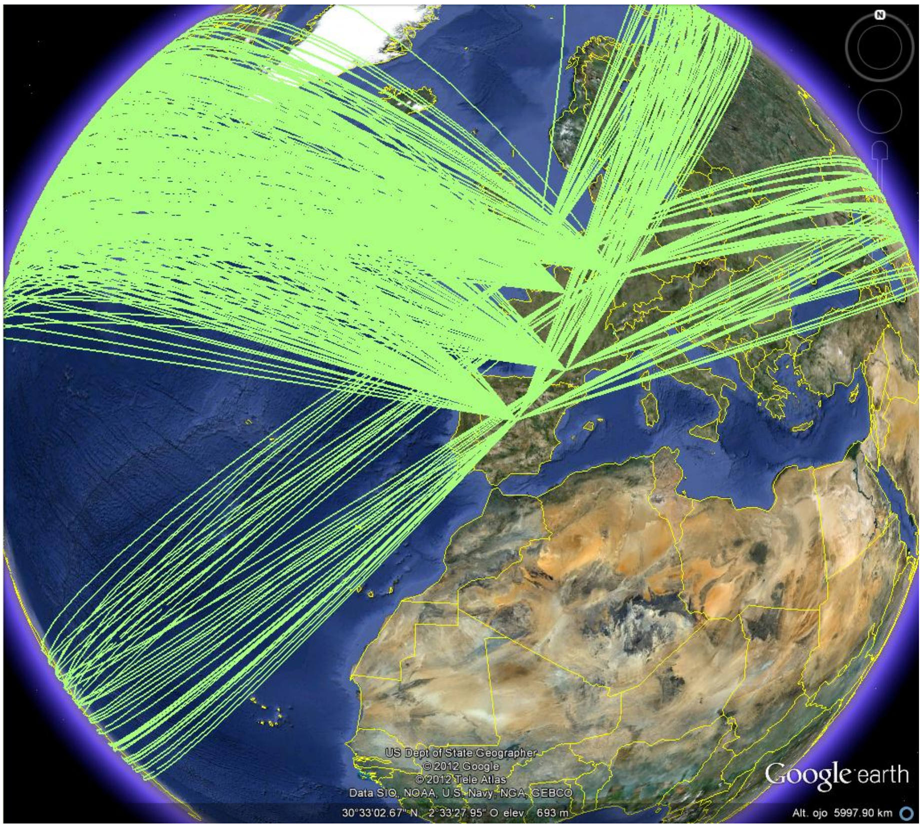


Figure 5-13: Trajectories with google earth without winds

The results with winds were the following:

Total Number of Flights optimized	940
Total Number of Failed optimizations	240
Total Number of Failed optimizations with Maximum Number of Iterations	229
Total Number of Failed optimizations with infeasible Problem	11
Total Number of Solved optimizations	700
Percentage of Failed Cases	25.53 %
Percentage of Solved Cases	**74.47 %**
Percentage of Infeasible Problems (from Failed)	4.58 %
Percentage of Maximum Iterations (from Failed)	95.42 %

The following picture shows the solved trajectories presented with google earth.

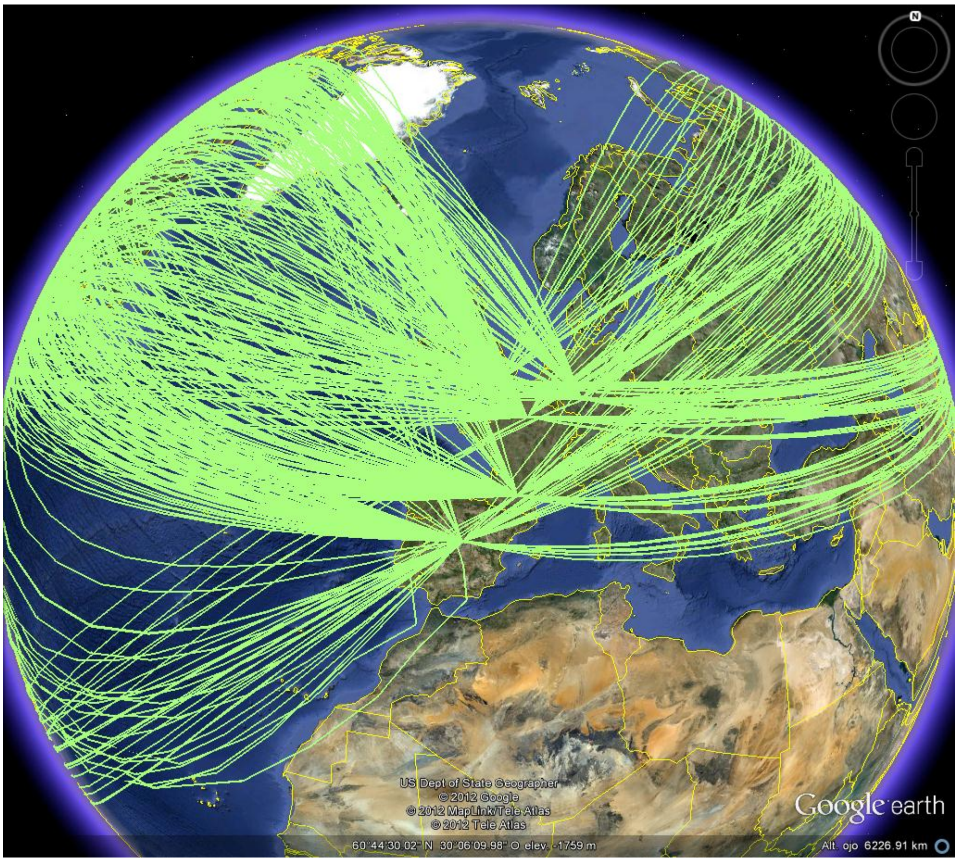


Figure 5-14: Trajectories with google earth with winds

As a summary the following table shows the test cases and procedures pass and failed.

The Table 5-10 shows the results for each pass fail criteria (PFC) and comments are added in those PFC that were not passed during the tests. The PFCs are grouped by test.

For more detail about the validation tests please refer to the VTP and VTR.

Table 5-10 Test results overview

Test	PFC	Passed/not passed	Comments
POTRA-VTC-1001	POTRA-PFC-1001		
	POTRA-PFC-1002		
	POTRA-PFC-1003		
	POTRA-PFC-1004		

Test	PFC	Passed/not passed	Comments
	POTRA-PFC-1005	✓	
	POTRA-PFC-1006	✓	
	POTRA-PFC-1007	✓	
	POTRA-PFC-1008	✗	Forbidden areas cannot be defined in this problem because only circular areas are definable as a constraint. Other features were given priority over this one.
	POTRA-PFC-1009	✓	
	POTRA-PFC-10010	✗	Most but not all the flight constraints can be changed through the HMI. Anyway they can be changed in the POTRA executable source code.
POTRA-VTC-1002	POTRA-PFC-10011	✓	
	POTRA-PFC-10012	✓	
	POTRA-PFC-10013	✓	
	POTRA-PFC-10014	✗	The option to change the flight limitations through the HMI is not available. However it is possible to manipulate them through the executable source code.
	POTRA-PFC-10015	✓	
POTRA-VTC-1003	POTRA-PFC-10016	✓	
	POTRA-PFC-10017	✓	

Test	PFC	Passed/not passed	Comments
	POTRA-PFC-10018	✓	
POTRA-VTC-1004	POTRA-PFC-10019	✓	
	POTRA-PFC-10020	✓	
	POTRA-PFC-10021	✓	
POTRA-VTC-1005	POTRA-PFC-10022	✗	The automatic connection to the NOAA web service was not implemented because other features were given priority. However the use can download manually the files and use them with POTRA.
	POTRA-PFC-10023	✗	Since the connection to the NOAA web service is not implemented it is not possible to download a file from the NOAA using the HMI.
	POTRA-PFC-10024	✓	
POTRA-VTC-1006	POTRA-PFC-10025	✓	
POTRA-VTC-1007	POTRA-PFC-10026	✓	
	POTRA-PFC-10027	✓	
POTRA-VTC-1008	POTRA-PFC-10028	✓	
	POTRA-PFC-10029	✓	
POTRA-VTC-1009	POTRA-PFC-10030	✓	

Test	PFC	Passed/not passed	Comments
	POTRA-PFC-10031	✓	
POTRA-VTC-10010	POTRA-PFC-10032	✓	
POTRA-VTC-10011	POTRA-PFC-10033	✓	
	POTRA-PFC-10034	✓	
POTRA-VTC-10012	POTRA-PFC-10035	✓	
POTRA-VTC-10013	POTRA-PFC-10036	✓	
POTRA-VTC-10014	POTRA-PFC-10037	✓	
	POTRA-PFC-10038	✓	
POTRA-VTC-10015	POTRA-PFC-10039	✓	
POTRA-VTC-2001	POTRA-PFC-2001	✗	Due to the lack of a commercial AMPL license, the problem cannot be reproduced in AMPL
POTRA-VTC-2002	POTRA-PFC-2002	✗	After the test was performed we realized that PLANEO and POTRA are two different tools not comparable, since PLANEO uses a point based algorithm that does not give an optimal solution.
POTRA-VTC-2003	POTRA-PFC-2003	✓	
POTRA-VTC-2004	POTRA-PFC-2004	✓	

Test	PFC	Passed/not passed	Comments
POTRA-VTC-2005	POTRA-PFC-2005	✓	
POTRA-VTC-2006	POTRA-PFC-2006	✓	

Total number of PFCs: 45

PFCs passed: 84%

The Table 5-11 shows the traceability of the requirements and whether they have finally been implemented in the tool or not. Comments are added for the relevant cases.

For more detail about the requirements definition please refer to the Technical specification document.

Table 5-11 Requirements implemented

Requirement	Test cases that verify the requirement	Requirement implemented	Comments
[TS1010]	[POTRA-VTC-2002]	✓	Although this requirement is implemented it couldn't be checked properly because we realized that PLANEO and POTRA are two different tools not comparable.
[TS1020]	[POTRA-VTC-1005]	✓	
[TS1030]	[POTRA-VTC-10010]	✓	
[TS1040]	[POTRA-VTC-10010]	✓	
[TS1050]	[POTRA-VTC-10010]	✓	
[TS1060]	[POTRA-VTC-10010]	✗	This functionality was not considered relevant for the general problem. Other major features were given priority.
[TS1061]	[POTRA-VTC-1001]	✓	
[TS1070]	[POTRA-VTC-10012]	✓	

Requirement	Test cases that verify the requirement	Requirement implemented	Comments
[TS1080]	[POTRA-VTC-1001]	✓	
[TS1090]	[POTRA-VTC-1007], [POTRA-VTC-1009]	✓	
[TS10100]	[POTRA-VTC-1007], [POTRA-VTC-1009]	✓	
[TS10110]	[POTRA-VTC-1001]	✓	
[TS10120]	[POTRA-VTC-1001]	✗	Most but not all the flight constraints can be changed through the HMI. Anyway they can be changed in the POTRA executable source code.
[TS10130]	[POTRA-VTC-1001]	✗	Forbidden areas cannot be defined in this problem because only circular areas are definable as a constraint. Other features were given priority over this one.
[TS10140]	[POTRA-VTC-1003], [POTRA-VTC-1004], [POTRA-VTC-1007], [POTRA-VTC-1008], [POTRA-VTC-1009]	✓	
[TS10150]	[POTRA-VTC-1002]	✓	
[TS10151]	[POTRA-VTC-1001]	✓	
[TS10160]	[POTRA-VTC-1002]	✓	
[TS10170]	[POTRA-VTC-1002]	✓	
[TS10180]	[POTRA-VTC-1002]	✗	For each aircraft not all the flight limitations can be changed through the HMI.
[TS10190]	[POTRA-VTC-1002]	✓	Although not all the limitations can be changed by the user they are defined inside the source code.

Requirement	Test cases that verify the requirement	Requirement implemented	Comments
[TS2010]	[POTRA-VTC-1001]	✓	
[TS2020]	[POTRA-VTC-1001]	✓	
[TS2030]	[POTRA-VTC-1001]	✓	
[TS2040]	[POTRA-VTC-1001]	✓	
[TS2050]	[POTRA-VTC-1001], [POTRA-VTC-1003]	✓	
[TS2060]	[POTRA-VTC-1001], [POTRA-VTC-1004]	✓	
[TS2070]	[POTRA-VTC-1002]	✗	Not all the flight constraints can be changed through the HMI.
[TS2090]	[POTRA-VTC-1001]	✓	
[TS20100]	[POTRA-VTC-1001]	✓	
[TS20110]	[POTRA-VTC-1001]	✗	Forbidden areas cannot be defined in this problem because only circular areas are definable as a constraint. Other features were given priority over this one.
[TS20120]	[POTRA-VTC-1006]	✓	
[TS20130]	[POTRA-VTC-10013]	✓	
[TS20140]	[POTRA-VTC-1007], [POTRA-VTC-1008], [POTRA-VTC-1009]	✓	
[TS20150]	[POTRA-VTC-1002]	✓	

Requirement	Test cases that verify the requirement	Requirement implemented	Comments
[TS20160]	[POTRA-VTC-1005]	✗	The tool is able to accept wind profiles through GRIB file. However is not able to download automatically the data from the web service.
[TS20170]	[POTRA-VTC-1005]	✓	
[TS20180]	[POTRA-VTC-1005]	✗	Since the connection to the NOAA web service is not implemented it is not possible to download a file from the NOAA using the HMI.
[TS20190]	[POTRA-VTC-1005]	✓	
[TS20200]	[POTRA-VTC-1005]	✓	The atmosphere class in the solver source code allows to implement other wind transformations.
[TS20210]	[POTRA-VTC-10011]	✓	
[TS20220]	[POTRA-VTC-10011]	✓	
[TS20230]	[POTRA-VTC-10011]	✓	
[TS20240]	[POTRA-VTC-1003], [POTRA-VTC-1004]	✓	
[TS20250]	[POTRA-VTC-1002]	✓	Except for those not implemented acording to [TS10120]
[TS3010]	[POTRA-VTC-1001]	✓	
[TS3030]	[POTRA-VTC-1001]	✓	
[TS4010]	[POTRA-VTC-10014]	✓	
[TS4020]	[POTRA-VTC-10014]	✓	

Requirement	Test cases that verify the requirement	Requirement implemented	Comments
[TS5010]	[POTRA-VTC-1001]		
[TS5020]	[POTRA-VTC-10011]		Only jet engines are considered. The turboprop engines were considered a minor functionality and other features were given priority.
[TS5030]	[POTRA-VTC-10015]		

Total number of requirements: 52

Requirements implemented: 83%

At the end of the project more than 80% of the test cases were passed and more of the 80% of the requirements have been implemented. This percentage is quite high considering that the requirements defined in the technical specification were quite challenging.

6. POTENTIAL IMPACT

The expected improvements that can be obtained with the new methods of optimization are the following:

- **Better 4D optimal trajectories**: These methods allow obtaining the 4D trajectories. That means that the optimization is not done in two steps, horizontal and vertical but in one step, therefore the computed trajectory is better in terms of optimal solution of the problem.
- **Lower fuel consumption and emissions**: These methods minimize the cost function, therefore new cost functions can be implemented and trajectories that minimize the fuel consumption, emissions or noise can be obtained.
- **Guidance law**: As an output of the solution this methods provide the guidance law of certain parameters, this guidance law could be injected in the FMS of an aircraft and fly exactly the optimized trajectory. This will be traduced in more optimal and greener ways of flying.

In summary those methods give a new vision and way of optimizing aircraft trajectories and could be the basis of new concept of flying and optimizing the resources of the airlines and the airspace.

END OF DOCUMENT