Free Route Airspace for Route Optimization

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Thesis to obtain the Master of Science Degree in

Aerospace Engineering

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October 2015

Acknowledgements

First and foremost, I would like to thank my supervisors Professor Dr. Rodrigo Ventura and Eng. Américo Melo, for the opportunity to work in this project in a company such as NAV Portugal, and, for all the knowledge and feedback during these last months. I would also like to thank Jesús Conde, Vanda Cruz and Martin Vicent for their constant help and patience teaching me how to properly use the NEST software.

I would like to say a special thank you to my brother, Nuno Pereira, for his endless support along my whole academic journey.

Additionally, I would like to express my gratitude to Rita Gomes, who have motivated me and made possible to finish within the planned time through her guidance on my ideas, helping me to express and write properly.

Finally, I would also like to thank all my close friends and family for all the support along the way.

Lisbon, 15th October 2015,
José Pereira

Resumo

Com o início da utilização da aviação para fins comerciais, e com o aumento exponencial registado do fluxo aéreo, a optimização do tráfego aéreo tornou-se, sem dúvida, uma área de investigação constante e essencial.

Numa situação ideal, não havendo necessidade de construção de estradas ou outras infraestructuras no transporte aéreo, uma rota entre dois pontos seria feita pelo caminho mais curto entre ambos, o que se traduziria numa *great circle line* entre esses 2 pontos. Contudo, numa situação real, devido a todas as normas de segurança exigidas e à elevada carga diplomática e histórica, torna-se extremamente difícil a escolha da rota mais eficiente. Este processo envolve diversas *Flight Information Regions* (FIRs), o que introduz complexidade ao processo, resultando na existência de normas que não se encontram uniformizadas, muito menos optimizadas.

Desta forma, apenas pequenas àreas e zonas bastante restrictas têm a designação de *Free Route Airspace* FRA, onde efectivamente, nesse troço da rota, é possível a escolha do itinerário mais eficiente. No caso de Portugal, existem duas FIRs, a de Lisboa e a de Sta. Maria, onde ambas, independentemente, funcionam como FRAs.

Assim, o âmbito desta tese prende-se no estudo da hipótese de expansão das duas FRAs existentes no espaço aéreo português, criando uma FRA conjunta. Pertende-se assim optimizar as rotas que passam neste espaço aéreo, tornando-o mais eficiente e consequentemente mais competitivo.

Numa outra fase, é também analisada a união desta FRA conjunta com as FIRs de Marrocos e Santiago & Astúrias. De salientar que esta união envolve diversos factores que vão introduzir alguma complexidade à análise e posterior implementação do mesmo, como a análise do congestionamento dos sectores e a necessidade de restructuração e cooperação entre as diversas FIRs.

Adicionalmente, e funcionando como um passo intermédio à criação de uma FRA conjunta, a localização dos actuais *Navigation Points* das respectivas FIRs é estudada, evidenciando e corrigindo possíveis ineficiências.

Os resultados mostram, que é possível introduzir melhorias ao actual cenário, reduzindo a distância, tempo e combustível gasto, e consequentemente reduzir os actuais custos. No entanto, como já referido, a implementação deste novo cenário só será conseguido com o total empenho e cooperação das partes envolvidas na restructuração do seu espaço aéreo.

Palavras-chave

Gestão de Tráfego Aéreo (ATM), *Free Route Airspace* (FRA), Optimização de Rotas, *Flight Information Region* (FIR).

Abstract

After the creation of comercial aviation, and with the registered exponential traffic growth, the optimization of air traffic flow became, with no doubt, a constant and essential research field.

In an ideal situation, without the need of road construction or other infrastructures in the air transport, a route between two points would be the shortest path between both, which would mean a great circle line between those two points. However, in a real situation, due to the required safety standards and the elevated diplomatic and historical load, it is extremely difficult to choose the most efficient itinerary. This process envolves several Flight Information Regions FIRs, which introduces complexity to the process, resulting in the existence of non-uniform standards, which are consequently non-optimized.

Therefore, only small and very restricted areas are designated free route, where in fact it is possible to choose the more efficient itinerary. In the case of Portugal, there are two FIRs, Lisbon and Sta. Maria, where both, independently, already work as Free Route Airspaces (FRAs).

Thus, these thesis is the result of the study of the possibility of expansion of the two existing FRAs in the portuguese airspace, creating a joint FRA, where the goal is to optimize the routes passing this airspace, making it more efficient and consequently more competitive.

At a later stage, is also analyzed an union between this joint FRA with the FIRs of Morocco and Santiago & Asturias. It is important to mention that this union involves several factors which will introduce some complexity to this analysis and posterior implementation, such as the analysis of the congestion between sectors and the need of restructuring and cooperation between the involved FIRs.

In addition, and working as an intermediate step towards the criation of a joint FRA, the localization of the Navigation Points of the respective FIRs is analyzed, aiming to evidence and correct possible inefficiencies.

The results have shown, that it is possible to make improvements in the current scenario, reducing the distance, time and fuel spent, and consequently reduce the current costs. However, as mentioned before, the implementation of this new scenario can only be achieved through a total commitment and cooperation between the parties involved in restructuring is airspace.

Keywords

Air Traffic Management (ATM), Free Route Airspace (FRA), Route Optimization, Flight Information Region (FIR).

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List of Acronyms

ACC Area Control Center

ATC Air Traffic Control

ATFCM Air Traffic Flow and Capacity Management

ATM Air Traffic Management

ATS Air Traffic Services

ECAC European Civil Aviation Conference

ESSIP European Single Sky ImPlementation

FAA Federal Aviation Administration

FIR Flight Information Region

FL Flight Level

FRA Free Route Airspace

LSSIP Local Single Sky ImPlementation

MATLAB Matrix Laboratory

NAS National Airspace System

NEST Network Strategic Tool

SES Single European Sky

SQP Sequencial Quadratic Programming

UIR Upper Flight Information Region

List of Symbols

CO_2	Carbon Dioxide
d	Distance
φ	Latitude
R	Radius of the Earth
λ	Longitude
NO_x	Mono-Nitrogen Oxide
J	Cost Function
x_x	Border Navigation Point
p_x	Previous Navigation Point
f_x	Following Navigation Point
n_x	Number of flights passing through p_x and f_x

Chapter 1

Introduction

Nowadays, it is widely recognised that the current air traffic management system will not be able to accommodate the air transportation growth at some level. In addiction, this level is being predicted to be reached in a relatively near future, where there is no more room to meet the society's expectations and needs for safe and economic air travel. Therefore, further capacity enhancements will be required, which may only be possible through a restructuration of the current air traffic management paradigms, (Kircher and Trouslard [15]).

In order to improve the current scenario, and with the need for route optimization, the current sources of inefficiencies in the air transportation need to be addressed. Accordingly to (Howell et al. [13]), there are five categories of sources of inefficiency in en route airspace in the United States, known as National Airspace System (NAS), which can be seen in the figure 1.1.

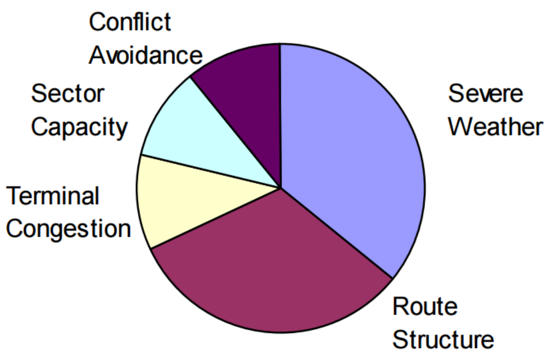

Figure 1.1: Enroute inefficiency sources in the NAS, (Howell et al. [13]).

Assuming a global trend of this inefficiency sources and extrapolating to a global scenario, one can assume that between this five categories, disregarding severe weather, the largest source of inefficiency is the current route structure. Thus, this thesis seeks to study possible alternative scenarios that could reduce or even completely eliminate this source of inefficiency (route structure), which we believe that can be achieved through a joint Free Route Airspace FRA.

Definition 1 (FRA).

In a Free Route Airspace, (FRA), users can freely plan their routes between an entry point and an exit point without reference to a route network.

In a FRA, users can freely plan their routes between an entry point and an exit point without reference to a route network. Thus, the implementation of a FRA offers many benefits for the operators, allowing operators to fly an optimal route, and not being required to pass any checkpoint. Despite the existing challenges, this is considered one of the most cost-effective changes in the Air Traffic Services (ATS) provision in Europe.

A FRA can reduce the flight time, CO_2 emissions and fuel waste since most flights will be using the shortest routes possible. This also ensures fewer conflicts and a better weight optimization, since the same number of aircrafts are spread over more routes, reducing the difference between the planned and the current route. However, some conflicts need to be addressed properly in order to not outweigh the benefits, since the benefits will only be achieved if the FRA is deployed over large areas, where proper measures need to be taken in order to avoid other conflicts such as bottlenecks on the aerodromes, (Skybrary [24]).

In a conventional airspace, the flight needs to pass by predefined navigation points, which consequently lead to the need to perform deviations during the flight. In a FRA, between an entry and exit point, one can freely choose the optimal possible route, without the need to perform any unnecessary deviations. However, the definition of optimal route still varies between the literature.

Route optimization is an active research field with growing interest in the recent years. The best route to fly depends on several factors, such as the forecast upper air winds and temperatures, the amount of payload and the time-based costs, which may vary from flight to flight. Due to winds, operational constraints and the value of the payload, the shortest path between two points, may differ from the cheapest and optimal route. In order to find and choose the optimal route, there are many multi-objective optimization algorithms, with several constraints, that can compute it, (Marceau et al. [16]).

The chosen route is assigned by the airlines through a flight plan, where its accuracy is a key factor when considering the efficiency of the flight. The knowledge and opportunity to use the optimal route is crucial for an efficient use of resources, resulting in lower operating costs and fuel emissions. If the route is not optimal, more fuel will be needed to complete the flight. More fuel leads to a heavier payload which, consequently, will burn more fuel, therefore, even more fuel is needed in the first place. Thus, accurate flight plan calculations can minimize this additional fuel, which are the result of several factors that combine engineering and information management.

In order to obtain insight on the relevance of the route choice a Boeing subsidiary, Jeppesen, performed a study focused on an airline that used fixed company routes. This study determined that using routes optimized with the most recent forecast winds, without disresgarding all the other Air Traffic Control (ATC) factors and requirements, the airline could save 1 million U.S. gallons of fuel per year, which would reduce the annual CO_2 emissions by about 20 million pounds, (Altus [1]).

However, this thesis doesn't seek to achieve a new optimal method to compute the perfect choice in terms of route. The main goal of this thesis is to reduce, and when possible completely eliminate, the current inefficiencies caused by airspace restrictions, which can be completely eliminated through a joint (FRA) from departure until arrival. Therefore, for the sake of simplicity, during all stages of this study it will be assumed that the shortest route is the optimal available route, and the route inefficiency would be defined by the amount of additional distance an aircraft flies in comparision to the shortest possible great circle route of flight (Which is in agreement with the study performed by (Howell et al. [13])).

Assumption 1 (Shortest Route)**.**

In this study, it is assumed that the optimal available route is the shortest route. Thus, the results will be all presented in terms of how the current route length can be shortened.

The shortest possible route between two points is defined as a great circle line, as explained by the definition 2, which can be seen in the figure 1.2. In the map the great circle line (in red) appears to be a longer distance than a rhumb line (in blue), this is due to the fact that the earth is not flat as the map but it is approximately a sphere. In the representation of the earth one can indeed see that the great circle line (in red) is the shortest possible route instead of the rhumb line (in blue) which takes a way longer route keeping the azimuth constant.

Definition 2 (Great Circle)**.** *A great circle is defined as any circle drawn on a globe with a center that includes the center of the globe. Thus, a great circle divides the globe into two equal halves. Therefore, a great circle line represent the shortest distance between two points following the globe's surface.*

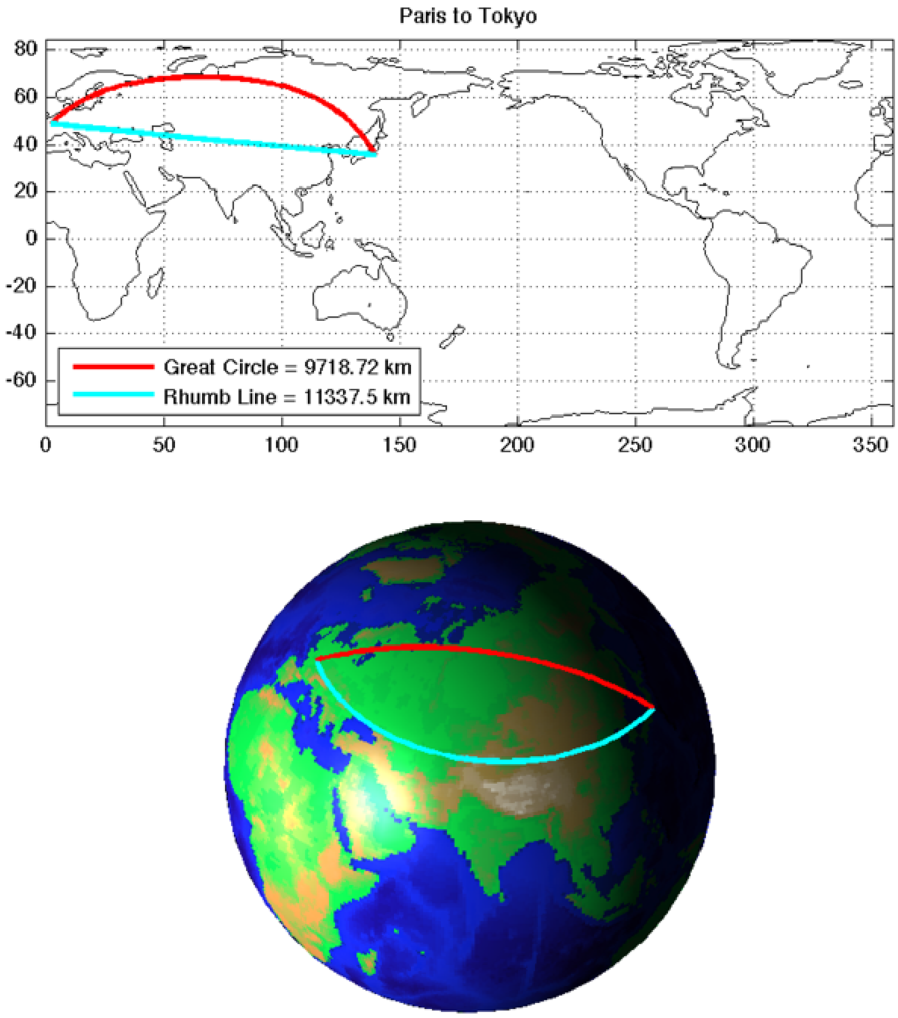

Figure 1.2: Great Circle Line - Example Paris to Tokyo (MATLAB [21])

1.1 Motivation and relevance

Portugal is a member of the international organisation EUROCONTROL since January of 1986. Due to severe delays to flights in Europe in 1999, a new initiative was launched in 2000 by EUROCONTROL, the Single European Sky package (SES). The aim of this initiative was to reduce the delays and costs associated with the air transport by improving its safety and efficiency, reducing the fragmentation of the air traffic management, (Eurocontrol [11]).

The SES package is part of the European Single Sky Implementation (ESSIP) Plan to ensure that each year the new improvements required by European Air Traffic Management (ATM) Master Plan for the European Civil Aviation Conference (ECAC) area, (Portugal is also member of the international organisation, ECAC, since 1955), (Eurocontrol [9]).

ESSIP intends to enable the performance achievements required. Specifically for the Portugal region, a LSSIP plan (Local Single Sky ImPlementation) was created in order to ensure the requirements fulfillment in this region, (Eurocontrol [10]).

The restructuration of the European airspace and respective air navigation systems has become an urgent need, since the European Comission started pressuring to ensure the creation of additional capacity, improved efficiency and interoperability of the ATM system in Europe. As an example, the free route projects implemented on the 2^{nd} of May, 2013, which led to additional Free Route Operations active at night in Croatia, Serbia, Poland and Czech Republic, offer potential annual savings of approximately 1.3 million nautical miles, which represents an equivalent of 8000 tones of fuel or reduced emissions of 27000 tones of CO_2, (Bucuroiu [4]).

In addiction, accordingly to the Head of Operations Planning Unit of Eurocontrol, in 2013 was expected that by 2014, 25 different Area Control Centers (ACCs) would be defined as FRA. This resulted in annual savings of 37 million euros, due to shortened routes, with less 7.5 million nautical miles in total, which consequently led to less 45000 tons of fuel and less 150000 tons of CO_2, (Bucuroiu [3]).

Considering the portuguese airspace, there are two different Flight Information Regions (FIRs), Lisbon and Sta. Maria, which independently work as FRA. With the SES initiative in mind, and with the eminent need to improve the current scenario, this thesis studies the possibility of expansion of the two existing FRA, making the portuguese airspace more efficient and consequently more competitive.

1.2 Research goal and main contributions

This problem can be split into three sub-goals that we seek to achieve:

1. In a first stage, this thesis analyzes the creation of a joint FRA in the whole portuguese airspace, removing the inefficiencies caused by the border between the two different FIRs (figure 1.3);

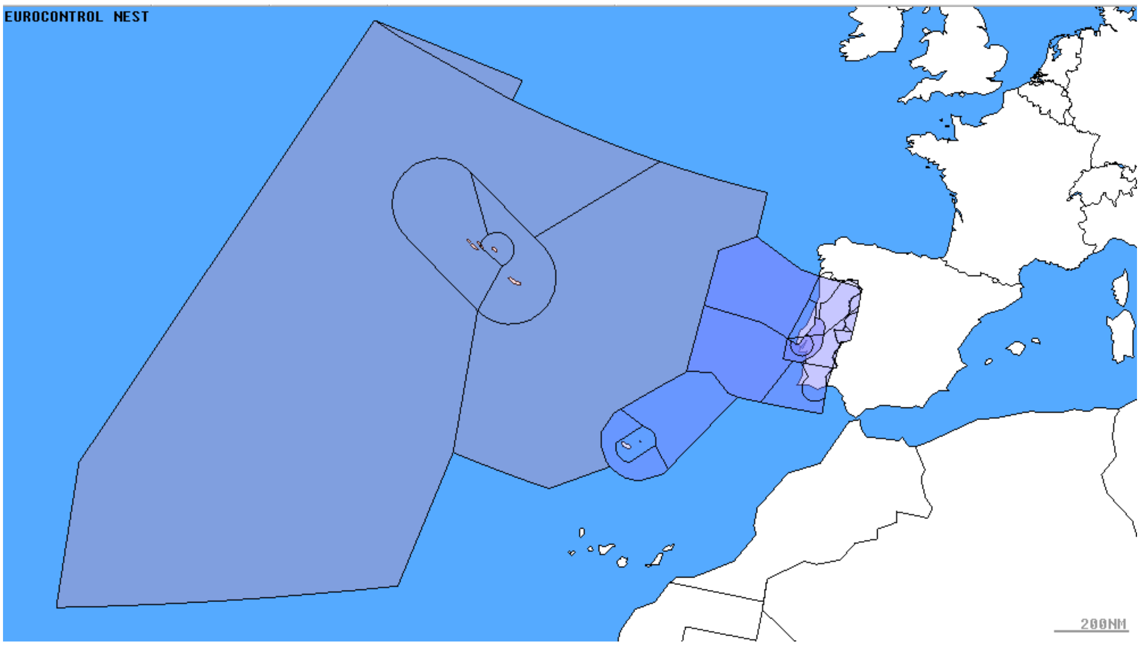

Figure 1.3: Joint FRA

2. In a later stage, this thesis analyzes the expansion of this joint FRA to other adjacent FIRs such as Morocco and Santiago & Asturias, expanding ambitiously the airspace and number of flights involved and consequently the improvements expected (figure 1.4);

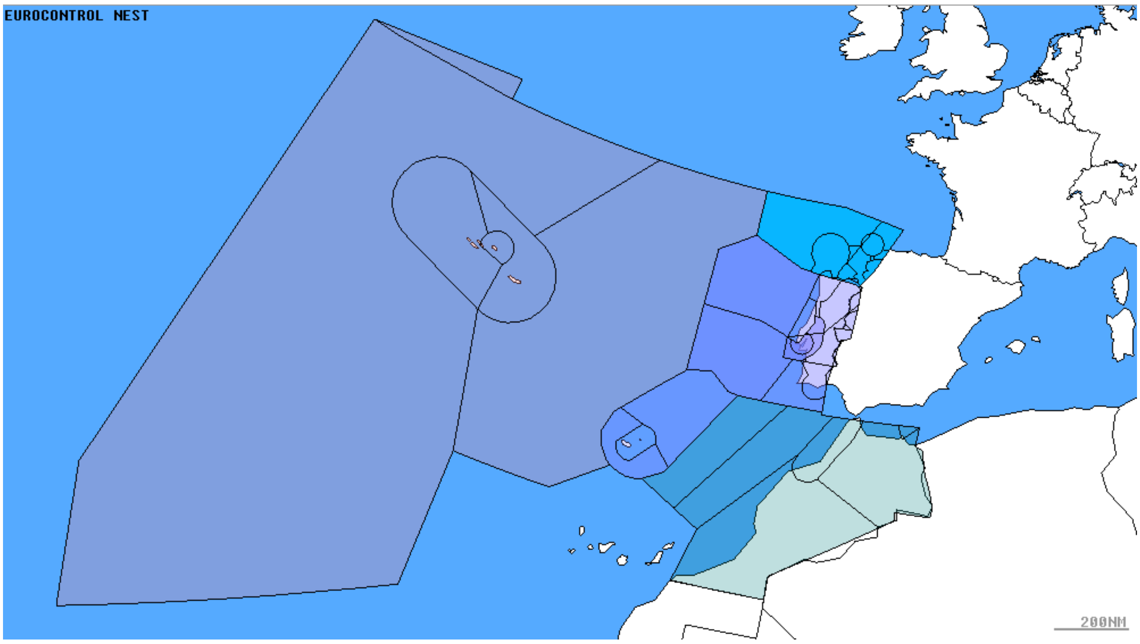

Figure 1.4: Expanded Joint FRA

3. As an intermediate step towards the joint FRA, the border between the two portuguese FIRs is analyzed, improving the current scenario and solving inefficiency problems (figure 1.5).

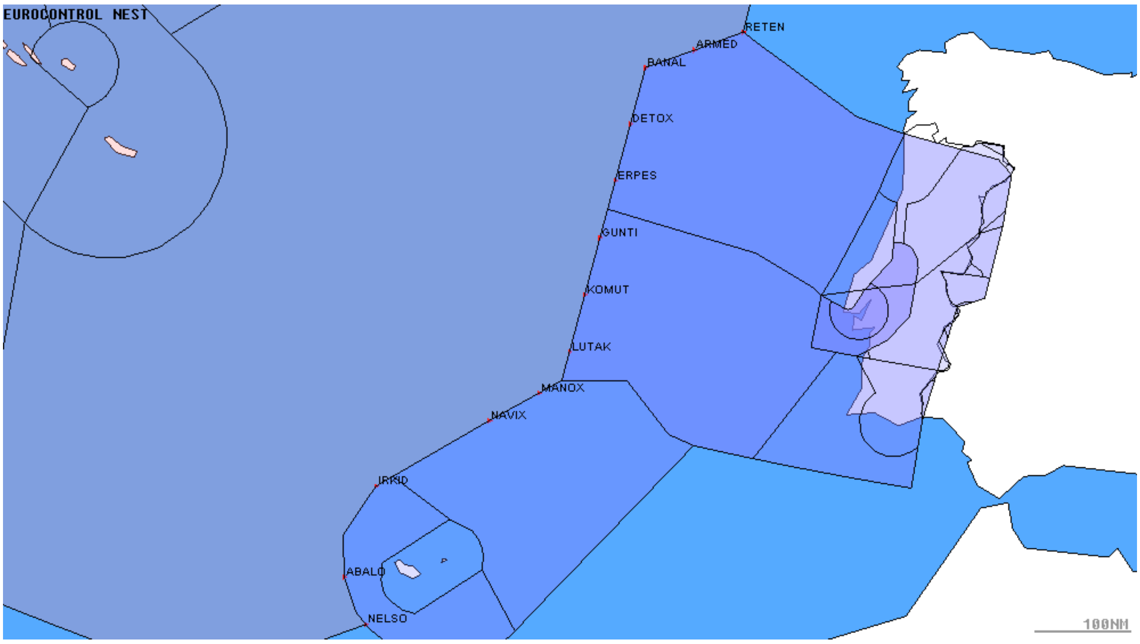

Figure 1.5: Navigation Points - Currentl Border between the two portuguese FIRs

The main contributions of this work are the following:

- Know-how on the current main inefficiencies in the portuguese airspace caused by the borders between the different FIRs.
- Solid alternative scenarios to the current approach, which are exposed and analyzed, showing the predicted improvements.

In order to achieve the main contributions of this study, the following software tools were used:

- The Network Strategic Tool Software (NEST 1.4) by Eurocontrol, which is a common platform for integrated planning which is used to optimise the available resources in order to improve performance at network level, (Eurocontrol [12]). Between all the features, the NEST software can prepare scenarios to support fast and real-time simulations, organize the traffic flows in the Air Traffic Flow and Capacity Management (ATFCM) strategic phase and also plan the capacity and perform related post operations analyses, (Martin et al. [17]).
- The MATLAB software (MATLAB R2013a) by MathWorks, which is a high-level language and interactive environment. MATLAB software can create scripts which interact (read and write) with other files such as (.xls) or (.txt), solve diverse optimization problems by minimizing a given cost function, create plots and graphs and even solve complex and diverse math problems.

1.3 Outline

The present Master's Thesis consists of eight chapters organised as follows.

- Chapter 1 - Introduces the topic, proposes the research goals that this thesis seeks to achieve and states the main contributions of this project.
- Chapter 2 - Provides a brief survey on the subject, analyses the most important literature on the topic and other related work, and compares our formulation with others.
- Chapter 3 - Discusses possible implementations and formally states the problem of the joint FRA.
- Chapter 4 - Formulates the optimisation process, in order to improve the current Navigation Points.
- Chapter 5 and 6 - Presents the simulation results, comparing the different hypothesis, respectively for the Joint FRA and the Navigation Points Optimization.
- Chapter 7 - Concludes the thesis giving a summary of the obtained results, relevant recommendations for NAV Portugal and to further studies on the area.

Chapter 2

State of the Art

In order to address the need for changes in the air traffic management system, new measures have been simulated and deeply studied in order to achieve a better global solution. It is to highlight the FRA, which is already being used in several ACCs and the possibility of expansion of those areas is a constant in the academic literature.

2.1 FRA - Pros and Cons

In the literature several authors have been supporting free routed traffic. Accordingly to an analysis performed in the United States, (Jardin [14]), it was suggested, in 2003, that enroute capacity could be increased by a factor of five, and that direct operating costs could also be reduced by about $500 million per year (4.5%), if aircrafts were allowed to fly in unconstrained routes, in a FRA. In addiction, the results of the study (Howell et al. [13]), also performed in the United States, have shown that a FRA could reduce in 4% the potential conflicts, mainly due to the fact that the current structure has a limited number of pathways, which concentrate a lot the traffic in certain points. Therefore, (Howell et al. [13]) suggests that a FRA approach should be used in all Federal Aviation Administration (FAA) programs claiming en route user benefits.

Europe has been following the same line of though, where a deep restructuration of the European airspace is already in motion with significant improvements, as explained in the section 1.1 of the chapter 1. Again, the literature has been supporting the expansion and further implementations of a FRA. (Kircher and Trouslard [15]) studied the potential application of the FRA concept in the mediterranean airspace, where there was evident the improvements in terms of efficiency that a FRA could bring. However, it also explains the main reason why it is not yet widely implemented. Historically the navigation of aircraft has been based on flying between beacons, or navigation points, whereas modern aircraft is capable of navigating on arbitrary flight paths, but air traffic procedures are still based on the classic route network. Thus, the difficulty that navigating on "free routes" inflicts on the air traffic control services is the dominant reason for the fact that route structures have been maintained up to date, (Kircher and Trouslard [15]).

Apart from the difficulty of changing the air traffic procedures, in a conventional route network potential conflicts between aircrafts would occur at expected merging points, where the air routes intersect each other, however, in a FRA aircrafts must be expected to navigate in almost any possible route which means that conflicts may occur at any point in a sector, which increases the workload and complexity of conflict detection to the air traffic controller. In (Modin and Schafer [22]), which studied the hypothesis of a FRA in the Marseille UIR (Upper Flight Information Region), they concluded that the memorization of routes and conflicts proved to be difficult, where controllers had to compensate with an increase in the requirement level of the tasks to be undertaken and the workload. However, the update of the air traffic management paradigm it's already happening, with better conflict detection software to help the controllers. Direct routings between origin and destination are preferable for economic and environmental reasons, where accordingly to (EUROCONTROL [8]), a 3% reduction in track miles could occur through the application of free routing. Where, in the study performed in the mediterranean area, the balance of workload was considered acceptable, stating that there were no major differences between the final flight profiles.

Besides the FRA, there are also alternatives, which are being studied (Soler et al. [25]), which try to optimize the current air traffic management paradigm, keeping the beacons as waypoints. This alternative presents worst results than the FRA, however can be presented as a more realistic approach in a short term for cases where the FRA cannot be easily implemented, where they try to combine an airspace structured in waypoints with a more flexible continuous motion of the aircraft.

2.2 Route Choice Factors

This thesis doesn't seek to achieve a new method to compute the optimal route, as it was clearly stated in the chapter 1, however, an overall understanding of how the research community have addressed and formulated the problem is given. The minimum CO_2 emissions and consequently minimum cost as an ultimate goal over specific route networks is defined in diferent ways which lead to diferent performance criteria and results differ within the literature.

In this thesis, the optimal route is considered to be a great circle line between two points, which represents the shortest horizontal route possible. This is a standard procedure nowadays, also implemented in the SES Performance Scheme, and presented in several studies. However, new state of the art techniques are being analyzed and compared, since the shortest route does not necessary mean the cheapest or the most efficient route.

Within the airspace, there are several different charging zones, with different overfly cost. Therefore, in some areas there might be an incentive to select a longer route, leading to lower charges and a lower total cost. This way, a route choice is always a trade-off between several factors such as route charges, fuel consumption (which depends on the route length, speed and weather) and route flight time (related with passengers due to possible delays, maintenance and crew costs). Thus, computing the best possible route for each case is a complex multi-objective optimization problem, with several constraints.

2.2.1 Different Charging Zones

In order to give some insight on the importance of the different charging zones for a company, in (Delgado [6]), this issue is addressed particulary for the European airspace, where it is visible a pattern which may lead to the choice of a longer route over the optimal one, which have three main flows presented:

- Flights between the north of Europe and the Canary Islands, it may be economically worthwhile to select a longer route via Portuguese oceanic airspace instead of a direct route via France and Spain, since the unit cost of the route charges are respectively 1,060 versus 7,184 and 6,592.
- Flights between central/north Europe and Greece/Cyprus area, the Italian airspace is more expensive than the adjacent airspaces of Croatia, Serbia and Bosnia-Herzegovina. In turn, those are also more expensive than the adjacent airspaces of Hungary and Romania.

- North-South routes in Easter Europe, may select longer routes through Poland or Czech Republic instead of Germany which is more expensive.

This happens since the total charge of a flight is composed by the sum of all the charges generated in the charging zones that will be overflown, where each of this charges is computed as the product of a distance factor, weight factor and a unit cost factor (which vary between the different charging zones). The distance factor is directly proportional to the distance flown, the weight factor is proportional to the weight of the plane while the unit cost factor only depends on the area being overflown (figure 2.1)

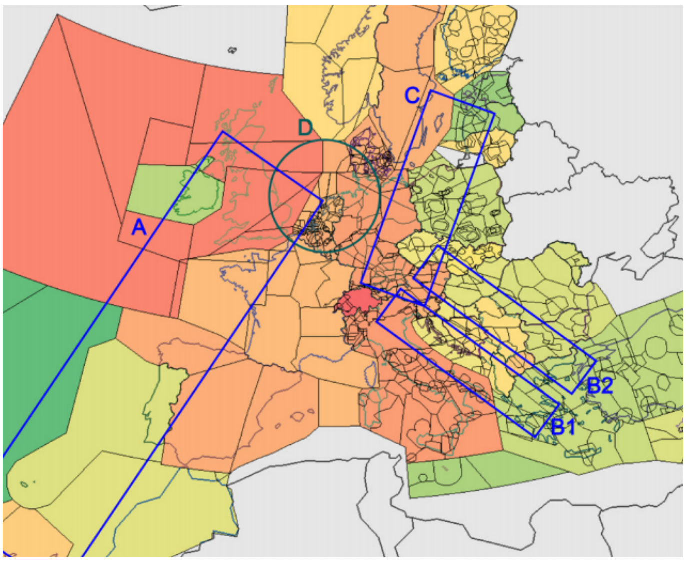

Figure 2.1: Airspace charging zones (colour indicates the relative unit cost), (Delgado [6]).

In a concrete case, two different routes (Route A and B), with the same aircraft type, between Manchester and Tenerife (EGCC to GCTS) on the 12^{th} September 2014 were also analyzed in (Delgado [6]). The Route A was filled by a low-cost operator, which by choosing a route 53 NM longer, through the Portuguese oceanic airspace, could save 352 € in route charges when comparing with the Route B performed by a charter carrier, through France and Spain.

2.2.2 Weather & Winds

Other important factor to take into account when looking for route efficiency is the weather conditions, in particular the strong winds. There is extensive literature addressing the development of optimal trajectories through a minimization of a cost function while satisfying constraints (Bryson and Ho [2]), however, due to computational complexity, most of this analysis have been done despising wind conditions (Reynolds [23]). Minimum fuel, minimum time and minimum operating cost are just some of the cost functions used, with several methods to avoid bad weather or even traffic congestion.

Nowadays, the efficiency of oceanic flights is lower due to higher airspace rescrictions and congestions caused by limited equipment for navigation and communication. In (Sridhar et al. [26]), a strategic planning of efficient oceanic flights is addressed through wind optimal routes. Transatlantic flights between United States and Europe constitute one of the busiest oceanic regions, where (Sridhar et al. [26]) examines the benefits of a wind-optimal trajectory. The analysis in (Sridhar et al. [26]) is based on the air traffic during July of 2012, and the results have shown improvement of efficiency of flight trajectories by 3 to 5% depending on the route and aircraft type, which gives a mean savings of 650kg per flight. For 460.000 fights flying annually this region, it could be expected savings of approximately 200 Million Dollars.

2.3 Enhanced Flight Efficiency

As previously explained, when considering an optimal route the standard procedure is to compute a great circle line between the entry and exit points, limiting the calculations to only the horizontal component of the flight. The Flight Efficiency Indicator, as implemented in the SES Performance Scheme, is used to measure how closely the flown trajectory are to the optimal trajectory. Here, the direct, geodesic route, is considered the cheapest and more efficient option, since it presents the shortest possible route disresgarding the vertical component. However, this method has limitations and some objections can easily arise, such as the absence of a vertical component and meteorological conditions. The paper (Calvo et al. [5]), explores the inclusion of the vertical component, and weather data, which considers a major improvement in the ATM Performance Monitoring field, the Enhanced Flight Efficiency Indicator, stating that captures better the fuel efficiency.

(Calvo et al. [5]) states that the Horizontal Flight Efficiency indicator does not always fully capture the optimum trajectories, where the error lies on the consideration of the Great Circle trajectories as being always the optimum ones. In addiction, the results presented in (Calvo et al. [5]) allow consideration of the Enhanced Flight Efficiency as a more accurate and representative metric in Flight Efficiency computation.

Chapter 3

Problem Formulation - Joint FRA

The main goal of this thesis is to study the expansion of the current FRA. Thus, a comparision needs to be addressed between the current scenario and a hypothetical scenario with the desired changes made, where a list of all the recent flights that pass through the studied airspace, with their complete route, will be needed.

After collecting all the flights and respective routes, the creation and analysis of the new scenario can be made. The new expanded FRA has to be specifically selected, where the entry and exit points of all flight routes have to be marked. Then, the new route can be drawn, replacing the fragment of the route between the entry and exit points with a great circle line, which represents the shortest route between two points.

Afterwards, the new routes created can be compared with the current scenario, where the differences in terms of route length between the two scenarios can be analyzed. A shorter route will consequently lead to less fuel burnt, a shorter flight and fewer CO_2 emissions. Therefore, through this measures it will be possible to improve the current scenario both in economic and environmental terms.

Problem 1 (Joint Free Route Airspace (FRA), analyze scenario)**.**

Given a set of airspaces to be studied as a joint FRA, it is defined the problem of computing the new hypothetical route, to be compared with the current traffic in order to analyze possible improvements that can be brought through a FRA.

This can be achieved with the algorithm 1:

Algorithm 1. - *With an area to be defined as a joint FRA, and the whole traffic crossing that area as inputs:*

repeat *for each flight*

1. Extract the entry and exit points of the joint FRA from the flight route;

2. Replace the route, between entry and exit points, with a great circle line; —State 3. Compare current route with the new computed route.

until *All the flights crossing the joint FRA were analyzed*

The length of the shortest route between the two given points, described by a great circle line, can be computed using the expression 3.1, which uses the haversine function, (EASA [7]):

$$d = 2\,R\,atan2(\sqrt{a}, \sqrt{1-a}), \tag{3.1}$$

where,

$$a = \sin^2(\frac{\Delta\varphi}{2}) + \cos(\varphi_1)\ \cos(\varphi_2)\ \sin^2(\frac{\Delta\lambda}{2}), \tag{3.2}$$

Assumption 2 (Spherical Earth).
The formula 3.1 is assuming a spherical earth, ignoring ellipsoidal effects, where $R \simeq 6,371km$.

Shall also be noticed that the φ_x represents the latitude of a given pair of coordinates of x, while λ_x represents the longitude, while the function *atan2* is expressed in the definition 3.

Definition 3 (atan2 function). *The function atan2 is the arctangent function with two arguments which can be expressed as follows:*

$$atan2(y,x) = \begin{cases} \arctan\frac{y}{x} & if\ x > 0 \\ \arctan\frac{y}{x} + \pi & if\ y \geq 0,\ x < 0 \\ \arctan\frac{y}{x} - \pi & if\ y < 0,\ x < 0 \\ \frac{\pi}{2} & if\ y > 0,\ x = 0 \\ -\frac{\pi}{2} & if\ y < 0,\ x = 0 \\ undefined & if\ y = 0,\ x = 0 \end{cases}$$

As mentioned before, this thesis studies current inefficiencies, mainly due to static inefficiencies in the current airspace route structure, considering any deviation from the shortest (optimal) route an efficiency, which one could argue that it is not entirely true. Nevertheless, it is completely reliable since any possible deviation that might be caused by other route choice factor (such as winds) was properly corrected with the creation of a simulated traffic, which is a trustworthy scenario for comparision. The simulated traffic created, simulates the current scenario, which considers the two different FIRs as independent, and separated, FRAs, and computes the theoretical best possible route with this premise, thus, eliminating any other source of inefficiency.

With the NEST software, it is possible to extract all the flights that comply with the desired especifications, reroute them, and compare with the current scenario, Martin et al. [18].

3.1 NEST Tool

First of all, the airspace to be free routed has to be chosen. Thus, a group has to be created with the desired ACCs. In a first stage it shall include the Lisbon and Sta Maria ACCs, named LPPCCTA and LPPOOCA respectively. Then, in a later stage, it shall also include the Morocco ACC, GMMMCTA, and the Santiago & Asturias traffic volume LECMSAI.

Secondly, a custom traffic flow has to be created, selecting the whole traffic crossing the chosen airspace. Note that the option crossing traffic includes all the traffic that will be influenced somehow by the airspace, which considers all the flights that departure, arrive or overfly the seleted region. Then, for each day, using the custom traffic flow as a filter, all the flights crossing the chosen airspace and respective routes are saved in a traffic file, which has real traffic data provided by EUROCONTROL.

Finally, through a SIM diagram, the initial traffic file can be compared with the free routed traffic generated with the program. The chosen FRA is given as input, as well as the traffic file with all the flights, for each day, generating a free routed traffic file in the chosen airspace. Also as output, a text file is generated which compares, flight by flight, the two scenarios in terms of route length.

The SIM diagram, for the joint FRA in the whole portuguese airspace, is presented in the figure 3.1, and detailed explained in the next page, which have two sets, each of them with four main processes, three inputs files and two output files.

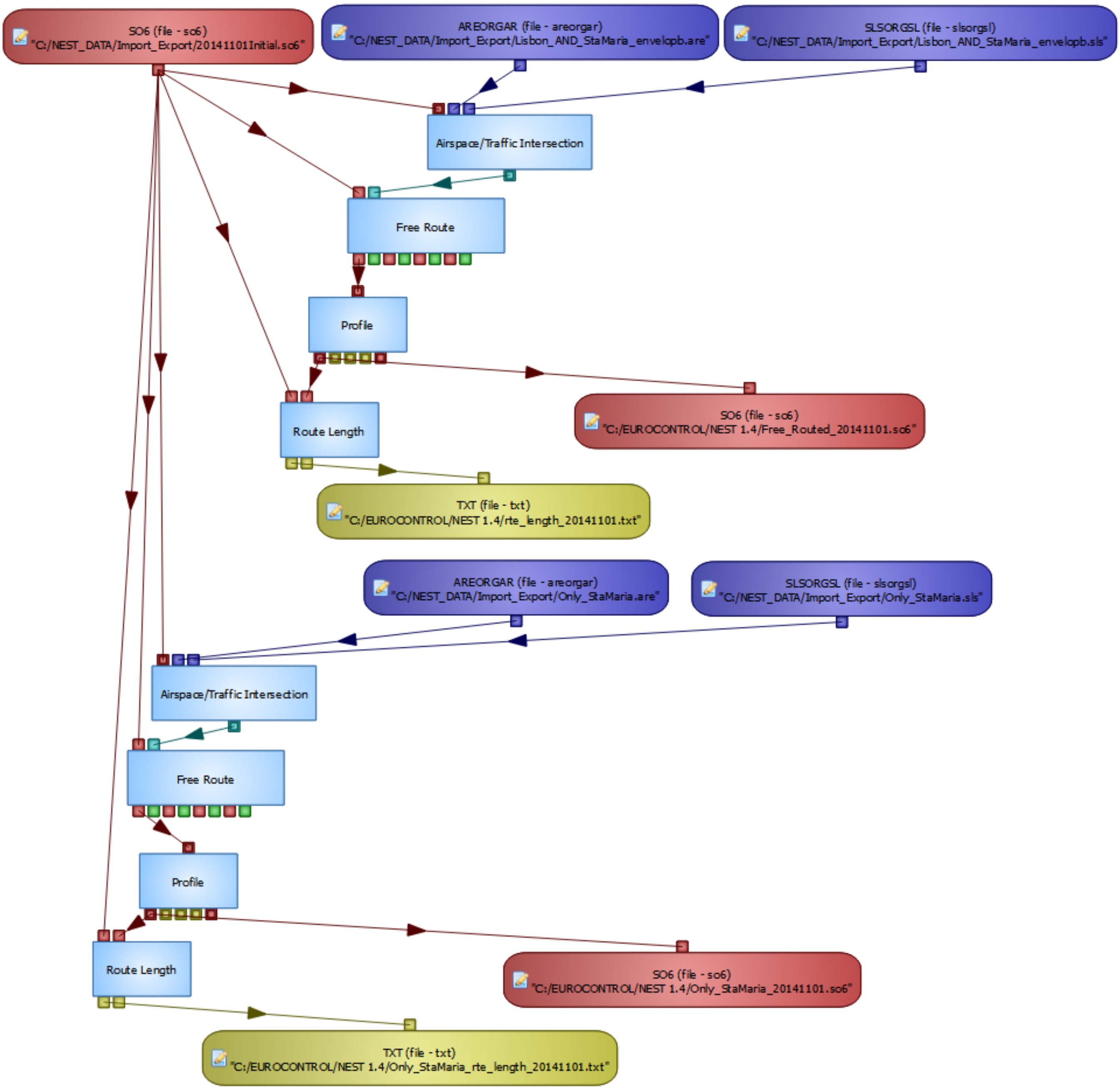

Figure 3.1: NEST - SIM Diagram

Shall be noticed that the second set (below) does exactly the same procedure as the first set (above). The main difference lies on the selected airspace as a FRA. Since there are more constraints envolved, which make impossible a direct route, than the ones that can be solved through a joint FRA, in addiction to the free routed traffic, a simulated traffic was also computed which considers the two FRAs separately.

In an ideal case, the simulated traffic would give the same results as the current traffic, however, due to different route choices because of the current winds, some sector overload or other route choice factor the current scenario cannot always meet the best theorical scenario. Therefore, as briefly mentioned before, the simulated traffic is a better term of comparision which gives a better notion of the real improvements that can be brought through a FRA.

The main processes are the following:

- The first process, Airspace/Traffic Intersection, computes 4D intersection of traffic with airspace volumes. This intersection is expressed with coordinates, flight level and time, for the entry point and the exit point. Thus, it receives as input the traffic file and the two airspace files.
- The second process, Free Route, calculates an intermediate file, used for profile calculation, with a 2D straight trajectory between entry and exit points for a particular Free Route Airspace. Therefore, receives the initial traffic file and the output of the Airspace/Traffic Intersection process as an input.
- The third process, Profile, generates a 4D trajectory file, from a 2D route file, adding time and flight level to each route point. This process support constraint data file, helping user to set departure and/or arrival and/or cruising flight level constraints for any flight or set of flights.
- The fourth process, Route Length, compares the two traffic files in terms of route length, the reference, which has the real traffic, with the scenario created. It gives as output an text file with comparisions flight by flight and overall comparisions.

The input and output files are the following:

- As an input, the traffic file (.so6), with all the flights and respective routes, for each day, that cross the defined airspace;
- As an input, the areorgar file (.are), which contains the coordinates of the chosen area to be designated as a FRA;
- As an input, the slsorgsl file (.sls), which contains the lower and upper FL (Flight Level) of volumes and association of volumes of the chosen area to be designated as a FRA;
- As an output, the traffic file (.so6), with the same list of flights given as an input, with the respective computed routes (free routed);
- As an output, a text file (.txt), with an overall comparision in terms of route length between the initial traffic file and the computed free routed traffic.

Chapter 4

Optimization Process - Navigation Points Optimization

Besides the study of the chapter 3, the navigation points on the border between the two portuguese FIRs were also studied as an intermediate step towards improving the current scenario and solving inefficiency problems. This can be achieved through a deep analysis of all flights crossing this border, the respective navigation points used and their possible relocation.

The flight path consists on a series of navigation points that the pilot needs to reach, therefore, in order to analyze the inefficiencies in the border between the two FIRs, for all flights crossing both FIRs, the respective navigation point used in the border, as well as the previous and the next one, are stored for a posterior analysis.

With the three consecutive navigation points and the equation 3.1, which computes the distance between them, it is possible to analyze the current route length, as well as the ideal length, where in an ideal scenario the pilot would go directly from the previous navigation point to the next one, crossing the border in a point alligned with the other two. However, in a realistic scenario there is a limit of navigation points to be placed in the border, thus, it would only be possible to meet the demands of the ideal scenario with a joint FRA as explained in the chapter 3.

The border currently has thirteen navigation points, as shown in the figure 1.5. By setting a limit of navigation points, and with the list of the previous and next navigation points for every case, it is possible to define the optimization process where the goal is to minimize the route length as much as it is possible by changing the current position of the navigation points, or even by adding new navigation points in a predefined position.

In addiction, NAV Portugal is currently considering the possibility of expanding the current number of navigation points from 13 to 18. Therefore, a study about those possible improvements is also performed, comparing it both to the current scenario and the optimized one as proposed.

4.1 Problem Formulation

Let X be a set of w coordinate pairs, as defined in the equation 4.1, for possible location of the navigation points in the border, defined as the variable of the optimization process.

$$X = [x_1, x_2, ..., x_{w-1}, x_w] \subset Border \tag{4.1}$$

where,

$$x_j = (\varphi_j, \lambda_j), \forall x_j \in X \tag{4.2}$$

Shall be noticed that (φ_j, λ_j) represents a coordinate pair of a border navigation point x_j, where φ_j represents the latitude and λ_j the longitude.

The quality criterion can be described by the minimization of the cost function J, defined by the equation 4.3, where the distances can be computed with the equation 3.1.

$$J = \sum_{i=1}^{K} n_i \left[distance(p_i, x_j) + distance(f_i, x_j) - distance(p_i, f_i)\right], \tag{4.3}$$

The goal is to determine the best set of X, for a given size w, so that the cost function J can be minimized to it's minimum, where in an ideal case $J = 0$.

$$p_i = (\varphi_i, \lambda_i), \forall p_i \in P \tag{4.4}$$

$$f_i = (\varphi_i, \lambda_i), \forall f_i \in F \tag{4.5}$$

$$n_i \in \mathbb{N}, \forall n_i \in N \tag{4.6}$$

Here p_i and f_i are defined as the previous and the following navigation points respectively, and n_i is defined as the number of flights in the whole sample that used this pair (p_i and f_i) of navigation points. K is defined as the size of P, F and N, which defines all the combinations of previous and following navigation points used by flights in the whole sample.

Thus, the optimization problem is defined by the minimization of the cost function 4.3, as presented in the problem 2 defined below.

Problem 2 (Border Navigation Points Location, optimisation problem)**.**

Given the performance criterion J 4.3, which uses the shortest distance between two points 3.1 and historical data stored as 4.4, 4.5, 4.6; it is defined the problem of computing the best set of coordinates $X := [x_1, ..., x_w]$ of w navigation points in the border.

$$\min_{X} \; J(P, F, N, x_1, ..., x_w)$$

$$\text{s.t.} \quad \begin{cases} X = [x_1, x_2, ..., x_{w-1}, x_w] \subset Border, \\ x_j = (\varphi_j, \lambda_j), \forall x_j \in X, \\ \text{For a fixed, and limited, navigation points in the border } (w) \end{cases}$$

In order to solve problem 2, a Matlab script has to be created which will use an optimization solver from the $OptimizationToolbox^{TM} solvers$. There are several solvers available, as well as several algorithms to apply in each solver, which should be chosen accordingly with the type of objective and constraints. In addiction, the NEST software has to be used again in order to extract all the necessary historical data.

Through a Matlab script, and with the historical data provided by NEST, the creation of the vectors P, F and N was possible, which represent the previous and following navigation points, as well as the number of flights using those routes during a six month analysis (from November 2014 until April 2015).

4.2 Interior Point Algorithm - Barrier Function

In order to properly choose the algorithm that best fits the problem, one needs to identify the type of objective function (Nonlinear) and the respective constraints (Nonlinear Inequality Constraints), which in this case led to the interior-point algorithm, which uses a barrier function, (van den Boom and Schutter [27]).

A general constrained nonlinear optimization can be specified by the equation 4.7.

$$\begin{aligned} &\min_x \quad f(x) \\ &\text{s.t.} \\ &\qquad \begin{cases} h(x) = 0 \text{ , nonlinear equalities} \\ g(x) \leq 0 \text{ , nonlinear inequalities} \end{cases} \end{aligned} \tag{4.7}$$

In the equation 4.7, h(x), and g(x) can be nonlinear functions and f(x) is a function that returns a scalar to be minimized. The main approaches to solve the optimization problem are the following, (van den Boom and Schutter [27]):

- Elimination of constraints
- Nonlinear equality contraints - using Lagrange
- Linear inequality constraints - using gradient projection
- Nonlinear inequality constraints - using barrier function or SQP (Sequencial Quadratic Programming)

In this case, since we are dealing with nonlinear inequality constraints, a barrier function or a SQP should be used. The SQP tries to approximate $f(x)$ by a quadratic function and $g(x)$ by a linear function, however, it used huge amounts of memory without the expected results. Thus, the interior-point algorithm which uses a barrier function was used with better results and satisfying bounds at all iterations.

Ideally the algorithm approximates the optimization problem as an unconstrained minimization problem shown in the expression 4.8.

$$\min_X \quad f(x) + f_{feas}(x) \tag{4.8}$$

where,

$$\begin{cases} f_{feas}(x) = 0, \quad if \quad \max\limits_i g_i(x) \leq 0 \\ f_{feas}(x) = \infty, \quad if \quad \max\limits_i g_i(x) > 0 \end{cases} \tag{4.9}$$

Since this feasibility function ($f_{feas}(x)$) is not smooth, the algorithm uses a barrier function ($f_{bar}(x)$) with the characteristics shown in 4.10.

$$\begin{cases} f_{bar}(x) \approx 0, \quad for \quad \max_i g_i(x) \ll 0 \\ f_{bar}(x) \rightarrow \infty, \quad for \quad \max_i g_i(x) \uparrow 0 \\ f_{bar}(x) \;\; undefined, \quad for \quad \max_i g_i(x) \geq 0 \end{cases} \tag{4.10}$$

The Matlab solver chosen to perform the described algorithm was the 'fmincon', (MathWorks [19]).

However, since the problem is not convex, the solver can't always recover from a local minimum, which compromisses the optimal solution without a multi-start technique. Therefore, in the next section a Global Search technique was also used to deal with this problem.

Shall be noticed that other methods were also tried before choosing a multi-start technique which is a more complex approach in terms of computational effort, however, any attempt to simplify the problem turning it in a convex problem, with a single minimum failed. The cost function 4.3, to be minimized, is a sum of several terms, multipled by a constant n_x, where each term is composed by a sum of distances expressed by the equation 3.1, which represent great circle lines.

The minimum of a sum is a non convex term, which is the presented case. Even if we could decompose all the terms, defining a fixed variable for each one, we would still get cost functions defined by a sum of distances defined by equation 3.1, again a minimum of a sum, which is a non convex term. In addiction, any attempt to simplify the equation 3.1, to make it two dimensional and more simplistic, which would be easier to work with, also failed, with results not close enough to the exact solution that would misrepresented the results.

4.3 Global Search Algorithm

In order to deal with local minimum, the Matlab Solver 'run' was chosen to find the global minimum. It is part of the Global Optimization Toolbox, which uses a Global Search class 'GlobalSearch' responsible to construct the new global search optimization solver with the desired properties.

Using the same problem structure, same optimization function, same variable and same boundaries, the main difference rely on the use of several multiple start points, where for which one the algorithm starts a local solver ('fmincon'), as shown in the figure 4.1.

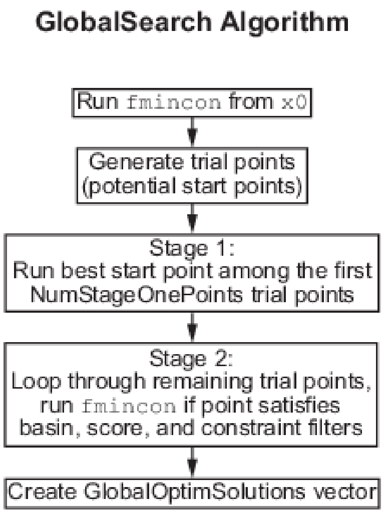

Figure 4.1: GlobalSearch Algorithm Overview (MathWorks [20])

Chapter 5

Results - Joint FRA

5.1 Case 1 - Lisbon & Sta Maria

The creation of a joint FRA in the whole portuguese airspace, as detailed explained in the chapter 3, was computed leading to results which show a considerable improvement on the current scenario.

There are more constraints envolved, which make impossible a direct route, than the ones that can be solved through a joint FRA. Thus, in addiction to the free routed traffic, a simulated traffic was also computed which considers the two FRAs separately.

In an ideal case the simulated traffic would give the same results as the current traffic, however, due to sectors overload or other congestion problems the current scenario cannot always meet the best theorical scenario, in addiction to that, due to winds or higher navigation charges in some sectors, the shortest route it's not always the cheapest route.

In short, the simulated traffic represents an ideal/theorical version of the current traffic, which can be presented as a safer and more realistic comparision to the free routed traffic (since it's also an ideal/theorical version of the proposed scenario).

Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	Total
4577	4950	5548	4811	5573	5777	31236

Table 5.1: Impacted Flights - Case 1

Based on a six month analysis with real flights, as shown in the table 5.1, and assuming an even relation in number of flights with the other six months, there are around 62500 impacted flights annually by this changes, which means that are around 62500 flights crossing both the FIR of Lisbon and Sta. Maria.

Scenario	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	Total
Current	16852535	17544800	20613150	17301875	19968048	19698391	111978800
Simulated	16818484	17539632	20537429	17250453	19895203	19656653	111697853
Free Routed	16784872	17504579	20496385	17215978	19855442	19617369	111474624

Table 5.2: Route Length (in NM) - Case 1

Splitted between this 31236 flights, and expanding the six month analysis, the proposal scenario estimates a total length reduction per year of more than 936000 nautical miles, which means an average of 15 nautical miles of length saved per flight, comparing with the current scenario.

This numbers suffer a considerable reduction when comparing the simulated scenario with the proposed scenario (free routed scenario). However the improvements are still above satisfactory, where there is a total length reduction per year of more than 446000 nautical miles, which means an average of slightly more than 7 nautical miles of length saved per flight.

Averages:	Free Routed vs Current	Free Routed vs Simulated
Length Saved Per Flight	15 NM	7 NM
Length Saved Per Day	2566 NM	1224 NM
Length Saved Per Month	78055 NM	37217 NM
Length Saved Per Year	936658 NM	446602 NM
Number of Flights Per Day	171	171
Number of Flights Per Month	5206	5206
Number of Flights Per Year	62472	62472

Table 5.3: Comparisions between Scenarios: Averages - Case 1

The difference between an ideal (Direct) route and the current route, according to the equation 5.1, can be seen in the table 5.4, which compares both scenarios. One may conclude that the proposed scenario would reduce significantly the current scenario, it wouldn't reduce this value to zero due to the fact that in most cases the joint FRA only represents a short segment of the total flight.

$$Difference_{Relative}(\%) = \frac{Real_{Route} - Direct_{Route}}{Real_{Route}} \tag{5.1}$$

Scenario	(%)
Current	2.88
Simulated	2.67
Free Routed	2.48

Table 5.4: Relative Difference between Real Route and Direct Route - Case 1

In the table 5.4, it is presented a reduction in terms of waste in 0.19% comparing with the simulated scenario, which has is value doubled (to 0.4%) if we compare with the current scenario.

This abrupt difference between the simulated traffic and the current traffic, which can't be seen in the following cases, help us realize that there are other constraints in the portuguese FIR of Sta Maria which disrupts their routes.

5.2 Case 2 - Portugal & Morocco

Now, considering the expansion of the joint FRA to the adjacent FIR of Morocco, also explained in the chapter 3, has shown again improvements over the current scenario. Again, it is been considered the whole traffic crossing the border between this two airspaces.

In this case, since this border doesn't intersect the FIR of Sta Maria, it is been considered the whole traffic crossing both the FIRs of Lisbon and Morocco.

Here, unlike the first case, the simulated traffic which represents an ideal/theorical version of the current traffic is disregarder since it didn't present any significant changes to the current scenario. Thus, the results with the simulated traffic were omitted since they complied with the results with the current traffic.

In the table 5.5 can be seen the results on the impacted flights in a six month analysis.

Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	Total
14313	16249	16249	14359	15608	14910	91688

Table 5.5: Impacted Flights - Case 2

Based on six month analysis with real flights, and assuming an even relation in number of flights with the other six months, there are around 183000 impacted flights annually by this changes, which means that are around 183000 flights crossing both the FIR of Lisbon and Morocco.

Scenario	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	Total
Current	26712746	30045949	29734836	26138480	28540812	26710849	167883671
Free Routed	26584343	29957856	29631110	26040624	28427637	26590900	167232470

Table 5.6: Route Length (in NM) - Case 2

Splitted between this 91688 flights, and expanding the six month analysis, the proposal scenario estimates a total length reduction per year of more than 1302000 NM, which means an average of slightly more than 7 nautical miles of length saved per flight, comparing with the current scenario.

Averages:	Free Routed vs Current
Length Saved Per Flight	7 NM
Length Saved Per Day	3568 NM
Length Saved Per Month	108534 NM
Length Saved Per Year	1302402 NM
Number of Flights Per Day	502
Number of Flights Per Month	15281
Number of Flights Per Year	183376

Table 5.7: Comparisions between Scenarios: Averages - Case 2

The table 5.8 shows the difference between an ideal (Direct) route and the current route according to the equation 5.1. Again, the proposed scenario would improve significantly the current scenario, reducing the current waste by 0.38%.

Scenario	(%)
Current	2.33
Free Routed	1.95

Table 5.8: Relative Difference between Real Route and Direct Route - Case 2

5.3 Case 3 - Portugal & Asturias

Finally, considering other possible expansion of the joint FRA, the adjacent FIR of Asturias was added to the FRA of the Case 1, as explained in the chapter 3. Again, the results have shown improvements over the current scenario, however, in this case, comparing with the previous cases, the computed scenario presents worst results, with only a slightly improvements over the current scenario.

Since the Asturias airspace has border with both portuguese FIRs (Lisbon and Sta Maria), the flights selected to perform this study was the whole traffic crossing both any portuguese FIR (Lisbon or Sta Maria) and Asturias, this way, it represents the whole traffic crossing the border between the Asturias airspace and the portuguese airspace.

As in Case 2, the simulated traffic which represents an ideal/theorical version of the current traffic is disregarder since it didn't present any significant changes to the current scenario. Thus, the results with the simulated traffic were omitted since they complied with the results with the current traffic.

In the table 5.5 can be seen the results on the impacted flights in a six month analysis.

Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	Total
11819	12859	12784	12003	13261	13882	76608

Table 5.9: Impacted Flights - Case 3

Based on six month analysis with real flights, and assuming an even relation in number of flights with the other six months, there are around 153000 impacted flights annually by this changes, which means that are around 153000 flights crossing both the FIR of Lisbon and Asturias.

Scenario	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	Total
Current	19981392	21658043	21854802	19803564	21650472	20572384	125520657
Free Routed	19954028	21655763	21841288	19758274	21608846	20468297	125286495

Table 5.10: Route Length (in NM) - Case 3

Splitted between this 76608 flights, and expanding the six month analysis, the proposal scenario estimates a total length reduction per year of more than 468323 nautical miles, which means an average of slightly more than 3 nautical miles of length saved per flight, comparing with the current scenario.

Averages:	Free Routed vs Current
Length Saved Per Flight	3 NM
Length Saved Per Day	1283 NM
Length Saved Per Month	39027 NM
Length Saved Per Year	468324 NM
Number of Flights Per Day	420
Number of Flights Per Month	12768
Number of Flights Per Year	153216

Table 5.11: Comparisions between Scenarios: Averages - Case 3

The table 5.12 shows the difference between an ideal (Direct) route and the current route according to the equation 5.1. In this case, the proposed scenario would improve the current scenario, reducing the current waste by 0.18%.

Scenario	(%)
Current	2.58
Free Routed	2.40

Table 5.12: Relative Difference between Real Route and Direct Route - Case 3

5.4 Joint FRA - Overview

Accordingly with the results in the three previous cases, a junction of the two current free routed portuguese airspaces, defined by the FIRs of Lisbon and Sta Maria would bring significant improvements to the current scenario in every case.

Each measure, individually, represent improvements to the current scenario, reducing the overall route length, and consequently, reduce the flight time, amount of fuel and amount of CO_2 emissions.

If we consider a full expansion of the joint FRA, encompassing the three previous cases (Lisbon, Sta Maria, Morocco and Asturias), it would affect more than 399000 flights annually, with an expected annual length reduction of more than 2217000 nautical miles, as can be seen in the table 5.13, presented below, which combines the results of the previous tables 5.3, 5.7 and 5.11.

Averages:	Lisbon & Sta Maria	with Morocco	with Asturias	TOTAL
Length Saved Per Flight	7 NM	7 NM	3 NM	6 NM
Length Saved Per Day	1224 NM	3568 NM	1283 NM	6075 NM
Length Saved Per Month	37217 NM	108534 NM	39027 NM	184777 NM
Length Saved Per Year	446602 NM	1302402 NM	468324 NM	2217328 NM
Number of Flights Per Day	171	502	420	1093
Number of Flights Per Month	5206	15281	12768	33255
Number of Flights Per Year	62472	183376	153216	399064

Table 5.13: Comparisions between Scenarios: Overall Averages

Shall be noticed that the results in the table 5.13 represent a comparision between the computed (free routed) traffic and the simulated traffic (which simulates a theoretical scenario of the current traffic).

In order to give a better insight on the results, an example for each case is presented in the figures 5.1, 5.2, 5.3. Here, both the current route (in red) and the new computed route (in green) are presented, where the improvements brought by the implementation of the FRA are visible.

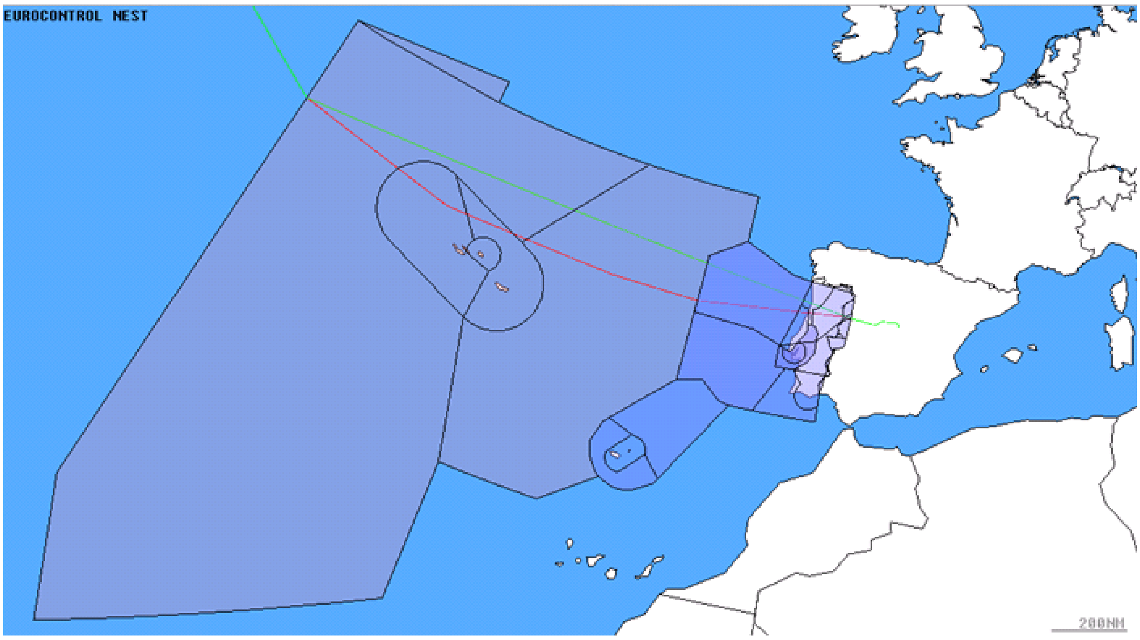

Figure 5.1: Flight Route - Example Case 1 (Flight ID: IBE6251)

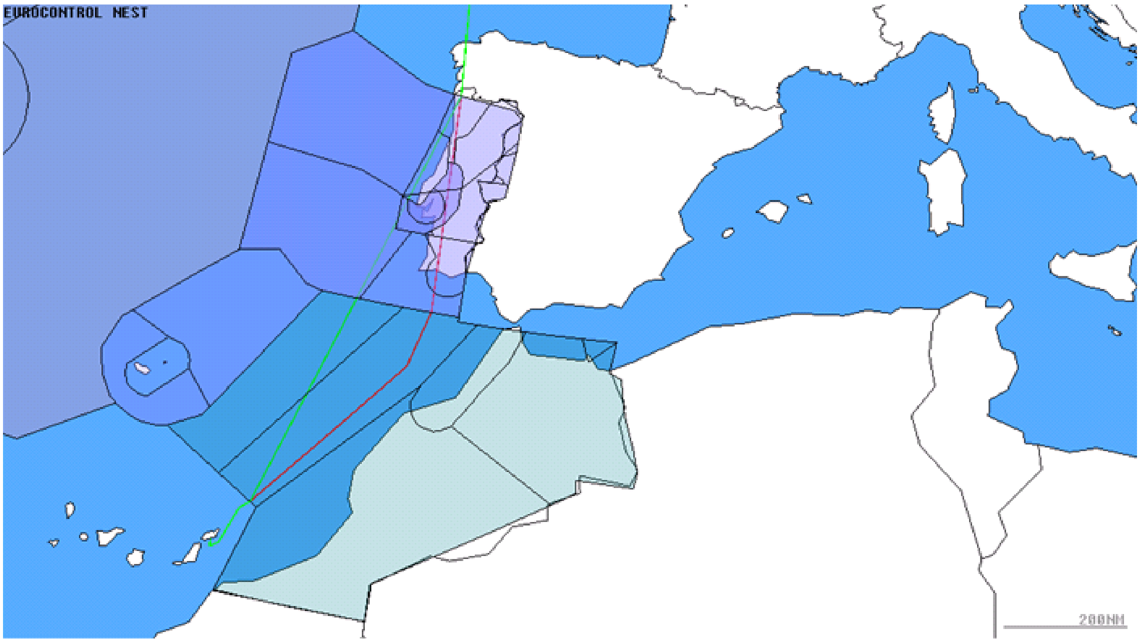

Figure 5.2: Flight Route - Example Case 2 (Flight ID: NAX9528)

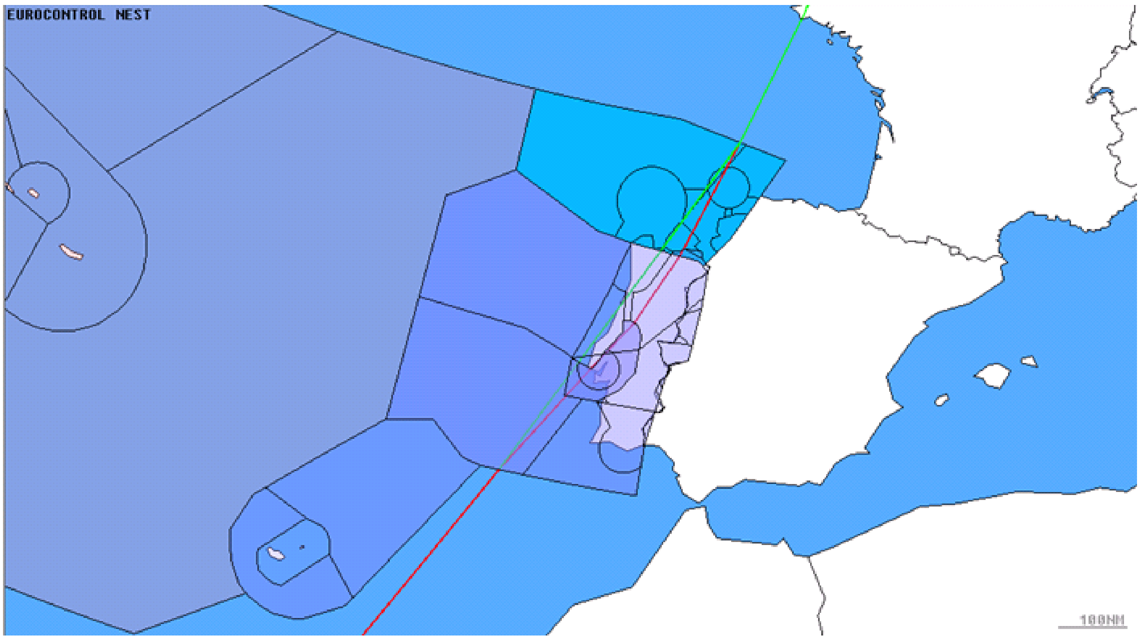

Figure 5.3: Flight Route - Example Case 3 (Flight ID: VKG6635)

Chapter 6

Results - Navigation Points Optimization

6.1 Border Navigation Points

The analysis of the Border between the two portuguese FIRs, as explained in the chapter 4, was computed based on six months of historical data, from November of 2014 until the end of April of 2015.

During this six months, 31236 flights crossed the border between the two portuguese FIRs, using more than 1500 different routes. The results shown that the current arrangement of navigation points in this border can be improved, either from adding few more navigation points or just by optimizing the position of the current ones.

Using an optimization solver from Matlab, $fmincon$, with a Global Search class, to deal with local minimum, and the algorithm $InteriorPoint$, which best suited the problem, the results obtained for several values of w are presented in the table 6.1.

Scenario	Cost Function J
Current ($w = 13$)	348.95
Proposed by NAV ($w = 18$)	178.76
Computed, with $w = 8$	760.83
Computed, with $w = 9$	586.98
Computed, with $w = 10$	443.29
Computed, with $w = 11$	357.22
Computed, with $w = 12$	302.22
Computed, with $w = 13$	256.22
Computed, with $w = 14$	223.51
Computed, with $w = 15$	188.45
Computed, with $w = 18$	141.81
Computed, with $w = 20$	129.67
Computed, with $w = 25$	73.78
Computed, with $w = 30$	51.90
Computed, with $w = \infty$	8.33

Table 6.1: Cost Function Values

Shall be noticed that w refers to the number of navigation points in the border.

The cost function J, has as minimum, and optimal value, zero, which represents the best scenario where the route could go straight from the previous navigation point through the following navigation point without any need to deviate from this route to pass through a defined navigation point in the border. Thus, the joint FRA, explained in the chapter 3, would reach this optimal value ($w = \infty$). This value is not zero due to the fact that some flights in an ideal case wouldn't pass by the border, they would pass below or lower, however, they choose a longer route due to higher navigation charges in the adjacent airspaces (e.g. Canarias).

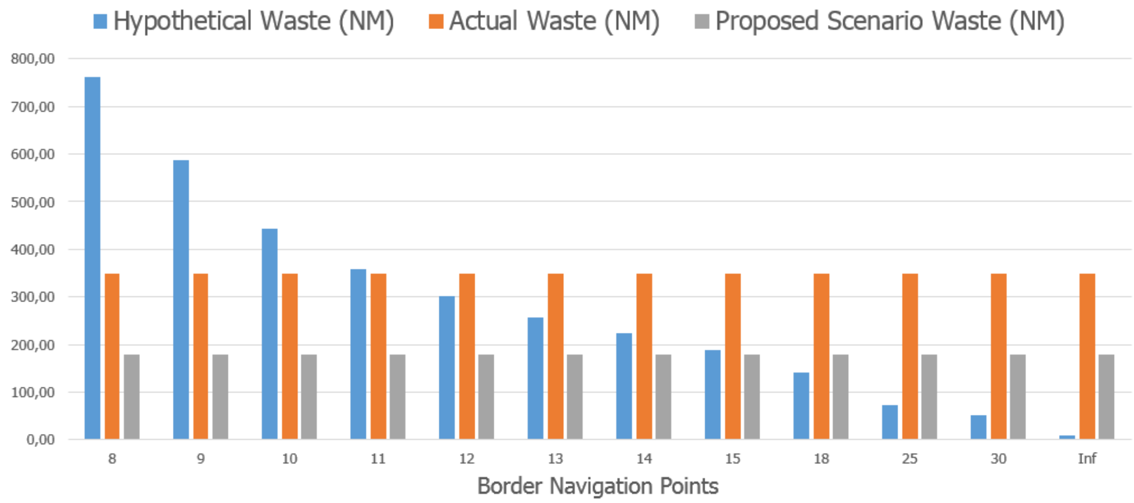

Figure 6.1: Current vs Other Scenarios: Waste (in NM)

Shall be noticed that the route waste, and consequently the cost function, is only analyzed between the previous and following navigation points, in relation to the border. If we expand the same method to further navigation points, the current improvements will deeply increase.

Analyzing the computed values of the cost function presented in the table 6.1, and consequently the figure 6.1, one can easily conclude that the current scenario can be improved. With only eleven navigation points (the current scenario has thirteen) it's possible to have a scenario close to the current one in terms of efficiency. In addiction, just by optimizing the current position of the current navigation points an improvement of 27% can be expected.

The scenario that is being proposed by NAV, which wants to add five more navigation points, would result in an improvement of 49%. With a scenario focused on the current traffic, just by rearranging this eighteen navigation points, this improvements could increase to 59%. This improvements in terms of percentage can be analyzed in the figure 6.2, which basically use the equation 6.1 presented below.

$$Waste_{Relative}(\%) = \frac{Current_{Waste} - Scenario_{Waste}}{Current_{Waste}} \tag{6.1}$$

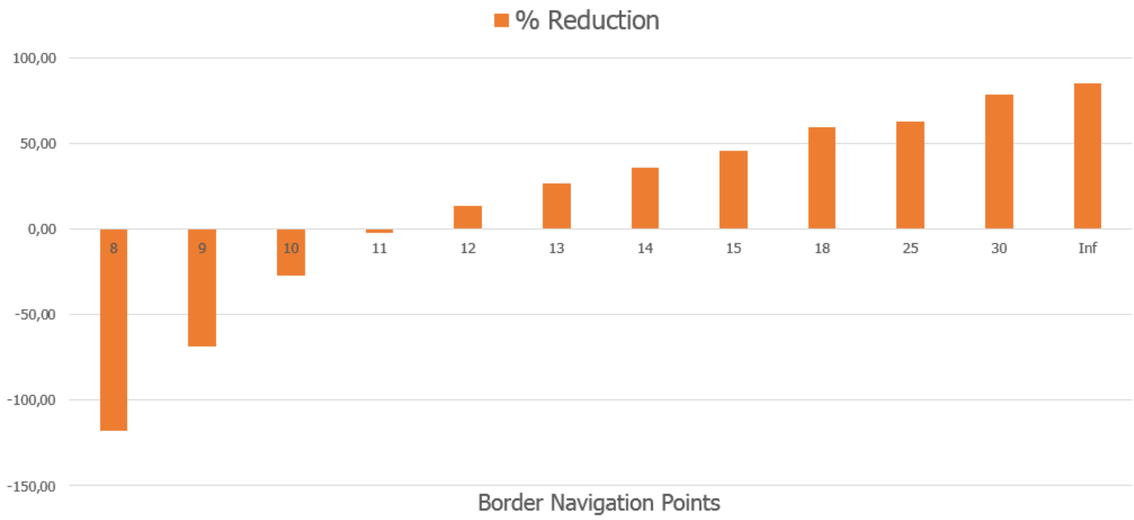

Figure 6.2: % of Waste Reduction, as a function of the number of border navigation points

As can be seen in the figure 6.2, in an ideal case, with $w = \infty$, the improvement expected would be of almost 98% with only a waste of 8.33 NM against an current waste of 348.95 NM. This scenario could be achieved through a joint FRA as explained in the chapter 3, since the flights could cross the border freely.

Therefore, the ultimate goal should be to work towards a joint FRA. However, in the mean time, the scenario proposed by NAV, which adds five more navigation points, could introduce an improvement of 49% which already ensures great benefits. The computed scenarios, which find an ideal location for the border navigation points, besides bringing good improvements, would require a higher level of changes since all the border navigation points would have to be replaced.

Now, three examples are given in order to better understand the source of inefficiencies in the border. Again, both the current traffic (in red) and the shortest possible route (in green) are presented.

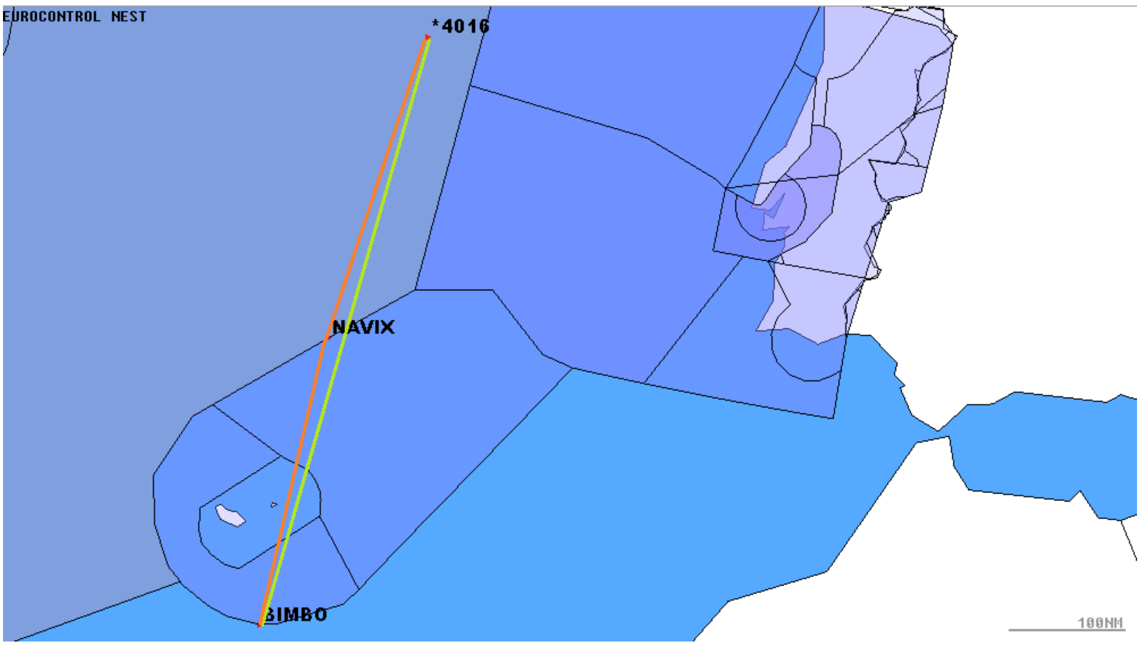

Figure 6.3: Flight Route - Border Navigation Points - Example 1

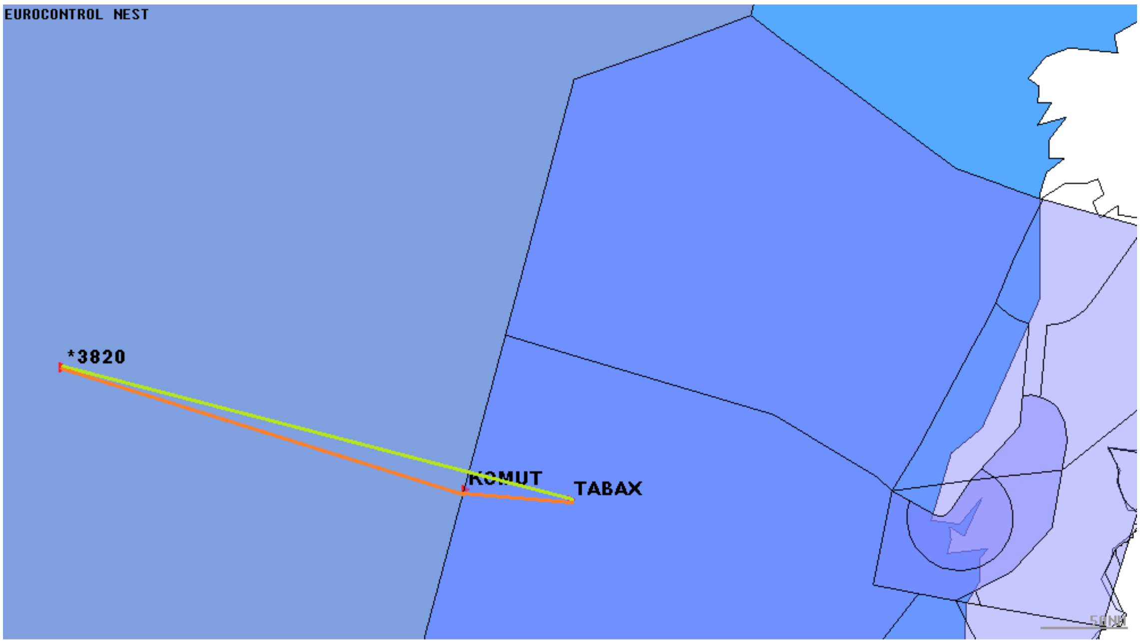

Figure 6.4: Flight Route - Border Navigation Points - Example 2

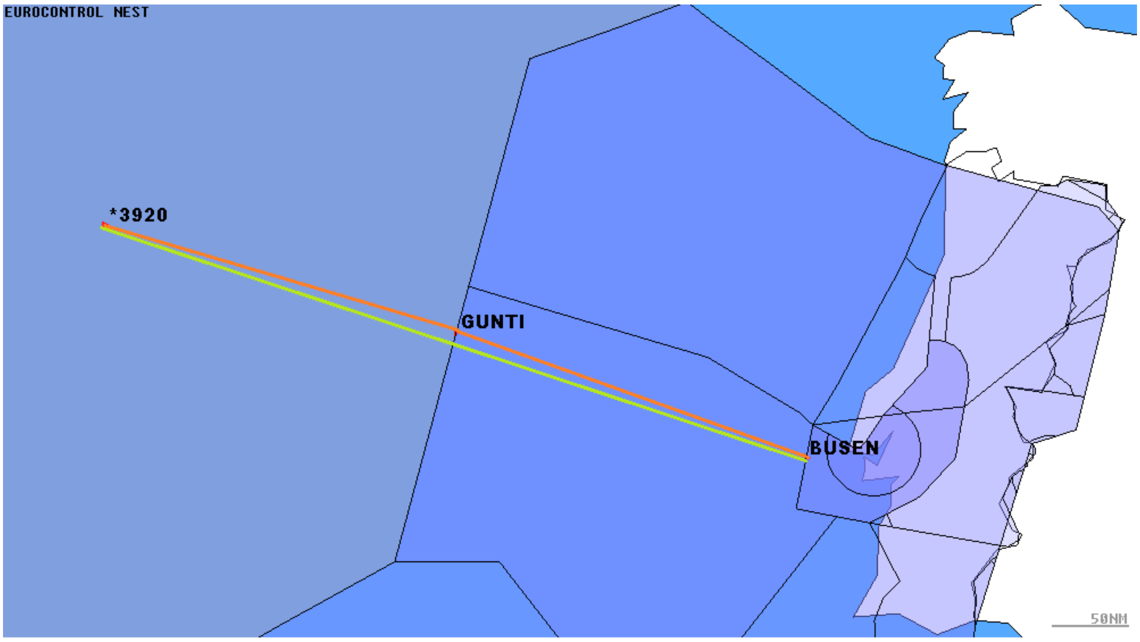

Figure 6.5: Flight Route - Border Navigation Points - Example 3

In all the presented examples the deviation can be considered small. However, only in this six month analysis, this routes were chosen by hundreds of flights which considerly increase the effect of this inefficiencies. Considering each of them individually, they were chosen by 1455 (figure 6.3), 963 (figure 6.4) and 669 (figure 6.5) flights.

6.2 Border Navigation Points - Coordinates

In order to give a better insight on the results, the position of the navigation points in the border between the two portuguese FIRs are now analyzed. Currently the border has thirteen navigation points, as shown in the figure 1.5, and their respective coordinates can be seen in the table 6.2.

Name	Latitude	Longitude
RETEN	43.00°	-13.00°
ARMED	42.50°	-14.00°
BANAL	42.00°	-15.00°
DETOX	41.00°	-15.00°
ERPES	40.00°	-15.00°
GUNTI	39.00°	-15.00°
KOMUT	38.00°	-15.00°
LUTAK	37.00°	-15.00°
MANOX	36.19°	-15.39°
NAVIX	35.52°	-16.23°
IRKID	33.93°	-18.07°
ABALO	32.33°	-18.13°
NELSO	31.68°	-17.46°

Table 6.2: Current Navigation Points (in degrees)

The proposal of NAV Portugal, which adds five more navigation points can be seen in the figure 6.6, and their respective coordinates can be seen in the table 6.3. The additional navigation points do not have any official name, thus, just for this study they were named *NAV1*, *NAV2*, *NAV3*, *NAV4* and *NAV5*. This navigation points were strategically placed exactly in the middle of the current navigation points, in the region with more traffic (the vertical line with -15°of longitude) in order to reduce the current need for deviations and avoid congestions.

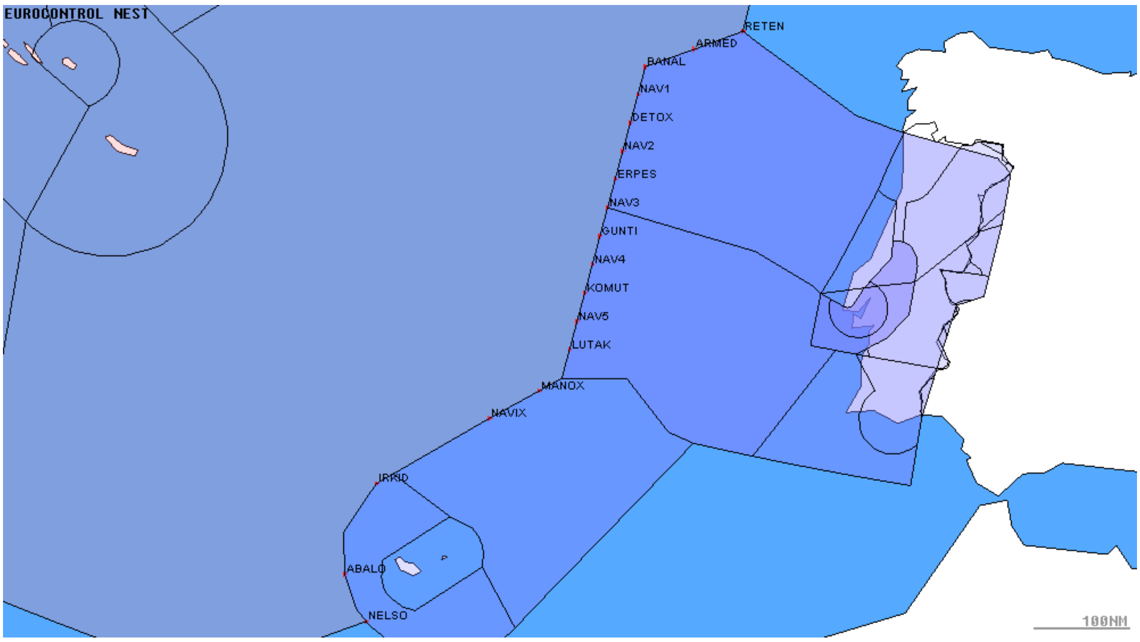

Figure 6.6: NAV Proposal Navigation Points - Border between the two portuguese FIRs

Name	Latitude	Longitude
NAV1	41.50°	-15.00°
NAV2	40.50°	-15.00°
NAV3	39.50°	-15.00°
NAV4	38.50°	-15.00°
NAV5	37.50°	-15.00°

Table 6.3: NAV Proposal - Additional Navigation Points (in degrees)

Now, considering the analysis of the optimized navigation points, computed by the optimization problem, and for the sake of simplicity, we will only consider the case with thirteen navigation points ($w = 13$).

In the figure 6.7 can be seen the navigation points, while the concrete value of their coordinates are specified in the table 6.4. Shall be noticed, that again, the new navigation points do not have any official names, thus, just for this study they were named *OPT1*, *OPT2*, *OPT3*, ... until *OPT13*.

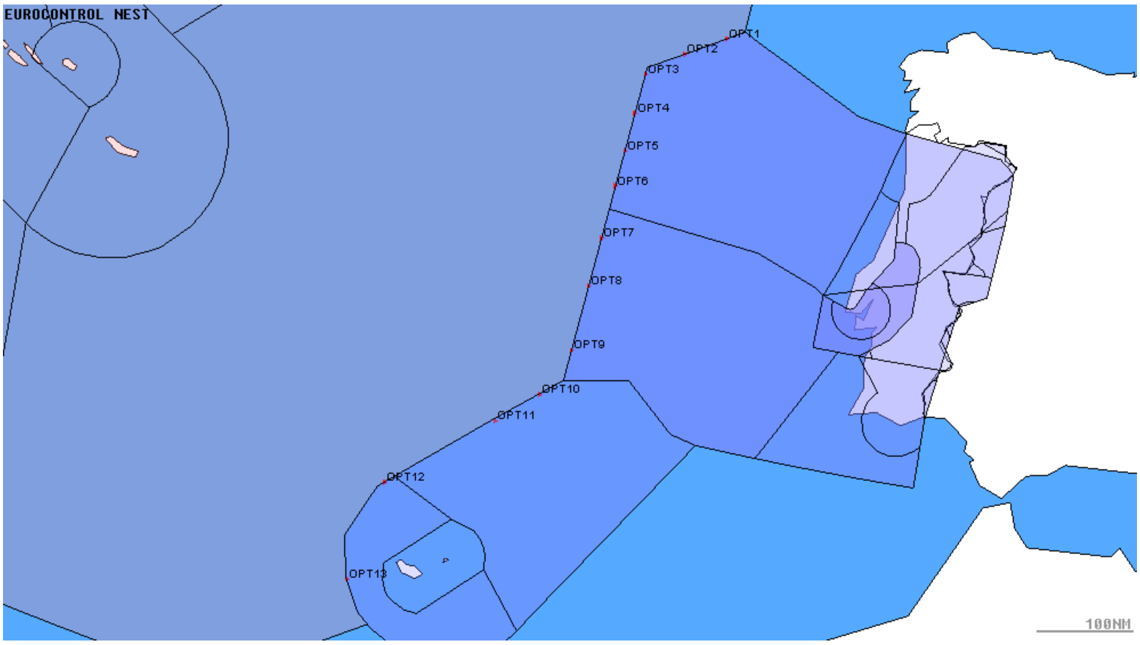

Figure 6.7: Optimized Navigation Points ($w = 13$) - Border between the two portuguese FIRs

Remembering that the cost function 4.3, defined in the chapter 4, is multipled by the term n_x, which gives more importance to the most common routes, one can easily see that the amount of traffic in the upper half of the border (mainly in the vertical line at -15°of longitude) is way higher than the amount of traffic in the lower half. It can be seen due to the position of the optimized navigation points, which are way closer to each other, in order to avoid unnecessary deviations, in the upper half of the border.

This thicker pattern in the upper half could be observed in all sets of computed navigation points, and also goes in agreement with the NAV proposal which aims to enduce a thicker pattern in that upper half (a navigation point at every half a degree) while the rest keeps the same distance (with a navigation point at every degree).

Name	Latitude	Longitude
OPT1	42.81°	-13.38
OPT2	42.38°	-14.23
OPT3	41.88°	-15.00
OPT4	41.19°	-15.00
OPT5	40.52°	-15.00
OPT6	39.91°	-15.00
OPT7	38.99°	-15.00
OPT8	38.15°	-15.00
OPT9	37.02°	-15.00
OPT10	36.16°	-15.40
OPT11	35.53°	-16.15
OPT12	34.03°	-17.95
OPT13	32.30°	-18.10

Table 6.4: Optimized Navigation Points ($w = 13$) (in degrees)

Chapter 7

Conclusion

In this work the topic of FRA for route optimization is addressed, showing that a considerable improvement can be achieved through an expansion of the current FRA.

7.1 Summary & Conclusions

Just considering the portuguese airspace, and by expanding the FRA to both portuguese FIRs (Lisbon and Sta Maria), can be expected savings of almost half a million nautical miles per year, which means an average of 7 nautical miles saved per flight (table 5.3). By expanding this research, adding the adjacents airspaces of Morocco and Asturias a total of more than two million nautical miles per year is expected to be saved (table 5.13).

With this results in mind, and following the worldwide trends, this thesis highlights that a special effort should be made in order to expand the areas designated as FRA, leading to shorter routes which would consequently lead to shorter flights, with lower levels of burnt fuel and lower CO_2 emissions

In addiction to the study of the FRA for route optimization, the border between the two portuguese FIRs was analyzed, showing that it's indeed a cause for inefficiencies in the portuguese airspace (figure 6.1).

In an ideal scenario, this inefficiencies could be completely eliminated through the expansion of the FRA to the whole portuguese airspace as proposed in this thesis. However, in the meantime, by adding five navigation points in this border (with latitudes in degrees of 37.5, 38.5, 39.5, 40.5 and 41.5), to a total of eighteen navigation points, an improvement of almost 50% could be expected (table 6.1).

This scenario is far from optimal, as shown in this thesis, where almost the same results achieved with this scenario could be achieved with only fifteen navigation points (table 6.1) if the border navigation points were restructured and optimized for the current traffic needs. However, it represents a way simpler scenario to implement, which is already being considered by NAV Portugal, which can improve the current results until a total FRA can be achieved.

It is important to notice that the optimization problem was defined to give insight on the current main inefficiencies of the border between the two portuguese FIRs (Lisbon and Sta Maria). Due to the fact that all flights when crossing that border, need to do it precisely at one of the thirteen navigation points available (table 6.2), one can conclude that would implicity require deviations on the flight, and therefore, would generate a longer route, which burns more fuel, and consequently leads to a less efficient route with higher operating costs.

Solving the optimization problem, defined by the cost function 4.3, one can conclude that this implicity required deviations could be significantly reduced by optimizing the border navigation points to the current traffic flows. This solution is versatile, and could adapt completely to any changes in the current traffic flows. In fact, with this optimization process, it would be possible to adjust in real-time the position of the border navigation points to any traffic set, where the number of border navigation points wanted can be defined freely by the user.

Ultimately, this solution could only achieve its maximum value with infinite border navigation points, where there is no need for any deviation on the flight since there is always a border navigation point in the exact position needed by each flight. Having infinite border navigation points is not feasible, however, this represents a border with a complete free route, which is what a joint FRA to the whole portuguese airspace stands for.

7.2 Recommendations

By studying the air traffic management paradigm, and knowing that nowadays the aircrafts, in order to flight safely, do not need to fly between beacons anymore, one can easily conclude that the ideal scenario would be to work towards a global free route airspace. With this premise in mind, and by looking at the results we suggest the expansion of the current FRAs as further as possible.

Since the whole portuguese airspace, with both FIRs of Lisbon and Sta Maria are regulated by the same entity (NAV Portugal), we recommend to start all the procedures in order to work towards a joint FRA in the whole portuguese airspace.

With a joint FRA in the whole portuguese airspace, and after a complete restructuration in the airspace, negociations with the adjacent airspaces (Morocco and Asturias) could start in order to improve even more the current scenario, with an ultimate goal in mind to reduce the flight distances, time and fuel spent, and consequently reduce the current costs and CO_2 emissions.

Knowing that a considerable change in the portuguese airspace might take some time, which might have heavy bureaucratic load associated with the need of a deep restructuration of the current paradigm, the current navigation points in the border between the two portuguese FIRs can suffer some modifications, working as an intermediate step towards a joint FRA.

Looking to this border, we would suggest NAV Portugal to proceed with the current hypothesis of adding strategically five more navigation points. This hypothesis is a simple and economical solution, which we believe to be the best short term solution. Using the optimized navigation points computed, would change all the border navigation points, bringing more obstacles without major improvements comparing with the current hypothesis.

7.3 Future Work

This work opens and suggests some challenges for future research. Here are pinpointed the research fields that we believe to be more interesting.

- The expansion of the current FRA to the whole portuguese airspace would cause major changes in the current traffic flow, therefore, an analysis to the current sectors would be needed where might be need some restructuration in order to ensure that all the sectors can support the incoming traffic changes.

- In addiction to some sector restructuring, it would be interesting to analyze the air traffic controllers workload, mainly due to potential conflicts and how the conflict detection is being made. As explained in the chapter 2, there is one of the issues which is slowing down the expansion of the FRA. In a FRA the traffic can come from any direction, thus, potential conflicts can occur in any point of the sector, while in a conventional airspace the flights follow designated pathways, and the potential conflicts would only occur in the intersection points between those pathways.

- The results shown in this thesis are solid, however, there are other route choice factors besides the distance, such as the winds or the route charges, as explained in the chapter 2, which would introduce new variables to this study. With this in mind, a new state of the art analysis could be made with the latest information on the forecast winds and route charges to compute the optimal route at each time instant, with this knowledge it's also possible to correlate all the flight routes in order to detect possible conflicts and avoid them.

Bibliography

[1] Steve Altus. Effective flight plans can help airlines economize. *AEROMAGAZINE, Boeing*, 2009. URL `http://www.boeing.com/commercial/aeromagazine/articles/qtr_03_09/article_08_1.html`.

[2] Arthur E. Bryson and Yu-Chi Ho. *Applied Optimal Control*. Taylor & Francis Group, 1975. URL `http://e.guigon.free.fr/rsc/book/BrysonHo75a.pdf`.

[3] Razvan Bucuroiu. Status of free route airspace developments. *Eurocontrol*, 2013. URL `https://www.eurocontrol.int/sites/default/files/rich_block/content/documents/events/Presentations/130124-uf-osd-free-route-airspace.pdf`.

[4] Razvan Bucuroiu. Free route airspace deployed in europe, June 2015. URL `https://www.eurocontrol.int/news/free-route-airspace-deployed-europe`.

[5] Esther Calvo, José Manuel Cordero, Luis D'Alto, Javier López-Leonés, Miguel Vilaplana, and Marco La Civita. A new method to validate the route extension metric against fuel efficiency. *ATM Seminar*, 2015. URL `http://www.atmseminar.org/seminarContent/seminar11/papers/460-Calvo_0126150243-Final-Paper-5-7-15.pdf`.

[6] Luis Delgado. European route choice determinants. *ATM Seminar*, 2015. URL `http://atmseminarus.org/seminarContent/seminar11/papers/487_Delgado_0126150532-Final-Paper-4-30-15.pdf`.

[7] EASA. *ATPL Ground Training Series - Navigation 1 - General Navigation*. Oxford aviation academy, 2008.

[8] EUROCONTROL. Eight-states free routes airspace project large scale real time simulations, south scenario, eec. *Experimental Centre, Report No 363 and 365*, 2001.

[9] Eurocontrol. European single sky implementation plan - edition 2014, 2014. URL `http://www.eurocontrol.int/sites/default/files/publication/files/pepr-essipplan2014-released.pdf`.

[10] Eurocontrol. Local single sky implementation portugal - year 2014 - level 1, 2014. URL `https://www.eurocontrol.int/sites/default/files/content/documents/official-documents/reports/lssip2014-portugal.pdf`.

[11] Eurocontrol. European single sky implementation. *Eurocontrol*, 2015. URL `http://www.eurocontrol.int/publications/european-single-sky-implementation-essip-plan-edition-2014`.

[12] Eurocontrol. Nest modeling tool, June 2015. URL `https://www.eurocontrol.int/services/nest-modelling-tool`.

[13] Dan Howell, Michael Bennett, James Bonn, and Dave Knorr. Estimating the en route efficiency benefits pool. *ATM Seminar*, 2003. URL `http://www.atmseminar.org/seminarContent/seminar5/papers/p_023_MPM.pdf`.

[14] Matthew Jardin. Real-time conflict-free trajectory optimization. *ATM Seminar*, 2003. URL `http://www.atmseminar.org/seminarContent/seminar5/papers/p_027_TFO.pdf`.

[15] Thomas Kircher and Philippe Trouslard. Simulated free routing operations in the marseille uir: Results and issues from a human factors perspective. *ATM Seminar*, 2005. URL `http://www.atmseminar.org/seminarContent/seminar6/papers/p_033_HF.pdf`.

[16] Gaétan Marceau, Pierre Savéant, and Marc Schoenauer. Strategic planning in air traffic control as a multi-objective stochastic optimization problem. *CoRR*, abs/1309.3917, 2013. URL `http://arxiv.org/abs/1309.3917`.

[17] V. Martin, S. Vicent, T. Champougny, and R. Bucuroiu. Airspace design and capacity planning - nest. 2012.

[18] V. Martin, A. Dixon, T. Rabillard, N. Boulin, A. Lindberg, and D. Deschaume. *NEST User Guide 1.3*. Eurocontrol, 2013-2014.

[19] MathWorks. Find minimum of constrained nonlinear multivariable function - fmincon, June 2015. URL http://www.mathworks.com/help/optim/ug/fmincon.html.

[20] MathWorks. How globalsearch and multistart work, July 2015. URL http://www.mathworks.com/help/gads/how-globalsearch-and-multistart-work.html#bsc9eec.

[21] MATLAB. Great circle, September 2015. URL http://www.mathworks.com/matlabcentral/mlc-downloads/downloads/submissions/37652/versions/4/screenshot.png.

[22] Elisabeth Modin and Dirk Schafer. A human factors perspective on free routing and airborne separation assurance in the mediterranean airspace. *ATM Seminar*, 2003. URL http://www.atmseminar.org/seminarContent/seminar5/papers/p_064_HF.pdf.

[23] Tom G. Reynolds. Analysis of lateral flight inefficiency in global air traffic management. *8th AIAA Aviation Technology, Integration and Operations Conference, Anchorage, Alaska, 14-19 September 2008*, 2008. URL http://old-www.arct.cam.ac.uk/Documents/ATIO2008_FlightInefficiency.pdf.

[24] Skybrary. Free route airspace, June 2015. URL http://www.skybrary.aero/index.php/Free_Route_Airspace_(FRA).

[25] Manuel Soler, Alberto Olivares, Ernesto Staffetti, and Pierre Bonami. En-route optimal flight planning constrained to pass through waypoints using minlp. *ATM Seminar*, 2011. URL http://www.atmseminar.org/seminarContent/seminar9/papers/90-Soler%20Arnedo-Final-Paper-4-15-11.pdf.

[26] Banavar Sridhar, Neil Y. Chen, Hok K. Ng, Olga Rodionova, Daniel Delahaye, and Florian Linke. Strategic planning of efficient oceanic flights. *ATM Seminar*, 2015. URL http://www.atmseminar.org/seminarContent/seminar11/papers/355_Sridhar_1222140649-Final-Paper-4-20-15.pdf.

[27] Ton van den Boom and Bart De Schutter. *Optimization in Systems and Control (Lecture Notes for the Course SC 4091)*. TU Delft, 2011.