Free Route Airspace for Route Optimization
Master Thesis

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Abstract

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 security standards and the bureaucratic and historical load, it is extremely difficult to choose the most efficient itinerary. 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 Flight Information Regions (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.

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 actual scenario, reducing the distance, time and fuel spent, and consequently reduce the current costs.

Keywords – Air Traffic Management (ATM), Free Route Airspace (FRA), Route Optimization

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1. Introduction

Nowadays, it is widely recognised that the actual air traffic management system will not be able to accommodate the air transportation growth at some level. Thus, further capacity enhancements will be required, which may only be possible through a restructuration of the actual air traffic management paradigms, [8].

In order to improve the current scenario, and with the need for route optimization, the actual sources of inefficiencies in the air transportation need to be addressed. Accordingly to [6], there are five categories of sources of inefficiency in en route airspace in the United States (US), which can be seen in the figure 1.

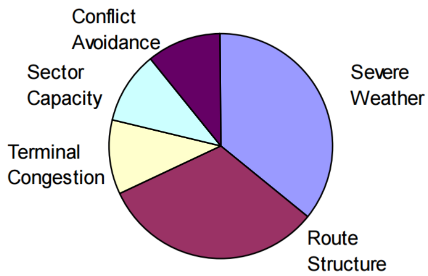

Figure 1: Enroute inefficiency sources in the US, [6].

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, which we believe that can be achieved through a joint FRA.

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, reducing the flight time, CO_2 emissions and fuel waste, while 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.

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.

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. Thus, 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 [6].

The shortest possible route between two points is defined as a great circle line, which can be seen in the figure 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, in the representation of the earth one can indeed see that the great circle line is the shortest possible route instead of the rhumb line (keeps azimuth constant).

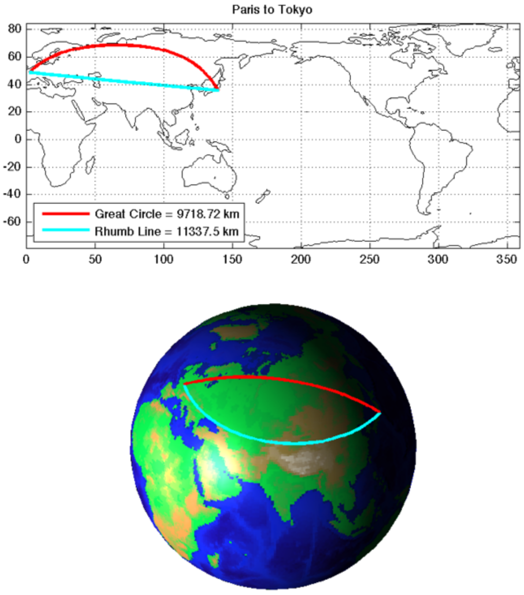

Figure 2: Great Circle Line - Example Paris to Tokyo (MATLAB [11])

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, [5]. The restructuration of the European airspace has become an urgent needwith the pressure to ensure the creation of additional capacity and improved efficiency. 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, [2]. 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, [1].

Considering the portuguese airspace, there are two different FIRs, Lisbon and Sta. Maria, which independently work as FRA. With the eminent need to improve the actual 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 3);

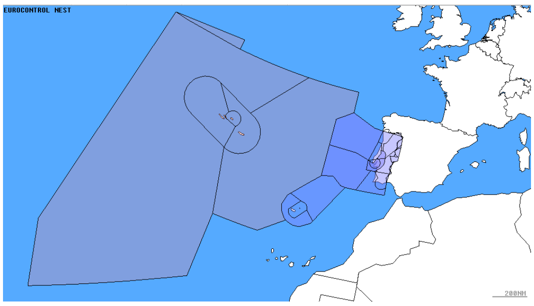

Figure 3: Joint FRA

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 4);

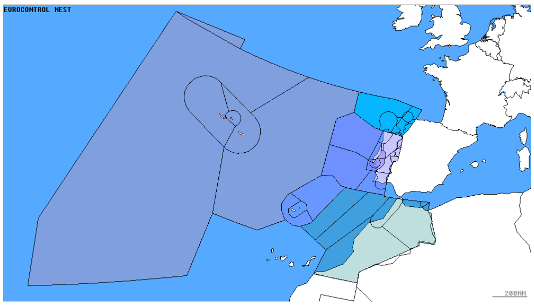

Figure 4: Expanded Joint FRA

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

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.

This paper consists in eight sections organised as follows. Section I introduces the topic and states the contributions of this work. Section II provides an overview of the relevant literature. Section III discusses possible implementations and formally states the problem of the joint FRA. Section IV formulates the optimisation process, to improve the current navigation points. Section V and VI presents the simulation results. Section VII concludes the thesis giving a summary of the obtained results. Finally, Section VIII gives relevant recommendations to further studies on the area.

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.

In the literature several authors have been supporting free routed traffic. Accordingly to an analysis performed in the US, [7], 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 addiction, the results of the study [6], also performed in the US, 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.

Europe has been following the same line of though, again the literature has been supporting the expansion and further implementations of a FRA. [8] studied the potential application of the FRA concept in the mediterranean airspace, where there was evident the improvements in terms of efficiency. 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, [8].

Apart from the difficulty of changing the air traffic procedures, direct routings between origin and destination are preferable for economic and environmental reasons, where accordingly to [4], a 3% reduction in track miles could occur through the application of free routing.

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 actual 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.

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 actual scenario, where the differences in terms of route length between the two scenarios can be analyzed.

The length of the shortest route between the two given points, described by a great circle line, can be computed using the expression (1), which uses the haversine function, (EASA [3]):

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

where,

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

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.

As mentioned before, this thesis studies actual 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 actual scenario, 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 actual scenario, [9].

3.1. NEST Tool

First of all, the airspace to be free routed has to be chosen. 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, 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 simulated and 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 both a simulated traffic file and a free routed traffic file in the chosen airspace. Also as output, a text file is generated which compares, flight by flight, the scenarios in terms of route length.

The SIM diagram, for the joint FRA in the whole portuguese airspace, is presented in the figure 5, which have two sets, each of them with four main processes, three inputs files and two output files.

In an ideal case, the simulated traffic would give the same results as the actual traffic, however, due to different route choices because of the current winds, some sector overload or other route choice factor the actual 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

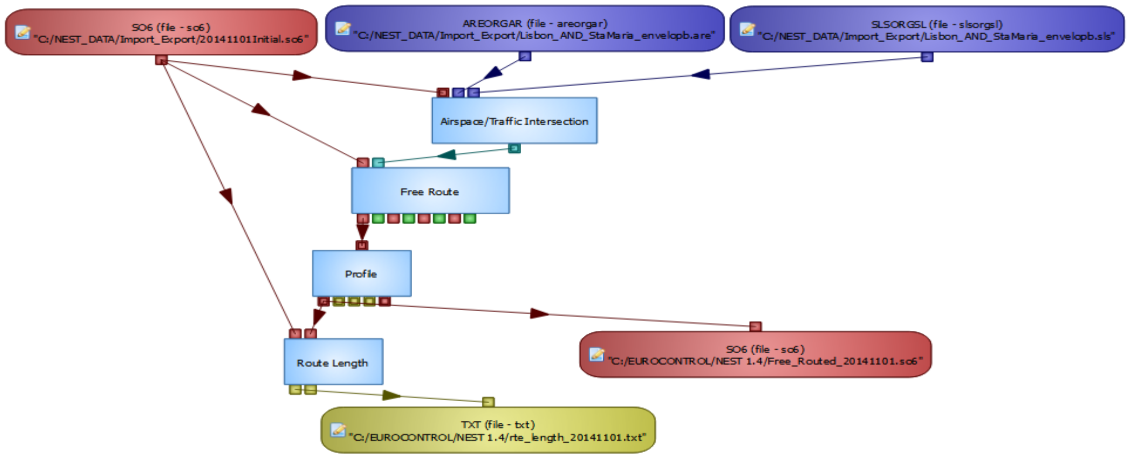

Figure 5: NEST - SIM Diagram

brought through a FRA.

The first process, Airspace/Traffic Intersection, computes 4D intersection of traffic with airspace volumes. 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. The third process, Profile, generates a 4D trajectory file, from a 2D route file, adding time and flight level to each route point. The fourth process, Route Length, compares the two traffic files in terms of route length.

4. Optimization Process - Navigation Points Optimization

In this section the navigation points on the border between the two portuguese FIRs can be studied as an intermediate step towards improving the current scenario and solving inefficiency problems. 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, 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, it is possible to analyze the actual 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 before. The border currently has thirteen navigation points, and by setting a limit of navigation points, 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.

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

4.1. Problem Formulation

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

$$X = [x_1, x_2, \ldots, x_{w-1}, x_w] \subset Border \quad (3)$$

where,

$$x_j = (\varphi_j, \lambda_j), \forall x_j \in X \quad (4)$$

Shall be noticed that (φ_j, λ_j) represents a coordinate pair of 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, where the distances ($dist$) can be computed with the equation (1).

$$J = \sum_{i=1}^{K} n_i \left[dist(p_i, x_j) + dist(f_i, x_j) - dist(p_i, f_i) \right], \quad (5)$$

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 $J = 0$.

$$p_i = (\varphi_i, \lambda_i), \forall p_i \in P \tag{6}$$

$$f_i = (\varphi_i, \lambda_i), \forall f_i \in F \tag{7}$$

$$n_i \in \mathbb{N}, \forall n_i \in N \tag{8}$$

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.

In order to solve this problem, 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 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), which in this case led to the interior-point algorithm, which uses a barrier function, [12].

In this case, since we are dealing with nonlinear inequality constraints, a barrier function should be used. Thus, the interior-point algorithm was used, satisfying bounds at all iterations.

Ideally the algorithm approximates the optimization problem as an unconstrained minimization problem shown in the expression (9).

$$\min_X \quad f(x) + f_{feas}(x) \tag{9}$$

where,

$$\begin{cases} f_{feas}(x) = 0, if \quad \max_i g_i(x) \le 0 \\ f_{feas}(x) = \infty, if \quad \max_i g_i(x) > 0 \end{cases} \tag{10}$$

Since this feasibility function is not smooth, the algorithm uses a barrier function $f_{bar}(x)$ to ensure that the constraints are met at each iteration. The Matlab solver chosen to perform the described algorithm was the 'fmincon', [10].

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 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, again a minimum of a sum, which is a non convex term. In addiction, any attempt to simplify the equation to make it two dimensional and more simplistic, 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').

5. Results - Joint FRA

5.1. Case 1 - Lisbon & Sta Maria

The creation of a joint FRA in the whole portuguese airspace, 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 short, the simulated traffic represents an ideal/theorical version of the actual 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).

Based on a six month analysis with real flights, which affected 31236 flights, 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	Total (31236 flights)
Actual	111978800
Simulated	111733772
Free Routed	111510471

Table 1: 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 actual 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.

The difference between an ideal (Direct) route and the actual route, can be seen in the table 2, which compares both scenarios. One may conclude that the proposed scenario would reduce significantly the actual 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.

$$Difference_{Relative}(\%) = \frac{Real_{Route} - Direct_{Route}}{Real_{Route}} \quad (11)$$

Scenario	(%)
Actual	2.88
Simulated	2.67
Free Routed	2.48

Table 2: Relative Difference between Real Route and Direct Route - Case 1

In the table 2, 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 actual scenario. This abrupt difference between the simulated traffic and the actual 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, has shown again improvements over the current scenario. Again, it is been considered the whole traffic crossing the border between this two airspaces.

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

Based on six month analysis with real flights, which affected 91688 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	Total (91688 flights)
Actual	167883671
Free Routed	167232470

Table 3: 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 actual scenario.

The table 4 shows that the proposed scenario would improve significantly the actual scenario, reducing the actual waste by 0.38%.

Scenario	(%)
Actual	2.33
Free Routed	1.95

Table 4: 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. Again, the results have shown improvements over the current scenario, however, in this case, only a slightly improvement over the current scenario was obtained.

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

Based on six month analysis with real flights, which affected 76608 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 Portuguese airspace and Asturias.

Scenario	Total (76608 flights)
Actual	125520657
Free Routed	125286495

Table 5: 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 actual scenario.

In this case, the proposed scenario would improve the actual scenario, reducing the actual waste by 0.18%.

Scenario	(%)
Actual	2.58
Free Routed	2.40

Table 6: Relative Difference between Real Route and Direct Route - Case 3

5.4. Joint FRA - Overview

Accordingly with the results in the three previous cases, each measure, individually, represent improvements to the actual 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 7, presented below, which combines the results of the previous cases.

	Average:
Length Saved Per Flight	6 NM
Length Saved Per Day	6075 NM
Length Saved Per Month	184777 NM
Length Saved Per Year	2217328 NM
Number of Flights Per Day	1093
Number of Flights Per Month	33255
Number of Flights Per Year	399064

Table 7: Overall Averages

Shall be noticed that the results in the table 7 represent a comparision between the computed (free routed) traffic and the simulated traffic (which simulates a theoretical scenario of the actual traffic).

In order to give a better insight on the results, an example for the first case is presented in the figure 6. Here, both the actual route (in red) and the new computed route (in green) are presented, where the improvements brought by the implementation of the FRA are visible.

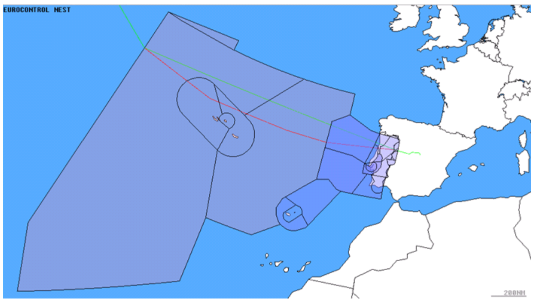

Figure 6: Flight Route - Example Case 1 (Flight ID: IBE6251)

6. Results - Navigation Points Optimization

6.1. Border Navigation Points

The analysis of the Border between the two portuguese FIRs 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 actual 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 8, where 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, 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 taxes in the adjacent airspaces (e.g. Canarias).

Scenario	Cost Function J
Actual ($w = 13$)	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 8: Cost Function Values

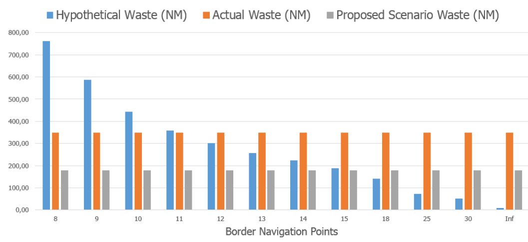

Figure 7: Actual vs Other Scenarios: Waste (in NM)

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 actual improvements will deeply increase.

Analyzing the computed values of the cost function presented in the table 8, and consequently the figure 7, one can easily conclude that the actual scenario can be improved. With only eleven navigation points (the actual scenario has thirteen) it's possible to have a scenario close to the actual one in terms of efficiency. In addiction, just by optimizing the current position of the actual 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 8, which basically use the equation presented below.

$$Waste_{Relative}(\%) = \frac{Actual_{Waste} - Scenario_{Waste}}{Actual_{Waste}} \tag{12}$$

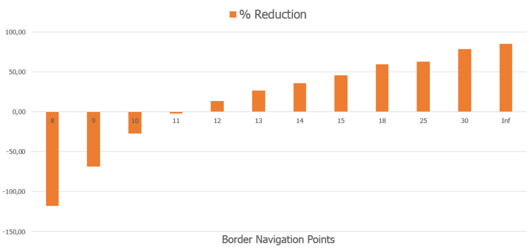

Figure 8: % of Waste Reduction, as a function of the number of border navigation points

As can be seen in the figure 8, in an ideal case, with $w = \infty$, the improvement expected would be of almost 98%. This scenario could be achieved through a joint FRA since the flights could cross the border freely.

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

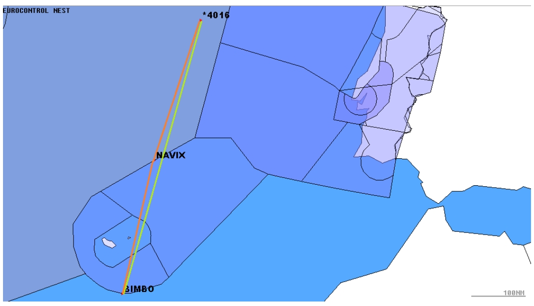

Figure 9: Flight Route - Border Navigation Points - Example 1

In 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. They were chosen by 1455 (figure 9) and 963 (figure 10) flights.

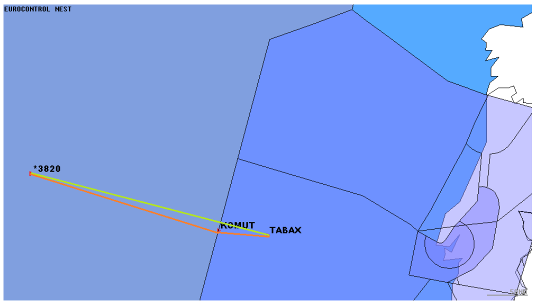

Figure 10: Flight Route - Border Navigation Points - Example 2

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 are now analyzed. Currently the border has thirteen navigation points, and their respective coordinates can be seen in the table 9.

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 9: Actual Navigation Points (in degrees)

The proposal of NAV Portugal, which adds five more navigation points can be seen in the figure 11, and their respective coordinates can be seen in the table 10. 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 actual navigation points, in the region with more traffic (the vertical line with -15°of longitude) in order to reduce the actual need for deviations and avoid congestions.

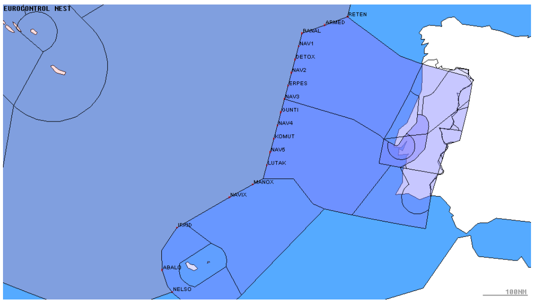

Figure 11: NAV Proposal Navigation Points in the Border between the two portuguese FIRs

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 10: 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 12 can be seen the navigation points, while the concrete value of their coordinates are specified in the table 11. 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*.

Remembering that the cost function 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

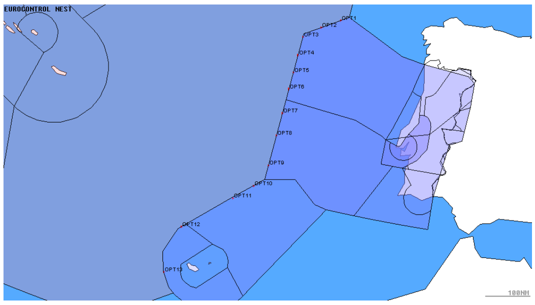

Figure 12: Optimized Navigation Points ($w = 13$) - Border between the two portuguese FIRs

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

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 actual FRA.

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. 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 7), leading to shorter flights, with lower levels of burnt fuel and lower CO_2 emissions.

Besides 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 7). 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, as proposed by NAV Portugal, to a total of eighteen navigation points, an improvement of almost 50% could be expected (table 8). This scenario is far from optimal, where almost the same results achieved with this scenario could be achieved with only fifteen navigation points (table 8) if the border navigation points were restructured and optimized for the current traffic needs.

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. 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 9), 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.

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.

8. 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 proposed joint FRA would cause major changes in the actual traffic flow, therefore, an analysis to the actual sectors would be needed where might be need some restructuration in order to ensure that all the sectors can support the incoming traffic changes.
- It would be interesting to analyze the air traffic controllers workload, mainly due to potential conflicts and how the conflict detection is being made.
- 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, 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.

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