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Conflict resolution of North Atlantic air traffic with speed regulation

Imen Dhief[ab], Nour Houda Dougui[a], Daniel Delahaye[b], Noureddine Hamdi[a]

[a]*Heteroginous Advanced Networking and Applications (HANA) Research group ENSI, Manouba, Tunisia*
[b]*Laboratory of Applied Mathematics, Informatics and Automatics for Aviation (MAIAA) ENAC, Toulouse, France*

Abstract

Since air traffic volume increased over the oceanic airspaces, it has been primordial to improve oceanic air traffic management procedures. One of the most important limitations in the oceans air traffic is the lack of radar coverage. The availability of new surveillance means, called automated dependence surveillance broadcast system (ADS-B), permits to enhance the strategic flight planning over the oceans by reducing the separation standards. Besides, oceanic flights are mainly subjected to strong winds caused by the jet streams. In this work, we focus on optimizing the strategic flight planning over the North Atlantic airspace. First, we organize the traffic inside a route structure that benefits from both the Jet streams and the exploitation of ADS-B systems. Indeed, from one side, these routes are merged inside the jet streams in order to be as close as possible from wind-optimal routes. On the other side, these routes are constructed to fit in with the new separation standards required when implementing the ADS-B systems. Then, we resolve conflicts between aircraft via an optimization model based on a speed regulation. Simulations were conducted for a real traffic data. Computational findings show that the proposed methodology provides satisfying results.

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Keywords: North Atlantic airtraffic, ADS-B, strategic planning, route structure, speed regulation

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Nomenclature

ADS-B	Automated dependence surveillance broadcast
GNSS	Global Navigation Satellite System
NAT	North Atlantic airspace
NM	Nautical Mile
OTS	Organized Track System
UTC	Coordinated Universal Time

1. Introduction

In the last few years, there has been a growing interest at improving the efficiency of oceanic air traffic situation. In fact, due to their long duration, oceanic flights consume 26 percent of the total fuel consumption in the world. Besides, these flights yield 49 percent of the International cargo revenue and 20 percent of the passenger revenue [4]. In particular, the North Atlantic airspace (NAT) is considered to be the most congested oceanic airspace since it connects two densely-populated area namely Europe and North America. The NAT airspace presents several particularities.

First, the density of traffic over the NAT is steadily increasing. In fact, the International Air Transport Association (IATA) statistics estimates that the traffic growth over the NAT airspace was about 4.8% more in 2015 in comparison with 2014.

Furthermore, due to passenger demand and time zone differences, the NAT air traffic is divided into two flows: westbound flow, travelling from Europe to North America in the morning and eastbound flow travelling on the opposite direction in the evening. Due to these flows, most of the NAT traffic is concentrated uni-directionally, with peak westbound traffic between 1130 Coordinated Universal Time (UTC) and 1900 UTC and peak eastbound traffic between 0100 UTC and 0800 UTC.

In addition, flights operating in the NAT airspace are subject to very strong winds caused by the Jet Streams. These streams are fast air currents running mainly in west direction. Thus, eastbound flights exploit the jet streams to benefit from tailwinds, however, westbound flights prefer to avoid the jet streams and stay away from headwinds.

Finally, most part of the NAT airspace suffers from lack of surveillance tools. In fact, as the traditional radar relies up on ground-based sites, flights are unable to be tracked using these means of surveillance.

Regarding these issues, it has been primordial to find safe, robust and efficient procedures to organize this dense traffic. The present study focuses on establishing the required separation between the scheduled flights in the NAT at strategic level. In this paper, we refer to our earlier work presented in [2], however, the focus is different. In fact, in our previous work, we present a new route structure model for the NAT. Nevertheless, in the present work, we develop an approach for conflict resolution, inside the pre-defined route structure, based on a speed regulation.

The remainder of the paper is divided into four sections. The first section gives an overview of the theoretical background related to our research topic. The second section presents the problem formulation. We mainly outline the given data and we describe briefly the new route structure. The proposed conflict detection and resolution methodology is presented in Section IV. Section V summarizes and analysis the experimental results of this work. Some conclusions are drawn in the final section.

2. Background

The present section gives a theoretical background related to air traffic management over the NAT. We start by exposing the OTS routes, which represent the actual route structure in the NAT. Then, we introduce the functionalities of the ADS-B system and the benefits behind its deployment.

2.1. The organized Track System

In order to simplify the huge traffic organization and control in the NAT, a system of pre-defined tracks is constructed referred as the Organized Track System (OTS). The OTS is created independently for eastbound and westbound traffic, so that to accommodate as many flights as possible close to their minimum time tracks and altitude profiles. Each OTS includes between 5 to 7 parallel or nearly parallel tracks spread within flight levels from FL310 to FL390. The OTS is constructed to take into account the shifting of west-east jet streams. Thus, it moves slightly every day to the north or to the south. Typically, the east-west tracks are located more in the north than the west-east tracks in order to benefit from the direction of the jet streams. About 10 waypoints are fixed in each track: the track entry and the track exit waypoints, and waypoints in between located almost every 10 degrees of longitude.

2.2. Separation norms

Separation standards refer to the minimum distance that must be kept apart between aircraft operating in controlled airspace. Typically, the flight levels are defined in such way that two aircraft at different flight levels are always separated. Furthermore, two aircraft traveling at the same altitude but on two parallel routes that never intersect and maintain a required distance are guaranteed separated. Finally, the longitudinal separation is ensured when the two aircraft following the same route at the same altitude are separated in time.

As in a non-radar environment, aircraft position prediction is less precise, safe separation becomes more crucial. For this reason, separation norms in oceanic airspaces are much higher than in the continental ones: lateral separation is extended to 60 NM (111.11 km), compared to 5 NM in continental airspace, and vertical separation is 1000 feet (304.8 m). The OTS is constructed to comply with these separation norms. Thus, OTS tracks maintain the lateral separation (60 NM) and OTS flight levels are separated by 1000 feet. Once aircraft enter the OTS system, controllers only have to ensure longitudinal separation between them. The longitudinal separation is defined in terms of time and represents the hold time between two aircraft in the same track. Currently, the longitudinal separation is 10 minutes between two aircraft in the same track. If an aircraft changes its track, this separation becomes 15 minutes. The three aforementioned separation standards are presented in Figure 1.

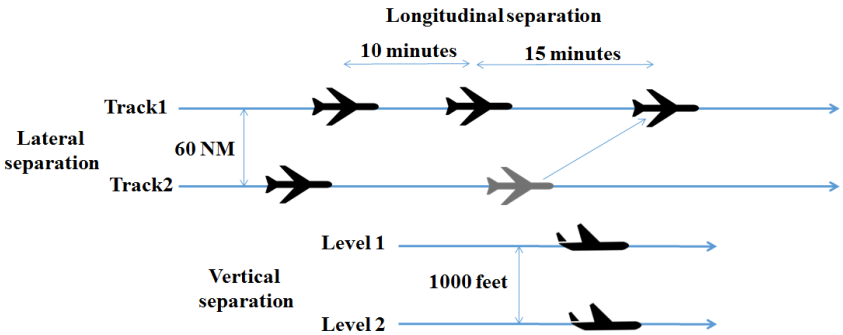

Fig. 1. Separation standards in oceanic airspace

2.3. ADS-B systems

Thanks to the global navigation satellite system (GNSS), such as GPS, GLONASS and Galileo, modern aircraft are becoming capable of detecting their positions much more precisly than the ground control. As secondary radars have a limited accuracy a new surveillance system was introduced, the Automatic Dependent Surveillance–Broadcast (ADS–B). ADS-B allows the aircraft determining their positions via satellite navigation. Then, each aircraft broadcasts its own information (identification, position, velocity and heading ...) which is received by both controllers and surrounding traffic. Thus, ADS-B allows air traffic controllers tracking aircraft in real-time almost anywhere in the world, and at the same time it provides nearby aircraft with situational awareness and allow self-

separation. ADS-B information is more accurate and reliable than the information available with secondary radar-based systems.

3. Problem statement

Oceanic controllers have to make sure that all aircraft crossing the OTS are conducted safely. Since there is no radar coverage, controllers rely on pilots to report their positions at regular intervals via High Frequency Voice Positions. As the controller's workload is usually high, some delays can be expected for responses to requests for an eventual change of flight level, route or speed. Therefore, oceanic controllers usually deny rerouting from one track to another inside the OTS and flights are more likely to keep the same track from the entrance to the exit of the OTS [1]. Thanks to the deployment of ADS-B systems, the separation norms will be relaxed which enables more flexible and efficient oceanic operations. On the other side, it is obvious that en-route fuel consumption is strongly influenced by weather conditions, such as wind speed and direction. Considering these issues, a new route structure that benefit from both, the reduction in separation norms and the speed and direction of wind, is presented in [2]. From the one hand, this route structure ensures reliable transitions between tracks when assuming that all aircraft are equipped with ADS-B. From the other hand, the considered route structure is merged inside the jet streams in order to benefit from wind direction. In the present study, we refer to this new route structure, and we propose a new conflict detection and resolution methodology based on speed regulation.
In this section, we start by describing the aforementioned route structure. Then, we present the problem formulation.

3.1. Route structure

The particularity of this route structure is that tracks are separated by 10 NM, instead of 60 NM in the OTS. This reduction is reasonable since it is assumed that all aircraft are equipped with ADS-B system. The construction of the route structure is as follows: the entry and exit points of the OTS tracks are kept, and beginning from the first points of each track, all tracks are merged to the center where there is the jet streams. Then, tracks are kept parallel and separated by 10 NM along 1000 NM. Finally, each track joins the corresponding exit point of the OTS system (see Figure 2.).

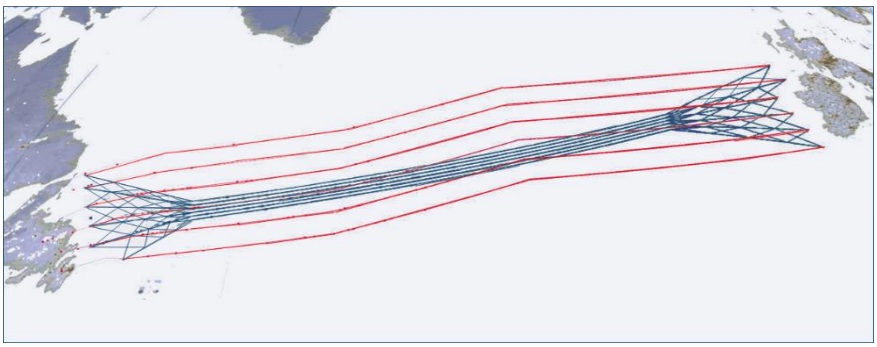

Fig. 2. Superposition of the OTS with the new route structure

Since the route structure enables transitions between the rails, sections before and after the parallel track region are considered as filters. In these sections, each track contains waypoints. Flights are allowed to change their tracks only on these waypoints. In each waypoint, the flight has three alternative maneuvers: whether it continues with the same track or it changes its track to an adjacent one (north or south).
The route structure can be modelled as a grid with N_y tracks, each track contains N_x waypoints and N_z flight levels. Figure 3 illustrates the grid model in horizontal dimension. When an aircraft enters a predefined track at a predefined flight level, it's required to follow the same track and flight level unless a maneuver is done. This maneuver can only be held on waypoints. Thus, arriving to a waypoint, a flight can rather change the flight level or pursue at the same altitude. Besides, when keeping the same flight level, it has also the possibility to change its track to an adjacent one.

Besides, in the portion where tracks are separated by 10 NM, aircraft are required to maintain their tracks until the exit from the parallel section.

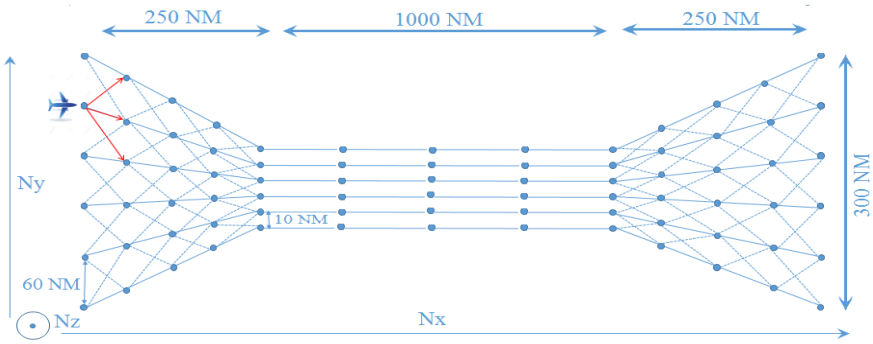

Fig. 3. Horizontal section of the route structure grid model

3.2. Problem formulation

We consider a set of N eastbound flights. Each flight is represented by a set of parameters which are:

- Entry and exit track,
- Track entry time,
- Flight level at waypoints,
- True airspeed in knots.

Some of these parameters have fixed values that will not change all along of the problem resolution, while the other values could be changed and represent the variables of our optimization problem. In fact, in order to meet as much as possible airline companies' preferences, aircraft flight levels at each waypoint do not change. On the other hand, it's important to extend the state space in order to guarantee conflict-free trajectories. Thus, entry delay less than 20 minutes is allowed. Moreover, the entry and exit tracks can be relaxed by allowing aircraft to enter and/or exit an adjacent track. Besides, we mainly do not prefer to change the speed of the aircraft, since it guarantees the optimal fuel-consumption. Nevertheless, we permit to change the requested speed only inside the parallel section of the route structure. This manoeuver is essential in order to resolve catch up conflicts. Evidently, this modification of flight speed is restricted. Let v_{opt} be the optimal speed of an aircraft. Then, the assigned speed must range closer to v_{opt} in order to not dramatically increase fuel consumption. A speed interval of $[v_{opt} - 6\%, v_{opt} + 3\%]$ is commonly considered for speed regulation of en-route airspace [3]. The entry data of our model are represented below:

- $Track_{In} \in \{1,2,\ldots, N_y\}$ the desired entry track
- $Track_{Out} \in \{1,2,\ldots, N_y\}$ the desired exit track
- T_{In} the entry time
- $FL_i \in \{1,2,\ldots, N_z\}$ where $i \in \{1,2,\ldots, N_x\}$, the flight level at each waypoint expressed in feet. The distance between each two consecutive flight level is equal to 1000 feet.

In order to represent the relaxation that we allow in some flight's parameters, we define the following decision variables:

- $ATrack_{In} = Track_{In}$ +/- 1 the assigned entry track.
- $ATrack_{Out} = Track_{Out}$ +/- 1 the assigned exit track.
- $D_{In} \in [0, 20\text{min}]$ the time delay at the entry point.
- Z_i where $i=1,2,\ldots,N_x-1$ binary parameter characterizing the flight altitude profile

$$Z_i = (FL_i - FL_{i-1})/10 = \begin{cases} 1 \text{ if the flight climbs to the next level at waypoint } i \\ 0 \text{ otherwise} \end{cases}, \text{ with } (Z_1 = 0).$$

- S_i where $i=1, 2\ldots, N_x-1$, a vector containing the speed of the aircraft in each link of its trajectory.

- X_i where i =1, 2…, N_x-1 binary parameter defining the flight routing manoeuvers

$$X_i = \begin{cases} 1 \text{ if the flight switches to the northern adjacent track at the waypoint i} \\ 0 \text{ if the flight continues with the same track} \\ -1 \text{ if the flight switches to the southern adjacent track at the waypoint i} \end{cases}$$

Further details related to the route structure construction and model are found in [2].

3.3. Wind network

In this section, we present the wind network adopted for the simulation of flight's progress. Thus, we compute for each aircraft the time of passing the waypoints of the route structure. Two factors affects these times. On the one hand, it varies upon the aircraft true airspeed. On the other hand, the passing time depends on the wind direction and speed. Considering the route structure, we have to compute wind vector in both waypoints and links. To do so, we calculate the wind vector in each node using a grid of wind data. We associate, for each node, the east wind component W_E and the north wind component W_N. The wind norm is then given by: $\|\vec{W}\| = \sqrt{W_E{}^2 + W_N{}^2}$ and the associated wind bearing $\theta_W = \arctan(\frac{W_E}{W_N})$. Since each link connects an origin node N_o and a destination one N_d, we can deduce its tail wind. In fact, let (ϕ_o, λ_o, z_o) and (ϕ_d, λ_d, z_d) be respectively the spherical coordinates of the nodes N_o et N_d. The associated bearing of each link l is given by the following formula:

$$\theta_l(N_o, N_d) = \arctan\left(\frac{\sin(\Delta_\lambda).\cos(\phi_d)}{\cos(\phi_o).\sin(\phi_d) - \sin(\phi_o).\cos(\phi_d).\cos(\Delta_\lambda)}\right) \quad (1)$$

Where $\Delta_\lambda = \lambda_d - \lambda_o$. The tail wind on each extremity of a link, TW_o and TW_d, is given by:

$$\begin{cases} TW_o = W_o.\cos(\theta_l - \theta_{W_o}) \\ TW_d = W_d.\cos(\theta_l - \theta_{W_d}) \end{cases} \quad (2)$$

Then, we associate to each link the average of those two tail wind:

$$TW = \frac{TW_o + TW_d}{2} \quad (3)$$

Finally, the time needed by the aircraft to reach node N_d from node N_o can be now deduced by:

$$t = \frac{d_l}{T_a + TW_l} \quad (4)$$

where d_l represents the great circle distance of the considered link and T_a is the true airspeed of the aircraft.

4. Conflict detection and resolution

4.1. Conflict detection

A conflict represents a violation of established separation norms. We assume that all aircraft are equipped with ADS-B systems. The route structure is build based on the reduced separation norms (tracks are separated by 10 NM and flight levels are separated by 1000 feet). It only remains for us to manage the longitudinal separation which is assumed to be 2 minutes if aircraft are in the same track, and 3 minutes when an aircraft changes its track. Besides, an aircraft has also the possibility to change its flight level (only by climbing). The aircraft position deviation in the horizontal plane is neglected, as well as the time required to reach the new flight level. However, when changing its flight level, an aircraft has to maintain a new separation norm with aircraft flying on the same track at the new flight level. The separation standard, in this case, becomes 2,2 minutes.
Conflicts are either detected at nodes or at links. At nodes level, conflicts are detected by sorting flights passing through a given node according to their transit time. Once sorted, we compute the difference in transit time between each two successive flights. A conflict is detected when this value is less than the longitudinal separation. Since each

link is delimited by two nodes, we can detect conflict at links level by comparing the sequence order of aircraft at the entry and exit nodes of a link. If there are two swapped flights, then a catch-up conflict is detected. Catch-up conflict can also be detected by the following method. Let f_1 and f_2 be two successive flights in the same link, and let v_1 and v_2 be respectively their velocities. Assume that t_{In1} and t_{In2} are the entry times of respectively f_1 and f_2 at the considered link and t_{Out1} and t_{Out2} are respectively the exit times. Now, we can derive the time at which a violation of separation between f_1 and f_2 is detected. This time t is given by:

$$t = d_{sep} - (v_2 * \Delta t) / \Delta v \tag{5}$$

With $\Delta t = t_{In2} - t_{In1}$, $\Delta v = v_2 - v_1$ and d_{sep} represents the required distance of separation between two successive flights in the same track. Thus, if the time t verify the inequality:

$$\text{Max}\ (t_{In1}, t_{In2}) < t < \text{Min}\ (t_{In1}, t_{In2}) \tag{6}$$

Then a conflict is detected.

4.2. Optimization process

The present study aims at providing optimal flight trajectories by optimizing cruising time while remaining conflict-free and satisfying some constraints such as respecting a maximum delay per flight. The problem has been divided into three stages for resolution. These stages are run sequentially. Based on the route structure aforementioned, the decomposition of the problem is illustrated in figure 4.

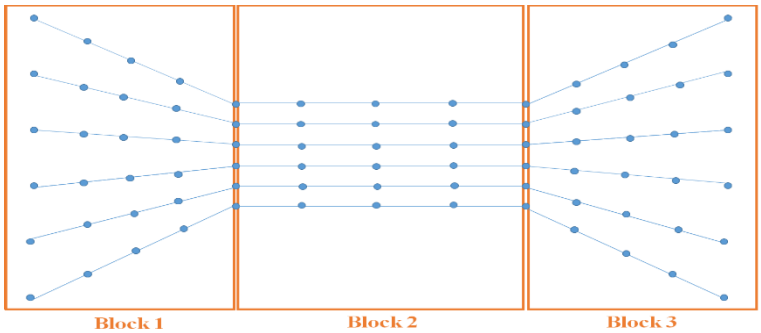

Fig. 4. Decomposition of the problem into blocks

Therefore, in each block, an optimization process in applied in order to find an optimal set of conflict-free trajectories in the considered section of the route structure. We proceed sequentially. Indeed, once a solution for a block is found, we proceed for searching the solution of the following block, while keeping the solution of the previous blocks unchanged. This decomposition is reasonable since the constraints differ from different blocks. In fact, considering the first block, the manoeuvres of resolution are: delaying the flight, changing the entry track and changing the route. Nevertheless, in the second block, since we forbid transitions between tracks, the only resolution manoeuver applied is the speed regulation. Speed regulation is not applied in block one and three in order to be as close as possible from the airline company's preferences.

For each block, we start with pre-processing the flight set using a sliding window method (SW). The latter consists in dividing the problem into a set of sub-problems. Then, each sub-problem is treated separately and sequentially via a simulated annealing algorithm (SA).

Further details about the optimization process based on the combination of SA and SW for this particular problem are found in [2].

5. Results

The present study presents a methodology to resolve conflicts between aircraft crossing the NAT based on a speed regulation. The simulations was conducted for real traffic in the NAT on 3rd August, 2006 and 4th August, 2006. Each flight set contains respectively 331 and 378 flight. We adopt the same simulation parameters presented in [2]. Besides, we add the number of flights that change their speed to the objective function applied in block 2. The initial number

of conflict was about 800 conflict in each set. The method finds a conflict-free solution in a reasonable time (about 30 minutes). We believe that the result emphasizes the validity of our model. Our findings appear to be very interesting since the de-confliction of trajectories does not affect the trajectory length. In fact, transitions from one track to another are only authorized in the same direction: for instance, if an aircraft enters the route structure at the first track and want to exit from the 3rd one. Then, it is required to climb to northern tracks, and decent is not allowed. Thus, the trajectory length is not affected. Besides, the choice of a very restricted speed interval allow to insert the aircraft without dramatically influence the fuel consumption. Therefore, our findings highlights the usefulness of a new wind-optimal route structure in the NAT airspace. Moreover, the utility of the application of a speed regulation inside an organized set of parallel tracks is stressed and validated. However, we aware that our research may have some limitations. First, the simulation data used are old which is due to the non-availability of the totality of these information in the air traffic control centers since it concerns the data from two different continent. Second, only one optimization process has been validated. We believe that applying different optimization algorithm such as genetic algorithm may strongly improve the result.

6. Conclusions

This paper has investigated the potential benefit from implementing a new route structure over the NAT airspace, and resolving the conflicts using a speed regulation. In this work, we assume that all aircraft are equipped with ADS-B so that a reduction in separation norms is conceivable. Simulations have been conducted to real traffic data. Computational results show that a conflict-free solution can be reached without influencing trajectory length which is directly related to fuel consumption.

In future work, we are planning to reevaluate our methodology with more recent traffic data containing more flights per day. Besides, we intend to estimate and analysis the impact of our method of resolution on the fuel consumption. Finally, we plan to compare our results using other optimization algorithms such as genetic algorithm.

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