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EVALUATING AIR TRAFFIC CONTROLLERS' WORKLOAD THROUGH COMPUTER SIMULATIONS

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ABSTRACT

Automatic Dependent Surveillance-Broadcast (ADS-B) has become one of the key technologies in modernizing the National Airspace System (NAS) by enhancing air traffic surveillance and improving situational awareness. In this study, we used the Global Oceanic Model - a fast-time computer simulation tool- to evaluate the potential workload of air traffic controllers (ATC) using satellite-based ADS-B and reduced separation standards in the North Atlantic (NAT) oceanic airspace. This study uses two metrics to quantify the potential ATC workload. First, the number of tactical resolution maneuvers (changing flight levels, changing Mach number and lateral deviations) used by ATC to resolve potential conflicts. Second, the number of events that ATC need to monitor when aircraft pairs are located within a protection boundary of 50% above the separation minima. Our results show that equipping aircraft with ADS-B technologies can reduce the ATC workload and increase the efficiency and capacity in the NAT airspace.

1 INTRODUCTION

The Federal Aviation Administration (FAA) has developed the Next Generation Air Transportation System (NextGen) to modernize the National Airspace System (NAS) since 2007. Improving the efficiency of flights over the ocean is one of the goals of NextGen. According to the United States Department of Transportation, oceanic fights generate 31 percent of air carrier passenger revenue and 40 percent of cargo revenue in the U.S. controlled airspace. Automatic Dependent Surveillance-Broadcast (ADS-B) has become one of the main technologies in the modernization of the air traffic system.

ADS-B is the successor to radar transmitting flights data such as an aircraft's position, altitude, and velocity to a network of ground stations, Air Traffic Controllers (ATC) and other participating aircraft. ”ADS-B Out” and ”ADS-B In” are two types of ADS-B technology which can be installed on an aircraft. Aircraft equipped with ”ADS-B Out” are able to continuously broadcast aircraft position to ground stations and other aircraft. This technology can benefit mainly the flights in remote oceanic areas without radar coverage with improved situational awareness. In 2010, the FAA published regulations which mandated all aircraft operating in designated airspace must be equipped with ”ADS-B Out” by January 1, 2020.

”ADS-B In” equipment provides the capability to receive the signals and surveillance information from the ground network and other aircraft. ”ADS-B In” is not mandated by the FAA. Airlines can voluntarily choose to equip their aircraft with ”ADS-B In” avionics which is a compatible display device to interpret the information in the cockpit (Izadi, Hinze, Trani, and Post 2019). Also, Automatic Dependent Surveillance Contract (ADS-C) and Controller-Pilot Data Link Communication (CPDLC) provide exchanging of text-

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based messages between pilots and ATC which improves the communication capabilities compared to traditional voice communication.

The United States has vast oceanic areas controlled by New York, Oakland, and Anchorage Air Route Traffic Control Centers (ARTCCs). The North Atlantic (NAT) region is the busiest U.S. oceanic airspace controlled by Canada, United Kingdom, and the United States. This study assumes that implementing satellite-based ADS-B in the North Atlantic region can reduce lateral and longitudinal separation standards and increase the airspace capacity, efficiency, and safety in the NAT airspace. The aim of this study is to evaluate the workload of ATC resulting from reduced oceanic separations in the NAT Flight Information Regions (FIRs). We propose two metrics to quantify the potential ATC workload. The first metric is the number of tactical conflict resolution maneuvers used by ATC to resolve the potential separation violations. The second metric is the number of situations that ATC should monitor the aircraft at the same flight level as they are approaching each other above the minimum separation criteria.

In this paper, Section 2 presents some of the previous studies about simulating flight traffic in oceanic airspace using computer simulation models. Also, there is an overview for the Global Oceanic (GO) model which is a fast time simulation tool developed jointly by the Air Transportation Systems Laboratory at Virginia Tech and the FAA to evaluate new concepts of operation for improving flight operations over global oceanic airspace. Section 3 provides the proposed modeling scenarios, and Section 4 discusses the modeling results. In the end, Section 5 concludes the results of the simulation.

2 LITERATURE REVIEW

In the literature, ATC workload is a confusing term with numerous definitions and models. Analysis of historical data on the separation loss between aircraft provided significant insights into the parameters influencing ATC workload and consequently the airspace capacity. (Mogford, Guttman, Morrow, and Kopardekar 1995) showed that the ATC workload is mainly driven by the situation of airspace, state of the equipment (i.e., the reliability of equipment in the control centers and aircraft) and state of the controller (e.g., the controller's age, experience, and decision-making strategies). One of the proposed approaches is the use of simulation modeling to study the potential parameters of airspace and traffic. (Majumdar and Polak 2001) provided a list of factors affecting the ATC workload and air traffic control complexity. These factors are divided into two main groups: sector factors (e.g., sector size, sector shape, airway configurations, and winds), and ATC factors (e.g., total number of aircraft, horizontal separation, vertical separation, minimum distance between aircraft, traffic and fleet mix, number of climbing and descending aircraft, and aircraft speed).

Human-in-the-loop (HITL) simulation and fast-time simulation are two main types of computer simulation tools for modeling air traffic systems. HITL models can simulate real-world scenarios regarding the interaction between machine and humans with high accuracy. However, human participants are relatively expensive and fatigue can impact their performances. Also, HITL simulations are restricted by the capacity of testing facilities, and they have limited flexibility and scalability. On the other side, fast-time simulation resolves several of the potential shortcomings of HITL methods. Fast-time simulation tools, which do not require direct human activity can provide flexible, inexpensive and rapid evaluations of policies and procedures in the air transportation systems (Volf, Jakubuv, Koranda, Sislak, Pechoucek, Mereu, Hilburn, and Nguyen 2014).

Computer simulation models have been used in numerous research efforts to investigate complex interactions between flights in oceanic airspace and estimate benefits of new procedures. The primary metrics used to measure the operational benefits are fuel consumption, delays, ATC workload, and level of safety. Fast-time simulation tools are divided into two categories. In the first group, simulation tools do not have algorithms for detecting and resolving separation violations. These models simulate traffic regardless of minimum longitudinal and lateral separations. The second group of simulation models has conflict detection and resolution logic, and they maintain separations between flights by evaluating the projected flight trajectories.

Transport Canada has developed the North Atlantic Traffic Allocation Model (NATTAM). The main goal of the model is evaluating the safety impacts related to changing the lateral and longitudinal separation standards in the NAT airspace (Gerhardt-Falk, Elasyed, Livingston, and Colamosca 2000). NATTAM detects and resolves the potential conflicts using decision trees checking different alternatives to find a conflict-free path through the airspace. (Chung, Noonan, and Post 2008) developed a North Atlantic Simulation model (NATSIM) to forecast future traffic demand and provide long-term operational estimates for changes to the air traffic system . NATSIM provides relatively fewer details about the microscopic movements of the flight traffic since NATSIM is a macroscopic model.

(Gunnam, Trani, Li, Graham, and Campos 2014) built a simulation model called North Atlantic Simulation and Modelling (NATSAM) to analyze the impacts of different Organized Track System (OTS) operational policies in terms of potential fuel savings. The scenarios tested in this study include reduced lateral and longitudinal separations with the data link application. (Li 2015) developed a microscopic simulation model allowing flights to have climb maneuvers inside the OTS tracks and switch tracks for higher fuel efficiency. (Tsikas 2016) simulated scenarios with different separation minima in the North Atlantic OTS tracks. This study simulated different scenarios and showed that the OTS configuration with applying 25 nautical miles of lateral separation and 8 nautical miles of longitudinal separation provides the best configuration. (Liang 2017) showed that that current OTS track configuration is unable to accommodate the NAT traffic in the year 2040 with an acceptable level of service. In this study, the level of service is defined as the percent of flights that obtain their optimal requested track and flight level. Learning from these studies, the Air Transportation Systems Laboratory at Virginia Tech developed a fast-time simulation model in collaboration with the FAA to assess benefits of advanced air traffic control policies and procedures in oceanic airspace.

2.1 GO Model Overview

The Global Oceanic (GO) model is a computer simulation model developed to quantify the operational benefits of advanced air traffic control procedures for oceanic flights. The model employs a discrete-time simulation algorithm that can simulate all phases of flight from takeoff to landing (Li 2015). Figure 1 shows how the GO model solves the aircraft equations of motion numerically and updates the position $(x_{t+\delta t} = x_t - (v)\delta t)$, altitude $(h_{t+\delta t} = h_t - (\frac{dh}{dt})\delta t)$ and aircraft mass $(m_{t+\delta t} = m_t - (\frac{dm}{dt})\delta t)$ based on the user-defined simulation time step (δt).

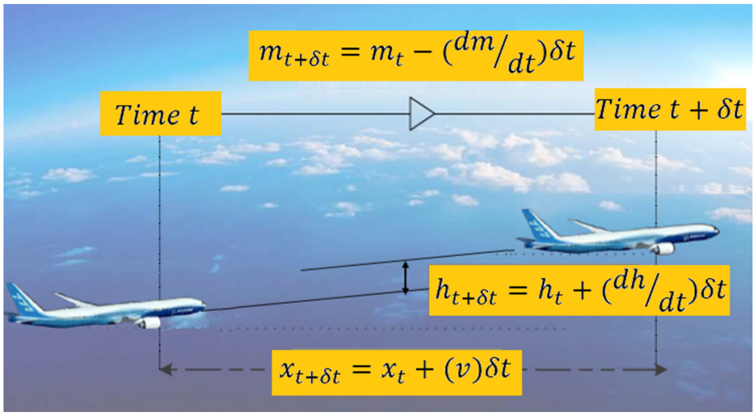


Figure 1: Simulation model paradigm.

To simulate the real-world traffic and model the interactions between flights over oceanic airspace, the GO model uses five modules including wind, aircraft performance, flight planning, track assignment, and conflict resolution modules. The wind module in the model uses the National Center for Atmospheric Research (NCAR) Reanalysis wind data. The aircraft performance module includes the Eurocontrol Base of Aircraft Data (BADA) 3.13 and 4.0. Traffic Flow Management System (TFMS) provides the main data including origins, destinations and departure times for the flight planning module. NAVCANADA uses Gander Automated Air Traffic System (GAATS) to control the traffic in the North Atlantic oceanic airspace. The flight planning module uses the assignment rules in GAATS and Notices to Airmen (NOTAM) for managing the flights intended to use the OTS tracks in the NAT region. The FAA uses the Advanced Technologies and Oceanic Procedures (ATOP) system to control the oceanic airspace system and provides satellite data link communication and surveillance capabilities. We had interviews with air traffic controllers in the New York (ZNY) and Oakland oceanic centers in 2016 and 2018. These interviews provide insight into the priorities of the conflict resolution strategies used by the ATC to resolve the conflicts. To model the interactions between pilots and ATC, we implemented three routines in the model including a pilot routine, an ATC routine, and a system update routine. The pilot routine controls each aircraft by simulating the behaviors of pilots. The ATC routine controls all the aircraft within FIRs by simulating the behaviors of air traffic controllers. The system update routine updates the status of all the aircraft in the simulation according to the pilot routine and ATC routine. Figure 2 shows the flowchart of the GO model.

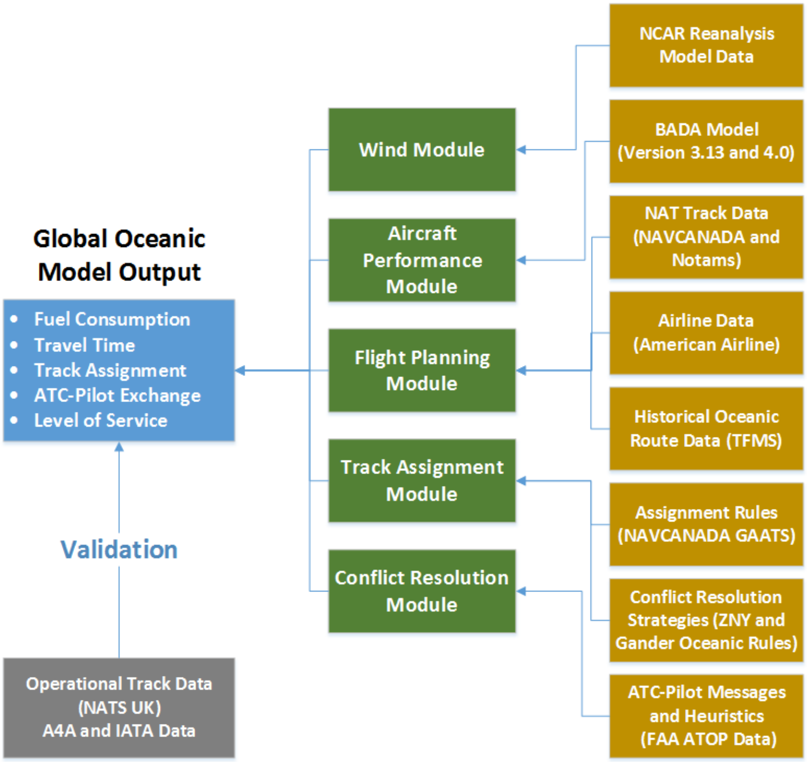


Figure 2: Global Oceanic model flowchart.

The air traffic between Europe and North America forms two major relatively concentrated unidirectional flows over the North Atlantic. Passenger demand, time zone differences and airport noise restrictions are the factors in creating the traffic peak for both eastbound and westbound traffic. Westbound traffic departing from Europe to North America in the morning and eastbound traffic departing from North America to Europe in the evening. The peak of the westbound traffic crosses the 30W longitude between 1130 UTC and 1900 UTC, and the peak of the eastbound traffic crosses the 30W longitude between 0100 UTC and 0800 UTC. Figure 3 shows an example of eastbound and westbound OTS tracks configuration related to June 25, 2016 (Liang, Izadi, Hinze, and Trani 2018).

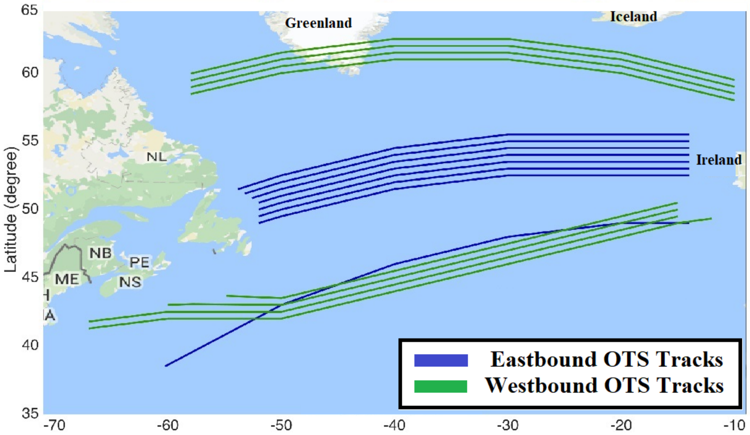


Figure 3: OTS tracks configuration (June 25, 2016).

To manage the traffic flows, two organized track systems are created on a daily basis to accommodate as many flights as possible. One of the most significant factors in designing the OTS tracks is meteorological conditions such as weather and wind patterns. The OTS tracks are designed such that eastbound flights could take advantage of the tailwind, and westbound flights could reduce their headwind. The GO model has a flight plan optimization tool using the NCAR Reanalysis wind data to generate wind-optimal flight trajectories worldwide (Spencer 2016). This module is used to create User-Preferred Routes (UPR) for flight plans. Note that utilizing the OTS tracks are not mandatory and aircraft can fly on UPR and remain clear of the OTS tracks.

The required input files for simulating traffic with the GO model are 1) flight traffic demand, 2) FIR boundaries, 3) ATC rules for each FIR, 4) NCAR Reanalysis wind sets and 5) OTS tracks configuration (Li, Gunnam, Trani, Spencer, Nikolaos, Hinze, Fan, and Zhang 2016). The GO model has conflict detection and resolution module for detecting and resolving strategic and tactical potential conflicts. Strategic conflict detection checks the projection of flights based on a user-defined parameter (e.g., one hour) before entering the oceanic boundary. If the model detects any conflict with the flights which are already inside the oceanic boundary, the strategic conflict resolution checks all the possible maneuvers to enter flights conflict-free to the oceanic boundary. When the flights are inside the oceanic boundary, the tactical conflict detection algorithm checks the projection of the flights for finding potential conflicts. Figure 4 shows conflict resolution rules based on their priorities which are changing cruise flight levels, changing cruise Mach number, and lateral deviations (Izadi, Hinze, Trani, and Gunnam 2018).

We implemented the rules and priorities used by oceanic air traffic controllers in the New York ARTCC. As the first strategy, the tactical conflict resolution module checks if the highest possible flight level resolves the conflict. The model checks the Mach number changes in each flight level. The range of changing Mach number is 0.02 Mach above and below the nominal aircraft's Mach number. if the model can not find a resolution, it checks the next lower flight levels until it reaches a user-defined parameter as ”Maximum Number of Flight Level Changes to Deconflict”. In this study, this parameter is set as five in all the FIRs. It means the module checks five flight levels lower than the current flight level and check different Mach number options to resolve the conflicts. Afterward, the module generates and checks lateral deviation alternatives up to 200 nautical miles to the right and left by 10 nautical miles increment. If the tactical resolution module does not find any solution, it continues checking lower flight levels until finding a conflict-free resolution maneuver.

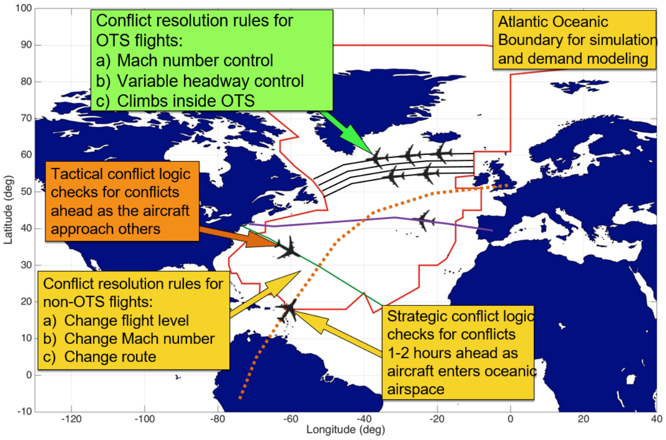


Figure 4: Strategic and tactical conflict resolution.

In this study, the simulation time step is ten seconds, and the model runs the strategic and tactical conflict detection and resolution every five minutes. For evaluating the oceanic Air traffic controllers' workload, the interaction of the flights managed by the tactical conflict resolution is considered in this study. The main output of the GO model is the detailed conflict-free trajectory which is generated based on the simulation time step for each flight. According to the simulation output, we proposed two relevant measures for evaluating the oceanic air traffic controllers' workload.

First, the number of tactical resolution maneuvers directly affect the ATC workload, since the pilots and ATC should communicate through text-based messages for verifying maneuvers. In other words, air traffic controllers need to send and receive several messages before granting a flight level change, Mach Number change or detour. Second, oceanic air traffic controllers start monitoring flights when two aircraft are located within a percent above the separation minima. This monitoring threshold can vary regarding different FIRs and air traffic controllers' confidence. This assumption is consistent with the interviews done with real air traffic controllers. This model has a post-processor to analyze the simulated trajectories and check the Closest Point of Approach (CPA) for each flight pairs. We modeled a larger rectangular separation envelope with 50% above the minimum lateral and longitudinal separations to find the number of events requiring close monitoring as a metric for potential air traffic controllers' workload.

We used the data from the Airline of America (A4A), operational track data from National Air Traffic Services (NATS) in the United Kingdom and International Air Transport Association (IATA) data to validate the fuel consumption and travel times results for each aircraft type. The GO model replicates the observed fuel trends within 97-98% accuracy. Also, we used the CPDLC messages between pilots and air traffic controllers to validate the aircraft climb performance (Izadi, Hinze, and Trani 2019).

3 MODELING SCENARIOS

The geographic scope of this analysis is the North Atlantic oceanic airspace shown in Figure 5. The NAT airspace includes eight FIRs managed by seven oceanic control centers including New York East and New York West (United States), Gander (Canada), Santa Maria (Portugal), Shanwick (United Kingdom - Ireland), Reykjavik (Iceland), Sondrestrom (Greenland) and Bodo (Norway).

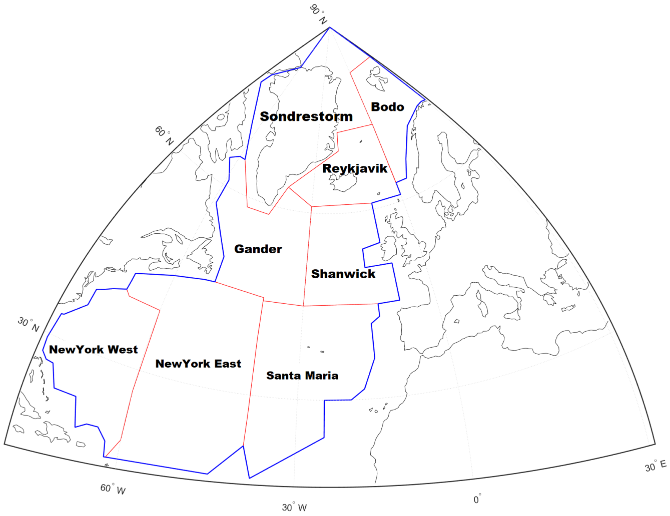


Figure 5: Simulation domain.

According to the FAA's published regulations, all aircraft operating in designated airspace (including North Atlantic airspace) must be equipped with ”ADS-B Out” by January 1, 2020. The simulation used three consecutive traffic days in all the FIRs. The FAA provided traffic data for June, (24-25-26), 2016 derived from the traffic flow management system. Having three days of traffic data allows the model to load the traffic on the NAT airspace and simulate the traffic of the middle day considering the complete interactions between flights. Note that all the provided results in this study are related to the middle day of the simulation. The traffic demand was adjusted using the NAT Economic, Financial, and Forecast Group (EFFG) outlook to reflect expected traffic growth in 2020 (ICAO. 2017)-(Campos, Graham, Grimes, and Joyce 2013).

In this study, we considered the long-range commercial flights entering the NAT airspace with the stage length above 600 nautical miles. The GO model simulated 4263 flights in 48 hours between 12:00 PM, 06/24/2016 to 12:00 PM, 06/26/2016. Figure 6 shows 2204 flights simulated in the middle day of the simulation. The green circles demonstrate the airports of origins and destinations. The composition of fleet mix shows that the majority of aircraft types operated into the NAT airspace are wide-body twin-jet aircraft. To estimate the operational benefits of full equipage level and reduced separation standards, we proposed three concepts of operations shown in Table 1.

In the baseline case (Scenario 1), the separation standards in all of the NAT FIRs (except New York and Santa Maria) for equipped aircraft pairs are 23 nautical miles (nm) for lateral separation and 40 nm for longitudinal separation. Based on current standards, the lateral and longitudinal separation minima for New York and Santa Maria FIRs are 30/30 nm. In Scenario 1, The OTS track system is active and the model accommodates the flights to the OTS tracks in their activation period. In Scenario 2, the lateral and longitudinal separations reduce to 15/15 nm for flights not using the OTS track. In Scenario 3, it is assumed that the OTS tracks are removed and all the flights can fly at their wind-optimal flight trajectories.

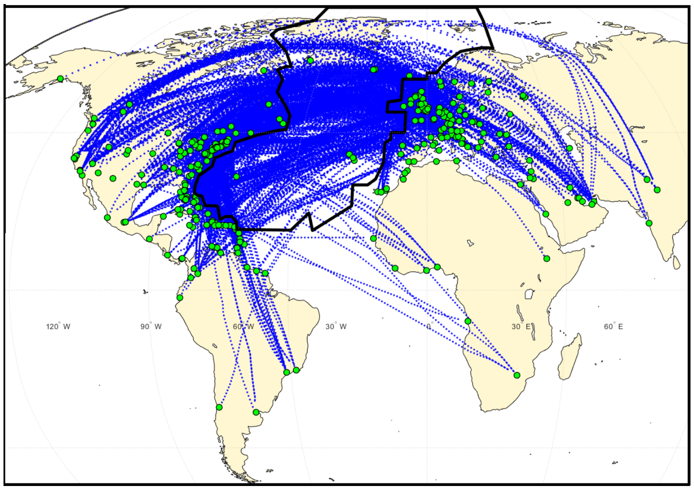


Figure 6: 2204 simulated flights in the middle day of the simulation.

Table 1: Modeling scenarios.

Assumptions	Scenario 1 (Baseline)	Scenario 2	Scenario 3
Lat/Lon separation (nm/nm) (New York and Santa Maria FIRs)	30/30	15/15	15/15
Lat/Lon separation (nm/nm) (Other FIRs)	23/40	15/15	15/15
Altitude Separation (feet)	1000	1000	1000
OTS Track System	Active	Active	Non Active
Percentage of OTS Flights	36 %	36%	0%
Step Climb Request Interval (min)	40	10	10

4 MODELING RESULTS

The tactical conflict detection and resolution logic in the GO model evaluates the projections of all flight trajectories inside the oceanic airspace and detects and resolves potential conflicts. Figure 7 shows the estimated conflicts resolution maneuvers for all non-OTS simulated flights. Based on the results, the number of tactical resolution maneuvers in Scenario 2 is reduced by 61% compared to the resolution maneuvers for the baseline scenario (Scenario 1). The reason is reducing the separation minima leads to increasing the capacity of the NAT airspace. So, flights in Scenario 2 benefit the capacity expansion by entering the oceanic boundary at higher average flight levels, and pilots request less for having step-climbs. Also, the probability of violating the separation envelope decreases by reducing the lateral and longitudinal separations. Scenario 3 shows a 182% increase in the number of tactical resolution maneuvers compared to the flights in Scenario 2 which flying with reduced separation and maintaining the OTS tracks. The reason is removing the OTS tracks will allow the flights to fly at their wind-optimal routes and this freedom cause more interactions and conflict probability among flights.

In air route traffic control centers, the advanced technologies and oceanic procedures system is constantly checking the projection of flight trajectories in all the FIRs. After detecting the conflicts in the projection of flight routes, oceanic air traffic controllers start checking different alternatives to resolve the conflicts. The monitoring threshold can be different based on air traffic controllers' confidence and the traffic in FIRs. To understand the impact of reduced oceanic separations on the number of events making ATC workload,

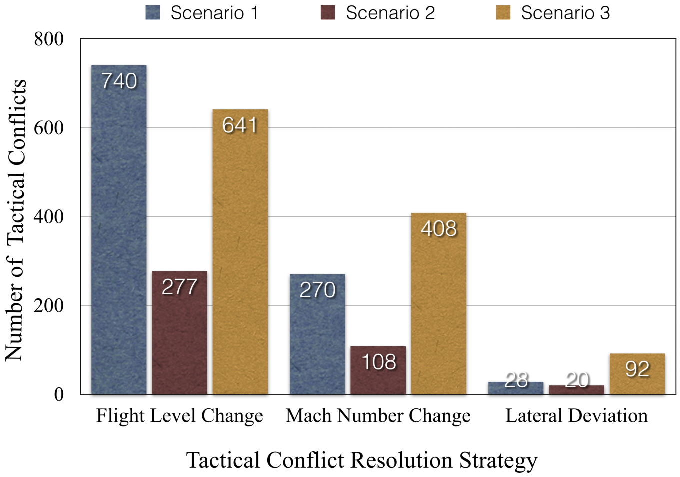


Figure 7: Estimated tactical conflict resolution maneuvers.

we modeled larger rectangular separation envelopes with 50% above the minimum longitudinal and lateral separations considering normal traffic in the NAT FIRs and moderate air traffic controller (see Figure 8).

In this study, we compared the number of monitoring events in Scenario 2 and Scenario 3 to understand the impact of removing OTS tracks in the NAT airspace. Therefore, we analyzed each pair of simulated flight trajectories and check the closest point of approach among them. If two aircraft are located in the larger rectangular separation envelope, it is considered as an event making potential workload for the air traffic controllers. Table 2 demonstrates the numbers of flights flown in each FIR, the number of monitoring events and the percentage of monitoring flights to the flown flights in each FIR for Scenario 2 and Scenario 3.

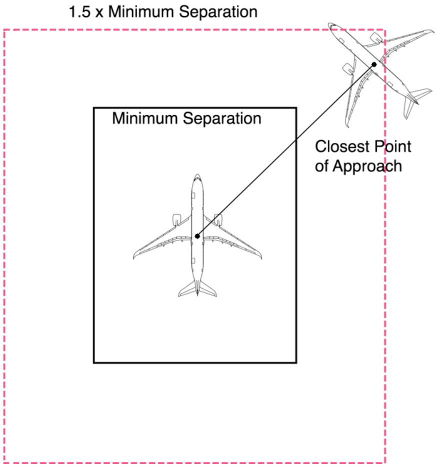


Figure 8: Separation criteria for potential ATC workload.

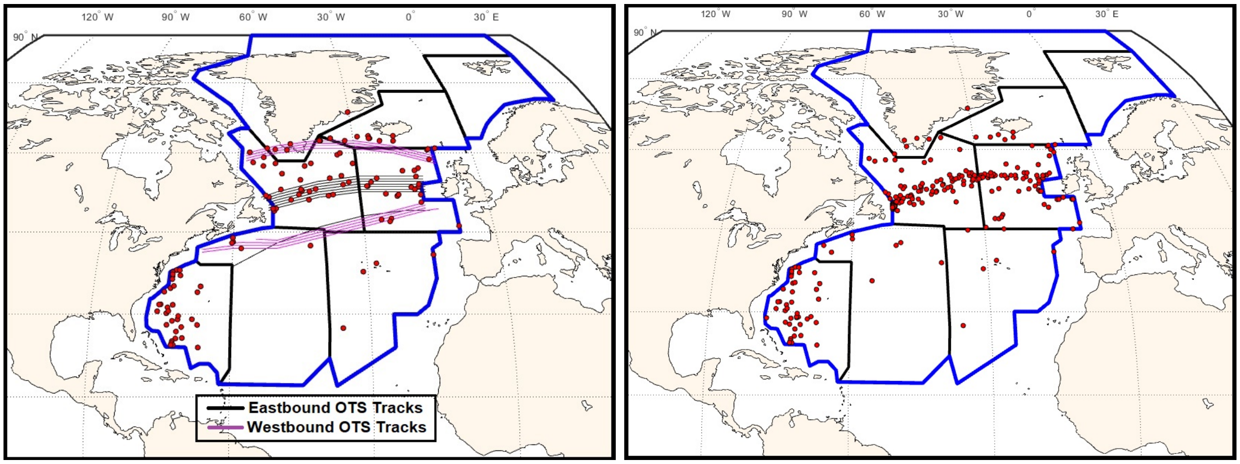
The simulation results provide insight into the distribution of events that may require closer ATC monitoring regarding the larger separation envelope (see Figure 9). The red points demonstrate the events when the closest point of approach among two aircraft at the same flight level is less than 50% above the minimum separations. The results show that the total number of events requiring close ATC monitoring in Scenario 3 without OTS tracks increased by 117% compared to Scenario 2 with the same separation standards and OTS tracks. The percentage of monitored events to the flown flight in each FIR shows that ”New York West”, ”Gander” and ”Shanwick” have additional air traffic controllers’ workload with allowing

Table 2: ATC monitoring events in Scenario 2 and Scenario 3.

Flight Information Regions	**Number of Flown Flights**		**Number of Monitoring Events with 50% Increase above Minimum Separation Standards**		**Percentage of Monitored Events to Flown Flights**	
FIR Names	***Scenario 2***	***Scenario 3***	***Scenario 2***	***Scenario 3***	***Scenario 2***	***Scenario 3***
New York West	573	674	34	42	5.9 %	6.2 %
New York East	273	510	5	8	1.8 %	1.6 %
Gander	676	1410	33	108	4.9 %	7.7 %
Shanwick	665	1367	24	73	3.6 %	5.3 %
Reykjavik	332	476	10	8	3.0 %	1.7 %
Santa Maria	194	333	4	5	2.1 %	1.5 %
Sondrestorm	350	494	5	6	1.4 %	1.2 %
Bodo	50	59	0	0	0 %	0 %
Total	**3113**	**5323**	**115**	**250**	**22.7 %**	**25.20 %**

the flights to fly at their UPR route. Note that ”Gander” FIR has the highest rise with 57% increase in the ratio of monitoring events to the flown flights.

On the other side, the results of the simulation show the average fuel consumption in Scenario 2 and Scenario 3 are 47,046 and 46,561 kilograms, respectively. It means that the flights in Scenario 3 which fly at their wind-optimal routes had in average 485 kilograms per flight of fuel consumption saving. This fuel saving is approximately 1.0 % of average fuel consumption in the NAT airspace, and it is equivalent to four and half minutes of fuel burn for a wide-body aircraft such (e.g., ”Boeing 777-200”) at cruise with nominal mass conditions. Hence, removing the OTS track in the NAT airspace is a tradeoff between efficiency and potential air traffic controllers’ workload.



(a) Monitoring events in Scenario 2.

(b) Monitoring events in Scenario 3.

Figure 9: Spatial distribution of ATC monitoring events with 50% above the reduced separation standards.

5 CONCLUSION

As the United States and Europe integrate the satellite-based ADS-B technologies into their automation platforms to meet the 2020 mandate for ”ADS-B Out”, it is important to assess the operational benefits (e.g., safety and capacity) of equipage requirement in the North Atlantic oceanic airspace. In this study, we used two metrics to evaluate the potential workload of air traffic controllers as one of the aspects of safety using a computer simulation tool called Global Oceanic model. The first measure is the total number of conflict resolution maneuvers (changing flight levels, changing Mach numbers and lateral deviations) used by ATC for resolving the traffic conflicts. The second metric is the number of events requiring close monitoring by ATC when the aircraft pairs are placed within 50% above the minimum lateral and longitudinal separation minima.

We simulated the current concept of operation in the NAT region with OTS tracks in place and with standard and reduced separation minima in NAT FIRs (Scenario 1 and 2). Comparing Scenario 1 and 2 show that the number of tactical conflict resolution maneuvers decreased by 61% with reducing the separation minima and consequently increasing the airspace capacity. We also simulated an advanced concept of operation allowing all the flights to fly at their wind-optimal route (Scenario 3). Comparing Scenarios 2 and 3 shows the total number of tactical conflict resolution maneuvers increased by 182% and the total number of events requiring close ATC monitoring increased by 117%. On the other hand, 485 kilograms fuel saving per flight is the benefit of removing the organized track system and allowing flights to fly at their wind-optimal route. This analysis indicates that future concepts of operation such as “user-preferred route” in the North Atlantic airspace can have a tradeoff between efficiency and safety, and decision-makers such as the FAA and International Civil Aviation Organization (ICAO) need to conduct more research to understand the impact of enhanced automation and communication technologies on flight operations.

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