Reduced Separation in US Oceanic Airspace
Benefits Analysis through Fast-Time Modeling

Dan Howell and Rob Dean
Regulus Group, LLC.
Washington, DC USA
dhowell@regulus-group.com

Joseph Post
Federal Aviation Administration
Washington, DC USA
joseph.post@faa.gov

Abstract—As part of an ongoing cost-benefit analysis, the Federal Aviation Administration (FAA) is investigating the potential operational impact of improved surveillance in oceanic airspace. Improved surveillance is possible via Space-Based Automatic Dependent Surveillance – Broadcast (ADS-B) and/or improved Automatic Dependent Surveillance – Contract (ADS-C). One of the primary benefits of improved surveillance is reduced separation minima. A detailed simulation of US oceanic airspace was developed and used to examine operations in the current oceanic environment and in several reduced separation scenarios. The modeling captures the impact of mixed aircraft equipage, pilot behavior, oceanic climb/descent procedures, and differing separation standards of neighboring Flight Information Regions (FIR). This paper describes the benefit mechanisms related to improved oceanic surveillance, the fast-time model and modeling assumptions, and the results of analyzing one of these benefit mechanisms: improved accommodation of altitude requests (and the associated reduction in fuel burn).

Keywords-component; Oceanic Separation, Oceanic simulation, Benefits, Space-Based ADS-B, ADS-C

INTRODUCTION

The International Civil Aviation Organization (ICAO) has delegated portions of airspace in the Pacific, Arctic, and Atlantic Oceans to the Federal Aviation Administration (FAA), as depicted in Fig. 1. Air traffic controllers in Oakland, New York, and Anchorage Area Control Centers (ZOA, ZNY, and ZAN, respectively) provide services for these areas. The current oceanic environment is characterized mainly by non-radar airspace lacking Very High Frequency voice communications. These limitations have resulted in large separation standards with potentially inadequate capacity to handle expected traffic growth.

Compounding these issues, oceanic flights are characteristically long in duration, ranging up to 14 hours in the Pacific/Arctic areas and up to 10 hours in the Atlantic. Aircraft operators obviously want to minimize fuel consumption. Oceanic flights frequently originate and terminate at popular international airports. Many of these airports are geographically clustered, causing high-density traffic flows in the oceanic airspace. In addition, many of these international flights are scheduled to depart within a narrow timeframe, resulting in clusters of aircraft transiting the oceanic Flight Information Regions (FIRs). While the oceanic airspace is immense, there can be significant competition for the most efficient flight trajectories (i.e., routes and altitudes) at the most popular departure times. While current separation standards provide a high likelihood for flights to achieve their preferred routing and altitudes, increases in oceanic traffic over the coming years will begin to have an impact.

To address shortfalls in the oceanic environment, in the 1990s the FAA deployed the Advanced Technologies and Oceanic Procedures (ATOP) system [2]. ATOP is designed to reduce the intensive manual process controllers historically have used to ensure separation. ATOP processes oceanic aircraft and weather data, calculating all separation criteria almost instantaneously and providing more efficient track and altitude alternatives through Conflict Prediction and Reporting. Additionally, ATOP interfaces with Future Air Navigation System (FANS) avionics, allowing controllers to assess time estimates and the position of aircraft more efficiently. FANS includes avionics to support performance-based navigation (PBN), Controller Pilot Data Link Communication (CPDLC), and Automatic Dependent Surveillance - Contract (ADS-C) position reporting. ATOP also enables controllers to identify airspace sectorization, and recognize separation minima based on aircraft equipage.

Although these advances have improved controller capabilities, numerous shortfalls are still associated with oceanic airspace. A lack of surveillance, and inefficiencies associated with communications, result in oceanic separation minima much higher than in radar airspace. In most oceanic sectors, separation is dependent on aircraft communication, navigation, and surveillance capabilities, leading to varying separation minima.

The FAA is investigating further ways to improve oceanic surveillance, enhancing operations in oceanic airspace by reducing oceanic separation standards below today’s minimum of 30 nautical miles (NM) lateral and 30 NM longitudinal (30/30) [3]. Two technological approaches have been conceived to improve surveillance timeliness and coverage in the oceanic domain. First, the frequency of aircraft ADS-C reporting can be increased from every 10 minutes to every 4 minutes. This increase in reporting frequency, coupled with appropriate modifications to the ATOP system, will reduce the uncertainty of aircraft position estimates, allowing reduced separation standards with an equivalent level of collision risk.
Second, Aireon LLC has deployed ADS-B receivers in space aboard Iridium NEXT satellites [4]. Sixty-six of these satellites now circle the earth in Low Earth Orbit (LEO), eleven satellites in each of six polar-orbiting planes. These receivers are capable of detecting all aircraft transmitting their positions using 1,090 MHz ADS-B squitters. Since these ADS-B squitters will be required of all aircraft in U.S. domestic airspace above Flight Level 180 beginning on January 1, 2020 [5], most aircraft transiting U.S. oceanic airspace at that time will be equipped. Update rates for Space-Based ADS-B (SBA) are expected to be approximately every 8 seconds. Even if every broadcast is not detected, the resulting position uncertainty should be reduced even further than with enhanced ADS-C, and allow even smaller separation standards.

It is expected that ICAO will approve new separation standards below 30 NM lateral and 30 NM longitudinal using SBA reports. ICAO has already approved 23 NM lateral using ADS-C reports.

Over the past two years the FAA conducted a cost-benefit analysis to justify the various investments needed by the government and operators to reduce oceanic separation standards, using either increased ADS-C reporting or Space-Based ADS-B surveillance. This paper describes the method used to analyze the potential benefits of reduced horizontal separation in U.S. oceanic airspace, and presents the estimated fuel savings.

**BENEFITS OF IMPROVED OCEANIC SURVEILLANCE**

The use of SBA and/or more frequent ADS-C periodic position reports will likely lead to reduced separation minima and the following associated benefits:

- Improved arrival/departure services at non-radar airports
- Reduced vertical collision risk
- Reduced convective weather impact
- Improved accommodation of descents, routing, and speed requests
- Improved controller situational awareness
- Accurate and timely information for search and rescue.

The following paragraphs describe each of these mechanisms in more detail. The remainder of this paper focuses on our quantification of fuel savings from improved accommodation of climb requests.

A. **Improved accommodation of climb requests**

Efficient altitude profiles can save fuel and reduce emissions. Legacy surveillance sources often prevent changes to more fuel-efficient altitudes because of separation constraints. Being trapped at an unsatisfactory altitude may result in a flight incurring extra fuel burn for prolonged periods. This is more likely to occur in procedural environments. Improved surveillance will enable a reduction in separation in current procedural airspace, reducing traffic congestion. This, in turn, will allow controllers to clear aircraft to more favorable altitudes more quickly and more often, reducing fuel burn.

The simple, BADA-derived performance model we use to analyze fuel burn assumes a nominal take-off weight that is related to the aircraft type and distance to be flown. It does not consider the actual flight planning process. In addition to the direct fuel savings from flight at higher altitudes, once fuel savings become routine, dispatchers and pilots can load less fuel, reducing take-off weight and resulting in additional
fuel savings. This indirect or “cost to carry” fuel savings was analytically estimated post-simulation and added to the direct fuel savings.

Finally, reduced fuel burn will lead to reduced greenhouse gas emissions. No attempt was made in this analysis to place a value on this.

B. More efficient arrival/departure services at non-radar airports

Within the Oakland oceanic FIR, there are a number of airports that do not have an approach radar and consequently require control by Oakland Center. The absence of radar approach at these airports necessitates substantial separation between operations, resulting in delays. Improved surveillance will lead to reduced separation requirements between consecutive arrivals and/or departures, and consequently improved schedule adherence at these airports.

C. Reduced vertical collision risk

The FAA’s 2012 Air Traffic Organization (ATO) Safety Report [6] and a 2015 ATO Top 5 Fact Sheet [7] identified “Clearance Compliance Altitude” as a major safety issue, and this is now on the FAA’s continuous safety hazard list. This issue addresses the hazard occurring when an aircraft is at an altitude other than expected by the controller. This can happen, for example, because of misinterpreted radio communications.

The FAA Technical Center measures altitude deviations using the frequency and duration of Large Height Deviations (LHDs). The Technical Center uses this metric to estimate vertical collision risk, expressed in terms of fatal accidents per flight hour (FAPFH) for different airspaces. The Fiscal Year 2016 rate for Western Atlantic Route System (WATRS) airspace was 219.2 x 10^-9 FAPFH, which is 50 times greater than the Target Level of Safety (TLS).

ADS-B Out can be used to transmit the Selected Flight Level (SFL) entered by the pilot into the Mode Control Panel / Flight Control Unit (MCP / FCU) or FMS. The SFL can be compared to the Cleared Flight Level (CFL) by the automation system, and alert the controller in the event of a miss-match. European Air Navigation Service Providers (ANSPs) have implemented SFL-CFL alerting using Mode S and have realized a 63 percent reduction in risk exposure resulting from incorrect altitudes [8].

While SFL is not required by the DO-260B ADS-B standard mandated by the FAA, over 90 percent of DO-260B-compliant commercial aircraft broadcast SFL to satisfy the European ADS-B Out mandate.

D. Other benefits

Weather Deviation - Pilots often request weather deviations to avoid hazardous weather or severe turbulence. While the majority of these requests are cleared, ATC must sometimes deny a request to maintain safe separation between aircraft. The pilot may then decide to accept the risk of travel along the current trajectory, or deviate to protect the passengers and crew. In the latter situation, controllers must move other aircraft to ensure separation. During episodes of bad weather within oceanic airspace, ATC may also impose severe route restrictions, causing periods of route closures and lateral flight deviations from the previously cleared route of flight. Improved surveillance can reduce the impact of convective weather events in oceanic airspace by allowing for more pilot-initiated weather deviations around weather and by reducing the duration and frequency of adjacent route closures. Improved overall routing will follow as a result of the reduction in the lateral separation minimum.

Improved accommodation of descents, routing, and speed requests - There are many factors which influence flight profile preferences, including the desire for a smooth flight, schedule, and noise abatement, to name a few. There may be barriers within the air traffic system, including conflicting traffic or insufficient information, which limit the realization of operator preferences. The more flexible, predictable and reliable the air traffic system is, the more likely customer preferences can be fulfilled.

Less restricted descents

To date we have only analyzed changes in aircraft climbs resulting from improved surveillance. These represent the vast majority of altitude requests. However, there are some situations (e.g., crossing jet stream, turbulence) where pilots would prefer lower altitudes, but do not request them because they are worried they could be stuck at the lower altitudes. Reduced separation minima should give them more confidence to make descent requests as well as climbs.

Less restricted routing

To ensure separation and reduce workload, many airspaces have a defined route structure that is dependent on the minimum separation between aircraft. The static route structure is unlikely to provide the most optimal path for a flight. Reduced separation standards can allow additional routes that are closer together and may allow a path closer to the optimal. In addition, improved surveillance should enable greater use of User-Preferred Routes (UPRs). More optimal routing was not modeled in this study because a new route structure was not considered likely by FAA operational staff. An examination of the frequency of UPR filings before and after previous separation changes (i.e., from 50/50nm to 30/30nm) proved inconclusive.

Less restricted airspeeds

Aircraft can optimize fuel consumption by varying Mach number as conditions change. The poor accuracy and low update interval of legacy surveillance sources can result in ATC providing separation using constant Mach speeds. Improved surveillance should allow increased use of variable speeds.

Improved controller situational awareness - Surveillance systems aid ATC monitoring of aircraft, closing the gap between air traffic controller expectations of aircraft positions, based on clearances or instructions issued to pilots, and the actual positions of these aircraft. Earlier we discussed how selected altitudes in the ADS-B Out message can be compared to the altitude cleared by the controller. In addition to selected altitude, the improved surveillance alternatives considered here will present surveillance at higher update frequencies, allowing controllers to detect discrepancies between actual trajectories and expectations more quickly. Quicker detection should allow ATC to better mitigate risks or respond more quickly to emergencies.

Accurate and timely information for search and rescue operations - Aircraft Locating and Emergency Response Tracking (ALERT) will be one of the services provided
globally by Aireon SBA [9]. Improvements in notification time and position accuracy following a mishap will allow a quicker response with reduced chance of loss of life.

MODELING APPROACH AND ASSUMPTIONS

A. Simulation Model

The Global Oceanic Model (GOM) [10] is a fast-time simulation tool, developed in MATLAB, for examining fuel burn and flight time in oceanic airspace. GOM was produced under a partnership between the FAA and the Virginia Polytechnic Institute and State University (Virginia Tech). It is a time-based model that simulates individual aircraft from origin to destination along specified paths. During a normal run, which typically represents a day of actual operations, aircraft request climbs as fuel is burned off. Pairwise separation is enforced for oceanic airspace, with conflicts resolved at least 30 minutes in advance. Most conflict resolution in oceanic airspace and in the model is performed using altitude changes, although the model will also use speed or vectors if necessary.

Randomness is built into GOM via two distinct random seed variables; one that is applied for aircraft weight distribution, and the second for the distribution of aircraft FANS equipage. This is described further below.

B. Flight Schedules

Performing the analysis on all days in a year is time prohibitive, so a set of representative days for each year was used. Each year, the FAA Performance Analysis office selects a set of representative days for the previous fiscal year (FY) to be used in analysis and simulations [11, 12]. The FAA fiscal year begins in October and ends in September. The days are chosen so that they represent a wide variety of traffic and weather conditions, and when extrapolated to a full year most closely match many yearly performance metrics. Oceanic metrics are included in choosing the days. Table 1 presents the 20 representative days chosen for FY 2016 and used in this analysis.

<table>
<thead>
<tr>
<th>Date</th>
<th>FAA FY2016 Representative Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/12/2015</td>
<td>03/03/2016 06/27/2016</td>
</tr>
<tr>
<td>10/13/2015</td>
<td>03/06/2016 07/18/2016</td>
</tr>
<tr>
<td>11/11/2015</td>
<td>03/17/2016 08/04/2016</td>
</tr>
<tr>
<td>12/04/2015</td>
<td>04/07/2016 08/30/2016</td>
</tr>
<tr>
<td>12/27/2015</td>
<td>05/06/2016 09/10/2016</td>
</tr>
<tr>
<td>01/09/2016</td>
<td>05/21/2016 09/23/2016</td>
</tr>
<tr>
<td>01/24/2016</td>
<td>06/17/2016</td>
</tr>
</tbody>
</table>

Flight schedules for future years were created by the FAA’s Systems Analysis and Modeling group using inputs from the Office of Aviation Policy and Plans growth projections for international flights [13]. We begin by mining historical flight plans from the FAA Traffic Flow Management System (TFMS) data archive for the days modeled. New flights are generated for future years by bootstrapping from the set of historical flights while varying the scheduled departure times. Since GOM does not represent airport or domestic airspace constraints, the resulting schedule is first input to the System-Wide Analysis Capability (SWAC) model [14, 15]. SWAC models many U.S. airports and domestic airspace. Using SWAC as a pre-processor for GOM ensures that wheels-off and oceanic airspace entry times for U.S. departures are realistic.

The years 2016, 2020, 2025, 2030, and 2035 were modeled, and results linearly interpolated for intervening years. Using current FAA policy on traffic growth for investment decisions, the growth was capped in 2028, based on a sliding 10-year window. Fig. 2 presents the average daily flight counts for each airspace for the lifecycle.

C. Aircraft Avionics

Current and future oceanic separation standards are dependent on aircraft communications, navigation, and surveillance capabilities. We refer to these capabilities generally as “aircraft equipage.” The scenarios examined here depend on one of two configurations:

1. ADS-B Out (1090) + ADS-C + CPDLC using Satellite Communications + Required Navigational Performance (RNP) -4 to support 15/15 NM separation

2. ADS-C (with faster update rate) + CPDLC using Satellite Communications + RNP-4 to support 23/23 NM separation.

The limiting equipage in both cases is CPDLC using Satellite Communications. The U.S. ADS-B mandate means that nearly all aircraft in oceanic airspace will be equipped by 2020. ADS-C and CPDLC using Satellite Communications (Datalink) are generally installed together as part of the FANS suite. Aircraft without FANS generally use High Frequency (HF) radio communications. While there are FANS mandates in oceanic airspace controlled by Canada, Great Britain, and Portugal, the same is not true in U.S. oceanic airspace. RNP-4 is also a constraint, but RNP-4 capability appears to be mirroring CPDLC in both the Atlantic and Pacific.

Fig. 3 and 4 show historical operations and equipage trends in U.S. oceanic airspace (for this analysis, we use a combined aircraft equipage in Oakland and Anchorage FIR). These trends are used to project future equipage levels using the following method:

1. Current FANS equipage levels by aircraft type were obtained from an analysis of flight plans provided by the MITRE Center for Advanced Aviation Systems Development for each ocean. Historical flights and bootstrapped flights were randomly assigned equipage using this data.

2. A logistics curve was fitted to the percentage of Datalink equipped aircraft time trend in each ocean (Fig. 3 and 4). These curves specify the target equipage level for future years.
3. FANS equipage was randomly increased by aircraft type until the fleet target equipage level was achieved.

4. Any remaining unequipped flights that transit Gander, Shanwick, or Santa Maria FIR were also changed to FANS to reflect the upcoming mandate in those regions.

Table II presents the final equipage projections for the years modeled. The faster growth of equipage in the Atlantic reflects the impact of the FANS mandate in neighboring airspaces (i.e., Gander, Shanwick, and Santa Maria FIR).

<table>
<thead>
<tr>
<th>Year</th>
<th>Atlantic</th>
<th>Pacific</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>89%</td>
<td>84%</td>
</tr>
<tr>
<td>2025</td>
<td>92%</td>
<td>94%</td>
</tr>
<tr>
<td>2030</td>
<td>97%</td>
<td>96%</td>
</tr>
<tr>
<td>2035</td>
<td>99%</td>
<td>97%</td>
</tr>
</tbody>
</table>

D. Routes and Route Structure

Since to feed the simulation we use historical flight plans, we have assumed that the existing route structure remains unchanged. While it is possible that changes will occur, the FAA could not predict exactly where or when these would happen over the geographical area and timescales considered.

In today’s system, many oceanic flights use UPRs that are not depicted on charts. The days modeled include several of these flights for certain city pairs. The frequency of future UPR flights is assumed to grow linearly with the growth of demand along the relevant city pairs. Additional expansion of UPR usage was not considered in this analysis.

E. Altitude Requests

In oceanic controlled airspace, as in all controlled airspace, aircraft must request an ATC clearance to deviate from their route, including any deviations in altitude. An altitude request is considered ‘handled’ when ATC has received and responded to the request. A request is cleared when ATC approves the requested altitude change.

Since the primary benefit of reduced separation is assumed to be increased accommodation of altitude change requests, the current frequencies of altitude requests and clearances are important factors. Historical data captured by the ATOP system was used to estimate these factors, and to adjust several model parameters that govern how often aircraft request altitude changes. Our analytical results are sensitive to these factors, since the more often aircraft can climb, the greater the fuel savings from reduced separations.

GOM parameters were adjusted to match the observed altitude change request frequency and clearance likelihood, as depicted in Fig. 5 and 6. Airline representatives who provided feedback on this study suggested that a reduction in separation minima would likely influence pilots to ask for more altitude changes. Indeed, observed ‘average altitude requests handled’ slightly increased following a decrease in separation minima in 2012 and 2013.

To test this hypothesis, we examined altitude request behavior during previous oceanic separation reductions. We regressed a time trend and a dummy variable representing previous separation reductions on monthly altitude requests per CPDLC flight from October 2007 through September 2016. For ZNY, the separation change dummy was significant and indicated a 15 percent increase over the average (from 0.66 to 0.76 requests per CPDLC flight), while the time trend variable was not significant. For ZOA and ZAN, the separation change dummy was also significant, with an increase of 11 percent over the average (from 1.11 to 1.23 requests per CPDLC flight), while the time trend variable was significant and negative, but very close to zero. We therefore assumed that a similar behavior change will follow future separation minima reductions, resulting in an increase of 10 percent in altitude requests after a reduction from 30/30 NM separation to reduced separation.

We also had to make assumptions as to the size of altitude changes to expect in each region. Reduced Vertical Separation Minima (RVSM) of 1,000 feet is allowed in both oceans; however, an analysis of historical track data indicated that 1,000 foot changes are most used in the Pacific, while the vast majority of altitude changes in the Atlantic are 2,000 feet. These findings were verified with oceanic controllers, who explained that many routes in the Pacific operate in one direction, so that all flight levels are open for climbs. Conversely, in the Atlantic, most routes operate in both directions, so altitudes are chosen based on direction of flight to reduce the risk of mid-air collision.
shows speeds at different altitudes were
d to satisfy a target level
late. Flight technology Roadmap 
for types projected in the
r the days modeled was obtained from
NCEP) and/or
re more fuel efficient than
raft Data.

iagrams, of “control by
load is
pe of the same size and range.

operating load (consisting of minimum fuel load, o
weight, less all justifiable aircraft equipment, and less the
payload segment data, and is used to calcu
s the T
Statistics (BTS) Air Carrier Statistics database, also known
combination of sources. The U
Bureau of Transportation
istics (BTS) Air Carrier Statistics database, also known
as the T-100 data bank [17], contains airline market and
segment data, and is used to calculate a distribution of
payloads for a particular aircraft type. Payload is defined as
the maximum takeoff weight of an aircraft, less the empty
weight, less all justifiable aircraft equipment, and less the
operating load (consisting of minimum fuel load, oil, flight
crew, steward’s supplies, etc.). The BADA 3.13 model
provides Operational Empty Weight (OEW) data for each
aircraft type in the model. Finally, payload/range diagrams,
which can be obtained from the aircraft manufacturer, are
used to estimate a distribution of possible OEW + Payload
values for a specified route distance and aircraft type. For
each flight, a value is randomly selected from the OEW +
Payload distribution based on expected flying distance
between origin and destination.

Wind data for the days modeled was obtained from the
National Centers for Environmental Prediction (NCEP)
dataset provided by the National Oceanic & Atmospheric
Administration (NOAA). In GOM, 42 aircraft types were
modeled, with other types mapped to these. Additional
information on the application of BADA to GOM can be
found in [18].

G. Fleet evolution
Future evolution of the fleet was considered in the
modeling.

The SWAC model used for schedule generation
incorporates a fleet evolution algorithm that replaces old
aircraft types with newer types, as specified by the FAA’s
Carrier Fleet Forecast for 2016-2037 [19]. The forecast
includes currently available aircraft types as well as projected
aircraft types not yet available. FY2016 flight schedules were
processed through SWAC to generate the evolved fleet for
each simulation year (2016, 2020, 2025, 2030, and 2035).

In general, newer aircraft are more fuel efficient than
older aircraft. Many aircraft from the FY2016 schedule were
evolved to types already available in GOM, so the fuel
efficiency of these was taken into account directly. Other
future aircraft types projected in the fleet forecast are not
currently supported in GOM. For these aircraft, we assumed
an increase in fuel efficiency of 40 percent compared to a
previous aircraft type of the same size and range. The
reduction was based on the maximum fuel reduction for new
long-range aircraft designs after 2020 documented in the
2013 IATA Technology Roadmap [20]. We consider this to
be a very conservative assumption, since the more efficient
the aircraft, the less fuel savings from altitude optimization
and thus the less benefit from reduced separation.

H. Separation and conflict management
Current operations in oceanic airspace use procedural
separation, based on future aircraft position as received and
interpolated from flight surveillance data. Surveillance data
originates from position reports from the aircraft via ADS-C
(from FANS aircraft) or HF radio via the radio operator
(from non-FANS aircraft). Position reports include current
position and intent information (i.e., Next waypoint position
and Next+1 waypoint position).

Procedural separation implies that flights are being
separated by executing a set of rules that are dependent on
conditions and which, when adhered to, satisfy a target level
of safety. ATOP was designed to support the application of
procedural separation using a model of “control by
exception” [2]. This means that the controller is only notified
when there is an actual/predicted separation violation and/or
when the flight is not following its cleared flight profile. The
controller does not continuously monitor aircraft positions to
actively ensure separation as he does when using tactical
separation, although he does maintain situational awareness.

FIGURE 5. ZNY AVERAGE ALTITUDE REQUESTS HANDLED AND
CLEARED PER CPDLC FLIGHT

FIGURE 6. ZOA + ZAN AVERAGE ALTITUDE REQUESTS HANDLED AND
CLEARED PER CPDLC FLIGHT

F. Aircraft Performance
Fuel burn and cruise speeds at different altitudes were
modeled using the European Organization for the Safety of
Air Navigation’s (EUROCONTROL) Base of Aircraft Data
BADA 3.13 performance model [16]. BADA uses a total
energy model to derive aircraft performance, including
standard aerodynamic coefficients and equations that are
used to estimate lift and drag. Additional parameters
including takeoff mass, wind, flap configuration, and phase
of flight are used to calculate fuel burn at any given point in
the flight profile.

Takeoff weight estimates are generated from a
combination of sources. The U.S. Bureau of Transportation
Statistics (BTS) Air Carrier Statistics database, also known
as the T-100 data bank [17], contains airline market and
segment data, and is used to calculate a distribution of
payloads for a particular aircraft type. Payload is defined as
the maximum takeoff weight of an aircraft, less the empty
weight, less all justifiable aircraft equipment, and less the
operating load (consisting of minimum fuel load, oil, flight
crew, steward’s supplies, etc.). The BADA 3.13 model
Non-radar time-based and distance-based separation rules are used to provide safe separation in oceanic airspace. Same-direction longitudinal separation is often 10 minutes for time-based separation but can be larger depending on the crossing angle. In addition to the procedural rules, reduced distance-based lateral and longitudinal separation with a value of 30 or 50 NM, depending on the aircraft equipage and ADS-C surveillance reporting rate, may also be used in designated airspace in accordance with ICAO rules.

ADS-C equipage is a key component in the application of the 50/30 NM longitudinal and 30 NM lateral separation standards. While reporting of present position and altitude is infrequent by radar standards (i.e., between 10 and 27 minute periodic reports, depending on the standard), the reports also contain intent information consisting of future position estimates. This information is critical for the trajectory-based operations of the oceanic controller and automation.

Currently, the smallest separation standard that can be applied is 30 NM longitudinal, 30 NM lateral, and 1,000 feet vertical, except during climb-through procedures described later. The use of 30/30 NM separation is limited to aircraft meeting the RNP-4 standard with active CPDLC connections and an appropriate ADS-C contract with a periodic reporting rate of every 10 minutes. Establishment of an ADS-C contract with lateral deviation event reports is also required.

The FAA began applying 30/30 NM separation standards for suitably equipped aircraft in Oakland’s oceanic airspace in 2007. An ICAO Amendment for 30 NM lateral and longitudinal separation was approved for Anchoragè’s oceanic airspace in December 2012. Within New York’s oceanic airspace, the 30/30 standard was implemented on December 10, 2013.

The advanced surveillance scenarios analyzed here examine lower separation minima. Table III lists the separations used in the modeling for FANS via SATCOM w/RNP and aircraft without FANS, for the legacy case and two alternatives. The procedural 10 minute separation standard is applied as 80 NM lateral and 80 NM longitudinal separation.

### Table III. Separation Standards for Simulation

<table>
<thead>
<tr>
<th>Aircraft Equipage</th>
<th>Legacy Case</th>
<th>More frequent ADS-C</th>
<th>SBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>FANS via SATCOM w/RNP</td>
<td>30/30 NM</td>
<td>23/23 NM</td>
<td>15/15 NM</td>
</tr>
<tr>
<td>No FANS</td>
<td>80/80 NM</td>
<td>80/80 NM</td>
<td>80/80 NM</td>
</tr>
</tbody>
</table>

a. All aircraft are assumed to be turbofans and equipped with ADS-B.
b. Current data suggests that nearly 100 percent of FANS aircraft are RNP-4 capable.
c. At the time of writing ICAO was considering a 20 NM longitudinal standard.

ATOP includes a conflict probe that examines potential conflicts two hours into the future for flights both within and scheduled to be in the airspace. The controller has some discretion on when to resolve the potential conflict, but must do so when it is projected to be 30 minutes or less in the future. The vast majority of conflict resolutions in US oceanic airspace are altitude-based (as opposed to a mix of vectoring, altitude, and speed resolutions used in domestic airspace). In GOM, resolutions occur 30 minutes prior to the potential conflict and are generally altitude-based, although speed and vectors may be used. Lower separation values result in fewer conflicts and more opportunity to resolve the conflicts efficiently.

### I. Interaction with neighboring ANSPs

The capabilities, operational evolution plans, and agreements with surrounding international ANSPs are a major factor in how the U.S. controls flights in oceanic airspace. If, for example, the neighboring FIR restricts aircraft to enter their airspace at specific fixes or altitudes, or with a larger longitudinal spacing, U.S. controllers must respond accordingly. These practices will likely cause flight inefficiencies that cannot be avoided. The FAA must consider the practices and restrictions of boundary FIRs when deciding if and when to approve reduced separation standards and procedures in U.S. airspace.

For simplicity, in this analysis separation requirements in neighboring domestic airspace were ignored (this is the same as applying zero separation).

Table IV lists our separation assumptions for neighboring oceanic FIRs for this analysis.

### Table IV. Separation Standards Assumed for Neighboring FIRs

<table>
<thead>
<tr>
<th>FIRs</th>
<th>Today</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gander (Canada), Sharwick (UK), Santa Maria (Portugal)</td>
<td>30/30 NM FANS, 80/80 NM non-FANS</td>
<td>15/15 NM FANS + FANS mandate</td>
</tr>
<tr>
<td>Port Moresby (Australia)</td>
<td>80/80 NM non-FANS</td>
<td>80/80 NM FANS</td>
</tr>
<tr>
<td>Fukuoka (Japan)</td>
<td>30/30 NM FANS, 80/80 NM all aircraft</td>
<td>80/80 NM all aircraft</td>
</tr>
<tr>
<td>Manila (Philippines), Ujag Pandang (Indonesia), Port Moresby (New Guinea)</td>
<td>80/80 NM all aircraft</td>
<td>80/80 NM all aircraft</td>
</tr>
<tr>
<td>Auckland (New Zealand), Tahiti, Nadi and Nauru (Airservices Australia)</td>
<td>30/30 NM FANS, 80/80 NM non-FANS</td>
<td>30/30 NM FANS, 80/80 NM non-FANS</td>
</tr>
</tbody>
</table>

### J. Service volumes

The model’s output is segregated into separate regions, known as Service Volumes (SVs), to aid with the analysis of results. Fig. 7 presents the SVs used for the Atlantic and Fig. 8 for the Pacific.

### K. Model validation

GOM was validated by comparing its output with operational data, using the following metrics:

- Number of altitude change requests
- Percentage of altitude change requests granted
- Distribution of flight time and distance traveled across oceanic regions
- Distribution of cruise altitudes upon entry of U.S. oceanic airspace.
We adjusted two model parameters to match the climb metrics: the “climb check” interval, which specifies how often a flight can check if it is light enough to request a climb to a higher altitude, and the “climb cool down,” which specifies the wait time before a flight can request another altitude change after its last altitude change request.

L. Climb and descent procedures

In 2017, two new climb/descent procedures were implemented in U.S. airspace. The ADS-C Climb Descent Procedure (CDP) enables aircraft equipped with CPDLC and ADS-C to climb or descend through altitudes with less than standard longitudinal separation. This procedure is initiated by the oceanic controller when standard longitudinal separation cannot be achieved because of an aircraft at an intermediate flight level. The ADS-B In-Trail Procedure (ITP) enables a similar maneuver for aircraft equipped with ADS-B In. Using this procedure, the aircraft desiring to climb or descend observes proximate ADS-B equipped aircraft using a cockpit display. The flight crew uses the information to determine if the ITP criteria have been met before making a request for the maneuver from the oceanic controller.

ITP and CDP have been directly incorporated in GOM. These procedures are available to all FANS-equipped aircraft in the baseline and reduced scenario cases. While ITP will only be applied by aircraft with the proper ADS-B In application, CDP is available to all FANS aircraft. The effect of the climb through procedures is a small increase in the approval rate for climb requests in the baseline case.

M. Limitations

GOM only considers conflicts between aircraft that penetrate oceanic airspace. Potential conflicts with non-oceanic traffic before entering or after leaving oceanic airspace are not considered. Likewise, while we have adjusted wheels-off times for departures from U.S. airports by using the SWAC model as a preprocessor, we have not attempted anything similar for departures from foreign airports bound for the U.S. Thus traffic entering U.S. airspace from abroad may be more closely spaced than in actuality. We do not believe that this effect is significant, since virtually all of this traffic will first pass through foreign oceanic airspace, which is represented by GOM.

While GOM does use historical wind data, it does not model convective weather or turbulence, which can have large impacts on trajectories in some regions.

RESULTS

GOM was used to model the legacy case (i.e., current separation standards) and two alternatives: more frequent ADS-C reporting, and SBA. The other factors in the test matrix were:

- The year represented (2020, 2025, 2030, 2035)
- The day of the year (20 unique days, repeated for each year)
- The region modeled (Atlantic, Pacific).

In all, there were 1,440 model runs to get a full set of results across days, years, oceans, and alternatives. Table V presents the annual direct fuel savings as computed with GOM, by year, oceanic region, and alternative.

<table>
<thead>
<tr>
<th>TABLE V. ANNUAL DIRECT FUEL SAVINGS (KG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBA</td>
</tr>
<tr>
<td>FY</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>2020</td>
</tr>
<tr>
<td>2025</td>
</tr>
<tr>
<td>2030</td>
</tr>
<tr>
<td>2035</td>
</tr>
</tbody>
</table>

As mentioned previously, GOM does not modify take-off weight based on anticipated fuel savings. To account for reduced fuel loading, and a consequent additional reduction in fuel burn, we adjusted the results using factors specified in the [21]. This report describes a methodology to quantify the incremental fuel impact of adding additional weight to an aircraft. The formula for incremental fuel burn in gallons is the weight penalty per aircraft in pounds (Wp) times flight
hours times 0.005 incremental gallons per flight hour per pound, or:

\[
\text{Incremental fuel} = Wp \times \text{flight hrs} \times 0.005
\]  

(1)

To estimate the change in the cost-to-carry benefit, we apply this formula to the estimated fuel weight savings (Ws) as opposed to the weight penalty. The formula is then:

\[
\text{Incremental fuel savings} = Ws \times \text{flight hrs} \times 0.005
\]  

(2)

To translate to kilograms we use 2.2 lbs/kg and 3.05 kg/gal.

Table VI presents the additional annual indirect, or cost-to-carry, fuel savings, by year, oceanic region, and alternative.

<table>
<thead>
<tr>
<th>FY</th>
<th>Atlantic</th>
<th>Pacific</th>
<th>Atlantic</th>
<th>Pacific</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>4,259,587</td>
<td>6,013,700</td>
<td>3,441,648</td>
<td>5,226,565</td>
</tr>
<tr>
<td>2025</td>
<td>5,575,130</td>
<td>7,865,542</td>
<td>4,302,496</td>
<td>6,000,308</td>
</tr>
<tr>
<td>2030</td>
<td>6,587,617</td>
<td>8,312,610</td>
<td>6,013,700</td>
<td>6,281,038</td>
</tr>
<tr>
<td>2035</td>
<td>6,695,970</td>
<td>8,070,657</td>
<td>4,927,289</td>
<td>6,106,602</td>
</tr>
</tbody>
</table>

Fig. 9 illustrates the results from Tables V and VI in stacked and clustered bar charts. The bottom of each stack represents the fuel savings estimated directly by GOM, and the lighter color at the top of each stack represents the cost-to-carry savings. Tables VII and VIII show the direct and cost-to-carry savings by oceanic sub-region or Service Volume. The additional fuel savings is substantial, but varies greatly based on the overall flight length. For relatively short flights (e.g., ZNY WATRS) the additional fuel savings can be less than 20 percent, while for long flights (e.g., ZOA Southeast) the additional fuel savings is nearly 40 percent.

![Figure 9. Total Fuel Savings (kg)](image)

Additional model runs were performed to examine the variability of results. First, we examined the sensitivity of results to the lateral separation minimum assumption for non-FANS equipped aircraft. For the results reported thus far we have assumed that aircraft must be separated laterally by 80 nm. A new release of GOM supports asymmetrical separation minima (i.e., different lateral and longitudinal minima). The FAA Air Traffic Control manual [22] indicates that 50 NM is the typical lateral separation minimum for aircraft using HF radio for position reporting and satisfying RNP 10 navigation requirements. We conducted some experiments using 50 NM lateral for HF aircraft (vice 80 NM), and found that, in most scenarios, the fuel savings for Space-Based ADS-B increased by about 10 percent.

We also conducted experiments by varying the seeds for two random variables in the model: one that impacts take-off weights, and another impacting which aircraft are chosen to be FANS equipped. The results indicate that the estimates presented here lie near the middle of the distribution, but there is considerable variability. Fig. 10 illustrates the distributions of the ratio of fuel savings for these random trials to the nominal fuel savings, for each ocean. Observe that the interquartile range of the distributions can be as much as 25 percent from just these two random variables.

![Figure 10. Distributions of Fuel Burn Savings Ratios](image)

CONCLUSIONS AND NEXT STEPS

Results from this analysis suggest that reduced separation in oceanic airspace produces significant benefits through improved accommodation of altitude requests. However, these results vary significantly by airspace volume, due to such factors as route length, traffic density, aircraft gauge, and aircraft avionics equipage. The results are also sensitive to a number of modeling assumptions, including aircraft gross weight, avionics capability, and separation standards for non-equipped aircraft. These results have already been used to justify improvements in the FAA’s ATOP automation platform. We continue to explore the potential of SBA to save fuel and provide other benefits for airspace users and the FAA.

ACKNOWLEDGMENT

The authors would like to thank the Advanced Surveillance – Enhanced Procedural Separation (ASEPS) project within the FAA Surveillance and Broadcast Services Program Office and the Systems Engineering and Integration Office who supported this effort. Research colleagues Christina David and Robert Raheb from Noblis Inc., Paul Truong and James Bonn of FAA, and Nicolas Hinze and Prof. Antonio Trani of Virginia Tech were vital in helping tune the model and produce results.
REFERENCES

[1] ICAO FIR viewer available at website http://gis.icao.int/flexviewer


AUTHOR BIOGRAPHIES

Dan Howell is a Senior Operations Research Analyst at Regulus Group. Dr. Howell holds a B.S. in Physics from Missouri State University and a Ph.D. in Physics from Duke University. He has supported multiple FAA programs including Surveillance and Broadcast Services, Time Based Flow Management, and Terminal Flight Data Manager.

Rob Dean is an Operations Research Analyst at Regulus Group. He holds a B.A. in Mathematics from the University of Virginia, a B.S. in Airport Management from the Vaughn College of Aeronautics, and a M.S. in Systems Engineering from George Mason University. Mr. Dean has worked as an air traffic control specialist with the FAA and obtained Certified Tower Operator qualification. He currently supports multiple FAA programs specializing in modeling and simulation.

Joseph Post is Acting Director of Systems Engineering & Integration at FAA. He holds a B.S. in Aeronautics and Astronautics from the Massachusetts Institute of Technology, an M.S. in Engineering & Applied Science from Yale University, and an M.A. in Economics from George Mason University. Mr. Post holds a commercial pilot certificate with instrument rating.