Effects of Future Launch and Reentry Operations on the National Airspace System

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Space launch and reentry operations are expected to increase in the coming years with the expansion of commercial space operators and spaceport development. Every launch and reentry in the United States requires the operation to pass through the National Airspace System, resulting in the implementation of protective airspace closures, which impede the flow of air traffic. This paper describes a fast-time computer simulation study conducted by the Federal Aviation Administration to quantify the effects of future launch and reentry operations on the National Airspace System and to demonstrate the possible benefits of one proposed strategy to reduce these impacts. Results showed that increasing the number of launch and reentry operations in the United States using current airspace closure methods would significantly affect the efficiency of flights in the National Airspace System. However, implementing new concepts to calculate more dynamic airspace closures would greatly reduce this impact.

I. Introduction

Many years ago, President Lyndon B. Johnson said, "The future of this country and the welfare of the free world depend upon our success in space. There is no room in this country for any but a fully cooperative, urgently motivated all-out effort toward space leadership. No one person, no one company, no one government agency, has a monopoly on the competence, the missions, or the requirements for the space program [1]."

The spirit of his message is more alive today than ever before. With the introduction of commercial space operators, an increase in space launch and reentry operations with a wide variety of missions is expected at existing and new locations across the United States [2]. Consequently, existing procedures and processes for managing and coordinating the operations will not efficiently accommodate this expansion of the National Airspace System (NAS). Different architectures, tools, procedures, and processes must be researched and developed to minimize the effects of increased commercial space launch and reentry operations (hereafter referred to as “space operations”) on the NAS. The purpose of the paper is to describe the objectives, methods, analyses, and results of a study used to quantify the effects of future space operations on the NAS and to demonstrate the possible benefits of one proposed strategy to reduce these impacts. The study summarized in this paper is fully documented in a U.S. Department of Transportation technical note [3].

A. Background

Historically, space operations have been infrequent, isolated events conducted for national interest or security. They were primarily initiated by NASA and/or the U.S. Department of Defense. To ensure the safety of other NAS users (i.e., airline, general aviation, etc.) during a space operation, these organizations coordinated with the affected Federal Aviation Administration (FAA) air traffic management (ATM) teams to block and manage airspace that could be impacted by the space operation [4,5]. This coordination was executed through a combination of Notices to Airmen (NOTAMs) and Air Traffic Control System Command Center Advisories. The FAA ensures the safety of aircraft during a space operation by collaborating with operation planners (such as range and vehicle operators) to determine which airspaces should be closed to air traffic. Closed airspaces typically include predefined special activity airspaces, such as warning and restricted airspaces, as well as new hazard areas created specifically for the operation. Several tools and methods to create hazard areas specific to a particular space operation have been documented [6–9]. Air traffic avoids these closed airspaces during an activation period defined in a NOTAM. Once the activation period expires, the airspace restriction is lifted, and air traffic can use the airspace as normal.

NOTAMs are published in advance of the operation, and many airlines preemptively change their flight route to avoid the blocked airspace. When necessary, controllers will direct air traffic around these airspace blockages. Current airspace closures are static and overly conservative; although they ensure the safety of NAS users, they do not allow for flexibility in air traffic control (ATC) maneuvering and significantly reduce the efficiency of flights during space operations. An analysis of the SpaceX Falcon 9 launch from Cape Canaveral on 1 March 2013 showed that the space operations caused affected flights in the Florida en route centers to travel a combined total of 6584 n mile longer, burn 99,620 lb more of fuel, and fly 13.6 h longer [10].

B. Related Research

With the expansion of commercial space operators and spaceports, the number of space operations is expected to greatly increase in the coming years across the NAS [2]. Figure 1 [11] illustrates current and future launch sites in the United States. The information shown in the figure was compiled in 2014 at the start of this study; several of these lists have changed with the addition of more licensed spaceports such as Houston Spaceport at Ellington Field, Texas.

As the number of space operations increases over the next decade, it will become increasingly difficult to efficiently accommodate this expansion of the NAS environment using existing procedures and processes. Consequently, different architectures, tools, and procedures must be researched and developed to safely and efficiently integrate commercial space operations into the NAS. An overview of research in managing commercial space vehicles is presented in [12]. The FAA’s Space Vehicle Operations (SVO) program developed a concept of operations (CONOPS) document that proposed innovative ideas for integrating space vehicle and air traffic operations into the NAS while maintaining current safety and separation standards [2]. The SVO CONOPS compiled existing
research by government, industry, and academia to describe a future NAS in which automation and procedures allow for more efficient planning and managing of airspace during space operations. The document presented a methodology for linking airspace management strategies during space operations to the probability of an off-nominal event during launch or reentry. This methodology assumes that the future NAS will be capable of reacting to highly dynamic and responsive ATM procedures through improvements to automation, communication, and surveillance tools.

One of the airspace management strategies detailed in the SVO CONOPS is space transition corridors (STC). A concept studied by NASA [13], STCs would be used to segregate air traffic from space operations when the likelihood of an off-nominal event for the space vehicle is moderate. Focusing on three spatial (length, width, and azimuth) and two temporal parameters (duration and midpoint of the airspace closure time window), the STC concept aims to ensure that FAA aircraft safety requirements are met without causing an excessive impact to air traffic. Although the corridors used in this strategy may remain static during the identified time window like seen today in current airspace closure strategies, the size and duration of the customized airspace closures are proposed to be significantly smaller. A simulation study evaluated the use of STCs during launch operations at Cape Canaveral [13]. The dimensions of the simulated corridor were kept constant (200 × 30 n mile with an unlimited vertical element), and the azimuth and time parameters were varied to capture the change in number of rerouted flights and their change in distance flown. The study did not attempt to isolate the benefits of using STCs over current airspace management strategies, but it concluded that similar simulation studies could be used to inform ATC and space operators during mission planning to proactively minimize the impact to air traffic during a launch or reentry operation [13].

Alternatively, Stanford University’s Aerospace Design Lab proposed the use of four-dimensional (4-D) compact envelopes to provide spatially and temporally dynamic airspace closures. The 4-D envelopes are calculated as a function of altitude based on probabilistic off-nominal risk analyses of space vehicle operations. A new open-source tool called the Stanford University Framework for Aircraft Risk Management (SU-FARM) is used to perform the risk analysis for each space vehicle and to calculate appropriate compact envelopes required to ensure that quantifiable aircraft safety levels adhere to FAA safety requirements [14]. Similar to the STC concept, the compact envelopes are customized for each space vehicle and consider their unique and current probability of failure. The concept assumes that automation, communication, and surveillance capabilities in a future NAS will allow for flights to dynamically react to off-nominal events during a launch or reentry operation and will minimize the reaction time required to make these maneuvers to avoid falling debris. Therefore, compact envelopes only protect three-dimensional airspace that is at immediate risk of collision with falling debris in an off-nominal event, and they rapidly activate and deactivate as the level of risk for that airspace changes.
provides a conceptual comparison of a current airspace closure (left, shown by the blue area) against a 4-D compact envelope (right, also shown by the blue area) given the same launch trajectory.

In parallel to the study described in this paper, a large fast-time simulation study was conducted to quantify the benefits of 4-D compact envelopes. The SU-FARM tool was used to calculate 4-D compact envelopes for a variety of space vehicle launches and reentries across the NAS. Three months of space and air traffic operations were simulated, and the efficiency of flights was calculated under two conditions: when traditional airspace closure strategies were used and when 4-D compact envelopes were used. This study concluded that 4-D compact envelopes could nearly eliminate current impacts to the NAS during a space operation [15].

II. Study Approach

A. Research Objective

The FAA’s SVO research program sponsored the FAA’s Modeling and Simulation Branch to conduct an experiment to quantify the potential effects of increased commercial space operations on a single day of en route operations in the NAS. The study also demonstrated the possible benefits of one proposed strategy to reduce these impacts: 4-D compact envelopes. Changes to flight distance, fuel burn, flight duration, and sector throughput caused by increased space operations across the United States in two future years were identified. Researchers collaborated with Stanford University to calculate 4-D compact envelopes to demonstrate the potential benefits of using more dynamic airspace management strategies.

This study answered the following research questions.

1) Using current ATC tools, procedures, and processes, how will the potential increase in commercial space operations affect en route traffic in the future?

2) Is it possible to reduce the potential effects of commercial space operations on the NAS by using new airspace closure procedures such as 4-D compact envelopes? If so, what are the potential benefits associated with this change?

A fast-time simulation was conducted to answer the two research questions. Fast-time modeling and simulation exercises are typically performed to examine system performance, including benefits assessment and the analysis of capacity, safety, risk, and efficiency. They are often used in the early stages of validation to get initial estimates of potential benefits. Fast-time simulation and modeling studies are also useful for identifying potential problem areas where real-time simulation studies are necessary for further exploration [16].

There are several fast-time simulation tools available with varying scopes and degrees of fidelity to study effects on the NAS. For this study, AirTop was used to simulate en route operations across the United States. AirTop is a commercial off-the-shelf, multi-agent simulation tool developed by AirTopsoft SA, a European company specializing in the development of air traffic simulation and optimization systems [17]. The AirTop simulation tool is designed to capture many aspects of the ATM domain. The tool includes a user-defined rule-based system, used to simulate en route restrictions and dynamic rerouting in this study.

B. Experimental Design

To answer the two preceding research questions, analysts performed three sets of fast-time simulation scenarios to quantify changes in flight distance, fuel burn, flight duration, and sector throughput caused by increased space operations across the United States in two future years. The simulation scenarios included six days of space operations at various locations and with multiple vehicles; in the simulation, airspace closures similar to those typically used today represented the space operations in the NAS. Finally, the third set of scenarios simulated the same space operations with the use of 4-D compact envelopes (4DEs).

For each set of simulation scenarios, two factors were varied: forecasted year and level of space operations. Traffic levels forecasted for 2018 and 2025 in the terminal area forecast were simulated to capture changes in NAS performance with increased amounts of traffic. This study used the forecasted flight schedules developed by the FAA’s Forecast Analysis group whose algorithm for creating future traffic schedules uses historical data on planned launches and departure times of commercial air traffic [18]. These years were chosen to represent a near-term as well as far-term increase in air traffic and space operations. The midterm of the FAA’s NextGen improvements has typically been considered 2018, whereas its far term is 2025 [19].

To mitigate the uncertainty in predicting future commercial space operations, three frequency levels of operations were modeled for each forecast year. The research team used projections from the FAA’s Office of Commercial Space Transportation as well as their own research findings to develop estimates for the number of yearly space operations in 2018 and 2025. The team created three levels to represent varying likelihood of space operations: low frequency (90% confidence that this frequency of space operations or higher will occur by the forecasted year), medium frequency (50% confidence that this frequency of space operations or higher will occur by the forecasted year), and high frequency (10% confidence that this frequency of space operations or higher will occur by the forecasted year).

Analysts in the SVO program used the yearly projections for each frequency level to create potential schedules of space operations for each day of the year. The schedules included the time, location, and type of space operation and were built with key constraints such as projected yearly operations by spaceport, planned space operations at each spaceport, and likely time of day necessary to meet the operation’s mission (such as daylight hours for tourist flights). A larger set of these daily schedules was used for a parallel study to quantify annual effects of space operations on the NAS [15].

Using these projected schedules, researchers established scenario assumptions for the space operations such as time, location, and type of operation. One day was chosen for simulation from the schedule per forecasted year (2018 and 2025) and space operations level (low, medium, and high), resulting in six different day scenarios with varying space operations occurring at different locations in the United States, including Hawaii and Alaska, which are key launch sites for commercial operations. The schedules were chosen such that the number of space operations was equal to the average number of daily operations calculated from the team’s yearly projections.

It is important to note that the six days used for simulation each contain different space operations in different locations throughout the United States. The launch of certain vehicles may have caused more disruptive airspace closures than others, and launches or reentries in some areas of the NAS (such as the Northeast or in close proximity to a major airport) may have been more impactful than in other regions. As a result, a direct comparison was not made between the six simulation days.

In summary, the frequency level of space operations is an experimental factor that is used to reflect uncertainty in the maturation rate of the commercial space industry. In addition, a diversity of operation types and locations was simulated to provide a wide variety of obstructions. These two factors are confounded, and separating the effects is not possible within the limits of this particular study. Because the schedules for each day are unique, the days cannot be directly compared to each other. However, the variation in schedules enriches the study by generating a broad range of possible future circumstances.

Table 1 presents a test matrix that defines the factors for each simulation scenario. The location of closed airspace in the last column is identified by the controlling air route traffic control center (ARTCC). The affected ARTCCs are located in Albuquerque, New Mexico (ZAB); Anchorage, Alaska (ZAN); Washington, DC (ZDC); Denver, Colorado (ZDV); Fort Worth, Texas (ZFW); Honolulu, Hawaii (ZHN); Houston, Texas (ZHU); Jacksonville, Florida (ZIX); Kansas City, Kansas (ZKC); Los Angeles, California (ZLA); Miami, Florida (ZMA); and Oakland, California (ZOA).

1. Framework for Study Analysis

Figure 3 depicts the simulation scenarios and their associated comparisons. To answer the first research question, scenarios...
representing increased space operations in 2018 and 2025 with today's typical airspace closures were compared against baseline scenarios with no space operations in the same years. This comparison allowed identification of changes to flight efficiency and sector occupancy caused by the introduction of commercial space operations. Then, as the figure illustrates, the same scenarios simulating space operations in the NAS using current airspace restrictions were compared against scenarios where 4-D compact envelopes were used to estimate benefits associated with the proposed mitigation strategy.

2. Representation of Airspace Closures for Space Operations

Space launches and reentries impact the NAS because of their resulting airspace restrictions that reduce the capacity of en route sectors.

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**Table 1  Matrix of simulated scenarios**

<table>
<thead>
<tr>
<th>Scenario ID</th>
<th>Airspace closure strategy</th>
<th>Number of flights</th>
<th>Space operations level</th>
<th>Number of space operations</th>
<th>Location of closed airspace</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 no space ops</td>
<td>None</td>
<td>51,749</td>
<td>None</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Current day 1</td>
<td>Current</td>
<td>51,749</td>
<td>Low</td>
<td>3</td>
<td>ZAB, ZDC, ZFW, ZHU</td>
</tr>
<tr>
<td>Current day 2</td>
<td>4-D compact envelopes</td>
<td>51,749</td>
<td>Medium</td>
<td>4</td>
<td>ZAB, ZDC, ZLA, ZOA</td>
</tr>
<tr>
<td>Current day 3</td>
<td>4-D compact envelopes</td>
<td>51,749</td>
<td>High</td>
<td>7</td>
<td>ZAB, ZDV, ZFW, ZHU, ZIX, ZMA</td>
</tr>
<tr>
<td>Current day 4</td>
<td>4-D compact envelopes</td>
<td>51,749</td>
<td>High</td>
<td>7</td>
<td>ZAB, ZDV, ZFW, ZHU, ZIX, ZMA</td>
</tr>
<tr>
<td>2025 no space ops</td>
<td>None</td>
<td>56,478</td>
<td>None</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Current day 4</td>
<td>Current</td>
<td>56,478</td>
<td>Low</td>
<td>6</td>
<td>ZAB, ZAN, ZFW, ZHU, ZIX, ZLA, ZMA</td>
</tr>
<tr>
<td>Current day 5</td>
<td>4-D compact envelopes</td>
<td>56,478</td>
<td>Medium</td>
<td>8</td>
<td>ZAB, ZDV, ZFW, ZHU, ZLA</td>
</tr>
<tr>
<td>Current day 6</td>
<td>4-D compact envelopes</td>
<td>56,478</td>
<td>High</td>
<td>15</td>
<td>ZAN, ZDC, ZDV, ZFW, ZHN, ZHU, ZIX, ZKC, ZLA, ZMA, ZOA</td>
</tr>
</tbody>
</table>

**Research Question #1**

*Using current ATC tools, procedures, and processes, how will the potential increase in space operations affect en route traffic in the future?*

**Research Question #2**

*Is it possible to minimize the potential effects of SV operations on the NAS by utilizing new airspace closure procedures such as 4D Compact Envelopes (4DE) concept?*

**Fig. 3** Simulation scenarios and associated comparisons.
Thus, each space operation was represented in the simulation by its associated airspace closures; the space vehicles themselves were not simulated.

This study simulated the NAS using airspace closures typically used today as well as 4-D compact envelopes. To model airspace closures used today, historical launches involving the same or similar operations as those included in the simulation scenarios were identified. The NOTAMs associated with these operations were obtained from the FAA’s NOTAM archive and used to define the shape and duration of the airspace closures modeled in this study. Some adjustments were made to the duration of the airspace closure when the operation was a test launch or occurred within restricted airspaces that were known to be continually active (such as restricted airspaces surrounding White Sands Missile Range). Also, input from the FAA’s Commercial Space Office and other subject matter experts was used to define the airspace closure boundaries and timing for vehicles that have not yet flown an operational mission, such as Virgin Galactic’s SpaceShip2 and XCOR’s Lynx.

Stanford University’s Aerospace Design Lab calculated the 4-D compact envelopes for each space operation simulated in this study using their SU-FARM tool. They provided the boundaries and timing associated with each compact envelope, and the information was reformatted to be used in the simulation model.

3. Metrics

The following metrics were used to quantify changes to NAS efficiency and sector occupancy in this simulation study.

**Total flight duration:** This metric represents the total time a flight flew in the NAS. It is used to quantify added flight delays or time savings for an individual flight.

**Total fuel burned:** This metric represents the total amount of fuel used during the flight while in the NAS. It is used to quantify the additional amount of fuel burned or saved by an individual flight.

**Total distance flown:** This metric represents the total distance of the flight in the NAS. It is used to quantify the additional distance flown or saved by an individual flight.

**Sector occupancy:** This metric is defined as the maximum number of flights in each sector within a 15 min time period, also known as maximum sector occupancy. It can be compared against each sector’s monitor alert parameter (MAP) value. MAP values represent a threshold standard for manageable sector occupancy, although it should be noted that they are theoretical in nature. MAP values for this study were obtained from the Performance Data Analysis and Reporting System. MAP threshold violations may indicate the potential for higher workload that would result from managing the sector airspace beyond its upper threshold associated with normal operations.

4. Assumptions and Limitations

A detailed account of all acknowledged assumptions and limitations of this study is presented in [3]. Those key to understanding the study are described next.

1) The air traffic and space operations in the 2025 scenarios were not a superset of those in the 2018 scenarios, although the number of flights and commercial space operations were greater. Similarly, the three levels of space traffic did not build on the lower levels; for example, the set of operations in the medium-level scenario did not contain the space operations in the low-level scenario. Therefore, the simulations with space operations should only be compared to their corresponding baseline and not to other scenarios with a different forecast year or level of space traffic.

2) The simulation modeled only rerouting maneuvers that were coordinated and executed in en route airspace and performed in response to blocked airspace from a commercial space operation. Impacts to terminal and ground operations as well as secondary effects of predeparture coordination and rerouting in en route airspace such as conflicts, traffic management initiatives, and sector boundary changes were not simulated. As a result, only direct effects to rerouted airborne flights can be quantified in this study. No conclusions were made on the overall NAS impact.

3) Flights that were rerouted to avoid entering a restricted airspace (e.g., current procedures or 4-D compact envelopes) were rerouted on the shortest path given key parameters to minimize the extra distance flown. In the simulation, these flights did not join an existing NAS playbook route as they may do today. Instead, the simulation model calculated a rerouted path around the closed airspace based on defined parameters to create realistic but optimal flight patterns. A rerouted flight began its diversion at least 30 n mile from the closed airspace to avoid sharp, unrealistic turns within its path. The aircraft’s rerouted path remained at least 5 n mile from the closed airspace at all times, and once the flight was past the constrained airspace, it rejoined its original route at least 30 n mile from the closed airspace to avoid unrealistic, sharp angles in its path. The rerouting capability used in this simulation did not allow some flights to be rerouted to avoid the closed airspaces. This is a limitation of the optimal rerouting algorithm chosen for this study, and affected flights were documented. A future study could attempt to mitigate this shortfall.

4) 4-D compact envelopes were used in this study to illustrate the potential benefits of changing today’s method of blocking airspace for space operations. Several other mitigation strategies have been proposed and may be viable solutions. This concept was chosen as an example of one of these strategies and requires more extensive research to prove its viability in the NAS.

III. Analysis and Results

A. Method of Analysis

Output from the AirTOp fast-time simulation model was collected from files created during the simulations. To quantify the effects of increased space operations on the efficiency of en route flights using today’s airspace restrictions, flights from scenarios representing current airspace closures were compared against flights from a scenario with no space operations (no space ops). Similarly, statistics were calculated to identify potential benefits of using a new procedure to mitigate the impact; for this analysis, the current scenarios served as a base for comparison against scenarios modeling 4-D compact envelopes.

In addition to an analysis of changes to flight efficiency metrics, a second analysis was performed to examine the potential effects on sector occupancy and controller workload. The maximum sector occupancy for each sector was measured in 15 min increments for the simulated scenarios and compared to known MAP thresholds. For this study, frequent exceeding of sector MAP values is interpreted as greater controller workload in those sectors. Significant shifts in simulated sector capacity may point to the need for carefully constructed solutions to reroute traffic while meeting traffic management restrictions and optimizing ATC staffing.

The rerouting maneuvers implemented in the simulation represented the smallest possible path deviations to successfully reroute flights to avoid hazard areas and did not consider MAP value assignments. In a real-world situation, traffic management policies would not allow MAP values to be greatly or frequently exceeded, and ATC would employ alternate solutions. Because these solutions would not be the smallest possible path deviations as simulated, real-world impacts to flight efficiency, sector capacity, and controller workload may be larger than those demonstrated in the simulated scenarios. In addition, the simulation did not include sector changes such as combining or joining two adjacent sectors to meet the demands of the rerouted traffic on sector capacity; thus, MAP values were measured for each defined en route sector in the NAS. In actual operations, some of these defined sectors are combined and worked by a single controller when traffic demand permits.

It is important to reiterate that a different set of flights and space operations was modeled in the 2018 scenarios from those in the 2025 scenarios, and even the simulated days within a year have varied space operation schedules, and so no direct comparisons should be made between 2018 and 2025 scenarios or between different scenario days.

B. Results

There were 51,749 flights simulated in each of the 2018 scenarios and 56,478 flights in the 2025 scenarios. However, the analysis...
excluded 2008 flights from the 2018 scenarios and 2037 flights from the 2025 scenarios due to known fuel burn modeling issues with two aircraft types (PA-28 and military fighter jet). Also, 13 flights in the current day 4 scenario were excluded from the analysis because of data recording errors.

In each scenario, aircraft whose flight paths would have intersected a closed airspace were identified as being affected by the space operations. These affected flights should have been rerouted by the simulation model’s rerouting algorithm; however, some of the affected flights were not successfully rerouted away from the closed airspaces. Such flights were left unchanged due to limitations in the model’s automatic rerouting algorithm. For example, a flight’s path was predicted to intersect a closed airspace, but the model could not find a viable rerouted path. In cases like this, the flights stayed on their original flight path and were simulated completely. This unsuccessful rerouting behavior was observed to be typical of flights entering or departing an airport’s terminal airspace, where rerouting maneuverability was limited by the model’s algorithm. Figure 4 shows the number of affected flights that were and were not rerouted in each current scenario, and Fig. 5 shows the same for each 4DE scenario. Please note the different scales in the figures, necessary to show the values for the different scenario types. Because the impact to the group of nonrerouted flights cannot be calculated, the results of this study are limited to the impact of space operations on flights that were successfully rerouted in the en route phase of flight. The effects on actual operations in the NAS would likely be greater than what can be concluded from this study.

1. Effects of Increased Commercial Space Operations on the National Airspace System

In every simulation scenario, the change in flight efficiency due to the introduction of space operations was operationally significant. Table 2 presents the average change in flight efficiency per rerouted flight in each scenario. The total change in flight efficiency across all rerouted flights in each scenario is also indicated. The impact to flights in the current day 2 scenario was larger than in the other 2018 simulation days. This was because several flights traveling from Australia, New Zealand, and Hawaii were rerouted around closed airspace off the Pacific coast of the United States for two space operations. The closed airspaces are large and resulted in a lengthy reroute for these flights.

Next, researchers investigated the throughput of all NAS sectors to identify possible workload issues resulting from flights rerouting around large restricted airspaces. Decreases in MAP threshold violations were likely due to part of the airspace being closed for a space operation. An increase in MAP threshold violations may indicate a higher demand on controller workload because a more complicated plan for rerouting aircraft would be necessary to maintain a manageable sector throughput.
Coordination between sectors and ARTCCs would be necessary to handle rerouted paths around the closed airspaces. For example, in the day 6 simulation scenarios, Jacksonville Center first closed airspace for a Falcon 9 launch at Spaceport Georgia, then for a launch of Spaceship 2 at Titusville, Florida, and finally for a Falcon 9 launch at Cape Canaveral, Florida. The airspace closures in ZJX during these operations caused changes to throughput in several ZJX sectors. An increase in maximum sector occupancy was seen in sectors ZJX049, ZJX050, and ZJX076, and a decrease was observed in sectors ZJX058, ZJX065, and ZJX068. Figure 6 illustrates these sectors as well as the closed airspaces. Closed airspaces are depicted in yellow, whereas increases in sector occupancy are in green, and decreases are in red. During the Falcon 9 launch from Spaceport Georgia, airspace within ZJX068 was closed, resulting in a decrease of throughput and, accordingly, MAP threshold violations in that sector. However, flights had to reroute into neighboring sectors ZJX049, ZJX050, and ZJX076 to avoid the constrained area, increasing the throughput in these sectors and ultimately the number of MAP threshold violations over the course of the day. These maneuvers would require additional coordination between sector controllers as well as possible sector staffing changes; thus, an increase in controller workload would be expected to protect air traffic during the space operations.

A comparison of the number of MAP threshold violations in the current scenarios against that of the no space ops scenarios revealed that the number of violations was affected by the introduction of commercial space operations. It was concluded that this change in sector throughput could result in additional air traffic management actions to safely manage air traffic around the space operations; controller workload would likely increase due to the coordination required to implement these maneuvers. Additionally, there may be ATC staffing impacts for sectors that experienced a change in traffic demand. Some sectors with increased traffic may be divided into multiple sectors to avoid exceeding the MAP threshold; this would require additional controllers to manage the new airspaces. Similarly, sectors with decreased traffic demand caused by flights rerouting away from the airspace may be joined with adjacent sectors, which would reduce staffing needs. Additional detailed analyses could be performed to detect patterns in the change to sector occupancy, but such analyses are outside of the scope of this study.

2. Potential Benefits of Dynamic Airspace Closures

Researchers performed a similar analysis to evaluate the changes to flight efficiency and sector throughput when today’s airspace closures are replaced with 4-D compact envelopes. As shown in

<table>
<thead>
<tr>
<th>Scenario ID</th>
<th>Number of rerouted flights</th>
<th>Average added distance per flight, n mile</th>
<th>Total added distance, n mile</th>
<th>Average added fuel burned per flight, lb</th>
<th>Total added fuel burned, lb</th>
<th>Average added duration per flight, min</th>
<th>Total added duration, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current day 1 (3 space ops)</td>
<td>103</td>
<td>12.97</td>
<td>1,336.28</td>
<td>160.16</td>
<td>16,496.42</td>
<td>1.50</td>
<td>154.57</td>
</tr>
<tr>
<td>Current day 2 (4 space ops)</td>
<td>91</td>
<td>39.52</td>
<td>3,596.09</td>
<td>841.31</td>
<td>76,558.89</td>
<td>5.07</td>
<td>461.12</td>
</tr>
<tr>
<td>Current day 3 (7 space ops)</td>
<td>223</td>
<td>13.14</td>
<td>2,929.47</td>
<td>160.55</td>
<td>35,803.67</td>
<td>1.93</td>
<td>430.60</td>
</tr>
<tr>
<td>Current day 4 (6 space ops)</td>
<td>165</td>
<td>31.45</td>
<td>5,189.38</td>
<td>275.25</td>
<td>45,415.86</td>
<td>5.28</td>
<td>871.42</td>
</tr>
<tr>
<td>Current day 5 (8 space ops)</td>
<td>279</td>
<td>21.11</td>
<td>5,888.79</td>
<td>279.64</td>
<td>78,020.18</td>
<td>2.99</td>
<td>832.95</td>
</tr>
<tr>
<td>Current day 6 (15 space ops)</td>
<td>548</td>
<td>28.46</td>
<td>15,595.82</td>
<td>305.66</td>
<td>167,500.59</td>
<td>3.91</td>
<td>2,143.87</td>
</tr>
</tbody>
</table>

2018 Forecast year

2025 Forecast year

Please note that ZJX076 overlies ZJX058, and the latter has a very slim footprint, making it difficult to see in Fig 6.
Fig. 3, the 4DE simulation scenarios were compared against the current simulation scenarios with corresponding simulation day. The difference in average flight efficiency per flight was calculated for total distance flown, fuel burned, and duration flown. For all comparisons, the difference between flight efficiency in the current scenarios and the 4DE scenarios was statistically and operationally significant. When 4-D compact envelopes were used on the six simulated days, no or very few flights were rerouted to avoid the small, dynamic, closed airspaces. Flight efficiency metrics for the 4DE scenarios were statistically the same as those in their corresponding no space ops scenarios, meaning little to no impact was measured during space operations when 4-D compact envelopes were used.

Changes to sector throughput were also analyzed. The number of MAP threshold violations was impacted for many sectors and ARTCCs in the current simulation scenarios. However, this effect was not observed in any sectors in the 4DE simulation scenarios. For all six simulation days, the number of instances where sector MAP thresholds were violated when 4-D compact envelopes were used was the same as when no space operations occurred in the NAS. This is because there were very few flights rerouted around the envelopes. Because the use of current airspace closures caused many changes to sector throughput, it could be concluded that 4-D compact envelopes reduce coordination time for planning reroutes and adjusting staffing requirements during space operations. This situation may lead to a decrease in controller workload; however, the workload required to manage the numerous activations and deactivations of closed airspaces necessary for 4-D compact envelopes was not studied and could offset any savings in coordination time for reroutes.

IV. Conclusions

Both research questions posed for this study were analyzed, and conclusions were formed based on the results presented. The two research questions of this study are restated next.

1) Using current ATC tools, procedures, and processes, how will the potential increase in commercial space operations affect en route traffic in the future?

2) Is it possible to reduce the potential effects of commercial space operations on the NAS by using new airspace closure procedures such as 4-D compact envelopes? If so, what are the potential benefits associated with this change?

To answer the first research question, a comparison was made between six single-day scenarios in which space operations in the NAS were managed using today’s airspace closures (“current” scenarios) and those with no space operations (“no space ops” scenarios). Differences in flight efficiency and sector throughput metrics were calculated and analyzed.

Flights directly affected by the airspace closures experienced significant changes on all six simulation days, although the difference in flight distance, fuel burned, and flight duration varied for each day modeled. These flight efficiency results were based on flights that had to be rerouted within en route airspace to avoid closed airspaces and excluded any additional effects from flights that would be required to hold or divert to another airport when landing during a space operation. Therefore, if commercial space operations in the NAS increase with no change in the use of airspace closures, the impact to flight efficiency would likely be greater than estimated in this study.

Maximum sector occupancies were also calculated and compared against the sector MAP threshold values. The number of MAP threshold violations in the current scenarios was compared against that of the no space ops scenarios, and it was determined that the number of violations was affected by the introduction of commercial space operations. This change in sector throughput could result in additional air traffic management actions to safely manage air traffic around the space operations, and controller workload may increase due to the coordination required to implement these maneuvers.

To answer the second research question of this study, a similar comparison was made between current and 4DE scenarios. When 4-D compact envelopes were used to protect air traffic during space operations, very few flights were rerouted to avoid the closed airspaces, which essentially eliminated any impact to flight efficiency on all six simulation days. This result was expected because the size of the envelopes and the duration of their activation were considerably smaller and shorter than the closed airspaces typically used today. Because impacts to arrival and departure flights were not captured in this study, these flight efficiency benefits are likely an underestimation of the potential savings.

For all six simulation days, the number of instances where sector MAP thresholds were violated when 4-D compact envelopes were used was the same as when no space operations occurred in the NAS. This is because there were very few flights rerouted around the envelopes. Because the use of current airspace closures caused many changes to sector throughput, it can be concluded that 4-D compact envelopes reduce coordination time for planning reroutes and adjusting staffing requirements during space operations. This could lead to a decrease in controller workload; however, the workload required to manage the numerous activations and deactivations of closed airspaces necessary for 4-D compact envelopes was not studied and could offset any savings in coordination time for reroutes.

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