3-3-2021

Sharing Airspace: Simulation of Commercial Space Horizontal Launch Impacts on Airlines and Finding Solutions

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Journal of Space Safety Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Space Safety Engineering

journal homepage: www.elsevier.com/locate/jsse

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A R T I C L E I N F O

Article history:
Received 12 December 2019
Received in revised form 1 July 2020
Accepted 5 February 2021
Available online xxx

A B S T R A C T

Commercial space transportation is becoming more affordable and accessible. Consequently, we expect to see significant expansion of commercial space launch activities in the coming decade. As space vehicles travel through airspace during the launch and re-entry stages, they potentially disrupt the regular operations of traditional users. This paper estimates the potential economic and operational impacts of commercial space horizontal launch activities on airlines under various launch scenarios using predictive fast-time simulation modeling, focusing on Cecil Air and Space Port in Jacksonville (Florida) and the rules governing the national airspace system (NAS) in the United States. Our results indicate that the existing 4-hour airspace closure rule impacts a significant number of flights, resulting in flight time delays, additional flight distance and fuel burn, as well as other direct operating costs. Safely reducing the duration of airspace closures could serve as a simple solution to mitigate the impacts on airlines and other traditional NAS users. More importantly, treating our studied launch vehicle as an aircraft and opening its departure/arrival corridor to air traffic during a horizontal launch and return would potentially reduce the impacts on airlines significantly, depending on the location of the spaceport, planned flight paths and the trajectory of the launch.

1. Introduction

The commercial space transportation industry has been growing by leaps and bounds over the last two decades. Development of reusable and more efficient launch vehicles (LVs) has started to bear fruit in helping to reduce launch costs. Commercial space transportation is becoming more affordable and accessible. Consequently, we expect to see significant expansion of commercial space launch activities in the coming decade. While many will reap significant economic benefits, key stakeholders outside the commercial space industry, including commercial aviation, view commercial space transportation with intrigue and caution. As space vehicles travel through airspace during the launch and re-entry stages, they potentially disrupt the regular operations of traditional airspace users.

In the United States (U.S.), the Federal Aviation Administration (FAA) serves more than 44,000 flights and 2.7 million airline passengers per day [1]. In addition, hundreds of thousands of business and private flights also share the airspace. Therefore, there are well-established rules that all aircraft operators must follow when they share the national airspace system (NAS). These rules are intended to ensure the safety of aircraft and efficient use of the airspace, by specifying flying altitudes, separation distances, airways/routes to follow, and requesting permissions to enter certain airspaces, etc. Yet, there is some flexibility for aircraft to alter their planned flight paths, if necessary. On the other hand, maneuverability of LVs varies widely. Many of these vehicles, depending on type, have limited ability to alter their trajectories once launched and minimal capability to take a different route when specific destinations are required in time and space. Consequently, it is left to airlines (and other NAS users) to alter their operations to allow space vehicles to pass through the airspace to reach their final destinations. That is, when an LV is launched from a spaceport, one or more pre-determined areas of the airspace surrounding its trajectory is closed to other users of the NAS for a period of time to allow for the safe operations of both the LV and aircraft. The impacted commercial flights are either re-routed or held on the ground (delayed departure), resulting in additional costs to the airlines and possible flight delays for passengers and cargo shippers, and, more importantly, the associated uncertainties.

In the past, airlines and other NAS users bore the impacts of government space activities without demurs for the goodness of humankind when limited space activities with sporadic frequency were carried out by governments for the purpose of space exploration and national security. Nowadays, however, the number of commercial space launches has increased significantly, and the commercial space industry has become a

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https://doi.org/10.1016/j.jsse.2021.02.001

Acronyms and other call-outs

ALPA	Air Line Pilots Association
ARTCC	Air Route Traffic Control Center (United States)
ASPM	Aviation System Performance Metrics
DDR2	Demand Data Repository
EAD	European AIS Database
EFT	Exploration Flight Test
ELV	Expendable Launch Vehicle
ET	Eastern Time
FAA	Federal Aviation Administration (United States)
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
LV	Launch Vehicles
MOA	Military Operations Area
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NOTAM	Notice to Airmen
PDARS	Performance Data Analysis and Reporting System
RLV	Reusable Launch Vehicle
SUA	Special Use Airspace
TAAM	Total Airspace and Airport Modeler
TFR	Temporary Flight Restriction

multi-billion-dollar industry. Inevitably, there has been a growing conflict of interests between commercial space operators and other NAS users over the disruptions caused by commercial space vehicles passing through the airspace. How to share airspace in a fair and efficient manner becomes a critical issue for the growth and development of both the commercial space industry and the continuously growing commercial aviation industry as well as other NAS stakeholders.

The first step to find an answer to this critical topic is to have a clear understanding of the impact of commercial space activities on airlines. Therefore, the first objective of this research is to assess the potential impacts of commercial space launch activities on airlines by developing simulation models to estimate flight delays and additional direct aircraft operating costs associated with various space launch scenarios. The secondary objective is to evaluate possible solutions that may mitigate the potential impacts of commercial space activities on airlines.

The study applies predictive fast-time simulation modeling in a comparative analysis of current and future airline traffic scenarios in the surrounding areas of a spaceport with horizontal space launch operations, focusing on the predicted space activities at Cecil Air and Space Port in Jacksonville, Florida and the rules governing the NAS in the U.S.. As each spaceport is unique in terms of types of launches supported, this spaceport was chosen for our research as being the most advanced conceptually in terms of anticipated closures and horizontal launch operations. It has an anticipated launch frequency of 52 horizontal launches per year [2], averaging one launch per week. It also lies outside the controlled airspace environments of a federal space center, in this case, that of Cape Canaveral in Florida. Furthermore, launches from this spaceport will impact a route heavily traveled by airlines along the eastern seaboard of the country. Lastly, it is emphasized that the majority of spaceports in the U.S. are attaining licenses for horizontal operations which gives further impetus to address impacts to airspace as a result of this type of operation.

The rest of the paper is organized as follows: Section 2 provides a brief background on the operations of various space vehicles as well as the current FAA practice of airspace closures associated with space launches; Section 3 reviews past studies on airspace simulation and modelling; Section 4 describes our simulation modeling process including the flight data, the simulation software, and alternative scenarios; and the results from the simulations are discussed in Section 5. Section 6 offers concluding remarks and explores future research.

2. Commercial space operations

The majority of the commercial space launches are in the U.S., and almost all commercial launches so far are vertical. In the U.S., there were a total of 114 orbital launches in 2018, of which 24 were commercial launches [3]. SpaceX has been the most successful commercial launch operator, focusing on the vertical lift market. As of June 2020, SpaceX had completed 86 successful missions since its first mission in June 2010. In the horizontal launch market, Virgin Galactic is now operating out of Spaceport America in New Mexico, following successful test completion at Mojave Air and Spaceport in California.

Space launches to date, whether using expendable launch vehicles (ELVs) or reusable boosters, commonly take off vertically, and the reusable boosters return vertically. However, there have been tremendous efforts to develop horizontal takeoff and horizontal landing concepts, particularly for the commercial launch market. There are three general space vehicle categories for horizontal operations [4]. Each vehicle category requires specific facilities and operating licenses at the spaceports they operate. Spaceports are generally not licensed for all types of horizontal LVs. Instead, they are "specialized" in one or two vehicle concepts.

A "Concept X" LV is a single unit Reusable Launch Vehicle (RLV). It would take off from a runway under *jet* power, similar to an airplane, flying to a pre-determined safe airspace area, then ignite its rocket engines to embark on the next phase of flight. Once its mission is completed, the Concept X LV will land horizontally like a regular airplane, either under jet power or unpowered (glider). These LVs would have the capability of providing suborbital flights for both passengers and cargo. An example of a Concept X LV is the Airbus Spaceplane. In comparison to other LV configurations, Concept X represents a possible competitor to traditional aviation, offering a service potentially disruptive enough to lead to changes in the industry.

A "Concept Y" LV is a reusable all-in-one vehicle that takes off horizontally under rocket power from a conventional runway. The Concept Y RLV would follow a steep ascent trajectory under *rocket* power until engines are shut down. After completing its launch profile, the RLV would land horizontally on the runway as a glider. An example of a Concept Y LV is the Lynx that was being developed by the now-bankrupt XCOR Aerospace. As of this writing, there is no known Concept Y vehicle in development.

A "Concept Z" LV consists of a reusable carrier aircraft and an attached RLV or ELV. The carrier aircraft takes off from a conventional runway powered by *jet* engines, carrying the mated LV to a desired altitude at which the latter detaches and launches under rocket power. The carrier aircraft flies back to the spaceport and lands as an aircraft. The de-mated LV either returns with a horizontal landing (RLV) or is expended (ELV) after completing its mission profile. The Northrop-Grumman Pegasus rocket and its carrier aircraft, a modified L-1011, and Virgin Galactic's SpaceShipOne and its carrier aircraft, the White Knight, are probably the best-known examples of Concept Z LVs. Like Concept X LVs, Concept Z LVs have the capability of providing suborbital flights for both passengers and cargo. Northrop-Grumman's Pegasus is capable of carrying satellites into orbit.

All space vehicles create safety hazards as they pass through the NAS to reach space, particularly at this early stage of development and test. Therefore, the U.S. FAA issues temporary airspace restrictions during space launches. These restrictions, known as standard hazard areas, usually take effect as Temporary Flight Restrictions (TFRs) or Special Use Airspaces (SUAs), which prevent aircraft from entering the hazard areas. A TFR is a type of Notices to Airmen (NOTAM) and defines an area restricted to air travel due to a hazardous condition, a special event, or a general warning for the entire FAA airspace. The text of the actual

TFR contains the fine points of the restriction. SUA consists of airspace of defined dimensions identified by an area on the surface of the earth wherein activities must be confined because of their nature, or wherein limitations are imposed upon aircraft operations that are not a part of those activities, or both.

These TFRs and SUAs often result in commercial airline flights being delayed and/or rerouted and the temporary shutdown of operations for smaller general aviation companies such as flight schools and aircraft rental businesses. Although there have been anecdotal reports on the impacts of these TFRs and SUAs on air traffic[1], the issue has received very limited attention among the academics. This study is intended to fill in this gap.

3. Literature review of airspace simulation and modelling

Most of the literature on the space traffic interspersing with air traffic in the NAS focus on risk analysis, estimation and projection of hazard areas of space launch and reentry, and developing air traffic control tools to integrate space activities into the airspace safely and efficiently. It is noted that many of these studies stemming from FAA's various initiatives and efforts in addressing the emerging issues in the rapidly evolving industry.

Larson [6] discusses the computation of risks of space operations to aircraft and the modeling of aircraft vulnerability as well as potential methods to mitigate the impacts of space operations on airspace. Anselmo and Pardini [7] provide a brief overview of the risks associated with reentries of satellites and debris and discuss the methods and techniques for estimating and predicting such risks. Larson, Carbon and Murray [8] describe the development of FAA's Shuttle Hazard Area for Aircraft Calculator (SHAAC). Although SHAAC was developed for NASA Space Shuttle, the underlying methodology could be applied to predict the hazard areas of other space vehicle operations.

Mazotta and Murray [9] note the fact that the current process for integrating space operations into the NAS is entirely manual and stress the need for developing technology and infrastructure vital for safer and more efficient NAS integration. Murray and Van Suetendael [10] discuss FAA's initiative in developing an integrated Space and Air Traffic Management System (SATMS). Mutuel and Murray [11] expound FAA's effort in developing Space Data Integrator (SDI) to provide a rapid and flexible method for integrating launch and reentry operations into the NAS.

Colvin and Alonso [12] proposes a new class of hazard area for space launch and re-entry, termed as compact envelopes that are "dynamic in time, contour in space as a function of altitude". The paper further compares the effects of the proposed compact envelopes with traditional hazard areas through simulations and conclude that compact envelopes could potentially decrease disruption to the NAS significantly. Colvin and Alonso [13] presents a probabilistic analysis of the disruption to the NAS by space operations using traditional hazard areas and the compact envelopes proposed in the authors' previous paper. Their results show near complete elimination of disruption to the NAS when the hazard areas are defined by the compact envelope.

Tompa, et al. [14] apply Markov decision process to model commercial space launches and their interactions with aircraft in the surrounding airspace. Based on launch vehicle trajectory, probability of anomaly, and potential debris trajectories of a two-stage-to-orbit launch from Cape Canaveral, and commercial aircraft at 35,000 feet (ft) in the NAS, the model produces dynamic safety regions and optimal rerouting policies that minimize disruption to the NAS while maintaining safety. The paper shows that the proposed dynamic safety regions would result in 3% less rerouted flights, and rerouted flight distances being cut in half, compared to the existing launch hazard areas. Tompa and Kochenderfer [15] proposes an adaptive spatial discretization (ASD) method to overcome the issue of computational tractability associated with Tompa, et al. [14]. The proposed ASD solution defines a smaller dynamic safety region, resulting in safer re-routes with smaller flight deviations. Moreover, their analysis shows that the number of impacted flights with ASD was less than 10% of the historically impacted flights.

Srivastava, et al. [16] presents their ongoing research on developing models to project, up to one year in advance, the impact of airspace closure associated with space operations. The authors state that their ultimate goal is to develop a projection model that will enable instantaneous assessment of the impact of blocking airspaces using a what-if analysis paradigm, and be accessible to a broad range of airspace users with no prior knowledge of air traffic. They believe that such capability will help increase transparency and promote collaboration among airspace users and air navigational services providers. Their current model uses yearly historical traffic patterns within the U.S. airspace to project NAS impacts.

There are a broad range of literature using simulations to study various issues related to airspace. For example, Sweet, et al. [17] evaluate new operational concepts for air traffic control using fast time simulations; Gaxiola, et al. [18] use simulations to assess the impact of Northern Europe Free Route Airspace deployment in terms of the aircraft loss of separation and the airspace complexity; Luchkova, et al. [19] conduct multiple simulations to analyze the impacts of volcanic ash on air traffic. However, studies that provide quantitative estimates of the impacts of space activities on the airspace are sparse.

Srivastava, et al. [20] propose a two-step approach to estimate the impact of a future space launch or reentry on airspace in terms of extra flight distances and delays of impacted flights, either delayed or re-routed, based on a sample of historical days similar to a scheduled launch day. The study considers two options for each impacted flight, re-routing or ground delay, and estimates a "cost index' for each option. Their model chooses the option with a lower "cost index" for each impacted flight in estimating the extra flight distance and delays. The study applies the proposed model to estimate the impact of NASA's Exploration Flight Test-l (EFT-1) operation that launched the Orion spacecraft from Cape Canaveral on 5 December 2014. The launch was originally scheduled for December 4, and the affected airspace (hazard areas) was blocked for the entire planned duration despite the launch being re-scheduled for the next day. The proposed model estimates that the impacted flights would travel an extra 4.34 NM with an average 0.72-minute delay as a result of the originally planned launch on December 4. The actual impact analysis of the blocked airspace on December 4 shows a total of 141 impacted flights with an average increase of 28 NM per flight. The paper notes that the "impacted flights" include those that may have rerouted due to unrelated reasons.

Young and Kee [21] perform a statistical analysis of the impacts of blocking airspace during SpaceX Falcon 9's launch from Cape Canaveral on 1 March 2013, and the subsequent re-entry of Dragon capsule off the California coast on 26 March 2013. Their results show that the Falcon 9 launch caused 25 to 84 NM extra flight distances, 1 to 23 minutes delays, and 275 to 2,387 lbs extra fuel burns for the impacted flights. However, the launch did not have any significant negative impact on the operations at the major airports in the region. The results also show that the reentry of Dragon capsule impacted flights to/from Hawaii and Australia, but not U.S. domestic and other international flights. Flights to/from Hawaii and Australia experienced 1.5 to 7 minutes delay, extra 15 to 27 NM flight distance, and additional 458 to 576 lbs fuel burn. Their operational analysis indicates that the air traffic controllers implemented procedures to fully utilize all available airspace surrounding the blocked airspace and to minimize the impact of the launch and re-entry on the NAS.

Young, Kee, and Young [22] conduct three sets of fast-time simulations on six sample days using AirTOp to analyze the impact of future space launch and reentry on the NAS under the existing airspace closure

[1] A White Paper produced by ALPA notes the differences in treatment of space launches versus aviation activities and discusses the negative effects increasing launch rates could have on commercial aviation [5].

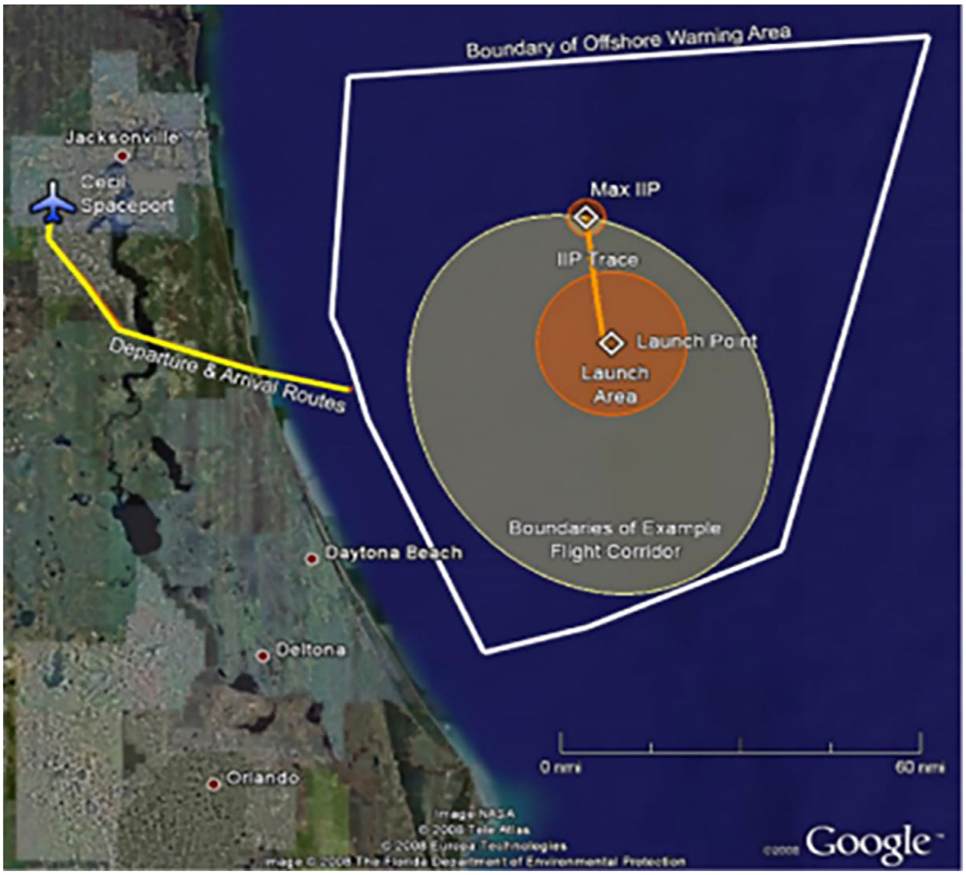

Fig. 1. General departure and arrival routes with example spacecraft launch point [26].

procedure, and to assess the potential benefits of the compact envelope proposed by Colvin and Alonso [12]. The impacts of the space operations are measured in terms of flight distance, fuel burn and flight delay as in Young and Kee [20]. The study finds that the compact envelopes would help reduce flight distance by 3.5 to 18.7 NM, fuel burn by 43.1 to 200.3 lbs, and flight time by 0.4 to 2.6 minute, compared to the existing airspace closure procedure. Their results also suggest that compact envelope could help alleviate air traffic controllers' workload.

Luchkova, et al. [23] attempt to examine the potential impacts on European airspace of SpaceLiner, a two-stage suborbital RLV, still in its early development phase at German Aerospace Center. The paper first discusses alternative scenarios of the trajectory of the SpaceLiner, then develops an airspace model based on EUROCONTROL's Demand Data Repository (DDR2) and the European AIS database (EAD) and a provisional hazard area model based on NASA's Columbia space shuttle accident debris data. The airspace model and the hazard area model are then used in simulations to evaluate the effect of SpaceLiner operations without closing any of the hazard areas. The objective of the simulations is to estimate the number of flights to be impacted, e.g. those flying through the hazard areas, and consequently affecting air traffic controller workload if any rerouting will be necessary.

While modeling and simulations continue to improve analytical solutions to airspace conjunctures, regulatory and operational solutions are slowly evolving. Kaul [24] discusses the need and the plausibility for ICAO (International Civil Aviation Organization) to take over Air and Near Space Traffic Management. This paper provides new evidence for the impacts of space activities on commercial aviation, and discusses possible operational solutions, which will contribute to the ongoing dialogues on how to better integrate space activities into the airspaces.

4. Methodology

Predictive fast-time simulation modeling is used in this study to analyze the impacts on airline traffic of horizontal launches of Concept Z space vehicles taking off from Cecil Air and Space Port (VQQ) in Jacksonville, Florida. The spaceport, owned and operated by Jacksonville Aviation Authority, is licensed to support horizontal launches of both Concept X and Concept Z vehicles with dedicated launch corridors and related warning areas. The spaceport forecasts 52 launches per year (48 Concept X and 4 Concept Z) in its 2014 Launch Site Operator Renewal Application [25], averaging one launch per week. This study focuses on the Concept Z vehicle as it was the first LV concept approved for the spaceport's site operator license, therefore information for the formal airspace closure size, process and timing are readily available[2]. Furthermore, out of the three concepts detailed above, new LVs based on Concept Z, such as that of Virgin Galactic, are one of the most advanced in terms of development, test, and forecasted use.

Because there has been no actual commercial space launch from Cecil as of this writing, the first step to develop our simulation model is to establish the anticipated operational and launch conditions, including the projected flight path of the Concept Z vehicle, launch window, airspace closures, and the schedules and flight paths of the commercial operations that may be impacted. It is emphasized that our research focuses on impacts on airlines; impacts on general aviation traffic were not considered in this study.

4.1. Establishing operational and launch conditions

As aforementioned, launching a Concept Z vehicle is a two-stage process. For the intent of this research, the carrier aircraft with mated spacecraft taking off from the runway is defined as the primary launch. The secondary launch is defined as the point in time and space when the de-mated RLV (or ELV) is air launched under rocket power. This occurs

[2] More recently, the spaceport has been approved for Concept X vehicles. With the addition of Concept X, there was no noted change in airspace closure characteristics. As such, the airspace closure area of Ref. [27] was the baseline.

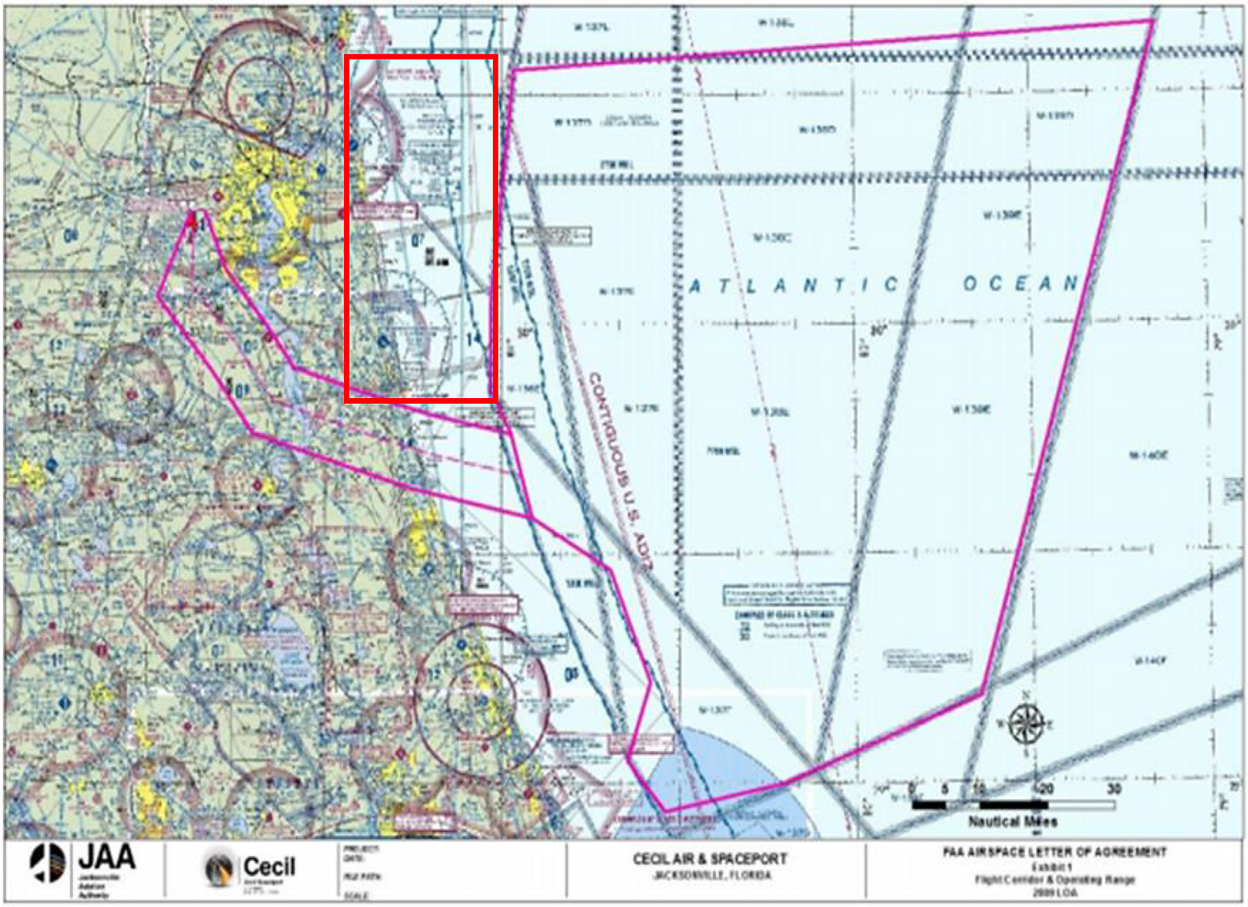

Fig. 2. Airspace areas of closure during launch operations for concept Z [27].

at a safe altitude of 40,000 ft – 60,000 ft and within the defined hazard area of the airspace closure. As commercial airlines do not currently fly above 40,000 ft and the airspace is closed due to the TFR, timing of the secondary launch is an important consideration for this research only to address a returning carrier aircraft and/or de-mated LV. Our baseline assumption is that both the carrier aircraft and the RLV return within the airspace closure time window. An LV that is expended or an RLV that lands at another spaceport is not considered for this research effort.

Fig. 1 illustrates the anticipated flight path of the Concept Z vehicle, heading in the southeast direction from Cecil spaceport, and the secondary launch point where the RLV will be released from the carrier aircraft and rocket(s) ignited to propel the craft on its suborbital trajectory. The carrier aircraft will return for a jet-powered horizontal landing with a projected path from the southeast through the same corridor while the RLV, if it lands at the spaceport, will return also from the southeast via the same corridor, functioning as a glider. Fig. 1 also shows the approximate boundaries of the flight corridor and the marked offshore warning area.

Fig. 2 highlights the approved airspace closure area (in pink, bold). The information used to define the airspace closure area and timings on launch day was obtained from the FAA Airspace Letter of Agreement [27]. Worth noting is the presence of a Military Operations Area (MOA) at the western edge of the TFR airspace closure zone denoted by the red rectangle. This section of airspace marks areas where military aircraft carry out training or operational activities (it can also include the utilization of other military systems). To the east of this airspace is a high-military-traffic zone wherein military aircraft can be expected to frequent for training purposes. These areas do not extend in altitude to a height which would be disruptive to launch or commercial aviation. Despite this, airlines and commercial space launch operators may seek to avoid any restrictive airspace such as to minimize possible disruptions to their operations.

As for the airspace closure times, the FAA Airspace Letter of Agreement [27] specifies that all space launches should occur prior to 9AM Eastern Time (ET) on Wednesdays and Saturdays, during which time, there is generally less airline traffic in the area. Our simulation models, however, are built based on the most congested airspace time period in order to examine the impacts under the worst-case scenario. Review of the FAA Aviation System Performance Metrics (ASPM) data indicates that the 8AM to 12 PM period on 2 May 2017 (Tuesday) was the busiest time period, thus chosen as the worst-case launch window for the simulation. Further, based on our interviews with FAA air traffic control personnel and spaceport representatives, airspace closures for space launches out of Cecil are assumed to be 4 hours in duration: beginning 2 hours prior to the scheduled launch time and remaining closed for 2 hours after launch[3]. It is noted that the FAA can re-open the restricted airspace as soon as conditions are considered safe with no anomalies. Furthermore, duration of airspace closures differs between spaceport location, launch vehicle, etc. Therefore, the most restrictive case scenario in our simulations representing current practice considers the 4-hour launch window starting at 8 AM and ending at 12 PM with the planned

[3] Although each launch window time length can be different, the 4 hour assumption was substantiated by a number of key sources with respect to Cecil operations, including additional studies by the authors that review launch windows for Kennedy Space Center/Cape Canaveral Air Force Station (KSC/CCAFS) vertical launch operations using historical NOTAMs. More recently, the spaceport has suggested a TFR of 1 hour before and 1 hour after scheduled launch is reasonable and became an input to Scenario 3.

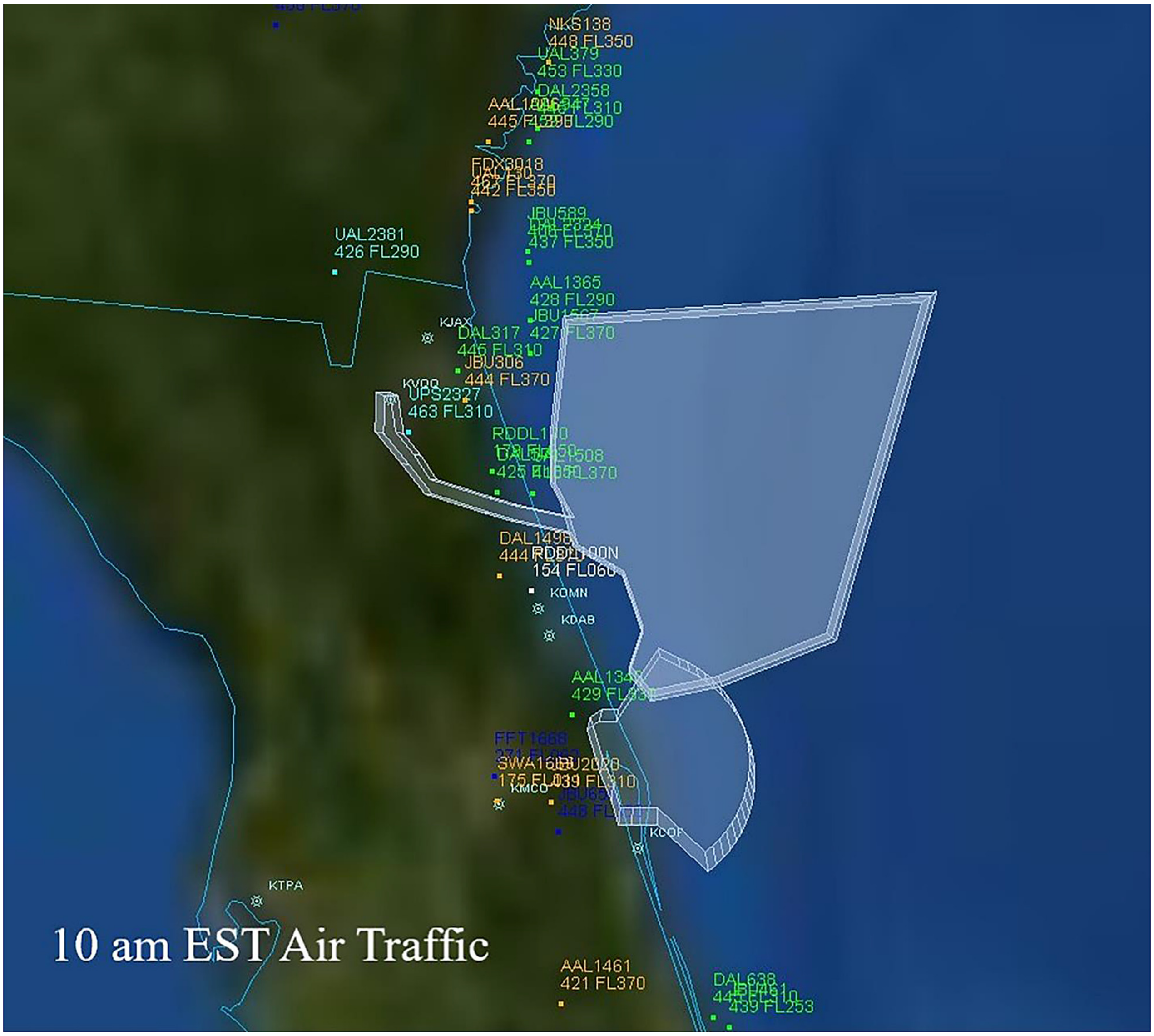

Fig. 3. Actual airline traffic on 2 May 2017 at 10AM.

launch at 10 AM on 2 May 2017. Two other scenarios with reduced launch windows are also simulated to show the potential benefits of more flexible launch windows and, as noted earlier and in the following section, are based on input from key stakeholders.

Jeppesen's Total Airspace & Airport Modeler (TAAM)[4] is used to simulate the interspersing of the space launch with commercial airline flights in the impacted area during the anticipated launch window under various scenarios. Actual airline flights data were obtained from FAA's Performance Data Analysis and Reporting Systems (PDARS)[5] and used as the basis for traffic schedules in the simulation process to mirror real traffic situations. Aircraft Situation Display to Industry (ASDI) data was used to create aircraft flight plans. In order to capture all flights that are impacted and to provide flexibility in scenario development, the flight schedules for the simulations were developed for a 24-hour period.

[4] TAAM Version 2018_3_0_R13_01. TAAM is a workstation-based, object oriented, computer program designed by Jeppesen (One Boeing) and simulates 4D (3D plus time) models of airspace and airports to facilitate decision support, planning, and analysis.

[5] PDARS consists of a dedicated network of computers located at FAA sites that use specialized software for collecting detailed air traffic management system data, providing quality-controlled flight track data.

Fig. 3 shows actual airline traffic conditions with no flight restrictions for 2 May 2017 at 10 AM, filtered by flights that were to be impacted by the airspace closure. Airline flights are largely routed down the eastern side of the Florida peninsula during normal operations; most air traffic naturally refrains from entering the trapezoidal area of TFR-airspace closure, but they all cross the TFR flight corridor for the Concept Z departures and arrivals. These flights, identified by their flight numbers and altitudes, include those of United Airlines (UAL), American Airline (AA), Spirit Airlines (NKS), Southwest Airlines (SWA), Jet Blue (JBU), Delta Airlines (DAL), Frontier Airlines (FFT), United Parcel Service (UPS) and FedEx Express (FDX). The restricted areas near KSC/CCAFS, Cape Canaveral, FL are also shown in Fig. 3 but were not activated for our simulation.

4.2. Developing simulation scenarios

While the baseline scenario mirrors the actual flights on 2 May 2017 without any launch operations, four launch scenarios are established for a 10 AM primary launch, reflecting various durations of launch windows and different extents of airspace closures. Scenario 1 represents the 4-hour launch window for a 10 AM launch and full airspace closure. As noted earlier, airspace may be re-opened prior to the completion of the

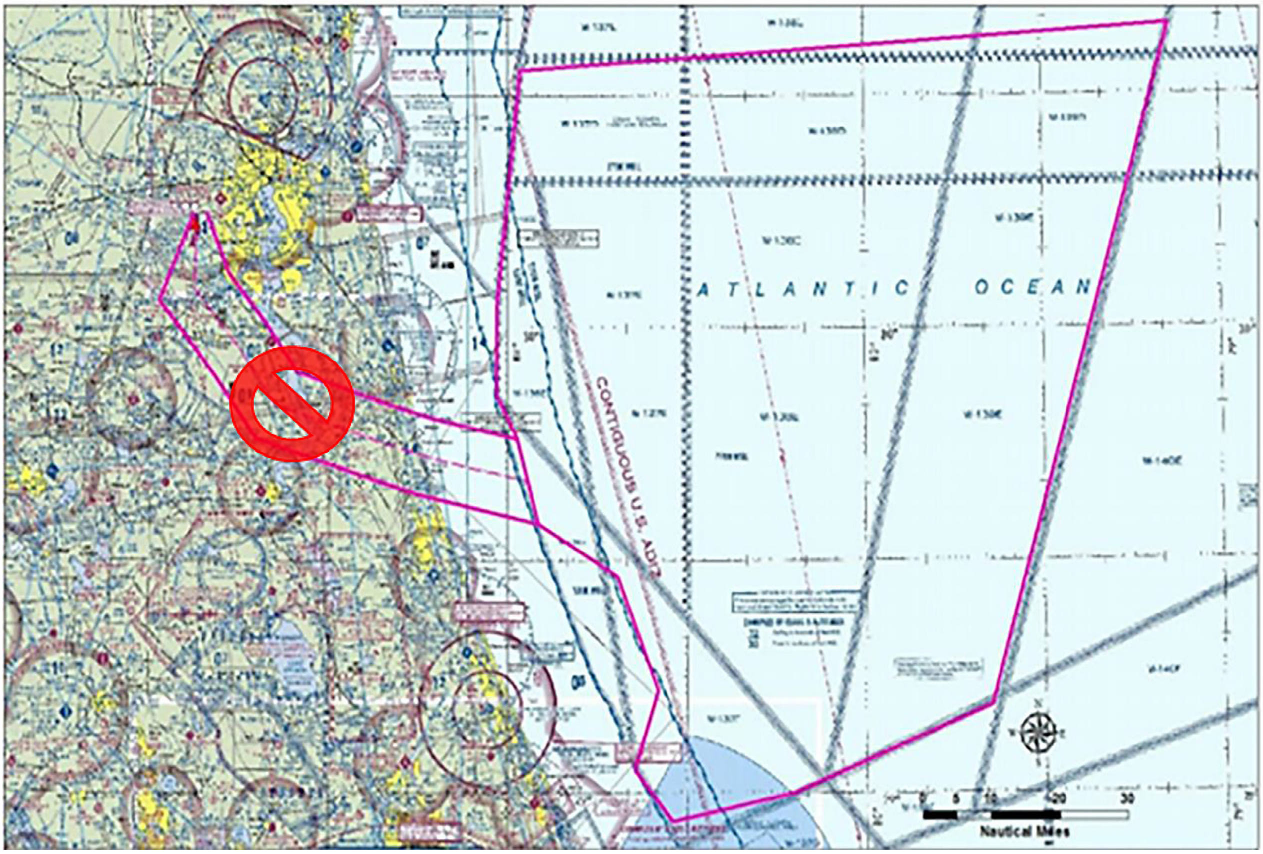

Fig. 4. Airspace areas of closure during launch operations for concept Z with departure/arrival corridor removed[6].

2-hour post-launch closure following a successful mission. Thus, Scenario 2 assumes a 1.5 hour launch window covering one hour before and 30 minutes after the 10 AM launch with full airspace closure; and Scenario 3 assumes a 2 hour launch window covering one hour before and one hour after the 10 AM launch with full airspace closure (justification noted in footnote 3). It is emphasized that shorter launch windows should not impose any additional safety risk associated with Concept Z operations; the FAA verifies traffic is cleared from the airspace prior to launch and remains clear during hazardous operations [27]. The following summarizes these three launch scenarios:

- Scenario 1 – Complete TFR with airspace blocked from 8 AM to 12 PM with a 10 AM launch from Cecil
- Scenario 2 – Complete TFR with airspace blocked from 9 AM to 10:30 AM with a 10 AM launch
- Scenario 3 – Complete TFR with airspace blocked from 9 AM to 11 AM with a 10 AM launch

As aforementioned, air traffic runs up and down the eastern side of the Florida peninsula, along the Atlantic Ocean coast. Although both the carrier aircraft and RLV are currently viewed as experimental, common understanding and FAA discussions indicate that neither are considered an extraordinary safety hazard during the take-off procedure and before they reach an altitude above 40,000 ft when the secondary launch (air) occurs. It is assumed that the aircraft and LV return to the spaceport with no extraordinary hazards, that is, either under normal jet power (carrier aircraft) or as a glider (RLV). Rocket propellant is assumed to be depleted from the RLV prior to its return to the spaceport. Therefore, Scenario 4 assumes no closure for the departure/arrival corridor airspace, as depicted in Fig. 4, but retains the trapezoidal airspace closure for the secondary launch. This no-corridor closure scenario is to examine the effects on airlines if the carrier aircraft is treated as a conventional aircraft through the entire duration of its flight, and does not require airspace restrictions, even if when it is carrying the RLV. (Note that the same assumption would apply to an ELV.) Thus,

- Scenario 4 - No departure/arrival corridor TFR with trapezoidal airspace blocked from 8 AM to 12 PM with a 10AM launch

Finally, in order to account for the variances between our worst-case air traffic scenarios discussed above and those stated in the Letter of Agreement for spaceport operations at Cecil [27] that requires all launches occur before 9 AM (Wednesdays and Saturday only), two additional scenarios are established as follows:

- Scenario 5 – Complete TFR with airspace blocked from 5 AM to 9 AM with a 7 AM launch
- Scenario 6 – No departure/arrival corridor TFR with trapezoidal airspace blocked from 5 AM to 9 AM with a 7 AM launch

As can be seen in Fig. 5, there is still a considerable amount of air traffic at 7 AM. While the majority of flights are of U.S. carriers, one international carrier, Air Canada Rouge (ROU), is also impacted. Again, KSC/CCAFS restricted areas were not activated for any simulation runs.

Both airline traffic and commercial space launches are expected to continue to grow over the next 20 years. As air traffic increases, the impacts on commercial aviation by a single space launch are expected to increase as well. Therefore, our simulations also estimate the economic impacts on airlines by a single space launch in 2027 and 2037 at the forecasted air traffic levels.

The 2027 and 2037 air traffic volumes in the simulated area are estimated based on FAA Aerospace Forecast for Fiscal Years 2017-2037 [28]. In particular, the air traffic growth in the impacted area is estimated as the weighted average of the FAA's IFR flights forecasts for

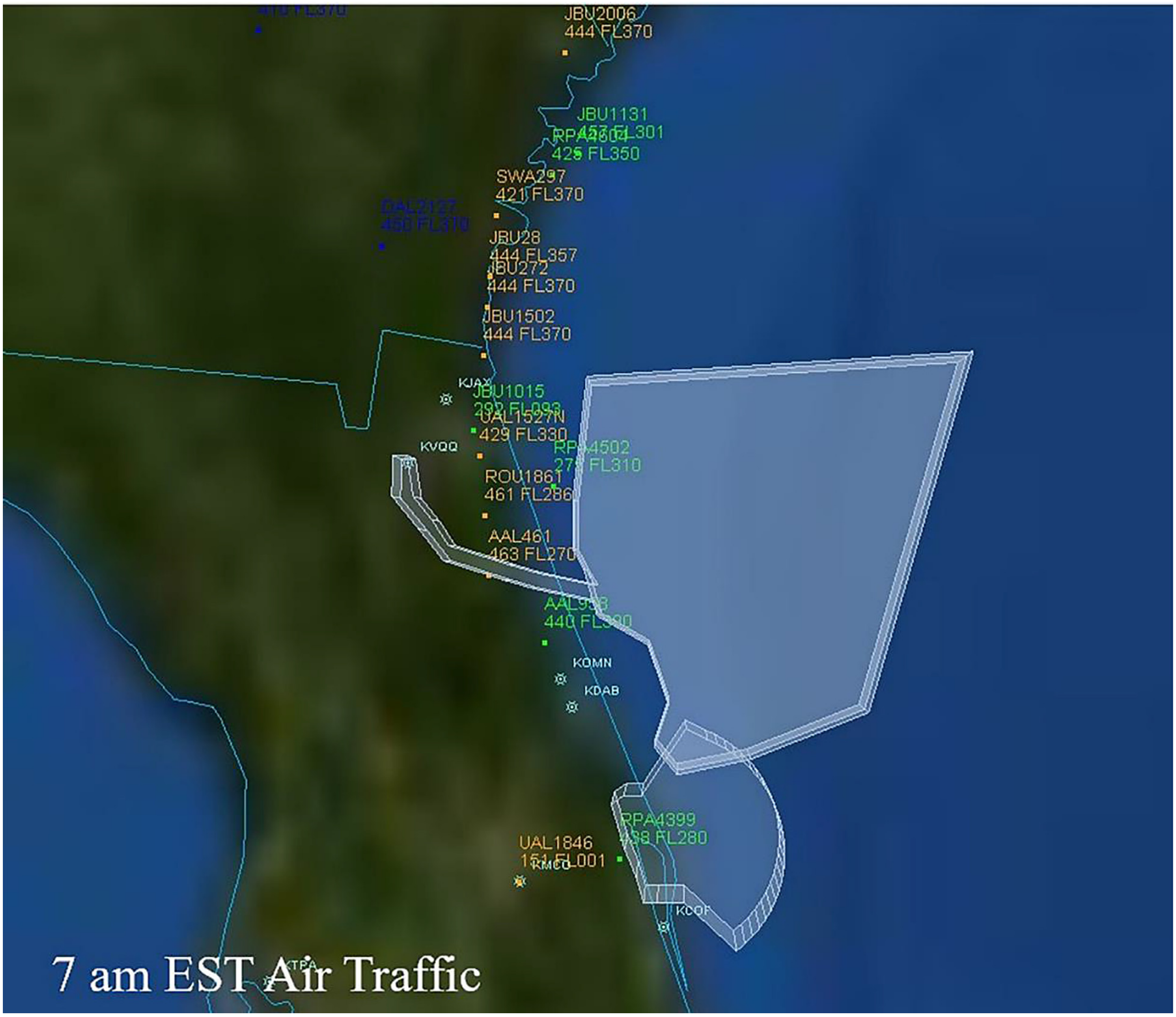

Fig. 5. Actual Airline Air Traffic on 2 May 2017 at 7AM.

Jacksonville Center (ZJX) and Miami Center (ZMA). Eqs. (1) and (2) calculate the traffic growth rates with respect to the 2017 traffic level.

$$2027\ Growth = \frac{(ZJX_{2027} - ZJX_{2017}) \times ZJX_{2027} + (ZMA_{2027} - ZMA_{2017}) \times ZMA_{2027}}{Total_{2027}} \quad (1)$$

$$2037\ Growth = \frac{(ZJX_{2037} - ZJX_{2017}) \times ZJX_{2037} + (ZMA_{2037} - ZMA_{2017}) \times ZMA_{2037}}{Total_{2037}} \quad (2)$$

Where ZJX_i denotes the FAA traffic forecast for Jacksonville center in year *i;* ZMA_i denotes the FAA traffic forecast for Miami center in year *i;* and $Total_i$ is the sum of the traffic forecast of the two centers in year *i*. Table 1 presents the air traffic forecasts for ZJX and ZMA as well as the weighted average growth rates.

Based on the estimated growth rates in Table 1, TAAM generates the flight schedules for 2027 and 2037 by randomly cloning flights from the original schedule. TAAM resolves cloned flight airspace conflicts automatically with FAA separation distances enforced in the simulations. Table 2 summarizes the baseline scenario and launch scenarios, including the established parameters of varying launch window durations and airspace closures.

4.3. Running simulations

TAAM does not have the capability to automatically determine reroutes of flights with user-defined airspace closures. Since no launches have occurred from the spaceport to date, no aircraft flight data showing the actual disruption of such an event are available. Therefore, a set of flight re-routing rules are developed based on the parameters of the airspace closure and current FAA regulation and procedures, and manually programmed into TAAM. These reroutes, considered strategic in nature, are activated on a case-by-case basis when affected aircraft

Table 1
Weighted average growths in IFR flights.

Scenarios	ZJX	ZMA	Total	Weighted Growth
2017	2,281,714	2,529,959	4,811,673	—
2027	2,678,874	2,834,247	5,513,121	15%
2037	3,195,151	3,270,859	6,466,010	28%

Source: FAA Aerospace Forecast for Fiscal Years 2017-2037 [28].

Table 2
Baseline and launch scenarios.

Scenarios	Parameters	2 May 2017	2027	2037
No Launch Baseline Scenario	No airspace closures	Actual Air Traffic	Forecasted Air Traffic	Forecasted Air Traffic
Launch Scenario 1	Complete TFR with airspace blocked 8 AM to 12 PM; 10 AM launch	Actual Air Traffic with Simulated Reroute	Simulated Air Traffic with Forecasted Growth and Reroute	Simulated Air Traffic with Forecasted Growth and Reroute
Launch Scenario 2	Complete TFR with airspace blocked 9 AM to 10:30 AM; 10 AM launch	Actual Air Traffic with Simulated Reroute	Simulated Air Traffic with Forecasted Growth and Reroute	Simulated Air Traffic with Forecasted Growth and Reroute
Launch Scenario 3	Complete TFR with airspace blocked 9 AM to 11 AM; 10 AM launch	Actual Air Traffic with Simulated Reroute	Simulated Air Traffic with Forecasted Growth and Reroute	Simulated Air Traffic with Forecasted Growth and Reroute
Launch Scenario 4	No corridor TFR; remaining airspace blocked 8 AM to 12 PM; 10 AM launch	Actual Air Traffic with Simulated Reroute	Simulated Air Traffic with Forecasted Growth and Reroute	Simulated Air Traffic with Forecasted Growth and Reroute
Launch Scenario 5	Complete TFR with airspace blocked 5 AM to 9 AM; 7 AM launch	Actual Air Traffic with Simulated Reroute	Simulated Air Traffic with Forecasted Growth and Reroute	Simulated Air Traffic with Forecasted Growth and Reroute
Launch Scenario 6	No corridor TFR; remaining airspace blocked 5 AM to 9 AM; 7 AM launch	Actual Air Traffic with Simulated Reroute	Simulated Air Traffic with Forecasted Growth and Reroute	Simulated Air Traffic with Forecasted Growth and Reroute

encounter key waypoints prior to entering the airspace closure, but allowing sufficient time for aircraft reroute, thus optimized to minimize airline impacts.

Using this method, all impacted aircraft are detoured around the closure with minimal additional distance traveled, and the affected aircraft rejoin the original flight path after rerouting. Aircraft could be rerouted either east or west of the restricted airspace, but any aircraft rerouted east over water must be certified to do so. Because of this restriction, most aircraft are rerouted west of the airspace closure. Such procedure is in line with FAA norms. For example, per FAA interviews, aircraft impacted by launches from KSC/CCAFS are rerouted west over the Florida peninsula, away from the direction of the eastward rocket path. It should be noted that our research focused on primary impacts only, that is, additional air traffic that is subsequently impacted by the rerouted flights are not considered.

5. Discussions of simulation results

We extract the following sets of data from the TAAM simulations for each of the launch scenarios and the baseline scenario:

- Time Flown:
  - Total time flown by a specific aircraft. Specifically, from take-off until landing (wheels up until wheels down).
- Distance Flown
  - Total distance flown by a specific aircraft in nautical miles (nmi)
- Fuel Cost
  - Total fuel cost for a specific aircraft (wheels up to wheels down). Fuel costs are calculated assuming the fuel price at $1.51/gallon. This was the price of jet fuel on 2 May 2017, the day of the 2017 Baseline Scenario.

The potential impacts of a single space launch on airlines are assessed by comparing the results of the launch scenarios with those of the baseline scenario, and are measured in terms of the number of impacted aircraft, additional flight time (delay), additional distance flown, and additional fuel costs:

- Flight Time Delay (minutes)
  - The "Time Flown" difference between each of the launch scenarios and the baseline scenario
- Additional Distance Flown (nmi)
  - The "Distance Flown" difference between each of the launch scenarios and the baseline scenario.
- Additional Fuel Cost (USD)
  - The "Fuel Cost" difference between each of the launch scenarios and baseline scenario.

TAAM output data are sampled every 1 second, thus we first filter out sampling errors in the results by removing flights that are impacted by less than +/- 1 second in order to obtain a more rigorous output data set. Table 3 presents the estimated total impacts for Launch Scenario 1 to Scenario 3, as defined by the following:

- Number of Aircraft Impacted by a Single Commercial Space Launch
  - The number of flights for which a launch scenario's "Time Flown" is longer than that of the baseline scenario.
- Total Flight Time Delay (minutes)
  - The sum of the "Flight Time Delay" for all the impacted flights under each launch scenario versus the baseline scenario.
- Total Additional Distance Flown (nmi)
  - The sum of the "Additional Distance Flown" for all the impacted flights under each launch scenario versus the baseline scenario.
- Total Additional Fuel Cost (USD)
  - The sum of the "Additional Fuel Cost" for all the impacted flights under each launch scenario versus the baseline scenario.

It is not surprising to see that Launch Scenario 1 leads to the largest impacts on airlines over the course of the full 4-hour TFR with the number of flights impacted ranging from 186 in 2017 to 235 in 2037. As shown in Table 3, Scenario 1 results in an estimated total of 609.73 minutes of flight delays, 4,388 nmi additional distance flown, and $12,522.11 additional fuel costs in 2017. In light of the forecasted traffic growth, the impacts on airlines by a single space launch are estimated to increase to 746 minutes in flight delays, 5,420 nmi additional distance flown, and $15,900 additional fuel costs in 2037, assuming the same fuel price.

[6] Original airspace closure information obtained from [27].

Table 3
Estimated impacts by a launch under launch scenarios 1 through 3.

Launch Scenarios		# Impacted Flights	Total Flight Delay (min)	Total Add. Distance Flown (nmi)	Total Add. Fuel Cost (USD)
2017	Scenario 1	186	609.73	4,388	12,522.11
	Scenario 2	72	241.08	1,747	5,450.39
	Scenario 3	95	287.40	2,073	6,333.98
2027	Scenario 1	211	707.92	5,134	14,894.56
	Scenario 2	83	256.22	1,888	5,875.57
	Scenario 3	109	318.52	2,310	7,051.87
2037	Scenario 1	235	745.87	5,420	15,883.83
	Scenario 2	94	267.73	1,988	6,242.70
	Scenario 3	121	336.13	2,452	7,444.31

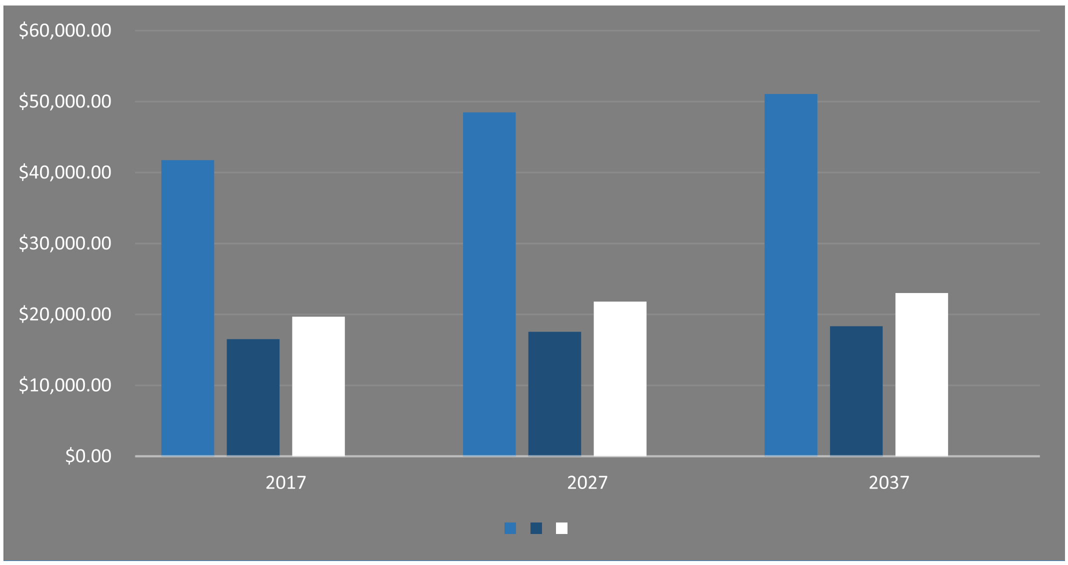

Fig. 6. Additional Direct Aircraft Operating Cost Due to Flight Delays.

Since TAAM only yields fuel costs for the simulated flights, we further estimate the impacts on airlines in terms of direct aircraft operating costs based on the simulated flight time delays and the average aircraft operating costs per block minute. According to Airlines for America (A4A), [29] the U.S. passenger airlines' average direct aircraft operating cost per block minute was $68.48 in 2017, which includes crew, fuel, maintenance, aircraft ownership, and other expenses. Fig. 6 shows that the estimated additional direct operating costs range from approximately $42,000 in 2017 to over $50,000 in 2037 under Launch Scenario 1. By safely reducing the duration of the airspace closures in Launch Scenarios 2 and 3, the economic impacts are greatly reduced. Scenarios 2 and 3 reflect the situations following successful launches, and/or when space vehicles have a safety record established.

By treating the carrier aircraft as a non-experimental aircraft and opening the departure/arrival corridor to regular air traffic in Scenario 4, we observe that no flights are impacted by the trapezoidal airspace closure that is located off-shore during the launch window. Hence, there are no delays, no additional distance flown, nor increases in fuel costs.

Launch Scenarios 5 and 6 depict conditions stated in the Letter of Agreement for spaceport operations at Cecil [27]. Accordingly, these scenarios are established with launch windows of 5 AM to 9 AM and a launch at 7 AM. Scenario 5 depicts a complete TFR and Scenario 6 removes the airspace closure along the departure/arrival corridor. Simulations are conducted for launch scenarios 5 and 6 with 2017 traffic only.

As expected, clearly less flights are impacted during the earlier morning hours, all other variables equal, when the results of Scenario 5 are compared with those of Scenario 1. With respect to Scenario 4 and 6, we observe that no flights are rerouted with the removal of the airspace closure along the departure/arrival corridor regardless of closure times. Table 4 presents the simulation results for Launch Scenarios 5 and 6.

All of the launch scenarios depict a single space launch, multiple launches in a day could lead to more negative impacts on airline fuel costs, delays and operating costs over an extended period. Further, as aforementioned, our simulations reroute only those aircraft that are to enter the TFRs. In reality, rerouted aircraft impact other aircraft, in a domino fashion. Such ripple effects are not considered in the simulations. Finally, it is noted that a very small number of simulated flights appear to consume less fuel with less distance travelled, which may be explained by the likelihood that the original flight paths of these flights are not optimal.

6. Summary and concluding remarks

Both the aviation industry and the commercial space industry need safe, effective and efficient integration of space activities into airspace, and are seeking fair and equitable solutions to achieve the goal. The results from this study provide evidences on the impacts of horizontal space launches on airlines as well as the efficacy of certain mitigating strategies, thus have important policy implications for governments and the industries.

Our results indicate that the existing practice of 4 hour airspace closure (Scenario 1) in the U.S. impacts a significant number of airline flights, forcing them to reroute, and resulting in flight time delays, additional flight distance, added fuel burn, and additional direct operating costs. Reducing the duration of airspace closure, as shown in Scenario 2 and Scenario 3, for the launch vehicle considered in this study, would not impose additional safety risk associated with the space launches, but could serve as a simple solution to mitigate the impacts on airlines

Table 4
Comparison of estimated impacts with corridor airspace closure and without corridor airspace closure.

2017	Scenario 1 (With corridor airspace closure; 8 AM to noon)	Scenario 5 (With corridor airspace closure; 5 AM to 9 AM)	Scenarios 4 and 6 (Without corridor airspace closure)
# Impacted Flights	186	114	0
Additional Fuel Costs (USD)	$12,522.11	$6,930.33	0
Total Flight Time Delay (min)	609.73	352.45	0
Total Distance Flown (nmi)	4388	2521	0
Direct Operating Costs (USD)	$41,754.54	$24,135.78	0

and other traditional NAS users, especially as air traffic control already often releases the TFR airspace early when the airspace is deemed safe following successful missions.

Our study further shows that opening the departure/arrival corridor to air traffic (Scenario 4) during the launch of a Concept Z vehicle would effectively eliminate almost all the potential impacts on airlines, as very few flights on non-launch days are routed through the trapezoidal airspace closure area, and most flights are routed along the Florida coastline. This is a significant finding. Of the seven spaceports in the U.S. licensed for horizontal launch, four are licensed for Concept Z. The question here is whether or not a Concept Z vehicle could truly be considered as a conventional aircraft during the takeoff and/or landing procedure. It is likely that airspace closures for such LVs will abate in the near future as the reliability of the vehicles continues to improve. To add further support, carrier aircraft with mated rockets have been treated as regular aircraft in the airspace (i.e. Lockheed 1011 with Pegasus rocket) for quite some time.

Internationally, the majority of the proposed spaceports are for horizontal takeoff and landing, and many of them would transition from current airports to become air and space ports. We anticipate this trend to continue. Particularly, for space tourism, Virgin Galactic is a driving force as Sir Richard Branson has reached agreement after agreement to enable his plans for this sector to be a viable reality in the near future. Point-to-point travel that includes a suborbital trajectory apogee without a full earth orbit will thrill space travel enthusiasts while allowing fast travel around the world. While Spaceport America in the U.S. may be the hub, Sir Branson plans to fly to the UAE, the UK, Italy, and other countries with spaceports that can accommodate the Virgin Galactic carrier aircraft and RLV, and where sufficient participant demand is forecasted.

The growing small satellite industry and corresponding increase in launch provider services are also trends to watch. The use of a carrier aircraft with mated rocket is often the transportation mode of choice for these satellites, encased in the rocket fairing. Virgin Orbit, Generation Orbit, among others, will provide their small satellite launch services via this platform. Generation Orbit is planning on launch from Cecil Air and Space Port in 2020.

With space launch increasingly becoming a commercial endeavor, and with suborbital launch activities (especially those focused on tourism) advancing rapidly into launch-capable status, space activities are expected to present a much larger disruption to the aviation industries due to more frequent and/or longer interactions with airspace. Further, in the short term, the unproven nature of the new LVs allows for an expectation of higher risk. As the primary goal of the FAA and other national aviation authorities is to ensure the safe, effective, and efficient passage of aircraft in the NAS and ultimately, the safety of the traveling public, many possible mitigation strategies may be discounted in the short term until new space LVs have been flight proven.

It should be noted that our research is limited to the launch of Concept Z vehicles out of one spaceport in the U.S, a spaceport that sits close to the Atlantic Ocean and north of Cape Canaveral, Florida. The impacted airspace areas in this study consist of various “pre-existing” restricted airspaces which airlines and other NAS users stay away from in their regular operations, thus the estimated impacts on airlines are likely to be less than that if the spaceport is located away from the coast and without any existing restricted airspace. Airspace closures due to launch activities are unique to the geographical location. Proximity to Jet airways and Victor routes, areas of restricted airspace, prohibited airspace, other special use airspace and population centers, among many other considerations, impact the size, shape, and timing of airspace closures. Additionally, the type and orientation (vertical versus horizontal) of LV, propulsion method, as well as anticipated payload will influence airspace closure requirements. Another limitation of this study is that secondary impacts on air traffic and potential disruption to airports are not considered. Depending on the location of the spaceport, there may be a significant volume of impacted general aviation traffic, also not considered in this study. These limitations will be addressed in our future research endeavors.

Author contributions

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Embry-Riddle Aeronautical University (ERAU) Faculty Innovative Research in Science and Technology (FIRST) Program. The authors would like to thank Mr. Todd Lindner of Cecil Air and Space Port, Mr. Donald J. Musser of the FAA Jacksonville Center, Professor Gregory McGuirk, ERAU College of Aviation, Mr. Todd Waller and Mr. Johnathan Pesce of ERAU NEAR Lab.

References

[1] FAA Air Traffic by the Numbers, Federal Aviation Administration, U.S. Department of Transportation, Washington DC, USA, 2019 June.

[2] Final Environmental Assessment for Jacksonville Aviation Authority Launch Site Operator License at Cecil Field, Florida (2009). Retrieved from https://www.faa.gov/about/office_org/headquarters_offices/ast/media/20090626_Final_Cecil_Field_EA.pdf.

[3] Bryce Space and Technology, 2018. 2018 Orbital launches year in review. Retrieved from https://brycetech.com/downloads/Orbital_Launches_Year_in_Review_2018.pdf.
[4] B. Gulliver, G.W. Finger, Can your airport become a spaceport? the benefits of a spaceport development plan, in: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, American Institute of Aeronautics and Astronautics, 2010.
[5] Air Line Pilots Association Addressing the Challenges to Aviation from Evolving Space Transportation, 2018 Retrieved from https://www.alpa.org/~/media/ALPA/Files/pdfs/news-events/white-papers/white-paper-aviation-space.pdf.
[6] E. Larson, 2013. Safety Design for Space Operations. (F. A. Allahdadi, I. Rongier, & P. D. Wilde, Eds.). Kidlington, Oxford: Butterworth-Heinemann is an imprint of Elsevier. doi: 10.1016/B978-0-08-096921-3.00010-6.
[7] L. Anselmo, C. Pardini, Computational methods for reentry trajectories and risk assessment, Adv. Space Res. 35 (7) (2005) 1343–1352, doi:10.1016/j.asr.2005.04.089.
[8] E. Larson, S.L. Carbon, D.L. Murray, Automated calculation of aircraft hazard areas from space vehicle accidents: application to the shuttle, in: Atmospheric Flight Mechanics Conference and Exhibit, American Institute of Aeronautics and Astronautics, 18-21 August 2008, Honolulu, Hawaii, USA, 2012, doi:10.2514/6.2008-6889.
[9] G. Mazzotta, D.P. Murray, Improving the integration of launch and reentry operations into the national airspace system, in: The 2nd Space Traffic Management Conference, Embry-Riddle Aeronautical University, Daytona Beach, Florida, USA, 12 November 2015 Retrieved from.
[10] D.P. Murray, R. Van Suetendael, A tool for integrating commercial space operations into the national airspace system, in: Atmospheric Flight Mechanics Conference and Exhibit, American Institute of Aeronautics and Astronautics, 21-24 August 2006, Keystone, Colorado, USA, 2012, doi:10.2514/6.2006-6378.
[11] L.H. Mutuel, D.P. Murray, Space data integrator: FAA's innovative platform for launch and reentry operations, in: 54th AIAA Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, 4-8 January 2016, San Diego, California, USA, 2016, doi:10.2514/6.2016-0218.
[12] T.J. Colvin, J.J. Alonso, Compact envelopes and SU-FARM for integrated air-and-space traffic management, in: 53rd AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, American Institute of Aeronautics and Astronautics, 5-9 January 2015, Kissimmee, Florida, USA, 2015, doi:10.2514/6.2015-1822.
[13] T.J. Colvin, J.J. Alonso, Near-elimination of airspace disruption from commercial space traffic using compact envelopes, in: AIAA SPACE 2015 Conference and Exposition, American Institute of Aeronautics and Astronautics, August 31-September 2, 2015, Pasadena, California, USA, 2015, doi:10.2514/6.2015-4492.
[14] R.E. Tompa, M.J. Kochenderfer, R. Cole, J.K. Kuchar, Optimal aircraft rerouting during commercial space launches, in: 34th Digital Avionics Systems Conference, IEEE/AIAA, (DASC), 13-17 September 2015, Prague, Czech Republic, 2015 pp. 9B1-1-9B1-9., doi:10.1109/DASC.2015.7311486.
[15] R.E. Tompa, M.J. Kochenderfer, Optimal aircraft rerouting during space launches using adaptive spatial discretization, in: 37th Digital Avionics Systems Conference, IEEE/AIAA, (DASC), London, United Kingdom, 23-27 September 2018, doi:10.1109/DASC.2018.8569888.
[16] A. Srivastava, T. Clair, G. Pan, On-demand assessment of air traffic impact of blocking airspace, Aeronaut. J. 122 (1258) (2018) 1985–2009, doi:10.1017/aer.2018.105.
[17] D.N. Sweet, V. Manikonda, J.S. Aronson, K. Roth, Fast-time simulation system for analysis of advanced air transportation concepts, in: AIAA Modeling and Simulation Technologies Conference and Exhibit, American Institute of Aeronautics and Astronautics, Monterey, California, USA, 5-8 August 2002 Retrieved from.
[18] C.A. Nava Gaxiola, C. Barrado, P. Royo, E. Pastor, Assessment of the North European free route airspace deployment, J. Air Transport Manage. 73 (2018) 113–119, doi:10.1016/j.jairtraman.2018.08.008.
[19] T. Luchkova, R. Vujasinovic, A. Lau, M. Schultz, Analysis of impacts an eruption of volcano stromboli could have on European air traffic, in: Eleventh USA/Europe Air Traffic Management Research and Development Seminar, June 23-26, 2015, Lisbon, Portugal, 2015.
[20] A. Srivastava, T.J. St. Clair, S. Zobell, D. Fulmer, Assessing impact of space launch and reentry operations on the National Airspace System (NAS) using historical traffic patterns, in: 34th Digital Avionics Systems Conference, IEEE/AIAA, (DASC), 13-17 September 2015, Prague, Czech Republic, 2015, doi:10.1109/DASC.2015.7311486.
[21] J. Young, M. Kee, SpaceX Falcon 9/Dragon Operations NAS Impact and Operational Analysis, U.S. Department of Transportation NextGen Implementation and Integration Office, Washington, D.C, 2014.
[22] J. Young, M. Kee, C. Young, Effects of Future Space Vehicle Operations on a Single Day in the National Airspace System: A Fast-Time Computer Simulation, U.S. Department of Transportation NextGen NAS Programming & Financial Management Division, Washington, D.C., 2015.
[23] T. Luchkova, S. Kaltenhaeuser, F. Morlang, Air traffic impact analysis design for a suborbital point-to-point passenger transport concept, in: The 3rd Space Traffic Management Conference, Daytona Beach, Florida, USA, 16-18 November 2016.
[24] S. Kaul, Integrating air and near space traffic management for aviation and near space, J. of Space Saf. Eng. 6 (2) (June 2019) 150–155, doi:10.1016/j.jsse.2019.06.004.
[25] Jacksonville Aviation Authority. October 2014. Cecil spaceport launch site operator license (LSO 09-012) renewal application.
[26] Cecil Spaceport, 2017. Spaceport operations. Retrieved from https://www.flyjacksonville.com/content2015.aspx?id=1091.Dickey, B. (2015, April 07). NASA Advances Effort to Launch Astronauts Again from U.S. Soil to Space. Retrieved November 19, 2017, from https://www.nasa.gov/press/2013/november/nasa-advances-effort-to-launch-astronauts-again-from-us-soil-to-space-station.
[27] Jacksonville Air Traffic Control Center, Jacksonville Approach Control, Fleet Area Control and Surveillance Facility Jacksonville, and JAA Center, Miami Center, Jacksonville Approach Control, Cecil ATC Tower, Fleet Area Control and Surveillance Facility Jacksonville, and Jacksonville Aviation Authority/Cecil Spaceport Operations Office. (October 1, 2009). Letter of agreement, operations at the cecil spaceport at cecil field, Jacksonville, Florida.
[28] Federal Aviation Administration, 2017. FAA aerospace forecast fiscal Years 2017-2037. Retrieved from https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/FY2017-37_FAA_Aerospace_Forecast.pdf.
[29] Airlines for America (A4A) U.S. Passenger Carrier Delay Costs, 2017 Retrieved from https://www.airlines.org/dataset/per-minute-cost-of-delays-to-u-s-airlines/.