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ABSTRACT

Launch Vehicle/Reentry Vehicle (LV/RV) operations are expected to increase across the National Airspace System (NAS) as their reliability and availability improve. LV/RV designs and the industry landscape have vastly changed since the 1960's, and the Federal Aviation Administration's (FAA) methods for handling these operations need to evolve to support the expected growth. Currently, large amounts of airspace are segregated for every LV/RV operation. This increases costs for NAS users and may limit LV/RV opportunities. The FAA's NextGen office recently proposed two more efficient separation concepts for LV/RV operations called Space Transition Corridors, and Four-Dimensional Trajectory Deconfliction. Prior safety research for LV/RV separation concepts has been limited to the interactions between falling debris and aircraft during in-flight breakup. However, there have been limited studies on the interactions between aircraft and LV/RV, aircraft and aircraft, and impacts on controller workload for LV/RV separation concepts and standards. Understanding these interactions is critical to implementing more efficient separation concepts and standards. The MITRE Corporation (MITRE) is building a flexible, fast-time modeling and simulation capability that fills this gap and provides operational measures of safety for each type of LV/RV operation using different separation concepts and associated standards, which helps support the FAA's Safety Management System process. This capability will allow the FAA to determine which separation concepts meet a target level of safety for each type of LV/RV operation and will provide insight into the required surveillance performance, air traffic control and pilot response times, and traffic limits to enable the concepts. This paper describes the research, modeling, and current progress of MITRE's analytic capability.

I.Introduction: The Need to Evaluate Launch Vehicle/Reentry Vehicle LV/RV Separation Standards

A new generation of commercial space companies is designing a variety of LV/RVs that are able to launch more often and from more locations across the country. As LV/RV operations

increase, and their reliability improves, the current approach of segregating large amounts of airspace for every LV/RV operation will increase costs for other NAS users and may limit the growth of the commercial space industry. Reducing the amount of airspace segregated for LV/RV operations is crucial for efficiently integrating these operations into the NAS. A re-entering spaceplane that has a small amount of fuel, some maneuverability, glider-like performance, and demonstrated reliability does not pose the same level of risk as a Delta II rocket launch with a full tank of fuel.

The FAA is developing new, more efficient separation concepts and associated standards for a variety of LV/RV operation types to minimize their impact on other NAS users. Two recently proposed separation concepts for LV/RV operations are called Space Transition Corridors (STC) (a method of airspace segregation) and Four-Dimensional Trajectory Deconfliction (4DT Deconfliction) (a method of separation). These are described in the FAA's Space Vehicle Operations Concept of Operations [1]. The separation concept employed would depend on the maturity and reliability of the LV/RV involved. These concepts also require associated separation standards for each type of LV/RV operation such as traditional orbital launches, fly-back operations (e.g., a powered booster landing), small suborbital vehicles, or hybrid vehicles.

The current approach for determining how much airspace to segregate for LV/RV operations (hazard volumes) focuses on mitigating the danger of falling debris to aircraft. It relies on calculating a probability of falling debris causing a casualty on an aircraft [2]. Focusing on this metric is sufficient when using traditional Temporary Flight Restrictions (TFRs) to segregate LV/RV operations. However, new separation concepts and standards that call for more dynamic airspace separation and controller involvement require examining the full range of operational safety considerations in addition to the risks of debris to aircraft. These other considerations include risks between aircraft and LV/RV, aircraft and aircraft, and impacts on controller and pilot workload. Operational considerations and metrics need to be taken into account such as how much time it might take an aircraft to exit a hazard volume, controller workload, possibility of loss of radar reparation between aircraft during stressful situations, and probability of Near Mid-Air Collision (NMAC). The traffic limits required for enabling new separation concepts also need to be determined. For example, what is the limit on the number of aircraft in the vicinity for controllers to safely reroute aircraft that are inside and outside a dynamically activated hazard volume? The FAA needs tools or methods to evaluate these various aspects of operational safety between aircraft and LV/RV, aircraft and aircraft, and the impacts on controller workload from new separation concepts and associated standards for LV/RV operations.

The MITRE Corporation (MITRE) is filling this gap by building a fast-time modeling and simulation capability that provides operational measures of safety of LV/RV operations with different separation concepts and standards that considers the interactions between aircraft and LV/RV, aircraft to aircraft, and impacts on controller workload. The capability produces several operational metrics that the FAA can use to determine which separation concepts and associated standards meet a target level of safety for each type of LV/RV operation. MITRE's capability

can examine operational risks of new separation concepts and provide insight into the required surveillance performance, Air Traffic Control (ATC) and pilot response times, and traffic limits to enable them. It can also support the FAA's Safety Management System process.

II. High Level Approach: Developing and Integrating Models to Evaluate Safety

This research builds upon MITRE's aviation domain expertise and capabilities by leveraging MITRE's aircraft, separation, conflict detection, and surveillance models. It also adds new spacecraft trajectory models to these modeling capabilities. The FAA analyst or researcher can vary the separation concepts and standards, LV/RV performance characteristics, ATC and pilot responses, and surveillance performance for each scenario. The results can be compared against a target level of safety to determine which separation concepts and standards are safe for each type of LV/RV operation.

As illustrated in Figure 1, the modeling framework requires integrating outputs from multiple models to evaluate the safety of LV/RV separation concepts and standards. Inputs to the model include a separation concept and standards definition, nominal and off-nominal STC (hazard volume) boundaries, trajectories for the LV/RV (including separable stages), probabilistic ATC and pilot response times, and aircraft traffic. The inputs and surveillance performance are adjustable parameters. MITRE's *algorithm*Evaluator [3] tool has been adapted and enhanced by the research to include ATC and pilot control algorithms, safety metrics calculations, an updated surveillance model, and the ability to run scenarios throughout a day a traffic by launching or reentering at different times throughout the day. The aircraft traffic is represented as actual historical as-flown flight tracks, which are assumed to be de-conflicted prior to the LV/RV operation. Based on these inputs, the model runs Monte Carlo simulations to generate various output metrics. The output metrics include NMAC (between aircraft and LV/LV as well as aircraft and aircraft), loss of radar separation (LORS), time spent in nominal or off-nominal STCs, and the time to clear the STCs of (non-LV/RV) air traffic. There is also a capability to visualize each scenario via Google Earth.
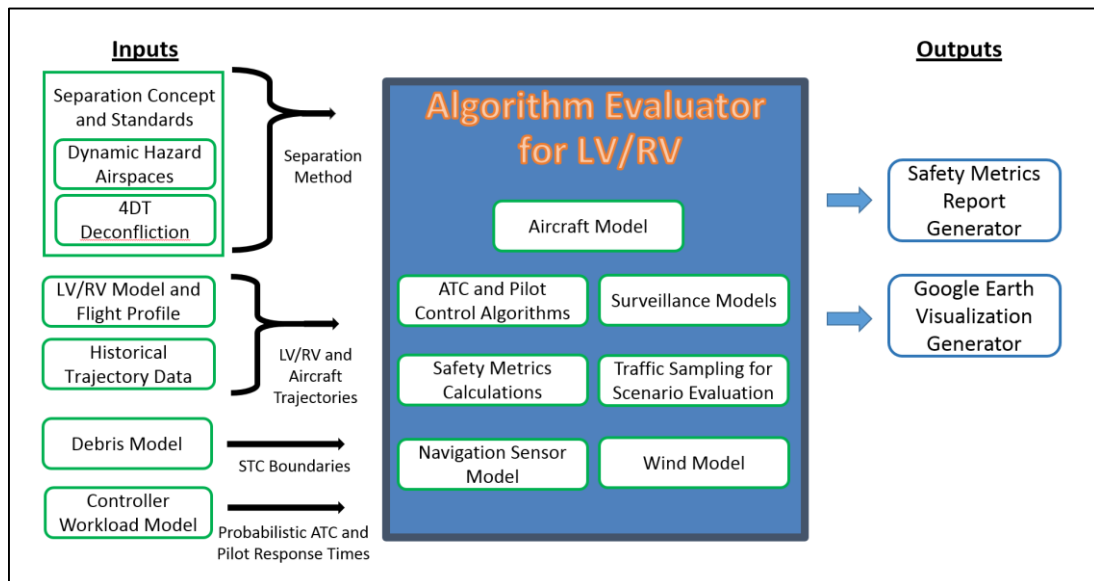
Figure 1. High Level Overview of Approach

III.Modeling Details: Nuts and Bolts of the Models

MITRE's *algorithm*Evaluator [3] is a Monte Carlo simulation capability that has been used for several tasks in the past including evaluating Sense and Avoid algorithms for Unmanned Aircraft Systems [4], En Route Automation and Modernization surveillance performance evaluation, and generating and validating surveillance requirements. The research team adapted and enhanced it to model, study, and demonstrate different separation concepts; aircraft and space vehicle trajectories; ATC and pilot actions; and surveillance performance. The simulation capability consists of the following models and algorithms: aircraft model, ATC and pilot control algorithms, wind model, navigation sensor model, and Automatic Dependent Surveillance – Broadcast (ADS-B) model. The debris model and space vehicle model have been developed separately. Figure 2 illustrates the simulation the models pertaining to a single aircraft. Details about the model are described in the subsections below.
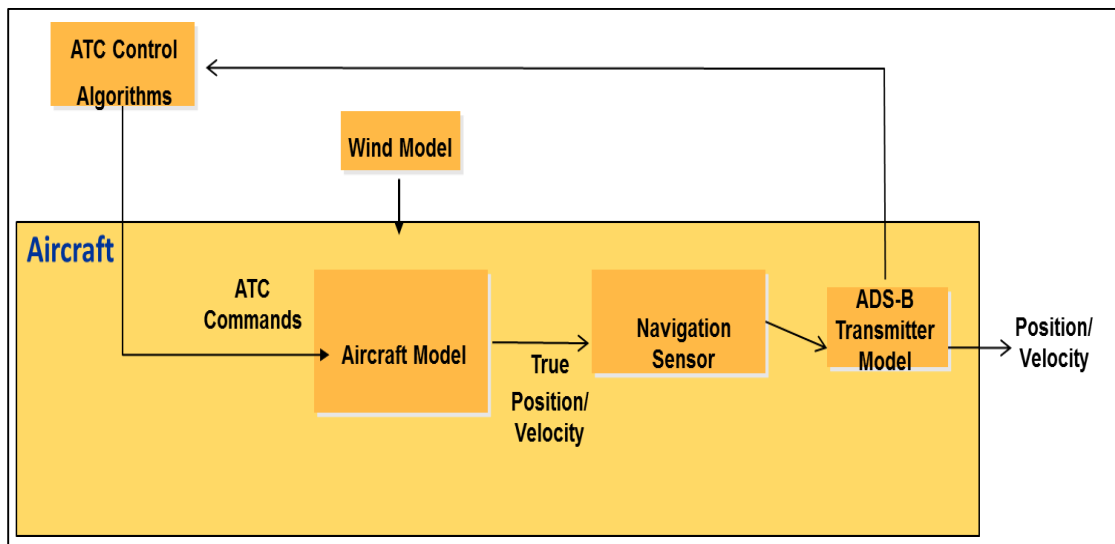

Figure 2. Relations among the Models Pertaining to an Aircraft

Aircraft Model

The aircraft model in the simulation tool generates aircraft trajectories. The aircraft model is based on a three-degree-of-freedom (3DOF) equation of motion and the parameters contained in the EUROCONTROL Base of Aircraft DATA (BADA). The input to the aircraft model includes waypoints along the nominal path of the aircraft.

ATC Control Algorithms

Different LV/RV separation concepts are embodied in the corresponding ATC control algorithms, which include 1) hazard-volume-evacuation algorithm, 2) hazard-volume-avoidance algorithm, and 3) 4DT de-confliction algorithm.

1. Hazard-Volume-Evacuation Algorithm

Hazard volumes involving launch or reentry space vehicles are modeled as convex polygons. If there are aircraft within a hazard volume when it becomes active, ATC needs to direct the pilots of those aircraft to exit the hazard volume quickly. The hazard-volume-evacuation algorithm simulates an air traffic controller's decision in such situations. The algorithm calculates heading commands for each aircraft within the hazard volume such that the aircraft can get out of the hazard volume as quickly as possible and in the meantime avoid getting into conflict with nearby aircraft.

2. Hazard-Volume-Avoidance Algorithm

When a hazard volume becomes active, an air traffic controller may need to direct aircraft outside the hazard volume to take necessary maneuvers in order to avoid entering the hazard volume. The hazard-volume-avoidance algorithm simulates an air traffic controller's decisions in such situations. The algorithm first calculates the vertices of a new, enlarged polygon encompassing the original hazard volume with buffer areas added around the original hazard volume. If the aircraft is predicted to enter the original hazard volume within a look-ahead time (say, 15 minutes), the algorithm directs the aircraft to vector to a vertex on the expanded polygon and, if necessary, fly along the edge of this polygon to another vertex on the expanded polygon to reach the next waypoint along its original path on the other side of the hazard volume.

3. 4D de-confliction Algorithm

In addition to evacuating from and avoiding a hazard volume, aircraft also need to avoid getting into conflict with spacecraft. The 4D de-confliction algorithm simulates ATC's direction to aircraft in a cases where aircraft may get into conflict with spacecraft. Based on the predicted trajectory of the spacecraft and the aircraft, the predicted vertical and horizontal distances between the aircraft and the spacecraft are calculated. To avoid conflict with the spacecraft, when the predicted horizontal distance or vertical distance is less than some threshold value, then the algorithm calculates a new waypoint for the aircraft to fly to and then fly to the next waypoint on the aircraft's original nominal route.

Wind Model

Wind is modeled with the National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) data. The RUC wind data contain wind speed at grid points (one degree latitude and longitude, and every 1,000 feet from sea level to 40,000 feet above sea level). RUC data representing true wind and predicted wind are included in the wind model. The true wind data is used in the aircraft model.

Navigation Model

The errors in the measurement of the aircraft's position and velocity are calculated by the navigation sensor model. GPS measurement errors are modeled in the simulation with a Gauss-Markov process, the output from which reflects the time-correlation of the position and velocity measurement errors as observed in GPS data. The input to the navigation model includes the 95% error bounds on the position and velocity errors, which are represented by the ADS-B

navigation accuracy categories for position and for velocity (Navigation Accuracy Category for Position [NACp] and Navigation Accuracy Category for Velocity [NACv]).

ADS-B Model

The ADS-B model consists of the model for the ADS-B transmitter (ADS-B Out) and the model for the ADS-B receiver (ADS-B In). The ADS-B transmitter model calculates the position and velocity in the ADS-B state report broadcasted from an ADS-B equipped aircraft. It uses the system specifications defined in RTCA DO-282B [5] to process the position and velocity received from the aircraft's navigation model, and then generates the ADS-B state report containing the processed position and velocity. The ADS-B receiver model calculates the received ADS-B state reports broadcast from other aircraft. The parameters used in these models include the quantization thresholds for position and velocity, transmission latency, probability of receiving, state-report update period, uncertainty in the time of applicability, and navigation accuracy categories for position and for velocity (NACp and NACv).

Space Vehicle Trajectory Model

Algorithm Evaluator requires Space Vehicle (SV) trajectories as inputs to the simulation. The SV trajectories must include the position and velocity vectors as a function of time, but may be computed using any external trajectory modeling or optimization tool. The work presented in this paper relies on a simple, in-house trajectory estimation tool that models an SV as a point-mass and captures the equations of motion with 3DOF. The tool does not include a formal or automated trajectory optimization capability, rather it simply propagates the SV through the atmosphere (either ascending or descending) using simple control modes that can be tweaked manually to better estimate a realistic SV trajectory. The trajectory model assumes inviscid (no boundary layers) and incompressible (subsonic) flows, as well as a standard atmosphere with no winds, and a non-rotating Earth. These simplifying approximations are clearly not appropriate for all applications, but they may yield acceptable accuracy for this work given its focus on the lowest 60,000 feet of the atmosphere. The in-house trajectory estimation tool is able to model multiple stages falling back to Earth during SV launches as well as parachutes and retro-firing rockets on falling launch stages or other re-entering vehicles.

Debris Model

Algorithm Evaluator also requires hazard volume definitions—for both nominal operations trajectories and off-nominal events (e.g., in-flight breakup)—as inputs. In collaboration with Stanford University, MITRE has built an in-house debris trajectory estimation tool to provide both definitions. This tool is an adaptation and enhancement of Stanford's debris propagator in their Range Safety Assessment Tool [6]. MITRE has re-written their debris propagation model to integrate it directly into MITRE's space vehicle (SV) trajectory estimation tool. This enables quick and easy initiation of debris modeling by defining an off-nominal event at any point along the nominal SV trajectory.

For off-nominal situations, the model simulates debris field propagation by first generating individual pieces of debris, either at a specific time for explosive failures during launch, or over a prolonged duration for inert breakups on re-entry. An input debris parts catalog defines the

masses and aerodynamic properties of the various debris pieces. Then the core 3DOF point-mass model propagates the individual debris trajectories until they all fall back to Earth.

For both nominal SV trajectories and off-nominal debris fields, the trajectory estimation tool can compute compact bounding volumes. The bounding volumes are extruded convex polygons of the minimum size required to contain the trajectory segments at various time steps, for discrete time durations. In other words, the bounding volumes define portions of airspace that must be clear of other aircraft at various times to protect aircraft from SV hazards. The hazard volume computation accepts optional vertical and horizontal buffer distances to add to the minimum bounding volumes, as well as the time duration and time step frequency of the output hazard volumes, as variable user inputs.

IV. Metrics: How to Measure Safety of New LV/RV Separation Standards?

Several metrics are calculated to understand how different separation methods with varying amounts of nearby air traffic affected safety. NMAC, LORS, and Closest Proximity of Approach (CPA) values are captured to help understand safety measures from an aircraft to aircraft separation perspective as well as from an aircraft to LV/RV perspective. The model also calculates time spent in hazard volumes (per aircraft) to evaluate length of exposure to potential risk.

The metrics include the number of aircraft inside a dynamically activated hazard volume (STC) and the number of aircraft entering a STC after it becomes active. These two metrics help understand the risk to these aircraft and the associated ATC workload for rerouting these flights out of the STC. The time until the first ATC reroute instruction is issued to a pilot after a STC becomes active is also calculated. This can help provide insight into the time this takes to execute reroutes given the ATC workload in each scenario. The time it takes for all aircraft to clear an active STC is also calculated, which helps provide understating about the overall safety risk to aircraft. Table 1 lists the metrics considered for analysis. Aggregation of all metrics totals is on a per scenario basis.

Sensitivity analysis can be performed by adjusting scenario parameters (such as surveillance performance, ATC and pilot response, or separation standard) and comparing the metric outputs after each adjustment. For NMAC and LORS, risk ratios can be used to compare the scenarios with different conditions. For example, the risk ratio between a STC and legacy case scenario is calculated as the probability of NMAC using STC divided by the probability of NMAC with the legacy case. The probability of NMAC is defined as the number of NMACs divided by the number of encounters. An encounter is defined as the pair-wise relationship between two airborne vehicles. If two vehicles are airborne at times that do not overlap, there is no encounter. Thus the number of encounters (e) at any given time is ($e = N*(N-1)/2$), where N is the number of airborne vehicles at that time. The risk ratio can be used to determine if a separation concept meets a target level of safety as compared to the legacy case or to another separation method with given level of surveillance performance, ATC and pilot response times, and air traffic volume.

Table 1. Analysis Metrics

Metric	Units of Measure	Notes
1. NMAC pairs (aircraft to aircraft and aircraft to LV/RV) Defined as a conflict with threshold distance <= 500 feet lateral and <= 100 feet vertical	- Counts - Counts/total encounters (percent) - Counts/total flight hours (rate) - Severity* - Risk ratios	- Reported on a per aircraft basis - Potentially multiple events per pair
2. Number of LORS pairs (aircraft to aircraft and aircraft to LV/RV*) Defined as conflict with threshold distance <= 5 nautical miles lateral and <= 1000 feet vertical	- Counts - Counts/total encounters (percent) - Counts/total flight hours (rate) - Severity* - Risk ratios	- Reported on a per aircraft basis - Potentially multiple events per pair
3. CPA for every pair (aircraft to aircraft and aircraft to LV/RV)	- Horizontal distance (meters) - Slant-range distance (meters) - Altitude (meters)	- Reported on a per aircraft basis - Singular event per pair
4. Time in hazard volume (*potential or actual* debris field)	Seconds	Reported on a per aircraft basis
5. Time in ellipsoid (*actual* debris field)	Seconds	Reported on a per aircraft basis
6. Number of aircraft in a hazard volume	Counts	Reported on a per hazard volume basis
7. Number of aircraft entering a hazard volume after hazard volume was active	Counts	Reported on a per hazard volume basis
8. Time until the first reroute was given to the pilot	Seconds	Reported on a per hazard volume basis
9. Time until all aircraft were clear of the hazard volume	Seconds	Reported on a per hazard volume basis

*The severity increases as the distance between two vehicles decreases (inverse relationship). It is a time-integrated score that measures the seriousness of an encounter (LORS or NMAC). An NMAC or a LORS is just a count, but the severity takes into account both the duration and time-varying distance for each encounter. For example, while a miss by a few feet pass and a collision would both show up as a count for LORS, the severity helps distinguish how close it is. More precisely, the current implantation defines severity as 1/distance (in feet), summed across the entire duration of an encounter, at 1-second intervals.

V. Initial Evaluation of Separation Standards using Identified Measures of Safety

The team performed initial evaluations with capability using three scenarios. Two of the scenarios use the STC separation concept and the third uses the 4DT de-confliction concept. Each scenario is run multiple times with different samples of air traffic. For example, a single scenario would be run many times throughout a whole day's of traffic where the time of the launch or reentry event shifts by 10-15 minutes. Varying the traffic sample helps identify outlier cases.

The STC scenarios are based on two scenarios used during FAA NextGen SVO Human-in-the-Loop (HITL) experiments conducted at the FAA W. J. Hughes Technical Center in October

2014, which evaluated the STC concept detailed in the SVO concept of operations [1]. An STC is a type of Special Activity Airspace (SAA) that is specifically designed for the unique characteristics of LV/RV operations that protect aircraft during LV/RV operations. STCs dynamically activate and deactivate on a just-in-time basis to enable LV/RVs to transition safely through the NAS while minimizing the effect on other NAS operations. In the event of an LV/RV failure or breakup, a new STC is calculated and immediately shared with ATC. The controllers' radar displays show how much time the controllers have left to get aircraft out of the newly-calculated STC to avoid potential collision with debris [7]. MITRE simulated scenarios of LV/RV operations that ascend or descend, and experience a vehicular breakup or other off-nominal events along its trajectory. The aircraft traffic used in these scenarios are based on historical flight tracks.

The third scenario simulates a spaceplane arrival (similar to a XCOR Lynx arrival profile) using the 4DT de-confliction separation method to separate aircraft and the reentry vehicle. Instead of providing ATC with a STC to avoid, a minimum separation distanced is set in front, behind, and on each side of the reentry vehicle as it operates its mission. ATC must keep aircraft separated from the reentry vehicle and other aircraft during the operation. In the en route environment between the surface and 41,000 feet, ATC separates aircraft from each other using separation standards of five nautical miles lateral and 1,000 feet vertical. Above 41,000 feet up to 60,000 feet, aircraft to aircraft vertical separation increases to 2,000 feet.

Scenario Descriptions

The launch scenario is based on the Horizontal Takeoff/Horizontal Landing (HT/HL) vehicle scenario from the October 2014 FAA HITL. A HT/HL vehicle takes off from a hypothetical spaceport near Denver, Colorado. An initial STC is reserved for this operation and covers roughly what is necessary to protect for the first few minutes of the operation. During ascent, the vehicle experiences an in-flight breakup several minutes after takeoff and a dynamic STC is calculated and displayed to the controllers.

The reentry scenario is based on the capsule reentry scenarios from the October 2014 FAA HITL. The capsule's target reentry point is on dry land near Colorado. In MITRE's version of the reentry scenario, the vehicle experiences a loss of communication during reentry, which requires a contingency STC to be activated.

For both scenarios, ATC instructions are given to aircraft to avoid or remove flights from STCs. Probabilistic times for ATC and pilots to issue, respond, and execute commands (e.g., due to pilot read-backs and delay until maneuver initiation) are used, and are based on prior MITRE research on controller workload [8].

One of the challenges with these scenarios is the simulation of aircraft to aircraft separation in addition to the aircraft to STC separation. Maneuvering flights around a given volume of airspace can result in compressing flights into a small area near the edges of the STC being avoided.

The 4DT de-confliction scenario shows an arrival of a HT/HL vehicle that has glider-like performance as it approaches the runway at Midland International Air and Space Port (MAF) in Midland, Texas. The reentry trajectory is based on a sample trajectory provided by the FAA's Office of Commercial Space (AST) for a notional HT/HL vehicle operation. During the descent, ATC must maintain minimum separation between aircraft and the reentry vehicle as well as aircraft and aircraft. ATC is assumed to know the flight profile beforehand and there are automation tools that can provide ATC with knowledge of when an expected conflict would occur. Once ATC is aware of the conflict, they would issue maneuvers to the affected aircraft.

The separation distance used for the reentering spaceplane is 15 nautical miles (NM) in front and on each side, 5 NM behind, and 5,000 feet vertical. A large separation distance is used due to the reentry vehicle having a fast descent rate and limited maneuverability. Further study is needed to determine if larger separation standards are needed. Definitive Right of Way rules are also needed.

Scenario Visualizations

Figures 3, 4, and 5 depict Google Earth visualizations of the space capsule reentry simulation with aircraft operating in the area. The blue lines are the aircraft trails and the white lines under the blue indicates distance to the ground. Figure 3 depicts aircraft maneuvering around the initial nominal STC (in red) in advance of the reentry. Figure 4 is a screenshot just moments after the new STC gets displayed on ATC's displays (due to loss of communications). The red dots indicate the space vehicle position. At this point most aircraft are still only avoiding the nominal STC and are just beginning to receive ATC instructions to exit and avoid the new STC. It is important to point out that the debris is considerably higher (in altitude) than all aircraft at that moment, and would not reach aircraft altitudes for a number of minutes. This provides time for ATC to issue instructions to flights to clear the STC before the debris reaches their altitudes. Figure 5 depicts all aircraft now clear of the STC. Note the volume of traffic clustered near the top and bottom edges of the enlarged STC, indicating that controller workload and sector loading would likely be much higher in those areas.
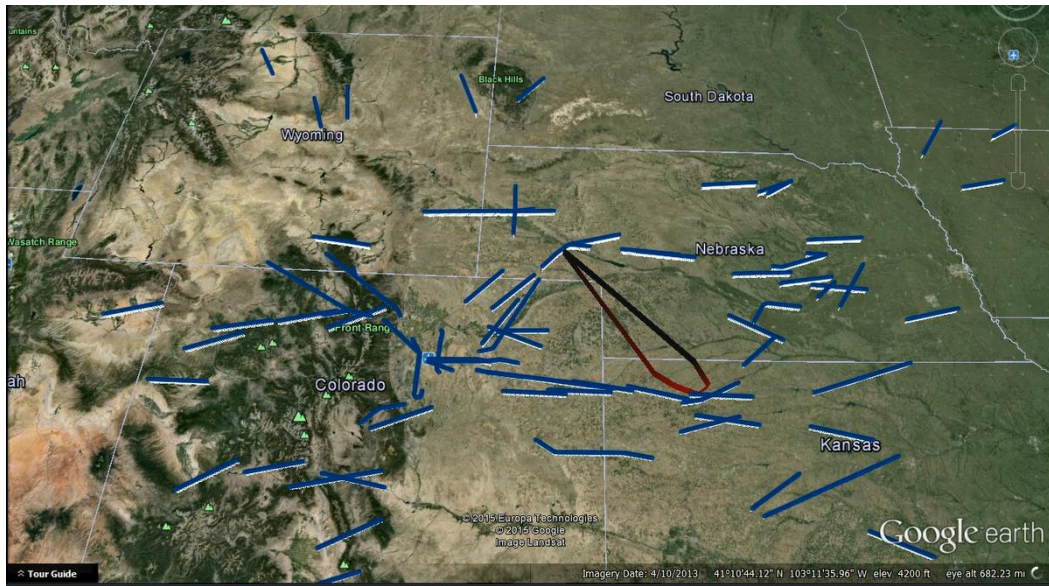
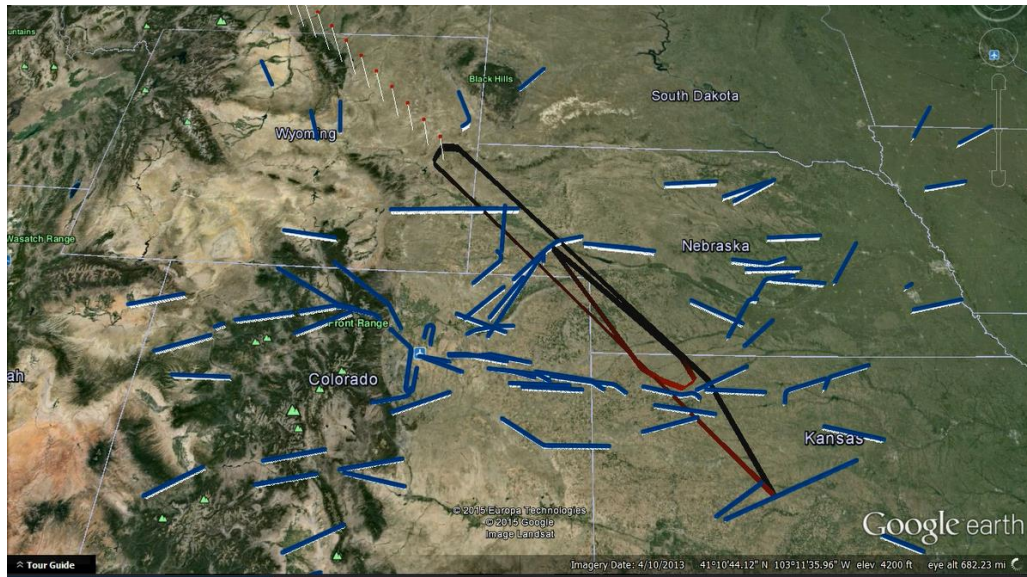**Figure 3. Simulation of Aircraft Circumnavigating the STC for Nominal Reentry**

Figure 4. New STC Calculated for Reentry Vehicle Breakup as Aircraft Begin to Respond
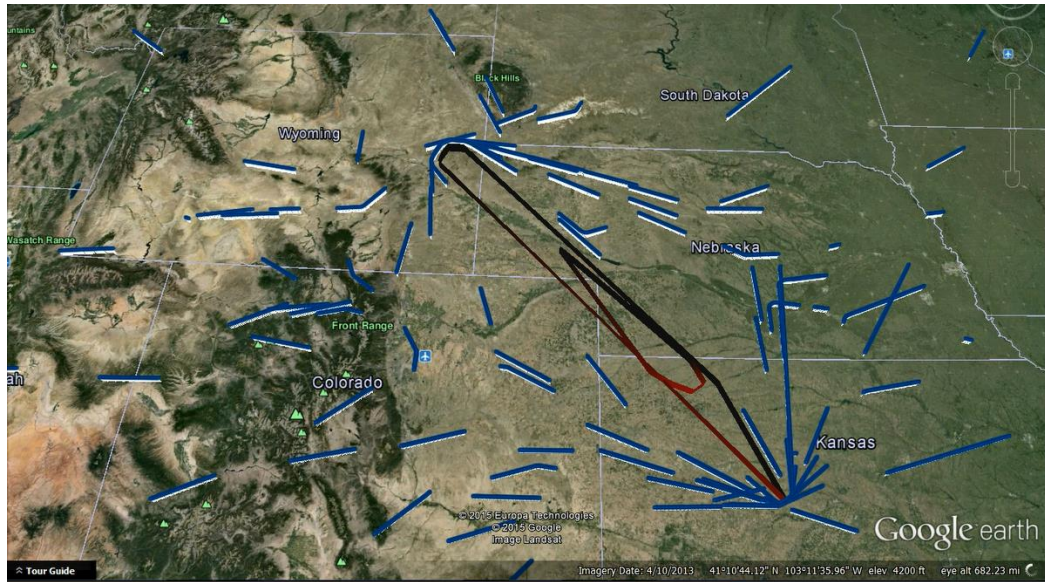
Figure 5. New and Initial STC with Aircraft Clear of and Circumnavigating Areas (Note the High Volume of Traffic at the Bottom of the New STC)

Figures 6 and 7 depict a sub-orbital HT/HL vehicle launching from a notional spaceport near Denver, Colorado. The white trails outside the red STC boundary indicate aircraft, and the white trail inside the red STC is the HT/HL vehicle. Figure 6 depicts aircraft maneuvering around the STC in advance of the launch. Figure 7 shows aircraft exiting and avoiding the STC.
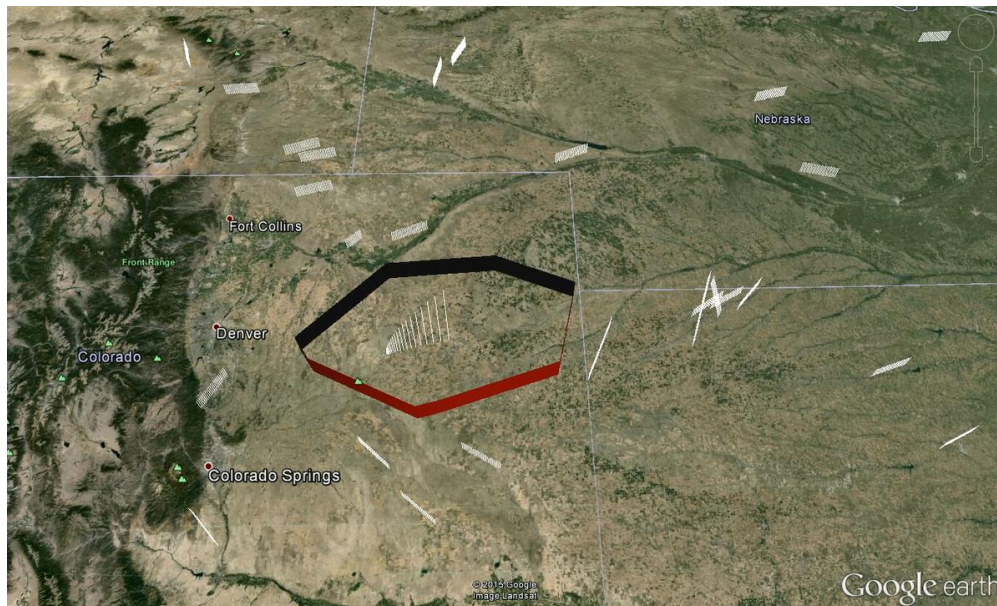
Figure 6. Simulation of Aircraft Circumnavigating STC for Nominal Launch
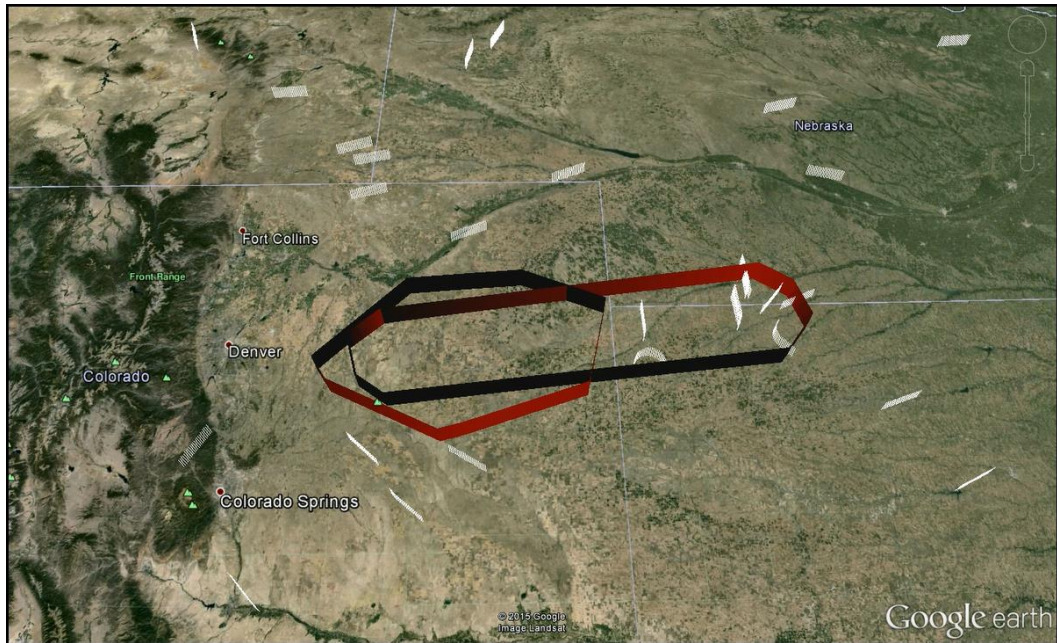
Figure 7. Aircraft Rerouting to Exit a Dynamically Activated STC

Figures 8 depicts the 4DT de-confliction scenario where the HT/HL vehicle arrives to MAF. An assumed automation conflict alert capability makes the controller away of conflicts between the SV and aircraft well before the SV starts the glider-like phase of its arrival. The controller makes reroutes to avoid the conflicts (shown as purple tracks). . The reentry vehicle is not yet shown in this figure. Figure 9 shows the reentry vehicle (in red) during its glider-like performance phase as it arrives to MAF. The aircraft in Figure 9 are de-conflicted with the SV.

Figure 8. Rerouted Aircraft (Purple Tracks) during Midland Arrival Scenario using 4DT Deconfliction

Figure 9. Reentering Spaceplane during its Glider-Like Phase with Deconflicted Air Traffic

Initial Qualitative Workload Results

Qualitative inspection of the scenario visualizations can provide significant insight about potential ATC workload, traffic congestion, and complexity issues from proposed separation concepts and standards. The capsule reentry scenario (Figures 3-5) shows that a sudden unplanned STC that spans a large area could potentially overload a sector due to the reroutes needed to avoid the new STC. This implies that some amount of traffic flow coordination needs to be made for each type of LV/RV operation when the potential STC is very large. The sub-orbital HT/HL launch in Figures 6 and 7 shows that a prioritization tool to help ATC decide which aircraft need to be rerouted first is needed to manage a scenario where a large number of aircraft need to exit a STC.

The 4DT de-confliction scenario in Figures 8 and 9 illustrates that implementing a 4DT de-confliction concept would largely depend on an automation capability to indicate to ATC when a conflict is expected to occur and how to resolve it. A large enough look ahead time is necessary to account for the reentry vehicle's performance and ensure aircraft can respond. This automation capability would be dependent on knowing the projected flight path of the vehicle, which would require both a 4D trajectory modeler for LV/RV and the ability for ATC automation to ingest LV/RV flight paths form some input source. Use of the 4DT de-confliction concept may require all 3 capabilities (LV/RV trajectory modeler, ingesting LV/RV flight paths, and conflict detection and resolution) in order to maintain safety when deviations from expected flight paths occur.

Initial Quantitative Results

The capabilities described here are still in development, and all quantitative metrics generated should be deemed preliminary, however, the initial metrics can be used to help establish preliminary bounds on required surveillance performance and response times from ATC and pilots. The simulations are not yet refined enough to compare specific separation standards (e.g., 15 NM vs 20 NM separations for spaceplane arrivals using 4DT de-confliction). Future work will focus on refining and assessing the capability's performance. The following tables summarize the initial quantitative metrics for each of the scenarios based on standard ADS-B surveillance performance.

Table 2. Analysis Metrics for Capsule Re-entry Scenario

Metric	Mean and Standard Deviation
Probability of NMAC (Number of NMACs divided by total encounters)	Mean: 8.1×10^{-4} STDEV: 6.6×10^{-4}
Probability of LORS (Number of LORS divided by total encounters)	Mean: 1.2×10^{-2} STDEV: 3.1×10^{-3}
CPA for every pair (aircraft to aircraft, in meters)	Horizontal: - Mean: 106383.07 - STDEV: 907950.46 Vertical: - Mean: 2922.10 - STDEV: 5595.52
CPA for every pair (aircraft to LV/RV, in meters)	Horizontal: - Mean: 3263323.53 - STDEV: 4302696.34 Vertical: - Mean: 110315.42 - STDEV: 248664.83

Time (seconds) in hazard volume (*potential or actual* debris field)	Mean:2.16 STDEV:1.80
Number of aircraft in a hazard volume	Mean: 4 STDEV: 3
Number of aircraft entering a hazard volume after hazard volume was active	Mean: 13 STDEV: 5
Time (seconds) until the first reroute was given to the pilot	Mean: 25.09 STDEV: 11.94
Time (seconds) until all aircraft were clear of the hazard volume	Mean: 409.62 STDEV: 503.50

Table 3. Analysis Metrics for Denver Launching Scenario

Metric	Mean and Standard Deviation
Probability of NMAC (Number of NMACs divided by total encounters)	Mean: 4.0×10^{-4} STDEV: 3.8×10^{-4}
Probability of LORS (Number of LORS divided by total encounters)	Mean: 1.2×10^{-2} STDEV: 0.005 4.9×10^{-3}
CPA for every pair (aircraft to aircraft, in meters)	Horizontal: - Mean: 164090.56 - STDEV: 1400554.46 Vertical: - Mean: 5778.67 - STDEV: 7410.99
CPA for every pair (aircraft to LV/RV, in meters)	Horizontal: - Mean: 2231648.40 - STDEV: 2226983.26 Vertical: - Mean: 46677.12

	- STDEV: 59366.15
Time (seconds) in hazard volume (*potential or actual* debris field)	Mean: 7.12 STDEV: 8.56
Number of aircraft in a hazard volume	Mean: 2 STDEV: 2
Number of aircraft entering a hazard volume after hazard volume was active	Mean: 6 STDEV: 5
Time (seconds) until the first reroute was given to the pilot	Mean: 14.75 STDEV: 13.26
Time (seconds) until all aircraft were clear of the hazard volume	Mean: 232.25 STDEV: 293.29

Table 4. Analysis Metrics for Midland Arrival Scenario

Metric	Mean and Standard Deviation
Probability of NMAC (Number of NMACs divided by total encounters)	Mean: 0 STDEV: 0
Probability of LORS (Number of LORS divided by total encounters)	Mean: 4.5×10^{-3} STDEV: 1.8×10^{-3}
CPA for every pair (aircraft to aircraft, in meters)	Horizontal: - Mean: 1488338.32 - STDEV: 6070222.86 Vertical: - Mean: 11259.47 - STDEV: 9668.16
CPA for every pair (aircraft to LV/RV, in meters)	Horizontal: - Mean: 3420267.30 - STDEV: 6063540.43 Vertical: - Mean: 35787.45 - STDEV: 69029.67

Tables 2-4 show that the probabilities of NMAC in the capsule re-entry scenario and the Denver launch scenario are at the same order of magnitude (i.e., 10^{-4}), while no NMACs occurred in the particular Midland arrival scenario. The Midland arrival scenario assumes the presence of automation tools to alert and resolve potential conflicts as well as ADS-B like surveillance, which is why the NMAC is so low. Additional sensitivity analysis of this scenario and the performance of such tools need to be examined, which may increase the number of NMACs. The probabilities of LORS in the first two scenarios are at the 10^{-2} order of magnitude, while the probability of LORS is at the 10^{-3} order of magnitude for the 3rd scenario (Midland Arrival). These and other metrics in Tables 2-4 are based on the simulation results from our simulation tool and the ATC algorithms in it. The team is still working on enhancing and testing the algorithms so these metrics should be deemed preliminary.

Figures 10 to 15 show box-and-whisker plots to illustrate the probabilistic characteristics and sensitivity analysis of some of the above metrics for the capsule re-entry scenario based on

two different surveillance performances—one with 1-second update interval for both aircraft and spacecraft (marked as "1--1") to simulate ADS-B like performance, and the other with 12-second update interval for aircraft and 4-second update interval for spacecraft (marked as "12--4") to simulate radar like performance.
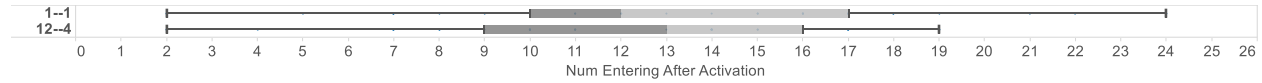

Figure 10. Number of aircraft entering a hazard volume after hazard volume was active
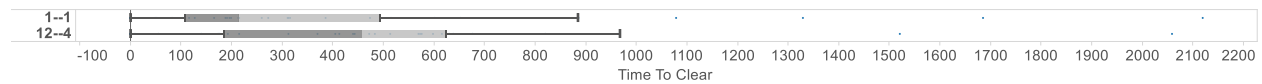

Figure 11. Number of aircraft inside a hazard volume at activation

Figure 12. Time until all aircraft were clear of the hazard volume
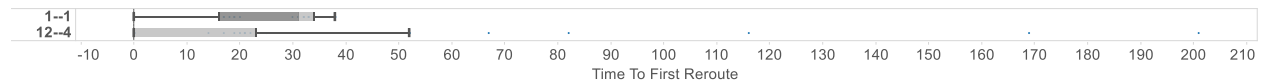
Figure 13. Time until the first reroute was given to the pilot
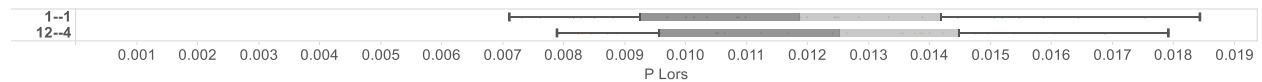
Figure 14. Probability of loss of radar separation
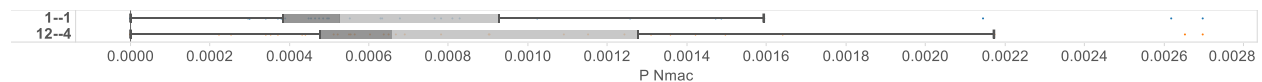
Figure 15. Probability of near mid-air collision (NMAC)

Figures 10-15 show how the surveillance update interval affects various metrics. In general, the better the surveillance is, the better the metrics are, as expected. The probabilistic variance and spread of each metric can also be seen in those figures.

VI. Summary: A Capability Built to Evaluate LV/RV Separation Standards

New, more efficient separation concepts and associated standards are being proposed to minimize the impact of LV/RV operations on the NAS and help facilitate the growth of the commercial space industry. The safety of these concepts and standards have largely focused on the interactions between falling debris and aircraft, which is sufficient for separating traffic from static SAAs as is currently done. However, new separation concepts and standards proposed by the FAA are much more dynamic, and require increased responsiveness and awareness from ATC. This requires examining operational risks when executing new separation concepts and standards such as impacts to controller workload, separation between aircraft and LV/RV, and separation between aircraft and aircraft. MITRE is building a fast-time modeling and simulation capability that is aimed at providing the FAA and the commercial space proponent community

with a fast-time capability to evaluate separation concepts and associated standards to determine if they meet a target level of safety for each type of LV/RV operation. Additionally, it will provide insight into the required performance of surveillance, ATC response times, and air traffic limits to enable the concepts/standards.

The basis of the modeling framework is a Monte Carlo simulation capability called *algorithm*Evaluator, which has been used by MITRE and the US Air Force for several tasks in the past including evaluating Unmanned Aircraft System Sense and Avoid algorithms, En Route Automation and Modernization surveillance performance, generating and validating surveillance requirements. The research team adapted and enhanced it to evaluate the two proposed separation concepts (STC and 4DT de-confliction) through new ATC and pilot control algorithms, updated surveillance model for LV/RV, safety metric calculations, and incorporating probabilistic ATC and pilot response times. Additionally, models for space vehicle trajectories, and debris (leveraging prior debris modeling from Stanford University) have been developed. The capability can calculate several quantitative metrics to assess safety and workload such as probability of NMAC, probability of LORS, and time to exit a hazard area.

The MITRE capability has been used to assess 3 LV/RV scenarios: capsule reentry, sub-orbital HT/HL, and 4DT de-confliction arrival scenario of a HT/HL vehicle. The first two are based on scenarios from FAA HITLS in October 2014. Multiple iterations of each scenario are run throughout a day's worth of traffic to sample different traffic patterns. Metrics and visualizations of each scenario are generated and evaluated. Initial qualitative inspection of the visualizations highlight key workload issues that must be addressed for scenarios involving STCs. Inspection of the 4DT de-confliction scenario identifies key capabilities and dependencies needed for ATC to safely implement the separation concept. Initial quantitative metrics have been calculated and presented for the 3 scenarios. One set of metrics in particular shows that the metrics are sensitive to surveillance performance. The team is still assessing the performance of the model and ATC control algorithms so the initial quantitative metrics for the above three scenarios should be deemed preliminary and are subject to further refinement.

VII.Next Steps: Confirming and Assessing the Model's Performance

The research team has recently finished its first year of work, and the initial capability has already shown promising insight about the safety of proposed LV/RV separation concepts and standards. Moving forward, the research team is focused on confirming and assessing the capability's performance. Additionally, the team is planning to improve the space vehicle trajectory model, acquire additional historical LV/RV trajectories, further enhance the ATC control algorithms, integrate the debris model into scenario evaluation, and perform additional scenario evaluations. The goal is to have the capability ready for the FAA to evaluate separation concepts and standards.

VIII.References
1. Federal Aviation Administration, "Management of Space Vehicle Operations in the National Airspace System Concept of Operations," Version 1.1, Washington, D.C., August 2014.

2. Wilde, P.D. and Draper, C., "Aircraft Protection Standards and Implementation Guidelines for Range Safety," 48th AIAA Aerospace Sciences Meeting, Orlando, Florida, January 2010.

3. Howell III, C. T., Stock, T. M., Wehner, P. J., et al., "Simulation and Flight Test Capability for Testing Prototype Sense and Avoid System Elements," 31st Digital Avionics Systems Conference, Williamsburg, VA, October 2012.

4. Wehner, P. J., Schwartz, J., Hashemi, D., et al., "Evaluating Prototype Sense and Avoid Alternatives in Simulation and Flight," AUVSI Unmanned Systems 2013, Washington, D.C., August 2013.

5. RTCA, "Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Services Broadcast (TIS-B)," Washington, D.C., December 2011.

6. Capristan, F. M., Alonso, J. J., "Range Safety Assessment Tool (RSAT): An analysis environment for safety assessment of launch and reentry vehicles," AIAA SciTech, National Harbor, January 2014.

7. Hatton, K., "Space Vehicle Operations Human-in-the-Loop (Presentation)," FAA, October 2014

8. Lindsay, K. S., Estes, S. L., Kamienski, J. C., and Kell, S. B., "Evaluation of Parameters for the En Route Controller Workload Model," MTR140292, The MITRE Corporation, Washington, D.C., September 2014.

IX. Acknowledgements

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