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PROTECTING AIRCRAFT IN REAL-TIME FROM A LAUNCH OR RE-ENTRY FAILURE

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ABSTRACT

The growing frequency of launches and re-entries of space vehicles has increased impact on other users of the National Airspace. Because these activities have a probability of failure far higher than aircraft, the FAA closes airspace proactively to mitigate the potential impact of debris resulting from a breakup event. The FAA Office of NextGen and Office of Commercial Space Transportation have been working to develop a systematic solution to reduce the spatial and temporal extent of airspace closures. A key element of the solution is developing the capability to respond in real-time to a failure. This requires data communication between the space vehicle and the FAA, procedures to communicate air traffic direction to pilots, and software to compute the real-time determination of the hazarded area. A key objective is to maximum the time allotted for aircraft to fly out of the hazarded region.

We have developed models, algorithms, and prototype software to compute four-dimensional aircraft hazard volumes within seconds following a presumed space vehicle failure. This process accounts for many physical processes, including the behavior of an intact vehicle from the last available state, breakup dynamics, fall of debris, the vulnerability of aircraft. The method characterizes uncertainty in each of these processes (also given that only limited information may be available in real-time). The resulting volume must be optimized to be small enough such that there is time for aircraft to exit it, but large enough to sufficiently mitigate the risk to aircraft. The approach is based on significant experience with probabilistic modeling of the hazards to aircraft, combined with testing numerous potential failure scenarios of launch and re-entry vehicles.

INTRODUCTION

Currently, launches and reentries are handled manually by the Federal Aviation Administration (FAA) Air Traffic Control (ATC) system as an exception to normal operations. The operations are significantly different than aircraft operations, as the vehicles usually have much steeper flight profiles, fly far faster, and are much more prone to catastrophic failures that could present hazards to other airspace users. As launch and reentry vehicle operations become more frequent, the FAA will need to safely and automatically accommodate them through the National Airspace System (NAS). New tools, processes, and procedures are being designed and tested to accomplish this task and safely minimize the effect of launch and reentry vehicle operations on the efficiency and capacity of the NAS.

Reliability of launch and reentry vehicles is orders of magnitude less than that of aircraft, so protecting against failures is an important aspect of mitigation. Modeling can be performed to predict the probable locations of debris and the resulting risk to aircraft[1]. Analysis of debris resulting from the breakup of the *Columbia* orbiter showed that the risk to aircraft was quite high, possibly as high as 1 in 100. [2] As a result the FAA developed a tool for the remaining

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re-entries after the return to flight that could be used to generate in real-time a hazard area for aircraft,[3] but this tool was specially designed for Space Shuttle Orbiter re-entries. It was also recognized that there was potentially several minutes of time to protect aircraft from debris due to a breakup during a launch[4], but significantly less time than from a breakup similar to *Columbia*. However, due to the complexity and computational requirements, the approach of developing pre-launch hazard areas from which aircraft are separated has continued to be applied.[5] Therefore, in effect, large volumes of airspace are currently affected, even though in most cases (successful missions), the hazard is contained to a very small area around the nominal flight path and jettisoned bodies.

Currently several different kinds of Special Use Airspace are used to protect aircraft from hazards associated with SV operations, and aircraft are limited in their ability to operate in those areas when a launch or reentry accident occurs. The types of SAA most relevant to launch and reentry operations are restricted areas, warning areas, temporary flight restrictions (TFRs), and altitude reservations (ALTRVs). The spatial and temporal extent of these regions is determined through computations that account for the potential failure behavior or the vehicle, the response of flight safety systems, the probability of failure and failure response modes, debris generated by breakup, the time it takes debris to fall and the consequences when impacting aircraft. The volumes are defined to account for both nominal and potential failure events.[1] These hazard areas typically extend from the surface to infinity and extend significantly downrange from the launch site. This is illustrated in Exhibit 1, which is again a side view of a launch trajectory. The downrange extent is limited by the location where the probability of an adverse outcome drops below a risk threshold. This typically extends at least one hundred miles from the launch or landing site and tens of miles wide.

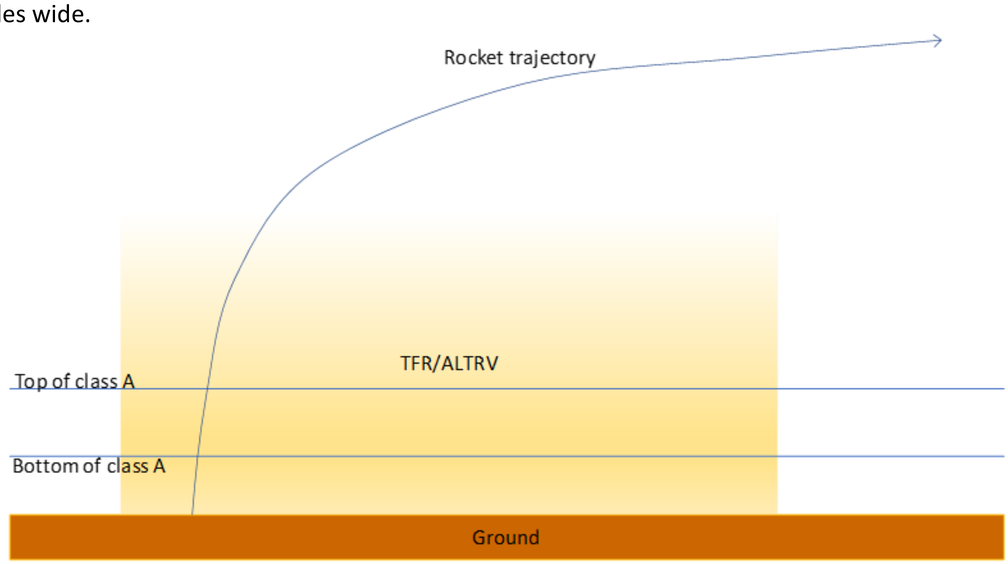

Exhibit 1. Current Special Use Airspace for an Example Rocket Launch

The FAA has been working to develop an approach for a real-time system that could protect aircraft subsequent to an accident. The Office of NextGen has been developing a Concept of Operations for Space Vehicle Operations. A key element of this is the use of Space Transition Corridors (STCs), [6,7] which are generated pre-launch, and Debris Hazard Volumes (DHVs), which are computed only when a failure occurs. The STCs are computed such that they encompass only the region of airspace for which debris can reach before it is feasible to move aircraft after an accident. This allows the STCs to be much smaller than the TFR/ALTRVs, as illustrated in Exhibit 2. The low-altitude TFR for Visual Flight Rules aircraft can also be smaller, as they are much smaller and flying slower so typically experience lower risk.

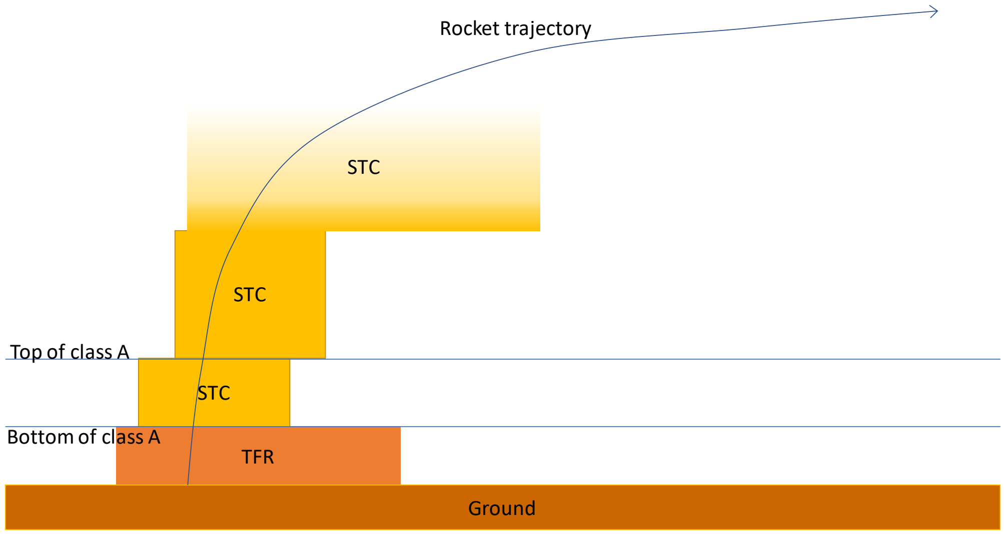

Exhibit 2. Illusration of Space Transition Corridors

Then, in real-time if a failure is believed to have occurred, a DHV is computed from the last known state vector, as illustrated in Exhibit 3. This region is smaller as well, since only the region affected by the actual accident needs to be protected.

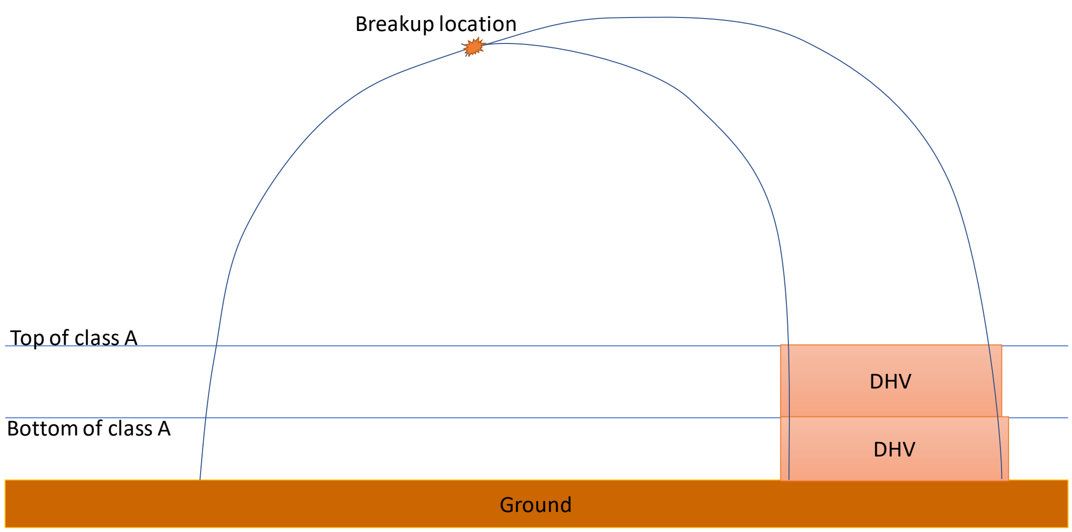

Exhibit 3. Example Debris Hazard Volume Computed in Real-Time

DEBRIS PROPAGATION VS. TIME

The important physical aspect of a failure scenario which was not previously accounted for which is fundamental to the ConOps is that there is pragmatically useful time between the failure event and the time the resulting debris reaches aircraft altitudes. This is illustrated in Exhibit 4, which pictorially represents the propagation of the debris cloud from a breakup of a launch vehicle. This is a "side view" in the plane of the velocity vector at breakup. The breakup is modeled at approximately 170,000 feet, and the vehicle was traveling mostly upwards (approximately 30 degrees from vertical) with a speed of 2700 knots. The debris spreads out primary due to differences in ballistic coefficient, β, which is the mass to area ratio ($\beta = \frac{m}{C_D A}$", where C_D is the drag coefficient). One minute after the breakup: the debris with higher ballistic coefficient fragments traveling up to over 300,000 feet, but the low ballistic coefficient fragments are slowed quickly by drag and thus do not travel very far upward. After two minutes, the low ballistic coefficient fragments are clearly falling, while the high ballistic coefficient fragments are near apogee—and are exo-atmospheric. The high ballistic coefficient pieces have also traveled significantly further down range, because the high ballistic coefficient experiences less drag, and there is positive feedback because then these fragments reach higher altitudes where the atmospheric density is lower, also significantly reducing drag. After three minutes, the lower ballistic coefficient fragments are still falling, but have significantly slowed as the atmospheric density increases. The high ballistic coefficient fragments are also now descending, but still at high altitudes. At this time, the shape of the debris cloud is a curve, like a banana, as the mid-range ballistic coefficient fragments are catching up to the lower ballistic coefficient ones. Between three and four minutes, the high ballistic coefficient fragments are falling very fast, from over 250,000 feet to below 100,000 ft. At four minutes, they are now at the lowest altitude, and the debris the debris cloud is close to flat, but still entirely above the typical region where aircraft

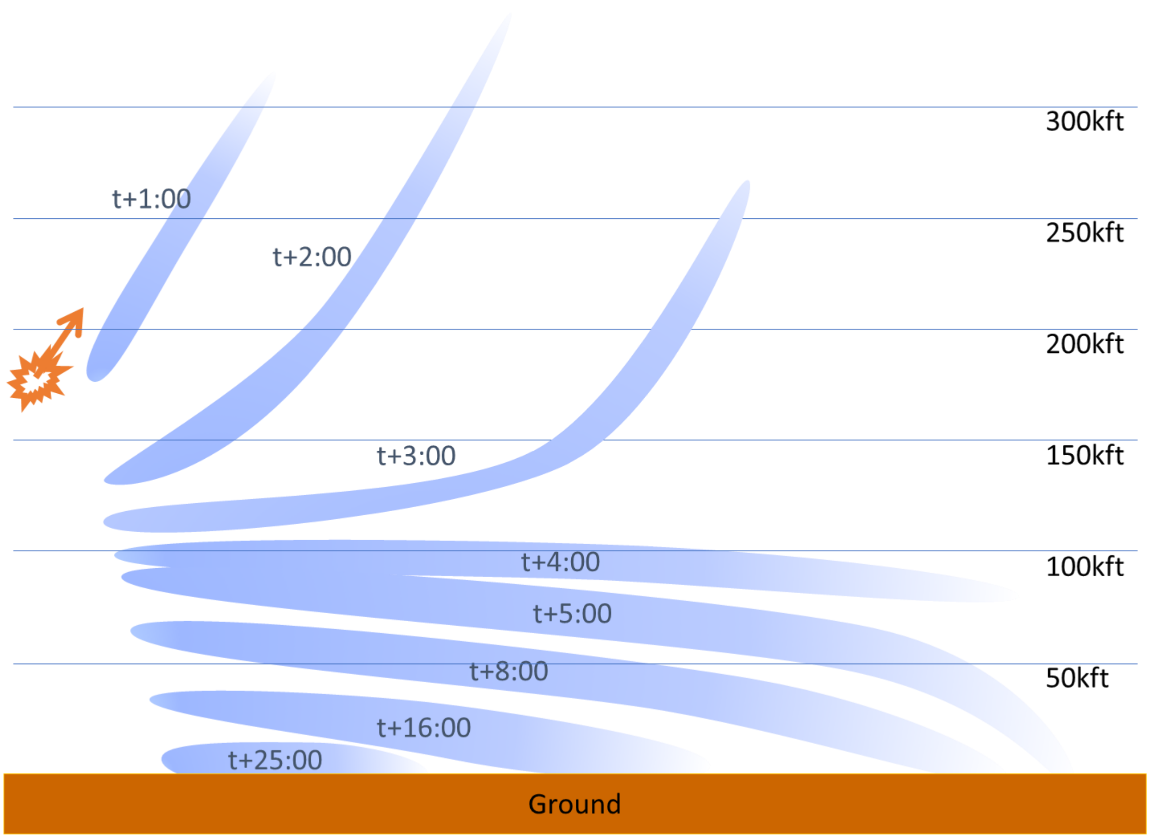

Exhibit 4: Debris Cloud Propagation with Time

fly. Between four and five minutes, the high ballistic coefficient fragments fall all the way to the ground passing through all levels of airspace. The remaining debris continues to fall, with the area hazarded by debris moving back from the location of the first impact of high ballistic coefficient debris back towards the location beneath the breakup. This is "backwards" moving of the hazard volume with respect to time is non-intuitive and very important, and thus needs to be communicated to the end users of the hazard region (such as air traffic personnel). By approximately 25 minutes, all debris is beneath the level of Class A airspace. This case illustrates that time-dependence could be leveraged to reduce the impact on air traffic of launch vehicle operations: four minutes may be sufficient to move aircraft, and the hazard area can be much smaller spatially if its movement with respect to time is accounted for.

One additional relevant aspect of the illustration is the depiction of the debris cloud with different shading. This is intended to represent the density of fragments. There are many fewer fragments that have high ballistic coefficients than low ones because ballistic coefficient is correlated with size and there are many fewer large objects resulting from a break than small fragments. Thus, an aircraft in the region with light colors has a lower likelihood of impact a fragment, due to the lower density, although the consequences of an impact are very significant.

APPROACH

This paper discusses an approach for computing the debris hazard volumes: the real-time calculation that occurs subsequent to a failure that could produce a hazard to aircraft. There are two key requirements that make the computation of real-time hazard volumes different from a typical pre-launch risk-based approach. First the calculation approach must accommodate that the total timeline available to reroute aircraft following a failure of a launch or reentry vehicle is only a few minutes. Second, the methodology must account for all the possible scenarios that could occur once a failure is identified—and this is complicated by the fact that the information about the failure is typically limited at first. Of course, the result must also be correct—the worst situation would be to direct an aircraft into a more dangerous location.

The timeline constraint has several implications. First, of course, the faster the calculation, the more time is available for moving aircraft. The goal is to produce a result on the order of a few seconds—there is little pragmatic difference between a calculation that takes a millionth of a second versus two seconds, but a ten to twenty second calculation would have a relevant effect on moving aircraft. Second, the smaller the volume, the more realistic it is to move aircraft away from it. Therefore, accounting for too much uncertainty or protecting to too high of a risk level would make the result not practically useful. The principal factor is not the total size however, but instead it is the size of the smallest dimension—a long, thin hazard area can be much more quickly sanitized than the same size circular area.

It is a significant challenge to account for all potential outcomes subsequent to failure identification – while avoiding creating excessive large volumes that are not useful. There are three basic phases to consider after a vehicle has failed: flight while still under powered or coordinated lift, intact ballistic "fall", and post-breakup fall of debris. Each of these phases must be adequately characterized, accounting for the uncertainty in the data, as well as the conditions which cause a switch from one phase to a subsequent one.

There are also important data management issues for a real-time software to be effective. There must be connection to best source state data on the vehicle, so the last known position and velocity are available. Some mechanisms need to be in place to identify a failure or potential failure. When a failure occurs, the correct dataset needs to be associated with the modeling, so changes in configuration need to be input. The system also needs to be able to quickly transit resulting hazard areas to the National Airspace System, as well as be able to update (if more data is available) or cancel (if the vehicle data stream recovers).

Modeling Intact vehicle "controlled" flight

After a failure, a vehicle may continue to fly while under "control," where the vehicle flies in a stable configuration while powered or has coordinated lift. The vehicle could be heading off-course, such as if the guidance system malfunctions or if the nozzle becomes stuck in the current position. If the vehicle state vector data is still available, there is no need to model subsequent flight. However, if the data stream fails (a loss of signal) and the last known state of the vehicle was that it was still stable, then subsequent flight must be modeled. The Falcon 9 CRS-7 failure is an example of this, as the first stage continued to fly unguided for eight or so seconds after the upper stage broke apart.

Modeling the subsequent flight depends on the control system used for a vehicle. We identified four fundamental types of control systems that are relevant: vectored thrust, lifting (gliding) vehicle, thrusting with aerodynamic control, and thrusting with attitude control. Most guided rockets of course have vectored thrust, but other types are less common. Some re-entry concepts are lifting bodies. Thrusting with aerodynamic control typically occurs when a vehicle uses fins to steer. An attitude control system while thrusting has been proposed for crew escape systems. Thus, the modeling for the loss-of-signal phase incorporates the control system design and the physical properties of the propulsion system or lift. A four-degree-of-freedom simulation, is used to quickly compute the failure flight envelope during this phase. Vehicle data, such as the thrust and weight of the vehicle are necessary to perform the simulation at the time of loss of signal.

To account for the range of possible failure response, the vehicle is modeled to turn in many different directions, with different magnitudes. The "magnitude' metric depends on the type of failure which may be associated with the control system. For example, for vectored thrust, the thrust vector could be set at various angles (a high angle will lead to a quick turn but will likely result in fast spin-up or breakup) where as a small angle will lead to a slow turn which can last for a significant duration.

The condition to exit stable flight are typically a maximum duration and structural limits on the vehicle. The maximum duration could be a reasonable limit on what stability is expected or better defined by observation. For example, it may be that state vector data is not available (or reliable) for a vehicle, but the duration of the intact controlled flight is known, such as through visual observation. Structural limits include Q-alpha limits, spin-up criteria, and aerothermal heating limits.

Modeling intact vehicle ballistic flight

Intact ballistic fall may occur as a result of failure or planned events. Planned events include re-entry of orbiting satellites, jettisoned bodies, and vehicles with parachutes attached. A three or five-degree-of-freedom ballistic propagation model that accounts for drag and gravity is used for modeling these intact vehicles. If a vehicle is expected to have changing stable orientations, a five degree-of-freedom model may be necessary to accurate compare against structural limits. However, in many cases, the vehicle is expected to either stabilize to a particular orientation or to tumble, in which case a three-degree-of-freedom model is sufficient. Two factors are important that must be accounted for: 1) a vehicle could change configuration during ballistic fall, such as having a drogue chute then a parachute, and 2) the drag coefficient depends on the Mach number.

The end conditions for ballistic fall are either intact impact or structural failure.

Modeling debris

Modeling of debris resulting from in-flight breakup of a vehicle is a challenge due to the time constraints. If a full debris model is applied, the calculation is computationally too expensive. Therefore, a pseudo-containment approach is used. The basic physics of the debris, the ballistic path considering winds, is modeled for a limited set of fragments. This accurately computes the "centerline" of debris in three-dimensions as a function of time. But the actual location of debris also has uncertainty. We assume that the uncertainty in wind is small as the error in debris propagation using an up-to-date forecast 3-D wind field is small. However, the uncertainty due to breakup-induced velocity and random lift are important factors which must be accounted for. Lift effects are relatively small, but can be important when other uncertainties are very small as found when modeling the breakup of the *Columbia* orbiter during re-entry.[2] Breakup induced velocity however, is quite important, as this directly relates to the width of the

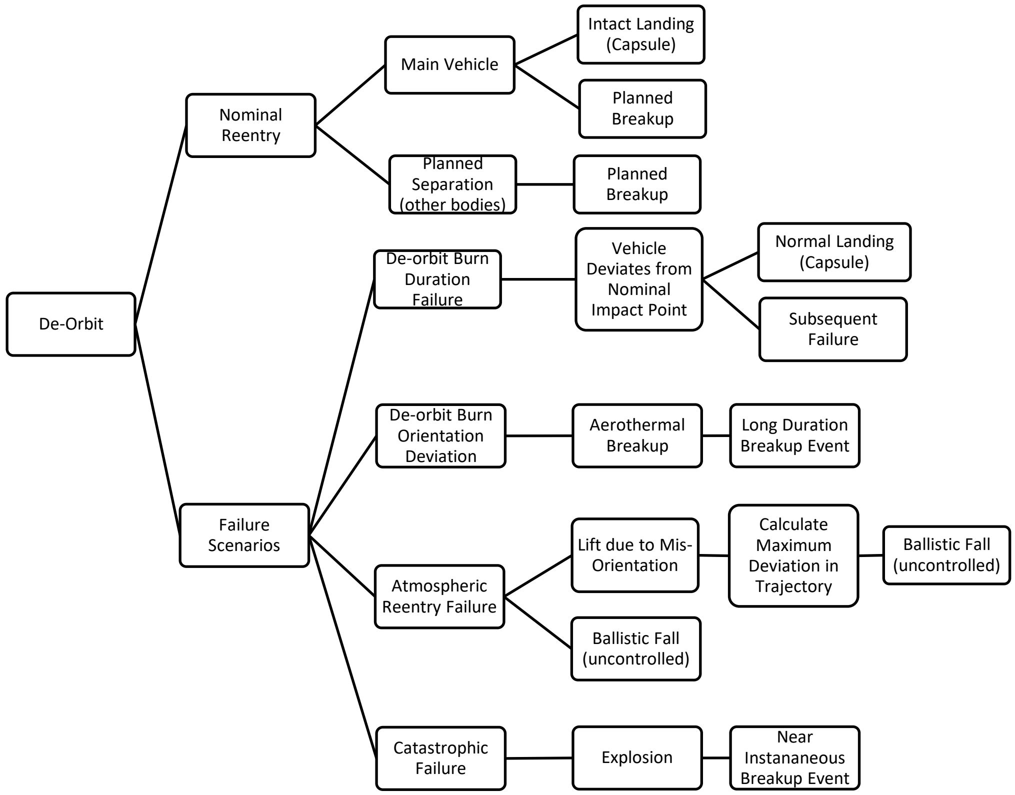

Exhibit 5. Event Tree for Considering Airspace Impacts of a Reentry Capsule

hazard region and the level of safety. Thus, this width of the hazard area above that of other effects is precomputed as a function of breakup altitude, using the full debris list for the vehicle.

Event Tree

Putting all these together involves careful consideration of the event tree for different scenarios. As an example, Exhibit 5 shows an example event tree for a re-entering capsule. Airspace can be affected by many different scenarios, each of which may put debris in different locations and/or different times. These all must be considered in the computation if the vehicle could potentially experience one of the scenarios.

PROTOTYPE EVALUATIONS

To evaluate the feasibility of the real-time approach, two different types of evaluation have occurred. One was a human-in-the-loop test (HITL), where the prototype software was used to generate hazard volumes in real time and various components of the National Airspace System responded. This provided quantitative metrics on NAS response and qualitative feedback on the process but was limited to two scenarios. The second was a more broad study to evaluate many types of launch and reentry vehicle scenarios. This allowed identification of how space transition corridors and hazard volumes differ between mission types and provide a more broad qualitative assessment of whether the proposed system is practically feasible.

Human-in-the Loop Test

The FAA NextGen SVO Project conducted a human-in-the-loop (HITL) experiment in October 2014 to demonstrate the SVO operational concept. The HITL included the depiction of the space vehicle trajectory and hazard volumes on the en route controller (ERAM) and traffic manager (ETMS) displays. Based on the displays, controllers provided re-routes to pilots of simulated aircraft based on the hazard volumes. The hazard volumes were generated and provided by the prototype Hazard Risk Assessment & Management software tool (SVO-HRAM), which implemented the above method. The HITL experiment included two example space vehicle scenarios (and only one included a failed vehicle).

The HITL failure scenario was of a structural breakup during ascent of a vehicle launching from a spaceport in northeastern Colorado. This area has a high volume of air traffic, as it includes cross-country traffic as well as planes departing and arriving at Denver airport. There was a pre-launch Space Transition Corridor (STC) in the immediate vicinity of the trajectory, but then the real-time DHV extended significantly outside the STC, as illustrated in Exhibit 6. The hazard volume was calculated when the failure scenario occurred and then sent to the displays. This experiment was run a total of four times (two scenarios each for two sets of controllers), intermixed with scenarios where no failure occurred. In nearly every case, all aircraft were able to be rerouted outside the hazard volume prior to debris reaching aircraft altitudes.

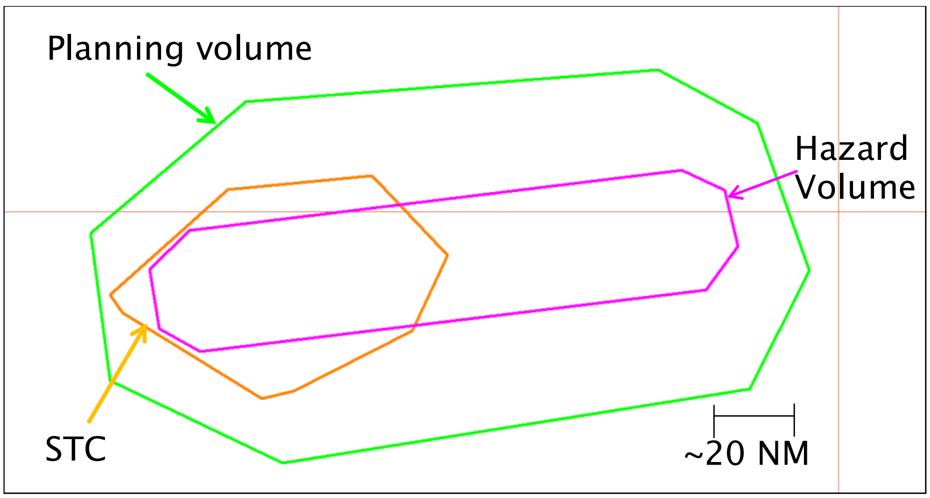

Exhibit 6. Failure Scenario for Human-in-the Loop Test

A residual risk assessment was then performed for the aircraft using a probabilistic risk analysis tool. There is some very low risk even to aircraft outside the hazard volume due to the random nature of the debris resulting from the accident. Every aircraft, including the one case where an aircraft did not quite exit the volume in time, had a residual risk (probability of a potentially-casualty producing impact) that was a factor of five below the current accepted threshold (1E-6), even though the probability of the event was one.

The results of the experiment were positive, as they validated many aspects of the concept, especially the idea that aircraft could be re-routed real-time around a debris field. To further explore the concept, additional experiments are necessary to examine more space vehicle scenarios. However, the cost to perform full human-in-loop simulations is high, and significant information can be obtained from lower-cost simulations. Thus, a next experiment was envisioned that significantly expanded the investigation of the ConOps but has much more limited simulation of the air traffic control environment.

Scenario Evaluations

The objectives for this experimental application of the ConOps are to:

- Evaluate the algorithms and processing using prototype software,
- Obtain feedback from an air traffic control perspective for incorporation into revisions of the concept,

- Assess the impact on the air traffic system of space vehicle operations, through measures such as the spatial and temporal extent of airspace affected,
- Develop test scenarios for use in future implementation into operational systems.

To evaluate the concept of operations to meet these objectives, a set of failure scenarios was identified. These scenarios needed to effective represent the scope of the potential future environment, in order that there are not future surprises as a system is implemented that require significant alternations of the Concept of Operations. Because space vehicle operations are quite diverse, and the Concept has some significant new elements, there is the potential that the concept may not meet its objectives (keep aircraft safe while reducing the impact of space vehicles on airspace operations). However, the number of scenarios is limited by budget and time constraints—each simulation has an associated cost, and the availability and interest in air traffic to provide feedback is limited.

Therefore, the scenarios needed to be selected thoughtfully. At the outset, the project office defined the task to include 15 scenarios, each including a planned space vehicle mission and a failure of the vehicle. To define the scenarios, we developed a structured approach to specify the meaning of a *variety* of space vehicle operations and *different* air traffic environments. First, categories of characteristics were defined and then specific values with in each category. Then scenarios were identified and evaluated as to how well the collection of desired characteristics were met. The potential options for scenarios were limited however by the availability of data and the limits of the simulation environment.

The products of the scenario development are hazard volumes of two types: Space Transition Corridors (STCs) and Debris Hazard Volumes (DHVs). An STC provides separation assurance between a space vehicle operation and other NAS users. The STC contains the nominal trajectory of a flight that is below the upper limit of the NAS and any expected performance variations as well as consideration of the effect of potential vehicle failures on other NAS users for a limited look-ahead time. STCs may also be used to define clearance volumes for planned jettisoned objects.

In identifying the desired scenario categories, both the process (including algorithms) for developing hazard volumes and the air traffic environment were considered. The location, spatial extent, and temporal sequence are important for impacts on airspace and safety of aircraft, and these are driven by the characteristics of the space vehicle operation. The location of the hazard volumes is important to the effect on air traffic; this is largely independent of the space vehicle properties (although currently space vehicles only operate from a few locations, it presumed they will someday fly from many more locations).

The characteristics of the space vehicles can be grouped into three categories: the mission type, the control system of the vehicle, and the failure scenario. With different characteristics in these categories, very different hazard volumes may result. They also are very important for evaluating the process for computation of hazard volumes. Four distinct types of vehicles/mission profiles were analyzed: a vertically launched thrust-vector controlled rocket, return of a reusable stage to vertical landing, ascent of an aerodynamically controlled fixed nozzle rocket, re-entry of a suborbital vehicle using aerodynamic surfaces to slow down, re-entry from orbit of a capsule with little lift, and re-entry from orbit of a lifting body. Failures were simulated at different points during the trajectories to simulate the failures.

The air traffic environment is important for assessing the impacts of potential hazard volumes to different control scenarios and traffic situations. Therefore, scenarios were designed to affect different airspace (related to current or planned spaceports), including both oceanic areas and areas crossing the continental United States.

A relatively, simple example is for a sample Falcon 9 launch from the proposed SpaceX launch site near Brownsville, Texas. In this scenario, the simulated failure was an engine explosion during second stage and is illustrated in Exhibit 7. Although the rocket was still only 20% of the way from Brownsville, the debris hazard volume is near the Florida Keys. From an air traffic perspective, this is particularly interesting because controllers working Miami airspace would not be affected by a nominal launch but would need to respond to the failure. This scenario also illustrates the added safety provided by a real-time system, as with current procedures, the hazard would likely

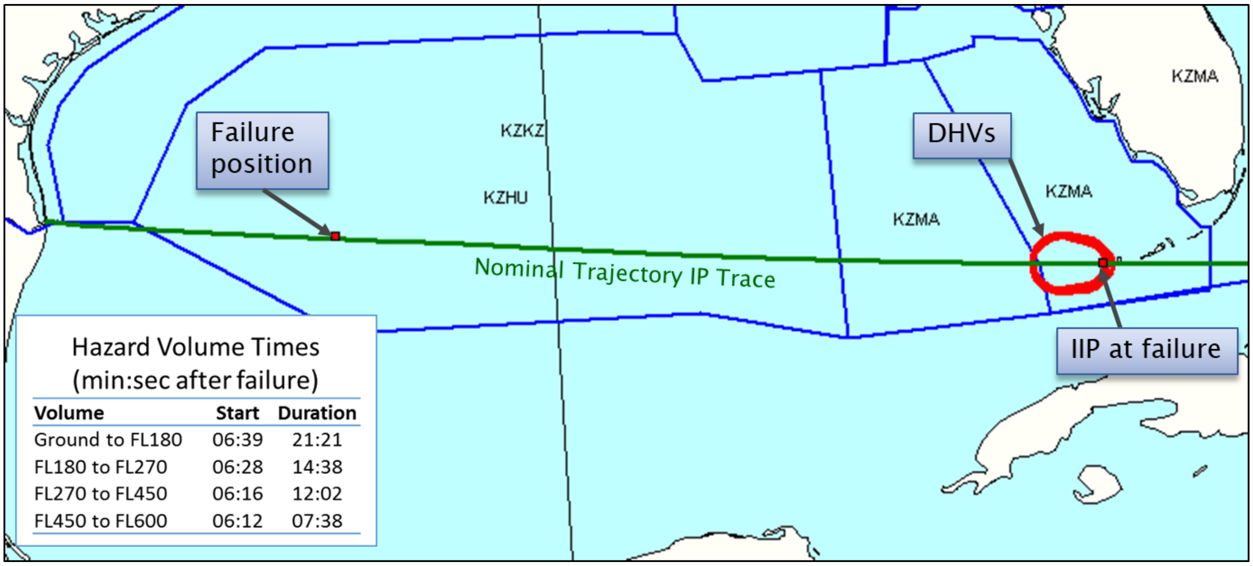

Exhibit 7. Example of Failure Scenario for Downrange Explosion during Launch

be outside of special use airspace. It is also valuable to note the timing of the hazard volumes. In this case, the first debris reaches aircraft altitudes over six minutes after the failure, allowing time for aircraft to clear the area. Also, with consideration of the timing of debris, typical class A airspace would only need to be cleared for around six minutes, until the debris falls to lower altitudes. Thus, the failure event would have very limited effect on air traffic.

A more challenging scenario is a failure earlier in the launch as the timeline is much shorter. An example of this (which mimics the failure that occurred during the Falcon 9 CRS-7 mission) is shown in Exhibit 8. This failure produces a large hazard volume for two reasons. Part of the downrange extent is because it occurred in the upper atmosphere, leading to a significant difference in impact locations of high and low ballistic coefficient fragments (similar to the illustration in Exhibit 4). The crossrange is because there was an eight second loss-of-signal: the second stage (which was feeding real-time data) broke up first, then the first stage continued to thrust for an additional eight seconds

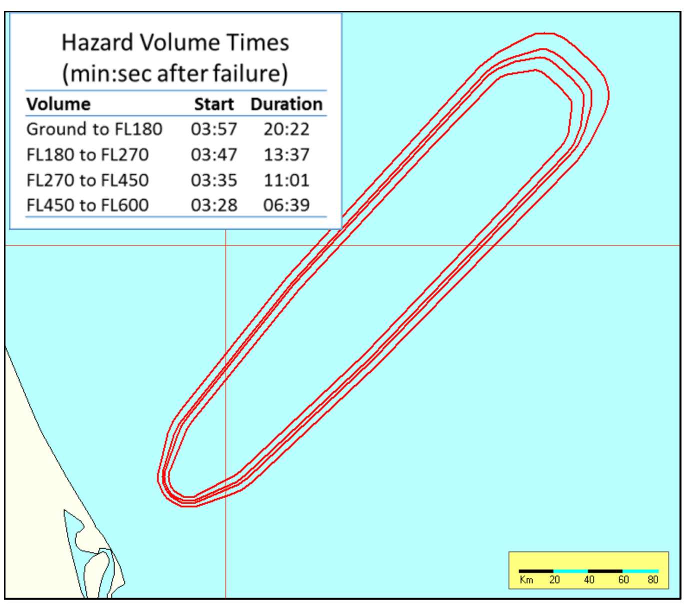

Exhibit 8. Example of Failure Scenario: First Stage Ascent Breakup with Loss of Signal.

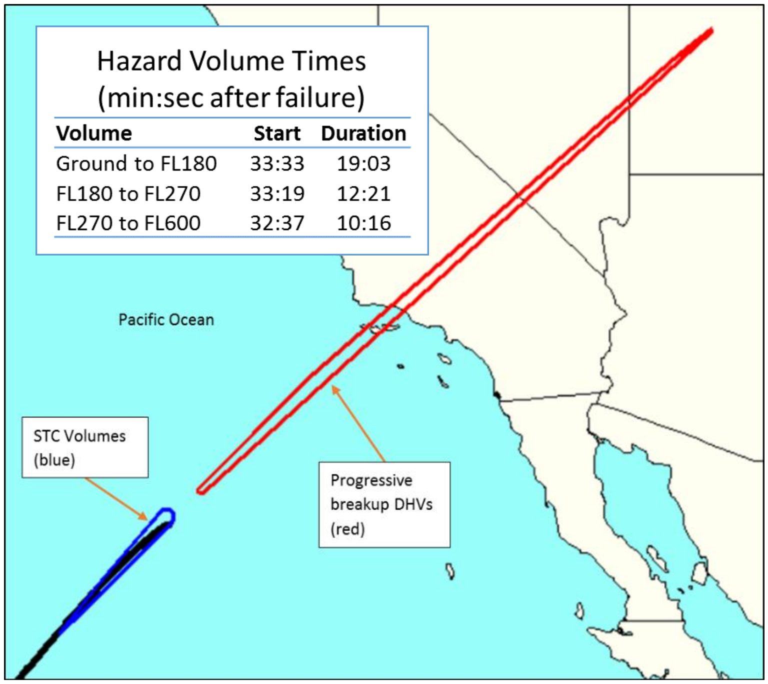

Exhibit 9. Example Scenario for Deorbit Burn Failure

with no guidance. The DHV generation accounted for this "unknown" flight—constrained only by physics, which potentially could have led to debris either to the left or right of the nominal path. This leads to over half of the width of the hazard volume (the remainder is due to breakup-induced velocity and random lift which exist even if the actual state vector at breakup were known). The fact that there were two breakup events also led to extending the region downrange (the first breakup constrained the uprange end and the second the downrange). This volume would be more difficult to manage from an air traffic perspective because there would be only three and half minutes between the failure and debris reaching aircraft altitudes. Therefore, at least some of this region (the uprange end near the launch site) would need to be in the Space Transition Corridor which would be preemptively cleared.

A very different scenario is failure during de-orbit burn of a capsule followed by aerothermal re-entry breakup. An illustration of this scenario, where the planned splash point is off the California coast, is shown in Exhibit 9. In this case, the debris hazard volume is very long and thin (due to the shallow angle of re-entry and the very different profiles of high and low ballistic coefficient debris). This DHV overshoots the landing point, again affecting airspace that would not be affected by a nominal mission. Although this long extent likely would significantly impact air traffic, there would be over a half an hour for controllers to prepare.

Re-entry scenarios are more challenging for failures that occur later in flight. For example, Exhibit 10 shows a breakup of a capsule due to a heat shield failure that causes aerothermal breakup. In this situation, the vehicle is entering from the southwest to a nominal landing point is in northwestern Kansas (a hypothetical location; no landing site is planned here). In this situation, the DHV dimensions are very similar to the deorbit burn failure, but the timeline is much shorter. This scenario prompted further investigation to allow for better ability to manage air traffic. A key observation is that the first debris to impact is nearest the landing site. Therefore, the first debris is in fact inside the STC. The debris impact area then moves away from the landing site as a function of time. This suggested the approach of a moving DHV. There are some challenges with this idea, however, as controllers not only need to know what will be closed both in the immediate term o as to begin sanitizing airspace as well as in the near-term, so they do not direct aircraft to a region that will soon need to be sanitized. A proposed solution is to have two levels of DHV. One volume would encompass the entire area that will need to be cleared, and it would not move

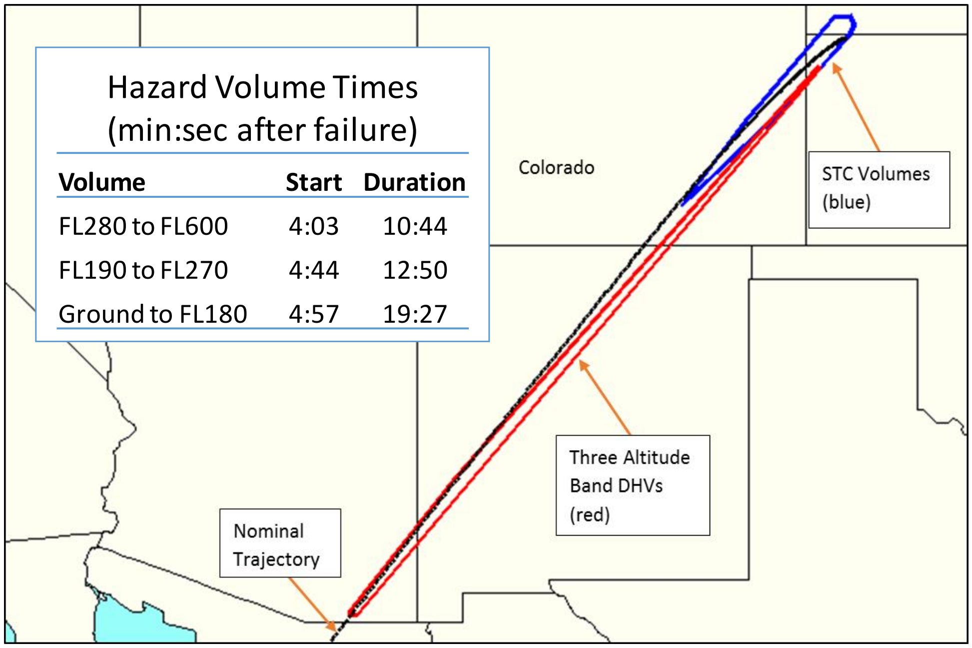

Exhibit 10. Example Scenario for Capsule Heat Shield Failure

or grow (but could shrink as airspace can be released). A second smaller volume would move with time that shows the area that is hazarded now or will be in the immediate term (i.e. within a few minutes). Then controllers would prioritize the volume that needs to be cleared urgently without increasing the traffic in the area that will soon be moved.

Many of the example scenarios were discussed with air traffic personnel at Miami and Los Angeles Air Route Traffic Control Centers. The concept was well received, and personnel responded very positively to the concept and prototype displays. Personnel saw the clear benefit of the SVO concept in reducing the workload in preparing for a space operation and reducing the footprint of the operation and therefore the impact on air traffic. They also saw that the only way these benefits can be achieved is by “putting it on the glass”; that is, displaying the affected airspace on the air traffic controller displays (ERAM and the Standard Terminal Automation Replacement System (STARS)).

CONCLUSIONS

The approach and simulations presented demonstrate that real-time response to a launch or reentry vehicle failure is a pragmatically reasonable approach to mitigating the risk of debris impacting aircraft. The time between failure and resulting debris reaching aircraft altitudes can be exploited to re-route aircraft. Physics-based modeling of the behavior of the vehicle and the subsequent propagation of debris can be performed in a few seconds. This allows for much smaller regions to be preemptively cleared than is currently done, thus significantly reducing the impact of launch and reentry activities on air traffic. The safety of the air traffic is also increased, as airspace can also now be cleared in real-time even for failures that were thought to be unlikely.

Modeling in real-time must balance fidelity, uncertainty, and speed. The failure response of the vehicle is critical, especially when the vehicle remains intact with thrust or controlled lift after real-time data ceases, as this behavior expands the region potentially at risk. Physics-based simulation of debris fall allows for accurate determination of the size and timing of the hazard volumes. In real-time, it is possible to use a pseudo-containment approach where the “debris list” is much smaller than is necessary for a probabilistic approach as is used in pre-launch. The resulting hazard volumes are small enough, so it is realistic to move aircraft out of them by the time the debris arrives.

The method has been demonstrated via simulation, both in a human-in-the-loop test and by examination of various scenarios. While some hazard volumes are large, especially in one dimension, all examples appeared to have volumes that were reasonable to clear in a few minutes. The most challenging scenarios are breakups in the upper atmosphere, especially when the velocity of the vehicle prior to failure is downward. It should be noted that the scenarios did not include oceanic airspace, where communication between controllers and air traffic is currently much slower, so a few minutes is not sufficient time. However, communication is likely to be faster in the future, and the proposed method is clearly viable for reducing the impact of launch and re-entry activities in the busier airspace over and near land.

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