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Automated Calculation of Aircraft Hazard Areas from Space Vehicle Accidents: Application to the Shuttle

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The Federal Aviation Administration (FAA) required a computational tool capable of generating aircraft hazard area regions based on Space Shuttle reentry trajectories and real-time state vectors. In response, the Shuttle Hazard Area for Aircraft Calculator (SHAAC) was developed to support FAA Shuttle Recovery Team efforts to prepare for and manage air traffic if an accident occurs during reentry, such as the *Columbia* disaster. In the case of an accident, the hazard regions produced by SHAAC would be input in real-time to the Air Traffic Control system, and controllers would then guide affected aircraft away from the hazard area in the time between the loss of control of the re-entering Orbiter and the time the debris from the breakup would reach the altitude at which aircraft are flying. The computation of hazard areas must be sufficiently conservative in accounting for debris uncertainty to ensure that aircraft are adequately protected. On the other hand, in order to maximize the time available to move aircraft out of the unacceptable risk regions, the computation must avoid excess conservatism in the size of the hazard areas. Minimizing data entry and quick calculation also increase available time. The design of SHAAC includes several approaches to meet the challenges of operational simplicity, conservatism, fidelity, and speed. The primary hazard area is calculated by debris propagation of a simplified progressive breakup through a three-dimensional real-time wind forecast. An additional buffer is determined through statistical/empirical methods to account for uncertainties in wind and fragment lift to drag ratio. This calculation is wrapped in an intuitive graphical user interface, with user input kept to the bare minimum, integrated with a geographic information system for display and validation of results. The tool, while currently applicable only to the Space Shuttle, serves as a prototype for managing air traffic around accidents of any space vehicle as envisioned in the FAA's Space and Air Traffic Management System (SATMS) initiative.

I. Introduction

SIGNIFICANTLY more debris pieces resulted from the Space Shuttle *Columbia* accident than had been anticipated, resulting in unacceptably high risk of impacting aircraft[1]. In response, the Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST) desired a computational tool capable of generating a time series of aircraft hazard area regions based on Space Shuttle reentry trajectories. This tool supports FAA Air Traffic Organization (ATO) Shuttle Recovery Team (SRT) efforts to monitor and manage air traffic in the National Airspace System (NAS) during planned Space Shuttle reentry activities[2].

Therefore, the FAA initiated the rapid development of the Shuttle Hazard Area for Aircraft Calculator (SHAAC) computer program. The initial requirements for the SHAAC tool were based upon the experience gained in the use of the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) Debris Analysis

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Group's Shuttle footprint computation tool. NASA JSC developed this tool after the *Columbia* accident to assist in the prediction of ground debris hazard areas and the computation of expected casualties for people on the ground. After *Columbia*, as the FAA and NASA collaboratively developed plans and procedures to protect aircraft from falling debris in the event of another Shuttle accident during reentry, NASA proposed the use of predicted potential debris hazard areas computed by its tool as a means for providing the FAA with increased situational awareness, both prior to and during a Shuttle reentry. NASA offered to construct these hazard areas in advance of each landing opportunity for subsequent Shuttle missions using its tool. In addition, in the event of an accident, NASA offered to use its tool to compute a best estimate of the debris hazard area to aircraft based on the Shuttle's last known position and velocity and provide that data to the FAA.

Several motivations prompted the FAA to initiate the development of its own Shuttle debris hazard area tool. First and foremost was the FAA's desire to increase the response time of air traffic controllers to a Shuttle failure on reentry by eliminating time lost in the transmission of essential data from NASA to the FAA. NASA has estimated that debris hazardous to aircraft could begin falling through aircraft altitudes in as little as six to ten minutes after a Shuttle breakup and could continue falling for as long as 90 minutes. According to the original plans developed by NASA and the FAA, once NASA confirmed a breakup, NASA engineers would execute their tool and fax the output to the FAA. The FAA estimated that as much as 15 to 30 minutes of response time could be gained in the event of an accident by developing and operating its own tool.

Secondly, by acquiring its own tool and the skills to operate it effectively, the FAA gains additional insight into the potential hazards to aircraft associated with space vehicle failures and the various approaches to mitigating these hazards. In this manner, operating the tool provides an opportunity for the FAA to acquire much needed experience in anticipation of a need for this capability during future commercial space operations. The FAA will use the SHAAC tool as a prototype for a future, more widely applicable tool.

Third, the FAA foresaw the need for several improvements and additions to the modeling beyond the capability of the NASA JSC tool. Two areas were immediately recognized: 1) the need to have more flexibility in accounting for winds, and 2) the desire to use more physics-based modeling instead of relying as significantly (as does the JSC tool) on the empirical data from the *Columbia* accident debris. Related to this, the FAA sought to relieve the resource burden that NASA had accepted in its offer to produce hazard areas for Shuttle missions and exercises.

Therefore SHAAC was developed by ACTA Inc. based on a set of top-level requirements assembled by the FAA. Within this requirement set, the FAA identified three primary requirements for tool's development:

1. Produce a tool that emulates the NASA tool's capabilities and produces similar results with a high degree of confidence in their accuracy
2. Utilize existing software functionality found in other, previously developed tools to the greatest extent possible in order to provide for a rapid development cycle
3. Develop a tool that is relatively easy to use and requires minimal training

Rapid development and test were essential to expedite the implementation process and the realization of potential gains in response time that would accompany the shift in responsibility for hazard area computation from NASA to the FAA. With FAA personnel computing the hazard areas at one or more of the FAA facilities monitoring the reentry event, the FAA could gain time otherwise lost in the communication of the need to compute the hazard areas and necessary input data within NASA and transmission of the results back to the FAA.

Based on this second primary requirement, ACTA was able to identify existing computational functionality in its previously developed Range Risk Analysis Tool (RRAT) and Common Real-time Footprint (CRTF) quantitative range safety risk assessment tools for direct application to SHAAC. Further, necessary mapping functionality was identified in ACTA's Flight Safety Analysis Geographic Information System (FSAGIS), a full-capability GIS software tool. Each of these tools had been developed previously and have been in use for a number of years in support of U. S. Army, Air Force, Navy, and commercial launch and reentry projects.

While it was envisioned that FAA/AST would initially be responsible for executing the tool operationally, Traffic Managers within the FAA's Air Traffic Organization were intended to be its ultimate users. Accordingly, since air traffic controllers do not typically have backgrounds in space operations and space vehicle debris modeling concepts, the FAA instructed ACTA to develop a tool that minimized the number and types of inputs needed and the number of steps to produce a result. Through the use of appropriately selected default values and file-based input data acceptance, ACTA was able to develop a tool that required minimal training for its users.

ACTA added technical detail to the FAA's top-level requirements, which served as the basis for the tool's development. These details produced the requirements for the physics-based debris dispersion and propagation methodology to be employed, as well as requirements for specific sources of wind and other input data and output mapping formats.

The regions calculated by SHAAC bound the locations of potential debris resulting from a Space Shuttle experiencing a gradual breakup during re-entry, such as that observed for *Columbia*, which could prove hazardous to aircraft flying in the vicinity of the accident. These areas overlap and converge at the planned landing site.

There are two different situations where the analysis is required:

1. A planning mode where potentially affected Air Route Traffic Control Centers (ARTCCs) are identified based on a planned (simulated) re-entry trajectory.
2. A real-time mode where the hazard area is computed based on the last-known position and velocity of the Shuttle at the time a "Breakup" is announced.

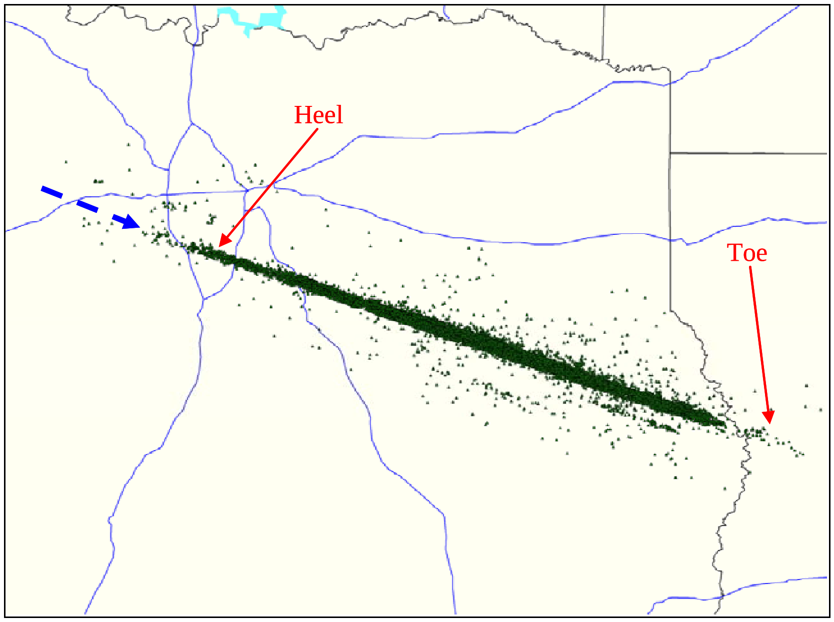

Figure 1. Debris impacts from *Columbia* accident

The two modes must perform the same computation, but have different input data (and uncertainty). A limit on program execution time exists since the hazard areas may have to be generated in under an hour using a trajectory obtained at just two hours prior to landing. In addition, a hazard area for a single state vector must be generated in seconds if an accident is thought to have occurred.

In order to understand the basics of the problem, a review of the data from *Columbia* is helpful. Figure 1 shows the recovered debris impact points of the Shuttle *Columbia* over east Texas[2]. The blue dashed arrow shows the direction that the vehicle was heading at the time of the breakup. Low ballistic coefficient pieces, such as thermal tiles and fragments of the payload bay doors, were found throughout the entire area (from "heel" to "toe"). The highest ballistic coefficient pieces, such as the landing gear and parts of the engines, were found near the toe (downrange end). Some of the scatter (especially the far cross-range pieces) is due to incorrect recording of impact location).

It might be expected that the low ballistic coefficient debris would impact only near the heel. However, the breakup of the vehicle was progressive rather than instantaneous. As the large, high ballistic coefficient pieces traveled forward toward the toe, smaller, low ballistic coefficient pieces broke off (called shedding). In addition, the wind, blowing mostly in the direction from the heel to the toe, carried a number of lower ballistic coefficient pieces closer to the toe. These became entrained in the wind as they fell, with some of them drifting considerable distances. Some of the low ballistic coefficient pieces were also capable of generating lift as they fell, increasing their potential to drift and scatter (both downrange and crossrange).

II. Methodology

A complete modeling of progressive breakup and then computation of propagation of debris to the ground is not practical for many reasons. There is insufficient knowledge of the breakup event to characterize it completely, as well as significant variability given nearly the same initial conditions. In addition, propagation of all debris pieces to the ground would require extensive computer time.

The determination of the hazard area was therefore simplified based on an understanding of the physics of the breakup corroborated by observations from *Columbia* debris. Three basic fragment types have been defined to model the extent of the paths debris fragments take from the point of breakup to the ground. This simplified model to bound the hazard area would be insufficient if a full impact probability distribution were known. The three fragments represent:

1. Minimum ballistic coefficient shed from the core at the point of breakup,
2. Maximum ballistic coefficient, initiated at breakup,
3. Fragments shed from core vehicle during descent, to represent demise.

To be conservative, the core vehicle is modeled as having the highest ballistic coefficient possible for any shed fragment. These fragments are illustrated in Figure 2, where only one fragment of type 3 is shown. There are in fact many fragments from type 3, representing shed fragments all along the core descent trajectory. Many shed fragments are needed because wind effects, which vary laterally, are responsible for the maximum cross-range extent.

Locations of all three of these fragment types are computed as they fall from the initial breakup altitude of the vehicle to the ground. They are recorded at a series of subsequent altitude levels that span the flight space for a typical commercial aircraft. The collection of the locations of these three fragment types, as shown above, represents the predicted extent of the airspace containing debris hazardous to aircraft. To account for uncertainties (discussed below), an additional buffer zone is also applied about these points.

Wind conditions at each 3-D position are included in the computation with appropriate estimates of uncertainty or variability. The preferred wind data source is the latest Global Forecast System[3] model from the National Oceanic and Atmospheric Administration (NOAA) appropriate for the time of the trajectory. A small amount of wind uncertainty, appropriate to account for the delay between the forecast and the time of landing, is then included as a buffer around each collected impact point (note that this wind uncertainty is not provided with the GFS forecast; we have arbitrarily applied wind forecast uncertainty from other sources). However, if the forecast is not available, either due to Internet problems or because planning is being performed more than five days in advance, monthly statistical wind data (Global Gridded Upper Atmospheric Statistics[4]) is used. When this dataset is used, a much larger buffer is included to account for the variability of wind within the month

A second source of uncertainty is the fragment lift over drag ratio. Depending on the orientation of the fragment, the lift force could be oriented in any direction. Although it is highly unlikely to have a constant orientation from breakup to the ground, the lift force may remain in the same orientation for a significant

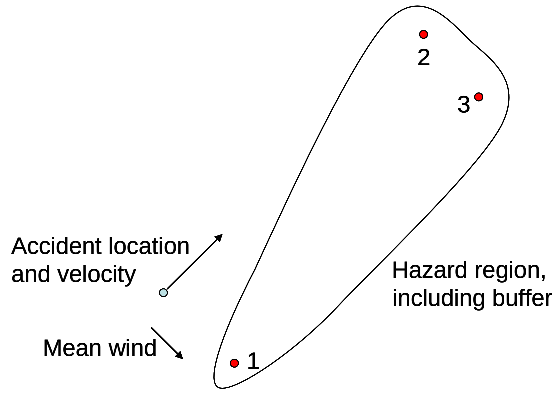

Figure 2. Illustration of Hazard Area

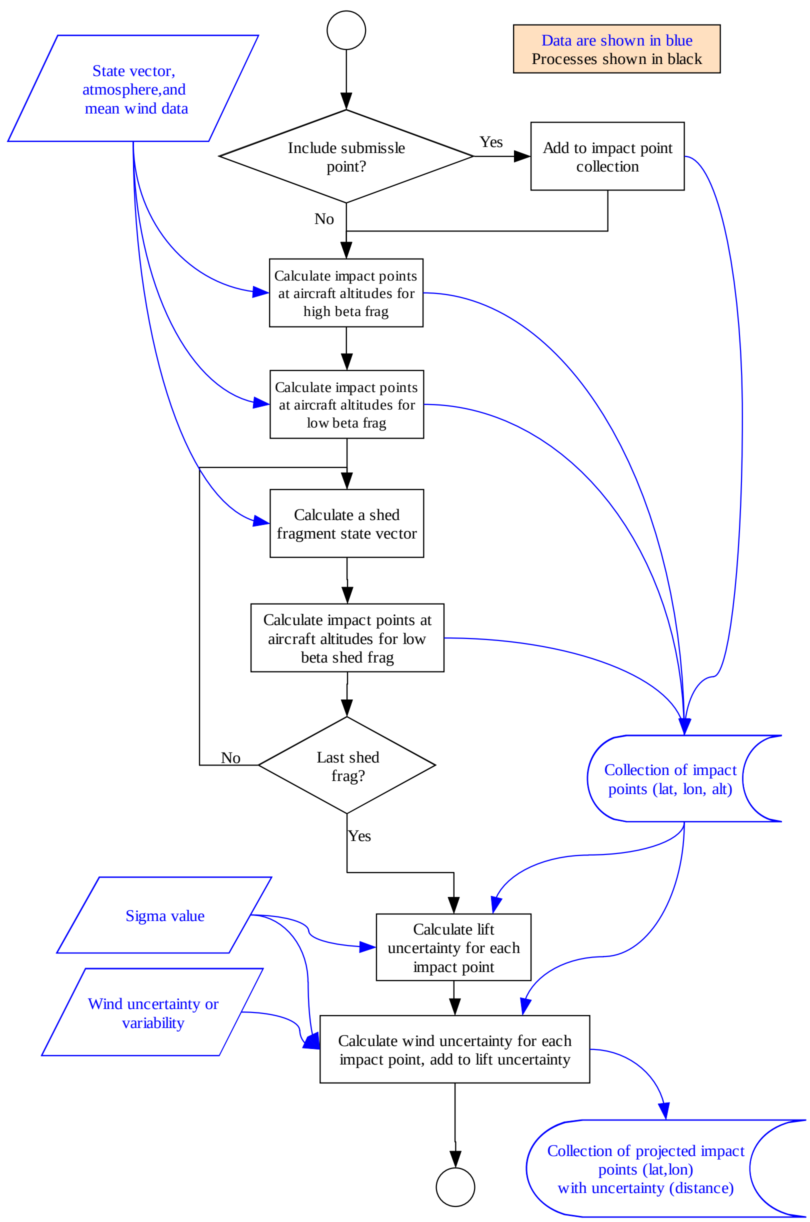

Figure 3. Flow of hazard area calculation.

duration, if it is spinning like a frisbee, for example. The uncertainty in the lift is therefore included in the calculation.

The effect on the buffer from both wind and lift is dependent on the number of standard deviations of uncertainty included. For an axisymetric bivariate normal distribution, the probability of containing debris, *C*, within a region is given by:

Table 1. Probability of Containment vs. Sigma Level and Number of Fragments

	ξ =3	ξ =4	ξ =5
N=100	32.72%	96.70%	99.96%
N=300	3.50%	90.42%	99.89%
N=1000	0.00%	71.50%	99.63%

$$C = \left[1-\exp\left(-\tfrac{1}{2}\xi^2\right)\right]^N, \qquad (1)$$

where *N* is the number of fragments that impact in the distribution and ξ is the "sigma level"—the number of standard deviations included in the determination of the region. The buffer around each calculated impact point is defined by the sigma level. Table 1 shows some example confidence levels as a function of N and ξ.

However, since the number of fragments impacting at each point is not known, confidence of containment cannot be determined. In order to provide sufficient conservatism, a sigma level (ξ) of five was initially selected. This value was found to provide hazard areas of reasonable size, so it is used as the default in the tool, even though a smaller value may be justified.

The hazard box is then defined as the smallest area rectangular box surrounding the impact points and the buffer around each. The box is defined in an equi-azimuth projection centered on the mean impact location of all debris. This is accomplished by trial and error—orienting boxes at different azimuths, finding the sides tangent to the most extreme point with buffer, and computing the box area. The processing methodology to define each hazard area is shown in Figure 3. In many cases it is impossible for debris to impact directly under the breakup point, but the hazard box also includes the breakup point when the user requests it (not in this work).

III. Example Results

An example set of hazard boxes, for the planned re-entry of STS-120 to Kennedy Space Center, is shown in Figure 4. The trajectory is shown as a thin blue line, and the hazard boxes in different colors, and the background map includes the boundaries of the Air Traffic Control regions. Each of the boxes shows a hazard area for single

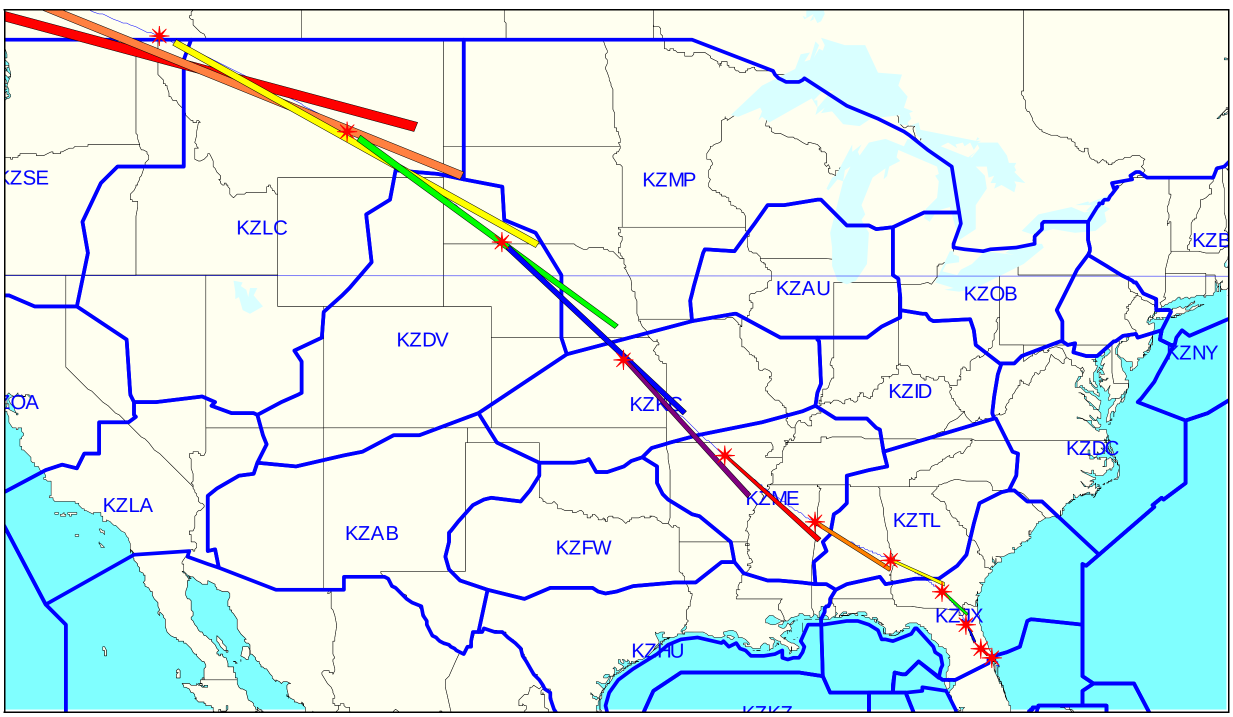

Figure 4. Hazard boxes for STS-120 with no wind and no uncertainty. Colors show boxes resulting from different state vectors.

state vector (which are at 100 second intervals along the trajectory). Only breakups above 20 km have been included, because the hazard box for lower altitude breakups is then contained within the restricted airspace around Cape Canaveral. No wind or uncertainty has been included, so the boxes are very narrow; the width is due only to Earth rotation effects. The hazard boxes extend down range from the breakup locations (shown with red stars) in the direction of the velocity vector. Due to the energy management maneuvers during the Shuttle trajectory, the hazard boxes extend to the sides of the trajectory. As the breakup points approach the landing site, the hazard boxes become both shorter and narrower. They are shorter because the initial velocity is less and altitude is lower, so the impact point of the highest ballistic coefficient debris does not extend as far down range. They are narrower because the fall time of debris is less, so Earth rotation differences are smaller. Figure 5 shows a more detailed plot of the width of the hazard boxes as a function of breakup altitude. For comparisons that follow, this is the "baseline" case.

Wind and wind uncertainty have strong effect on the width of the hazard boxes, but only a small effect on the length. The width of the boxes as a function of breakup altitude is shown in Figure 6 for the same trajectory for two cases in comparison to the baseline case. The first case includes a 3-dimensional wind forecast, which blows debris, especially those pieces with low ballistic coefficient. This leads to an increased width of the hazard box. The effect of wind generally occurs below all breakup altitudes, because the power of the wind (square root of atmospheric density times wind speed) is generally largest between 7 and 14 km. Therefore, the effect on hazard box width is complicated because the orientation of the trajectory relative to the wind varies. In general, the width of the box is increased 10 to 20 km due to the wind, and sometimes the boxes are shifted, especially when the trajectory is perpendicular to the jet stream. Wind uncertainty, which is due to the typical error between the forecast and the actual wind, increases the width of the hazard boxes at all altitudes between 12 and 18 km (with the lower breakup altitudes having the smallest effect). In this case, a five sigma wind uncertainty has been applied. The forecast wind uncertainty does not vary as a function of location.

When the analysis is run prior to a wind forecast being available, however, it is necessary to use a statistical database of winds, which are cataloged on a monthly basis. In this case, the monthly variability is applied, which is much larger than the uncertainty in a single wind forecast. Therefore, the hazard box widths are much larger, as shown in Figure 7. Typically, the hazard boxes are now 80 to 140 km. However, the width does not always decrease monotonically as a function of altitude; because the statistical variability depends on location and direction. These large hazard areas are less practical than the ones generated with a forecast and corresponding small uncertainty for two reasons. First, the larger width results in more time required for aircraft to fly out of the

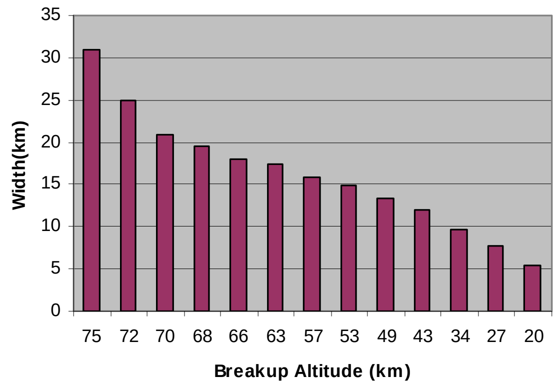

Figure 5. Hazard box width as a function of breakup altitude with no wind and no uncertainty.

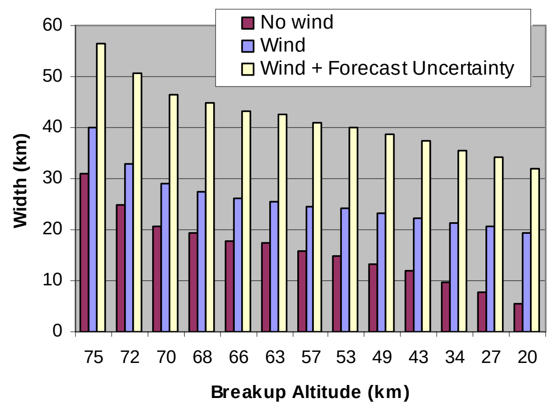

Figure 6. Effect of wind and wind uncertainty upon hazard box width.

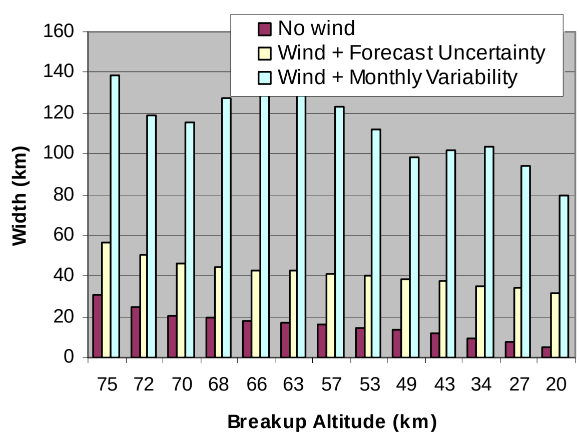

Figure 7. Effect of wind forecast uncertainty and monthly variability upon hazard box width.

hazard box. Flying the half-width of the box (60 km) requires about five minutes for commercial jets and this is comparable to the debris fall time of the fastest falling pieces, leaving little time for processing and communication. Secondly, the larger hazard boxes are less desirable because they would tend to cause Air Traffice Control to overestimate the area at risk, perhaps leading them to move more planes than necessary and block off more airspace, creating capacity issues.

The effect of lift uncertainty, also with five sigma values, is shown in Figure 8. It typically results in an increase in the hazard box width of five to fifteen kilometers, somewhat smaller than the effect of wind uncertainty. The effect of lift/drag tends decreases as a function of breakup altitude.

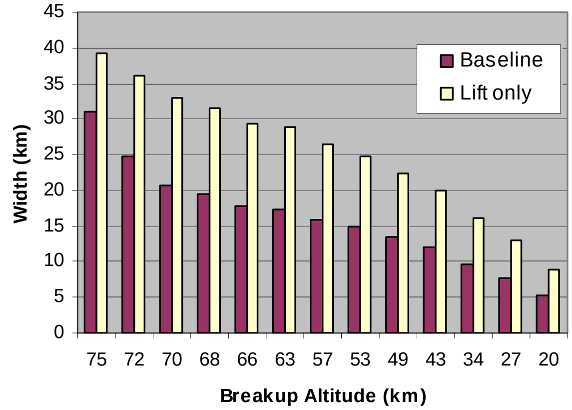

Figure 8. Effect of lift/drag uncertainty upon hazard box width.

The upper and lower ballistic coefficient are dependent on the assumptions about the vehicle breakup. The default values are 0.2 psf and 250 psf. Alternate values may be used instead, which affect the uprange and downrange impact points, as well as the width (if there is wind) of the hazard box. Adjusting the maximum ballistic coefficient to 2000 psf, extends the hazard area downrange an additional 20% to 45%. Increasing the lowest ballistic coefficient to 2 psf shortens the hazard areas by up to 20% (shifting the uprange point further downrange (this is illustrated in Figure 9). Debris with a smaller ballistic coefficient value than 0.2 psf is not considered individually as hazardous to aircraft because it is of too small mass.[5] A collection of debris, e.g. volcanic ash, can be a hazard en masse to aircraft, but it is not envisioned that there is sufficient amount of this debris from a re-entry accident to create a collective hazard to aircraft.

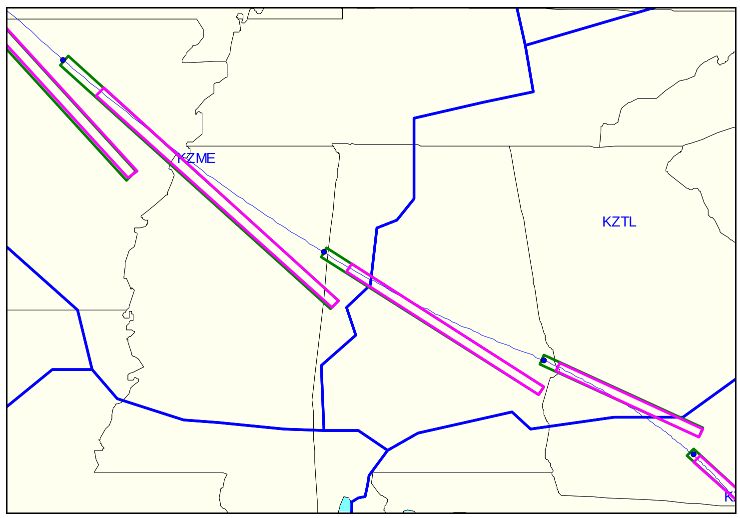

Figure 9. Comparison of hazard areas with lower ballistic coefficient of 0.2 pdf (green) and 2 psf (magenta), with no wind and no uncertainty.

The effect of varying the number of standard deviations of wind and lift/drag uncertainty is linear with additional width added. The five sigma value was chosen because it contains 1000 fragments for each impact point at 99% confidence.

In these illustrative examples, a few specific state vectors have been shown. However, in actual practice, the analysis is performed more frequently than every 100 s (e.g. every one to four seconds). Then a reduced set of hazard areas is determined from this large set by combining consecutive hazard areas into a larger region. An illustration of the final set of “planning” hazard areas is shown in Figure 10. These are used to communicate with Control Centers the regions that might be affected by a Shuttle accident.

IV. Lessons Learned

In the initial use of the tool for recent Shuttle re-entries, two operational effects were found to be important but had not been included in the calculation. Both effects will have the consequence of increasing the size of the hazard boxes, one in planning mode and one in real-time.

First, the predicted re-entries of the Shuttle were not as accurate as were anticipated. This led to the real-time position of the Shuttle sometimes being significantly away from the path, and therefore the planning mode hazard boxes would not have contained the real-time hazard box if an accident had occurred. The solution to this issue is in process: gather pairs of planned and actual Shuttle re-entries, and calculate the hazard boxes for each pair. The

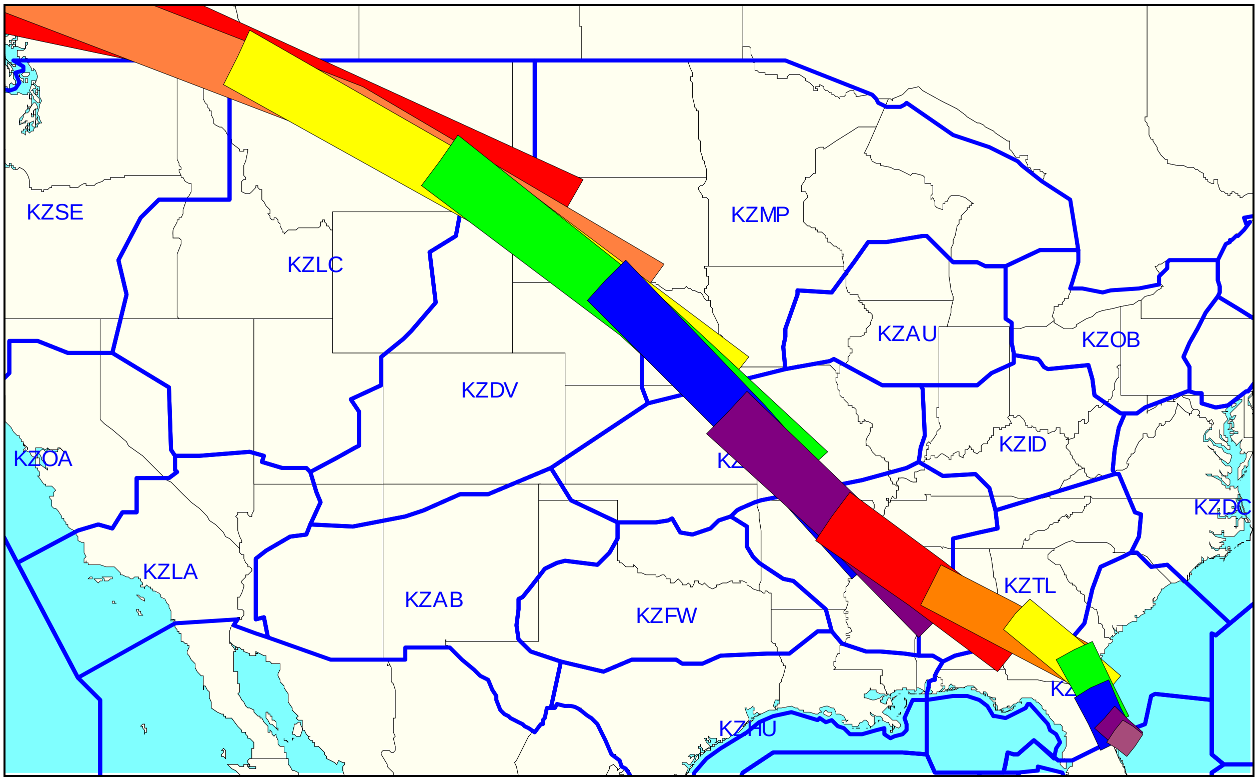

Figure 10. Example Hazard Areas for a Shuttle Re-entry in Planning Mode

difference between these pairs will then be used as an additional source of uncertainty in the planning mode hazard box determination.

Secondly, it was recognized that the unknown behavior of the Shuttle during a radio frequency (RF) blackout period[6] (due to plasma generation) was not accounted for. During the RF blackout, no tracking data from the Shuttle is received. If breakup occurs during this period, the Shuttle will have advanced from the last known state vector, but the direction is unknown, because there is significant lift during re-entry. The solution to this issue is to apply the maximum lift (given the Shuttle's last known altitude) for a reasonable period of RF blackout. The lift is applied in many directions to determine a maximum additional distance cross-range and downrange that the Shuttle may have proceeded since the last known state vector. These distances may then be added to the real-time hazard box.

Both of these effects are currently in process of being implemented. The effect of the unknown behavior during RF blackout can be quite significant if the blackout period lasts for more than a minute or two. A longer blackout period than this is not expected to occur for the Shuttle (due to the use of a satellite relay), so the hazard boxes remain of a practical size. However, this will likely be a constraint on other future re-entering vehicles—in order to effectively mitigate the risks by redirecting air traffic after an accident, the planned RF blackout times will need to be limited.

V. Conclusion

This methodology establishes a prototype method for real-time protection of aircraft from debris following a space vehicle accident. The method incorporates sufficient physical and statistical modeling to result in hazard areas that are reasonable for real-time use. This has been demonstrated for re-entry trajectories of the Space Shuttle, and could be further applied to other space vehicle operations, such as launches, when other factors (such as explosive potential) are considered.

Acknowledgments

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