EVOLUTION OF NATIONAL AIRSPACE SYSTEM PROTECTION FOR SPACE SHUTTLE LAUNCH AND LANDING

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ABSTRACT

The breakup of the Space Shuttle *Columbia* on 1 February 2003 during the entry phase of the STS-107 mission occurred above a significant number of aircraft operating in the National Airspace System (NAS). Although no aircraft were struck by falling debris, the incident led the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) to seek cooperative ways to better protect aircraft operating in the NAS during Space Shuttle launch and landing operations. Applications were developed and improved by both the FAA and NASA to provide pre-operation and near real-time groundtracks and debris footprints to enable Air Traffic Controllers (ATC) to vector aircraft away from the debris field in the event of a Space Shuttle breakup. Real-time coordination processes were also developed to provide the FAA data and insight into ongoing Space Shuttle operations in order to protect the NAS. The processes and procedures developed for Space Shuttle operations are extensible and applicable to future NASA and commercial spacecraft.

Overview of the National Airspace System

The Federal Aviation Act of 1958 established the FAA and made it responsible for the control and use of navigable airspace within the United States. The FAA created the National Airspace System (NAS) to protect persons and property on the ground, and to establish a safe and efficient airspace environment for civil, commercial, and military aviation. The NAS is made up of a network of air navigation and air traffic control facilities, airports, technology, and appropriate rules and regulations that are needed to operate the system.

There are four types of airspace in the United States: controlled, uncontrolled, special use, and other airspace. Controlled airspace is made up of five classes: Class A, Class B, Class C, Class D, and Class E. The FAA defines these classes as follows[i]:

- Class A: Generally, that airspace from 18,000 feet above mean sea level (MSL) up to and including 60,000 ft MSL, including the airspace overlying the waters within 12 nautical miles of the coast of the 48 contiguous States and Alaska; and designated international airspace beyond 12 nautical miles of the coast of the 48 contiguous States and Alaska within areas of domestic radio navigational signal or ATC radar coverage, and within which domestic procedures are applied.
- Class B: Generally, that airspace from the surface to 10,000 feet MSL surrounding the nation's busiest airports in terms of IFR operations or passenger enplanements.
- Class C: Generally, that airspace from the surface to 4,000 feet above the airport elevation (charted in MSL) surrounding those airports that have an operational control tower, are serviced by a radar approach control, and that have a certain number of IFR operations or passenger enplanements.
- Class D: Generally, that airspace from the surface to 2,500 feet above the airport elevation (charted in MSL) surrounding those airports that have an operational control tower.
- Class E: Generally, if the airspace is not Class A, Class B, Class C, or Class D, and it is controlled airspace, it is Class E airspace.

In addition, Class G airspace is uncontrolled airspace, and it is that portion of airspace that has not been designated as Class A, Class B, Class C, Class D, or Class E airspace. The relationships between these classes of airspace are depicted graphically in Figure 1Figure 1.

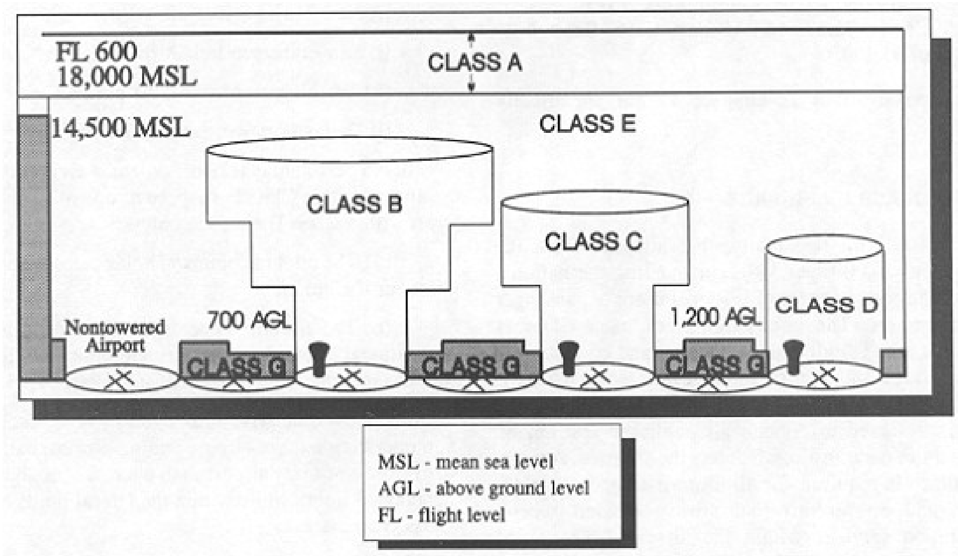


Figure 1: Classes of Airspace

Special use airspace consists of that airspace wherein activities must be confined because of their nature, or wherein limitations are imposed upon aircraft operations that are not a part of those activities, or both. Prohibited and restricted areas are regulatory special use airspace and are established in 14 Code of Federal Regulations (CFR) Part 73 through the FAA rulemaking process. Compliance with the rules associated with these airspaces is mandated by law. Warning areas, military operations areas, alert areas, and controlled firing areas are non-regulatory special use airspace. Compliance with the rules associated with these airspaces is not mandated by law.

Other airspace includes temporary flight restrictions (TFRs). TFRs are used to: protect persons and property in the air or on the surface from an existing or imminent hazard associated with an incident on the surface when the presence of low flying aircraft would magnify, alter, spread, or compound that hazard; provide a safe environment for the operation of disaster relief aircraft; prevent an unsafe congestion of sightseeing aircraft above an incident or event which may generate a high degree of public interest; protect declared national disasters for humanitarian reasons in the State of Hawaii; protect the President, Vice President, or other public figures; and provide a safe environment for space operations.

Overview of Space Shuttle launch and landing profiles

During ascent, the Space Shuttle accelerated from an earth relative velocity of 0 mph to approximately 17,000 mph during a powered flight phase lasting approximately 8.5 minutes. For 51.6˚ inclination missions to the International Space Station (ISS), the Space Shuttle followed a groundtrack that roughly paralleled the east coast of the United States and Canada. In the event that multiple Space Shuttle Main Engines (SSME) failed during ascent, the Shuttle had some capability to perform a contingency landing at sites in the U. S. or Canada. The exact capability windows varied with factors such as launch time, number of SSME failures and the timing of those failures. To protect for the possibility of a contingency landing during the ascent phase, NASA had identified airfields in the U. S. and Canada where a landing would have been attempted. These are shown relative to a 51.6˚ inclination launch groundtrack in Figure 2.

Figure 2: Space Shuttle Launch Abort Sites in the United States and Canada for ISS Missions

Relative to most air traffic events, Space Shuttle reentries were extremely dynamic. The amount of time that elapsed from the time of the initiation of the deorbit burn, which committed the Shuttle to a particular landing location at a particular time, to the time of touchdown was approximately one hour. In that time, the Shuttle decelerated from roughly 17,000 mph to 215 mph, and descended over 175 miles in altitude as it traversed the 13,000 miles to its landing site[ii]. This path took it over multiple air traffic regions in the NAS. During a typical landing, the Shuttle passed through 60,000 ft altitude (FL600) at supersonic speeds, less than 15 miles and 5 minutes prior to touchdown.

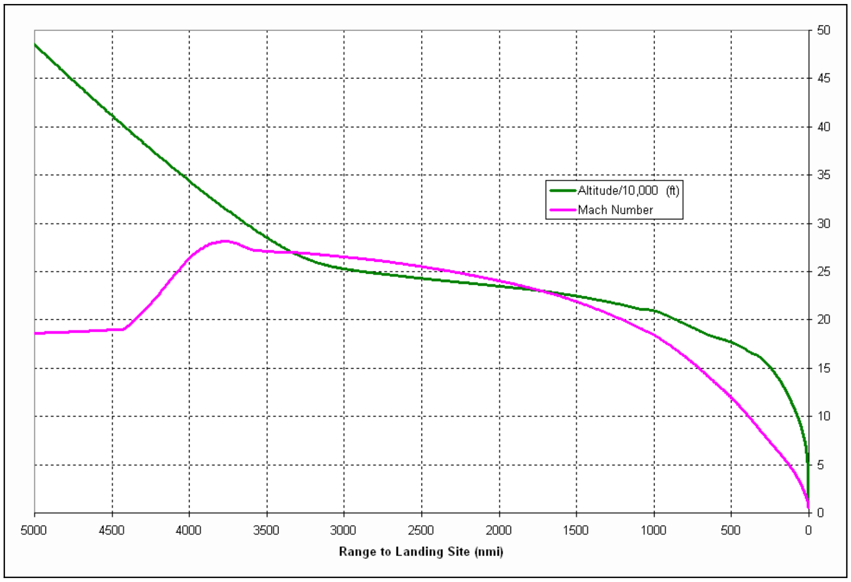


Figure 3: Typical Shuttle Reentry Profile

Shuttles approached their designated landing sites from west to east on a very steep angle of descent, as shown in Figure 3 above. The primary landing site was Kennedy Space Center (KSC) in Florida. Two alternate sites existed, the first at Edwards Air Force Base (EAFB) in California, and the second at White Sands Space Harbor (WSSH) in New Mexico. For cost and scheduling reasons, NASA preferred to land the Shuttle at KSC.

Orbital dynamics and the glide characteristics of the vehicle allowed for four to six opportunities to each site each day. Approximately half of the opportunities occurred as the Shuttle approached the site on a descending reentry trajectory (moving from north to south as the vehicle approached the landing site) and the other half occurred from an ascending reentry trajectory (moving from south to north toward the landing site). Due to crew timeline constraints, NASA could only utilize one of the sets of opportunities (ascending or descending) and generally preferred the ascending opportunities. The ascending opportunities also generally required less propellant for the deorbit maneuver and avoided potential issues with noctilucent clouds.

Dynamic weather conditions in south Florida sometimes prevented the use of one or both of the KSC opportunities. The chance of thunderstorms, precipitation, high winds, cloud ceilings and low visibility all factored into NASA's decision to proceed with an opportunity. NASA decided to extend some missions by a day or two to allow for better weather at KSC as opposed to landing at an alternate site. Since Florida weather is so dynamic, the decision to cancel a landing opportunity in favor of the next opportunity could be made up to the time of ignition of the deorbit burn, as late as approximately one hour prior to the original landing time.

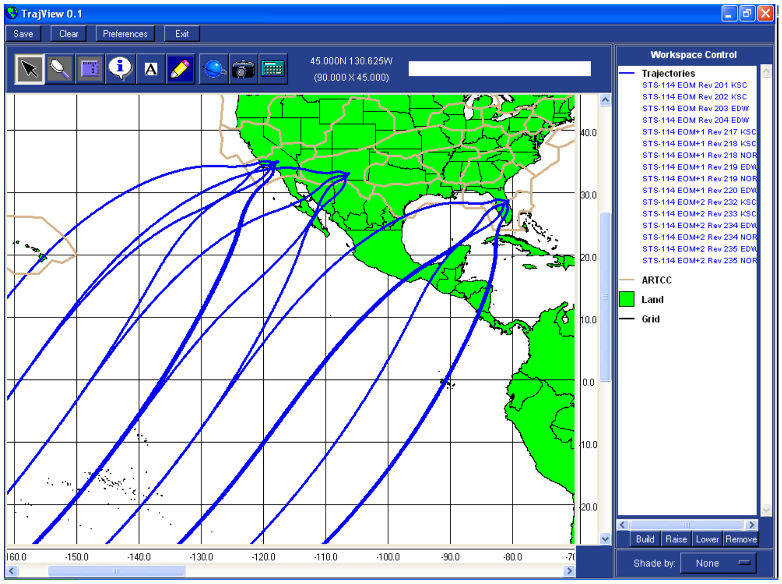


Figure 4: Example Shuttle Ascending Landing Opportunities

Although the ascending trajectories minimized the flight time over the continental U.S., a large number of uninvolved aircraft were still at risk from a Shuttle accident. As Figure 4 shows, the Shuttle could overfly aircraft traversing the Pacific Ocean, the Gulf of Mexico and Gulf Coast, the Los Angeles basin, and southern Florida.

NAS Protection prior to STS-107

Shuttle launches were coordinated through the Aerospace Control Officer (ACO) at the Air Force 45th Space Wing's Eastern Range, in accordance with Air Force Procedures Document 13-201 [iii]. Notices to Airmen (NOTAMs), TFRs, and special use airspace, including restricted areas and warning areas, were activated for these events. The ACO coordinated these actions with the FAA's Air Route Traffic Control Center (ARTCC) in Miami, Florida (Miami Center) according to the notification procedures prescribed in Procedures Document 13-201.

In the event of an emergency during a launch, NASA could have attempted to land the Shuttle at one of the emergency-landing sites located along the eastern seaboard of the United States and Canada shown in Figure 2 above. Fortunately, such a landing was never necessary. The FAA and NASA maintained a dedicated, two-way line of communication, known as the "shout-down loop", to distribute and receive information needed for air traffic controllers to manage the airspace. Upon notification over this line of the need for an emergency landing from the Shuttle Landing Support Officer (LSO) in NASA's Mission Control Center (MCC) at the Johnson Space Center (JSC) in Houston, Texas, Miami Center and the Air Traffic Control System Command Center (ATCSCC) in Herndon, Virginia would initiate steps to clear the airspace within a 30 mile radius of the intended landing site to prevent collisions between aircraft and the approaching Shuttle.

Once on-orbit, an emergency situation, such as a leak of the Shuttle crew cabin, could have forced NASA to attempt an emergency reentry and landing, known as an "anytime deorbit". If such an event had occurred, NASA would have first attempted to land the Shuttle at one of its three designated primary landing sites, if possible. However, if the situation did not permit such a landing, NASA flight controllers would have selected alternate sites based on a defined list of criteria in priority order. The base requirement was that the runway had to have usable dimensions of at least 7500 ft length by 130 ft width.[iv]

The *Columbia* accident in relation to the NAS

The Federal launch ranges manage risk to the public according to criteria established by the Range Commanders Council (RCC). This criteria limits the probability of an uninvolved aircraft being struck by planned and unplanned inert debris generated by flight tests and space launches conducted at Federal ranges to 0.0000001 (1 in 10,000,000). With its release of 14 CFR Parts 413, 415, and 417, the FAA's Office of Commercial Space Transportation (AST) requires commercial space operators to establish aircraft hazard areas that provide an equivalent level of safety to that provided by aircraft hazard areas implemented for launch from a Federal launch range [v]. NASA is not subject to either of these limits and includes the risk to aircraft in the total cumulative risk calculations and requirements. However, the *Columbia* accident showed that a Shuttle failure during reentry could produce risks to aircraft that exceed these values by several orders of magnitude.

As a result, in the 40 minutes required for the majority of the debris from *Columbia* to fall to the Earth's surface, as many as nine instrument flight rated (IFR) aircraft flew through the falling debris. Although no damage was reported to any of these aircraft, a study conducted by ACTA, Inc. of Torrence, CA showed, using data retrieved from the accident investigation, that the probability of one of these aircraft being struck by a piece of falling debris could have been as high as 0.1 (1 in 10) to 0.003 (3 in 1,000) [vi].

While NASA applied a number of corrective measures to the Shuttle program to prevent such an event from occurring again, NASA predicted that the probability of another catastrophic failure of a Shuttle on reentry is 0.01 (1 in 100) [vii]. This value applied to an orbiter with no known damage to its thermal protection system. If this system had been compromised in any way, the probability of failure could be much higher. Applying this probability to the ACTA results produced probabilities of 0.001 (1 in 1,000) to 0.00003 (3 in 100,000) of an aircraft in the region of a Shuttle breakup being struck by debris. These values are summarized in Table 1.

Probability of an aircraft being struck by debris during the *Columbia* accident	0.1 – 0.003
Probability of catastrophic failure of another orbiter on reentry	0.01
Probability of an aircraft being struck by debris from a catastrophic failure of another orbiter on reentry	0.001 – 0.00003
Criteria used by Federal launch ranges for acceptable level of risk to uninvolved aircraft	0.0000001

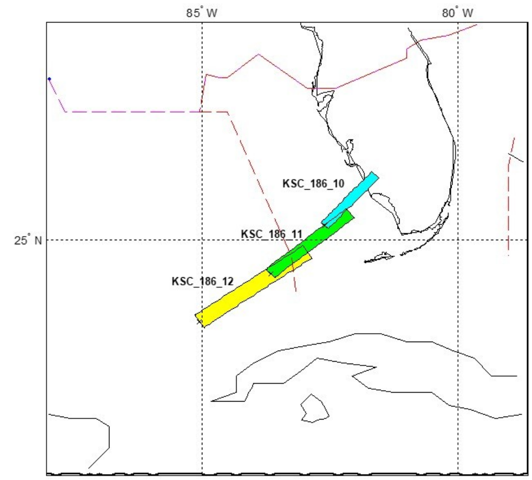
Table 1: Summary of Probabilities

Simply multiplying probabilities together oversimplifies a complex problem, but the results suggest that the potential for a debris strike may exceed the RCC and FAA criteria. In fact, in the event of an accident during subsequent Shuttle reentries, the probabilities could have been higher than those computed for *Columbia*, since several of those reentries took place at times and over locations where more aircraft were traversing through the NAS.

In addition to the increased awareness of the hazards that spacecraft debris can impose on aircraft, the *Columbia* accident also demonstrated a need for improved communication and information-sharing between NASA and the FAA during Shuttle reentry operations. During the accident, reports have indicated that the majority of the debris had already impacted the ground by the time the affected FAA ARTCCs had been notified that an accident had occurred. Even in the event that this notification had arrived any earlier, the air traffic controllers at those Centers would have had little, if any, indication of the extent of the airspace that was affected, making it difficult to identify and reroute the airplanes that flew through the falling debris. While NASA's difficulty in confirming that an accident had taken place was the primary cause for this delay, additional time was lost due to the lack of a dedicated communications and information-sharing plan.

Debris footprint application development post-*Columbia*

STS-115 Entry: KSC Orbit 186



LOCs between 175,000 and 145,000 feet; GMT 10:08:00 – 10:11:00

Figure 5 Sample debris footprint for STS-115 landing

With the Space Shuttle's return to flight (STS-114), NASA began producing and delivering Shuttle debris footprint packages, such as the sample shown in Figure 5, for potential landing opportunities to the FAA for use in clearing airspace if determined necessary. A Shuttle debris footprint represented an expected area and location of Shuttle debris falling through the airspace as a result of a breakup at a particular time, such as STS-107 *Columbia* accident. Using predicted reentry trajectory data, NASA computed a series of footprints for each Shuttle reentry opportunity that it then provided to the FAA in a footprint package. The footprint computation was based on assumed characteristics of the falling debris generated by a Shuttle breakup and the effect of winds on those debris[viii]. For ease of input into existing air traffic management tools, NASA conservatively simplified the resulting footprint ellipses to a rectangular shape, thereby requiring only four corner points to define each area along an identified entry trajectory. This simplification also improved the FAA's ability to transmit the footprint coordinates verbally to affected parties who did not have access to the airspace management tools.

Debris footprints can vary in size and orientation depending upon their location along the entry trajectory and the characteristics of the vehicle state vector at the point of loss of control. In consideration of these variations, the NASA debris footprint packages contained footprints at one minute intervals until approximately 150,000 feet and then at 30 second intervals thereon until landing. The first footprint of each set was typically created to model a loss of control between 240,000 and 225,000 feet altitude. To increase the FAA's situational awareness and to assist in cross-checking the footprints once they had been entered manually into the airspace management tools, NASA included an image of each footprint and a listing of its initial conditions with each set of footprint corner points in a footprint package.

As the debris footprint process developed, the FAA's need for their own independent means of producing this data became better understood. The FAA contracted ACTA, Inc. to develop a means of computing debris footprints for Space Shuttle reentries based on the methodology and techniques of NASA's tool. The FAA imposed additional requirements for the Shuttle Hazard Area to Aircraft Calculator (SHAAC) tool to use forecasted wind data, to produce the minimum number of footprints necessary to adequately represent a typical landing opportunity, to produce footprints that overlapped with adjacent footprints, to simplify the user interface, and to limit the computation time required.

Once a prototype for SHAAC was developed, the responsibility for debris footprint development began transitioning from NASA to the FAA with the STS-120 mission in November of 2007. The transition was gradual with NASA and the FAA independently producing their respective debris footprint packages and comparing the results. Data from past missions was also used to verify the SHAAC tool's accuracy and joint NASA-FAA exercises were conducted to verify its ability to produce a best estimate debris footprint in a timely fashion in realtime, operational conditions. Based on these exercises and flight-following activities, the FAA identified additional requirements for incorporating predictions in the uncertainty of the Shuttle state vectors into its footprint predictions and for modeling breakups during loss of signal periods.

With the completion of the debris footprint development transition, the FAA took over primary responsibility for generating the entry debris footprints for the remaining Shuttle missions. However, the data continued to be shared among the two agencies. The FAA and NASA then began identifying the appropriate operational implementation of the debris footprints during a contingency scenario.

Real-time coordination processes between the FAA and NASA

For Shuttle missions after the *Columbia* accident, the launch was still coordinated with the FAA through the 45th Space Wing ACO. In addition, the LSO sent a notification letter to FAA Headquarters, the ATCSCC and the Miami, Los Angeles and Albuquerque ARTCCs at Launch - 25 days detailing the expected launch and landing dates and times. This information was also posted to NASA-internal web sites to which the FAA was provided access.

On launch day, the FAA Space Mission Operations Team (SMOT), composed of members of the FAA's Air Traffic Organization Systems Operations service unit and the Office of Commercial Space Transportation, convened at the ATCSCC. The ATCSCC established a teleconference between the SMOT and the appropriate ARTCCs. The LSO at the MCC in Houston tied this telecon into the MCC communications system (via the "shout down" loop) at launch - 40 minutes. The LSO provided verbal mission status updates for the remainder of the launch count and the ascent phase to the teleconference participants.

In addition to the dedicated communications line, a system was put into place beginning in June 2007 (STS-117) that allowed the FAA SMOT to view Space Shuttle state vector information in real-time. The system used existing NASA MCC technology to push the information through the MCC firewall to a secure website for viewing and use by the FAA SMOT. For launch, this data was available from approximately five minutes prior to launch until Main Engine Cutoff (MECO). A representation of the data display is shown in 6.

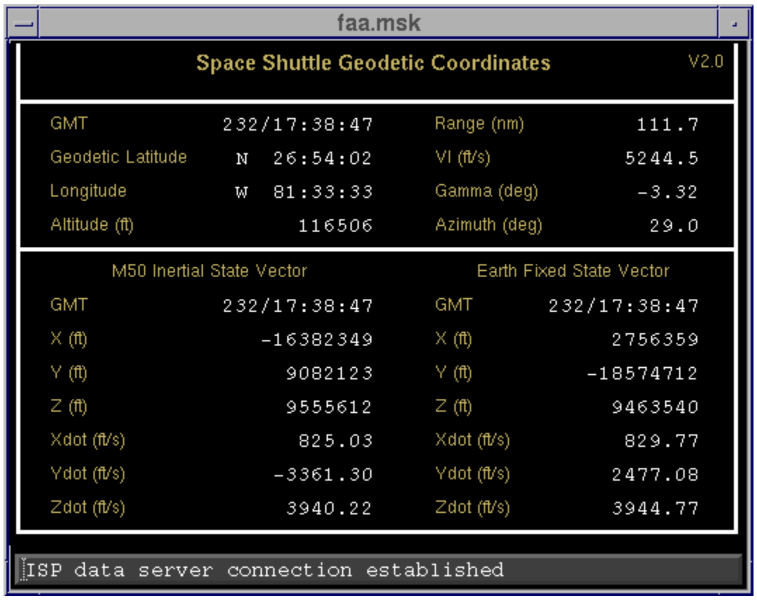


Figure 6: FAA State Vector Information Display

Under the SMOT procedures, an FAA operator manually input the Space Shuttle position coordinates into the FAA's Traffic Situation Display (TSD). This allowed NAS air traffic managers to view a representation of the Space Shuttle ascent or entry ground track. The LSO had access to this data also via a web based version of the TSD. The real-time data was also used to compute an actual debris footprint in the event of a Shuttle breakup.

Eventually a Google Earth display of the real time ground track was also made available. The added visualization capability assisted operators with improved situational awareness of the Shuttle's location.

For a nominal launch, the SMOT teleconference was dropped from the MCC communications system after Main Engine Cutoff (MECO). In the event of a situation requiring a landing attempt at an east coast airfield, the LSO would have informed the SMOT of the situation and the intended landing site, and the LSO would have requested assistance with airspace clearance and airfield notification. The LSO would also have contacted the tower directly to provide notification, verify Shuttle required landing/navigation aid settings and confirm airspace clearance. This dual notification route provided a redundant path for notification of the airfield in a time-critical scenario as the Space Shuttle approached the site. The direct contact with the tower also would have allowed the LSO to provide information to the tower controllers on the Space Shuttle landing profile and any problem or hazard information that would have been required by emergency response personnel at the airfield.

During orbit operations, the LSO conducted a daily teleconference known as the Primary Landing Site (PLS) teleconference with ground operations representatives at the three NASA sites as well as Department of Defense (DoD) support personnel to discuss mission status and plans. The FAA did not participate directly in these meetings, but select FAA personnel did receive the notes from this daily teleconference. Significant events such as a mission extension were communicated with the appropriate FAA personnel via telephone or e-mail.

Three days before the planned end of mission (EOM) landing, the MCC Flight Dynamics Officer (FDO) posted planned entry trajectory information for the EOM landing opportunities to a secure website accessible to FAA personnel. Using this data, FAA personnel generated the planning debris footprints for the landing opportunities. These footprints were displayed on the TSD as Flow Evaluation Areas (FEA) during the actual entry to assist air traffic controllers with airspace protection/traffic management initiatives in the event such action was required. An example is shown in 7. If significant changes in the trajectory plan occurred prior to EOM, the FDO posted the updated entry trajectory data to the website no later than 24 hours prior to landing.

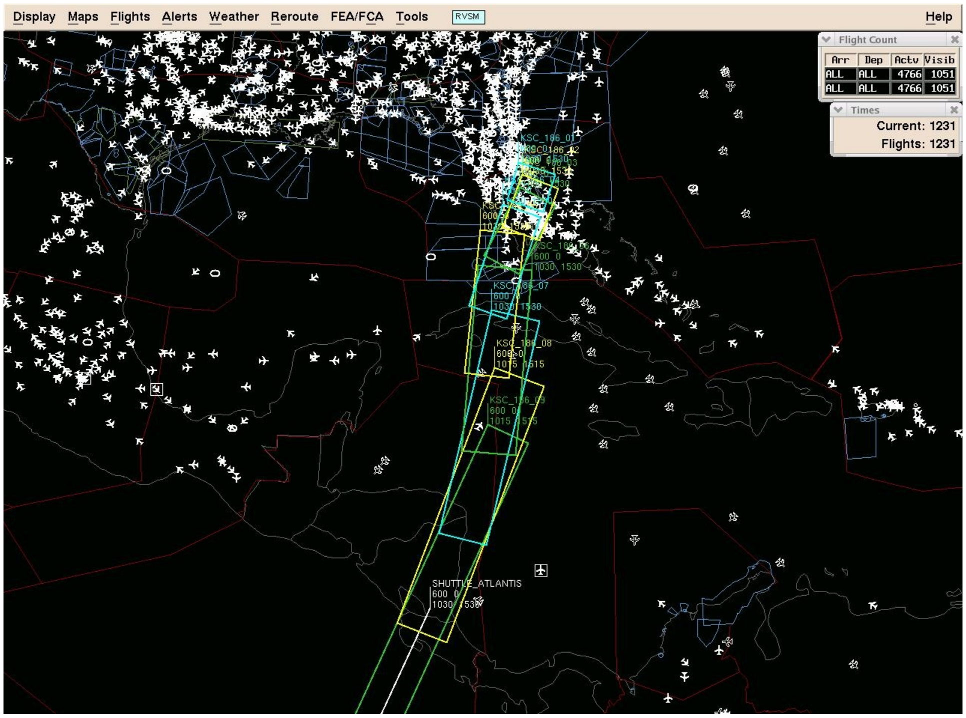


Figure 7: TSD Configured for a Shuttle Landing at Kennedy Space Center

On landing day, the FAA SMOT again convened at the ATCSCC. The ATCSCC established a teleconference between the SMOT and the appropriate ARTCCs. The LSO at the MCC in Houston again tied this telecon into the MCC communications system (via the "shout down" loop) at landing - 2 hours. The LSO provided verbal mission status updates for the duration of the deorbit preparation and entry phase to the teleconference participants.

Once NASA committed to a particular landing opportunity and landing site, the ATCSCC sent an advisory to concerned NAS parties confirming the selected opportunity, confirming the system's readiness and configuration with the ARTCCs, and cancelling any unnecessary NOTAMs.

As for the launch phase, real-time Space Shuttle state vector information was sent to the FAA SMOT via a secure website for manual input and display on the TSD. Error: Reference source not foundThis real-time information was available from an altitude of approximately 500,000 ft (Entry Interface - 5 minutes) until touchdown.

In the event of a Space Shuttle breakup during either the launch or landing phase, the LSO would have informed the SMOT of the situation using the proword "BREAKUP". This was the cue for the ATCSCC to implement traffic management initiatives to protect the NAS from falling Space Shuttle debris. These initiatives could have included rerouting aircraft, increasing the separation distance between aircraft, or holding aircraft on the ground. Initially, the FAA would have identified the two predicted footprints that bounded the expected loss of control location, and started implementing traffic management initiatives as necessary. Using the latest Shuttle state vector provided by the NASA LSO, the FAA would then have used SHAAC to develop a refined footprint with the intention of minimizing the impact to airspace and focusing on the most likely location of the falling debris.

Depending on the particular scenario resulting in a breakup, NASA may have been unable to immediately confirm that a breakup had indeed occurred. For example, a breakup could have occurred during one of the brief "blackout" periods experienced by the orbiter during reentry, when voice and data communication was sometimes impeded by plasma effects and antenna geometry. In such loss of signal cases, the most likely indication that a breakup had occurred would have been that the MCC failed to receive communications from the orbiter at the predicted acquisition of signal time. The FAA would then have used SHAAC to propagate the last state vector before the blackout forward in time to account for the amount of time that had transpired since the loss of signal, effectively growing the footprint by the distance that the orbiter could have flown in that amount of time. Although the LSO provided the best information available in the MCC to the FAA, there could have been situations where the FAA would have needed to unilaterally initiate traffic management initiatives in the NAS prior to NASA confirmation of a Space Shuttle breakup.

Conclusion

At the time of writing this paper, the FAA began incorporating lessons learned from its support of the Shuttle program to develop requirements for the next generation spacecraft hazard to aircraft calculator. These requirements address a variety of space vehicle types, including reentry vehicles like the SpaceX *Dragon* and the Lockheed Martin *Orion*, as well as suborbital vehicles like the Virgin Galactic *SpaceShipTwo*. Now called the Space Data Integrator[ix], this tool will ultimately be fully integrated into the FAA's traffic flow management system and interface with enabling technologies from the FAA's Next Generation Air Transportation System (NextGen) program. These developments will allow a responsive approach to airspace management like that used for the Shuttle to be applied to the launches and reentries of commercial space vehicles. In such circumstances, airspace will not have to be closed in advance of the space operation, limiting the impact to the NAS and its other users while maintaining the high level of safety that the air travelling public has come to expect.

The Columbia breakup raised the awareness of potential hazards to airspace resulting from spacecraft overflight. Together, the FAA and NASA jointly pursued an opportunity to develop an approach that integrated a spacecraft entry trajectory within congested airspace. In doing so, this partnership developed and implemented operational tools and techniques for the remaining Space Shuttle missions and paved the way for future space missions, both government and commercial.

i FAA Aeronautical Information Manual, Federal Aviation Administration, February 2010, http://www.faa.gov/air_traffic/publications/atpubs/aim/

ii NASA Fact Sheet FS-2000-05-30-KSC, "Landing the Space Shuttle Orbiter at KSC", NASA, May 2003, http://www-pao.ksc.nasa.gov/kscpao/nasafact/landinghist.htm

iii 45th Space Wing Instruction 13-201, "Eastern Range Airspace Management Procedures", Air Force 45th Space Wing, February 2000, http://www.e-publishing.af.mil/

iv "Space Shuttle Operational Flight Rules, Volume A - All Flights", National Aeronautics and Space Administration Johnson Space Center, Houston, Texas, January, 2008.

v 14 CFR Parts 401, 406, and 413, et al., "Licensing and Safety Requirements for Launch; Final Rule", Federal Aviation Administration, August 2006, http://www.faa.gov/about/office_org/headquarters_offices/ast/licenses_permits/media/LSRL_25aug2006_06-6743.pdf

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