Space Data Integrator: FAA's Innovative Platform for Launch and Reentry Operations

Laurence H. Mutuel[1]
Sierra Nevada Corporation, Sparks, Nevada, 89434

Daniel P. Murray[2]
Federal Aviation Administration, Washington, District of Columbia, 20591

In response to the predicted increase in frequency and complexity of commercial launch and reentry operations, the FAA must continue its effort to develop integrated capabilities to meet the Administration's objectives and realize the anticipated operational benefits of the integration of these operations into the National Airspace System (NAS). The Space Data Integrator (SDI) platform is such a capability that automates the FAA's currently manual, time-consuming and resource-intensive procedures to support commercial launch and reentry operations. The objectives of the SDI are to allow for extending the operations' planning to include filing a flight plan, to provide situational awareness to the Joint Space Operations Group (JSpOG) at the FAA Air Traffic Control System Command Center (ATCSCC) on the launch and reentry vehicle position and mission parameters during the full operations, and to support the detection and response to abnormal events. The SDI is the result of a non-traditional approach for FAA that is flexible, with high-implementation readiness, directly tailored to the end-user needs, and both low-cost/low impact on existing NAS automation systems. The SDI can be used as a shadow system while continuing to mature, a training tool for the JSpOG personnel, and a familiarization tool for commercial space vehicle operators, spaceport representatives and air traffic control personnel.

I. Introduction

ACTIVITIES in space are typically divided into three sectors: civil, military, and commercial. The National Aeronautics and Space Administration (NASA) represents the civil sector, while the Department of Defense (DoD) represents the military sector. For decades, the Federal Aviation Administration (FAA) has played a critical role in supporting NASA and DoD space launch and reentry operations by ensuring the safety of the National Airspace System (NAS). Using current procedures, volumes of airspace are temporarily closed during these operations, where the size, location, and duration correspond to the type of vehicle being operated, the location of the operation, and the duration of the operational window. In some cases, these closures can span hundreds of miles, cover the full height of the NAS, and last for several hours.

These airspace closures can have significant effects on NAS performance and capacity, imposing delays, excessive fuel burn due to route changes, or even diversions and cancellations on other NAS stakeholders. Nevertheless, the FAA's primary mission of ensuring NAS safety is never compromised, and the cost to other NAS operators has been deemed acceptable in view of the national importance attributed to NASA and DoD-sponsored launches. This critically important role is not expected to change in the near term or beyond.

For over 25 years, the FAA has also regulated the launches and reentries of commercial space transportation. Since 1988, the FAA has licensed or permitted over 250 commercial launch and reentry operations. Generally, the airspace management approach applied to these launches is the same as the approach applied to NASA and DoD launches. Since these operations have been conducted at a relatively low frequency and mostly from Federal ranges, they have, until recently, received little attention from other NAS stakeholders. This traditional role of the FAA is unlikely to change, although it may become more visible to both the legacy NAS stakeholders and the public.

---

[1] Safety Lead, 444 Salomon Circle, AIAA Senior member.
[2] Manager, AST-100, 800 Independence Ave SW, AIAA member.

II. Evolution of Commercial Space Transportation

Recent activities across the commercial space transportation industry indicate that significant growth in commercial space is underway, including commercial operators providing launch and reentry services to the government, space tourism and suborbital science operations. These activities include the successful provision of commercial cargo service to the International Space Station (ISS) by SpaceX and Orbital/ATK, and the recently awarded contract to Sierra Nevada Corporation. SpaceX and Orbital/ATK for providing commercial cargo resupply services. At the same time, prospective commercial launch site operators continue to approach the FAA seeking launch site operators licenses. In each case, the state and local governments are making significant financial investments to advance the development of these sites, in addition to the sizeable resource commitments from space vehicle operators. Furthermore, test flights of suborbital vehicles from Virgin Galactic, Blue Origin, and XCOR Aerospace are anticipated to generate multiple suborbital launches per day from existing spaceports, including Spaceport America in New Mexico, Midland International Airport in Texas, or other sites currently being proposed in Texas, Florida, Colorado, Hawaii, and Alabama.

Due to a number of factors, including public safety in the potential event of a failure during launch or reentry, the FAA must restrict the access of other NAS users to a relatively large volume of airspace for a significant time period. As the commercial launch and reentry operations gain in predictability and maturity, efforts are directed at reducing the volume of restricted airspace and/or the duration of the restriction, with the objective of efficiently managing the NAS. These endeavors entail early coordination between the FAA, the commercial space operator and other stakeholders. This coordination allows for the collaborative consideration of strategies to reduce the effect of the operation on NAS efficiency and capacity, while still providing opportunity for the launch or reentry operator to achieve mission success. Several strategies have been identified for consideration, including adjusting the launch window by reducing its length or shifting its start to avoid air traffic peak times. The resulting gain in NAS availability can be significant, even as the volume of affected airspace remains unchanged. With the potential for increase in commercial space launch and reentry operations, it is imperative that the FAA continue to find ways to optimize NAS efficiency and capacity during these operations[1].

Since 2012, the FAA has continued to improve the management of the NAS during commercial space launch and reentry operations. A small team of representatives from the Office of Commercial Space Transportation (AST) and the Air Traffic Organization (ATO) currently works on a mission-by-mission basis to identify and implement planning and operational strategies to minimize the effect of commercial launch and reentry operations on NAS performance and capacity without compromising the space operator's opportunities for mission success. This team is known as the Joint Space Operations Group (JSpOG) and is hosted at the ATC System Command Center (ATCSCC) in Warrenton, Virginia. Using available tools that were not designed for these purposes, the current efforts are manual in nature, time-consuming and resource-intensive. As a consequence, the existing capabilities are not able to respond to dynamic conditions. The existing tools are not interfaced with telemetry or planning information from the launch and reentry operators, so data transfer across tools and networks is manual and relies on written and verbal communications between JSpOG personnel. Multiple manual checks implement mitigations against human error. As the frequency and complexity of commercial space operations has increased, the FAA team has struggled to keep pace. Nevertheless, the successes of numerous operations has demonstrated the potential for how effectively the FAA can safely and efficiently manage the NAS during launch and reentry operations with the assistance of some near-term process improvements. In 2014, the FAA's Administrator announced his Strategic Initiatives for the agency, including a sub-initiative dedicated to developing technology and infrastructure enabling the integration of commercial space operations into the NAS. This paper reports on the development and testing of a proof-of-concept demonstrator, a decisive and visible step towards the successful integration of commercial space launch and reentry operations into the NAS.

III. Approach to Demonstrating Successful Integration of Commercial Space Transport into the NAS

As part of the FAA's Administrator Strategic NAS Initiatives, the joint AST and ATO team defined a stepped approach to safely and efficiently accommodate commercial space launch and reentry operations in the NAS. The key objectives of efficient NAS management during launch and reentry operations are coined as "Reduce, Respond, and Release". *Reduce* pertains to the amount of airspace that must be blocked in advance of a launch or reentry operation: by using novel planning tools and advanced analysis techniques, the FAA intends to safely adjust the duration and volume of unavailable airspace. *Respond* addresses the capability to predict, detect and mitigate risk: the FAA focuses on automating safety calculations and integrating with Air Traffic Control (ATC) via data transfer to monitor and maintain safety during launch and reentry operations, and to effectively respond to contingencies.

Finally, *Release* applies to the timely return of the previously-blocked airspace volume to normal use, once the launch or reentry operation no longer affects it: the FAA focuses on data processing and exchange with ATC to support a more time-efficient release.

The second step, which is the focus of the present paper, was launched in 2015. It aims at automating several of the manual processes currently used by the FAA to monitor launch and reentry operations, and respond to off-nominal scenarios. This step concludes with a demonstration of these automated capabilities. The initial demonstration described in this paper therefore focuses on the capabilities supporting the *Respond* key objective of the FAA's Strategic Initiative.

The primary goals of this initial demonstration are:

- To provide time-accurate data for automated situational awareness;
- To provide the capability to monitor the commercial space launch and reentry vehicle when it transitions through the NAS; and
- To provide the capability to detect and answer to off-nominal situations.

Currently, situational awareness is provided via the manual entry of vehicle position, planned trajectory and launch or reentry-related predicted hazard area information onto an FAA's Traffic Flow Management System (TFMS) Traffic Situational Display (TSD). The awareness of an off-nominal situation is achieved through verbal exchanges over a hotline that connects the air traffic control center which airspace is affected by the operation, the JSpOG personnel on duty, and the commercial space vehicle operator mission control with a dedicated person as interface. Not all operations support telemetry to the ATCSCC, and when available, the mission is also followed via webcasts.

A prototype platform called the Space Data Integrator (SDI) has been specified to meet all of the abovementioned objectives of the initial capability demonstration by:

1) Automating the transmission of launch and reentry vehicle mission state vector information to TFMS automation, including filing an acceptable ICAO flight plan;
2) Developing an Enhanced Space Data Display (ESDD) function to automatically process and display mission information for situational awareness, monitoring and detecting abnormal situations; and
3) Automating the transmission of state vector information into the safety analysis tool called Risk Range Assessment Tool (RRAT) to decrease the time lapse between the detection of an abnormal scenario and the provision of safety guidance to address the situation.

In addition, the demonstration platform's architecture inserts itself into the FAA's process flow for integrating new systems into the NAS, so that the SDI can more easily transition from a prototype capability to an operational system. The FAA intends to use the SDI to support current and upcoming operational scenarios, including those associated with NASA's Commercial Resupply Services (CRS) Program, designs with fly-back boosters, inland reentries from orbit including those associated with NASA's Commercial Crew Program, and other complex mission designs that are submitted to FAA's AST.

The current constraints on existing FAA automation capabilities and communication networks have led to the definition of a complex distributed architecture with SDI components installed within the TFMS Processing Center (TPC) at the FAA William J. Hughes Technical Center (WJHTC) in Atlantic City, New Jersey, and in the Event Management Center (EMC) at the ATCSCC in Warrenton, Virginia. Additionally, FAA AST Safety Analysis and Training Laboratory (SATlab) at FAA Headquarters in Washington, D.C., is provided with an additional user-interface and mission monitoring capability. Figure 1 sketches the distributed SDI architecture. Three TFMS Remote Sites (TRS) provide access to a TFMS Auxiliary Platform (TAP) for the insertion of the launch and reentry vehicle flight plan and track information. All TRS workstations also include a TSD on which the user can input representations of the airspace restrictions. The platform is distributed over three networks as detailed below.

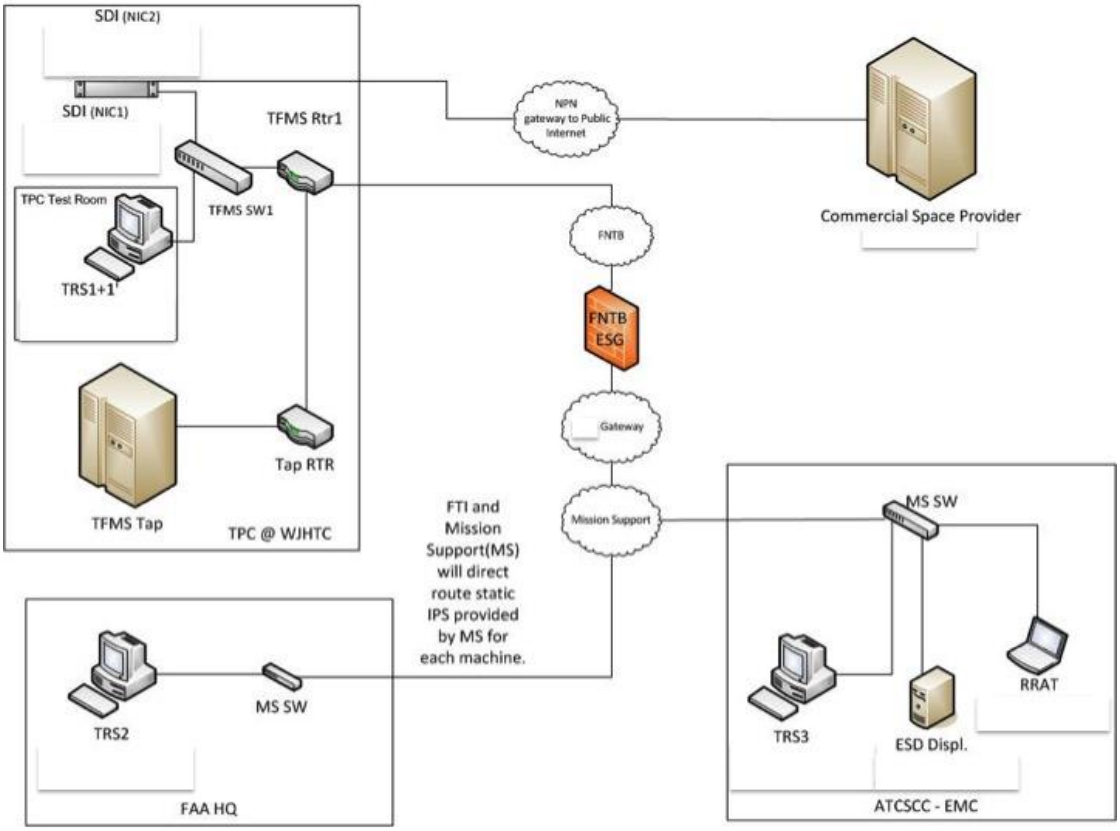


Figure 1. Space Data Integrator distributed architecture.

A. Integrating the SDI within FAA Infrastructure

Each element of the demonstration system architecture has been selected to support continuity with the current concept of use by ATO and AST personnel, while allowing the safe integration of new information needed to support the launch and reentry operations. Accommodations have been made and documented, so that the current systems may be modified at a later date.

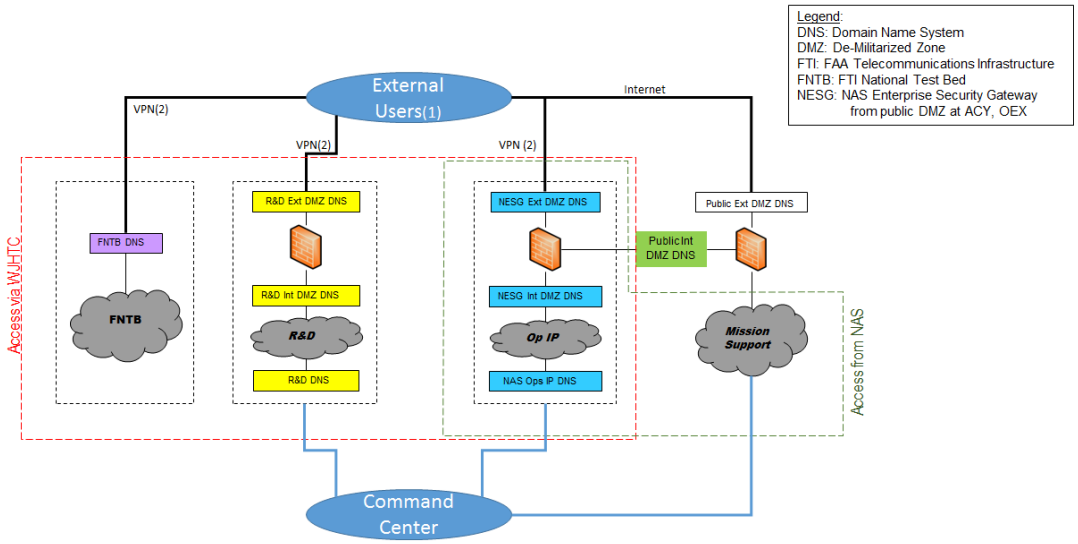
1. Network Infrastructure

The demonstration platform design phase consisted of a series of trade studies leading to design decisions based on the following constraints:

1. The demonstrator cannot interfere with the FAA operations;
2. Any data provider external to the FAA must access the FAA network infrastructure via existing secure gateways;
3. The intellectual property of the commercial space launch and reentry vehicle data must not be compromised;
4. The FAA's current automation capabilities and interfaces cannot be modified.

By integrating these constraints into the SDI design definition, the resulting platform achieved technical and implementation readiness levels beyond that of traditional proof-of-concept demonstrators for which the TFMS software had been modified from its operational baseline. The FAA maintains three types of network, each supporting a different implementation readiness. The NextGen Prototyping Network (NPN) supports FAA's NextGen research and development (R&D) activities. The NPN is hosted and managed by the FAA WJHTC and accepts connections from entities outside of the FAA through a secured gateways. The FAA Telecommunication Infrastructure (FTI) National Test Bed (FNTB) is the network used by all systems to demonstrate technical readiness before being deployed into the NAS. It is segregated from the operational network but has the same characteristics and provides access to automation systems. The third network is the operational network (OPIP). NAS systems

typically transition from NPN to OPIP through FNTB, as they meet readiness milestones. Figure 2 is a conceptual illustration of the above networks and access points. The fourth network is the Mission Support (MS) network that carries the non-essential and non-operational activities (e.g., email, internet, intranet, administrative services).



(1) External users include public, NASA, DoD, airlines...
(2) VPN network are site-specific

Figure 2. Conceptual illustration of FAA network structure.

Use of, or even access to, the OPIP is prohibited by constraint #1. A demonstrator cannot risk impacting the NAS operations. The commercial space launch or reentry vehicle operator is an external entity at the present time from the FAA's standpoint. The connection to the FAA network infrastructure is therefore made through the NSG to the NPN. The SDI must ingest the launch and reentry vehicle data and submit the information in the appropriate interface format to the Air Traffic Management (ATM) automation that is connected on the FNTB. Therefore the SDI must be a node on both the NPN and the FNTB networks. Finally, the MS network is currently the only network with wired ports in the EMC.

2. ATM Automation

For the initial phases of the project, the targeted FAA automation system to insert the launch and reentry vehicle within NAS traffic is the TFMS. While operational TFMS is on the OPIP, and therefore inaccessible to the demonstration platform, four TFMS Auxiliary Platforms (TAPs) exist that are not on the OPIP and they are accessible at the WJHTC for specific purposes (e.g., backup, research, system transition, or maintenance). A TAP manages flight plan and track data for all active flights in the NAS. The use of the TAP dedicated to research development programs was negotiated with the TFMS program office at the WJHTC. Constraint #4 prohibits changes to the TFMS and therefore to the TAP. During the evaluation of the SDI, specific behaviors of the TFMS were identified as potentially erroneously misleading and marked as candidate for improvement (see section III.0).

TSDs are used in ATM operations to depict the location, density and movement (flow) of aircraft through the NAS. The aircraft information consists of a symbol, which form and color is selectable by the operator, a data block, and route. The data block shows flight plan information (e.g., identifier, departure airport, arrival airport) and track information (e.g., ground speed, reported altitude). The route information can be displayed as segments between elements in the flight plan on the display or as the filed flight plan in the data block. The TSD is user-configurable to some extent. To maintain an operational continuity, the TSD is used to display the launch and reentry vehicle information to JSpOG personnel and traffic managers at the ATC centers monitoring the mission. Dedicated human factors sessions identified the elements of the TSD that would need modification to highlight the specificities of launch and reentry vehicles (see section III.G). Figure 3 shows a TSD configured to show the NAS traffic (aircraft icons in white), the airports (cyan 3-letter FAA code), the routes (grey dashed lines), special use airspace boundaries (blue polygons), affected ATC sectors (yellow polygons), predicted reentry hazard area (red polygon) and predicted reentry trajectory (yellow solid line).

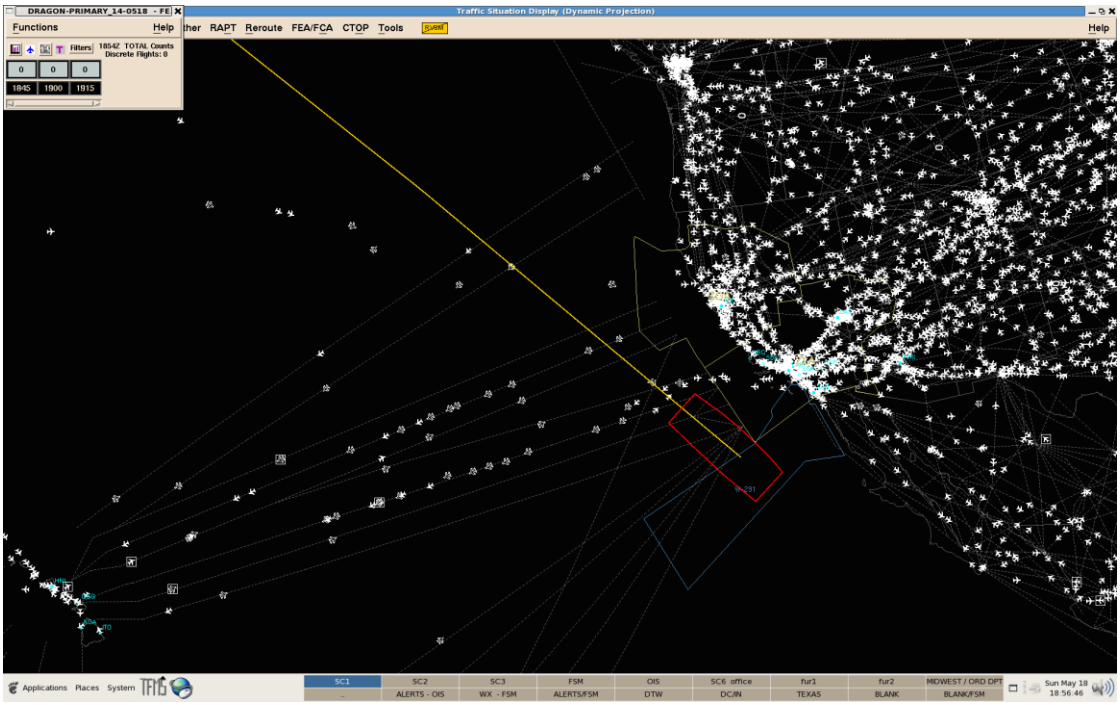


Figure 3. Example TSD configuration.

In a future phase of the project, the FAA intends to complete the flow of data across other ATM interfaces, including the En Route Automation Modernization (ERAM) system and the Standard Terminal Automation Replacement System (STARS), to facilitate tactical air traffic control at the Center ARTCC and Terminal levels respectively.

B. Generating Traffic Flow Data Exchange Messages for Launch and Reentry Vehicles

To meet the interface requirements of the TFMS, a launch or reentry vehicle needs to present itself like the other NAS users. Launch and reentry vehicles are however different from the current NAS users on several levels: their flight dynamics, their equipage, and the trajectories being flown. The constraint of legacy automation interfaces, combined with the launch and reentry operations specificities, complicates the generation of the required messages to be exchanged for flow management.

1. Data Exchanges with the Commercial Space Vehicle Operator

The commercial launch and reentry vehicle operator currently provides data to the FAA by two different means. The mission planning data is provided according to the conditions of the Letter of Agreement (LoA) between the operator and the FAA, required by regulation. The planning information includes the operation's agreed-to time windows (nominal and back-up), nominal trajectory, predicted nominal timestamps of specific events, additional applicable operating constraints, and aircraft hazard areas. In the context of the SDI, the nominal time window and trajectory are used for filing the flight plan (see section III.B.2). Event timers are entered in the SDI to be used for mission monitoring (see section III.C.**Error! Reference source not found.**). Aircraft hazard areas are entered as Flow Evaluation Areas (FEAs) by the JSpOG operator to allow them to be displayed on the TSD.

During the mission execution, the commercial launch or reentry vehicle operator needs to open the point-to-point connection established with the FAA's NPN. During the development of the SDI platform, an interface control document was developed to allow for the FAA to connect with different operators using standardized message formats. The required information is typical of telemetry messages, so that the effort to support the FAA is minimized. The basic data includes identification information (e.g., operator identifier), state vector information, event triggers and status information. The potential for growth resides in the provision of more event triggers and status information, which support the tasks of mission monitoring and response to abnormal situations. In spite of this automated interface, the hotline remains in use for aural communication of verified triggers and statuses, confirmation of event status information, and a backup means for passing critical information. The hotline is

particularly important during periods when the operator expects a loss of signal with the vehicle. During some missions, particularly reentries from orbit, the loss of signal period can last several minutes. During this time, neither FAA nor the operator can receive any telemetered data on the vehicle's trajectory or status. An independent verification of the vehicle's trajectory is also not available, like it would be using primary surveillance radars for aircraft. The FAA uses the hotline to confirm with the operator that the loss of signal was expected, that the vehicle's status going into the period was nominal, and the time at which the acquisition of signal is expected. The operator informs the FAA of reacquisition of signal; the JSpOG operator would then confirm that the data flow resumed using the ESDD. Loss and acquisition of signal are currently only predicted: determining the parameter or combination thereof that would automatically communicate their verified onset could require some development effort for the commercial launch or reentry operator. Software development on the operator's end was purposely kept to a minimum, as the participation of commercial launch and reentry operators in the SDI proof-of-concept demonstration is on a voluntary basis.

2. Selected Interface for Filing Flight Plan

After several discussions with TFMS subject matter experts within the FAA, the design decision was made to file the flight plans and send track messages as an International Data Provider (IDP)[2]. The selection of this interface allowed for a faster implementation using existing TFMS capabilities through the TAP, and a smaller number of accommodations to meet the interface requirements of U.S. En Route Automation (ERA) systems, as modified by the IDP interface requirements. On the other hand, the IDP interface is a one-way data exchange that has limited functionalities, as discussed in section III.B.5.

Note that the FAA is currently on-ramping TFMS data exchanges onto its System-Wide Information Management (SWIM) implementation. The timeline of the TFMS SWIM on-ramping was the last quarter of 2015. Therefore, the current implementation of the SDI system does not comply with SWIM message definition and subscriber/publisher registration requirements. The sunset of the IDP as a result of the migration to SWIM is likely to impact, or precipitate, a change from IDP to a U.S. domestic ERA interface in future development phases of the SDI.

3. ICAO Flight Plan for Launch and Reentry Vehicles

The SDI supplies the ICAO Flight Plan message, or FPL, for the launch and reentry vehicle. Each appropriate field in the FPL is populated based on available applicable data describing the mission. However, several accommodations need to be made when building the FPL for fields with required entries for which there are no equivalent applicable launch or reentry parameters. The FAA provision for submittal of FPL message is 24 hours prior to the Estimated Off-Block Time (EOBT). The first accommodation is therefore the definition of EOBT for a launch and reentry vehicle. EOBT is a time marker associated with motion of the vehicle indicative of commitment to the mission. Although TFMS has built-in flexibility with its handling of the time difference between the EOBT and the receipt of the first track message (indicative of motion), a significant gap between the EOBT in the flight plan and the first track message may result in the flight plan not attaching to the incoming track data of the vehicle. For launch, the EOBT could correspond with the liftoff of the vehicle (T_0 time) from the ground, as the FAA would expect to start receiving data from the operator before this occurs. For reentry from orbit, the FAA expects to start receiving data shortly before the deorbit burn. For this reason, the association of EOBT with an earlier time, such as the time at which the reentry vehicle detaches from the ISS, was discarded in favor of EOBT marking the de-orbit burn start time. For launch, the EOBT is associated with the T_0 time.

The aircraft identification in the flight plan refers to the ICAO designator with a flight identifier, or a registration mark when the aircraft is not equipped with radio. The latter fits the case of a launch and reentry vehicle. In the absence of an existing registration mark, the FAA has chosen to represent the launch and reentry vehicle identification as a three-letter code for the operator, a three-letter code for the mission (e.g., CRS for ISS cargo resupply), and a number representing the flight number. The selected codes for the commercial launch or reentry operator are checked against registered ICAO designators to avoid conflict within TFMS. Using the mission code in the aircraft identifier allows for distinguishing reentry from launch, and suborbital. The main issue is that, based on the aircraft identifier, TFMS makes assumptions on the type of mission, such that an identifier with 6 letters is associated with a military flight, regardless of whether "scheduled air service" is explicitly entered or not as the type of flight. Military flights being handled differently, the aircraft identifier was oftentimes reduced to mission and number during testing.

The flight rules parameter is the next required parameter in the FPL message, indicated by the rules (IFR for Instrument Flight Rules or VFR for Visual Flight Rules) and the type (scheduled air service, non-scheduled service, general aviation, military or other). For a launch, reentry or suborbital flight, the FAA chose to indicate the flight

rules as IFR since the vehicle flies in Class A airspace, for which IFR is the minimum requirement for aircraft (although no similar requirement exists for launch and reentry vehicles). TFMS does not cross-check for coherency between declaring IFR and indicating no Communication, Navigation, and Surveillance (CNS) equipage. There is no type of flight that corresponds to launch, reentry or suborbital flights, therefore "other" is being used. Type of flight is primarily used for filtering purposes within traffic flow, and is optional for domestic flights, so the impact of not being able to be specific is limited to the user's ability to highlight this flight against other active flights on the TSD.

There is no appropriate ICAO aircraft type designator for launch and reentry vehicles. In the flight plan, the FAA chose to use an aircraft type of "other" with the details being provided in the field reserved for other information. TFMS uses the aircraft type to associate with specific aircraft performance profiles but it does not process any information from the optional field 18 "other information". This absence of aircraft type designator for a launch or reentry vehicle is one of the reasons the FAA observed the TFMS erroneously propagating the launch or reentry vehicle position in the absence of track message during a loss of signal period, or why it automatically assumes a holding pattern based on a vertical launch or reentry profile, leading to erroneous symbol display on the TSD. During testing, all attempts to circumvent this issue still led to erroneous interpretations from TFMS that the user could not correct. With the removal of the designator code for Concorde from the list of available codes, the only remaining code for a supersonic vehicle is that for SR71. When this type designator is entered, the performance profile is a better fit for horizontal velocity but still not adequate and the flight is automatically tagged as a military flight. The appropriate solution would be to create new performance profiles used by TFMS for the launch and reentry vehicles and add them in the U.S. adaptation, so that there is no need in the medium term for an ICAO designator. This work requires cooperation between the FAA and the launch and reentry vehicle manufacturers.

The wake vortex category is entered based on the definitions for aircraft, although the launch and reentry vehicle do not generate wakes in the way fixed wing aircraft do. Their trajectory is also significantly different that the use of a wake vortex category as it relates to ATC separation minima should not apply. The FAA chose to set the wake category for the reentry vehicle to "light" based on its mass at de-orbit burn start, while the wake category for the launch vehicle is set to "heavy" based on its mass at launch. Note that the wake category in the flight plan does not allow for in-flight transition between categories, but launch vehicles will see their mass drastically change as they shed stages. Finally, a wake category of heavy allows for additional filtering capabilities on the TSD.

Equipment and capability is a very relevant field in the flight plan. Currently, there is no ATC equipage mandate that is levied on the launch and reentry vehicle, even as it transitions through classes of airspace where there are mandates for airplanes, such as Mode S transponder or Automated Dependent Surveillance – Broadcast (ADS-B). The launch and reentry vehicle is cooperating via the satellite-based tracking system capturing its telemetry, but it is not collaborating with ATC in the traditional sense as the communications are routing via the operator's mission control. The FAA is conducting research on developing ADS-B solutions for launch and reentry vehicles[3], in anticipation that a surveillance mandate could be eventually levied. The information entered in the flight plan is thus "N/N" to indicate no capabilities for radio-communication, navigation and approach aid, and no surveillance. As explained earlier, this indication is taking advantage of the absence of coherence check against the flight rules and the classes of airspace.

The next information items that require adaptation are the aerodromes. The difficulties are two-fold: the departure aerodrome of a reentry vehicle is only defined by a position, as it is associated with the EOBT and corresponds to the de-orbit burn start. The departure aerodrome for a launch vehicle may have a U.S. location indicator (or ICAO indicator) for established launch sites (e.g., Cape Canaveral, Vandenberg) or airport (e.g., Mojave, Midland). Using the IDP format, however, prohibits the use of U.S. or Canadian departure aerodrome indicators. For arrival aerodromes, the IDP allows U.S. or Canadian indicators, which supports suborbital flights or in-land reentry. For reentries that involve splashdown, the arrival aerodrome indicator is a position. When the aerodrome is defined by a position, the flight plan is filed with "ZZZZ" for the aerodrome and the location (latitude/longitude) is entered as additional information in the field 18. There are several issues with the aerodrome information and how it is handled by TFMS. If the first track message received indicates a position that is far (e.g., over 150Nm) from the departure aerodrome, then the flight plan may not attach to the incoming track data, in spite of the flight identifier being unique for 24 hours and the same between the flight plan and the track message. If the departure and/or arrival aerodrome information is not specific enough, the planned route cannot be drawn on the TSD: since the TFMS does not process the specific location that is indicated in field 18, using ZZZZ as aerodrome indicators will result in the unavailability of the "draw route" function on the TSD.

The last information item is the route, which includes cruising speed and level in addition to route elements. While cruising speed and level do not make sense for launch and reentry, values must be entered in the flight plan for it to be interpreted by TFMS as valid. These values are only requests to ATC; they do not bear any constraint on

the vehicle to actually meet these values. Therefore, it was arbitrarily decided that the top level of Class A airspace would be selected as the cruising altitude and the corresponding speed when the vehicle crosses the top of Class A airspace be selected as the cruising speed. These values are provided by the launch and reentry vehicle operator in advance of the mission as part of the nominal trajectory. Launch and reentry vehicle trajectories do not follow defined Air Traffic Services (ATS) routes, which are typically identified using a series of navigation fixes. The route elements must therefore be significant points defined by latitude and longitude coordinates in degrees-minute-direction format. The total allowance for the flight plan message is 1,000 characters. This significantly constrains the number of 11-character coordinate points that can be entered in the route portion of the message. In the demonstrator, the FAA determined that 74 coordinate points could be accommodated. To limit the cases in which TFMS does not associate the flight plan with the vehicle track, the first point in the route is set to the coordinates of the departure aerodrome and the last to the coordinates of the arrival aerodrome. For the needs of the initial demonstration, a simple algorithm extracted the remaining 72 points from the nominal trajectory file provided by the launch and reentry vehicle operator; these points were regularly spaced. The limited precision of the point format poses an issue to trajectories that are almost vertical because the translation to degrees-minutes results, most of the time, in duplicate points that are rejected. For future upgrades of the SDI, a smart algorithm should be developed to select points that are not regularly spaced so that we can make the best usage of the limited allowance in route elements.

Per the Letter of Agreement (LoA) between the FAA and the launch and reentry vehicle operator, predicted nominal data supporting the flight plan are provided up to 5 days in advance of the mission day (e.g., predicted de-orbit burn start, predicted nominal trajectory). The SDI provides the capability to prepare and locally save the flight plan (as well as alternates) before its filing.

4. Track Message for Launch and Reentry Vehicles

The SDI supplies the NAS Track message, or TZ, for the launch and reentry vehicle. This message is sent to TFMS at the rate of 1Hz, which is the internal SDI rate and a common data display rate in launch and reentry vehicle operations. Note that the raw telemetry data from the launch or reentry vehicle operator is available at much higher rates, up to 10 or even 100Hz. The decision of 1Hz took into account the possibility to overload the TAP with messages while the TSD refresh rate is fixed to about once a minute.

The track message contains the aircraft identifier that matches the one in the flight plan, the vehicle ground speed, the vehicle altitude and the track position coordinates. Speed (in units of knots) and altitude (expressed in terms of flight level) are limited to three characters, meaning that the maximum speed is 999 knots, and the maximum altitude is flight level 999. For launch and reentry vehicles, these values can be exceeded, therefore the SDI must cap the actual values received from the vehicle telemetry data to these maxima. Consequently, the information appearing in the TSD data block does not most of the time correspond to actual values. One recommendation is to extend by one character the allowance or to add a symbol next to the value in the data block indicating a “roll over” of digits or that the actual value exceeds the displayed value. The second option has been proposed as a mitigation if the modification to TFMS value bounds is estimated to be a significant software modification.

5. Limitations

The approach to the development of the SDI platform and its integration within the FAA infrastructure is novel compared to traditional demonstration paths at the Administration, as discussed in section IV. The design decisions that were made allowed the team to achieve an unprecedented level of implementation readiness for a proof-of-concept stage in a very short period of time, as opposed to developing a prototype in an isolated and adapted laboratory environment. As a direct consequence, the implementation required some components to be deviated from their original intended use to accommodate launch and reentry operations. Limitations resulted from this usage.

The main limitation arose from the use of the IDP as interface into the TFMS. When a flight plan is filed in the U.S., the TFMS allows for interaction on the flight plan. This includes the transmission of an acknowledgement of the flight plan from the TAP back to the submitting location, which can help identify any error in the filing, the possibility to modify the flight plan in case of a delay, or a cancellation.

The absence of acknowledgment message was circumvented by the use of a TRS workstation to verify the acceptance of the flight plan. A TRS has indeed the capability to monitor the message traffic through the TFMS into the TAP. After creating a flight plan on the SDI and submitting it, the engineers used the IDP logs on the TRS during both integration and demonstration to verify the flight plan had been accepted, or to refile if an error had been detected but not communicated back. As experience and confidence were gained through testing, this capability became a mere confirmation that filing was indeed performed.

The issue of delay between the predicted time of the launch or reentry and the actual time however was more difficult to address. Launch and reentry operations are susceptible to delays. These delays can manifest themselves in different ways, each different from how commercial air operations are run and therefore from how the original flight plan capability was designed. When using automation messages to address delays, the rule for eligibility to change the flight plan is tied to the time at which the control of the flight plan transitions from the ARTCC to the ATC Tower, typically 30 minutes before the proposed departure time (P-time). Flight data services can be called in most places 24/7 to extend the P-time for up to four hours. The flight plan may be dropped from the system if the flight has not occurred between two and four hours after P-time.

On the other hand, when a launch or reentry operations is planned, a primary window is negotiated with FAA, as well as up to two back-up windows for the following days. Reentries are typically delayed to the next window opportunity on the following day; this next opportunity will be described by a new trajectory file provided by the launch or reentry vehicle operator. In this case, the flight plan would have to be re-filed with the new date, departure time and route. Less likely, a reentry change can move up or postpone the scheduled committal to reentry significantly enough that a change in the flight plan would be needed. The IDP interface does not support the flight plan change message. The JSpOG operating the SDI would have to resubmit a flight plan with a modified aircraft identifier to avoid a duplicate flight plan that would be rejected by the TFMS. This scenario never presented itself during testing, although the operator was trained to submit flight plans within 15 minutes of the scheduled departure (i.e. liftoff or deorbit burn) time. Finally, in case the amended flight plan cannot be submitted in time into the system, the result is that the flight plan would not attach to the launch and reentry vehicle at reception of the first track message because of the difference with the scheduled departure time and potentially because of the difference in initial position.

These limitations are expected to be resolved once the interface between the FAA automation systems and the launch and reentry vehicle is transferred from IDP format to U.S. domestic.

C. The Space Data Integrator (SDI) Platform

The SDI was developed by Millennium Engineering and Integration Corporation (MEI) of Satellite Beach, Florida, under contract from the FAA. The SDI builds on the capabilities of MEI's Joint Advanced Range Safety System (JARSS) Configurable Real-time Environment (CoRE™) system that is currently used by the US Air Force, NASA, and other government customers.

The SDI performs three functions during the pre- and post-mission execution phases:

- Provide flight planning capability in compliance with ICAO and FAA procedures;
- Provide mission management capability, including logging of mission information; and
- Provide support to familiarization training.

The SDI performs three functions during the mission execution phase:

- Provide automated situational awareness;
- Monitor launch and reentry missions from the time the telemetry is established from the launch and reentry vehicle to the nominal termination of the telemetry flow, including the full transition through the NAS; and
- Allow for detection and response to abnormal events.

The logical functions of the SDI include:

- Interfacing as the user-entry node for flight planning, including the submittal of an ICAO flight plan;
- Interfacing as the entry node with the launch and reentry vehicle telemetry data, processing the incoming data messages, parsing it, and converting it for use by the demonstration platform subsystems: the TRS and the RRAT;
- Routing the information through the demonstration platform networks;
- Computing additional mission information for display to the JSpOG personnel;
- Logging and restituting mission configuration and execution information.

The SDI user-interface, known as ESDD, was developed as a usage-specific multi-window web-based application, as a result of several design meetings with JSpOG personnel representing the end-users. The ESDD supports flight planning via the mission configuration capability, flight monitoring via maps providing situational awareness in a complementary manner to the TSD, and alerting via a series of status lights and event monitors. An additional window dedicated to the communication with the RRAT operator was designed as both contingency and reversion in case of a network loss between the ESDD operator position and the RRAT operator position.

Figure 4 shows the ESDD mission configuration. The top-left panel contains the mission identification information, including its operator-defined name, type (e.g., launch or reentry, operator, vehicle), source for the data

(e.g., a live streaming connection or a data file), the drag model to be used for the impact point calculation, and the capability to browse for the nominal trajectory file. The bottom-left panel covers the configuration of the events. The events are fully customizable for the mission, including their number, name, date and time-related tolerance. The panel on the right side addresses the ICAO flight plan parameters (see section III.B.3); for each, the entry of flight plan information is checked against validity rules. The route can be entered manually, however, simple text files were used to limit human error. Once the entry is completed for all panels, the mission is created in the SDI database. The mission configuration is then verified, before the operator clicks the "submit" button to file the flight plan with TFMS.

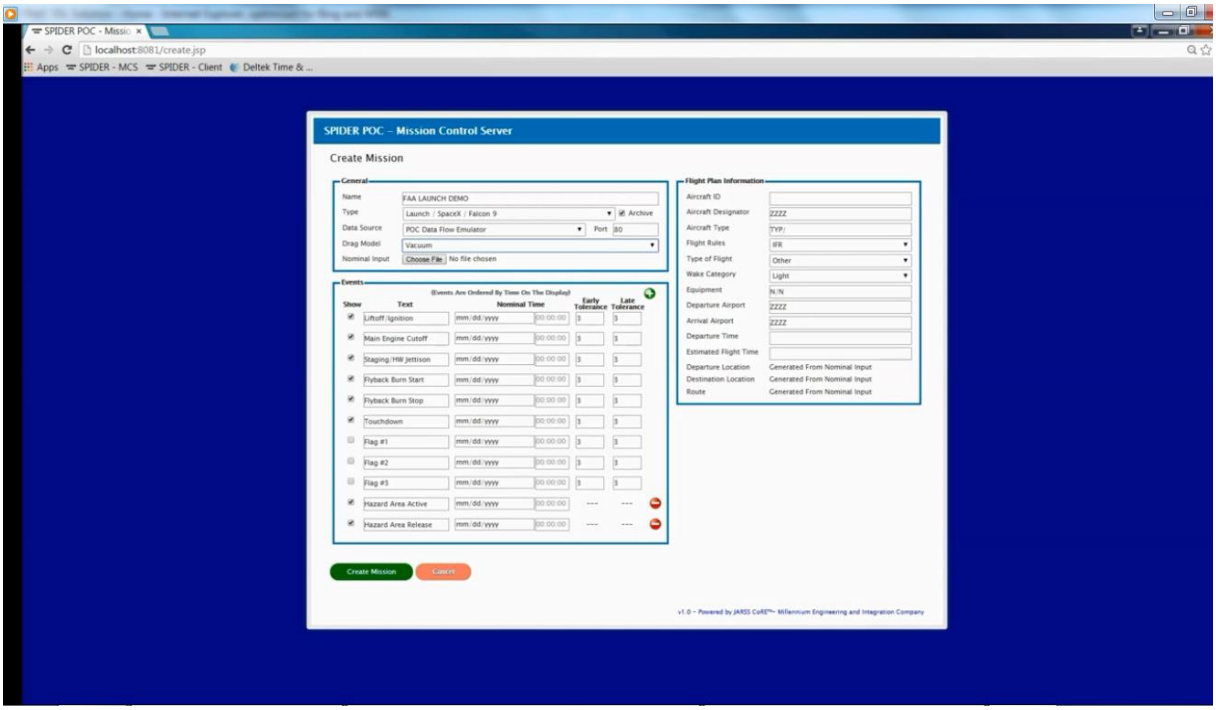


Figure 4. ESDD mission configuration window.

Figure 5 shows the multi-window configuration of the ESDD for mission monitoring, and detection of abnormal conditions for a reentry operation. The left-side blue vertical band concentrates mission identification, mission status and system action buttons. The event list shows the times entered in the mission configuration window as predicted, while the event triggers in the live data feed populate the actual times. When the actual time matches the predicted time within a prescribed tolerance, the event turns green. Discrepancies (lateness or earliness) in these times change the color of the event to red. Two status lights report on the connectivity to the launch and reentry vehicle operator: one for the status of the link and one for the connectivity to the vehicle. The latter turns red when the signal from the vehicle is lost. The lower window titled "generated for RRAT" displays the state vector that is required as input to the RRAT. On the upper right side of the ESDD, a map displays the launch or reentry vehicle trajectory either as a horizontal 2D map with adjustable scale, or as a variable-scale 3D map. The predicted trajectory is displayed in yellow, while the trace of the actual trajectory is shown in blue. Below the map is an altitude versus range plot of the same trajectories. One of the objectives is to achieve maximum coherency between the ESDD and the TSD, until the end goal of merging all information onto one display can be achieved. Figure 5 shows the aircraft hazard areas identical to the FEAs on the TSD. The advantages of the ESDD include the higher fidelity of the mission information, in particular:

- The ESDD is refreshed at least 60 times while the TSD is refreshed once. The JSpOG operator's situational awareness is therefore enhanced in integrity and continuity;
- The ESDD ceases updates the position during loss of signal. The actual discontinuity in the trajectory is visible to the JSpOG operator.

In the future, the ESDD would also be capable of displaying the active flights in the NAS on the map display.

Figure 5. ESDD multi-window configuration for reentry operation.

Figure 6 shows the ESDD multi-window configuration for a launch operation. The red line represents the instantaneous impact point that is associated with the current position of the vehicle.

Figure 6. ESDD multi-window configuration for launch operation.

D. The Range Risk Analysis Tool (RRAT)

The RRAT was developed by ATCA, Inc. of Torrance, California. RRAT provides high-fidelity algorithms for performing risk analysis on events, such as launches or reentries. RRAT includes a visualization capability to perform spatial analyses, and make decision based on the results of these analyses.

The FAA uses RRAT to assess the risk to other aircraft in case of a catastrophic failure of a launch or reentry vehicle at any point along its trajectory. Using the vehicle's last known state vector and other information, the risk is expressed in a series of geo-referenced contours representing the predicted probability of an impact of an aircraft with the debris field associated with the breakup event. To transform this information into information interpretable for ATC operations and actionable for controllers, a box is manually constructed around the risk contours, as shown in Fig. 7.

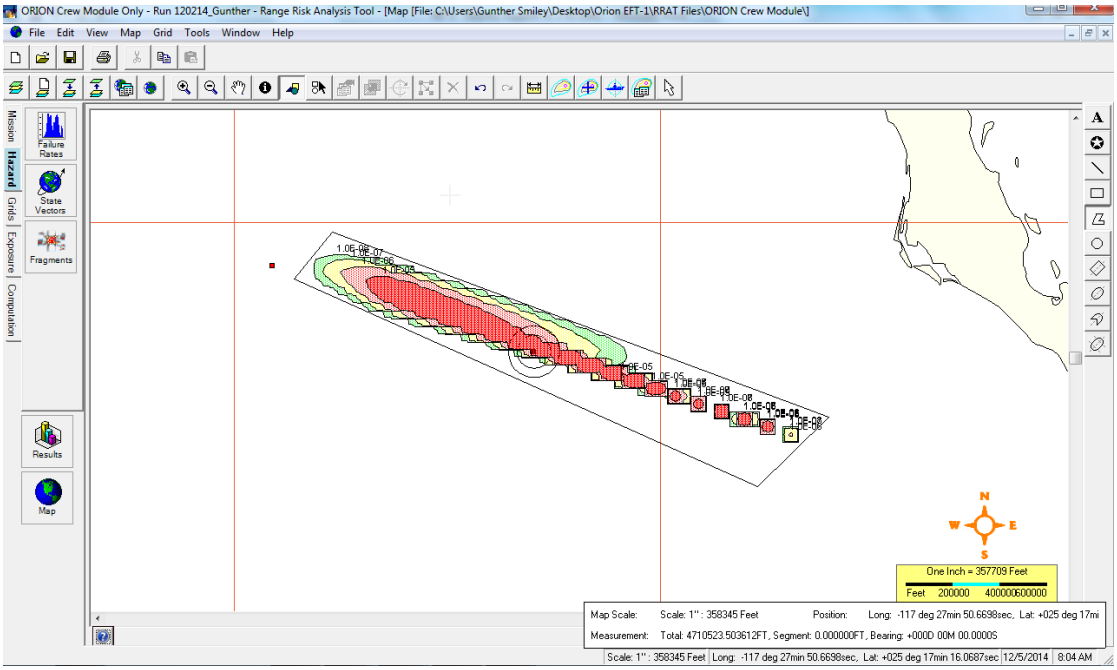


Figure 7. RRAT debris contours and box overlay for Flow Evaluation Area.

The coordinates of the box are saved in a text file that is automatically transferred to a TRS and translated into a FEA, and entered in the TSD for display to the JSpOG operator. Once it is entered in the TSD, the FEA is available for recall on other controller's TSD so that aircraft can be vectored away from the area, if necessary. During the planning phase of the launch and reentry operation, FEAs are entered by JSpOG personnel to identify predicted aircraft hazard areas (AHA) in nominal operation, such as a splashdown area.

E. Initial Capability Demonstration

The demonstration platform, as sketched in Fig. 1, is composed of the SDI, the ESDD, three TRS workstations, with three TSDs, and a laptop hosting the RRAT. A TRS interfaces directly with a TFMS hub or TAP. The TAP manages flight plan and track data on all active flight plans in the NAS. By using the TRS, a flight plan was inserted into the TAP as if it were submitted by an International Data Provider, while track messages were inserted into the TAP as if they were coming from surveillance means (radar or other). All necessary formatting, converting, and validating was performed upstream, so from the TAP's perspective, the launch and reentry vehicle was no different from the other NAS users.

1. Phased Integration and Verification

The elected non-traditional approach to favor implementation readiness and therefore to develop a proof-of-concept platform around the operational needs of the end-user generated complexity in the architecture. The connectivity map to the FAA infrastructure is the most visible element of that complexity. The integration and verification approach was driven by a stepped integration that moved the platform from a centralized architecture to its final distributed form.

The first stage was to integrate all components of the SDI platform at the FAA WJHTC, where the NPN and the FNTB network are hosted. This configuration was known as the local configuration. The SDI laboratory was setup in the room next to the TFMS operations room, which proved useful when manually transferring NAS information from the OPIP to the FNTB in support of testing and demonstrations, or when requesting subject matter expertise to monitor the traffic through the TAP on days where delays were abnormally high (see section III.0). The SDI server was installed in its final location in the TFMS rack room adjacent to the SDI laboratory. A physical connection was drawn between the NPN integration laboratory and the rack room. All three TRS were installed and integrated in the SDI laboratory: final location for the TRS#1 and temporary location for TRS#2 and TRS#3. Finally, the ESDD was connected to the SDI and installed in the SDI laboratory as a temporary location. The FNTB requires that connections be defined point-to-point and port-to-port. The SDI platform IP map was drawn in collaboration with the FTI team and FAA IT security office.

The second phase was to keep all components in the SDI laboratory at the FAA Technical Center, but to emulate the external Mission Support network, including the secured gateway. This intermediate step was designed to evaluate the SDI performance on the FAA Mission Support network while keeping all hardware collocated for the eventual troubleshooting. The ESDD, the RRAT laptop and TRS#3 are the hardware elements which final location is at the ATCSCC in the EMC room. The FTI team at the FAA WJHTC provided the mapping to a virtual mission support network via a local NAS Enterprise Security Gateway (NESG). The test series performed after the platform was integrated in its local configuration were re-run as non-regression. The network loading was measured on the virtual Mission Support network to confirm the absence of impact from the SDI data exchange flow. The SDI laboratory at the WJHTC is shown in Fig. 8 as it configured was for the first demonstration, the SpaceX Dragon CRS6 reentry mission.

Figure 8. SDI platform setup at FAA Technical Center.

The last phase was to distribute the platform elements to their final location: ESDD, RRAT laptop and TRS#3 to the ATCSCC, and TRS#2 to the FAA HQ SATlab. Prior to physically shipping the hardware components, FAA Security had to perform a scan to verify compliance with FAA policy. This is mandatory for all non-FAA hardware installed on FAA networks not designed for research. Non-compliances detected by the scan were addressed by

applying the recommended software patch or setting restrictions on the software. In addition, the SDI platform use of the Mission Support network was a design decision based on the convenience of using existing connections at the ATCSCC; the Mission Support network is not designed to support demonstration activities. Therefore, precautions were taken at hardware and software level to show no impact of the SDI components on the normal use of the network. This required a joint effort between FAA AST and ATO, the network security teams at the WJHTC, the ATCSCC and Headquarters, and FTI support team. This level of collaboration was novel in many ways, including from the project's scope and use of network, from the variety of physical locations, and from the FAA internal procedures. In addition, the ATCSCC and the SATlab were surveyed prior to the shipping, so that specific ports could be enabled. All but one port were already wired, and only had to be opened and authorized for specific data flows. After the equipment was installed and the final IP addresses collected and provided to the FTI team for routing, integration and verification tests were repeated as non-regression.

2. CRS6 Reentry

Launch and reentry missions were not too numerous between the first time the SDI platform was ready for validation testing and the objective to complete the proof-of-concept demonstration before the end of the fiscal year. From its outset, SpaceX participated in the SDI development initiative as an industry partner, providing vehicle operator expertise, external network connectivity assistance, data sets for testing, and opportunities to simulate live missions through the flow of simulated data. With SpaceX's assistance, the CRS6 mission reentry was elected as an initial end-to-end 'shakedown' of the SDI platform at the FAA WJHTC with the virtual Mission Support network. The JSpOG team provided mission support in the traditional way from the ATCSCC, while a dedicated team of engineers shadowed from the WJHTC SDI laboratory.

The SDI team joined on the mission hotline for situational awareness and to collect the aural annunciations of the events occurring, as reported by the reentry vehicle operator, SpaceX. Technical exchanges between the FAA WJHTC and the ATCSCC EMC were supported by live chat capability on dedicated laptops, additional to the setup. The datalink provided by SpaceX to the ATCSCC EMC was rebroadcasted to the WJHTC as shown on the upper right side of Fig. 8. To provide an idea of the mission information display on the ESDD to the ATCSCC support team, the ESDD screen was rebroadcasted in real-time to the EMC using a dedicated laptop, partially shown on the upper left side of Fig. 8. This complex setup allowed the early socialization with ATCSCC JSpOG and ATO personnel with the additional information that the ESDD brings to enhance the JSpOG support to the reentry operation. Finally, the TSD information, shown in the central large screen in Fig. 7 was shared between the WJHTC (shadow) and the ATCSCC EMC (live). Both the operational and the shadow systems displayed the predicted aircraft hazard areas. In addition, the shadow system displayed the predicted nominal trajectory on the TSD. This trajectory was entered as a replacement to the inability to draw the route from the TSD tools. The notable difference was that the SDI updated the vehicle position on the TSD at the WJHTC while it was manually entered to show on the TSD at the ATCSCC.

Per the procedure, the CRS6 flight plan was successfully entered in the WJHTC shadow system within the 24h window. The ESDD showed the nominal sequence of event timers, while the difference between the predicted and the actual onsets of each event was recorded manually for comparison. The CRS6 reentry was uneventful, it allows thus to collect data on the use of the SDI in favorable conditions. This mission marked a significant milestone in the development of the SDI platform and the demonstration of its capabilities; it was also the first time the vehicle icon was displayed on a TSD with the active flights in the NAS.

Later, the type of information that can be entered on the TSD was expanded to included planning for delayed departure time (i.e., de-orbit burn start time) as shown in Fig. 9. Additional FEAs were created to account for late or early de-orbit burn start times.

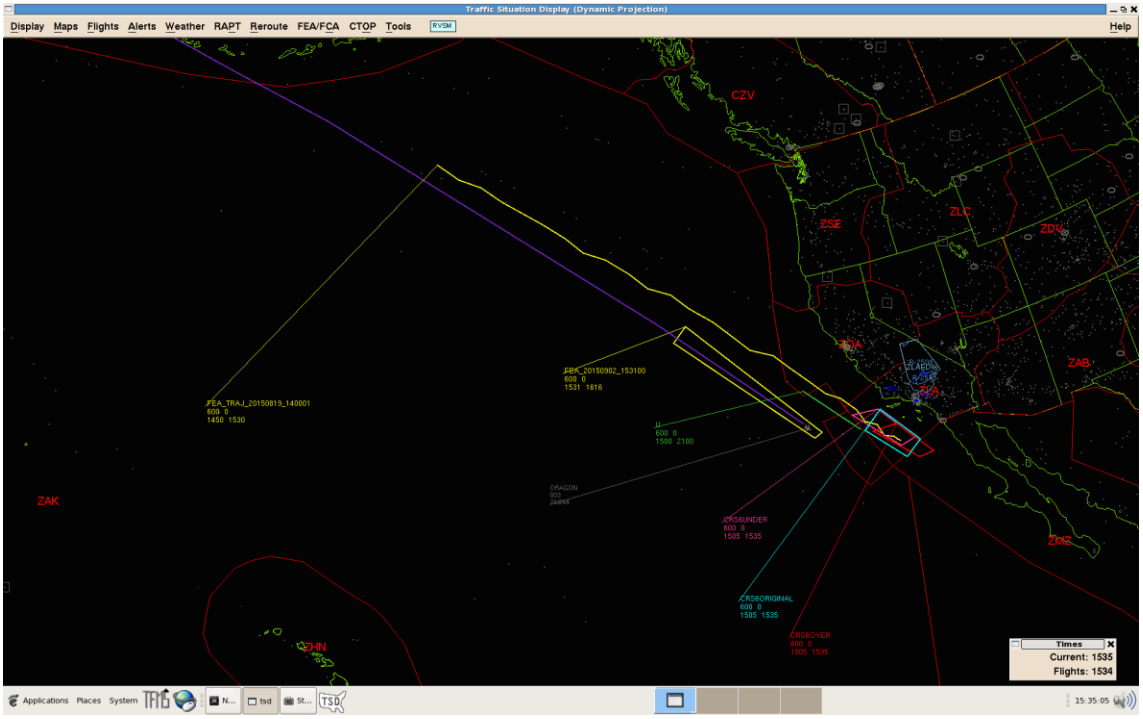


Figure 9. Traffic Situation Display for CRS6 including trajectories and hazard areas.

Figure 9 is a simulation of CRS6 reentry showing additional information as part of operator evaluation exercise. Using the TSD FEA functionality, the portion of the predicted nominal trajectory transiting through the NAS is shown with a solid yellow line and the predicted nominal splashdown area is displayed in cyan. 'What-if' scenarios of the de-orbit burn start being late or early lead to the definition of two additional splashdown areas, displayed in pink and red. There is operational benefit to having these 'what-if' areas ready for the JSpOG operator to activate and communicate to the ATC facilities. In this simulation, the actual trajectory of the Dragon capsule (the solid purple line, with the actual vehicle position shown in grey) deviated from the predicted nominal trajectory, so that a new FEA for splashdown had to be created from the RRAT on-the-fly. The result is shown as a yellow solid polygon that was disseminated to ATC as part of the scenario. This example is meant to show the versatility of use of the FEA functionality in both planning and execution.

3. Exercising the SDI Capabilities

Based on nominal trajectory files developed by FAA AST analysts, the SDI engineering team started producing mission files to exercise the SDI and demonstrate its applicability to the variety of mission types in use today and expected in the near term. Demonstrations using these data sets build confidence in the system and allow for operational feedback to the SDI developers. The SDI initial design was specified for reentry; using launch trajectories and suborbital flight trajectories was necessary to develop the requirements for the next SDI software update. In addition, all files were built not only to contain the trajectory information, but also the event timers. This capability later allowed for the operational evaluation of the SDI (see section III.G).

By the end of the fiscal year, the database of launch, reentry and suborbital flights was a good starting point for covering different vehicle dynamics and geographical locations, as illustrated in Table 1.

Table 1. List of available FAA-generated mission files.

Operation	Description
Launch	Orbital Sciences/ATK Antares launch from Wallops Island
Launch	SpaceX Falcon 9 launch from Cape Canaveral
Launch	SpaceX Falcon 9 first stage flyback launch from Vandenberg Air Force Base
Launch	United Launch Alliance Atlas 5 launch from Vandenberg Air Force Base
Launch	Blue Origin suborbital flight from West Texas Launch Site
Launch	Scaled Composites SpaceShipTwo suborbital flight from Mojave spaceport
Launch	Scaled Composites SpaceShipOne suborbital flight from Mojave spaceport
Launch	XCOR suborbital flight from Midland spaceport
Reentry	NASA Space Shuttle reentry example trajectory
Reentry	NASA Orion EFT-1 reentry
Reentry	SpaceX CRS6 Dragon reentry
Reentry	SpaceX Dragon C2 reentry

Collaboration with the commercial space operators and the spaceports is expected to further the development of mission files that can be used for mission rehearsal or familiarization, operational evaluation, or training. The SDI platform requires a minimum advance notice, typically less than one hour, to be turned on and usable. Moreover, each mission is recorded and is therefore immediately available for replay.

Figure 10 shows the ESDD for a FAA-generated data file of a Blue Origin suborbital flight. One of the objectives of this scenario was to validate the ESDD usability for trajectories where the departure coordinates and the landing coordinates were significantly close (within 1.5 Nm). The ability of the SDI to adapt to the very varied scales (horizontal and vertical) of the flight profiles was a key requirement derived from such validation exercise.

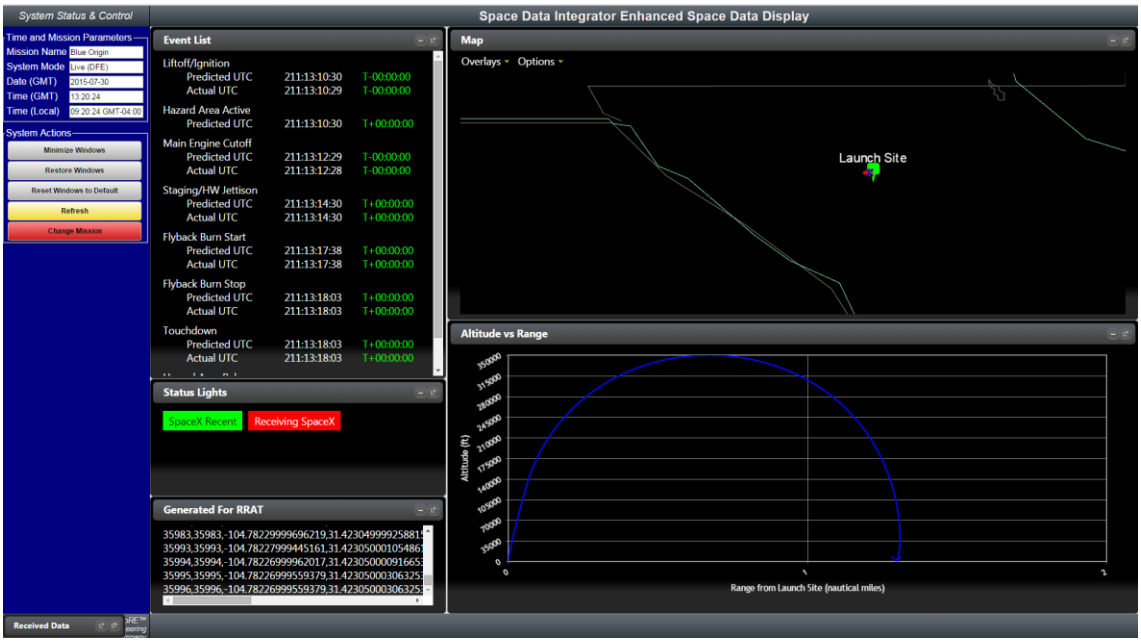


Figure 10. Example SDI configuration for simulated Blue Origin suborbital flight.

F. Challenges Related to the Automation

1. Handling Loss of Signal or TFMS Coasting Capability

During a reentry, the telemetry signal from the vehicle will be lost for a predicted time window that can be several minutes long. During that time, the displayed position of the vehicle on the TSD will only be predicted but not verified in the absence of data. The Loss of Signal (LOS) and the Acquisition of Signal (AOS) are predicted timed events in the mission information provided to FAA. As a direct consequence of the reentry vehicle's telemetry no longer being transmitted, the SDI no longer receives message updates. In the absence of track messages, the TFMS will (1) continue to propagate the position based on assumed vehicle dynamics that are not the reentry vehicle's (see section B.3) and (2) stop displaying the vehicle icon on the TSD after a certain number of update cycles without new track message. Both situations are undesired.

From the reentry operational standpoint, the desired behavior to be displayed on the TSD would be that the reentry vehicle icon remained in a static location with a specific symbology indicating no signal is being received. Several strategies were investigated to obtain this behavior. Unfortunately, none was successful in preventing TFMS from erroneously propagating the position information. For example, if the last known state vector is repeated by the SDI in the track messages, the messages are discarded before reaching TFMS as being redundant (same position information) and thus TFMS keeps propagating the position.

An acceptable compromise would be for TFMS to propagate the reentry vehicle position based on accurate dynamics. This requires the generation of TFMS adaptation for a vehicle type and dynamics profile, but does not require modification to the TFMS software.

2. TFMS Latency

During the integration and testing phase of the SDI platform, delays were captured as a major source of erroneous situational awareness. The launch and reentry vehicle telemetry rate was set to 1Hz, although 10Hz is not uncommon. The downgrade was decided to avoid overloading the TFMS and TAP with track messages. However, when considering the speed range of a launch, reentry and suborbital vehicle, an update of 1Hz can lead to significant changes between two positions.

The current update rate for the TSD is once per minute. This rate is acceptable for an intended use of situational awareness based on commercial air transport flight dynamics. In addition to the TSD update rate, TFMS performs batch processing on an average of 20 seconds; it is impossible to accurately predict which of the 1Hz position message will be selected by the TFMS processing software. Finally, for a single vehicle, the worst case delay between the reception of the state vector information by the SDI and the display of the launch, reentry or suborbital vehicle position on the TSD is about 80 seconds.

This delay is worsened by the amount of traffic messages to be processed. During the first series of testing, the increase in the number of active flights as the day progressed was clearly correlated to an increase in the overall delay. This delay reached up to 4 TSD cycles (or 4 minutes) on several occasions. A welcome improvement occurred following a software update (or 'refresh') of the TAP to significantly improve its performance. The demonstration platform was connected to a refreshed TAP #4 so that the delay creep with the number of flight was significantly reduced from about 4 TSD cycles to one or two.

3. Other TFMS Assumptions

Several TFMS automated features generated misleading display of the launch and reentry vehicle on the TSD. When the LOS period extends beyond 5 minutes, the TFMS stopped propagating the reentry vehicle position icon on the TSD and 'dropped' the target. Most predicted LOS periods in the reentry trajectory files had a duration in excess of 5 minutes. The reentry vehicle icon – after being erroneously coasted for 5 minutes – would therefore disappear. After the signal was reacquired and track messages restarted flowing to the TFMS, one or two additional display cycles occurred before the vehicle target icon reappeared on the display. The delay has been evaluated by JSpOG operators as inappropriate for situational awareness and mission monitoring. In the event of an unexpected LOS, this delay is even more critical as it directly impacts the ability to timely provide a response to this abnormal situation.

Another automated feature that cannot be adjusted by the system user covers the symbol used when 'aircraft' is selected for the target on the TSD. Based on the horizontal distance between two consecutive track message updates, the TFMS may assume that the aircraft is in a holding pattern (represented by an oval track) or is in motion (represented by an aircraft symbol). In addition, heading is deducted from the position information in the track message, not by using the actual heading information from the vehicle. As a combination result of the reentry and launch, or suborbital, vehicle track message processed by TFMS, the target icon would change to holding pattern

especially in the more vertical portion of the reentry (e.g., Orion's FT-1 almost vertical path to splashdown, the climb to altitude of SpaceShipTwo), or would indicate an erroneous heading (e.g., with up to 90 degree error). The recommendation is to allow for an adaptation of the selectable vehicle icon on the TSD and to input specific flight dynamics profiles. In addition, the icon would change appearance during LOS periods, in a similar way to aircraft icons being hollowed when not in radar coverage. Other symbols that showed automatically, such as RVSM non-compliance should be removable based on the adapted launch and reentry vehicle profiles.

G. SDI as a Familiarization and Training Tool

The user interface of the SDI is being hosted at the FAA ATCSCC, where the JSpOG supports commercial space launch and reentry operations from the EMC. After validation of the SDI platform, the natural next step was to develop evaluations centered on the human processes. The SDI is developed to support a two-person team: a JSpOG operator whose role is centered on the performance of the mission and the safety of the other NAS users and a FAA AST operator whose role is focused on the safety of the mission. This is a significant paradigm shift from the current operations.

1. Evaluations and Training

The SDI capability to ingest data files in addition to live data enabled the development of scripted scenarios to evaluate both key performance indicators on the system but also to shakedown the new procedures. For the execution of the training, two groups were created: the testers who were following the script and answering the JSpOG operators, and the JSpOG operators paired with a RRAT operator. The testers had access to the full scenario, including the nature and schedule of any specific unplanned events, while the operators only had access to the information provided in the briefing.

The key performance indicators related to the system were the same as for the validation:

- The contribution of the SDI to enhancing the situational awareness of the operators;
- The contribution of the SDI to enhancing the mission monitoring capabilities of the operators;
- The detection and identification of abnormal events;
- The support of SDI to the operators' decision making process in response to abnormal events.

The processes to be trained on included:

- The ability to monitor the mission via the ESDD and the air traffic on the TSD with a single operator;
- The coordination between the JSpOG operator and the RRAT operator after the detection of an abnormal event down to the execution of mitigation actions;
- The interaction between the JSpOG operator and the other actors on the hotline, including the ATC centers and the commercial space operator.

Using existing personnel already familiar with the SDI from its validation, the evaluation/training sessions required:

- Testers (on the hotline): one person playing the role of the commercial space operator, one person playing the role of the ATC centers. Depending on the complexity of the scenario, two centers, the spaceport or a launch range could be scripted in the scenario;
- Testers (technical support): one person at the FAA WJHTC is responsible for initiating the data file at the departure time and for monitoring the data exchanges with the TFMS. This person is listening to the testers on the hotline but does not intervene in the scenario;
- Operators (in the EMC): two independent teams of one JSpOG operator and one RRAT operator;
- Test coordinator: one person delivers the briefing, coordinates with the technical support at the FAA Technical Center, captures observations while the scenario is executed, and manages the debriefing. In the event that the tester team is unsure how to address the operators' requests, the test coordinator would provide an answer. Moreover, the test coordinator records the timing of key sequences of events, such as the detection time and the time to respond to the onset of an abnormal situation.

With this makeup, each scenario could be played twice with two separate teams as the operators' teams were not to discuss between sessions. For two months, the weekly evaluations/training allowed to engage with all personnel currently involved. A typical session would involve the following four phases:

1. Briefing with the operators:
   During the briefing, the expected mission planning information from the fictitious commercial space vehicle operator was provided, so that the JSpOG operator could input the mission configuration for the monitoring and flight plan filing, as well as create the FEAs on the TSD.

2. Mission preparation:
   While the JSpOG operator files the flight plan and configures the TSD, the RRAT operator runs through the existing checklist. The hotline is being setup and roll calls are performed per the existing procedure. The new elements pertain to checking the infrastructure and connections of the platform. If any malfunction is detected in this phase, reversion to the corresponding manual procedure is decided between the JSpOG operator and the RRAT operator. For example, loss of connection between the ESDD and the RRAT laptop was detected on several occasions; in this case, the JSpOG operator would read aloud the last state vector displayed on the ESDD and get a readback from the RRAT operator before the state information would be manually entered in the RRAT.
3. Mission execution:
   At departure time, the scenario file is played through the system as if it were live data from the commercial space operator. Common communication protocol is used for either information request or normal scripted annunciations. Part of the evaluation is the insertion of readbacks and the determination of the responsible source for providing clarification on the unplanned event when detected. The scenario concludes when either (1) the abnormal situation is adequately mitigated or (2) the mission is ended.
4. Debriefing:
   Two types of debriefing were used. A "hot" debrief with the operators about 15 minutes after the end of the scenario, and a "cold" debrief wherein the operators would provide their feedback the next day. The debrief included the description of the objectives of the scenario, a step-by-step review of the observations noted by the test coordinator, including timing, and the use of replay as necessary.

The types of scenarios included:

- Unexpected loss of signal;
- Spurious loss/acquisition of signal;
- Missed acquisition of signal after a planned loss of signal;
- Errors in planned event sequence (late events, early events, out-of-sequence events);
- Break-up events;
- Deviations from nominal trajectory (longitudinal and/or vertical);
- Complex trajectories (suborbital flights).

Figure 11 shows the TSD configuration for a scenario based on a suborbital flight out of Mojave spaceport. This scenario played on the complexity of both the vehicle trajectory and the airspace structure (Edwards Air Force Base R-2508), and the multiplicity of affected parties (Los Angeles ATC, Joshua approach control, Edwards Air Force Base). Furthermore, the vehicle's simulated trajectory deviated from its predicted nominal path significantly enough that it exited the confines of the restricted airspace. The refresh rate of the TSD was not adapted to the timely detection of this abnormal event. The JSpOG operator spotted the deviation in the trajectories from the ESDD map and range vs. altitude displays, and started the coordination with the testers playing the launch vehicle operator and the ATC facilities. However, the precise depictions of the airspace structure as well as the connectivity with the RRAT are only available on the TSD. The intention to merge the detailed and tailored information for the operation with the NAS specific information and access available via the TSD and the TRS would be beneficial in this type of scenarios.

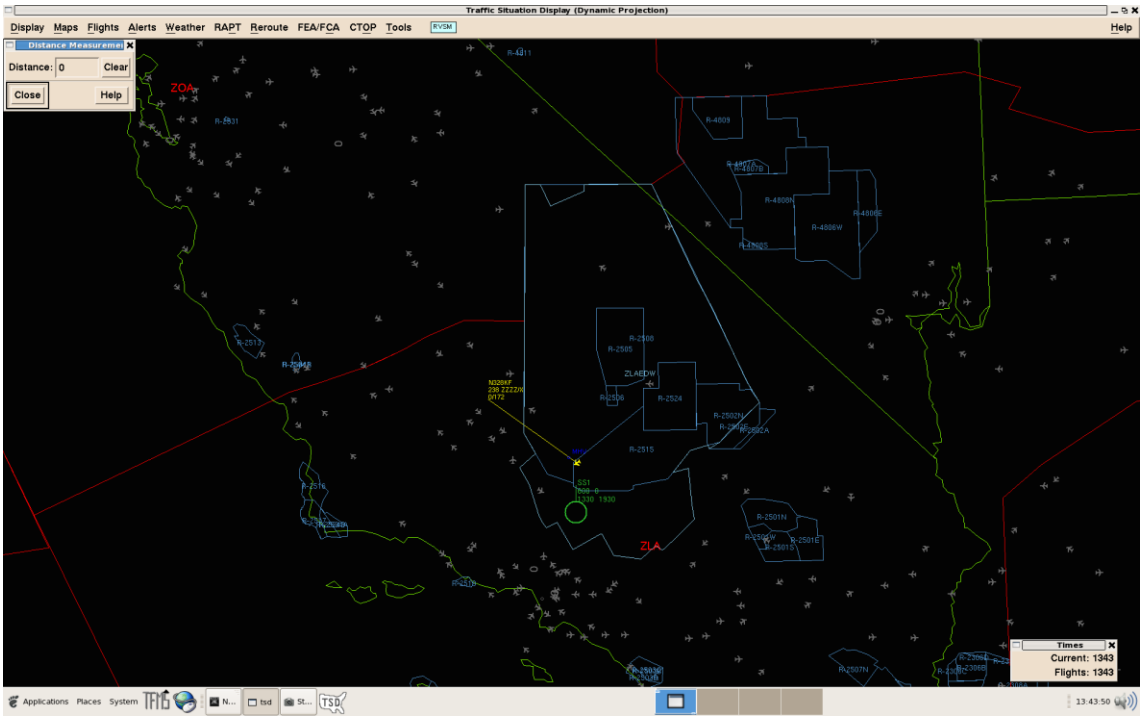


Figure 11. TSD configuration for training scenario based on Scaled Composites' SpaceShipOne suborbital flight.

The timing of these events is also relevant to the overall performance. These events were inserted at higher workload periods or, in the opposite, later in time so that the attention would have lessened. While the execution time of a reentry or launch is typically counted in minutes, some suborbital flights used in the scenarios run for over an hour.

These evaluations/training sessions provided a list of requirements for the next generation of SDI software application, and recommendations for JSpOG procedures and training curriculum.

2. Familiarization

The immediate availability of the SDI at the FAA ATCSCC using either data files or replay allows the JSpOG to demonstrate the FAA capabilities to visitors, including air traffic controllers from facilities collocated with spaceports, or from facilities expected to be affected by the increase in the development of launch or reentry, or suborbital, commercial space flights.

The ease with which a data file can be created from existing telemetry data enables the demonstration to be meaningful of the specific operations. For example, suborbital flights can be played from specific domestic U.S. spaceport locations or proposed locations, simulating vehicle dynamics of the commercial space vehicle that is most likely to be active at that spaceport.

This capability can be used by FAA AST to support discussions during evaluation phases of either a spaceport or a commercial space operator, using the adage that a picture is worth thousand words.

IV. Summary of Findings

A. A Successful Non-traditional Approach

The approach to the SDI proof-of-concept demonstration is not common for the FAA. Although some of the design decisions were more dictated by constraints rather than by best fit-for-purpose, the approach to the demonstrator architecture represented a low risk. Moreover, all connectivity elements can easily be undone and reset. The latency resided in the administrative approvals, rather than in the technical setup.

One key characteristic of the SDI approach is that it implements small, incremental steps, but these steps will show visible process and performance improvements in the short-term. For example, the SDI automates the current

processes in place within JSpOG when supporting a launch and reentry operation, and with commercial space vehicle operators. Subsequent steps will include incremental enhancements to the current process.

Another key and unusual feature of the SDI demonstration platform is that it brings the test environment to the users (the JSpOG) at the point of its primary intended use (the ATCSCC). In more traditional research projects with the FAA (or with NASA), the users must travel to the testbed location (e.g., the FAA WJHTC, NASA research Centers). Impromptu use or demonstration is therefore not realistic. The SDI, on the other hand, can be operational within an hour for use of "canned" mission data files in a dynamic test environment. The addition of replay capability of the SDI output enhances the significant flexibility in usage of the platform. Perhaps most importantly, operational demonstrations, in which the SDI is executed in "shadow" mode during actual launch and reentry operations, are possible and readily accommodated with this approach, allowing the users to directly experience the benefits that the SDI's automation provides in the actual operational environment.

The FAA AST is convinced that this approach delivers the desired level of efficiency, flexibility and time-effectiveness to support the necessary pace of its capability growth, which must strive to match the pace of industry progress and innovations. The drawbacks of this approach included the architecture complexity and the organizational challenges to work across branches. Nevertheless, the recommendation is for the FAA to consider this type of approach when the drawbacks are manageable against the achievement of short-term return.

B. Lessons Learned from the Demonstration

The initial capability demonstration, including the use for training, was rich in lessons learned. As expected, the application of the constraint to use the NAS systems "as-is" resulted most of the time in an inappropriate handling of the launch and reentry vehicle. The most significant cause for the mishandling was traced to vast variations in flying properties between the launch and reentry vehicle and the other NAS users (e.g., altitude, velocity, vertical profile). While the TFMS intended use is mostly situational awareness, some observed behaviors could be considered as erroneously misleading when the inappropriate handling was sustained over several minutes; for example during extended periods of loss of signal wherein the TFMS propagates the vehicle position based on erroneous dynamics. Similarly, the refresh rate of the TSD, while appropriate for aircraft velocities, causes the display of the launch and reentry vehicle position to appear more "jumpy" as the vehicle covers a significantly larger distance over one refresh cycle (e.g., the width of the state of California). The ESDD closes some of these gaps, but the ultimate goal is to integrate the situational awareness information on a single display.

Validation activities were paramount for the user-interface design. While a formal human-factor design process has yet been not deployed for the SDI development, several design sessions were held with the end-users. The validation testing highlighted the need for human centered design because the system, while partially automated, is still very much relying on the human-in-the-loop to identify and respond to the information it presents. Akin to cockpit automation issues, it was determined that automation has the potential to decrease the user's ability to timely detect the onset of an off-nominal condition. The initial design was based in visual indications based on the auditory environment in the EMC during a mission (e.g., multiple actors, hotline). The change in color of the status lights on the ESDD was not detected in a timely manner on several test occasions, and was not always effective in getting the JSpOG operator's attention. A multi-sensory approach is now envisioned to capture the operator's attention.

Resource management was a significant source of lessons learned. In the concept of use, two operators are needed: one for the SDI (JSpOG personnel) and one for the RRAT (AST personnel). The distribution of labor and the interactions between the two operators were found to be a driver in maintaining the best environment to efficiently respond to abnormal situations. The JSpOG operator must monitor the information on both the ESDD and the TSD as one task, so that the RRAT operator can be dedicated to running that tool. Development of clear distinction of labor and training is critical to a sustained sterile environment in the EMC.

These are just a few of the lessons learned documented from validation and evaluation testing. Until the system is fully integrated and in use, the FAA will continue to capitalize on lessons learned through the subsequent system developments.

C. Conclusion

The predicted increase in frequency and complexity of commercial launch and reentry operations, the FAA must continue its effort to research and develop both technologies and integrated capabilities to meet the objectives and realize the anticipated operational benefits of the integration of these operations into the NAS. The non-traditional approach implemented on the project provided the appropriate level of efficiency and flexibility, while allowing the users to have a direct and live input into the system.

The FAA's SDI system focuses on achieving the "Respond" objective by providing the means to monitor operations, and to timely and adequately respond to abnormal conditions occurring during the transit through the

NAS. These capabilities will sustain the FAA's approach to a safe and efficient management of the NAS while transitioning launch and reentry from special events to more routine operations.

D. Next Steps

Several axes are being investigated from for the SDI platform itself, from the operational scope and from the NAS system readiness standpoint. The non-traditional approach that allowed for rapidly obtaining tangible results is maintained for the next phases.

Regarding the SDI platform, in addition to loading the next software package upgrade, the weak element of the complex architecture is the Mission Support network which original use was not to support implementation readiness of NAS systems. This network was the readily accessible entry point to the EMC. Further work will investigate a more robust and longer-term solution for connecting the users at the ATCSCC to the launch and reentry vehicle operators, while complying with FAA's infrastructure maturation prior to turning the system operational.

Regarding the operational scope, the underlying principle is to test the scalability of the SDI design. The scalability includes both the accommodation of several other commercial space operators, and the preparation to an increased number of missions. The point-to-point connectivity between the FAA and the vehicle operator may show its limitations when the number of operators significantly increases. In addition, the ICD, although quite rudimentary, may not be acceptable by all operators. The FAA is currently reaching out to additional commercial space operators for partnership opportunities to develop their connectivity to the SDI platform. Now that the platform has demonstrated its usefulness and operational benefit to the Administration, it is anticipated that other validations will take place in the coming year. The operators contacted by the FAA include Blue Origin, Sierra Nevada Corporation and United Launch Alliance.

In the longer term, it is expected that the recommendations for change in the FAA automation systems will be inserted in the software package upgrade definitions. Priority would be given to the automation behaviors that may lead to erroneous information for the JSpOG operators monitoring the mission.

Acknowledgments

The authors thank the TFMS, NPN and FTI personnel at the FAA Technical Center for their continued support to the Space Data Integrator demonstrator, the JSpOG team at FAA Air Traffic Control System Command Center and AST-100 team for their invaluable inputs and availability during the evaluation/training, MEI engineering team for their support during the integration and verification of the SDI, and SpaceX for accepting the challenge of being the first operator connected to the SDI.

References

[1]Murray, D., "The FAA's Current Approach to Integrating Commercial Space Operations into the National Airspace System," 2013, URL: http://www.faa.gov/about/office_org/headquarters_offices/ast/reports_studies/media/REMAT-Murray-FAA-FINAL.pdf [cited 01 December 2015].

[2]CSC, "Interface Requirements Specification (IRS) for the TFMS for the Traffic Flow Management-Modernization (TFM-M) Program," Release 7, Revision 5.0, 2011.

[3]Demidovich, N., Purcell, P., Dewey, R., "Progress in Dual Frequency ADS-B Payload Flight Experiments on Stratospheric Balloons," Proceedings of the 2015 IEEE Conference on Integrated Communication, Navigation, and Surveillance (ICNS), CFP15CNS-CDR, IEEE, New York, 2015.