SPACE LAUNCH AUTOMATION AND INTEGRATION: A COMMON ARCHITECTURE FOR MISSION ASSURANCE, SAFETY, AND LAUNCH OPERATIONS

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ABSTRACT

For decades, the gateway to space has been through the Eastern and Western Launch Ranges (E/WRs). The collaboration of the governing agencies, FAA, USAF, and NASA provides a commercial alternative to past practice with greater reliance on telemetry and automation.

The need for mission assurance and public safety in all phases of flight, on-orbit operations, and reentry through mission planning, launch/reentry operations, streamlined telemetry processing, real-time situational awareness, and autonomous flight safety system (AFSS) use will drive launch operations and range costs down, increasing launch availability, and allowing Spaceport development at non-traditional launch locations. Today, industry has multiple new entrant's vying for the projected increased capacity with re-entry operations; we must capture synergy with ascent tools and regulations must complement this concept. Further, government and commercial providers, with increasingly more responsibility, are required to ensure public safety in the event of a vehicle failure, driving the importance of launch data integration into National Airspace System (NAS) operations.

The need for a cost-effective, reliable, accessible mission assurance and flight safety solution is imperative given the strategic importance to assure access to space. Implementation of an AFSS, coupled with the full spectrum of support from complete autonomy to situational awareness with man-in-the-loop awareness, is critical. This capability provides tremendous resource savings (people, hardware, financial) while meeting requirements.

Millennium explores the integration of AFSS technology, mission assurance planning, NAS integration, weather monitoring, surveillance, and streamlined telemetry processing systems providing real-time situational displays. Building on the E/WR heritage tools and our legacy of delivering telemetry-based mission assurance and flight safety expertise to the USAF, NASA, FAA and commercial space industry, Millennium's overview of range automation can provide the industry with an integrated common approach to automate, plan, validate, assure, and execute affordable space launches and reentry operations anywhere in the world.

INTRODUCTION

The Launch and Test Range System (LTRS), consisting of the Western Range (WR) at Vandenberg Air Force Base (AFB) in California and the Eastern Range (ER) at Patrick AFB / Cape Canaveral Air Force Station in Florida, has provided the portal to space. This capability is critical for a variety of interests including National Security. Space-based assets have become paramount for civil and defense communications, navigation, and other uses. With the increasing demand for communication data bandwidths and the introduction of smaller scale satellites such as CubeSats providing increased capability, there are new demands for launch of payloads to various orbits. Coupled with the existing demand for scientific, civil, and defense space-based needs, commercial interests are set to exceed the capability of the LTRS.

Currently, launch operations are conducted through a collaboration of government agencies and organizations to include the US Air Force (USAF), National Aeronautics and Space Administration (NASA), and the Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST). These agencies have recognized the increase in demand, and have taken a multi-pronged approach to meet these needs. This includes the use of alternative federal ranges for launch operations, such as Wallops Flight Facility (WFF), and the licensing of commercial spaceports in Alaska, California, New Mexico, Oklahoma, Texas, Virginia, and Florida, as well as other potential states in the future. In addition to increasing the number of potential launch sites, the government has invested in modernization of range instrumentation and the development of new technologies.

To meet this increased need in both demand and capability for commercial space activities, the ER and WR must conduct operations with a greater reliance on automation for both schedule/planning needs and cost savings. The introduction of autonomous flight safety systems (AFSSs) has provided an alternative to past practices with a greater reliance on range telemetry instrumentation with a reduction in need for costly radar and command systems. Use of range automation tools such as weather monitoring will further expand the capability to assure and expand launch and reentry operations as required to meet government and industry demands.

MOTIVATION FOR AUTOMATED RANGE SYSTEMS

Cost and Accessibility

For years, the launch ranges have worked to become more cost-effective via the traditional approaches of reducing staff and modernizing equipment. These reductions have led to the divesting of uprange and downrange installations, leading to the current LTRS baseline, and have driven down costs, but at the expense of reduced capability.

During the 1990s, these reductions in capability were accommodated by a reduction in the operations tempo as the NASA Space Shuttle and Delta II programs came to dominate the flight schedule. With the introduction of the Evolved Expendable Launch Vehicle (EELV) Atlas V and Delta IV programs, and Orbital ATK vehicles, the launch tempo did not exceed the range capability for scheduling operations. In the 2000s, as Space Exploration Technologies Corporation (SpaceX) began initial launch operations, the tempo remained mostly unchanged due to the end of the Delta II and Shuttle programs. Recently, however, new entrants such as Blue Origin have begun developing launch capabilities that will exceed the current schedule capability, with estimates of 40+ launches per year from the ER alone. These new commercial launch providers are experimenting with a multitude of new approaches such as returning boosters directly to land for reusability, with likely potential to strain the current LTRS baseline to support concurrent operations.

Flight Safety and Mission Assurance

Access to space begins with operations planning and scheduling. Inclusion on the range schedule is constrained by the availability of required range instrumentation, range personnel, and any other critical needs. Using tools such as Millennium's Joint Advanced Range Safety System (JARSS) Mission Planning (MP) Tool Suite, ranges can conduct planning for traditional launch and reentry operations and determine Expected Casualties (E_c), Probability of Impact (P_i), Destruct Lines, and other critical safety analysis elements. Additionally, there is a need to track the vehicle during periods of flight where debris may impact the Earth and poses a critical element where Flight Safety and Mission Assurance converge. These tracking sources are used to determine vehicle position in relation to flight limits such as the vehicle destruct lines, or areas wherein a vehicle must be terminated to ensure that no debris will cause a loss of life or property. Tracking sources consist of multiple beacon-track or skin-track radars, optical trackers, and GPS metric tracking and Telemetry Inertial Guidance (TMIG) data. Data from these sources are fused and evaluated to determine the position of the vehicle, and to guard against inaccurate information received from a hardware or software failure.

With an AFSS, operations do not have the traditional requirements for multiple, diverse look-angle, tracking radars, optical trackers, or multi-directional and omni-directional command termination transmitting antennas and associated ground instrumentation to support these systems (See **Exhibit 1**). The vehicle instrumentation will be capable of determining vehicle position from GPS and TMIG avionics, and then evaluate flight data against a pre-determined set of mission rules. Violations of these rules will result in pre-defined decisions for handling an errant vehicle up to and including destructive termination. Moreover, recent failures of aging range instrumentation have impacted launch operations, with the most critical instrumentation being the use of radar and command systems for traditional Flight Termination System (FTS) operations. To meet the reliability requirements of 0.999 at 95% (system level), the LTRS requires redundant power, communication, and other hardware and software elements to ensure there are no single points of failure. These requirements have expanded the size of the range subsystems such as Radar, Command, Telemetry, Timing, and Communications. For these reasons, it is critical that ground-based FTS functions be performed on-board the vehicle. In February 2017, an ER launch from Kennedy Space Center's Launch Complex 39A, was operated by carrying a Dragon Spacecraft as part of the Commercial Resupply Services (CRS)-10 mission. This launch vehicle utilized an AFSS as the primary flight safety system for both the first and second stage boosters on the SpaceX Falcon-9 rocket. While this is not the first launch to carry an AFSS, this marked the first time that an AFSS was used as the primary flight safety system. This launch utilized Millennium's Flight Analyst Workstation (FAWS) tool to define and encode the mission rules to independently assess flight safety rules. The FAWS is part of a full AFSS suite that Millennium has developed which exceeds the reliability requirement while addressing the FTS functions on-board the vehicle (**Exhibit 1**).

Exhibit 1: Millennium's Sentry™ AFSS, which includes operations from pre-launch through flight and end of mission.[1]

EXPANDED UTILIZATION OF AUTOMATED RANGE SYSTEMS

While more and more vehicles will be using an AFSS in the coming years, there will still remain a need to support traditional FTS systems on other vehicles. Some programs may have existing inventory of commanded FTS flight hardware where the cost benefit of switching to an AFSS may still be too great to justify the change. Others may need to complete further test and evaluation of an existing AFSS system, may be limited in the ability to provide capital investment in the development of a proprietary AFSS, or may be limited due to other factors. Therefore, ranges will still need to maintain a level of range instrumentation needed to support traditional FTS, while providing flexibility to support AFSS operations. For instance, according to the 45th Space Wing Commander, during the first AFSS operation by SpaceX in February 2017, range costs dropped by 50%, which included a 60% reduction in personnel associated with the launch operation[2]. However, other users may not see the same reduction in range costs due traditional range telemetry system utilization as SpaceX utilized their own telemetering antennas for acquisition and data processing. Therefore, this decrease in range costs will likely impact the continued operations and maintenance funding available to the ranges, requiring more launch operations to provide the current levels of income to offset range operating costs. As a result, ranges will need to explore other potential areas of automation and cost savings. These areas for range automation can occur during the three phases of any operation: pre-mission, mission, and post-mission, as detailed in the following section. Lastly, the automate range systems allow for an accelerated and updated timeline for launch and reentry operations.

OPERATION TIMELINE

Pre-Mission (Planning and Scheduling)

Range Scheduling

Pre-Mission operations begin when a mission is first placed on the launch manifest. As ranges begin to handle the projected increase in the launch tempo, the minor operations leading up to a major operation will need to be streamlined. This includes the need to limit the number of range operations on the range schedule, including scheduled and unscheduled maintenance of instrumentation systems, testing of modifications, upgrades to existing systems, or installation of new range systems. To handle this, ranges need to transition from the traditional radar-centric paradigm to a telemetry-based range, where acquisition of data from the vehicle's on-board avionics is more critical. This includes the need to handle concurrent operations on the schedule such as engine static-fire tests, vehicle checkout, or other pad checks. For range users without their own telemetry acquisition capability, these concurrent operations will require range telemetry systems for data acquisition and retransmission. To support this, the ranges will need to ensure that there exists enough telemetry assets to handle concurrent operations simultaneously from various locations. Additionally, range planners and schedulers must also consider the types of missions that are requesting time on the range.

As more complex requests for time on the range increase, ranges will need to consider improvements to current methodology and plans for implementing levels of automation in their schedule management. One example would be the development of a solution that is based on vehicle configuration. This solution could automatically generate a mission schedule, containing associated minor and major operations such as static fire engine tests, and place those operations on the range schedule in anticipation of a requested launch date. These automatically generated place holders would need to be refined over time by analyzing predicted versus actual dates of execution. Developing statistical models for these operations to occur within the requested or predicted timeframe would allow schedule management to take a more proactive approach rather than a passive and reactive response. In addition to altering systems for management, encouraging range users to move their schedules forward in cases where the vehicle preparation is complete, and mission assurance is not impacted would shift range users to become more collaborative with scheduling of assets. This increase in collaboration between range management and range users can provide better insight and potentially find solutions when schedule conflicts occur.

Range Safety Analysis

While the number of launch operations increases on a given range, that range must also consider the addition of returning boosters as evidenced by SpaceX's current operations methodology, and companies such as Blue Origin's and Masten's concepts for returning stages of the vehicle. Additionally, reentry vehicles are becoming more prevalent, from lifting-body reentry vehicles such as the USAF X-37 Orbital Test Vehicle (OTV) and Sierra Nevada Corporation's Dream Chaser, to ballistic reentry vehicles like SpaceX's Dragon and Boeing's CST-100 capsules. Each of these reentry vehicles brings a unique capability that the ranges must be able to support from water-based landing to runway and land-based landings. With these various missions comes the need to evaluate each individual operation from the perspective of Range Safety prior to the major launch or reentry operation.

Ranges must utilize faster methods for performing range safety analysis in order to meet the increased demand for operations. Currently, analysis of destruct lines, and other key safety elements may take as much as 30 days to generate before analysis can be performed on the mission parameters. The length of time can be partially attributed to antiquated methodology for determination based on historic vehicles and not on realistic flight dynamics, focusing more on unrealistic potential risks versus actual risks. Furthermore, the use of Monte Carlo statistical analysis requires the use of processing clusters of servers, and can take weeks to complete. Conversely, alternative algorithms such as a Julier-Uhlmann algorithm, such as those used by Millennium's JARSS MP tool can be used to perform certain types of analysis in either a quick-look approach prior to committing clusters, or to perform the analysis where needed. This requires advanced tools like those in Millennium's JARSS MP software for government agencies, or Sentry™ MP for commercial spaceports and ranges. By reducing the time to complete the analysis, range safety analysts are able to handle the projected increase in launch tempo.

For AFSS operations, flight analysts take the resulting safety analysis and generate a Mission Data Load (MDL) to be loaded onto the Autonomous Flight Safety Unit (AFSU) flight hardware if the AFSU is utilizing the Government-developed Core Autonomous Safety Software (CASS). To accomplish this, vehicle operators or government analysts can use a tool such as Millennium's FAWS software to validate the resulting MDL based on the safety analysis.

Mission Assurance

As stated previously, major operations such as landing or launch operations, require that several minor operations be conducted for mission assurance. These include preparation of ground systems, crew personnel, and the vehicle itself. For AFSS operations, the flight hardware will be loaded with the previously generated MDL file, and the resulting loaded AFSU will be verified. A system such as Millennium's Ground Support Console (GSC) (**Exhibit 2**) will checkout the AFSU in a laboratory bench environment, on-board the vehicle in the integration facility, or on the pad prior to lift-off.

In addition, range telemetry systems will ensure that they overcome any limitations to downlink bandwidth and provide the capability to support telemetry acquisition for multiple vehicles from the various launch pads, and telemetry processing systems that can only be committed to concurrent operations. Given the other operations that must be conducted with range support prior to a launch, and coupled with crew-rest requirements, the ability for the ranges to consistently turn around to support launches must be improved. To accomplish this, ranges need to examine current industry offerings for compact, modernized telemetry equipment as they far exceed the performance of previous generations of telemetry systems. During the development of the prototype Streamlined Telemetry Processing System (STPS), Millennium engineers identified best athletes in the areas of data quality and not signal strength. Millennium then identified a cost-effective solution that could be rapidly implemented into existing range infrastructure. This design provides for ease of expandability to meet range needs while ensuring safe reliable operations.

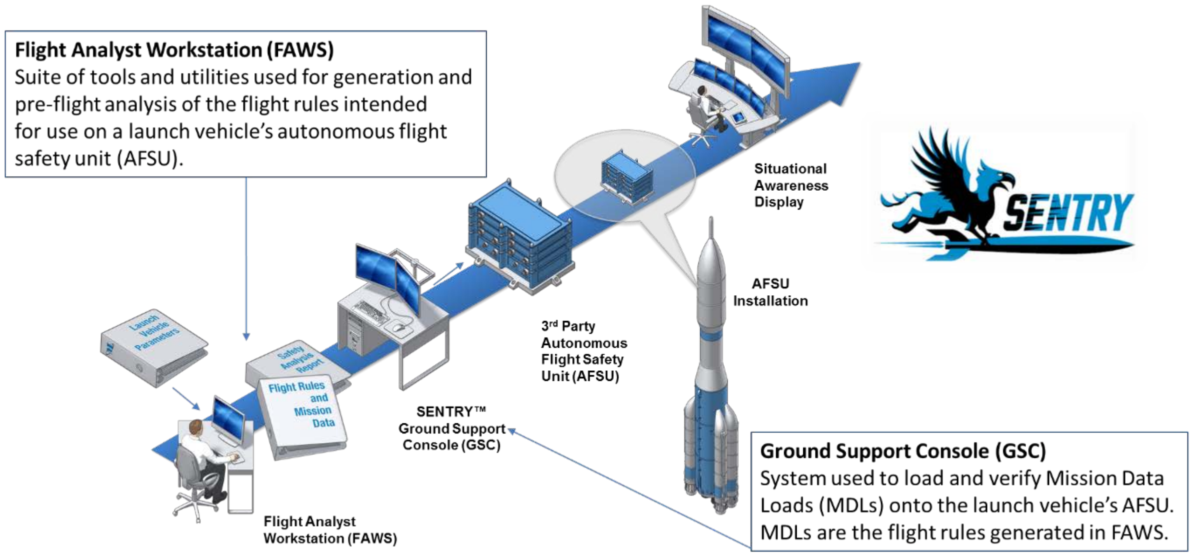

Exhibit 2: Millennium's Sentry™ AFSS Approach

Lastly, ground personnel must be properly trained on the systems, mission types, and various scenarios to ensure successful execution of operations. This training includes the ability to train on operational or approximated systems, and through the various off-nominal scenarios possible for a given operation. Millennium is currently implementing their Flight Analysis and Trajectory Optimization Modeler (FANTOM) 6 Degree of Freedom (DoF) model into a mission planning trajectory builder to create a mission simulator, providing nominal and off-nominal scenarios. By combining this simulation capability with Millennium's telemetry solutions, nominal and off-nominal simulated telemetry streams can be used for both training and evaluation of range personnel and systems in the operational environments. These training and evaluation operations will need to be conducted without impacting active operations. To accomplish this, ranges will need to look at both the number of personnel required for a given active mission, then provide adequate additional staffing to support alternate crew for training and concurrent or adjacent operations schedules. While ranges may not be able to see an overall reduction in range operations personnel, range users could see a reduction in personnel required for their specific operations once streamlined and automated systems are put in place. This includes the cost reductions associated with AFSS operations.

Mission

Minus-Count Activities

While AFSS operations have eliminated the requirements for beacon-tracking radar, command, and real-time Range Safety systems, they have not reduced other systems on the range. There still exists a need for other systems such as Area Surveillance, Weather, Timing and Count, Communications, Telemetry (in most cases), Data Handling, and others. Range personnel will need to consider automation and streamlining where appropriate, in order to find efficiencies and reduce maintenance and operations costs.

One area of reduction is the change in perception of risk associated with maritime surface vessels. Given the size of those vehicles and the debris models associated with a vehicle, the risk values do not rise to levels of concern. Therefore, certain risks can be accepted or eliminated. For operations where surveillance of vessels is still needed, tools such as Millennium's commercial Surveillance Control Officer (SCO) Tool, currently in development, will allow a range to receive voluntary position information from mariners and aircraft directly through their mobile devices.

For Meteorological systems, the variety of different instrumentation, vendors, and displays requires Launch Weather Officers (LWOs) to analyze multiple displays separately. Alternatively, investments in tools like the Sentry™ Weather Tool (**Exhibit 3**), originally developed by Millennium for demonstration to the 45th Space Wing Weather

Squadron, would allow an LWO to see an integrated display of weather data such as three-dimensional cloud reflectivity and two-dimensional lightning information along with the nominal launch trajectory. This would allow the LWO to determine status of weather rules more accurately and expeditiously, and even afford the ability to automate the analysis and display of other weather rules given the appropriate conditions. Future phases of the Sentry™ Weather Tool will incorporate Launch Commit Criteria (LCC) rules for evaluation and analysis in near real-time. These weather rules can then be assessed automatically by the system, and alert the LWO to real or potential violations of these rules for disposition and/or action. This idea of integrating diverse systems into a single display also extends to other systems as well.

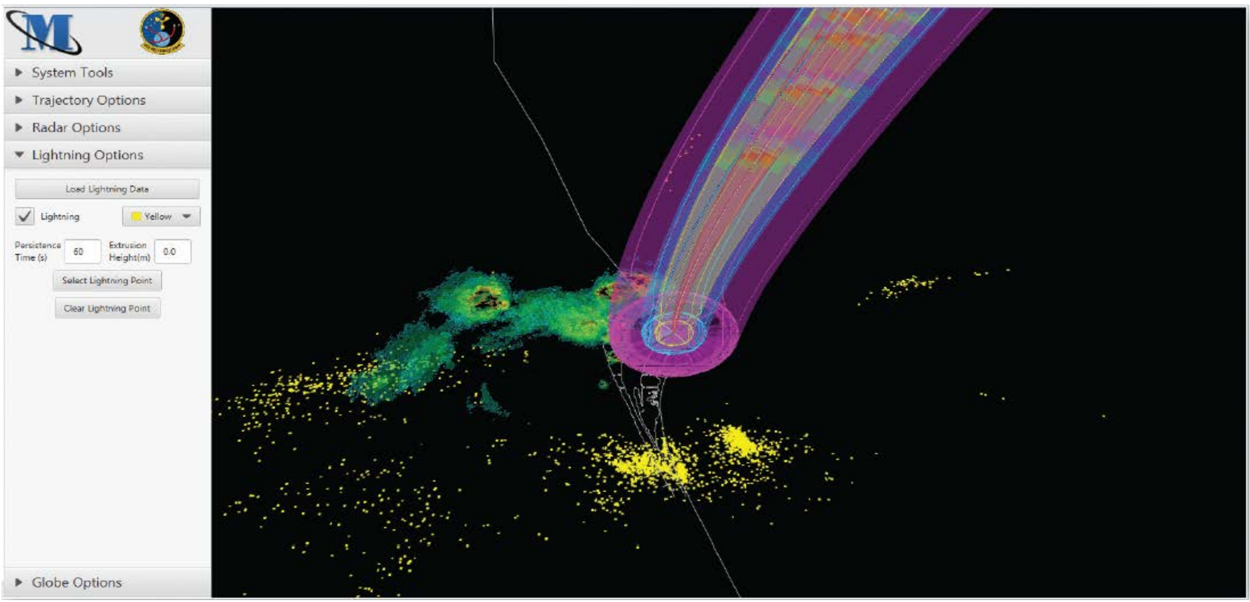

Exhibit 3: Millennium's Sentry™ Weather Display Tool

Plus-Count Activities

With the advent of AFSS, both telemetry and range safety systems need to handle both traditional displays as well as potentially provide situational awareness displays for AFSS operations. A range could require that a range user utilizing an AFSS provide a situational awareness display, but this creates an issue where operations personnel will now need to be trained on each situational display provided from each separate vendor. The preferred solution is to develop situational awareness displays for AFSS flights that would function in the same manner regardless of vehicle and vehicle operator. This capability has been developed for FAA AST, resulting in Millennium's development of the Space Data Integrator (SDI) and Space Program Integrated Data and Estimated Risk (SPIDER) programs to integrate launch and reentry vehicles into the NAS regardless of vehicle format. Millennium's Situational Awareness Display tool, built upon the SDI and SPIDER tools, also provides vehicle-agnostic display capability by utilizing a third-party front end-processor (FEP) feeding a network of independent customizable displays. These displays can all be developed to the specific role of the given operator, and subscribe to available data published by the FEP. These displays can be colocated or geographically diverse, and can even be connected through a mobile network if proper cyber security protections are in place.

To handle off-nominal scenarios, these situational awareness systems will process in near-real-time, the state vector of an off-nominal vehicle, and generate a hazard area representing the vehicle debris footprint in a manner similar to Millennium's Errant Landing Vehicle Information System (ELVIS), Aircraft Protection Tool (APT), or Shuttle Aircraft Vectoring System (SAVeS). This resulting hazard area and data can then be provided to other government agencies and first responders in response to a catastrophic event. By integrating this display to receive area surveillance and weather data, ranges are better able to react and manage different scenarios. Millennium's suite of JARSS and Sentry™ tools allow ranges to become more automated to respond to these off-nominal scenarios.

Post-Mission

After a mission is complete, the range will analyze and evaluate performance of the vehicle, range instrumentation, crew, and procedures. This effort begins with the Hot Wash immediately following the operation, and serves to evaluate and identify areas for continuous improvement. Systems may be identified for deprecation or placed in an Integrated Priority List (IPL) for maintenance, upgrading, or replacement. With use of an AFSS, range officials may not perform these critical tasks as there is no obviously visible need to perform range safety activities during the operation. In actuality, AFSS use may require greater evaluation of range performance as there is no longer range operator control of the vehicle during flight. Range operators must evaluate MDL files and reports such as those generated by Millennium's FAWS, and analyze CASS results to determine if the AFSU performed as expected, then examine possible improvements, as required. By utilizing new systems such as those previously mentioned, ranges could receive automatically generated quick-look reports and data that can be used for rapid response and initial observations from cursory analysis. More in depth analysis can be conducted in the time after the operation. In the event that an AFSU terminates the flight of an errant vehicle, the range will determine the cause and either lead or assist in the resulting investigation. Data from previous operations will be critical to this effort, as will immediately available data from range systems and personnel.

Updated Timelines

With this level of automation, timelines for operations can be better streamlined as shown in **Exhibits 4** and **5**. These timelines can be continuously evaluated and improved along with range procedures, methodologies, and instrumentation.

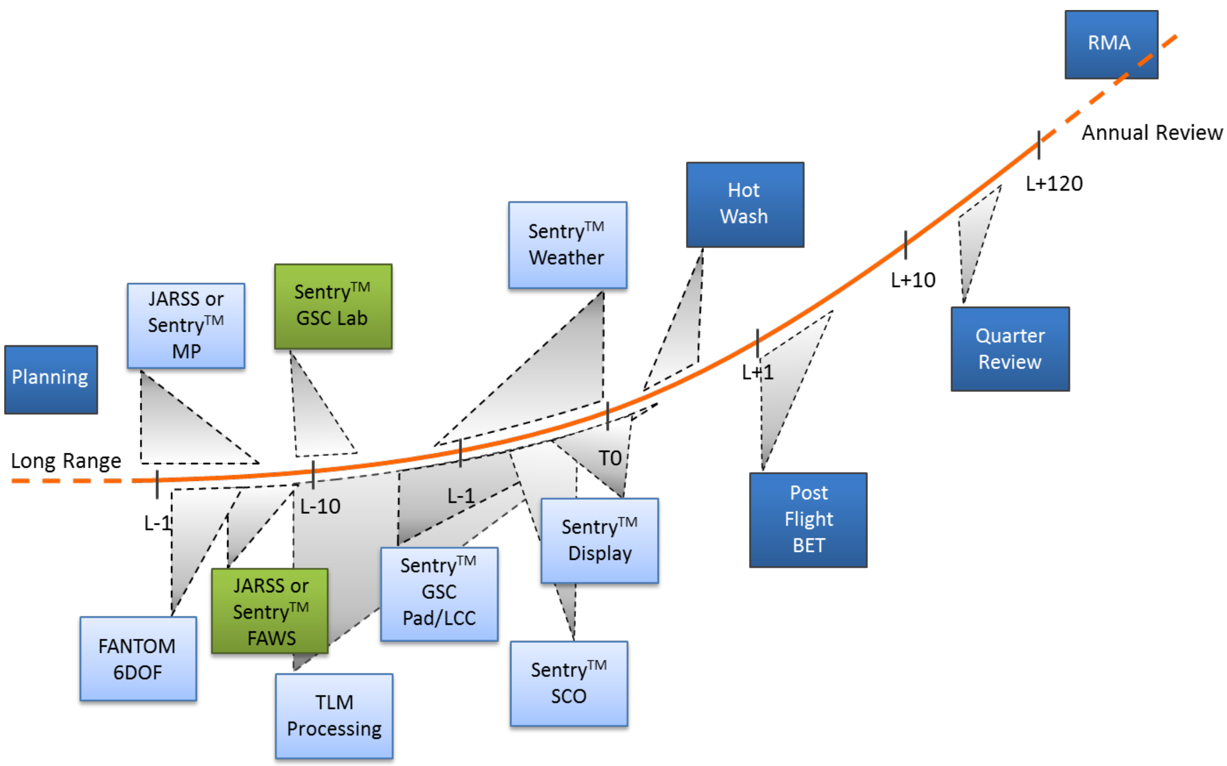

Exhibit 4: Launch Operation Timeline

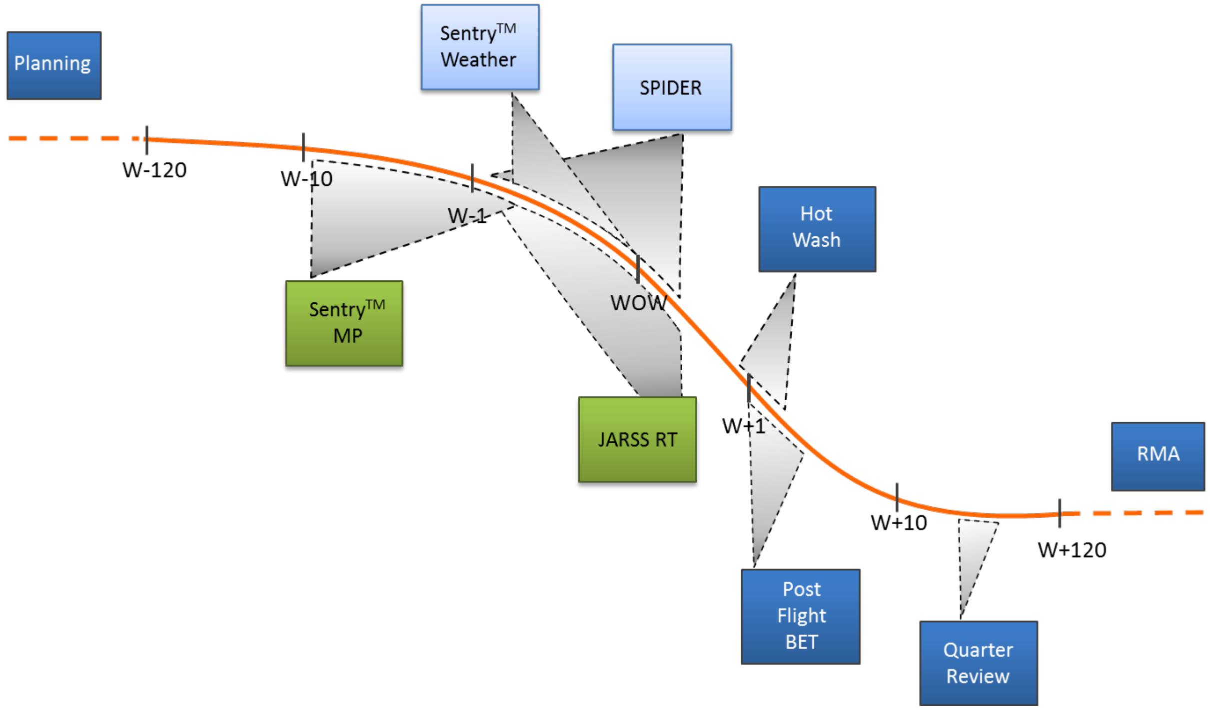

Exhibit 5: Reentry Operation Timeline

SUMMARY

Millennium continues to expand on its heritage of providing flight safety systems and tools to improve range operations at our Eastern and Western Ranges. Centered around the Sentry™ AFSS tools which provide validation of an on-board FTS that exceeds range reliability requirements, Millennium has developed additional tools to expand range automation. These tools provide real-time situational awareness across the full spectrum of launch operation activities to include missional assurance planning to weather monitoring to post-flight analysis. Millennium's integrated common approach will continue to provide safe, reliable, and assured access to space by executing affordable launch operations.

[1]Powell, O., Lyle, J., Wassel, A., and Pancholi, K., "Assured and Affordable Access to Space: An Autonomous Flight Safety Solution", 32nd Space Symposium, Technical Track, Colorado Springs, CO, April 11-12, 2016.
[2]Dean, J., "Only on Falcon 9: Automated system can terminate SpaceX rocket launches", Florida Today http://www.floridatoday.com/, accessed March 11th, 2017.