Multi-Payload Integration Lessons Learned from Space Test Program Mission S26

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ABSTRACT

Space Test Program Mission S26 (STP-S26) was a complex multi-payload mission launched from Kodiak Launch Complex, Alaska on November 20, 2010. A Minotaur-IV launch vehicle placed ten objects into two different orbits. The Stage 4 rocket motor placed four Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class satellites and two CubeSats into the primary orbit. A Hydrazine Auxiliary Propulsion System (HAPS) then delivered two test ballast masses into a secondary orbit as a technology demonstration to prove dual-orbit capability of the Minotaur-IV. In addition, a CubeSat, ejected from one of the free-flying ESPA-class satellites on January 20, 2011, and one of the ESPA-class satellites (FASTRAC) separated into two satellites on March 22, 2011. Multi-payload missions always present unique challenges and STP-S26 was no exception. Through the use of a "lessons learned" database, the STP-S26 program office was able to leverage the experiences gained from previous multi-payload missions. One previous mission in particular was the STP-1 mission launched on an Atlas V in March 2007. STP-1 separated four ESPA-class satellites and a larger satellite pair into two orbits. This paper will review the key challenges and lessons learned from the STP-S26 mission pertaining to multi-payload integration and launch. Lessons were derived from requirements and interface management, technical, logistical, and managerial aspects of the mission. Some of the areas reviewed in the paper include:

- Unique requirements for multi-payload missions and verification of those requirements
- Mechanical fit checks
- Procedures for integrated operations such as multi-satellite mate
- Integrated tip off and separation analysis
- Multi-payload coupled loads analysis
- Meeting environmental, debris, and de-orbit requirements
- Logistic scheduling of payload arrival and pre-launch checkout in a shared processing facility
- Efficient & timely communication across teams
- Finite Element Model and mass properties early requirement definition
- Risk Management Process
- Interface Control Document verifications
- Space Debris Assessment Report (SDAR), Launch Conjunction Assessment Support Package (LCASP), and policy exception processes

The number of multi-payload missions is expected to grow with the trend toward smaller spacecraft. Multi-payload enablers such as ESPA Standard Service, Minotaur-IV Multi-payload Adaptor, and Poly-Picosatellite Orbital Deployer (P-POD) CubeSat capabilities will continue to create rideshare opportunities in the future for the small satellite community. The DoD Space Test Program has been at the center of developing and demonstrating the utility of launching multiple payloads from a single launch vehicle. Applying the lessons learned from STP-S26 and

previous multi-payload missions will reduce the technical risk and help maximize success for future multi-payload missions.

MISSION OVERVIEW

The Department of Defense (DoD) Space Test Program (STP) is the "front door" to space for either DoD payloads requiring a spacecraft bus or Space Vehicles (SVs) requiring a ride to space. Each year the DoD Space Experiments Review Board (SERB) meets to review and rank-order experiments.

The DoD SERB ranks experiments based on its military relevance and a justified need for space flight to execute their missions. STP uses the SERB list to manifest rides to space if funding and launch opportunities exist.

The Space Test Program-S26 (STP-S26) was a multi-payload mission executed by STP at the Space Development and Test Directorate (SMC/SD), Kirtland AFB, NM. The mission was designated STP-S26 to correspond to the 26th small launch vehicle mission in STP's 40-plus year history of flying DoD space experiments.

The mission was the first converted Peacekeeper Intercontinental Ballistic Missile (ICBM) to launch six space vehicles and demonstrate dual orbit capability. It was the first time this type of mission had been attempted so several challenges arose requiring innovative solutions.

STP-S26 successfully launched from Kodiak Launch Complex (KLC), AK using a Minotaur IV launch vehicle on 19 Nov 2010 at 1625 local time (20 Nov 2010 0125 UTC) (shown in Figure 1).

Figure 1: STP-S26 Launch

The satellites launched from KLC were the STP Satellite 2 (STPSat-2), Fast Autonomous Science & Technology Satellite-Huntsville 01 (FASTSAT-HSV01), Falcon Satellite 5 (FalconSAT-5), Formation Autonomous Spacecraft with Thruster, Relnav, Attitude and Crosslink (FASTRAC composed of FAST-1 and FAST-2 satellites), Organisms/ORganics Exposure to Orbital Stresses (O/OREOS), and Radio Aurora eXplorer (RAX). A few weeks following launch the NanoSail-D-002 (NSD-2) CubeSat was ejected from the FASTSAT-HSV01 satellite. Figure 2 shows the STP-S26 Mission Patch with depictions of each SV and the Stage 4.

Figure 2: STP-S26 Mission Patch

Prioritized Objectives

The STP-S26 Mission had four objectives. In prioritized order they were:

- Provide access to space for STPSat-2. STPSat-2 is an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class SV and the first flight of STP's Standard Interface Vehicle (SIV).
- Demonstrate the ability of the Hydrazine Auxiliary Propulsion System (HAPS) to deliver payloads into a secondary orbit for the Minotaur IV launch vehicle. For the STP-S26 mission, the HAPS performed an "orbit raising maneuver" after all other payloads were deployed and delivered two ballast masses into a secondary orbit.
- Demonstrate the multiple payload capability of the Minotaur IV. This was accomplished through the Multi-Payload Adapter (MPA) which allowed four ESPA-class SVs to be mated to the launch vehicle.
- Fly the maximum number of SERB experiments possible. The three secondary ESPA-class SVs each hosted SERB experiments.

Capability Enablers / Mission Firsts

The mission implemented several capabilities aimed at enabling responsive access to space for small experimental satellites and payloads. It paved the way for operational implementation of responsive space capabilities for the DoD. The STP-S26 mission was the:

- First flight of STP SIV, an ESPA-class satellite designed to accommodate a variety of experimental payloads reducing the integration and test time for a vehicle by establishing a standard bus.
- First use of Multi-Mission Satellite Operations Center (MMSOC) Ground Support Architecture (GSA), used by the STP SIV on the STP-S26 mission, ultimately will allow multiple satellites to operate on the same ground system at decreased integration cost by utilizing a common open-architecture core system.
- First flight to the Minotaur IV MPA, allowing four ESPA-class satellites to launch from a single small launch vehicle.
- First use of the Hydrazine Auxiliary Propulsion System (HAPS) to obtain dual orbit on a Minotaur IV, maximizing flexibility to achieve multiple orbits for future missions with minimal cost.
- First flight of Poly-Picosatellite Orbital Deployers (P-PODs) on the Minotaur IV and first CubeSat deployments on the Minotaur IV, allows additional flight opportunity for very small satellites
- First CubeSat deployed from a free-flying ESPA satellite, allows CubeSat ejection and operations to begin after some time on orbit.
- First Minotaur IV launch from Alaska's Kodiak Launch Complex (KLC) commercial launch facility which provides a definitive launch schedule for experimental missions increasing the opportunity for launches from the west coast and to high inclinations.

All of these firsts ensured that experimental satellites and experiments which are of interest to warfighters can be rapidly demonstrated to fill capability gaps.

The STP-S26 mission manifest became increasingly complex. Two satellites were analyzed as potential replacements for a secondary satellite that became an unfeasible option late in the mission. A dual-path manifest was taken with two SV's, FASTSAT-HSV01 and CUSat, to evaluate the ability to meet the launch schedule, cost of the mission, and the contribution to maximizing the number of SERB experiments. In the end, the FASTSAT-HSV01 satellite was chosen. Meanwhile, two CubeSats were added to the mission for deployment from P-PODs attached to the Stage 4 rocket motor.

(Figure 3 shows the mission evolution of STP-S26. The changes at each time are highlighted in red).

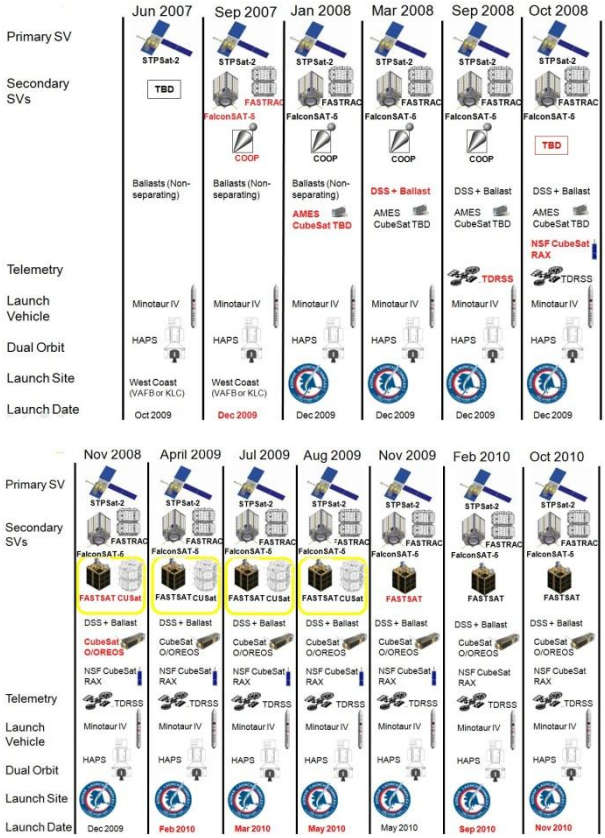

Figure 3: Mission Evolution

The STP-S26 mission had a total of 16 experiments on seven separate payloads and one technology demonstration. The STP-S26 mission is valued at $170M and was the organizations most complex mission in over twenty years. The ESPA-class satellites are sponsored by the DoD Space Test Program (STPSat-2), US Air Force Academy (FalconSat-5), Air Force Research Laboratory University NanoSat Program (FASTRAC), National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC) (FASTSAT–HSV01). The three CubeSats are sponsored by the National Science Foundation (RAX), NASA Ames Research Center (ARC) (O/OREOS), and NASA MSFC (NSD-2).

A Demonstration Separation System (DSS) was provided by Boeing. This was the first time the DSS was demonstrated by separating two ballast payloads into the secondary orbit on STP-S26.

The DoD SERB

Every year each military service's Space Experiments Review Board (SERB) meets to rank their respective

service experiments. Experiments then go on to the DoD SERB to brief and be ranked. Ranking factors consist of 60% for military relevance, 20% based on the experiment's technical data, and 20% based on the rank each respective service has given the experiment, prior to entering the DoD SERB. Military relevance is the main driver for each experiment's ranking.

The DoD SERB meets twice a year. The full SERB is held annually in November. Here experiments are presented and competitively ranked among each other according to military relevance and technical quality. Experiments are normally only ranked at the fall cycle DoD SERB. Though, sometimes an available flight opportunity exists for an experiment that has not been briefed to the SERB. In this case, experiments can brief the mid-cycle DoD SERB in May. If accepted, experiments briefed at the mid-SERB are placed on the approved SERB list without a rank. Once the experiment has been ranked at the fall cycle DoD SERB or listed as a Mid-SERB experiment, the DoD STP at SMC/SD is charged with actively assisting in the endeavor to provide access to space for each of these experiments.

Nine of the 16 experiments launched aboard the STP-S26 mission were ranked during SERB fall cycles. Two of the experiments flown were mid-SERB payloads. Three experiments were non-SERB experiments. Refer to the Table 1 for the listing of all experiments flown on STP-S26 and their SERB ranking.

Table 1: Experiments Flying on STP-S26 and SERB Rankings

Integrator	Satellite	Experiment	Org	SERB
Space Test Program	STPSat-2	• Space Phenomenology Experiment (SPEX) • Ocean Data Telemetry Microsat Link (ODTML)	AFRL/RY ONR	#1 2006 #9 2006
USAFA	FalconSat-5	• Integrated Miniaturized Electrostatic Analyzer (iMESA) • Wafer Integrated Spectrometers (WISPERS) • Space Plasma Characterization Source (SPCS)	USAFA USAFA AFRL/RZ	#26 2006 #31 2006 N/A
AFRL	FASTRAC	• Formation Autonomous Spacecraft with Thruster, Relative Navigation, Attitude & Crosslink	AFRL/RV	#33 2007
NASA Marshall	FASTSAT	• Threat Detection System (TDS) • Thermospheric Temperature Imager (TTI) • Plasma Impedance Spectrum Analyzer (PISA) • Miniature Imager for Neutral Ionospheric Ions and Magnetospheric Electrons (MINI-ME) • Nanosail-D (CubeSat) • Mini-Star Tracker (MST)	AFRL/RV USNA/GSFC USNA/GSFC USNA/GSFC NASA/MSFC AFRL/RV	#28 2008 #55 2008 #57 2008 #59 2008 Mid-SERB Mid-SERB
NSF	RAX	• Radio Aurora Explorer (CubeSat)	NSF/SRI	N/A
NASA Ames	O/OREOS	• Space Environment Survivability of Live Organisms (SESLO) • Space Environment Viability of Organics (SEVO) • Deployable De-Orbit Mechanism	NASA/ARC	N/A

VERIFICATION OF MULTI-PAYLOAD REQUIREMENTS

Interface Control Document Verifications

Verification of interface requirements is a crucial part of a successful mission. Verification begins by properly documenting all requirements. For STP-S26, these requirements were documented in the Interface Control Documents (ICDs). The two CubeSats/P-PODs on the Stage 4 rocket motor each had their own ICD, whereas, the Space Vehicle to Launch Vehicle (SV-to-LV) ICD included interface requirements for the four SVs on the MPA and the DSS/Ballast on the HAPS cylinder. The first draft of the SV-to-LV ICD was delivered approximately 20 months prior to launch. At the first ICD line-by-line review, the accompanying Requirements Verification Matrix (RVM) was not reviewed by the team. An early review of the RVM by all parties involved would have mitigated many of the STP-S26 requirements verification issues.

The combination of eight items being attached at three different interfaces resulted in confusion as to which requirements applied to which satellite. The Program Office (PO) responded by making sure the RVM included one requirement line item per spacecraft, even if the requirement applied to all items. In the future STP will request separate ICDs for each LV interface controlled in order to make requirements and interfaces more definite.

Requirements Verification Issues

The STP-S26 Program Office encountered many requirements verification problems that could have been mitigated by clearly establishing and enforcing expectations, and/or providing guidelines to which the SV teams could work. Some specific examples are:

- The PO should have enforced the requirement for an SV to deliver environmental test procedures to the PO no later than two weeks prior to testing. Two weeks were required to ensure the environmental tests showed testing would meet the mission requirements. By not delivering test procedures two weeks prior to testing there was not enough time to receive comments from the PO. This should have delayed testing. SVs teams that completed testing without PO concurrence were not inclined to re-test if the PO thought it was necessary, as the cost and schedule impacts were too great.
- The PO should have established the expectation that SV teams should not break configuration of the SV after environmental testing, and especially after permission to ship to the launch site has been granted by the STP Director. All three secondary MPA SVs performed post-environmental-testing disassembly and repair of their spacecraft without authorization of the program office. After the Program Office was informed, spacecraft providers resisted workmanship/regression testing required by the PO/Aerospace per MIL STD 1540E. In one case the incident occurred after requirement

verification was completed, necessitating re-verification.

- The PO should have provided guidelines for test reports, test procedures, and SV modeling. Significant problems occurred on the STP-S26 mission in areas, including: Finite Element Model (FEM) correlation; mass properties testing, data reporting, and data reduction; and SV dimension verification method that could have been mitigated with established guidelines. STP is considering writing a secondary payload user's guide or creating a library of example documents our SVs can use as guidance.
- Resistance was encountered when additional information was requested of the SVs when it came time to verify requirements. The roles of all STP personnel (government, military, contractors, and Aerospace) should have been made clear to the SV teams at mission kick-off and re-iterated throughout the program. This would have set the expectation that Aerospace will be asking probing questions and looking for additional insight.
- The PO should have enforced the requirement that the requirements verification package be received 30 days prior to the Pre-Ship Review (PSR). The requirements verification effort did not begin until after all SVs completed environmental testing. It would have been beneficial to begin verification earlier. Requirements verification was started late; therefore, verification was not complete in time for any of the SV PSRs. This caused all SVs to have a lien against their PSR until all ICD requirements were verified. An early RVM review with SV teams should have been performed. This would have provided a time to define required/appropriate artifacts. An actual verification artifact name could then have been assigned in the RVM. This would have prevented a lot of confusion on the SVs part and saved time spent arguing over the appropriateness of artifacts. Appropriately defined artifacts with an assigned estimated completion date (ECD) could have been put into the deliverables list, which was tracked by the PO. This would allow verification to begin as soon as the artifact was generated.
- STP only tracked the verification status of the SV requirements, not the LV requirements. In fact, at the Final Readiness Review (FRR), only the SV verification status was reviewed. In a late version of the ICD, the LV provider relinquished responsibility for attaching lower halves of the Motorized Lightband (MLB) to the SV providers. In the process, an LV requirement verification that was supposed to happen in conjunction with the MLB attachment was dropped. This requirement was to verify resistance across the interface. It remained on the LV requirements list and was never noted on an SV list. During integration, personnel at the launch site had to improvise a solution to produce the required artifact. The Program Office should have maintained insight into what LV requirements needed to be verified at the range so even if the team missed the transfer of responsibility for a requirement everyone could still see the requirement remained to be verified. As mitigation, STP will ask for the LV RVM status from the LV provider two weeks before the start of field site operations. As an additional mitigation, when requirements change in the ICD, STP will confirm the party responsible for requirement verification is correctly identified.

COMMUNICATION ACROSS TEAMS

When dealing with multiple organizations, as with the STP-S26 mission, communication across all teams with different functions can be a daunting task. The STP-S26 Program Office was the communication node that routed the necessary information to the appropriate parities. Some teams tried using mass e-mails as means of communication, sending every single piece of data to every person even remotely involved in the mission. This should be avoided at all costs to help control floods of irrelevant information into email inboxes. Our approach was more difficult to implement, and required a great deal of discipline to ensure timeliness and accuracy, but was much more effective at accomplishing our goals.

Another essential tool for effective communication is a web-based file sharing system. Large attachments cannot be e-mailed on most systems making a file sharing system necessary. The two main technical considerations for any file sharing system should be accessibility and maintenance. Most government based file share systems will limit certain types of file sharing. Maintenance of accounts/passwords and file structure was time consuming for the hosting organization. Early determination of mission needs is required to identify an appropriate file sharing method.

RISK MANAGEMENT PROCESS

The Program Office took charge of compiling and tracking all important risks from different aspects of the mission including SV's, CubeSats, Launch Vehicle, Ground System, and Launch Range. Risks were rated according to likelihood and consequence using a unique 5x5 matrix designed specifically for STP. (See Tables 2 and 3 for the metrics used to rate risks on the STP-S26 mission) The scale used to rate risks uses higher likelihood percentages than standard Air Force missions

because STP, as an R&D organization is inherently more risk tolerant than other programs.

Table 2: Consequence Metrics used for STP-S26 Risks

Level	Technical Performance	Schedule	Cost	Impact on Teams
Negligible	Minor affect or no impact	Minor slip; no impact to key schedule milestone	< $10K or minimal	None
Minor	Ability to meet experiment req'ts affected; performance degraded	Slip affecting minor milestones; still able to meet key need dates	$10K - $50K or <5%	Some Impact
Moderate	Inability to meet some experiment req'ts; individual experiment affected	Minor slip affecting key milestones/minor impact to launch date (<1 week)	$50K - $200K or 5-7%	Moderate Impact
Serious	Inability to meet functional req'ts of key experiments	Major slip affecting key milestones/critical path schedule/launch impact (4-6 weeks)	$200K - $1M or 7-10%	Major Impact
Critical	Mission failure or unacceptable experiment performance	Inability to meet major program milestones/launch impact (>6 weeks)	>$1M or >10%	Unacceptable

Table 3: Likelihood Metrics used for STP-S26 Risks

Very Likely	> 50% chance of an occurrence
Likely	25% to 50% chance of occurrence
Possible	10% to 25 % chance of occurrence
Unlikely	4% to 10 % chance of occurrence
Very Unlikely	1% to 3% chance of occurrence

All organizations use their own specific risk matrix definitions and it is important to normalize all mission risks, regardless of source, using a standard definition for risks. It is important to identify the mission risk definitions at the beginning of the mission. Be aware that when briefing risks, the audience may not be familiar with the mission risk definitions because they may be used to their own risk definitions. Define risk definitions early in briefings to avoid confusion.

With a multi-payload mission it is important for one organization to hold one set of overarching mission risks. This helps to separate out mission level risks from individual team risks.

INTEGRATED OPERATIONS

Importance of Mechanical Fit Checks

Fit checks are vital to risk reduction for multi-payload missions. They check for interference from hardware such as other SVs, harnesses, integration equipment and tool access. Fit checks can also be used to verify pin-outs of flight hardware, attachment points, and proper use of male-female connectors as well as connector screw posts.

STP-S26 held multiple fit checks to ensure all of the payloads and the launch vehicle would integrate seamlessly at the launch site. Initial analysis was completed using Computer Aided Design (CAD) models to determine whether the SVs were within their allowable volumetric space. Following the CAD analysis, physical models were used in conjunction with the integration procedures at the fit checks.

STP-S26 discovered it is absolutely necessary to include all protrusions into high fidelity CAD models. Some details were left off SVs CAD models which made it impossible to determine the effect of the omissions using only CAD models. In one case, the risk was compounded when the PO discovered that omissions were made on two MPA satellites on adjacent faces. Protrusions from both satellites required further analysis of the volumetric representation and the tip off analysis. It also became higher concern during the physical model fit check. Luckily as it turned out, the protrusions did not require changes to the design.

The process used during the fit check should be the same process used at integration. The order of integration was different during the SV to LV integration for the DSS hardware. The new order of integration was not analyzed for interference until the actual integration. Fortunately, no issues materialized at the launch site.

The same cannot be said of the interference between FalconSAT-5's Remove Before Flight (RBF) items and an accelerometer on the MPA plate. This interference was not previously identified because the accelerometer was not included in the CAD analysis or fit checks. The removal of RBF items resolved the interference.

As we learned with every single one of our SV's, CAD models and diagrams can only take you so far. The completeness of the CAD model is important. Items recommended for inclusion in CAD models are RBF items, harnessing, tool access, Ground Support Equipment, separations systems, hydrasets, cranes and platforms.

Logistics of Sharing a Payload Processing Facility

STP-S26 was launched from a remote site that required integration for seven satellites and one technology demonstration, as well as the launch vehicle. With so many moving pieces of this multi-payload mission, much logistics planning went into scheduling each satellite's arrival and pre-launch checkout in the shared Payload Processing Facility (PPF). Sound logistical practices of satellite arrival and efficient satellite processing were key events which led to a successful and timely launch. Without this, the shipping and

processing operations could have led to serious problems impacting the launch campaign schedule or potentially put personnel and hardware at risk. The STP-S26 Program Office realized early in the planning stages there would be a number of issues if all satellites shipped and arrived simultaneously. Some factors considered in development of the processing schedule for the remote launch site were manning restrictions, area constraints for satellite activities, and amount of time needed for processing.

Margin was built into the launch campaign schedule to effectively stagger the satellites throughout functional testing and integration, while still maintaining the integrity of the subsequent milestone events leading to launch. It was imperative to give teams enough time to enter and process in the PPF. However, it was also important not to leave too much margin in between events. By decreasing the amount of margin between teams leaving and entering the facility to a reasonable amount, hundreds of thousands of dollars were saved. If teams needed more time than was allotted to them they were able to work with the incoming team to de-conflict with each other's hazardous operations and work simultaneously.

Careful consideration of the remote launch site had to be taken into account when scheduling arrival of personnel and equipment. Shipping took several days to KLC and personnel usually took at least a day to travel there. It was not uncommon for flights to Kodiak to be cancelled due to weather restrictions which added complexity to scheduling.

At the launch site, small incidences could have become huge impacts to the mission. Staggering the date of satellite arrivals helped control the PPF environment and limit the number of moving parts during day to day operations. Staggering satellite arrival also offered respective satellite program offices enough time to enter the receiving bay to the payload processing facility, unpack and clean all items, safely move the satellite and equipment into the designated location within the processing facility, then begin functional testing. Once moved into the processing facility, the next satellite arrived and started the process over again. The maximum amount of satellites arriving at the receiving bay at any time was two. This process of staggering alleviated concerns of equipment being damaged or mishaps concerning personnel/hardware occurring.

A manning restriction was in place to help minimize the number of particulates brought into the clean room. In addition to restricting the number of personnel allowed in the PPF, the work space was also limited. Specific areas were designated to each satellite team to organize the flow of traffic during entry into the PPF and mate onto the integrated payload stack.

Multi-Satellite Mate Procedures

The multi-payload mate operation was one of the riskiest procedures run on the STP-S26 mission. Several SV teams, operating independently and in close proximity of each other made for a tense time for all. To mitigate risk, the procedures were scrutinized, rehearsed together, edited, and scrutinized again. This mate rehearsal was critical in that several procedures were identified that were mutually exclusive and required de-confliction from several parties. Several possible safety violations were noted and procedures had to be re-written to take those into account.

Some issues still developed at the launch site despite the effort put into risk mitigation. In original procedures and rehearsal, a RBF item was not taken into consideration. By itself this would have been a non-issue, but a last minute harness re-routing (a very minor and fully vetted change) proved a holdup during the mate procedure when the RBF item could no longer fit on the MPA plate. A work around was established, but that showed us that in CAD modeling RBF items must be properly modeled.

Another issue was lack of familiarity with procedures. We took for granted that the same teams who attended the rehearsal payload mate would be the ones performing the procedure at the launch site. A delay of several months resulted in personnel turnover on many of the teams, also causing valuable experience to be lost. A pre-mate readiness review was held to ensure procedures matched, and all teams were ready, which helped to ensure everyone was on the same page. Nothing could replace the experience of actually previously performing the mate operations. While no damage occurred, there were several tense moments as neophyte teams paused to figure out the mechanics of their next step.

In the end all satellites were successfully mated with no mishaps. Figure 4 shows a photo of the full Integrated Payload Stack (IPS). The four ESPA-class satellites are mated to the MPA plate located on top of the HAPS.

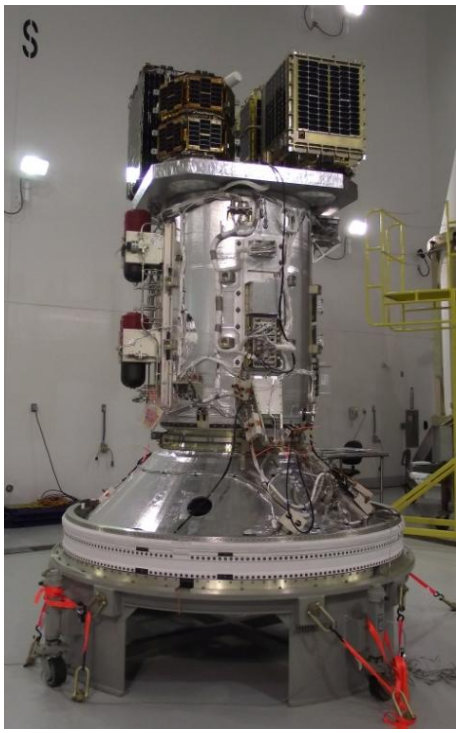

Figure 4: Integrated Payload Stack

LAUNCH CONJUNCTION ASSESSMENT SUPPORT PACKAGE (LCASP)

To ensure that the STP-S26 mission was launched safely from Kodiak, AK into its intended orbit, the launch team worked closely with the Joint Space Operations Center (JSpOC) located at Vandenberg AFB, CA. By performing a conjunction assessment, the JSpOC verifies that the mission will not encounter any known objects in space during the launch and deployment sequence.

Mission data provided to the Joint Space Operations Center for conjunction assessment was delivered in the LCASP. The STP-S26 Program Office did not have an Air Force Instruction describing the information required for the LCASP. Therefore, the STP-S26 Program Office utilized the last multi-satellite mission (STP-1) as a LCASP template. This created a challenge because it was unclear which STP-1 mission data fields were standard and which were mission unique or variable based upon launch vehicle or some other mission component. Obvious standard mission data included mission objects that would attain an orbital altitude such as the six satellites, ballasts, launch vehicle upper stage and the Hydrazine Auxiliary Propulsion System (HAPS). The not-so-obvious mission unique data included the launch dispersion screening criteria for collision avoidance (COLA) associated with launch vehicle variations and the probability/miss distance requirements.

An example of launch vehicle dispersion screening variations is provided by comparing the STP-1 Atlas V launch vehicle to the STP-S26 Minotaur IV launch vehicle. The launch COLA, required for screening the Atlas V, required +/- 5 second launch dispersion versus the Minotaur IV +/- 1 second launch dispersion. The team identified the difference during interface meetings with the JSpOC. Using the Atlas V requirements for the Minotaur IV would have caused JSpOC to over analyze the launch COLA for STP-S26.

The probability and miss-distance requirements are directed by Air Force Instruction (AFI) 91-217; however, AFI 91-217 did not specify launch COLA requirements for inactive satellites and debris. Additionally, the Range Control Officer and Mission Director required slight differences for launch COLA requirements. The Range Control Officer required miss distance for inactive satellites and debris, while the Mission Director required a probability of collision that was more restrictive ($< 1 \times 10^{-7}$) than AFI 91-217 ($< 1 \times 10^{-6}$). COLA products provided by the JSpOC were based upon miss distance probability calculated only for mission components violating the miss distance criteria. In contrast, Aerospace provided an independent COLA based on collision probability with the miss distance calculated for each instance identified in their COLA. To satisfy all the mission launch requirements, both COLAs were utilized for launch.

SPACE DEBRIS ASSESSMENT REPORT (SDAR)

With twelve objects to analyze, distributed among eight mission partners, the initial challenge in producing the STP-S26 Space Debris Assessment Report (SDAR) was coordinating data deliveries and bringing the analysis results together in a clear, coherent document. Initial requests for information were made about two years prior to launch and the first draft of the document was ready for review in September 2009. After this initial draft document was produced, two significant policy changes occurred that precipitated a reporting of our draft and altered reporting.

In February 2010, AFI 91-217 was released followed in June by the National Space Policy of the United States of America. These documents updated space debris requirements and the process for gaining approval to launch with policy violations. These changes were enforced by the Air Force immediately, having a great impact on the STP-S26 mission. Analysis of the twelve objects that the mission would place in orbit had identified multiple violations of the orbit lifetime requirement. Eight of the twelve STP-S26 objects would not de-orbit within 25 years of completing their missions. Additionally, one object would violate the limit defined in AFI 91-217 specifying the maximum

probability of collision with large objects over its orbit lifetime (0.001).

Prior to the new policies, the STP-S26 Program Office was already seeking risk acceptance from the Space and Missile Systems Center (SMC) Commander for objects that did not comply with the 25-year de-orbit requirement. Under the new Space Policy, the mission was required to seek an exception from the Secretary of Defense to allow for violations of the orbit lifetime requirement, greatly complicating the process.

In order to launch with these policy violations the STP-S26 mission had to demonstrate that there were no viable alternatives that could meet mission objectives and be implemented within schedule and budget constraints. A number of options were explored. For the primary orbit (650 km, circular) they included: 1) adding de-orbit technology, 2) adding or using thrust to de-orbit, 3) changing the mission orbit profile. For the secondary orbit (1200 km, circular) the only alternative option was to change the mission orbit profile.

As is often the case on Space Test Program (STP) missions, most of the STP-S26 spacecraft were near completion by the time these policy violations were identified, so their designs could not be modified to add de-orbit mechanisms within the timeframe and budgets available. Also, any change to payload design would mean a change to final mass properties, resulting in the need for a new coupled loads analysis, significantly impacting mission schedule and cost. Three of the satellites and the two launch vehicle upper stages had existing thrust capability, but none of these objects possessed sufficient thrust to meet their mission objectives and perform a de-orbit maneuver. Changing the mission profile was not feasible for either orbit since both the primary and secondary orbit altitudes were required to meet mission objectives. Note that the mission was designed around the primary payload, STPSat-2, which did not have any policy violations; other spacecraft, taking advantage of a ride-share opportunity, could not influence the orbit profile.

Being among the first SMC missions made to comply with the new requirements, the process for submitting a request and pushing it through the chain of command was not well defined. At the time the STP-S26 policy exception request was being drafted, the SECAF was addressing launch vehicles with a fleet exception to policy request. Because STP-S26 did not meet the fleet definition their request was submitted separately. After multiple iterations of staff packages and nearly three months of tracking through the chain-of-command, the Office of the Secretary of Defense approved the policy exception November 10, 2010, the day of the STP-S26 Flight Readiness Review.

With heightened interest on the crowding of orbits often used by the small satellite community, the STP-S26 mission is evidence that the future holds ever-increasing scrutiny of space debris policy violations. Both primary payloads and rideshare partners should consider all options available to ensure compliance. STP is currently funding a Small Business Innovation Research (SBIR) project to develop a deployable de-orbit mechanism for use by ESPA spacecraft residing at altitudes up to 800km.

INTEGRATED TIPOFF, SEPARATION, AND RE-CONTACT ANALYSIS

The design of the SV deployment sequence, to mitigate issues with tipoff, separation, and re-contact presented a unique challenge for the STP-S26 mission.

The highest priority was to ensure the safety of STPSat-2, the primary payload. It was deployed first in the sequence, minimizing the opportunity for contact with other vehicles on the MPA. Also, deploying in the $+\vec{V}$ direction, it drifted significantly behind the other spacecraft that followed. The remaining spacecraft were then deployed in the $-\vec{V}$ direction in order of decreasing along-track component of $\vec{V}$.

The ESPA-class satellites were to be separated in order of highest delta-v to lowest. This was complicated by dual-path. To meet schedule, the design had to be finalized prior to selecting the fourth ESPA spacecraft, so the same deployment order had to provide acceptable results whether the 147 kg FASTSAT-HSV01 or CUSat, with a mass of just 52 kg, occupied the final slot.

To ensure good separation between objects and mitigate re-contact in the first few orbits, the difference in separation velocity between spacecraft was designed to be greater than 5 cm/sec. However, since the Motorized Lightband (MLB) separation system used by the four ESPA spacecraft (Seen in Figure 5) was a long-lead item, decisions for the number of springs used to achieve the desired separation velocity had to be made based on early estimates of SV mass. The placement of springs around the Lightband, which is optimized to balance the force imparted on the spacecraft and mitigate the effects of spacecraft center of gravity (CG) offsets, also had to be decided using early estimates of spacecraft CG locations. This increased the risk of spacecraft contact during deployment due to tipoff rotations.

Figure 5: Deployed Motorized Lightband

Additionally, separation of the ESPA-class spacecraft produced off-axis forces on the LV stack resulting in rotation that had to be considered in the final tipoff analysis. This also resulted in rates that had to be nulled prior to the next separation, affecting separation timing.

Ultimately, complications arising from the dual-path manifest and the need for early procurement of each spacecraft's MLB separation system resulted in the need for an additional launch vehicle maneuver to deploy two satellites 30° off $\vec{V}$ to ensure good separation. The final mission launch profile and timeline is shown in Figure 6.

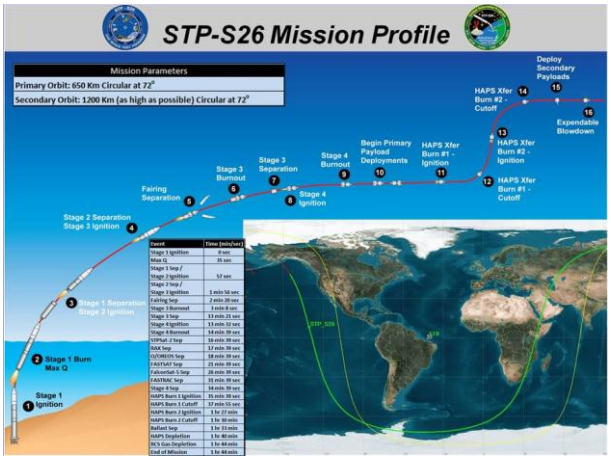

Figure 6: Mission Profile

Results vs. Expectations

The STP-S26 deployments were successful in the sense that the satellites continued to separate from one another after deployment. Two Line Element Sets (TLEs) for each of the spacecraft a few days following the deployments were used to determine the relative drift rate between the satellites and from this the difference in their deployment $\Delta\vec{V}$s. However, there was a wider than expected difference in the $\Delta\vec{V}$s of consecutive deployments.

STPSat-2 was deployed in the opposite direction of the rest of the satellites so there was little concern about its re-contact with the others. The expected $\Delta\vec{V}$ difference between STPSat-2 and FASTRAC was 53.8 cm/sec, but the actual difference was 42.5 cm/sec. This may be attributable to some un-modeled $\Delta\vec{V}$ imparted to FASTRAC as a result of the re-orientation of the upper stage.

The expected $\Delta\vec{V}$ difference between FASTRAC and FalconSat-5 was 16.3 cm/sec while the actual difference was 10.2 cm/sec. Again, the difference between the expected and actual result could be the result of the 30° re-orientation prior to the FalconSat-5 deployment. Since the expectation vs. actual is greater than 5 cm/sec, which was used as a minimum difference in the deployment planning, this could be an indication that the minimum separation in the $\Delta\vec{V}$s during planning should have been increased beyond 5 cm/sec, and a better understanding of the effects of the re-orientation on orbit is needed.

The expected $\Delta\vec{V}$ difference between FalconSat-5 and FASTSAT was 12.8 cm/sec while the actual difference was 8.8 cm/sec. While the discrepancy between expected and actual is less than the 5 cm/sec planning buffer, it approached that buffer, and since no re-orientation took place between these deployments, the difference must be attributed to errors in the deployment modeling. Again, arguing for an increase in the 5 cm/sec buffer when planning for multiple deployments.

CONCLUSION

Though STP-S26 was a successful mission there were many stumbling blocks along the way that could have jeopardized the mission. Nearly 100 lessons learned were documented to aid in future multi-payload missions. As STP continues to fly ground breaking experiments we hope that the lessons learned on STP-S26 have helped to pave the way for multi-payload missions that will fly the futures technology.

References

1. *15 inch Motorized Lightband Deployed*. Planetary Systems Corporation. 6 June 2011. <http://www.planetarysystemscorp.com/downloads.htm>.