STPSat-1: The First Space Test Program Mission to Capitalize on the New ESPA Secondary Launch Capability

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ABSTRACT
The Space Test Program Satellite-1 (STPSat-1) mission is the first STP mission explicitly designed to utilize the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). At this writing, STPSat-1 is fully operational on-orbit, after being integrated with the ESPA ring and payload stack earlier this year, prior to a successful launch on March 8, 2007 aboard an Atlas V launch vehicle (AV-013 / STP-1).

The STPSat-1 space vehicle hosts two DoD experiments, SHIMMER and CITRIS, both built by the Naval Research Laboratory (NRL).

This paper summarizes the multitude of technical challenges encountered by the STPSat-1 team during the development cycle, including designing to the highly-constrained and uncharacterized ESPA environment, accommodating the restrictions imposed on secondary payloads for non-interference with a primary payload, and range safety challenges including new rules for Lithium-ion battery usage. It will also address the organizational and integration challenges inherent with being one of six spacecraft on a DoD EELV launch.

Because STPSat-1 is launched on the first flight of ESPA, these results translate into valuable lessons-learned for the small satellite community as they consider additional missions to capitalize on the new ESPA launch capability.

INTRODUCTION
AeroAstro’s STPSat-1 is the first commercially developed spacecraft designed and fully qualified for compatibility with the ESPA developed by the USAF. STPSat-1 was successfully launched on March 8, 2007 (see Figure 1). The primary mission objectives of STPSat-1 are: to provide a successful one-year duration mission in the target orbit after a one month checkout, that satisfies the two on-board experiments’ nominal success criteria; to aid STP’s objective of “Getting technology to space for the war fighter,” and to provide a pathfinder for future STP ESPA missions. After the first year, the payload sponsors or another organization may fund on-going operations with STP’s approval.

STPSat-1’s primary experiment, built by the Naval Research Laboratory (NRL) in Washington, D.C. is the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER), a high-resolution ultraviolet spectrometer based on the new optical technique known as Spatial Heterodyne Spectroscopy (SHS). It will demonstrate that SHS facilitates the design of low mass, low power, low volume, high throughput spectrometers for space-based remote sensing. SHIMMER will image the earth’s limb at low and mid latitudes, measuring the hydroxyl (OH) resonance fluorescence around 308nm. These long-term, global-scale measurements will contribute significantly to the small set of existing atmospheric OH observations. These will help to answer the numerous outstanding questions about the chemical and dynamic processes in the middle
Atmosphere, allowing better model validation and forecasting capabilities.

Figure 1: Atlas V AV-013 / STP-1 Launch on March 8, 2007

The secondary experiment, also built by NRL, is the Computerized Ionospheric Tomography Receiver in Space (CITRIS), a four frequency receiver connected to an antenna located on the top face of the STPSat-1 satellite. Transmissions from Coherent Electromagnetic Radio Tomography (CERTO) beacons located on other space vehicles including the PICOSat, C/NOFS (not yet launched), and six (6) COSMIC satellites, are detected by the CITRIS receiver to provide measurements of satellite-to-satellite Total Electron Count (TEC) and signal fluctuations. There are also more than 20 other orbiting beacons that may be monitored such as the Navy Navigation Satellite System (NNSS) TRANSIT and Russian COSMOS constellations along with the Russian NADEZHDA and TSIKADA satellites. Occultation of the earth’s ionosphere can be used to derive electron density profiles from the TEC measurements. The receiver will make both amplitude and phase measurements to provide scintillation data at Very High Frequency (VHF), Ultra High Frequency (UHF), and L-Band frequencies.2,3

A third experiment, the Micro-Electro-Mechanical (MEMS)-based Picosat Inspector (MEPSI), was de-manifested in October 2006. The Picosat Launcher Assembly, or PLA, is flying with the space vehicle and contains two inert mass simulators instead of Picosats. The mass simulators will remain within the PLA and will not be released any time during the mission.

The Space and Missile Systems Center’s (SMC) Space Test Group located at Kirtland Air Force Base in Albuquerque, New Mexico provides command and control of the spacecraft throughout all phases of the mission from the Research, Development, Test & Evaluation (RDT&E) Support Complex (RSC). The RSC is a multi-mission satellite operations center (SOC) providing on-orbit services for USAF research and development space vehicles. The Air Force Satellite Control Network (AFSCN) provides telemetry, tracking and commanding services to the STPSat-1 mission. The Space Test Group coordinates with the AFSCN through the mission planning function to schedule passes (supports) and other required services.

SPACECRAFT OVERVIEW

The STPSat-1 space vehicle (see Figure 2) consists of seven spacecraft subsystems and the three payloads, SHIMMER, CITRIS, and the MEPSI PLA. The seven spacecraft subsystems are 1) Mechanical, 2) Power, 3) Thermal, 4) Command and Data Handling, 5) Software, 6) Communications, and 7) Attitude Determination and Control. Each payload is considered a separate subsystem and is integrated onto the spacecraft within a structural component identified as the payload module. The integrated spacecraft and payloads make up the complete space vehicle system.

The space vehicle is designed to provide a stable platform for on-orbit operations of the science instruments while meeting technical and mission requirements. The space vehicle mass at launch was approximately 164 kg, and is approximately 63 cm x 63 cm x 98 cm in size (solar panels stowed). The power subsystem delivers approximately 171W of average orbit power @ 28V with the solar arrays deployed. A picture of STPSat-1 in its stowed configuration is shown in Figure 3.
The space vehicle is designed to operate as a nearly autonomous system. Each of the subsystems is configured to monitor failure modes and recognize anomalous situations for autonomous execution of saffing commands.

ESPÀ INTERFACE

STPSat-1 is mechanically attached to the ESPÀ ring using a standard Lightband separation system provided by Planetary Systems Corporation. The Lightband attaches to both STPSat-1 and the ESPÀ with 24 (twenty four) ¼” diameter bolts in an equally spaced 15” diameter bolt pattern as shown in Figure 4. The Lightband is activated by heating and cutting a retaining line. When the line is cut, spring loaded clamps open up, allowing springs to separate the two halves of the device.

Use of the Lightband presented unique challenges for access to the Lightband when STPSat-1 was mounted to the ESPÀ, or an ESPÀ-like simulator. Limited access between the integrated STPSat-1/Lightband and the ESPÀ ring presented a problem for attaching the Lightband to the ESPÀ ring. To mitigate this, AeroAstro sent the STPSat-1 Engineering Development Unit (EDU) structure with the Lightband to Boeing, the STP-1 Integrating Contractor for a trial fit on the ESPÀ ring during development phase of the spacecraft bus. The fit check and integration were successfully accomplished with few problems. Shortly after this fit-test was performed, the launch vehicle was changed from a Delta IV to an Atlas V. Fortunately, the change in the launch vehicle had no bearing on this access issue because the same ESPÀ ring was used for the STP-1 launch.
ESPA MECHANICAL ENVIRONMENT

Another challenge faced by the STPSat-1 design team was that the ESPA ring was not well characterized (in the satellite design phase) in terms of launch loads that would be transferred to the ESPA satellite payload. If the ESPA launch environment is characterized too late in the development phase, then there is a strong probability that the spacecraft and payloads may either be over-designed or under-designed. Specifically, if the space vehicle is over-designed, then it may have a higher mass than necessary. If under-designed, then the space vehicle or payload structures may need to be later reinforced or redesigned resulting in a schedule and cost impact.

AeroAstro worked with the STP-1 Integrating Contractor and The Aerospace Corporation to determine the launch environment, and design and test the space vehicle with adequate safety margins. However, the change in the launch vehicles from Delta to Atlas meant that the previous coupled loads analysis used to design the EDU structure testing had to be redone. Unfortunately, this was not completed until after the flight structure was built, and shortly before the start of its random vibration testing. Regardless of the revised launch loads, the spacecraft was designed to withstand a quasi-static load of 10.6 g in any two axes simultaneously. AeroAstro had no choice but to continue to design to these levels. Even if these levels were to be reduced in the future, schedule constraints prevented any changes to the spacecraft design.

The path forward was to increase test levels for the vehicle by using guidelines in Mil-Hdbk-340A for unit qualification testing to provide some test margin, testing the flight structure to Proto-Qualification (PQ) levels. The flight structure was successfully tested (with mass models for avionics and payloads) in May 2004. However, PQ levels were later reduced for the space vehicle random vibration testing.

Full verification was accomplished by a combination of space vehicle vibration testing (successfully completed in May 2006), unit-level vibration testing of flight equipment, and vibration testing of the Flight Structure in performed in May 2004.

SECONDARY PAYLOAD DEPLOYMENT ISSUES

STPSat-1 was one of five spacecraft to be deployed via the ESPA ring on the STP-1 mission. The Integrated Payload Stack (IPS) included the four ESPA spacecraft (STPSat-1, MidStar-1, FalconSat-3, Cibola Flight Experiment [CFE]), and one non-deploying mass model (NPSAT-1) along with the larger payload, Orbital Express, that consisted of two spacecraft (ASTRO and NextSat). STPSat-1 on the IPS is shown in Figure 5 as the left-most space vehicle on the ring (bottom). The Atlas/Centaur first released Orbital Express and one of the ESPA payloads (MidStar-1), then performed an altitude and plane change and then released STPSat-1 at a target circular orbit of 560 km ± 7.5 km altitude with an inclination of 35.4° ± 0.5°.

The complex STP-1 secondary payload deployment sequence was found to present challenges due to a number of factors including separation time constraints, a possible pyroshock event from separation of the primary payload, and possible interference with the launch vehicle’s transponder.

The separation time constraints relate to the long period that STPSat-1 remained on the IPS before deployment (deployment at Launch+3388 seconds), and presented a potential thermal issue for STPSat-1. Fortunately, the IPS maintained a “rotisserie” roll normal to the sun. This IPS roll kept STPSat-1 within its thermal specifications. Other STPSat-1 time constraints...
included consideration for additional ADCS performance to counteract larger tip-off rates if the Launch Vehicle rate damping was cut short. Also, STPSat-1 required deployment either in the IPS velocity vector or anti-velocity vector direction, which was accommodated on STP-1. Another time constraint consideration for the STPSat-1 deployment included delta-velocity separation and a timed delay on the automatic solar array deployment to allow proper physical separation of the space vehicle from the IPS, to minimize the chance for contamination from any residual plume.

As mentioned previously, Orbital Express (OE) was deployed from the Atlas/Centaur before STPSat-1. OE deployment presented a shock event (separation from the Atlas/Centaur) and provided a shock spectrum, but not until well after STPSat-1 had begun integration. The risk here was that some STPSat-1 components may not have been compatible with this shock environment. Therefore, AeroAstro undertook a component shock study to determine the presence of shock sensitive components (e.g., crystals, ceramics, relays, etc), their location on the STPSat-1 spacecraft, and review heritage shock qualification data, as available. Using pyroshock environment data at the ESPA ring interface provided in the report from the STP-1 Integrating Contractor, AeroAstro predicted the shock input to sensitive components by analysis and determined if component testing was necessary for shock sensitive components. This analysis showed that additional testing was not necessary. The Aerospace Corporation conducted an independent assessment based on the predicted shock environment. Based on the results of the analysis, Aerospace concluded there was low-medium risk to the spacecraft due to the lack of shock testing at the unit or integrated spacecraft level. The Air Force customer opted to accept the mission risk in lieu of adding more testing to the program, as well as possible integration schedule delays.

Another potential source of damage from the LV was identified late in the program. A launch vehicle transmitter, at S-band, was in close proximity to STPSat-1 and radiated at a power sufficient to cause damage to the space vehicle’s communication equipment. To mitigate this for the accent phase, AeroAstro implemented a 45 second delay before boot up to allow for spatial separation to preclude any damage to the communication equipment from the launch vehicle’s transmitter.

LAUNCH RANGE SAFETY CONSIDERATIONS

STPSat-1 was launched from Cape Canaveral, and therefore, was required to be compliant to the Launch Range Safety Document EWR 127-1. Range safety considerations had particular significance, due to the number of satellites associated with the STP-1 launch.

To satisfy range safety requirements, AeroAstro was required to submit a number of documents demonstrating compliance to safety considerations. Prominent among these documents was the Missile System Prelaunch Safety Package (MSPSP). This comprehensive document addressed many aspects of the space vehicle flight hardware subsystems, and the ground support equipment which is used for launch site operations. For this document, STPSat-1 was required to provide a list of hazards associated with the spacecraft and all safety critical functions associated with spacecraft. In addition, the space vehicle had to include a hazard category and likelihood of the hazard occurrence. If needed, a hazard analysis was required to show design controls and verifications.

One area of close scrutiny was the satellite system design which prevented unintentional deployments while integrated with the launch vehicle prior to launch (e.g., solar arrays, antennae, etc.), and unintended power-up of the satellite resulting in RF transmissions harmful to the launch vehicle and other integrated satellites. STPSat-1 has multiple levels of ‘inhabits’ for both deployment events and RF transmissions and complied with EWR 127-1 by having at least two inhibits present to prevent deployments (critical hazard), and two inhibits to prevent RF transmissions at all times when safety devices (Safe Plugs) were not in use. Some of these inhibits included: arming plugs, separation switch sense lines, and hardware interlock inhibits (e.g., functionality inherent in the design of FPGAs). The STPSat-1 design also included monitor points which allowed detection of an inhibit failure and were actively monitored during pre-launch activities up to four minutes before launch.

One subject of concern to range safety was STPSat-1’s use of Lithium-ion (Li Ion) batteries. Within eighteen months of launch, AeroAstro was presented with the Joint 30/45 SW/SE Interim Policy for Lithium-Ion Batteries. This document defined safety requirements (in addition to those contained in EWR 127-1) for Li Ion battery systems used in flight and aerospace ground equipment (except for those used in UL or MSA-approved appliances). Subjects addressed by this policy letter include Li Ion battery charging and discharging, connection and disconnection, transport, storage, individual cell voltage monitoring, high pressure protection for cells, and evaluation of the batteries/cells for toxic, reactive, flammable and combustible materials. Demonstrating compliance to this new policy letter required intensive effort. AeroAstro, with the help of the battery manufacturer,
COM DEV, provided comprehensive data showing compliance to most of these subjects, but still sought (and was granted) waivers for individual cell voltage monitoring, and testing of cell venting.

The STPSat-1 electrical power system (shunt regulator and battery control electronics) presented a very small parasitic load on the spacecraft batteries at all times, even when the vehicle was powered off. The batteries needed to be charged periodically to keep them topped off, but the State of Charge would slowly drop over time once the battery charging was stopped. To ensure STPSat-1’s optimal configuration of arriving on orbit with nearly fully charged batteries, AeroAstro sought to charge the spacecraft batteries as close to the time of launch as possible. To permit battery charging with the allowable number of inhibits once the Safe Plugs were removed, AeroAstro modified an umbilical harness to allow battery charging while the vehicle was powered off, and still permitted battery voltage monitoring during charging, for range safety considerations.

Although extensive data on the batteries was provided as part of the MSPSP, as well as battery charging procedures, the possibility of the batteries overheating during battery charging was another area of close scrutiny. Initial battery charging on STPSat-1 while mated to the launch vehicle was classified as a hazardous operation (level clear) with a maximum allowable charge rate of C/10 for only 30 minutes. This was well below that required to fully charge the batteries, but established that battery charging could be performed safely. Periods of charging STPSat-1 batteries on the launch vehicle had to be closely coordinated with range safety. In order to gain desired charge on the batteries (94% State of Charge) with these restrictions, the time required to perform battery charging increased. By implementing the procedures and changes described previously, use of the Li Ion batteries at the launch site on STPSat-1 resulted in an optimum battery charge configuration at launch, and no unexpected operational impacts during launch processing.

CONCLUSION

STPSat-1 was successfully launched on March 8, 2007 with the other STP-1 payloads, with no negative effectives due to the use of the ESPA secondary payload accommodation. The spacecraft is fully-functional on-orbit, providing SHIMMER and CITRIS experimenters with data as part of its one-year mission. The success of this space vehicle supports the usefulness of the ESPA approach to enable multiple missions (and orbits) from a single launch. Many of the ESPA and launch site related issues faced by STPSat-1 are likely to be faced by subsequent ESPA missions. STPSat-1’s approaches to these issues are valuable lessons-learned for the small satellite community as they consider additional missions to capitalize on the new ESPA launch capability. From the SMC Space Development and Test Wing perspective, the integration of the entire STP-1 mission presented many unique technical challenges. These were actively worked within the community and valuable lessons-learned will be applied to future ESPA missions.

References