Balancing Capability and Cost on the STPSat-5 Microsatellite Mission

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ABSTRACT

STPSat-5 is a small technology demonstration satellite developed for the DoD Space Test Program, recently launched in December 2018. The STPSat-5 space vehicle is hosting five separate space experiments in Low Earth Orbit on a single Microsatellite platform. This paper discusses the development and operation of the STPSat-5 mission with an emphasis on methods used to achieve high capability with low-cost solutions. The application of CubeSat-class hardware in a Microsatellite-class space vehicle is reviewed. Attention is given to approaches for establishing flight readiness for commercial hardware. In addition, this paper covers lessons learned in adapting heritage flight software for operation on new, lower-cost processor systems as well as suggested testing approaches. Suggestions for interfacing multiple small experiments on a single platform are addressed as well as approaches to data handling. Utilization of a large-scale commercial rideshare mission for launch is also discussed, including guidelines to facilitate space vehicle to launch vehicle integration. The topic of lean mission operations is also covered with suggestions for areas of emphasis, guidance for troubleshooting, and an update on the current operational status of the STPSat-5 mission.

INTRODUCTION

The charter of the U.S. Department of Defense (DoD) Space Test Program (STP) is to provide opportunities to demonstrate and test new space technology to enable increasingly advanced space missions. (1) The last several years have seen rapid growth in space innovation and there is increasing demand to provide space flights for maturing an expanding stable of technologies. At the same time, there is a continued need to improve affordability of space experiments as their numbers grow. Several developments have made these seemingly conflicting objectives a possibility, such as low-cost CubeSat hardware that is scalable to larger platforms, increasing availability of commercial rideshare options, and agile multi-mission operations centers that can be readily configured for new small satellites. The recent Space Test Program Mission 5, STPSat-5, sought to utilize these options for maximum benefit to the DoD. (2) During development and operations of STPSat-5, our team found that a balance between performance and cost, with awareness of the capabilities and limitations of emerging approaches, provides the best chance for mission success.

The STPSat-5 mission was conceived as a means for demonstrating five science and technology payloads from four DoD organizations. The Strontium Iodide Radiation Instrumentation (SIRI) experiment, produced by the Naval Research Laboratory (NRL) sought to demonstrate a new gamma radiation sensor in space. The Ram Angle and Magnetic field Sensor (RAMS), also from the NRL, was developed to demonstrate a new attitude determination sensor for small missions. The integrated Miniaturized Electro Static Analyzer (iMESA), from the US Air Force Academy, was built to collect space weather data to aid mitigation for RF communication and navigation signals. The Rad Hard

Electronic Memory Experiment (RHEME) was developed by the Air Force Research Laboratory (AFRL) to test new radiation hardened memory solutions. The High Bandwidth Anti-Jam Low Probability of Intercept/Low Probability of Detection (LPI/LPD) Optical Network (HALO-Net) payload from the Space and Naval Warfare Systems Command was designed to demonstrate components of a new satellite laser communications system. Each of these experiments had unique hosting requirements that needed to be balanced to fit within the capacity of a microsatellite.

The STPSat-5 spacecraft is based on the SN-50L platform from Sierra Nevada Corporation. (3) STPSat-5 was designed for compatibility with multiple small payloads within the volume allowance of a rideshare mission on the EELV Secondary Payload Adapter (ESPA), and can accommodate a wide range of LEO orbits. To meet the needs of high-performance small payloads, STPSat-5 utilizes several hardware units originally developed for CubeSats and nanosatellites but scaled up for microsatellite mission. The block diagram for STPSat-5, in Figure 1, shows a multiple-processor architecture, including separate small computers for the main avionics, attitude control, and two processors for payload data handling. Other small units utilized for STPSat-5 include a 4 Mbps/ 2 Msps S-band software-defined radio, and a card-sized GPS receiver integrated with the attitude control processor and a small Spacecraft Auxiliary Box for power conditioning and battery protection.

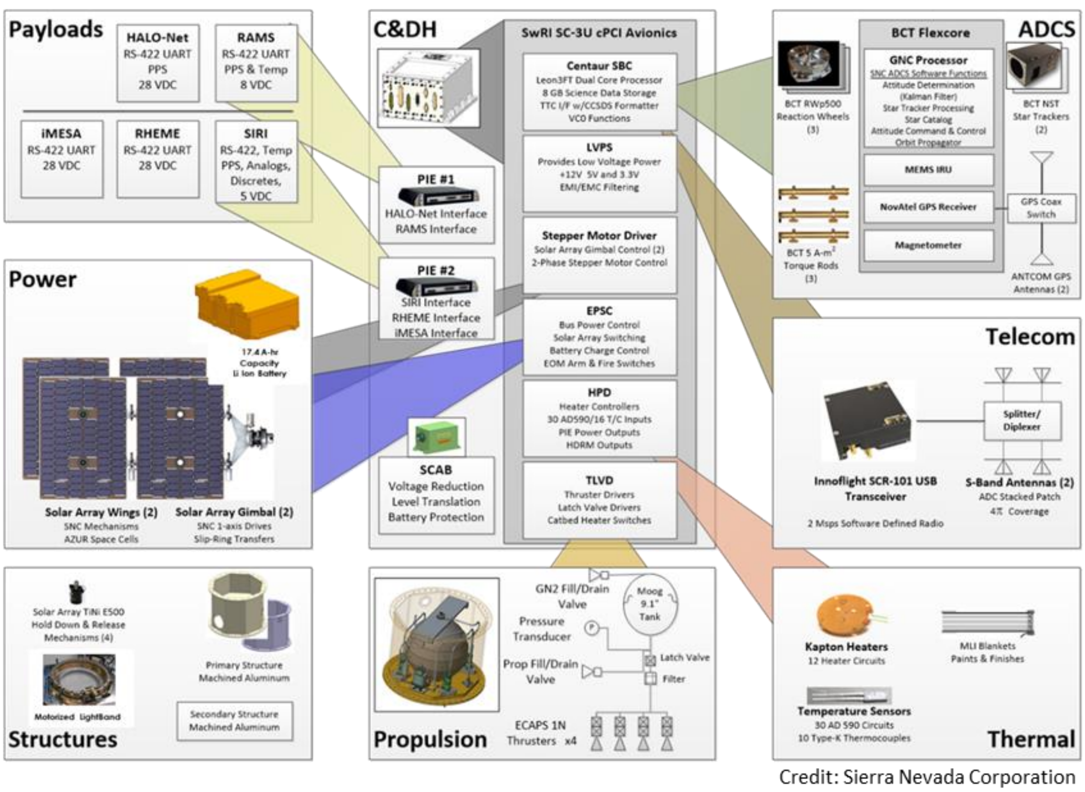

Figure 1: STPSat-5 Space Vehicle Block Diagram (3)

Utilization of newer small electronics on STPSat-5 brought advanced capabilities as well as challenges that needed to be overcome. These challenges included managing the space vehicle resources devoted to the payloads and maintaining high experiment duty cycles. Key space vehicle resources included payload data capacity, payload field of view, and available power. The project team found ways to satisfy the needs of each payload by balancing resources through design and vehicle operations.

Hosting Multiple Experiments on a Single Microsatellite Platform

Hosting five different experiments on a microsatellite presents a distinct challenge for resource planning. Limits on microsatellite capabilities require careful planning to ensure each payload has the resources needed. Since space-capable electronics have improved significantly in terms of size, mass, and required power, it is now possible to host a suite of experiments on a very small satellite. The new challenge for the small satellite community is how to handle these more capable payloads, particularly data handling, integration, and more agile operations.

Five separate experiments brought a diversity and volume of data to be stored and downlinked. To meet this challenge, a standard method of encapsulating data was utilized based on the CCSDS Space Packet Protocol (5), and the mission concept of operations was conceived to manage the collection, storage, and transmission of data to fit within the capability of the processors, data handling subsystem, and communications subsystem. The project established daily data volume allowances as well as limits on payload-to-spacecraft data rates. Experimenters were also requested to provide high, medium, and low data rate options to permit operational flexibility. Through testing with the satellite testbed "Flatsat" and testing on the flight vehicle, further limits were established regarding when experiments could perform large data transfers from the payload to the spacecraft data storage system. Careful attention needed to be paid to coordination of data transfer to avoid packet loss and overutilization of the on-board processors. Data downlinks are also balanced between low data rate ground station passes and high data rate passes to provide enough capacity to transfer the data to the ground in a timely manner while minimizing higher cost high rate passes. For satellite operations, high rate passes are typically planned after critical or data intensive events.

To simplify payload to spacecraft integration and provide the required instrument field of view access, payloads were arranged on a payload interface plate as shown in Figure 2. The payload suite was assembled separately from the spacecraft bus which allowed for parallel integration activities. To facilitate enclosure design and mounting for the payloads, a standard 5 cm grid pattern for #8 fasteners was used in keeping with the Space Plug and Play Architecture Physical Interface Standard. (6)

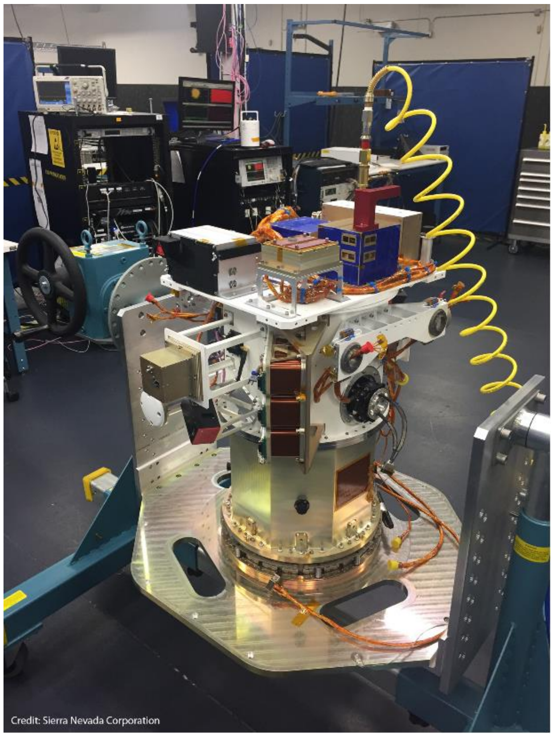

Figure 4: STPSat-5 System Integration and Functional Testing (2)

Due to the size of the STPSat-5 solar arrays and the use of solar array gimbals, the space vehicle generates more than enough power to operate all instruments simultaneously, so adjustments are made by flight software to manage the number of active strings needed to maintain the battery charge. (4) STPSat-5 utilizes software-driven switching to activate the necessary strings. A side benefit of having this extra power has been the ability to provide ample margin in the event of radiation-induced upsets which tend to happen more frequently when utilizing more commercial electronic parts than conventional satellites. Extra energy in the battery provides capacity to handle hardware resets and extra array power provides the ability to quickly recover from a low battery state of charge.

Verification of proper function in a flight-like manner has proven critical to space mission success. (7) STPSat-5 benefitted from basic system functional testing as well as mission simulations intended to produce flight-like conditions as nearly as practical. However, the amount of testing needed to be balanced with cost and schedule constraints. STPSat-5 is shown in Figure 4 in its ground test-ready configuration during space vehicle Integration and Test. A key flight-like test that was beneficial to

STPSat-5 included hardware-in-the-loop testing of the GPS receiver with representative mission profiles which resulted in an antenna configuration change and firmware update. Critical testing was also performed to evaluate data handling during a variety of experiment data collection scenarios. Other flight-like tests were conceived, but constrained due to schedule concerns. Another series of tests that would have benefitted the program included a more thorough set of mission downlink scenarios to simulate expected rates during early orbit operations.

A key tradeoff with more capable small satellite missions concerns the tradeoff between test perceptiveness and meeting tight launch schedules. Ideally, thorough ground testing provides added confidence to test all flight configurations, though practical concerns of cost and schedule may not always allow this. Among the most critical tests concerned validating a robust safe mode. Safe mode ground testing greatly benefitted STPSat-5 and helped the team to address other items not discovered during ground testing prior to launch.

Utilization of Large-Scale Commercial Rideshare

Options for microsatellite and CubeSat launch to low earth orbit have increased recently. Emerging new small launchers can deliver to a specific final mission orbit with a small rideshare group or dedicated launch. Deployment from the International Space Station (ISS) is an available option for microsatellites and CubeSats that require a similar orbit inclination as the ISS (at 51.6 deg) or if the mission is insensitive to orbit. Rideshare on a mid-size or larger vehicle with a large primary payload can be an option of interest if the large and small missions have complimentary needs, such as orbit, and the small mission can comply with the large mission interface requirements. Large scale rideshare with all small satellites on a mid-size or larger launch vehicle is another option which has recently become available, arranged by launch integrators.

In 2015, Spaceflight Industries embarked on a “dramatic new vision”. (8) The goal was to buy a Falcon 9 launch vehicle and fill it with Rideshare spacecraft. It was to have no ‘prime’ payload. This turned out to be a new experience for STPSat-5 as well, as it was the first time that a STP mission occupied a slot on a commercial Rideshare. The STP understood that STPSat-5 would be a secondary payload and as such, would not constrain the mission's orbital parameters, launch timeline, or integration/payload processing sequence of STPSat-5 onto the launch vehicle. This mission was called the SSO-A (Sun Synchronous Orbit-A). This was to be the first (A) of a planned series of launches.

STPSat-5, as an ESPA-volume spacecraft, was to be integrated as a rideshare vehicle on an Integrated Payload Stack (IPS) along with other rideshare spacecraft on the Falcon 9. The desired injection orbit parameters for STPSat-5 were an altitude of 550km +/- 50km, 90+/- 10° circular orbit. Right Ascension of Ascending Node (RAAN) was desired to be between 0600-1800, but not a requirement. SSO-A was to be launched into a circular orbit of ~575 Km and at an inclination of 97.75°. The MLTDN (Mean Local Time of the Descending Node) was to be ~10:30 UTC. Following insertion, the SV would eventually lower its orbit to ~450 X 550 Km when desired. All experiments on board STPSat-5 could function below 600 Km, so that in the event the orbit lowering could not be performed due to some failure, the payloads on board STPSat-5 could still collect important science data while working to resolve any propulsive burn delay. This opportunity was a good match of orbital requirements.

There were several launch vehicle requirements that had to be considered in the design of STPSat-5. A key requirement was that contribution to deployment tip-off rate for from the launch vehicle was to be less than 2° per second. In addition, the satellite was not allowed to utilize any post-separation mechanical deployments, attitude maneuvers or transmitter operations for at least 2 minutes after satellite separation from the launch stack and had to delay at least 12 hours for any propulsive maneuvers. The satellite had to be complaint with Air Force Space Command range safety requirements and provide a Missile System Pre-launch Safety Plan (MSPSP), a Ground Operations Plan, and a Certificate of Compliance for the space vehicle. The power system of STPSat-5 was to be electrically disconnected from the rest of the vehicle before integration to the IPS and remain in such condition until separated from the integrated payload stack on orbit.

Some requirements required a waiver. One example of such a waiver was the bakeout requirement. The original requirement was bakeout at 60° C for 16 hours. A waiver was granted to reduce the temperature to 30° C for 32 hours due to some hardware temperature sensitivities. STPSat-5 was able to reach agreement on all requirements with Spaceflight and those of SpaceX and Vandenberg AFB through Spaceflight services.

A picture of the satellite attached to the ring is shown in Figure 5. STPSat-5 is an ESPA volume SV, but its mass is less than the typical 180kg limit at only ~115 kg. STPSat-5 had to be integrated horizontally while mating the SV, separation ring and the clocking ring. The adapter ring used to integrate STPSat-5 to the SSO-A launch stack was part of an assembly referred to as the Upper Free-Flyer. Launch adapters used in the Upper Free-Flyer are shown in Figure 6. During deployment, the Upper Free-Flyer separated from the full SSO-A launch stack. Adapters used for the complete launch stack are shown in Figure 7.

Figure 5: STPSat-5 Horizontal Integration to Launch Stack

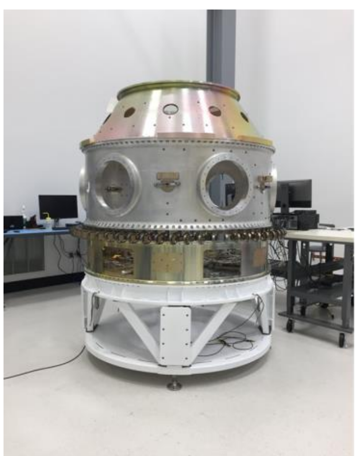

Figure 6: Launch Adapters Used in SSO-A Upper Free-Flyer

Figure 7: Launch Adapters Used in the Full SSO-A Launch Stack

On Monday December 3rd, 2018, SpaceX launched the SSO-A Falcon 9 at 10:34 AM PST from Vandenberg AFB. Contained on board were a total of 64 spacecraft, comprised of 49 CubeSats and 15 MicroSats, of which STPSat-5 was one. The design on the fairing signifies the multiple rideshare space vehicles as shown in Figure 8. From the perspective of STPSat-5, the launch and deployment of the satellite successfully achieved all objectives.

Figure 8: SSO-A on the Day of Launch

Lean Mission Operations

There was a lot of anticipation in the Mission Operations Center (MOC) when it came time for the first contact attempt. Contact was quickly established at 1:51 PM PST, and there was celebration amongst the team, as Launch and Early Orbit Phase (LEOP) activities were set to begin.

Considerable pre-launch effort had been applied towards ground operations. The SV was to operate from the NASA Ames Research Center Multi-Mission Operations Center (MMOC). The MMOC was to distribute data between NASA, payload representatives, and SNC. The procurement of ground resources was made utilizing the NASA NEN (Near Earth Network) and the MMOC. End-to-end testing had been performed prior to the deployment of STPSat-5, and NASA personnel had made the trip to Sierra Nevada Corporation in Louisville Colorado to observe testing of the satellite and train on operations to the extent possible.

On the day of launch, SNC, AMES and the STPSat-5 program office were all at the MMOC, and a launch and early orbit plan (LEOP) was in place. This plan and the baseline schedule ultimately proved to be too aggressive, as many issues were encountered that slowed the process. This plan including commanding of the vehicle, checkout of the bus and its subsystems, and the commissioning and characterization of all payloads. In normal operations, most payloads remain on during the mission modes of the vehicle, collecting science data and download via the ground operations center. The exception is HALO-Net, which operates intermittently, with planned events occurring monthly for a period of about 1 week. Each experiment with HALO-Net runs for approximately 20-30 minutes. HALO-Net is powered off during all other times, once data transmission to the bus has completed. The SV is intended to be in Mission Mode A (4 payloads on, payload deck pointed in RAM direction) for most of the mission life. Mission Mode B is employed to change the pointing to a ground spot for the HALO-Net experiment. All other payloads remain on and collect data during Mission Mode B.

It was NASA Ames' responsibility to design, develop and test the STPSat-5 ground system and verify it meet mission requirements. They had to interface between STPSat-5 program office, SNC, AFRL, NRL, USAFA and SPAWAR for STPSat-5 operations planning, pre-flight compatibility/verification tests, and the first year of on-orbit operations support. NASA Ames was responsible for developing pass plans which include command procedures and operations based on the On-Orbit Operations Handbook (OOH) provided by SNC, and the L&EO timeline. The ground operations team had to execute contingency command procedures as required with input from the STPSat-5 program office and SNC. It was also the ground operations team's responsibility to manage the mission impact of anomalous space vehicle performance. The ground operations team and space vehicle developers at SNC had to work together closely to support the pass plan development and review cycle for LEOP. SNC also assisted with anomaly resolution, code uploads and command sequences. The ground operations team in turn provides regular status reports on the operations and health of the space vehicle as shown in Figure 9.

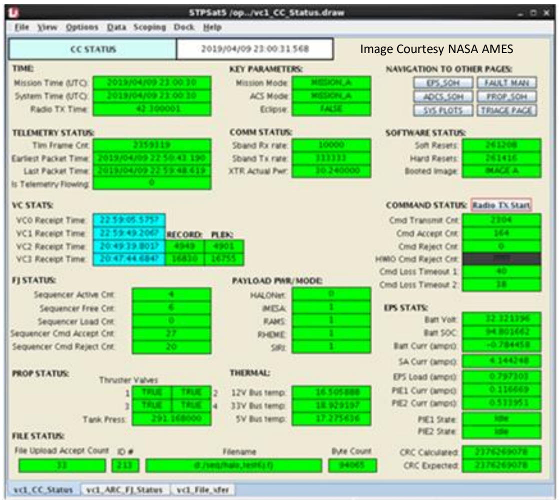

Figure 9: Typical readout of SV Status

Originally, normal operations were intended to be mostly automated. However, that plan had to be modified due to the periodic radiation upsets of the CubeSat components, which resulted in the need to promote the space vehicle back to normal operations from safe mode after discussions with spacecraft developers at SNC. As mentioned earlier, this again demonstrates the need of a good safe mode ground testing program to resolve previously unknown on orbit problems. As the ground operations team has become more familiar with the signatures of commercial electronics upsets on the space vehicle, it has become less necessary to reach back to the developers and the space vehicle is steadily accumulating more experiment operations time.

Conclusion

Since launch in December 2018, STPSat-5 nominal operations are in process, and the payloads are working through the ground operations team at NASA Ames Research Center to resolve any issues that arise. The main goal of the STPSat-5 is to meet data collection objectives for the five payloads onboard. Although delayed from the baseline LEOP plan early on, a process has developed that is downlinking the desired science data for the payloads and STPSat-5 is on its way to meeting mission requirements. From this standpoint, STPSat-5 is a huge success.

Utilizing commercial components and streamlining development and test as compared to more traditional satellites can still result in a successful mission, but evaluations of the relevant risks must be performed, as these approaches can easily cost more in engineering effort and test failures than more expensive components that have a great deal of heritage and a good pedigree. Doing these types of activities require acceptance of those risks, a robust test plan, a very solid and well-tested safe mode that can be autonomously maintained for long periods, and a power system that can sustain the SV as unexpected issues arise on orbit. 'Test like you fly' becomes more important for these types of missions and is not a recommended area to save time and money. Plan for the unexpected, in the sense of time and testing, both in integration and LEOP activities.

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