

STPSat-1 – One Year of Successful Operations

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ABSTRACT

STPSat-1 was launched on March 8, 2007, into a 560 km orbit as one of the payloads on the maiden flight of the EELV Secondary Payload Adapter (ESPA) ring. This Class “C”, single-string satellite with a prelaunch calculated reliability less than 0.75 is currently on orbit and exceeding the per-orbit data collection requirements of the two active experiments onboard: the Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER) and the Computerized Ionospheric Tomography Receiver in Space (CITRIS). The Air Force/AeroAstro team completed the STPSat-1 Launch and Early Orbit checkout (LEO) activities within three weeks after launch, supporting an early start of the nominal operations phase and experiment data collection. On multiple occasions STPSat-1 has shown robustness in software and hardware implementation, allowing the satellite to continue its mission while dealing with issues that would have stymied a less robust design. This paper will follow the in-orbit history of STPSat-1’s proposed one-year mission life from launch to the expected end of life, currently scheduled for June 2008. The challenges presented to the mission and the implementation of the solutions will be discussed.

INTRODUCTION

The Space Test Program (STP) STPSat-1 mission was initiated in 2001 as the first space vehicle explicitly designed to launch on the ESPA as a secondary payload (Figure 1). The space vehicle (SV, satellite bus plus payloads) weighs 164 kg, and carries two active experiments on board: SHIMMER (Spatial Heterodyne Imager for Mesospheric Radicals) is a deskjet printer-sized rugged spectrometer designed to measure solar resonance fluorescence of hydroxyl (OH) in the Earth’s middle atmosphere; while CITRIS (Computerized Ionospheric Tomography Receiver in Space) investigates and characterizes ionospheric radio scintillations that can seriously degrade the performance of space systems providing communications, navigation, and geolocation. AeroAstro is the prime contractor for the STPSat-1 space vehicle; both experiments were provided by the Naval Research Laboratory. Previous papers presented at this conference have detailed the design challenges (SSC02-V-08) and ESPA accommodations (SCC07-VII-5) associated with the STPSat-1 mission.

The satellite bus design was intended to be as simple as possible with a minimum of non-recurring engineering. Although there was no mission requirement specifying a quantitative probability of success, STPSat-1 was required to provide a mission life of one year, beginning after Launch and Early Orbit checkout (LEO). As a Class C satellite, all critical bus components were single string, and only selectively redundant. Shortly before launch, the final calculated reliability prediction showed only 75% probability of success to meet the one year goal. However, over the course of the first year of on-orbit operation, the design proved to be highly robust, which permitted continued performance to mission requirements in the presence of on-orbit anomalies. This paper discusses those challenges to the mission, and implementation of solutions, as well as payload successes over the first year of operation.

STPSat-1 was launched on the STP-1 Atlas V from Cape Canaveral on March 8, 2007, with Orbital Express as the primary payload and several other ESPA

secondaries. After a complex series of engine burns and maneuvers, STPSat-1 was successfully released into its target orbit (35.4° inclination, 560 km circular).



Figure 1. Illustration of fully-deployed STPSat-1 SV on orbit, with CITRIS antenna on SV front, and circular standard separation adapter on back.

STPSat-1 on-orbit operations are conducted from the RDT&E Support Complex (RSC) at Kirtland Air Force Base (KAFB) in Albuquerque NM, utilizing the Air Force Satellite Control Network (AFSCN) family of ground installations to provide contacts to the vehicle. AeroAstro provided on-site technical support during the initial checkout phase described in subsequent sections, and at this writing, continues to provide factory support to the RSC for telemetry trending analyses, maneuver planning, and on-call anomaly resolution.

LEO TEST PHASE

The Launch and Early Orbit checkout phase of operation began immediately after STPSat-1 separation from the ESPA ring into the target orbit, and was scheduled to be completed in four weeks. Successful conclusion of the LEO phase would mark the beginning of the first year of normal satellite operations, and collection of scientific data by both payloads.

The objectives of this LEO were to verify spacecraft subsystems performance, characterize individual payload's functionality, identify acceptable fixes (or work-arounds) to all anomalies, and successfully demonstrate and characterize combined spacecraft/payload operation. For this extensive testing, AeroAstro provided 24x7 on-site support at the RSC including AeroAstro experts from each of the major satellite subsystems, system engineers, and the mission operations lead.

All available data indicates that the STPSat-1 Space Vehicle (SV) successfully withstood the launch

environment and arrived on orbit without any launch-induced anomaly to the satellite. The separation system operated as expected in separating the STPSat-1 SV from the ESPA ring, with low tip-off rates observed.

Following initial power-on of the main Command & Data Handling (C&DH) and power avionics contained in the Integrated Electronics Module (IEM), the on-board flight software booted properly and began execution from its default settings. This permitted the avionics to correctly issue the deployment commands to the QWKNut actuators restraining the four deployable solar panels to the satellite body. Deployment of the CITRIS antenna followed successful solar array deployment. However, the failure to receive the 'final motion' sensor reading from the CITRIS antenna's microswitch (confirming antenna lock at hardstop) brought into question whether the CITRIS antenna was fully deployed. Finally, after CITRIS testing and telemetry analysis, the CITRIS experimenters concluded the antenna had fully deployed by analyzing (1) the spacecraft attitude transient profile seen at deployment, (2) change in temperature profile for the antenna trough (consistent with the antenna leaving the trough), and (3) the CITRIS performance during LEO.

During the course of LEO, all major subsystems were checked for functionality and performance. Most subsystems encountered no problems at all, including the C&DH, Telemetry Tracking & Command (TT&C), and Thermal Subsystem.

The STPSat-1 Power Subsystem is a direct-energy-transfer system utilizing shunt regulation to shed excess generated power. Tests on the power subsystem proved nominal performance for the solar arrays, battery, and shunts. Comparisons were made for on-orbit performance of the power subsystem against the pre-launch power simulation. Figure 2 shows the pre-launch power simulation output for the solar arrays, battery and shunts over 11 orbits.

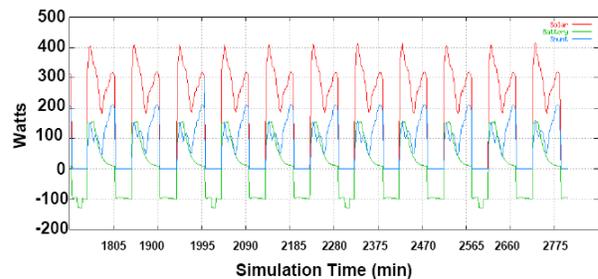


Figure 2. STPSat-1 Power Simulation Output of Bus Power – Solar Array Output (red), Battery (green), & Shunts (blue) – for 11 orbits.

When comparing this data to the actual on-orbit performance during LEO shown in Figure 3, similar peak values and trending are apparent. The “double-peak” of the solar array output during an orbit is caused by direction of the sunlight moving over the solar panel edge from the front to backside of STPSat-1’s double-sided deployed solar arrays. The simulation not only tracks the on-orbit data well, but comparison of the peak values illustrates the conservative approach used in the simulation.

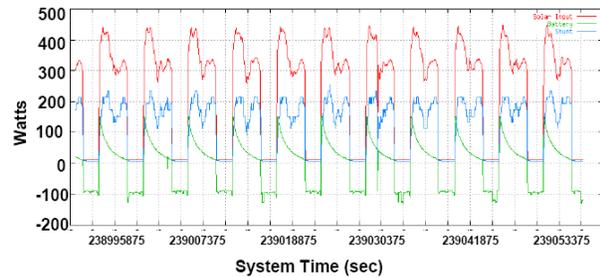


Figure 3. STPSat-1 On-Orbit Bus Power – Solar Array Output (red), Battery (green), & Shunts (blue) – for 11 orbits.

The Attitude Determination and Control Subsystem (ADCS) met and largely exceeded mission requirements for attitude pointing ($\leq 0.10^\circ$ error in all three axes). LEO analysis of ADCS on-orbit performance showed strong correlation between real orbit data, and the pre-launch ADCS simulation tool.

The on-board GPS receiver, an SSTL SGR-05, initially performed well enough during LEO that transponder-based ranging by ground assets was discontinued after one week due to the high quality of GPS position and velocity data downlinked in telemetry.

During this phase, some transient hardware anomalies caused by ionizing radiation were discovered that affected both STPSat-1’s star tracker and GPS (discussed later in this paper). However, mitigation approaches were identified during LEO, and later proved successful.

Payload testing for CITRIS, including testing of the Coherent Electromagnetic Radio Tomography (CERTO) Satellite Beacon Mode, the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Ground Transmitter Mode, and noise floor measurements showed the antenna and receiver electronics were operating as expected.

SHIMMER payload testing during LEO indicated the interferometer was not damaged during launch, the moving parts (door and shutter) were performing well, and the detector (CCD) temperature and electronics

temperatures were well within the operational limits. No indication of any significant contamination could be detected. Judging from the LEO data, SHIMMER was working as expected.

As mentioned previously, the LEO had been scheduled for four weeks in duration. Due to the smooth operation of the space vehicle during this time, all objectives were accomplished in three weeks, culminating in a Normal Operations Readiness Review (NORR) that reviewed all data and activities during this phase and authorized the start of nominal operations.

SHIMMER SHUTTLE RE-POINTING

STPSat-1 is a three-axis stabilized, nadir-pointing satellite. Prior to launch, the only specific slewing maneuvers planned were a SHIMMER calibration that pointed the instrument to the Sun for several minutes, and a 180-degree yaw maneuver once every six months to avoid sun incursion into the star tracker’s field-of-view. STPSat-1 does perform active roll slewing each orbit to compensate for Earth oblateness, but this small change to the roll angle was designed, tested, and extensively analyzed prior to launch. However, AeroAstro designed an additional capability (that was originally not required) for a small attitude adjustment (constant bias) to the satellite pointing in each axis should it be required after launch. This robust capability was later utilized to further the scientific return on the SHIMMER payload by providing the ability for SHIMMER to observe the altitudes of the thermosphere in which a significant part of the Space Shuttle exhaust plumes are deposited during the Shuttle’s launch.¹

Liquid hydrogen and oxygen are used to fuel the main engine of each Space Shuttle. At launch, the exhaust from the shuttle’s main engine deposits about 300 metric tons of water vapor between 108-114 km altitude.² By pointing the SHIMMER instrument slightly higher to include the altitude region around 110 km, SHIMMER observations are potentially able to include the Shuttle plume. These observations could give additional information about the dynamics of this altitude region and the temporal development of the plume. Furthermore, these measurements could lead to a better understanding of plume related mesospheric cloud formation.²

However, re-pointing of the SV to observe this plume would require a rotation in roll, and this case was not specifically analyzed prior to launch. Fortunately, the amount of required slew is small (less than one degree), and prior to launch, attitude biases of up to five degrees were simulated by ADCS testing. Prior to the STS-117 shuttle launch, analyses of the thermal and power

implications of performing the maneuver were performed, in addition to a number of ADCS simulations to confirm that SV re-pointing could be achieved without detriment.

On June 7, 2007, one day before the launch of STS-117, STPSat-1 was successfully rolled to observe the plume from this shuttle launch. The SV remained in that orientation for approximately one week to allow the SHIMMER instrument to collect data. This re-pointing in roll did not affect the ability of the CITRIS payload to obtain data.

This SHIMMER Shuttle Re-Pointing was also accomplished for several subsequent launches over the past year including STS-118, 122 and 123. As of this writing no Shuttle plume was identified in SHIMMER data, most likely due to the temporal and spatial discrepancies between the SHIMMER measurements and the plume.

ADCS PERFORMANCE

The required ADCS space vehicle attitude pointing error is defined in the STPSat-1 Mission Requirements Document to be no greater than ± 0.10 deg (3-sigma). SV pointing is controlled with a combination of three momentum/reaction wheels (procured from RoBi Controls) with momentum unloading accomplished by magnetic torque rods (from Microcosm, Inc.), to provide stable, momentum-biased, three-axis pointing. Pre-launch ADCS performance simulations predicted attitude pointing excursions not to exceed ± 0.10 deg error, and generally center about ± 0.05 deg error. Figure 4 trends the on-board calculated attitude pointing errors during the LEO phase, indicating close agreement with the pre-launch ADCS simulations. In fact, from this data, one can see that the attitude error in all three axes does not exceed ± 0.05 deg error, resulting in a performance margin of $(0.10 / 0.05) = 2$, or twice better than required. The “three-sigma” aspect of the requirement permits occasional violation of the pointing requirement, but no more than 0.25% of the time. However, as can be seen from this graph, STPSat-1 holds this pointing margin consistently.

Nearly one-year after LEO, the ADCS performance is still twice better than required. Figure 5 shows attitude errors over a two week period from 12-Feb-2008 to 26-Feb-2008.

It’s apparent that the vast majority of errors are within ± 0.05 deg. The average RSS error over this period is 0.02 degree, or about five times better than required SC pointing. Analysis shows that for those times STPSat-1 has an attitude excursion over 0.10 deg, the occurrence is brief. The standard backorbit telemetry rate from the

satellite is once-per-thirty-seconds. Even if we conservatively estimate the duration of pointing excursion to include the entire 30 second time span, the cumulative percent of excursion is only 0.16% of the time, well within the three-sigma requirement.

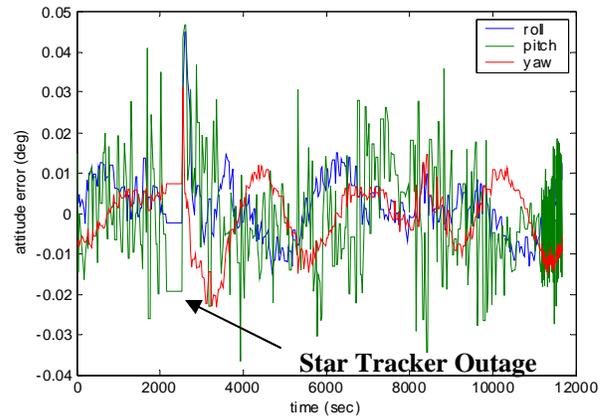


Figure 4. STPSat-1 Attitude Pointing Errors in Roll (blue), Pitch (green), and Yaw (red) axes during a three-hour time span in LEO.

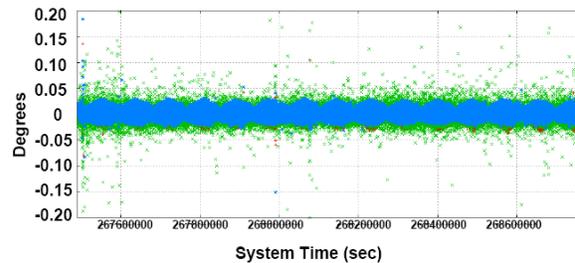


Figure 5. STPSat-1 ADCS Performance One Year after Launch. Attitude Pointing Errors over two weeks are shown in Pitch (green), Yaw (blue), and Roll (red, but largely not visible due to overlapping blue and green data).

Star Tracker Radiation Hits

The main factor contributing to the out-of-spec attitude excursions is caused by an ionizing radiation effect on the star field imaged by STPSat-1’s star tracker, the primary attitude determination hardware. Most precision-pointing spacecraft that use star trackers are relatively costly (compared to most microsatellites) and may have several attitude sensors (e.g., star trackers plus gyros, multiple star trackers, etc.). As a Class C spacecraft, STPSat-1 is single string and only selectively redundant. There is only one star tracker aboard STPSat-1 from which the ADCS software can calculate spacecraft attitude. Further, there are neither gyros nor secondary ADCS hardware of sufficient accuracy to provide attitude knowledge in the event of short-term star tracker outage. The decision to use this

approach was made in the design phase of STPSat-1 not only for cost considerations, but also for mass and volume constraints on this ESPA-class satellite. This aspect of STPSat-1 design was extensively discussed and agreed upon between AeroAstro and the customer.

During the LEO phase of on-orbit operation, it was discovered that the CCD imager of the CT-633 star tracker would occasionally lose star lock, and hence, stop output of attitude data. These occurrences were most prominent over the South Atlantic Anomaly (SAA), see Figure 6.



Figure 6. Geo-location of several attitude disturbances during LEO initiated by Star Tracker Loss-of-Lock, identified in this illustration as red dots.

It is well known that various electronic devices (CCDs in particular) are susceptible to ionizing radiation hits, and that such hits are common in the SAA, where STPSat-1's orbit has substantial exposure. Analysis of STPSat-1's on-orbit raw star tracker pixel data telemetry by the star tracker manufacturer indicated radiation transients as the cause of these loss-of-lock events. Further, there were instances of simultaneous hits on both the star tracker CCD, and the SHIMMER CCD, further corroborating ionizing radiation as the initiating event for the attitude disturbance.

When the star tracker would lose star lock, the on-board Failure Detection & Correction (FDC) strategy implemented in the ADCS software "froze" actuator commands to the most recently commanded value (i.e. repeated torque commands to wheel and mag torque actuators) until the star tracker regained star lock. The purpose behind this technique is to take advantage of

low body rates (typical of 3-axis stabilization) prior to loss-of-lock, and so minimize attitude excursions. This approach to reaction wheel commanding permitted the wheels to remain close to their set speed, while the (repeated) torque commands overcame bearing friction – zero-torque commands would have eventually led to wheel spin-down. This highly effective approach is illustrated in Figure 4, where a star tracker loss-of-lock of approximately eight minutes caused an attitude excursion of less than 0.05 deg (within spec). However, STPSat-1 later experienced some radiation hits that caused longer outages, resulting in larger (out-of-spec) attitude errors, and in some cases forcing the FDC to initiate SV safing actions. Although the star tracker manufacturer studied the raw on-orbit data and determined there was no long-term impact to the lifetime of the star tracker, mitigation of this issue was necessary because the loss-of-lock events could impact mission performance.

To mitigate against future radiation hits, the star tracker's manufacturer provided AeroAstro a star tracker software patch which lessened the effect of these occurrences. AeroAstro's robust on-board flight software design permitted software patch uploads directly to the star tracker so that the on-board star tracker may update its internal software. Interestingly, this is a software feature that was not required – AeroAstro simply implemented this feature to provide capabilities. This feature has proved very useful in a number of instances, and helped in closing this anomaly.

GPS Radiation Hits

STPSat-1's GPS receiver provides orbital position and velocity data as well as accurate time pulses for the numerical attitude integration software. In the first few months of on-orbit operation, it was discovered that ionizing radiation affected two aspects of GPS operation. First, the pulse-per-second (PPS) output of the GPS would unexpectedly become disabled, preventing output of the once-per-second GPS time tick, used for on-board time synchronization. Second, the GPS would output position and velocity data with higher than expected residuals (noise-related error). These effects were predominant during periods of elevated space weather (higher than normal background-radiation).

The PPS anomaly was quickly remedied by limit checking in telemetry the PPS enable flag, warning satellite operators to send the re-enable command when the PPS autonomously became disabled.

The position and velocity residuals issue was successfully analyzed by the GPS manufacturer (Surrey

Satellite Technologies Ltd) who provided a simple power-cycle solution. Periodic trending of the GPS position data indicates timeframes when residuals may impact mission performance, and a power-cycle of the GPS receiver corrects this situation (this occurs approximately monthly). The robustness of the ADCS software permits extended dropouts of GPS data without impact to mission performance, including those dropouts (several minutes in duration) that occur when there is a power-cycle of the receiver.

Yaw Maneuver

Since STPSat-1 has only one star tracker, and does not possess alternate ADCS sensors to provide accurate attitude knowledge in the event of star tracker outages, it was necessary for STPSat-1 to perform a pre-defined 180-degree yaw maneuver every six months to avoid star tracker “blinding” by the sun. This ADCS maneuver uses a combination of momentum wheels and magnetic torquers to perform this slew.

This maneuver can only be executed at certain times during the year, when SV pointing to either orientation can be tolerated by the star tracker (i.e. no blinding). This aspect of SV operation made testing of this maneuver during LEO impossible, since only one of the two 180-deg-orientations of the SV could be tolerated by the star tracker at that time. When the slew was performed on-orbit for the first time in October 2007, the satellite unexpectedly transitioned into Detumble (safe-hold) Mode shortly after the satellite executed the slew command. This was due to an incorrect command parameter used in the upload to define the direction of slew. The parameter used in the command was from the satellite command and telemetry database, but the database was in error – the ADCS software required a parameter not present in the database.

Recovery of the satellite into the original orientation was relatively straightforward, but was time-consuming due to repeated sun interference in the star tracker during the detumble recovery process. Due to cost and potential operational impacts of making a database change at the RSC, AeroAstro developed an alternate yaw maneuver approach that did not require use of the omitted command parameter. Instead, this maneuver used the incremental slew described earlier to accomplish the SHIMMER Shuttle Re-pointing. However, in this case, successive ten-degree yaw slews were performed sequentially. This maneuver resulted in finally achieving the correct 180° yawed orientation, after several attempts were thwarted by star tracker / sun interference. A subsequent yaw maneuver performed in April 2008 accomplished the correct yaw slew via the original yaw maneuver.

POWER PERFORMANCE

Power System Description

STPSat-1 has a direct energy transfer system that utilizes approximately 5.3 square meters of solar panel area with Triple Junction Gallium Arsenide solar cells (by Spectrolab, Inc.) laid down in a 0.9 to 0.95 packing factor. In addition to the four body-mounted solar panels, there are four deployed solar arrays, each of which is populated with solar cells on both sides (double-sided).

The power subsystem handles voltage regulation, battery charging, and the shunting of excess power. The nominal bus voltage is 28 VDC +6/-4 VDC. The bus voltage is controlled to 33.6 volts in sunlight by the use of passive shunts. Shunting of excess array power is accomplished by switching of external heater loads, most of which are mounted to the edges of the deployed solar arrays. Only two of the 18 total shunt loads are located internal to the SV bus. The remaining 16 loads are on the SV body panels and deployable panels, affixed by epoxy. Loads are switched on sequentially as shunt current increases. None of these loads are redundant.

Eclipse power is provided by a 72-cell COMDEV Lithium Ion battery comprised of Sony 18650 (AA) cells, laid out in a nine by eight configuration. The battery is apportioned into three separate three-by-eight packs and has a Beginning of Life (BOL) nameplate capacity of 13.8 amp-hours.

Performance at BOL

The panels provided a peak power of just over 460 watts at BOL with sunlit average power of 362 watts. The demand, including battery charge, at BOL was approximately 177 watts averaged over the sunlit portion of the orbit. Several orbits of solar panel power and bus power at BOL are shown in Figure 7.

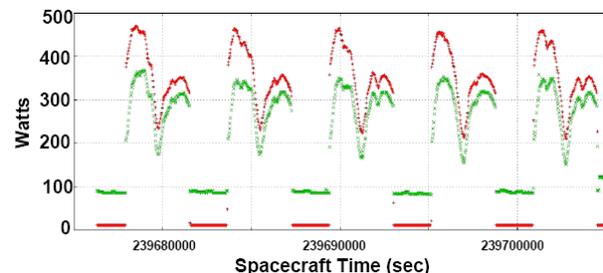


Figure 7. Five orbits of BOL solar panel power (red) and bus power (green).

The battery Depth of Discharge (DOD) at BOL was approximately 11% and the End-of-Discharge Voltage

(EODV) remained above 31.5 volts. Individual cell voltage telemetry is not available; however, the three 9x8 pack voltages are reported separately. At BOL the maximum pack to pack voltage variation averaged 161mV.

Performance after First Year of Operations

After one year in orbit the peak solar array current is little changed; however, the average sunlit power now measures approximately 351 watts; a 3% degradation. The demand, including battery charge, at this time is approximately 300 watts averaged over the sunlit portion of the orbit. The pre-launch estimate for degradation due to environmental effects was between 2.5 and 3%, so the performance is in line with the predictions. These data are shown in Figure 8 for several orbits at EOL.

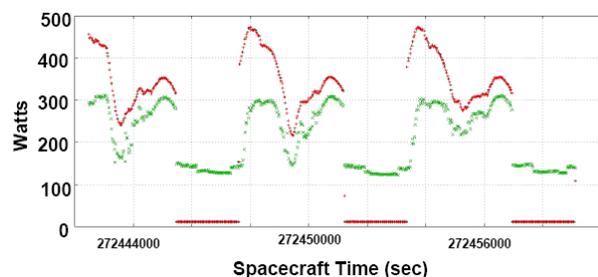


Figure 8. Three orbits of SV power after one year of operation from the solar panels (red) and bus power (green).

The battery DOD now runs at approximately 19% and the EODV is just below 31 volts, which is slightly better than expected, given the increased DOD. The maximum pack to pack average voltage variation was 162mV showing matching remained constant over the mission, with no indication of cell anomalies. Comparison of BOL battery current over one orbit with battery current after one year of operation is made in Figure 9.

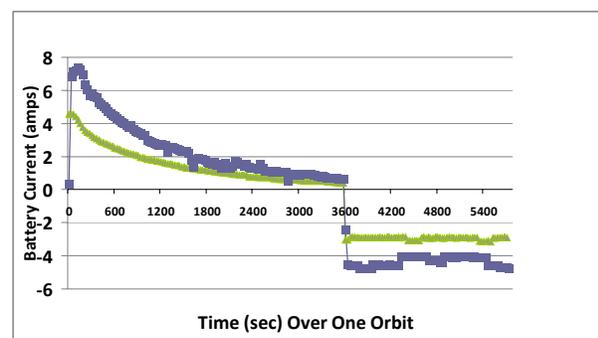


Figure 9. STPSat-1 battery current over one orbit at BOL (green) and after one year on orbit (blue).

Shunt Anomaly

STPSat-1 was originally launched in to what is referred to as the “CITRIS-Ram” on-orbit orientation – the CITRIS antenna on the front face of the vehicle (see Figure 1) is coincident with the ram direction. Seven months after beginning normal operations, a 180° yaw maneuver was scheduled for STPSat-1 to prevent the star tracker from encountering sun incursions (see *ADCS Performance / Yaw Maneuver* section above). This 180-degree yaw maneuver results in a “CITRIS-Wake” orientation – an orientation where the satellite appears to be “flying backwards.” STPSat-1 then holds this orientation, and continues normal operations for up to six months. Normal operations using both of these orientations of the satellite were extensively studied prior to launch from a power, thermal, and ADCS perspective.

There has been one anomaly associated with the power system on STPSat-1. Approximately 6 months after launch, the ability of the shunt system to properly shunt excess current appeared to be degrading. This became apparent shortly after the first planned 180-degree yaw maneuver to achieve a CITRIS-Wake orientation. This new SV orientation resulted in a change to the double-peak profile of power generation by the solar arrays – the larger of the two peaks now occurred over the second-half of the sunlit portion of the orbit. Hence, this increased the demands on the shunt system during the second peak of power, since the battery charging still occurred during the first peak. Power and temperature telemetry in this orientation indicated that several of the external shunts may have degraded or failed, due to the inability of the shunt system to perform as designed during the second peak.

As previously described, the solar panels on STPSat-1 are arranged in four deployable arrays and four body-mounted panels, and the deployable arrays are populated with solar cells on both sides. In the CITRIS-Ram attitude, the four body-mounted panels and the forward side of the four deployed panels are illuminated at sunrise. By sunset only the rear of the deployable panels are directly illuminated, giving the array output the distinctive non-symmetrical double-peak signature shown in Figures 7 & 8. In CITRIS-Ram the first peak is the larger of the two peaks resulting from the sunlit portion of the orbit, but battery charging consumes most of the excess array current during this first peak, reducing shunting requirements in this orientation.

Almost immediately after achieving the desired CITRIS-Wake orientation, internal shunt load temperatures rose dramatically to undesirable levels. The satellite was temporarily commanded to a

‘roisserie’ mode – a pre-defined safe mode – while the situation was studied. This roisserie mode results in lower orbit average power and reduces temperatures.

Analysis revealed that the deployable shunt loads were not drawing any current and therefore the remaining internal loads were carrying the entire excess array capacity. The internal loads were built to shunt the entire array, but only for very brief periods of time – seconds during eclipse-to-sun transitions – hence, the dramatic temperature increase. The issue with the external loads was not evident in CITRIS-Ram due to the battery charging occurring coincident with the larger array output peak. Reduced shunting requirements during the larger peak masked the failure of several shunts. However, when STPSat-1 was commanded into CITRIS-Wake, the larger of the two peaks occurred in the later portion of the sunlit portion of the orbit, after the initial battery charging had occurred. Excess array current during this half of the sunlit period required much greater shunt operation – with several shunts failed, the effect was evident.

Further analysis indicated that previous recoveries from Detumble Mode, caused by star tracker loss-of-locks resulted in SV geometries (e.g., inertially fixed attitude) where sustained sunlight would overheat the epoxy affixing the external shunt loads (heaters). Delamination of any load would prevent adequate heat sink of that load to the array panel. Excessive heat causes the shunt current to burn through the heater wire resulting in an open circuit, rendering the heater useless for excess current dissipation.

Fortunately, the pre-launch STPSat-1 power budget was proven to be very conservative in comparison with actual on-orbit performance. Pre-launch estimates permitted SHIMMER operation for its required 40 minutes per orbit, and CITRIS operation for 40 minutes per day. Further, the SGLS transmitter was only allowed to operate a total of 35 minutes per day. A power study just prior to the anomaly confirmed the observations of the on-orbit performance and concluded that all these time restrictions could be relaxed – permitting longer duty cycles and enhanced payload operations. After the anomaly occurred, the mitigation strategy was obvious – a strategy beneficial to both payloads permitting longer operation. Further mitigation was possible by longer transponder operation (to download the additional payload data). Since the main purpose of the (failed) shunts was to consume excess power, extended use of satellite loads (e.g., payloads and transponder) accomplishes the same purpose – consuming excess power. As a result, CITRIS was left powered on, as was the SGLS transmitter. SHIMMER operation was increased from

40 minutes per orbit to 70 minutes (the command database prevented longer than 70 minutes per orbit). Additional mitigation was provided by heater operation. Heaters which otherwise would have remained power off, were instead enabled, and were operated without detriment to any hardware since thermostatic control prevented over-temperature. These strategies not only maintained the internal shunt temperatures within design limits, it also allowed the scientific payloads the opportunity to collect more data on orbit than originally planned.

Further illustrating the robust thermal design is the fact that the internal Shunt Power Board, which was only designed to handle the full load for a short period, and a nominal load of 40 watts, instead handled loads in excess of 90 to 100 watts for extended periods and continues to operate nominally.

It is important to note that at no time during this anomaly did bus voltage regulation suffer in any way. Bus regulation in sunlight remained controlled at 33.6 volts continuously.

As of this writing, the satellite has been returned to CITRIS-Ram attitude as planned, the payloads and transmitter on-times are still extended, and the internal shunt temperatures are well within the design range. The one-year power data referenced above was taken with the satellite in the CITRIS-Ram attitude.

EXPERIMENTS’ SUCCESSES

Both SHIMMER and CITRIS have performed as expected since completing the LEO phase of the STPSat-1 mission, returning valuable science data during the first year of operations.

SHIMMER has already returned several hundred thousand atmospheric OH measurements, contributing to our understanding of mesospheric hydroxyl. Moreover, the experiment’s unprecedented local time coverage allows investigation of how atmospheric dynamics influence Mesospheric Clouds (MCs) and their environment, and thus potentially bias the interpretation of multi-decadal cloud frequency and brightness trends.

To date, SHIMMER data have already led to three significant science results.

- Mesospheric clouds show a systematic daily variation; the dynamic range of this signature is unexpectedly large and will help reconcile existing satellite data sets that consist of observations at discrete local times;³

- Identification of discrepancies in the expected diurnal variation of OH, which will help to update current standard models;⁴
- Unusual SHIMMER cloud observation consistent with Navy weather models, potentially supporting forecasting of MCs much as tropospheric clouds are forecast.⁵

The CITRIS receiver supports study of the ionosphere using data obtained from radio transmissions from ground and space beacons. The data from CITRIS is helping to update and validate theories on the generation and effect of ionospheric irregularities known to influence radio systems. By using simultaneous beacon transmissions from the DORIS ground network and from low-Earth-orbit (LEO) beacons in space, observations of ionospheric total electron content (TEC) are being obtained in remote regions over the ocean and land with unprecedented accuracy.⁶

CITRIS is designed to lock onto LEO beacons on the COSMIC, DMSP/F15, NIMS, and the recently-launched C/NOFS spacecraft, as well as the 56 ground radio beacons that are part of the French DORIS network. CITRIS operates in radio frequency bands near 150, 400, 1066 $\frac{2}{3}$ MHz, and 2036 $\frac{1}{4}$ MHz to obtain TEC and radio scintillation parameters. Using the satellite to satellite measurement technique, up to 48 independent TEC scans over 7000 km range can be obtained from the CITRIS data set; using DORIS, separate scans of TEC and UHF scintillations are obtained continuously through the day. These measurements are providing valuable data to improve the accuracy of space weather models on a global scale; in addition, the amplitude and phase fluctuations recorded by CITRIS can be used to determine the locations of ionospheric irregularities that disrupt radio systems used by civilian, Navy and other DoD agencies.^{7,8}

CONCLUSION

In its first year of mission operations, STPSat-1 has successfully achieved mission and experiment objectives, and at this writing continues to provide valuable science data from SHIMMER and CITRIS. The mission overcame several anomalies by leveraging robust spacecraft design capabilities and software features, and implementing creative operations approaches. Lessons-learned from this mission will inform subsequent ESPA launches, as well as similar vehicles like STP's Standard Interface Vehicle (STP-SIV).

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