www.DeepakPublishing.com

Swartwout, M. (2013): JoSS, Vol. 3, No. 1, pp. 265-281
(Peer-reviewed Article available at www.jossonline.com)

www.JoSSonline.com

The Colorado Student Space Weather Experiment (CSSWE) On-Orbit Performance

David Gerhardt[1], Scott E. Palo[1], Quintin Schiller[2], Lauren Blum[2], Xinlin Li[2], and Rick Kohnert[2]

[1] University of Colorado at Boulder, Aerospace Engineering Sciences, Boulder, CO, USA
[2] University of Colorado at Boulder, Laboratory for Atmospheric and Space Physics, Boulder, CO, USA

Abstract

The Colorado Student Space Weather Experiment (CSSWE) is a three-unit (10cm × 10cm × 30cm) CubeSat funded by the National Science Foundation and constructed at the University of Colorado (CU). The CSSWE science instrument, the Relativistic Electron and Proton Telescope "integrated little experiment" (REPTile), provides directional differential flux measurements of 0.5 to >3.3 MeV electrons and 9 to 40 MeV protons. Through a collaboration of more than 60 multidisciplinary graduate and undergraduate students working with CU professors and engineers working in the Department of Aerospace Engineering Sciences and at the Laboratory for Atmospheric and Space Physics (LASP), CSSWE was designed, built, tested, and delivered in three years.

On September 13, 2012, CSSWE was inserted into a 478km × 786km, 64.7˚ inclination orbit. After a 20-day commissioning phase, the REPTile instrument was enabled, providing high quality, low noise science data return that is complementary to the NASA Van Allen Probes mission, which launched two weeks prior to CSSWE. To June 2014, the CubeSat had downlinked data from 426 days of on-orbit science operations, well past its full mission success goal of 90 days of science operations.

Although operations continue, the CSSWE team is focused on analysis of the on-orbit data. The CSSWE attitude converged to the local magnetic field within one week of launch using a passive magnetic attitude control system. Satellite interior temperatures were found to remain within their design range, even during multi-week periods of insolation. However, not all systems behaved as expected: CSSWE experienced four on-orbit anomalies over the first nine months of the mission. The student-led CSSWE team has grown in experience and knowledge throughout design, build, test, delivery, launch, and operations of this small satellite. An overview of the CSSWE system, on-orbit performance, and lessons learned is presented, with a focus on the first nine months on-orbit.

Corresponding Author: David Gerhardt - dtgerhardt@gmail.com
Publication History: Submitted – 07/12/13; Revision Accepted – 08/3/14; Published – 08/14

1. Introduction

Until recently, CubeSats (Heidt et al., 2000; Twiggs, 2008) have been considered little more than educational tools. This thinking is being reversed, as these nanosatellites begin to make serious scientific contributions. One such CubeSat is the Colorado Student Space Weather Experiment (CSSWE) (Palo et al., 2010; Li et al., 2011; Li et al., 2013a), developed at the University of Colorado (CU) as a three-unit (3U) (10cm × 10cm × 30cm) CubeSat to study space weather. After one year of preliminary design work, CSSWE was selected for NSF funding in January 2010. Figure 1 shows CSSWE as delivered in January 2012, next to its Poly-Picosat Orbital Deployer (PPOD). As part of the NASA ELaNa VI launch on September 13, 2012, CSSWE was inserted into a 478km × 786km, 64.7˚ inclination orbit, along with ten other CubeSats (Skrobot, 2011; Skrobot and Coelho, 2012). These CubeSats were launched as the secondary payload of an Atlas V rocket operated by the United Launch Alliance (ULA) containing a classified National Reconnaissance Office (NRO) primary payload. This secondary payload was made possible by the Naval Postgraduate School's NPSCul, a box that holds eight 3U PPODs and is bolted to the Aft Bulkhead Carrier (ABC) of the Atlas V (Willcox, 2012).

The science objectives of CSSWE are to investigate the relationship of the location, magnitude, and frequency of solar flares to the timing, duration, and energy spectrum of solar energetic particles reaching Earth, and to determine the precipitation loss and the evolution of the energy spectrum of radiation belt electrons (Li et al., 2012). CSSWE has a single science instrument: the Relativistic Electron and Proton Telescope "integrated little experiment" (REPTile). REPTile provides directional differential flux measurements of 0.5 to >3.3 MeV electrons and 9 to 40 MeV protons (Schiller et al., 2014a). REPTile is a miniaturization of the REPT instrument (built by engineers at LASP) on board the NASA Van Allen Probes satellites (Baker et al., 2012). CSSWE makes measurements that are complementary to those made by the two Van Allen Probes as charged particles in earth's outer radiation belt with small pitch angles reach low earth orbit at latitudes >55˚.

Compared to the REPT instrument (Baker et al., 2012), the REPTile instrument (Schiller and Mahendrakumar, 2010) is reduced in mass by 10× (13.4 kg vs. 1.25 kg), reduced in volume by 73× (21900 cm^3 vs. 300 cm^3), and reduced in power consumption by 9× (6.2 W vs. 0.68 W). However, the REPTile instrument also has lower performance than REPT, which has five more silicon detectors (and thus more energy bins for each particle species), and measures particles at higher levels of signal-to-noise. (The REPT instrument uses more shielding to prevent high-energy particles from penetrating the detector stack from other directions than the collimator.) The REPTile instrument provides journal-quality science data to complement the REPT instruments aboard the Van Allen Probes (Li et al., 2013b; Blum et al., 2013; Schiller et al., 2014b).

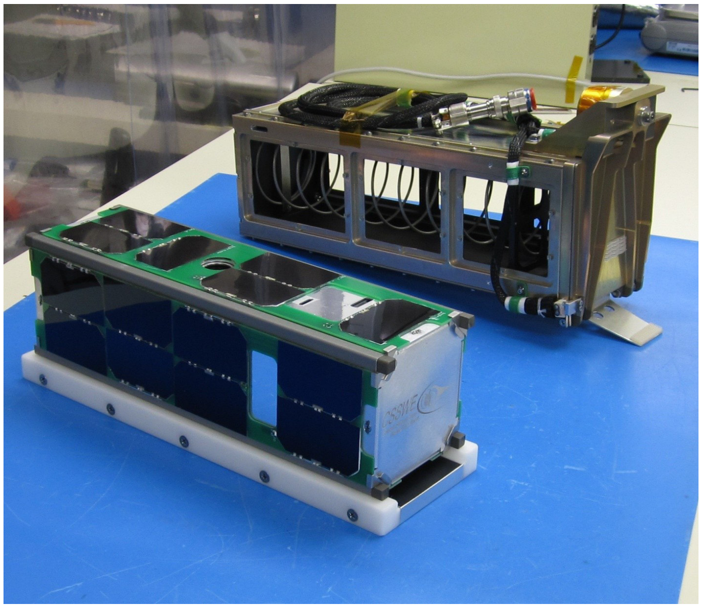

Figure 1: The Colorado Student Space Weather Experiment (CSSWE) CubeSat as delivered (lower left), shown with the Poly-Picosat Orbital Deployer (PPOD, upper right).

CSSWE is run as a graduate projects course with student leadership, faculty oversight, and technical support from LASP professional engineers. More than 60 multidisciplinary students have participated in the design, construction, integration, test, and operation of the system, either through the course, independent study, or as volunteers. A UHF ground station was designed and built for CSSWE operations in Boulder, CO, which was upgraded to autonomous operation over the duration of the mission. Operating in the 70cm band (437 MHz) allowed amateur operators around the world to participate in the mission; CSSWE beacon decoding software was freely supplied to encourage data collection by any interested party.

CSSWE was designed for a 30-day (maximum) commissioning period followed by a 90-day science mission. On orbit, the commissioning period was completed in 20 days, with the science instrument operational as of October 4, 2012. To date (June 2014), CSSWE is operational and has been on-orbit for 652 days, with the science instrument active for 426 days. The discrepancy is due to the commissioning period and a loss of contact experienced from March 8, 2013 to June 18, 2013 (explained in the Anomalies and Responses section of this article).

An overview of the science mission results is presented in the Science Overview section (detailed science mission results are in preparation). The Subsystem Performance section describes the CSSWE subsystems and their performance over the lifetime of the mission. Anomalies encountered during the mission are addressed in the Anomalies and Responses section. Finally, the Lessons Learned section gives an overview of the knowledge acquired while guiding this small satellite mission from proposal to the end of the extended mission.

2. Science Overview

As previously mentioned, CSSWE is designed to address critical space weather questions. The sole science payload onboard is the Relativistic Electron and Proton Telescope “integrated little experiment” (REPTile), which measures protons in the energy range of 9 to 40 MeV and electrons from 0.5 to >3.3 MeV in differential energy channels. The challenges of miniaturizing an energetic particle detector to fit within the constraints of a CubeSat dictated a number of REPTile design features. Strict mass and volume budgets for CubeSats restrict REPTile’s size, and the resulting space, power, and data transmission limitations played a large role in the design of the electronics (Schiller and Mahendrakumar, 2010).

The REPTile instrument is a loaded-disc collimated telescope designed to measure energetic electrons and protons with a signal to noise ratio of two or greater. The instrument consists of a stack of four solid-state doped silicon detectors manufactured by Micron Semiconductor. Using coincidence logic among the fourdetectors, the instrument electronics can determine the energy range of the particle. The particle species is determined by the amount of energy deposited in each detector. Figure 2 illustrates the instrument geometry. The detector stack is housed in a tungsten (atomic number Z=74) chamber, which is encased in an aluminum (Z=13) outer shield. Tantalum (Z=73) baffles within the collimator prevent electrons from scattering into the detector stack from outside the instrument’s 52° field of view, and give the instrument a geometric factor of 0.52 $\text{sr}\bullet\text{cm}^2$. The materials were chosen based on a combination of their ability to shield energetic particles and minimize secondary electron generation within the housing. The 0.5mm thick beryllium foil at the front of the detector stack acts as a high-pass filter that stops low-energy electrons and protons, visible light, and ultraviolet light from entering the detector stack. The high flux of low energy particles and UV photons would otherwise overwhelm the detector electronics. The total instrument mass is 1.25kg, with a cylindrical envelope of 4.6cm (diameter) × 6.0cm (length). As beam testing was not within the $840,000 budget of the CubeSat, detailed instrument modeling and radioactive source testing was conducted to characterize REPTile performance (Schiller and Mahendrakumar, 2010; Blum and Schiller, 2012).

Instrument commissioning began in early October 2012, and consisted of powering on the detectors one at a time. After a few days, it was determined that the third detector was not performing as expected, so it was turned off to conserve power. For flexibility, the onboard binning logic was designed to account for failure of one detector, so CSSWE returns three energy channels per species instead of four, as originally designed. Figure 3 shows measurements from the lowest energy electron channel, 0.5 to 1.7 MeV (top), as well as the highest energy proton channel, 30 to 40 MeV (bottom), along the CubeSat ground track for the first 20 days of science operations. The large enhancement in flux of both protons and electrons off the coast of Argentina is due to the South Atlantic Anomaly (SAA), a region of decreased magnetic field strength due to the tilted offset nature of the Earth's internal dipole magnetic field. These particles are contained within the relatively stable inner Van Allen radiation belt. MeV electrons also appear in two ribbons at high magnetic latitudes. These correspond to the footprints of the outer radiation belt, a highly dynamic torus of relativistic electrons. Energetic protons and electrons in both the inner and outer radiation belts are capable of disrupting and damaging spacecraft (Baker, 2002), and characterizing the variability of these zones is critical to understanding the near earth radiation environment.

The data returned from CSSWE are exceptionally clean, as demonstrated in Figure 3. Together with other in situ measurements, such as those from NASA's Van Allen Probes mission, REPTile measurements enable studies making use of the REPTile data to help characterize the nature of particle acceleration and loss processes contributing to the overall dynamics of the radiation belts (Blum, et al., 2013; Schiller, et al., 2014b).

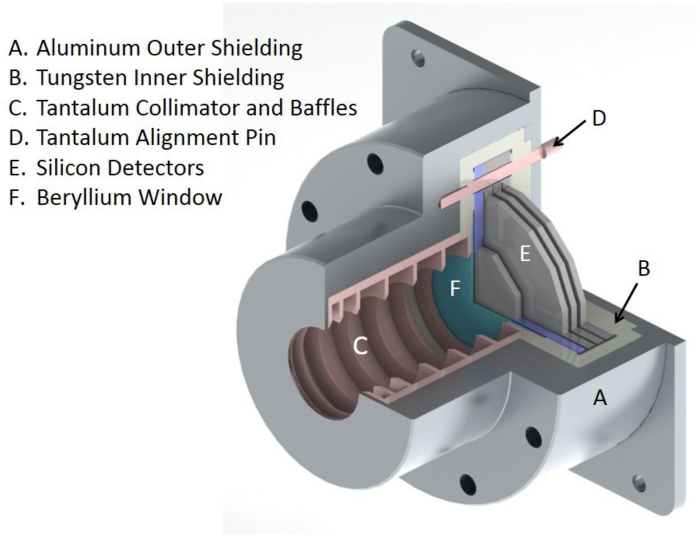

Figure 2: Solid model of the REPTile instrument with components labeled.

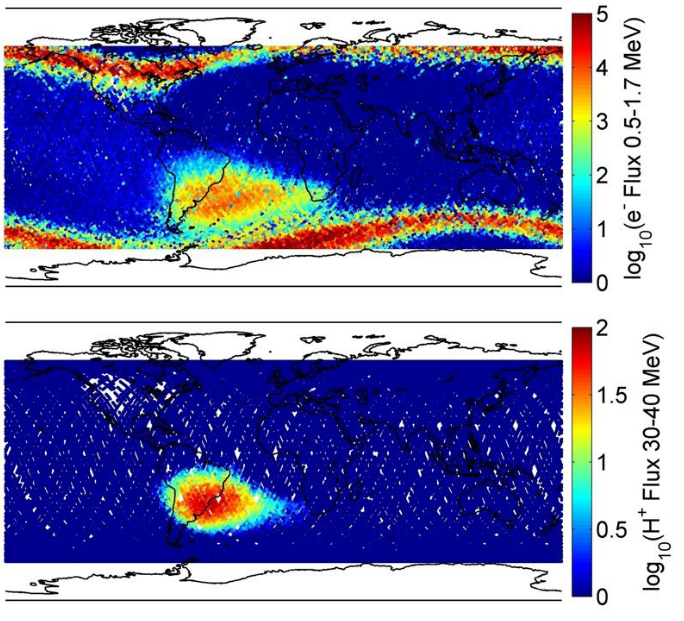

Figure 3: Measurements of 0.5 to 1.7 MeV electrons (top) and 30 to 40 MeV protons (bottom) from the REPTile instrument onboard CSSWE. The data were collected from October 5, 2012 to October 25, 2012.

3. Subsystem Performance

Figure 4 labels the major components of CSSWE. CSSWE uses a centralized processor architecture with the Command & Data Handling (C&DH) board running a simple Real Time Operating System (RTOS) developed by the team. The C&DH board is the commercially-available Pumpkin™ motherboard, which was selected to reduce development schedule impact because this was the first CubeSat the team had constructed. Although the CSSWE team originally aimed to design its own radio, the project schedule necessitated the switch to a commercial off-the-shelf (COTS) solution. Thus, the AstroDev© Lithium-1 radio is the heart of the CSSWE communications (COMM) board. The Electrical Power System (EPS) board was developed by CU, but is based on the general architecture of the RAX EPS board (Cutler and Bahcivan, 2013). A Pumpkin™ 3U solid shell is used for structural support and to protect interior electronics from on-orbit radiation dosing. An interior aluminum skeleton was designed to support both the electronics boards and REPTile, which accounts for >40% of the total satellite mass due to energetic particle shielding requirements. A 48.3cm tape-measure antenna is coiled within the satellite while stored in the PPOD and deployed autonomously after orbit insertion.

The CSSWE sensors are divided into two categories: attitude and housekeeping. The attitude sensors (photodiodes and magnetometer) are queried with a

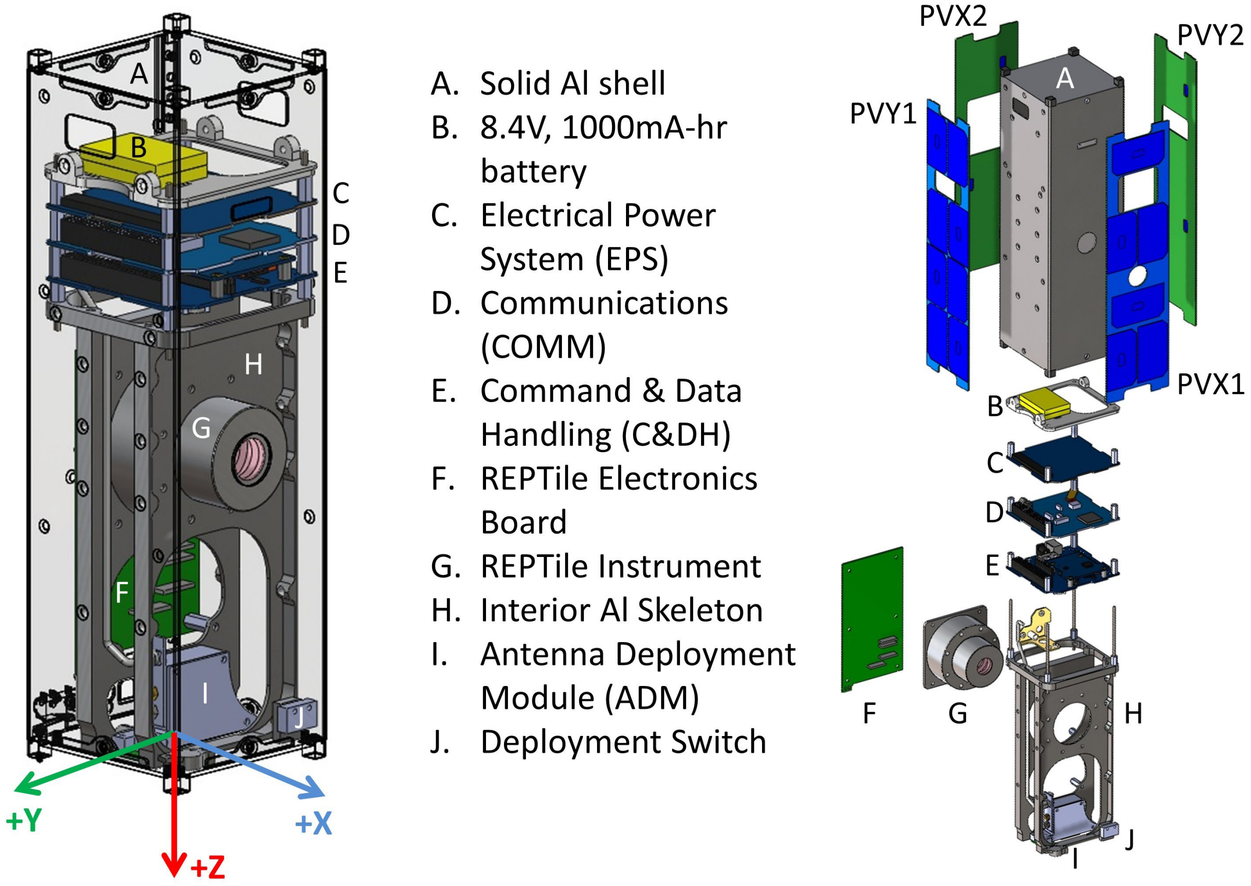

Figure 4: Solid models of CSSWE: (left) interior layout; (right) exploded isometric view. Subsystems and major components are labeled. The coordinate system is also shown (+X parallel with REPTile collimator, +Z aligned with antenna and +Y completing the right-handed set).

six second period for simultaneous acquisition with the science data product. The housekeeping sensors (temperatures, currents, and voltages) are queried once each minute to form a ten minute average, maximum and minimum value for each sensor. CSSWE operates in two modes: SAFE and NORMAL. In SAFE mode, CSSWE transmits a beacon containing instantaneous sensor and state data once every 18 seconds. In NORMAL mode, the REPTile instrument is powered and no beacon is transmitted (ground testing showed that satellite transmissions disrupted REPTile data collection). Satellite telemetry has helped verify the on-orbit performance of the spacecraft, including the Communications (COMM), (Electrical Power System (EPS), Thermal, and Attitude Determination and Control (ADCS) subsystems, which are detailed below.

3.1. Communications (COMM)

Two hours after PPOD deployment, the antenna was autonomously deployed by heating a resistor which burned through nylon fishing line holding the antenna coiled within the Antenna Deployment Module (ADM). Directly following the antenna deployment, CSSWE began transmitting its beacon. Less than five hours after antenna deployment, amateur operator DK3WN of Germany received the first CSSWE beacons using decoding software made available to the amateur community. Figure 5 shows the Received Signal Strength Indication (RSSI) and CSSWE location for 25,000+ unique beacons collected worldwide. RSSI is a relative measure of received power provided by the AstroDev© Lithium-1 radio. As shown, east Asia and

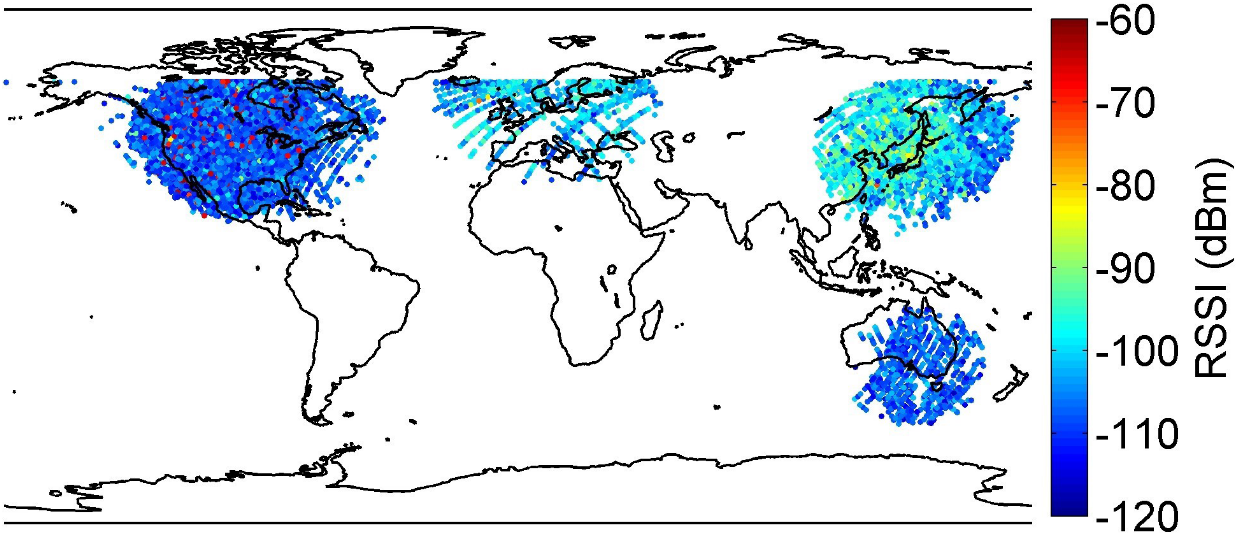

Figure 5: World map of CSSWE beacon received signal strength indication. Beacons are received by the ground station over Boulder, CO, as well as through a network of amateur operators using freely-available packet decoding and forwarding software.

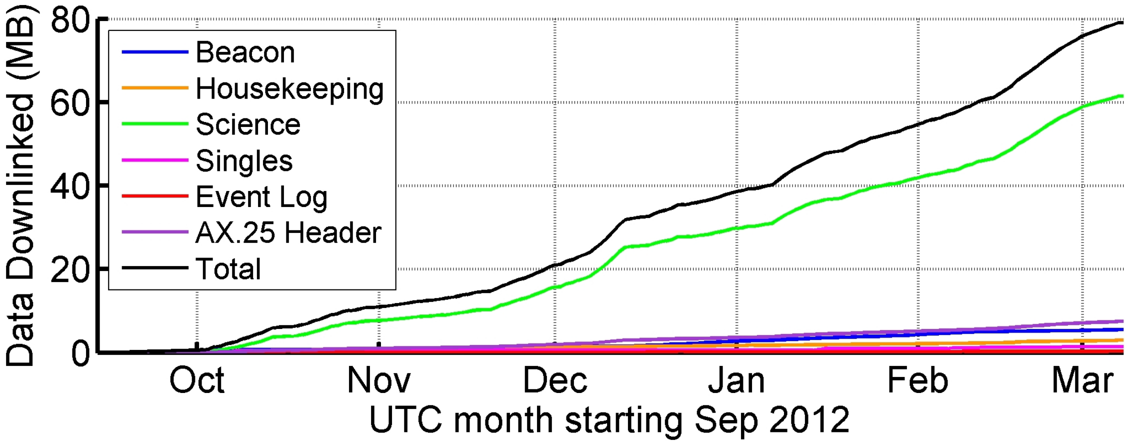

Figure 6: Cumulative data received from CSSWE. CSSWE uses five primary packet types: beacon, housekeep- ing, science (binned REPTile data + attitude data), singles (raw detector hits), and event log. Each packet uses an AX.25 header of identifying information.

Europe had higher ambient noise levels at 437 MHz than Australia or North America; this has been independently observed by another NSF CubeSat (Springmann et al., 2012). A few high-RSSI beacons can be seen over North America; these are when CSSWE was commanded by the LASP ground station. Figure 6 shows the history of data collected from CSSWE over time. The majority of data generated by CSSWE are science packets that contain REPTile, magnetometer, and photodiode data, as measured every six seconds. Of the 80 MB collected from the CubeSat during the first six months of operations, over 60 MB is science data.

An Automated Commanding System (ACS) developed for the LASP ground station was enabled for use on December 19, 2012. The system was operational in time to save operators from late-night passes over the holidays. (The automated system enable is marked as E4 in Figures 8, 11, and 14.) This system runs passes in a fully autonomous manner and is responsible for calculating which data to request, as well as sending appropriate commands to dump data. During each pass, the ACS uses beacon telemetry to determine the health of the spacecraft. After comparing to user-set thresholds, an appropriate-length data dump is requested based on CubeSat health. Between each pass, the ACS determines which data has been adequately received and generates a prioritized list of data dump commands for the next pass. The ACS also uses the downlinked data to generate plots in real time that the operations team can review. Automatic pass update emails are also generated, and text alerts are sent if an anomaly occurs. The ACS has become a reliable tool for CSSWE mission operations, and will be useful for future CU satellites as well.

3.2. Electrical Power System (EPS)

The EPS system uses power from the solar panels to charge the 8.4V, 1000mA•hr, lithium polymer battery and supply 3.3V and 5V power lines to the bus. Four solar panels are used, one on each 3U face of the CubeSat; the panels are labeled in Figure 4. PVX1 and PVX2 each have six solar cells in series, while PVY1 has eight cells and PVY2 has seven operational cells (one was damaged during ground testing). Figure 7 shows the daily maximum solar panel voltages over time. As shown, the solar panels experienced a degradation in output voltage during the first month on orbit (the PVY1 voltage maximum saturated its analog to digital converter until early October 2012) but the degradation slows thereafter. This degradation is likely due to atomic oxygen pitting the solar cells; no cover glass was used for the solar cells due to the complexity of assembly and the anticipated mission length. Also visible is an inverse relationship between the solar panel efficiency and the orbit insolation percentage (and thus the average temperature of the panels). Although the maximum recorded panel voltage decreases over time, the current increases to match the battery load.

After one month of on-orbit operations, it was discovered that CSSWE was not always power positive

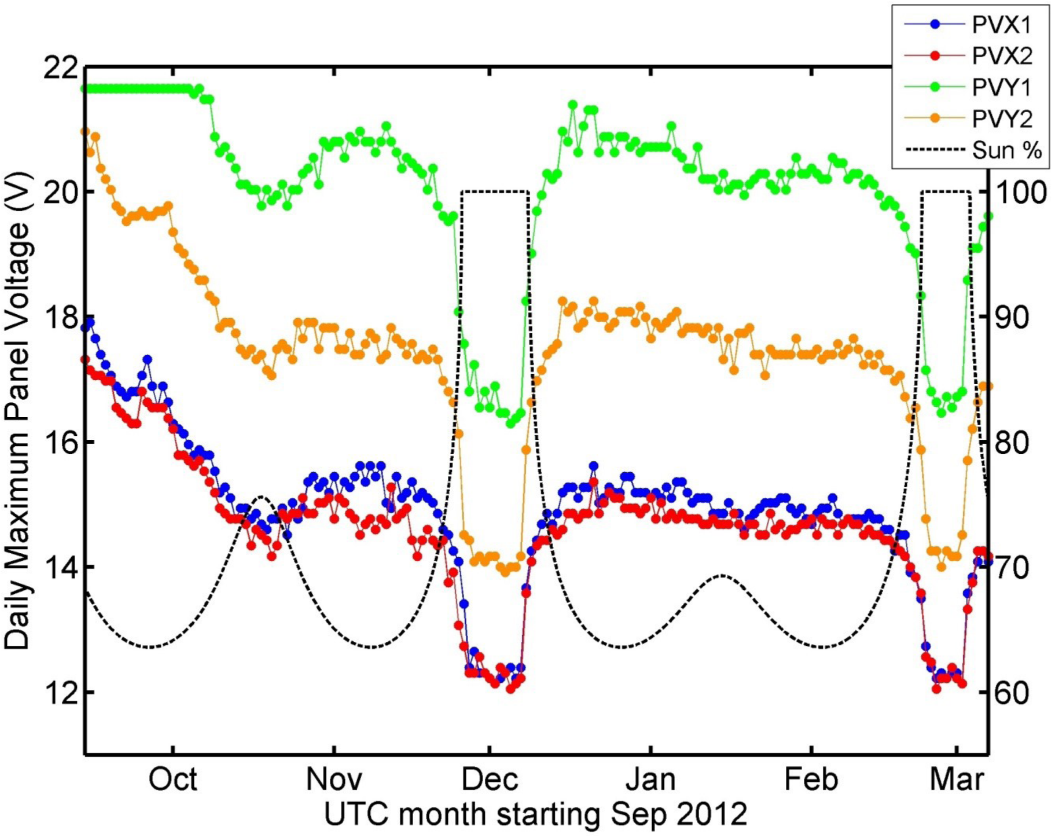

Figure 7: Maximum daily solar panel voltage output and orbit insolation fraction over time. The solar panels degraded sharply during the first month, but degradation slows thereafter. As expected, the solar panel outputs degrade when the panels are hotter, such as during periods of high insolation percentage.

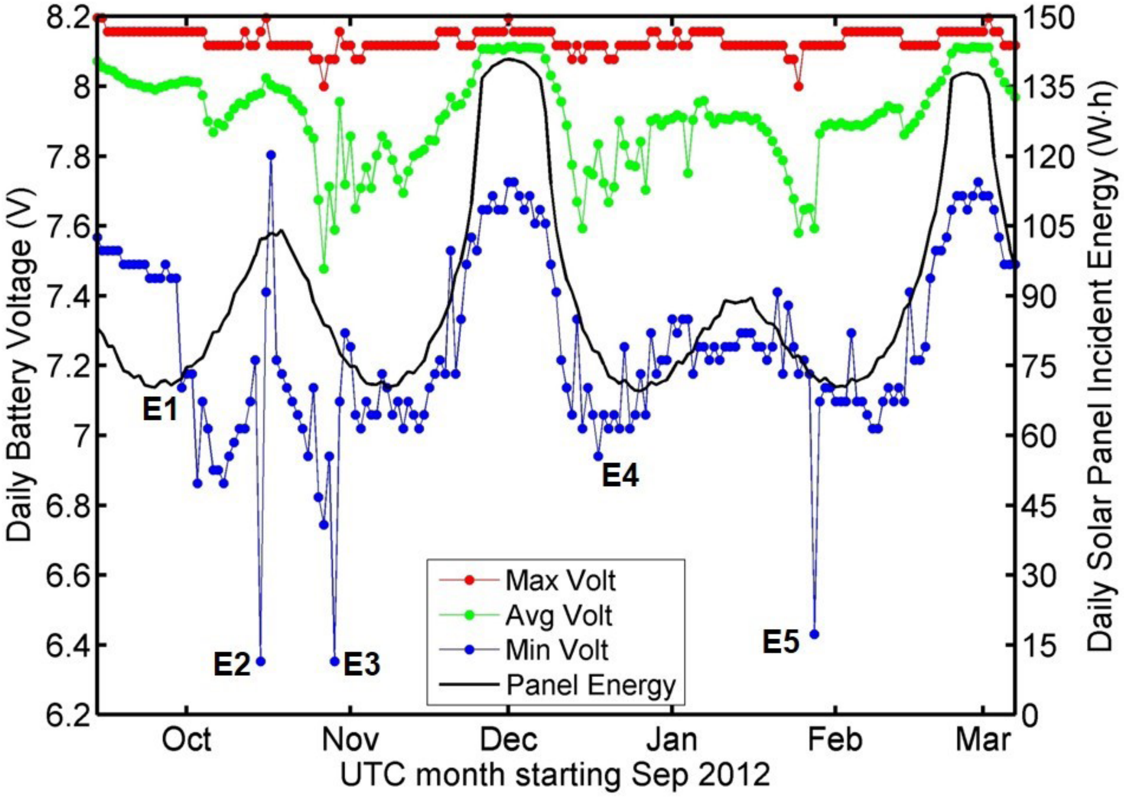

Figure 8: Daily battery voltage and solar panel incident energy over time. The maximum, average, and minimum daily voltages are shown. Select mission events are labeled consistently with Figures 11 and 14.

when REPTile was enabled. Figure 8 shows the maximum, average, and minimum daily battery voltage over the length of the mission, as well as the incident energy absorbed by the solar panels. The incident energy takes into account the orbit insolation period, which varies with orbit solar beta angle, and the angle between the solar panels and the sun (solar panel power production decreases as the cosine of the incidence angle). The science instrument was duty-cycled, to maintain the battery voltage and ensure an overall positive CSSWE power balance. Figure 8 also labels select events over the length of the mission; event E1 marks when the science instrument was first enabled on October 4, 2012. Events E2, E3, and E5 correspond to anomalies, while event E4 represents the ACS enable.

3.3. Thermal Control

CSSWE primarily uses a passive thermal control system. Throughout design and development, a model built- in Thermal Desktop® was used to determine the necessary design modifications to ensure that the temperatures within the spacecraft remained within design levels. Based on the thermal model, thermal windows were placed on all 3U sides of the electronics stack (visible in Figures 1 and 4). These thermal windows are covered with high-emissivity silver coated Teflon tape, which keeps the electronics stack cool. The only active component of the thermal control system is a battery heater/thermistor to ensure that the battery temperature is ≥5˚C. The battery is also wrapped in Multi-layer Insulation (MLI) to decrease heater use.

Although not required by the funding agency (NSF) or the launch provider, the CSSWE team chose to perform a thermal vacuum (TVAC) test to verify the performance of the satellite over the temperature extremes experienced in the on-orbit environment. The team used a LASP TVAC chamber to keep CSSWE below 10^{-6} Torr while completing eight temperature cycles over a period of ten days. Each cycle is defined by a six-hour soak at each of the cold and hot extremes (-25˚C / +40˚C). The temperature of the aluminum shell was measured independently of CSSWE housekeeping sensors, using the average of four external thermistors to determine when soak thresholds had been met. Figure 9 shows three cycles from the TVAC test as measured in December 2011. During the TVAC test, the software control for the battery heater was set to ensure the battery temperature never fell below 10˚C (this threshold was set to 5˚C for on-orbit operations).

Figure 10 shows the daily average temperature of various interior components of CSSWE as measured on orbit. These daily averages closely follow the orbit insolation percentage (visible in Figure 7), albeit with minor offsets. The REPTile board temperature is seen to have a significant offset starting in mid-October. A system anomaly (discussed later) affected some CSSWE Analog to Digital Converters (ADCs) which caused this behavior. The REPTile board temperature was corrected using redundant telemetry (both original and corrected REPTile board temperatures are shown in Figure 10).

Figures 9 and 10 show that TVAC testing gives a good estimate of the relative temperatures of various components as experienced on orbit. However, there are differences attributable to the test setup. The TVAC chamber had both radiative and conductive heat transfer though the mounting mechanism, while the orbital environment is almost exclusively radiative heat transfer. Also, the cold soak was never experienced on orbit

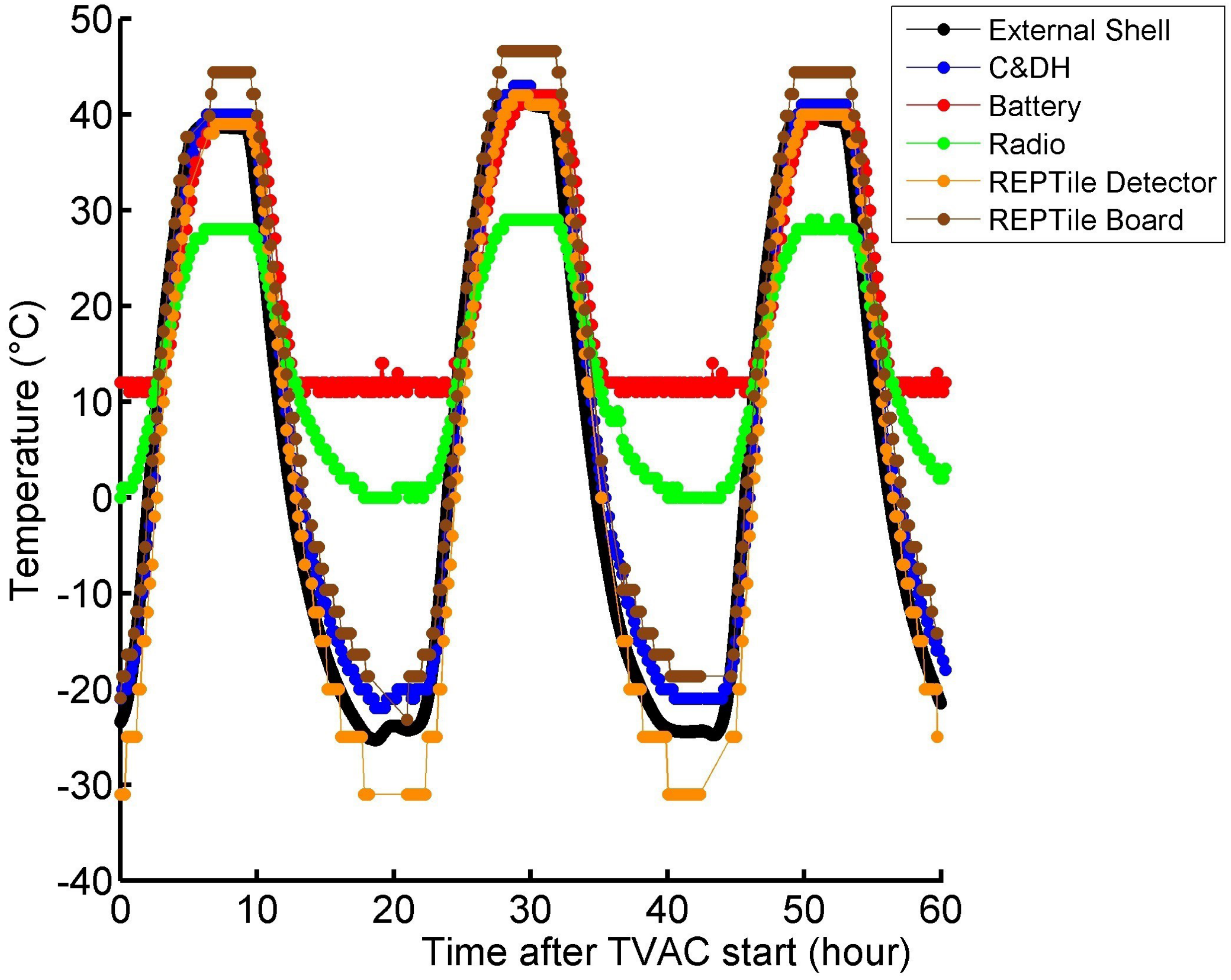

Figure 9: Interior temperatures over time, as measured during TVAC testing in December 2011. The external shell temperature was calculated from the average of four thermistors and was recorded once every 68 seconds. All other temperatures are ten-minute averages recorded by CSSWE.

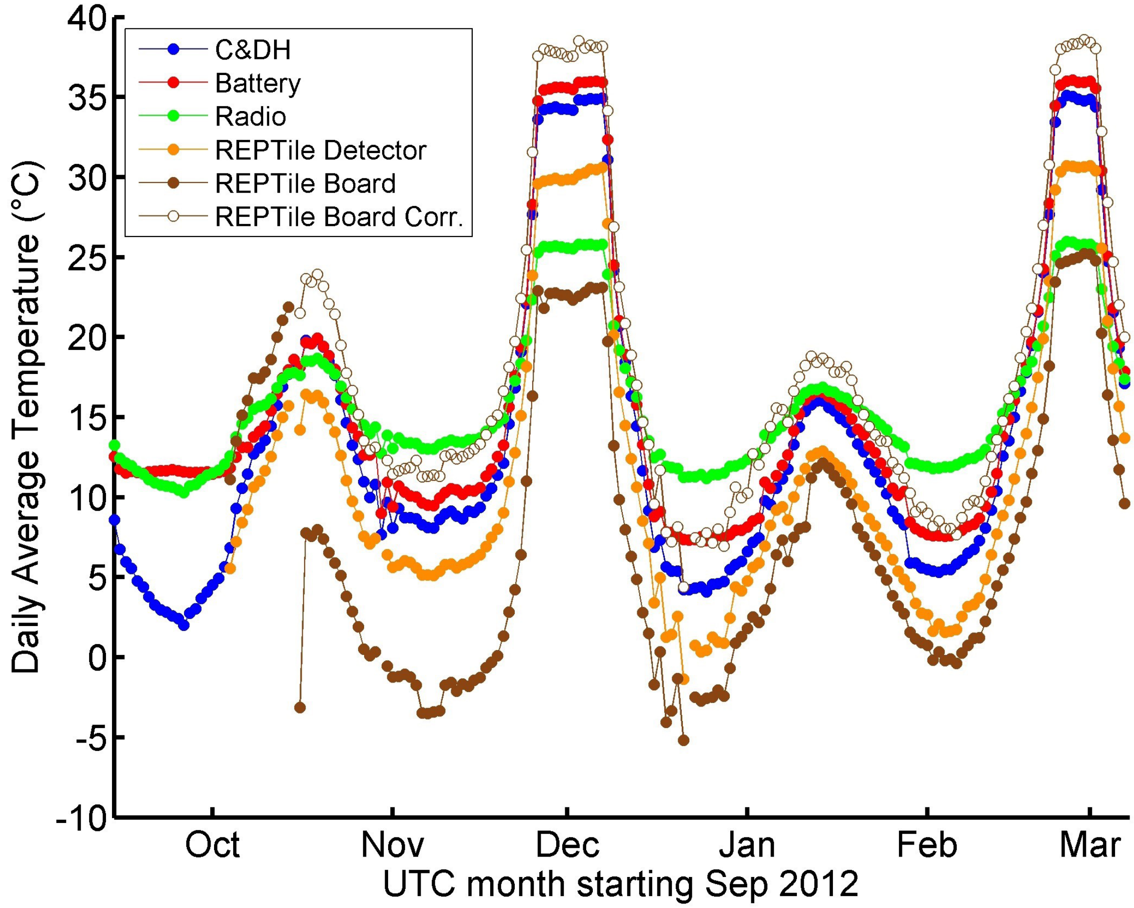

Figure 10: Daily average on orbit interior temperatures. The REPTile board temperature was effected by an anomaly occurring 10/14/2012. This telemetry has been corrected using redundant telemetry.

(the maximum eclipse experienced by CSSWE was 34 minutes), thus the TVAC test was significantly colder than the worst case on-orbit environment.

The daily minimum, average, and maximum temperatures experienced by the C&DH board are shown in Figure 11. Similar to other internal telemetry points, C&DH experienced daily temperature fluctuations of 10˚C to 15˚C. The largest swings between minimum and maximum temperatures occur close to beta angle zero, when the satellite experiences the longest eclipse time. Select mission events are labeled consistently with Figures 8 and 14.

Table 1 compares the design mission-allowable temperature ranges to those recorded on orbit. The on- orbit temperatures were almost always within the mission design range, and mostly within the thermal model expected range. However, the on-orbit solar panel temperatures do not fit within the mission design range; these showed spikes of 110˚C to 120˚C at two points in the mission. These spikes in temperature occur when the roll rate of the satellite is near zero and each side of the satellite sees the sun for an extended period of time. Also, the thermal model predictions are as much as 10˚C to 15˚C off from the on-orbit data. CSSWE did not have the resources to complete a thermal balance test, which would have resulted in a more accurate thermal model. Instead, the TVAC boundaries were set to test temperatures beyond the thermal model predictions (where possible, due to limits of TVAC chamber).

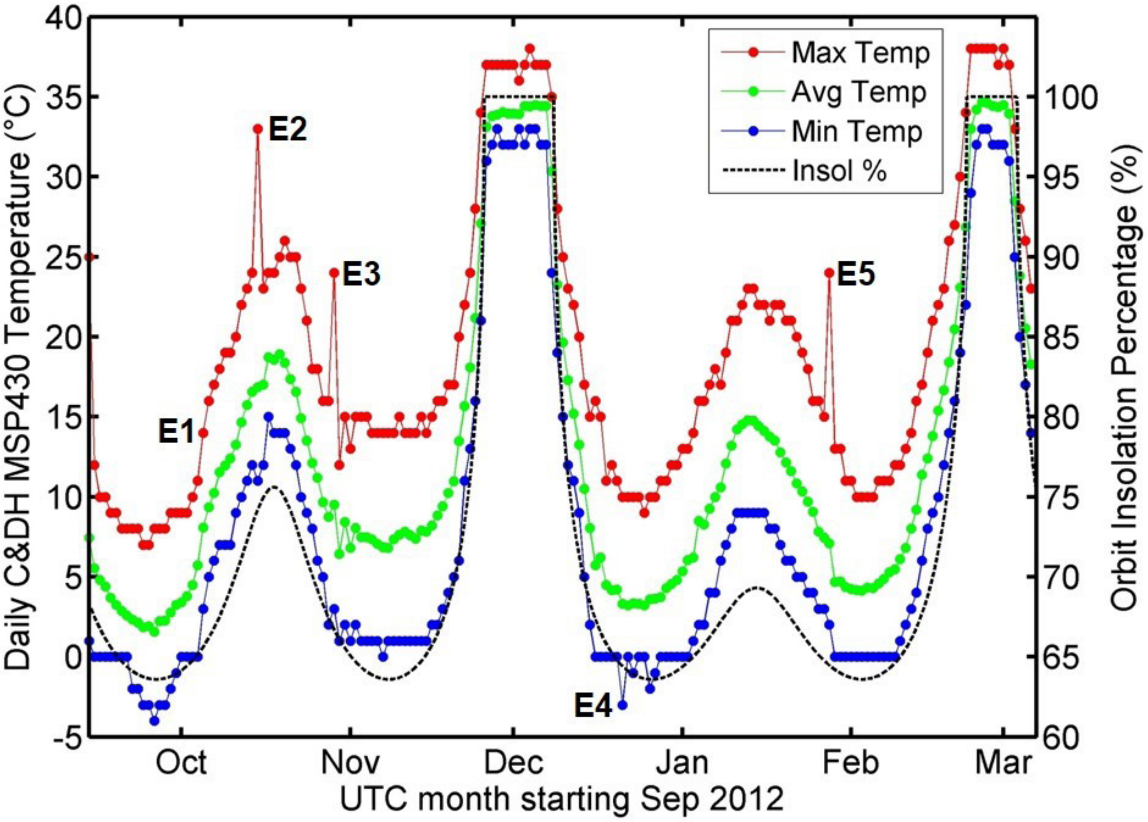

Figure 11: Daily C&DH temperature and orbit insolation percentage over the mission duration. The maxi- mum, average, and minimum daily temperatures are shown. Select mission events are labeled consistently with Figures 8 and 14.

Table 1: The mission was designed with specific temperature limits in mind, and a thermal model was iterated with design changes to best match the designed temperature range. The on-orbit temperatures experienced are mostly within the designed temperature range.

Part	Design Range (˚C)	Model Predict (˚C)	TVAC Test (˚C)	On Orbit (˚C)
Board Stack	-30/+40	-5/+26	-25/+40	-4/+35
REPTile Detectors	-20/+30	-7/+21	-25/+40	-4/+35
Battery Case	0/+60	+22/+47	+10/+40	+5/+38
Solar Panels	-55/+40	-50/+55	-35/+45	-60/+60*

*Spikes of up to 120˚C were experienced during near-zero roll periods.

3.4. Attitude Determination and Control System (ADCS)

CSSWE uses a Passive Magnetic Attitude Control (PMAC) system (Gerhardt and Palo, 2010). This system is composed of one hard-magnet cylinder to restore the spacecraft to the local magnetic field and six soft- magnet hysteresis rods to dampen the angular velocity of the spacecraft. The PMAC system causes the satellite attitude to converge to a limited oscillation about the local magnetic field with an amplitude of ±15˚ or less. Figure 12 shows the attitude response of CSSWE over the first 20 days on orbit. As shown, CSSWE converged to within 15˚ of the local magnetic field after one week in orbit.

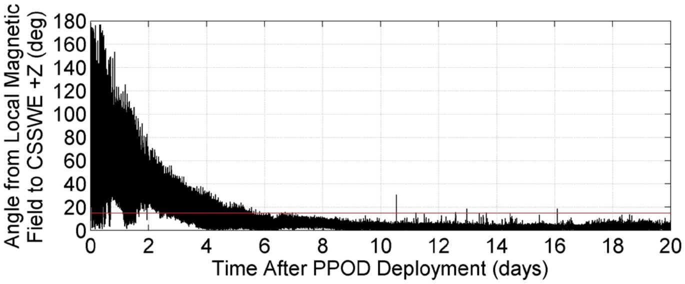

Figure 12: The angle between the local magnetic field and the CSSWE Z-axis is shown over the first 20 days on-orbit. The red line indicates an angle of 15˚. CSSWE converged to within 15˚ of the magnetic field one week after orbit insertion.

The attitude determination is performed using one three-axis magnetometer (located on the REPTile elec- tronics board) and four photodiodes (one on each solar panel); these sensors are sampled once every six seconds by C&DH. Ground-based processing is performed using a Multiplicative Extended Kalman Filter (MEKF) specially developed for CSSWE. The CSSWE MEKF uses a spacecraft torque model to predict the angular velocity of the spacecraft, instead of a rate gyro (more commonly used by an MEKF). The magnetometer was calibrated both on the ground preflight (Foster and Elkaim, 2008) and using an on-orbit calibration (Springmann and Cutler, 2012), which removes the effects of scale/offset error, non-orthogonality errors, magnetometer temperature and battery charge/discharge currents. The daily maximum output of the photodiodes is shown in Figure 13 below. As shown, the maximum photodiode output degrades significantly over the lifetime of the mission. This is thought to be due to UV-induced darkening of the plastic covering on each photodiode. Quantization of the photodiode output is also visible after mid-October, when an anomaly affected 3 of the 4 photodiode ADC outputs. A future publication will describe the simulation and performance of the PMAC system in more detail.

4. Anomalies And Response

CSSWE experienced four anomalies during the first nine months on orbit; two of these anomalies are suspected to be due to the same issue. Figure 14 is helpful for this discussion; it shows the daily REPTile duty cycle and orbit solar beta angle magnitude over the first six months of the mission. CSSWE was not able to keep REPTile powered indefinitely during periods of low solar beta angle magnitude; instead, the instrument was duty-cycled, so the spacecraft would remain power neutral. The anomalies and major mission events are labeled as in Figures 8 and 11.

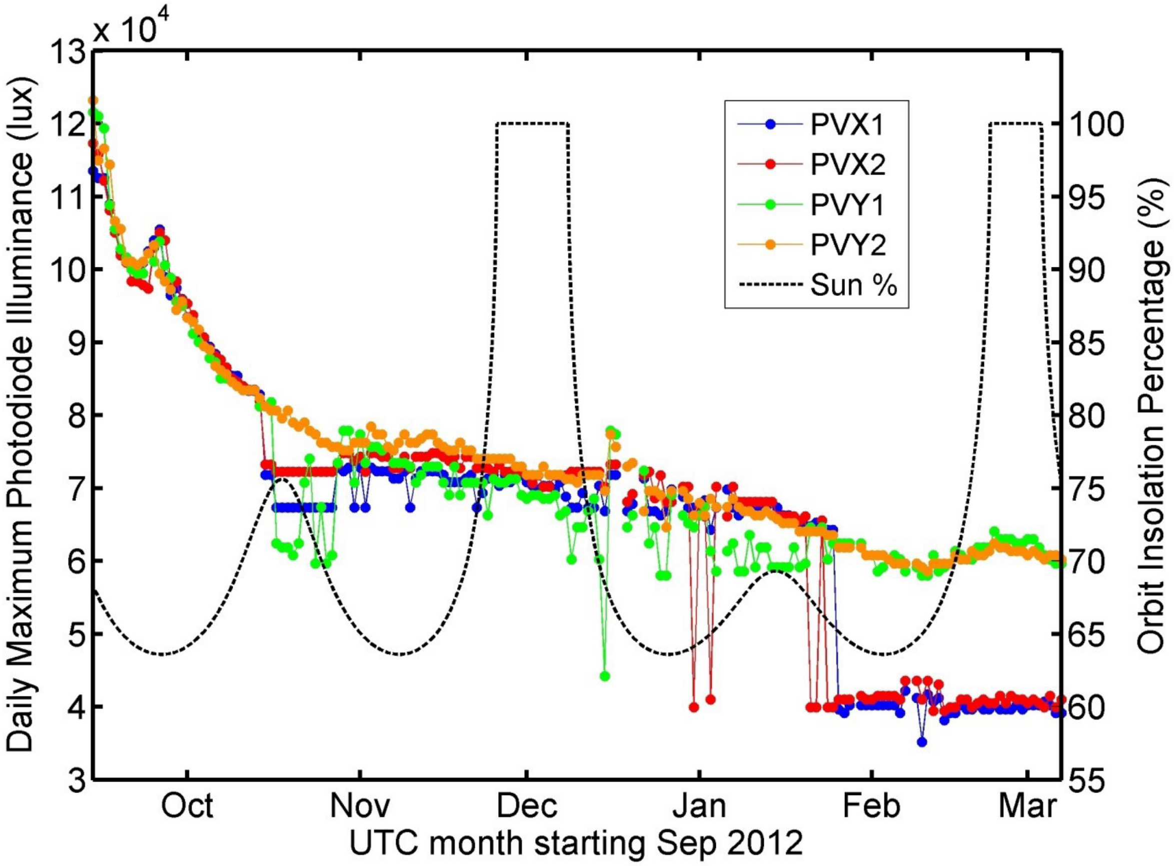

Figure 13: Maximum daily photodiode output and orbit insolation percentage. UTC days with less than 2500 six-second samples downlinked have been omitted. The degradation of the photodiode output over time is visible.

4.1. ADC Latch-up

Beginning at 10/14/2012 23:28:45 UTC (E2), all of the devices on the housekeeping I2C line stopped responding to data requests. CSSWE was on the edge of the SAA (just off the coast of Peru) when the anomaly began. The I2C line cutout continued until a C&DH reboot occurred two hours later. After this reboot, the battery began to recharge from a low value and the internal temperatures began to decrease from a high value (E2 on Figures 11 and 14). After the event, the housekeeping ADC responsible for measuring voltage and current telemetry from the REPTile detectors no longer responded to queries, though all other devices on the same I2C line regained communication. However, select outputs of two other ADCs on the same I2C line showed significant quantization after the event. This quantization (visible for PVX1, PVX2 and PVY1 in Figure 13) is the result of 1-3 bits of the 8-bit ADC no longer functioning.

The CSSWE team resolved that these events were consistent with a latch-up of the ADC monitoring REP- Tile detector currents and voltages. The latch-up caused one of the I2C lines from the ADC to be held high, disrupting all I2C communication on that line. The current through the ADC was significant enough to drain the battery within two hours, causing a low-voltage reset which power cycled the ADC chip and cleared the latch-up. By that time, the ADC was inoperable, and select outputs from two other ADCs had been damaged. The CSSWE budget did not allow for high-cost, radiation-hardened components which may have fared better. Fortunately, CSSWE was designed to be robust to battery charge from very low voltage, which allowed for successful recovery.

4.2. Battery Drain Anomalies

Beginning at 10/29/2012 17:05:55 UTC (E3), there is a gap in the telemetry recorded by CSSWE. CSSWE

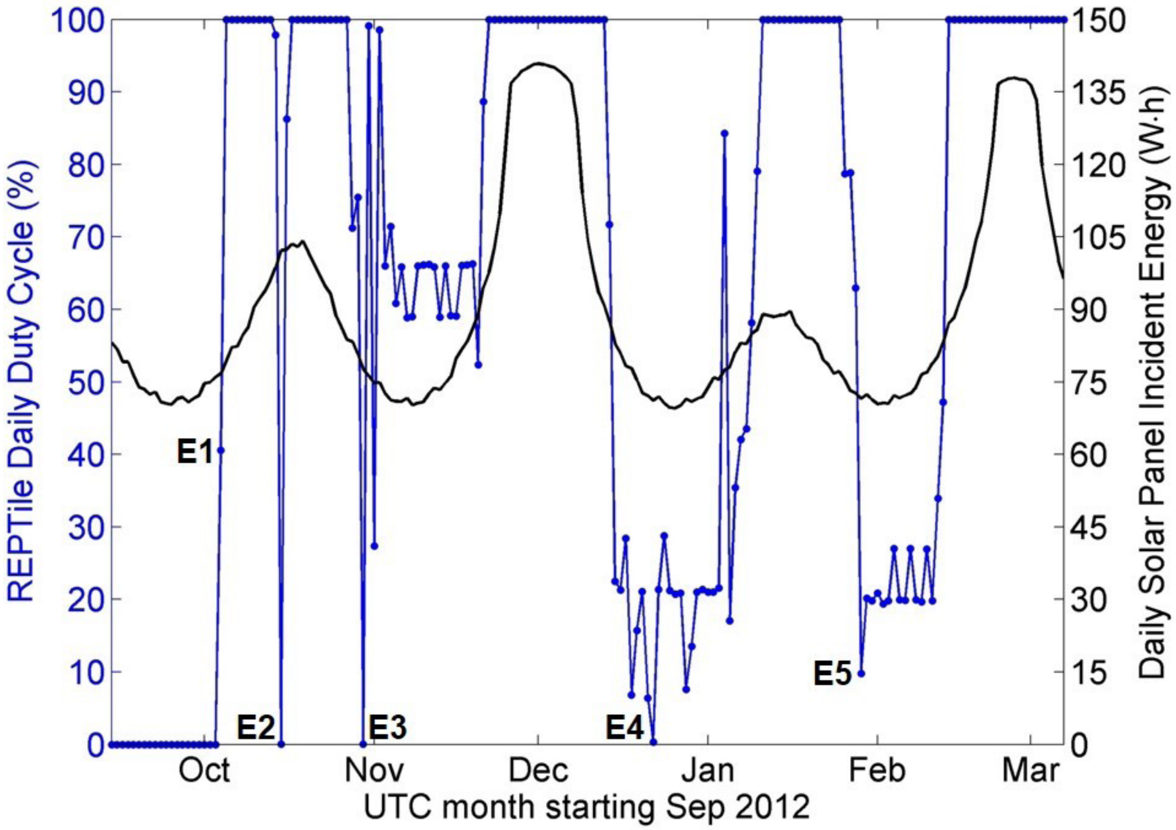

Figure 14: The duty cycle of the REPTile instrument is overplotted with the CSSWE solar panel incident energy over time. Select mission events are labeled consistently with Figures 8 and 11.

was in the middle of the SAA (SE coast of Brazil) and transitioning from high to low solar orbit beta angle magnitude when the anomaly began (see Figure 14). One hour later, a reboot occurred, restoring telemetry, showing high internal temperatures and a low battery voltage directly following the reboot. This same behavior occurred again at 01/28/2013 19:26 UTC (E5), although for the second event, the battery reset occurred within 51 minutes of the telemetry gap start, and the anomaly began when CSSWE was at the edge of the SAA (again, just off the coast of Peru). C&DH protects the SD card from damage by disabling write capability when the battery voltage is <6.25V. This explains the gap in recorded telemetry. However, the cause of the battery drain is unknown at this time; all systems recovered fully after each event. It is interesting that both anomalies occurred during the transition from high to low orbit solar beta angle magnitude, when the CubeSat begins to experience lower temperatures again due to the increasing eclipse period.

4.3. Communications Blackout

The LASP ground station received a CSSWE data packet at 03/07/2013 22:35:45 UTC; this was the last CSSWE packet received for over three months. During the blackout, the CSSWE team performed a fault tree analysis, verified ground station functionality, sent a multitude of commands to CSSWE, and held an end-of-mission review. No communications could be established; the team had all but given up on contact with CSSWE. Due to minimal resource cost, the ACS was used to attempt contact during every pass over Boulder. The ACS captured the first beacon after the blackout on 06/18/2013 17:24:45 UTC.

The timeline of the blackout can be pieced together by reviewing the on-board telemetry, which was recorded by C&DH throughout the blackout. The event log shows that C&DH attempted a COMM software reset approximately eight hours after the last ground station contact (C&DH is programmed to attempt a software re- set if COMM is unresponsive for five minutes). C&DH to COMM communications remained non-operational after twelve software reset attempts over four days (the event log filled after the fourth day, so more resets may have occurred). The first reset attempt marks the beginning of the blackout, as radio telemetry (RSSI and radio temperature) was recorded before, but not after, the attempt. Housekeeping data from EPS shows that the current draw on the 3.3V line (which supplies the digital components aboard COMM) increased by 40mA during the blackout.

Two weeks before the blackout ended, a third battery drain anomaly occurred, causing a C&DH reboot and setting all configuration settings to default. The default battery heater threshold temperatures are higher than the normal operation thresholds, and thus cause increased heater (and power) use. The combination of higher heater thresholds, an additional 40mA current draw from the 3.3V line, and a near-zero orbit solar beta angle (maximum eclipse period) caused a full system reset (3.3V and 5V power lines). After this full system reset, C&DH was able to resume communications with COMM. The first beacon was recorded by the ACS less than 20 minutes after the full system reset. After a ten-day recommissioning period, CSSWE began science operations once again with no loss of functionality.

The CSSWE team has not been able to replicate the blackout using identical ground-based hardware; the exact cause is unknown. However, the telemetry shows that the radio was not responding to commands from C&DH for a three-month period, until a full system reset occurred. As of this writing, no further communication blackouts have occurred. Ultimately, CSSWE continues to perform because of its robust design and unique ground station capabilities.

5. Lessons Learned

Since CubeSats were first proposed in 1999, there have been several orbital missions and many more design-only missions, yet teams seldom document their lessons learned. As a student-led mission, over 60 multidisciplinary graduate and undergraduate students have been part of the CSSWE team. These students started with an idea and ended by operating a spacecraft they designed, built, and tested using a ground station they designed, built, and tested. This section aims to collect the lessons learned over the six+ year lifetime of the CSSWE project from development to operations and analysis.

5.1. General

Although trite, the following general principles guided CSSWE through the design process. First, in the face of severe resource constraints, simplicity is the cheapest way to minimize mission risk. Complexity always comes with cost. Design to meet the mission requirements, no more and no less. Second, test early and often. Testing is crucial to understanding performance; it should begin as soon as hardware and software are available.

5.2. Select Commercial Hardware Carefully

Four on-orbit anomalies are discussed above; two were likely attributable to particle interactions with hardware components. Radiation-hardened components were not available because of monetary constraints. Although the CSSWE team did not know until after CubeSat delivery, there exist multiple electronic component parts lists that collect radiation susceptibility information for commercially-available, non-hardened components. Using the parts on these publicly-available lists may have avoided some on-orbit anomalies. NASA has a variety of open-source radiation test results for various components available online.

5.3. Design with Analysis in Mind

CSSWE was designed from the ground up; this sometimes led to a sub-optimal design in terms of the end data product. For example, early in the design phase, the team decided that the housekeeping would be ten-minute minimum, maximum, and average values for each telemetry point. In hindsight, instantaneous measurements taken every 200 seconds (an equivalent data size) is preferable, as it would allow for a more rigorous analysis. All other things being equal, the better design considers what is best for post-mission analysis.

5.4. Documentation and Review is Critical

CSSWE was organized as a projects course; individuals would work on the CubeSat (or a different project) for two semesters to fulfill their degree requirements. Due to student turnover, high-quality documentation was critical for CSSWE success. Early in the CSSWE mission design, a structuring system was developed to ensure each document revision was peer reviewed before release into a mission catalog. This system ensured that documents were readily available to reference or revise as work progressed. Design reviews fit nicely into the class structure of CSSWE. Held twice per semester, these reviews gleaned critical information from attending LASP professionals. Their feedback helped avoid common pitfalls and ensure design robustness.

6. Conclusion

CSSWE is an example of a successful 3U CubeSat, having met its educational objectives and fully realized its science goals. The high quality of CSSWE science data complements the NASA Van Allen Probes mission, proving that a CubeSat can perform serious scientific measurements. To date, CSSWE has far exceeded its 90-day design mission lifetime, by providing on-orbit measurements of energetic particle directional differential flux for 426 days, and continues to operate well.

The system bus enabled the science mission success. The communication system performed well with data collected by a ground station at LASP, as well as a worldwide network of amateur radio operators. The CSSWE attitude converged to within 15° of the local magnetic field after seven days in orbit. Interior satellite temperatures stayed within the design limits and were well-matched with the thermal model. The system design was robust to an electronics latch-up, two battery drain anomalies, and a communications blackout, recovering to nominal science operations after each anomaly. The CSSWE team attributes the mission success to a focus on simplicity, substantial testing, and a culture of documentation and review.

Acknowledgments

CSSWE is supported by the National Science Foundation grant AGS 0940277. The CSSWE launch was coordinated by the NASA Educational Launch of Nanosatellites (ELaNa) program. The Naval Postgradu- ate School (NPS) designed NPSCul and donated vibration testing time. The National Reconnaissance Office (NRO) graciously allowed NPSCul as a secondary payload aboard their Atlas V rocket. Students at CalPoly handled CubeSat to launch vehicle integration and enabled communication between teams. The authors thank all current and previous CSSWE team members for their dedication, as well as many LASP professionals for their guidance throughout the project. The support of the HAM radio community worldwide was also greatly appreciated.

References

Baker, D., et al. (2012): The Relativistic Electron-proton Telescope (REPT) Instrument on Board the Radiation Belt Storm Probes (RBSP) Spacecraft: Characterization of Earth's Radiation Belt High-energy Particle Populations. *Space Science Reviews*, vol. 179 (1-4), pp. 1-45.

Baker, D. N. (2002): How to Cope with Space Weather. *Science*, vol. 297 (5586), pp. 1486-7.

Blum, L. W., et al. (2013): New Conjunctive CubeSat and Balloon Measurements to Quantify Rapid Energetic Electron Precipitation. *Geophysical Research Letters*, vol. 40 (22), pp. 5833-7.

Blum, L. W. and Schiller, Q. G. (2012): Characterization and Testing of an Energetic Particle Telescope for a Cubesat Platform, in Proc. *26th Annual Small Satellite Conf.*, Logan, UT.

Cutler, J. W. and Bahcivan, H. (2013): Radio Aurora Explorer: A Mission Overview. *J of Spacecraft and Rockets*, vol. 51 (1), pp. 39-47.

Foster, C. and Elkaim, G. (2008): Extension of a Two-step Calibration Methodology to Include Non- orthogonal Sensor Axes. *Aerospace and Electronic Systems*, vol. 44 (3), pp 1070-8.

Gerhardt, D. T. and Palo, S. E. (2010): Passive Magnetic Attitude Control for Cubesat Spacecraft, in *Proc.24th Annual Small Satellite Conf.*, Logan, UT.

Heidt, H. et al., (2000): Cubesat: A New Generation of Picosatellite for Education and Industry Low-cost Space Experimentation, in *Proc. 14th Annual Small Satellite Conf.,* Logan, UT.

Li, X., et al., (2011): Small Space Weather Research Mission Designed Fully by Students. *Space Weather,* vol. 9 (4).

Li, X., et al., (2012): Colorado Student Space Weather Experiment: Differential Flux Measurements of Energetic Particles in a Highly Inclined Low Earth Orbit. *Geophysical Monograph Series, vol. 199 (Dynamics of the Earth's Radiation Belts and Inner Magnetosphere)*, pp. 385-404.

Li, X., et al., (2013a): Small Mission Accomplished by Students – Big Impact on Space Weather Research. *Space Weather*, vol. 11 (2): pp. 55-6.

Li, X., et al., (2013b): First Results from CSSWE CubeSat: Characteristics of Relativistic Electrons in the Near-Earth Environment During the October 2012 Magnetic Storms. *J of Geophysical Research: Space Physics*, vol. 118 (10), pp. 6489-99.

Palo, S., et al., (2010): Conducting Science with a Cubesat: The Colorado Student Space Weather Experiment, in *Proc. 24th annual Small Satellite Conf.,* Logan, UT.

Schiller, Q., et al., (2014a): Design and Scientific Return of a Miniaturized Particle Telescope Onboard the Colorado Student Space Weather Experiment (CSSWE) CubeSat. in Proc. *35th annual IEEE Aerospace Conference*, p. 8.

Schiller, Q., et al., (2014b): A Nonstorm Time Enhancement of Relativistic Electrons in the Outer Radiation Belt. *Geophysical Research Letters,* 41 (1), pp. 7–12.

Schiller, Q. and Mahendrakumar, A., (2010): Reptile: A Miniaturized Detector for a Cubesat Mission to Measure Relativistic Particles in Near-Earth Space in Proc. *24th Annual Small Satellite Conf.,* Logan, UT.

Skrobot, G. L., (2011): ELaNa Educational Launch of Nanosatellite Enhance Education through Space Flight, in Proc. *25th annual Small Sat Conf.*, Logan, UT.

Skrobot, G. L. and Coelho, R., (2012): ELaNa Educational Launch of Nanosatellite Providing Routine RideShare Opportunities, in Proc. *26th Annual Small Satellite Conf.*, Logan, UT.

Springmann, J. C. and Cutler, J. W., (2012): Attitude-Independent Magnetometer Calibration with Time-Varying Bias. *J of Guidance, Control, and Dynamics*, 35 (4), pp. 1080-8.

Springmann, J. C., et al., (2012): Initial Flight Results of the Rax-2 Satellite, in Proc. *26th Annual Small Sat Conf.*, Logan, UT.

Twiggs, R. (2008): Origin of CubeSat, in Small Satellite: Past, Present and Future, H. Helvajian and S.W. Janson, (Eds.) El Segundo, CA: The Aerospace Press, pp. 151-173.

Willcox, T. (2012): Atlas V Aft Bulkhead Carrier Rideshare System, in Proc. *26th Annual Small Satellite Conf.*, Logan, UT.