Design and Scientific Return of a Miniaturized Particle Telescope Onboard the Colorado Student Space Weather Experiment (CSSWE) CubeSat

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***Abstract*—The Relativistic Electron and Proton Telescope Integrated Little Experiment (REPTile) is a loaded-disc collimated solid-state particle telescope designed, built, tested, and operated by a team of students at the University of Colorado. It was launched onboard the Colorado Student Space Weather Experiment (CSSWE), a 3U CubeSat, from Vandenberg Air Force Base on September 13th, 2012, as part of NASA's Educational Launch of Nanosatellites (ELaNa) program.**

REPTile takes measurements of energetic particles in the near-Earth environment. These measurements, by themselves and in conjunction with larger missions, are critical to understand, model, and predict hazardous space weather effects. However, miniaturizing a power- and mass-hungry particle telescope to return clean measurements from a CubeSat platform is extremely challenging. To overcome these challenges, REPTile underwent a rigorous design and testing phase. This paper highlights some of the design and testing which validates the data as a valuable contribution to the study of space weather.

CSSWE uses a keep-it-simple design approach to minimize risks associated with low budget and student built missions. A coherent testing plan confirmed that the spacecraft would remain healthy and take reliable measurements in orbit. This paper also highlights the system-level design and testing that verified spacecraft performance pre and post launch.

Despite the risks inherent CubeSat missions, REPTile to date has returned over 300 days of valuable science data, more than tripling its nominal mission lifetime of 90 days. Initial in-flight instrument results are presented, including engineering hurdles encountered in receiving and processing the data. Also, the preliminary scientific contributions of the mission are covered in this paper to demonstrate the capabilities of a low-budget CubeSat mission. As an affordable, robust, and simple instrument and mission design, CSSWE demonstrates that small satellites are a reliable platform to deliver quality science.

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1. INTRODUCTION

In general, CubeSat missions are regarded as premature for performing high quality science on orbit. They have been thought of as either educational tools or simple proof-of-concept platforms to increase component technology readiness level (TRL). However, recent successes by science-targeted CubeSat missions, many of which are enabled by the National Science Foundation (NSF), prove that CubeSats can provide influential science on a limited budget. One such CubeSat is the Colorado Student Space Weather Experiment (CSSWE).

CSSWE is a 3U (10cm x 10cm x 30cm) CubeSat developed at the University of Colorado (CU) as a collaboration between the Laboratory for Atmospheric and Space Physics (LASP) and the Aerospace Engineering Sciences Department. A rendering of the spacecraft can be seen in Figure 1. Funding for CSSWE was received in January 2010 for $840k from the NSF. CSSWE's primary science objective is to study space weather in Earth's magnetosphere [1]. The science payload, the Relativistic Electron and Proton Telescope integrated little experiment (REPTile) [2], is a miniaturized version of the Relativistic Electron and Proton Telescope (REPT) [3] on board NASA's Van Allen Probes mission [4]. REPTile measures energetic electrons and protons within Earth's magnetosphere from a low Earth orbit (LEO) altitude of 478 km x 786 km and a 64.7 degree inclination. The measurements compliment the Van Allen Probes mission, as well as other spacecraft, balloon, and ground-based measurements.

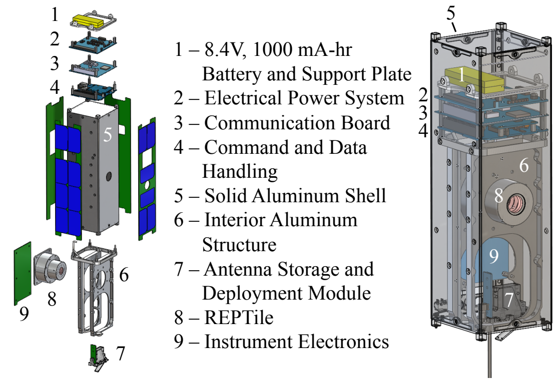


Figure 1 – Computer renderings of CSSWE.

As with many CubeSat projects, there are parallel science and educational goals. CSSWE's educational objective required a student-led team to deliver the CubeSat system. To fulfill this requirement, CSSWE was designed, built, tested, and operated by students at the University of Colorado. Over 60 multidisciplinary students were involved in the mission during their undergraduate or graduate student careers. Professors in the Aerospace Engineering Department and professionals at LASP, and other facilities, provided mentorship for the students.

On September 13, 2012, CSSWE was launched from Vandenberg Air Force Base as the sixth of NASA's Educational Launch of Nanosatellites (ELANA) program [5]. It was, along with 10 other CubeSats, a secondary payload to a National Reconnaissance Office (NRO) satellite. The launch vehicle was an Atlas V-401 operated by the United Launch Alliance (ULA).

REPTile, the science payload, was activated on October 4, 2012, after a three-week spacecraft commissioning phase. As of the writing of this paper, CSSWE continues to operate and return quality science data. To date, CSSWE has taken almost 300 days of science data, more than tripling the three-month expected mission lifetime. Operationally, the mission is a resounding success. Moreover, the quality of science data returned, as well as the tenacity of a student-developed mission, far surpasses the expectations for any CubeSat mission.

2. SCIENCE BACKGROUND

In the modern era there is considerable investment in aircraft. Applications range from commercial to recreational and military to scientific. One commonality among aircraft is that airplane pilots constantly check the weather report to minimize environmental risk to themselves and the airplane. Like aircraft, spacecraft are also subject to hazardous environmental conditions. These conditions can be adverse to both spacecraft and astronauts, but the near-Earth space environment lacks a reliable and accurate space weather report.

The lack of predictive capability is caused by the immaturity in understanding the dynamics in Earth's magnetosphere, and beyond that, the Sun's heliosphere. In fact space weather, which can be equally as hazardous as its terrestrial counterpart, is far less understood. Society's increasing dependence on space-based technology motivates the major investment being put into risk mitigation for space-based assets. A significant portion of which is applied to understanding exactly what physical processes are responsible for the adverse space weather effects.

The first space weather threat is relativistic electrons, moving close to the speed of light and having energies on the order of one million electron volts (MeV). These particles can damage to spacecraft components via surface charging or deep dielectric discharging. A second threat is energetic ions, with energies up to GeVs, that can disrupt electronics or cause single event upsets (SEUs) in component memory. Very high-energy protons can have harmful, potentially lethal, radiation effects on astronauts in space [6]. Unfortunately, unlike terrestrial weather, the governing dynamics are currently not sufficiently understood to accurately and reliably predict these dangers. In fact, there are two major outstanding questions concerning the hazardous populations.

The first concerns source, loss, and transport processes of hazardous energetic electrons in Earth's Van Allen radiation belts. The Van Allen radiation belts consist of two torus shaped regions which encircle the Earth; the inner radiation belt is confined to approximately 1.2 to 2 Earth radii (R_E) and the outer radiation belt extends from roughly 3 to 7 R_E. Both belts contain relativistic electrons; the inner belt contains a moderate but persistent population (stable on the timescale of years) while the outer belt can be far more intense, but it is extremely variable. The relativistic electron population in the outer belt can be created or eliminated in a matter of hours. Definitive answers to questions like "what mechanisms cause sudden enhancements or precipitation into the atmosphere?", "what is the intensity of the atmospheric precipitation?", or "is activity correlated with solar or geomagnetic activity?" will be significant breakthroughs in predicting space weather. Moreover, the outer belt region is of particular interest because it contains many popular spacecraft orbits, such as geosynchronous orbit (GEO) and global positioning system (GPS). These orbits reside in the heart of the outer radiation belt and, as a result, are especially exposed to energetic electron space weather effects.

A second outstanding topic is in regards to solar flares and their relationship with solar energetic particle (SEP) events. Ultimately, like terrestrial weather, even Earth's magnetospheric system is driven by the Sun. When solar magnetic field lines are violently reconfigured near the Sun's surface, they can cause a sudden and rapid release of up to 10^{25} J of energy. These events are known as solar flares and they can also propel electrons and protons to velocities close to the speed of light. This release of relativistic particles is known as a SEP event. If they are directed Earthward, SEP events can penetrate deep into the Earth's atmosphere, guided by magnetic fields at high-latitudes. The result can disrupt radio and GPS communication and increase radiation doses for crews and passengers on polar flights. The relationships between solar flares and SEPs are not fully understood. An outstanding question is: how does flare location and magnitude relate to the timing, duration, or energy spectrum of SEPs reaching Earth?

Addressing these critical space weather questions requires in-situ measurements of relativistic outer belt electrons and energetic solar protons. Multiple observational spacecraft to sample an array of latitudes, longitudes, and radial extents would be an ideal configuration. In reality, however, quality in-situ space weather measurements are few and far between. Currently, CSSWE provides the only differential LEO observations of both SEP protons and radiation belt electrons. Furthermore, conjunctive measurements between CSSWE and other missions, such as GOES, THEMIS [7], the Van Allen Probes, and BARREL [8] will provide the opportunity for multi-point observations of radiation belt electrons and SEP protons.

Specifically, many of CSSWE's measurements are directly relevant to instruments from the Energetic Particle, Composition, and Thermal Plasma (ECT) suite the Van Allen Probes [9], particularly for radiation belt electrons. The Van Allen Probes, in a GEO-transfer-like orbit (700km x 5.8 R_E, 10°

inclination), traverse the heart of the radiation belts near the geographic equator. Although the mission provides the most sophisticated measurements of the radiation belts to date, the onboard instruments cannot resolve which electrons will precipitate into the atmosphere. At the equator, precipitating outer belt electrons have pitch angles (the angle between the momentum vector and the local magnetic field line) of less than roughly 5 degrees. These electrons travel along magnetic field lines and are lost to collisions with neutrals near the footpoint of the magnetic field line in the polar regions. Similar processes for lower energy electrons cause the aurora. CSSWE directly measures the precipitating particles as they pass by the CubeSat on their way into the atmosphere. These measurements quantify the number of electrons lost at a given time, and conjunctive measurements with the Van Allen Probes in the heart of the radiation belt allow for a quantitative estimate of precipitation loss and its impact on the total population, and thus a better understanding of full electron dynamics.

CSSWE also measures the energy spectrum and time evolution of SEP particles at LEO. These measurements are used to better understand the relationship between flares and the deeply penetrating SEP particles at Earth. Ultimately, they provide insight to the dynamics of SEP particles in the magnetosphere and will lead to a better understanding of their behavior to improve models and predictions.

3. Science Payload – REPTile

Instrument Design

To measure SEP protons and radiation belt electrons, the students on CSSWE miniaturized the REPT instrument [3] onboard the Van Allen Probes. The resulting payload, the Relativistic Electron and Proton Telescope integrated little experiment (REPTile), measures protons from 9 to 40 MeV and electrons from 0.58 to >3.8 MeV in three energy channels as outlined in Table 1.

REPTile is a loaded-disc collimated solid-state particle telescope. It consists of four doped silicon detectors (labeled 1 in Figure 2) housed in a heavy tungsten (atomic number [Z] = 74; atomic symbol = W) shielding chamber (labeled as 2), which is in turn encased in an aluminum (Z=13; Al) outer shield (labeled as 3). At the front of the detector stack is a 0.5mm thick beryllium (Z=4; Be) window, which acts as a high-pass filter by absorbing low energy particles that would saturate detector electronics. The Be window (labeled as 5) absorbs electrons with energy less than ~0.4 MeV, and protons with energy less than ~8 MeV. Higher energy particles punch through the Be window and into the detector stack. The instrument's field of view is 52 degrees, which is defined by the tantalum (Z=73, Ta) lined Al collimator (labeled as 6). Seven knife-edged Ta collimator baffles prevent stray particles from scattering off of the collimator walls and entering the detector stack. The particles to be measured by REPTile are capable of penetrating through relatively large amounts of shielding (which is how they are able to damage internal spacecraft components). Measuring them is a trade-off between shielding mass and measurement noise caused by shield-penetrating particles. Thus, energetic particle measurements are challenging from the mass-restrictive CubeSat platform. As a result, the total mass of the REPTile instrument is 1.25 kg, approximately 42% of the total spacecraft mass. The instrument is contained in a cylindrical volume of 4.6cm (diameter) x 6.0cm (length) and is held straight by three Ta alignment pins (labeled as 4 in Figure 2).

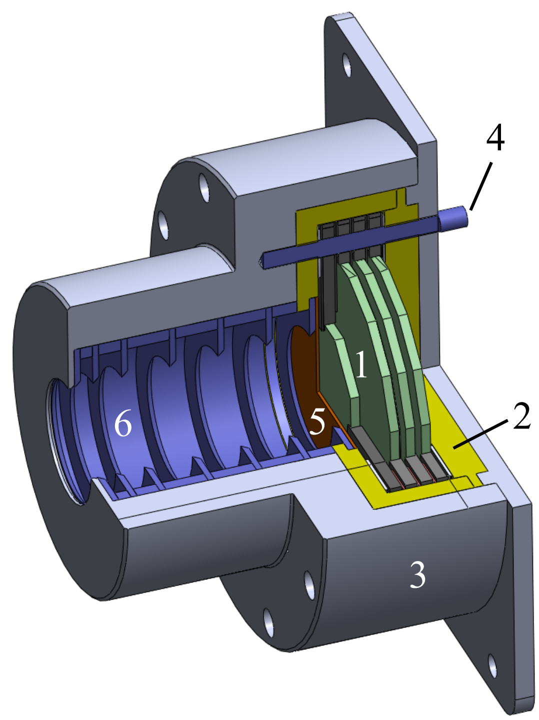


Figure 2 – Computer rendering of the REPTile instrument.

Data are returned from CSSWE as raw six-second count rates in four energy channels for both electrons and protons. It is of note that only three of REPTile's four detectors survived launch; the third detector in the stack failed to operate consistently post-launch. The loss of the detector rendered one electron energy channel and one proton energy channel invalid. However, due to the simple yet robust design doctrine engrained in the program, REPTile was able to operate with the remaining three detectors and the data are recalibrated accordingly on the ground.

The onboard binning logic automatically determines the species and energy of the incident particle, accumulates the counts over six seconds, and stores the eight count rates (four electron energy channels and four proton energy channels) in the onboard SD card. When requested, the raw counts are transmitted to the ground where they are processed into differential flux units. Details of this conversion are specified in Li et al. [10].

Table 1: REPTile Species and Energy Channels

Species	Channel 1	Channel 2	Channel 3
e-	0.58–1.63 MeV	1.63–3.8 MeV	>3.8 MeV
H+	9–18 MeV	18–30 MeV	30 – 40 MeV

Traditional testing tactics for particle telescopes are not within the scope of CSSWE's relatively small $840k budget. Methods typically include beam tests using a high-energy particle beam to simulate the radiation environment encountered in orbit. The particle flux from the beam can be compared with instrument results to characterize the behavior of the instrument. Instead, CSSWE uses a software package called Geant4 [2]. Geant4 was developed by physicists at the European Organization for Nuclear Research (CERN) to simulate particle-matter interactions for particle instruments and is the most advanced modeling package available [11].

Traditional particle telescopes use pulse height analysis to determine the incident energy of the particle. That is, a particle travels down the collimator, through the Be window, impacts the detector stack, and deposits some of its energy into the detectors. The amount of energy deposited, or pulse height, on each of the detectors is analyzed to determine species and incident energy. However, this requires either a complex and power-hungry onboard binning logic scheme to analyze the pulse heights in real-time, or a large communication link

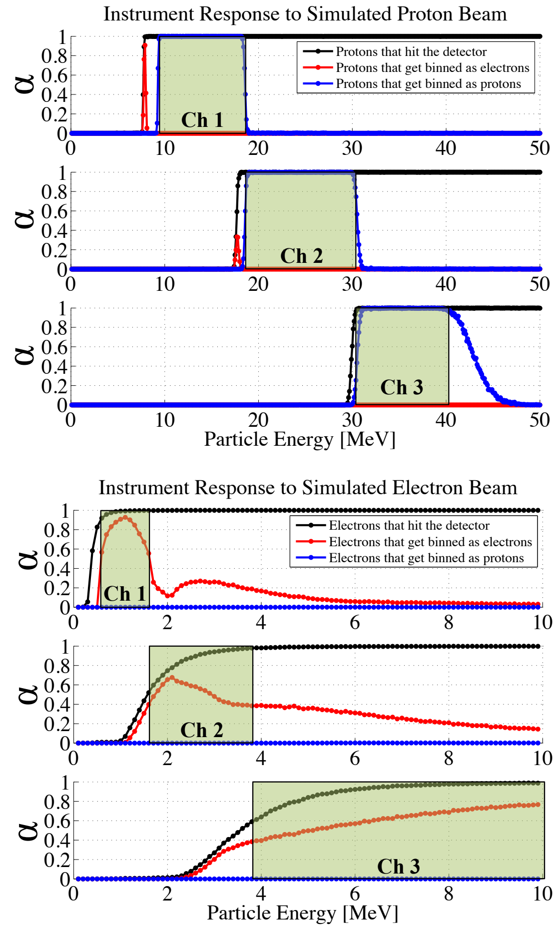


Figure 3 – Instrument response, as simulated using Geant4, for protons (top) and electrons (bottom). The top panel of each set corresponds to the first detector, middle to the second, and bottom to the fourth. The black line represents the % of particles as a function of energy that impact the detector, blue the % binned as protons by the onboard binning logic, and red the % binned as electrons. Energy channel widths are highlighted in green.

margin to transmit every particle impact to the ground for analysis. With neither of these options a feasible solution with the limited budgets of CSSWE, REPTile alternatively uses a unique onboard binning scheme.

Instead, REPTile uses the pulse height of each particle to determine species. It uses the depth of penetration into the detector stack to determine particle energy. Based on extensive simulations with Geant4, it was shown that electrons typically deposit less than 1.5 MeV into a detector, and protons typically more than 4.5 MeV. Thus, the binning logic counts particles depositing 0.25 MeV

< E < 1.5 MeV as electrons, and particles depositing E > 4.5 MeV as protons. Particles which deposit 1.5 MeV < E < 4.5 MeV are indeterminate and discarded as noise, but accounted for in post-processing. The depth of penetration into the detector stack is then used to determine incident energy, as more energetic particles are able to punch deeper into the detector stack.

The channel energy thresholds are determined using Geant4 and an onboard coincidence logic scheme [12], and are outlined in Table 1 and Figure 3. α in Figure 3 represents the normalized response efficiency for each detector, which can be thought of as "% of simulated particles". The energy channel widths are determined using the instrument response and are shown in Figure 3 with green boxes. The third detector response is omitted due to its post-launch failure. Note the contrast between the well-behaved protons and the more random behavior of the electrons. The statistical response of electron interactions with matter is a driving factor for the detailed characterization of the instrument.

Instrument Validation

Beam tests, as previously described, are an efficient way to characterize and validate instrument performance. Although beam tests were not available due to CSSWE's restrictive budget, REPTile was still tested end-to-end. Two methods were used instead: 1) measurements of naturally occurring muon populations and 2) testing with a radioactive source [12].

Muons, which are a natural byproduct of cosmic ray collisions with Earth's atmosphere, reach the surface of the Earth and do not interact significantly with matter, which means they can penetrate instrument shielding. Thus, muon count rates are proportional to detector size, as opposed to instrument pointing for example. To measure muons, the instrument is simply turned on and allowed to collect statistics. The results of the REPTile muon test are detailed in Table 2. The detectors are circular, with diameter shown in the first column. Expected values are calculated using the measured value of 0.01 muon/s/cm^2/sr [13]. The actual ambient muon rate depends on only a few factors, such as elevation and solar cycle.

Table 2: Averaged Muon Countrates (#/6s)

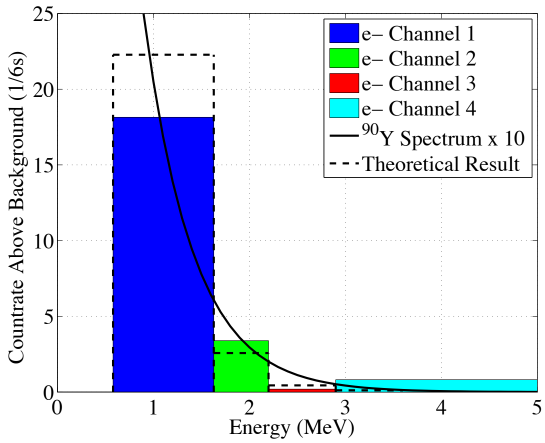
Detector	Measured	St. Dev.	95% Conf.	Expected
1 (20mm)	1.07	1.03	0.02	~1.2
2 (40mm)	3.67	1.93	0.04	~4.7
3 (40mm)	3.47	1.85	0.04	~4.7
4 (40mm)	3.42	1.85	0.04	~4.7

Radioactive source testing is another alternative to beam testing. REPTile's radiation source was a strontium 90 (^{90}Sr) radiation source. ^{90}Sr decays into ^{90}Y by beta decay (electron release) with maximum energy of 546 keV with half-life of 28 years. ^{90}Y decays into zirconium 90 (^{90}Zr) with half-life of 2.7 days via beta decay with maximum energy of 2.28 MeV. The electrons from beta decay are released in an exponential decay spectrum, which was independently measured prior to the test. The radiation source test was done in flight configuration, including the Be window. The results of the test are shown in Figure 4 for original, four detector processing (top) and the recalibrated on-orbit processing for the three remaining detectors. Agreement between measured counts and expected counts closely agree. Over counting in the second and fourth detector (top panel: channels 2 and 4; bottom panel: channels 2 and 3) is likely due to residual electronic noise on the signal chains. Both muon and radiation source tests verified REPTile system performance.

4. CSSWE VALIDATION

In addition to instrument tests, rigorous system level validation was performed on the complete CSSWE system. The radio frequency (RF) link, including ground station packet decoding and parsing, was used whenever possible during top-level validation testing, including aforementioned instrument tests.

On orbit, the spacecraft is operated from a ground station at the LASP. The ground station consists of two phased and circularly polarized Yagi antennas operating single-duplex at 437.350 MHz in the amateur frequency band with a bandwidth of 15kHz and capable of 9600bps data rates. This system was designed and built by CSSWE students, with input from local amateur radio operators, specifically for the CSSWE mission, but is also adaptable to be used in future CU small



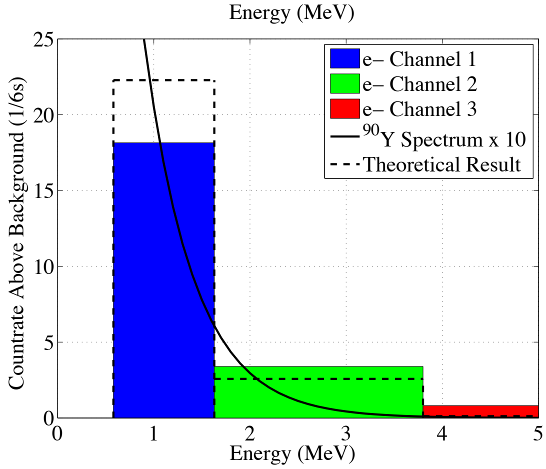


Figure 4 – Instrument response to the ^{90}Sr radiation source test. Top panel: results using data from all four detectors. Bottom panel: recalibrated results using data from the three operational detectors on-orbit with the reconfigured instrument response.

satellite missions. The end-to-end RF link, which employs communication between the onboard radio (via the spacecraft antenna) and the decoding software (via the ground station), was also tested repeatedly. These tests often included a simulated on-orbit deployment from the launch vehicle. To perform the long-distance communication tests, the spacecraft was driven to a location with a line-of-sight distance of approximately 5 miles to the LASP ground station. The spacecraft was "ejected" from the launch vehicle by the release of a mechanical switch on a footpeg of the structure. As designed, the antenna deployed two hours after power up and began transmitting with the ground station and receiving commands. Additional attenuation was added to match orbit-to-ground communication conditions after the link was established. The satellite performed well throughout the test, even with attenuated communication.

Unlike most CubeSats, CSSWE also underwent thermal vacuum (TVAC) chamber testing. It experienced eight temperature cycles in the chamber covering both operational extremes. The system was required to perform functionality tests at hot dwell, cold dwell, and in transition. It passed all functionality milestones during TVAC testing. A whip antenna and RF-attenuator tiles were also included within the TVAC chamber, allowing CSSWE to test RF performance while in the TVAC chamber. The successful results in temperature and vacuum conditions validated system performance in the real on-orbit environment

5. ON ORBIT PERFORMANCE

The rigorous validation procedures provided confidence that the spacecraft would operate successfully on orbit. Furthermore, they generated a baseline for comparison during spacecraft operations. After the launch on September 13th, 2012, comparisons were made between on-orbit results and the ground-based nominal operations data. The two were homologous, verifying successful on-orbit spacecraft operations. In-detail descriptions of on-orbit performance are outlined in Gerhardt et al. [14]. The most significant anomaly during spacecraft commissioning was the recognition that the third detector in the REPTile detector stack suffered a complete failure. However, CSSWE's robust design allowed continuing operations with the remaining three detectors.

Anomalies and Current Operations

Contact was temporarily lost with the CubeSat on March 7, 2013, when the onboard radio ceased responding to internal or external commands. During this anomaly, the spacecraft could not transmit or receive communication. However, all other subsystems were nominal; in fact, REPTile continued to take science data for an additional few days after communication was lost. The radio returned to nominal operation on June 18, 2013, when low battery voltage caused a full system reset. Within days of reestablishing contact, REPTile was activated after 110 days of inactivity.

Figure 5 shows the amount of data received from the spacecraft since launch. The radio malfunction is apparent, as is a noticeable increase in downlinked housekeeping data immediately after

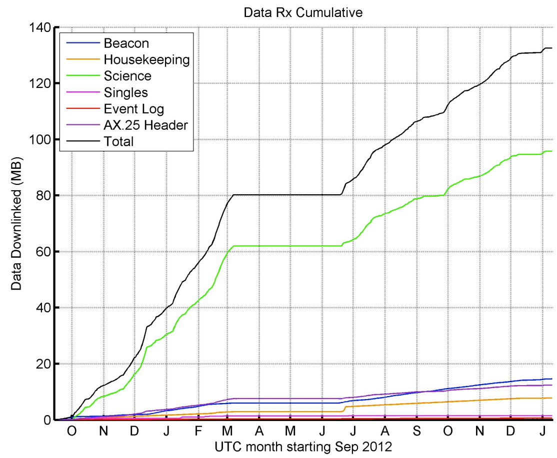


Figure 5 – Cumulative data received from the spacecraft from launch to mid-November 2013.

communication was reestablished. REPTile went through a prompt re-commissioning and was quickly reactivated. Notice that the majority of the data down linked over the course of the mission is in the form of science packets, which reflects on the overall success of the mission.

Current mission operations are dictated heavily by the spacecraft's solar beta angle, which is defined as the angle between the orbital plane and the sun vector. Primarily, solar beta angle determines the amount of sunlight the spacecraft receives. This angle varies over time for all spacecraft orbits, but most strongly affects LEO spacecraft, which can spend more of their orbit in eclipse. With an already thin power budget, a low beta angle often determines whether CSSWE is power positive with REPTile activated.

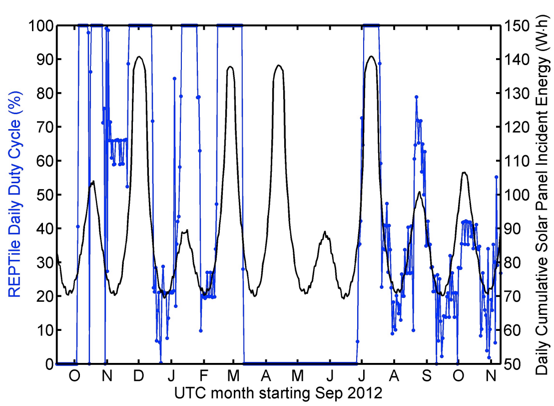


Figure 6 – Daily averaged % time REPTile was on (duty cycle) in blue and daily averaged incident energy acquired by the solar panels in black.

During periods of especially low beta angle, the incident energy on the solar panels is insufficient to allow REPTile to run 100% of the time. Thus, REPTile is duty-cycled to help conserve battery capacity. The effect of the solar beta angle on REPTile duty cycling can be understood better in Figure 6, which shows the daily averaged percent of time REPTile was on, plotted with the daily averaged solar energy received. In general, less than 90 W·h causes the system to be power negative. However, as the battery and solar cell performance degrades over time, the spacecraft requires more incident energy to remain power positive. To maximize mission longevity, CSSWE spends less time in science mode as these components deteriorate. The system is designed so that, in a power negative state, REPTile is shut off automatically to prevent significant battery discharge. This happens when the battery voltage falls below an adjustable threshold, which was set to 6.8 V in early mission and then to 7 V to improve battery longevity. Extreme variations in REPTile's duty cycle (e.g. mid- and late-October 2012) are due to other anomalies, such as component latch-ups or changes in ground control algorithms [14].

6. SCIENCE RESULTS

After the reentry of the SAMPEX spacecraft on November 11, 2012 [15, 16], CSSWE is the only spacecraft in LEO to measure differential flux of energetic protons and electrons in specified energy ranges. REPTile measurements are clean, as can be seen by the clear species separation, which will be discussed later in this section. Additionally, the data have a low noise floor (~1s-10s counts per sec) and high dynamic range (over 4 orders of magnitude). These qualities are critical to produce accurate and reliable measurements of high-energy particles and verifying that REPTile measurements are adequate for scientific use. Specifically, flux observations measured from low altitude are used to quantify atmospheric precipitation loss; in this regard, CSSWE fills a valuable scientific niche. The data have been used in long-term and event specific studies, which will be discussed in this section.

Electrons in the Radiation Belts - Observations

An example of typical REPTile science results, plotted in geographic coordinates, is shown in Figure 7. These data are from January 18-23, 2013, and are taken during a period with a

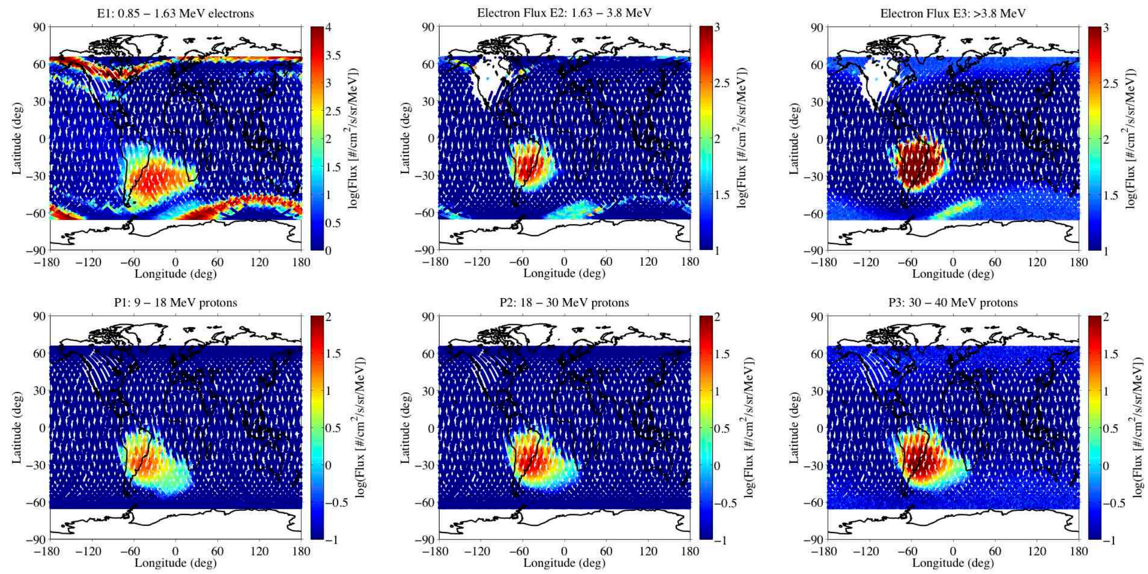


Figure 7 – Science results from January 18 to 23, 2013. Spacecraft position is plotted in geographic longitude (x-axis), geographic latitude (y-axis), and flux in color. Electrons are plotted in the top row, protons in the bottom row. Energy channels are increasing to the right. Data was removed for E2 and E3 during transmission, as these channels are sensitive to transmission noise.

relatively static, but intense, outer radiation belt. The region of increased flux over South America is due to low magnetic field strength caused by the offset nature of Earth's magnetic field. This phenomenon is commonly known as the South Atlantic Anomaly (SAA). The ribbons of electron flux towards the poles are the outer radiation belt. The inner radiation belt is just equator-ward of the outer radiation belt, noticeable only in the upper left panel (E1). While there is some cross contamination (specifically >100 MeV, shield-penetrating protons), the measurements are still clean, as can be seen by the different morphologies presented by the two populations in the SAA. Fortunately, shield-penetrating protons are short lived outside of the inner radiation belt and contamination of outer belt measurements is trivial.

Spacecraft in LEO can observe the Van Allen radiation belts, the heart of which is located at 3-6 R_E, because of basic electromagnetism principles. Most relevant is the magnetic trap, which is a uniform magnetic field that is then compressed on either end, creating regions of increased magnetic field strength called mirror points. Charged particles in the presence of a magnetic trap bounce between mirror points. Earth's magnetic field is a type of magnetic trap, where the mirror points are near the poles. Particles map out the torus shape of the radiation belts while bouncing from pole to pole, passing through the heart of the radiation belt at ~5 R_E as they do so. The radial distance of their equatorial crossing is quantified in the L parameter, which, although dimensionless, is essentially in units of Earth radii [17]. For every measurement at LEO, the particles trajectories can be mapped to the equator to determine the L value measured by CSSWE. This concept is shown in Figure 8.

A similar visualization of the flux data to Figure 7 can be seen in Figure 9. Figure 9 incorporates the distance to the measured particle's radial crossing, or L, which is a more physical parameter than the geographic location of the measurement. It shows the electron flux as a function of L for all three of REPTile's electron energy channels. The data in

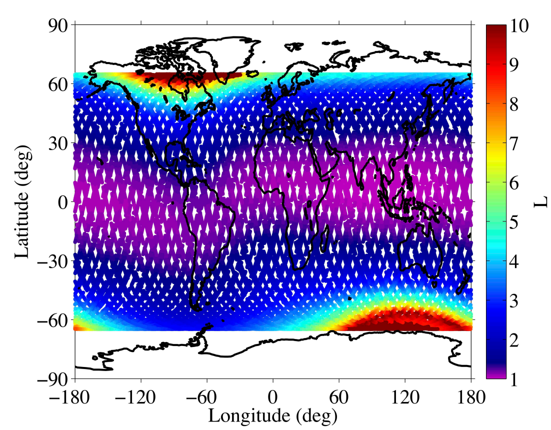


Figure 8 – Spacecraft geographic coordinates mapped to L, where L is the radial distance in Earth radii of the particle's equatorial crossing.

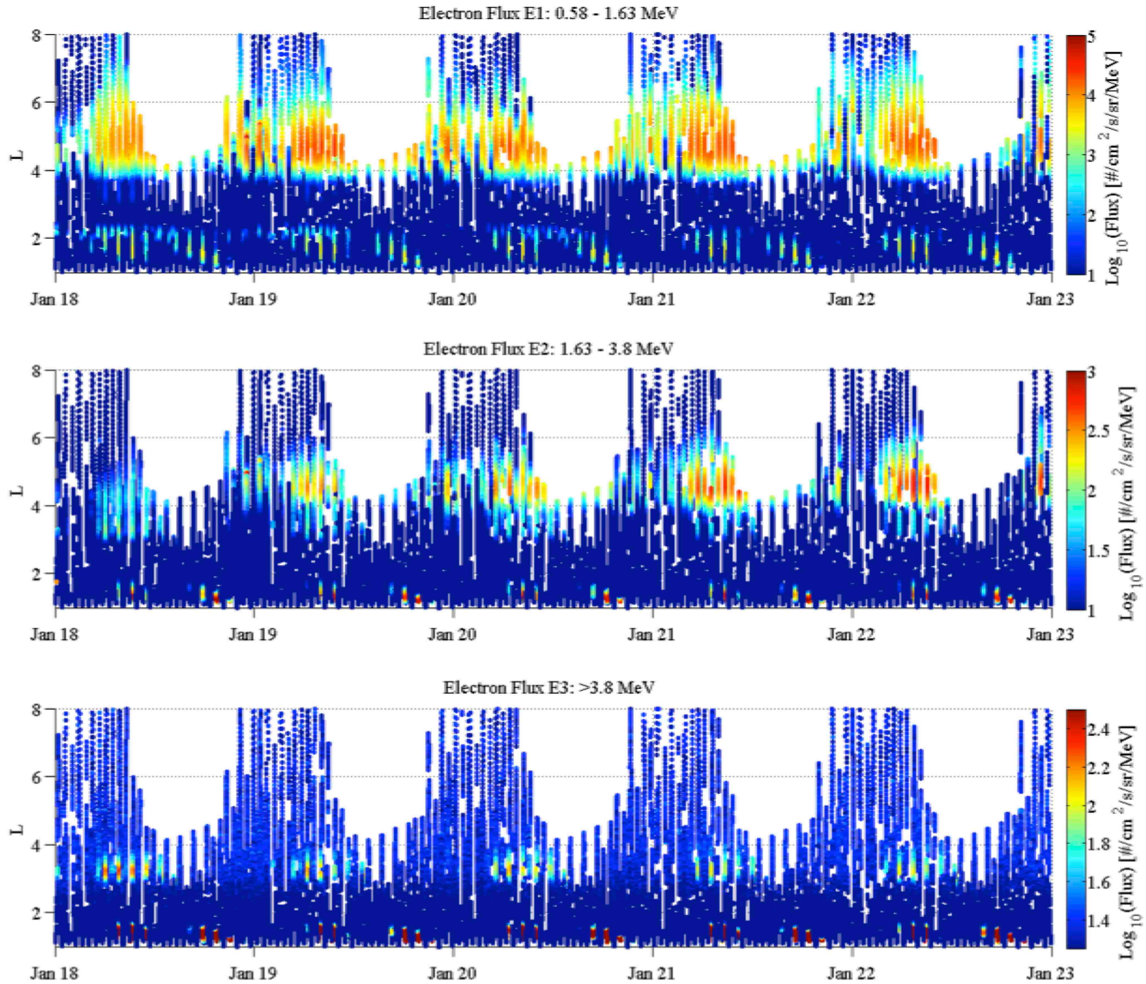


Figure 9 – Electron flux as a function of time and L for January 18 to 23, 2013.

Figure 9 are for the same period as Figure 7: during a relatively stable period from Jan 18 to 23, 2013. The intensity of the outer belt has an apparent daily fluctuation that is closely related to the picket fence-like sampling at higher L. Both of these phenomena are caused by a combination of CSSWE's orbit and the variation in longitudinal sampling, which is more apparent in Figure 7. For example, the inner radiation belt is most visible when the spacecraft crosses through the SAA and can measure the inner belt population. Similar effects occur on orbits that pass over Russia and the southern tip of South America, where the CubeSat cannot sample measurements above L~4.5. An interesting feature during this period, which is not always the case, is the inner belt which can be seen in the first electron channel near L=2 in Figure 9, but only to the west of the SAA in Figure 7.

Electrons in the Radiation Belts - Applications

As previously discussed, loss, acceleration, and transport mechanisms in the outer belt are intensely entangled. Only by measuring each process individually can the full system dynamics be unraveled. CSSWE's measurements are critical in quantifying atmospheric precipitation, a major loss mechanism. Ultimately, precipitation rates vary depending on geomagnetic conditions. Typically, increased geomagnetic activity increases precipitation, but it also increases acceleration and transport mechanisms that are closely tied to the location, magnitude, and cause of precipitation.

Geomagnetic storms, which play a pivotal role in magnetospheric dynamics, can be measured by the Dst index [18]. The Dst index is a quantification of the storms' perturbation on the horizontal component of Earth's magnetic field at the equator. Specifically, it is the difference between the decreased magnetic field due to storm processes and the nominal magnetic field strength, which is approximately 31,000 nT. Stronger storms have a larger effect, and thus are indicated by a more negative index. For reference, a Dst index of < -100 nT (a perturbation of ~0.3%) is considered an intense geomagnetic storm [19]. However, the presence of a storm does not guarantee certain effect on the radiation belts. In fact, only half of geomagnetic storms have a net increase on the electron population, 20% cause a net decrease, and 30% result in no change [20]. REPTile observations during the large Oct. 9th, 2012, storm provide insight towards which storms have the net effect of erasing the outer belt content and which storms amplify it by quantifying the relative contributions of loss and source.

A large geomagnetic storm (Dst < -100 nT) occurred on Oct. 9th, 2012, within a week of turning REPTile on. This storm caused an enhancement in the outer radiation belt electron flux of nearly three orders of magnitude in 18 hours [21], as measured by the Van Allen Probes. Although a net intensification, REPTile measurements during this storm separate the contribution of loss mechanisms from the net acceleration that occurred, specifically by quantifying the relative contribution from precipitation loss. Results from CSSWE analysis for the storm and succeeding electron flux increase are published in Li et al. [10]. The authors showed that, when including atmospheric precipitation, the enhancement was at least 12.7% and 14.6% stronger for 0.58 MeV and 1.63 MeV electrons, respectively. The findings suggest that the mechanism responsible for the sudden flux enhancement was significantly larger than the Van Allen Probe measurements indicate.

While storm-time conditions have a more volatile impact on outer belt electrons, a recent study found that rapid outer belt enhancements occur during non-storm times as well [22]. The study investigated an enhancement on January 13-14, 2013, that occurred with very little geomagnetic activity yet enhanced outer belt fluxes by more than 330x. Using CSSWE to measure atmospheric precipitation, the authors showed that enhancement was even larger than the flux measurements suggest: 5% and 16% larger for 0.6 MeV and 1.8 MeV electrons, respectively. This study directly addresses the outstanding question regarding correlations between radiation belt enhancements and geomagnetic activity.

CSSWE's measurements are also used to map the physical extent of precipitation regions. Blum et al. [23] used REPTile measurements in conjunction with high-altitude balloon measurements to do this analysis. The Balloon Array for Radiation Belt Relativistic Electron Losses (BARREL) observed relativistic electron precipitation simultaneously with REPTile on January 18-19, 2013. The authors combined the measurements from the two missions to create a spatial and temporal map over which the electron precipitation occurred. Finally, incorporating the precipitation map with estimates of the total outer belt electron population, the authors calculated that just one of the observed precipitation events was strong enough to precipitate at least 5% of the total outer belt content for 0.58 and 1.63 MeV electron populations. Only ~20 of these relatively common events would be sufficient to remove the entire outer belt, suggesting that precipitation loss is a significant loss mechanism for outer belt electrons, and directly addressing the science question of quantifying electron precipitation.

As demonstrated in the Blum et al. study [23], storm-time conditions drastically strengthen the mechanisms that cause precipitation loss. However, in addition to the storm-time precipitation, there is also a constant slow diffusion of particles into the atmosphere that occurs even during non-storm time conditions. Quantifying this diffusion rate separates the variable, storm-time processes from the underlying background precipitation. CSSWE's measurements were used in quantifying the quiet-time diffusion rates in Jaynes et al. [24]. They found that 97.7% of radiation belt electrons were lost due to the background diffusion, specifically broadband wave-particle interactions known as plasmaspheric hiss [25], during an extended quiescent period from December 22, 2012, to January 13, 2013. These findings constrain current radiation belt flux models and forecasts by providing more realistic hiss-induced precipitation loss timescales.

Energetic Protons from SEPs

Unlike energetic electrons, which are nearly always measurable in the Van Allen radiation belts, SEP protons can only be measured when the Sun provides a SEP event. Fortunately, on September 30, 2013, the Sun emitted a large SEP event. Although REPTile was operating at a ~%30 duty cycle, its measurements of the SEP event are depicted in Figure 10. REPTile was not active

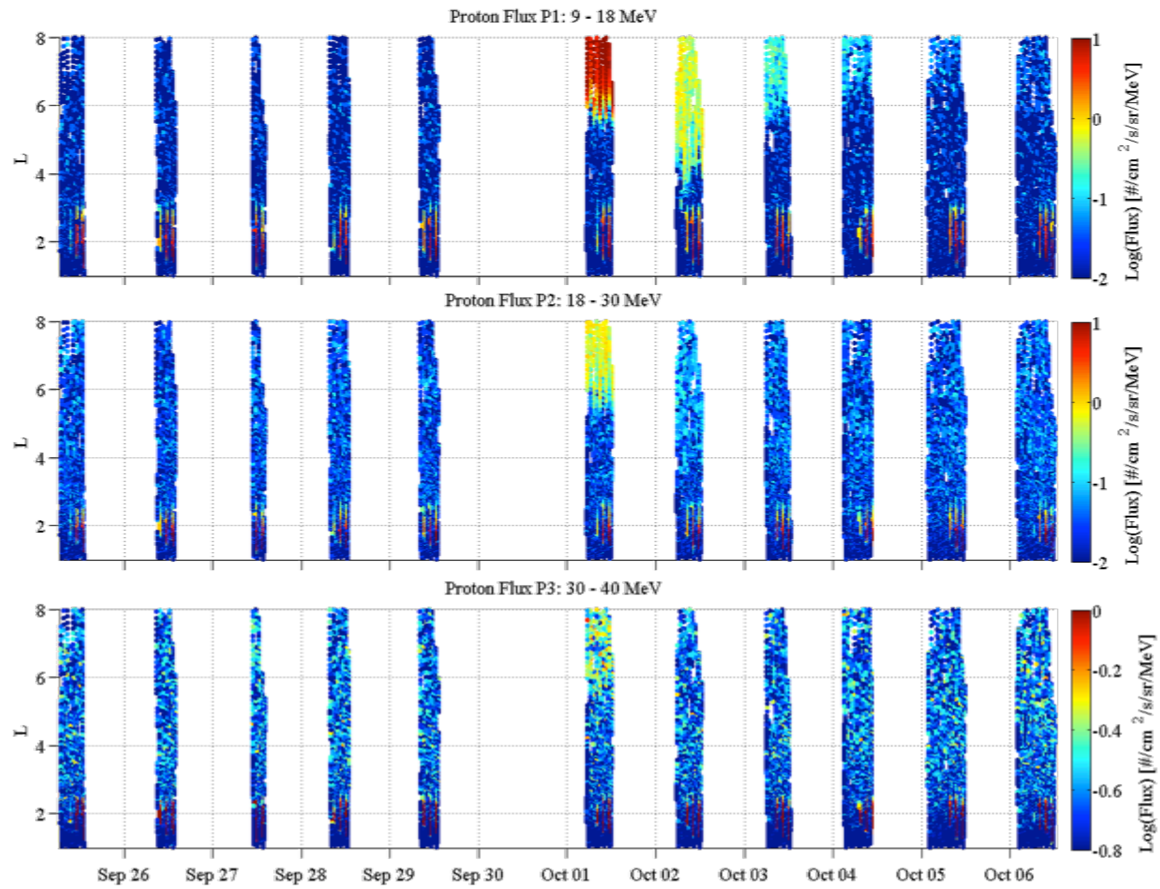


Figure 10: Proton flux for the September 30 SEP event.

during the onset of the event, but it still took measurements for the ensuing days. The inward penetration of the protons can be seen progressing from L~6 on October 1 to L~4 on the 2nd before retreating to L~6 on the 3rd and then to L>6 on the 4th. On October 5, the protons are no longer observed. As CSSWE is the only spacecraft in LEO capable of measuring the differential particle flux, the REPTile observations are critical in advancing the models of this event, as well as the models to predict the evolution of SEP penetration into Earths magnetosphere.

7. Conclusions

Recently, the satellite community has progressed considerably in regards to small, low cost missions and their access to space. A major player in the small satellite arena is the CubeSat. Although CubeSats are often considered as proof-of-concept missions, methods to increase TRL for commercial products, or simply educational platforms, the recent successes of the Colorado Student Space Weather Experiment has shattered this existing conviction.

The National Science Foundation awarded funding to the CSSWE team for $840k in January 2010. Within budget, CSSWE was designed, built, tested and operated by students at the University of Colorado at Boulder with mentorship from professionals in the Aerospace Engineering Sciences Dept., LASP, as well as other sources. Despite the heavy student involvement and high CubeSat infant mortality rates, CSSWE has exceeded full mission success in all categories.

Most importantly, CSSWE's science payload, the Relativistic Electron and Proton Telescope integrated little experiment (REPTile), continues to take valuable science measurements of the near-Earth plasma environment. A number of papers have been accepted to peer-reviewed scientific journals, demonstrating that CSSWE returns publication-quality measurements regarding electrons in Earth's radiation belts and protons in Solar Energetic Particle events. While CSSWE does not directly offer predictive capabilities, the mission directly improves the understanding of these space weather affects and in turn, risks and costs associated with space weather operations are reduced. CSSWE's science mission success, in tandem with the full mission success, proves that CSSWE is the paradigm for big science on a small budget.

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