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Characterization and Testing of an Energetic Particle Telescope for a CubeSat Platform

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The *R*elativistic *E*lectron and *P*roton *T*elescope *i*ntegrated *l*ittle *e*xperiment (REPTile) instrument has been designed, built, and tested by a team of students at the University of Colorado. It is scheduled to launch on a 3U CubeSat, the Colorado Student Space Weather Experiment (CSSWE), this August, 2012. The instrument will take measurements of energetic particles in the near-Earth environment, which are vital to understand, predict, and mitigate hazardous space weather effects — an area identified as a critical area of research by NASA's Living With a Star program. However, the task of designing a payload to return accurate and reliable data is extremely challenging due to the resource limitations imposed by a CubeSat platform. REPTile has undergone rigorous testing and calibration to verify its functionality and certify the validity of its measurements. This paper focuses on characterizing the telescope detectors and individual electronic components, as well as the integrated space craft system. The response to environmental conditions is quantified, and the variability minimized through on-board data handling as well as post-processing during mission operations. Thorough testing and calibration validates the data as a valuable contribution to outstanding questions in the study of space weather. The ability to address these questions by making differential energy measurements of energetic particles with an affordable, robust, and simple instrument design is what sets this instrument apart from others.

1. Introduction

THE near-Earth space environment is a highly dynamic region, composed of numerous particle populations and variable magnetic and electric fields. Understanding this environment is becoming increasingly critical as society becomes more dependent on space-based technologies. Large variations in the particle population around Earth, caused by solar activity and other space weather events, can have deleterious effects on satellite subsystems and harmful effects on the bodies of astronauts.[1]

A number of outstanding questions remain regarding the generation, transport, and effects of energetic particles in space. Various mechanisms can generate harmful particles, such as solar energetic particles (SEPs) or energetic electrons, which threaten space based assets. The relationship between solar flares and the production of SEPs must be further investigated in order to understand the timing, duration, and energy spectrum of the SEPs measured at Earth. Additionally, relativistic electrons in the Earth's outer radiation belt, a toroidal region of highly energetic electrons trapped between 3 and 7 Earth radii, overlap a variety of popular satellite orbits. Electrons in this region can penetrate through spacecraft shielding, causing dielectric breakdown and discharging within sensitive electronics.[2] A number of spacecraft anomalies (e.g. Galaxy 15[3]) have been attributed to geomagnetic activity and sudden enhancements in energetic electron fluxes.[3,4] Geomagnetic storms and substorms, often associated with activity on the sun, can cause large fluctuations in both the location and overall magnitude of the outer radiation belt. Better understanding of the acceleration, loss, and transport processes affecting these energetic electrons will enable more accurate predictive capabilities to better protect assets in space.

A student led, National Science Foundation (NSF) funded CubeSat has been designed and built at University of Colorado to address these critical space weather questions. The *R*elativistic *E*lectron and *P*roton *T*elescope *i*ntegrated *l*ittle *e*xperiment (REPTile) instrument will measure SEP protons in the energy range of 8.5-40MeV, and radiation belt electrons from .5->3MeV from a high-inclination, low-altitude orbit. Both species will be measured in differential energy bins, an

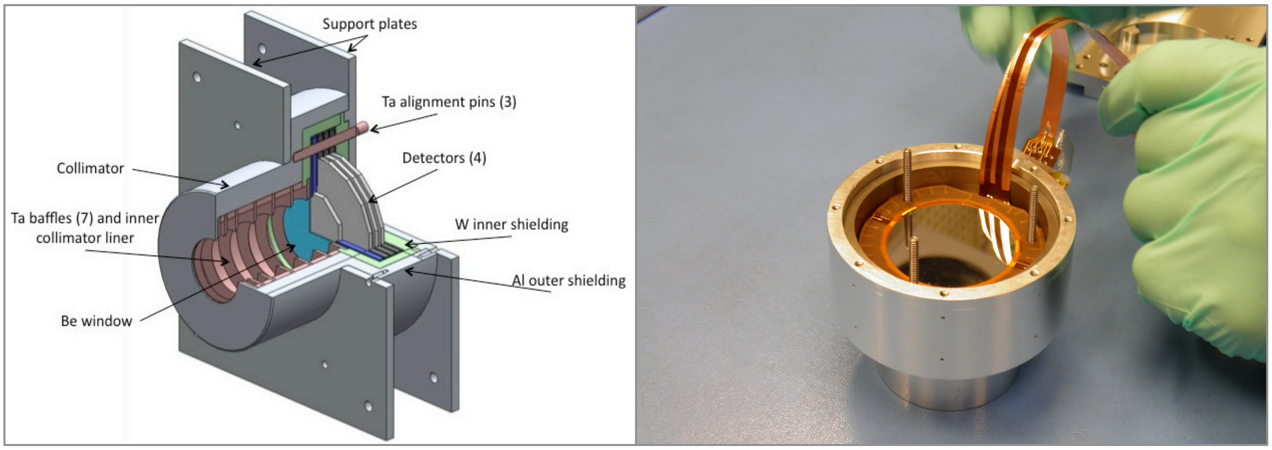

Figure 1. Left: Cross sectional view of the instrument geometry. Right: Flight instrument during integration. The collimator is facing down in the image, and the back plate not yet attached, so the fourth detector in the stack is visible.

improvement on currently available measurement from a small satellite. Designed and built primarily by students over the past four years, the Colorado Student Space Weather Experiment (CSSWE) CubeSat was delivered this past January for integration as a secondary payload onto an Atlas-V launch vehicle, and is scheduled to launch August 2, 2012. An identical satellite, without the structural components, has been fabricated for testing and calibrations while the spacecraft is integrated and on orbit.

Due to the power, mass, volume, and budgetary constraints of a CubeSat, the telescope and instrument electronics have been miniaturized and simplified. These constraints, combined with the inherent difficulties in measuring energetic particles, demand careful characterization of REPTile. The outcome of the analysis is an instrument capable of returning reliable in-situ measurements of energetic protons and electrons. Moreover, this mission will provide greatly needed differential flux measurements of high energy particles from low-Earth orbit, as well as demonstrate that accurate measurements can be made from a CubeSat platform.

In this paper, we briefly discuss the REPTile design (Section 2), then focus on the testing and calibration of both the detectors and electronics. Section 3 outlines detailed testing done on a component-level, Section 4 describes a mitigation technique applied to the on-board binning logic, and Section 5 illustrates tests performed as a fully integrated spacecraft.

2. REPTile Design

The following section describes the general design of the REPTile instrument onboard the CSSWE CubeSat. The detector stack, instrument geometry, and data processing electronics are detailed below. The challenges of miniaturizing an instrument to fit within the constraints of a CubeSat dictate a number of the REPTile design features. Strict mass and volume budgets for CubeSats restrict REPTile's size, and the resulting space, power, and data transmission limitations play a large roll in the design of the electronics. Careful preflight testing and calibration is critical to understand and optimize instrument performance.

2.1 Design of the Energetic Particle Telescope

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. The front detector has a diameter of 20mm, while the following three are 40mm across. Higher energy particles penetrate deeper into the detector stack and, as they do, they generate electron-hole pairs in the doped silicon.[5] A bias voltage is applied across each detector to accelerate the loosened electrons to an anode, where they are collected and measured by instrument electronics. Using coincidence logic, the electronics determine which detectors the particle impacted, and thus the energy range of the particle.

Figure 1 illustrates the instrument geometry and various components. The detector stack is housed in a tung-

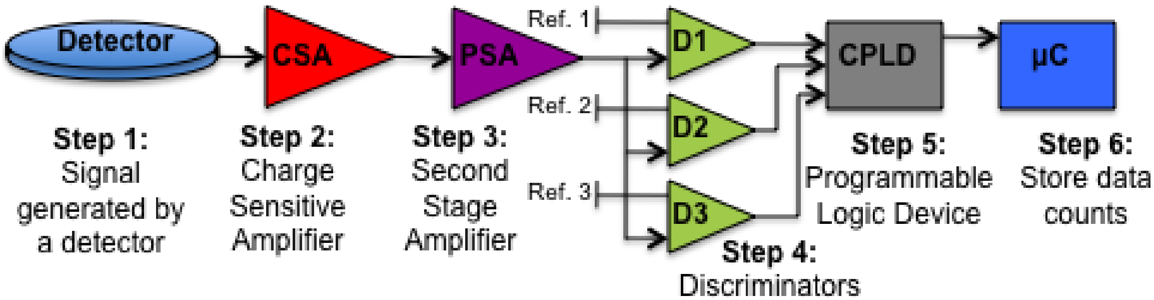

Figure 2. Instrument electronics block diagram.

sten (atomic number Z=74) chamber, which is encased in an aluminum (Z=13) outer shield. The materials were chosen based on a combination of their ability to shield energetic particles and minimize secondary electron generation within the housing. 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 $0.52\text{Sr} \cdot \text{cm}^2$. Tantalum is used because it strikes a balance between stopping power and relatively low secondary particle generation.

The instrument and its response to energetic particles have been modeled using Geant4, a software tool developed at the European Organization for Nuclear Research (CERN) to simulate the passage of particles through matter. As beam testing was not within the $840k budget of the CubeSat, detailed modeling of the instrument, as well as radioactive source testing, was conducted to characterize its performance. The current instrument shielding has been shown in Geant4 to stop all electrons with energies $<$ 10MeV and protons up to 85MeV from penetrating through the outer casing and reaching the detectors from directions other than the collimator aperture. The 0.5mm thick beryllium foil at the front of the detector stack acts as a high-pass filter, stopping all electrons $<$ 400keV and protons $<$ 8MeV. This determines the cutoff energy on the lowest energy channel, and mitigates saturation of the detectors from the high count rates of lower energy particles.

The instrument will measure electrons in four energy bins: 0.5-1.5, 1.5-2.2, 2.2-2.9, and >2.9MeV. Protons will be measured and binned into four differential energy channels of 8.5-18.5, 18.5-25, 25-30.5, and 30.5-40MeV. More details on instrument design and simulations are available in Schiller and Mahendrakumar.[6] The total instrument mass is 1.25kg, with a cylindrical envelope of 4.6cm (diameter) x 6.0cm (length).

2.2 Instrument Electronics Design

The REPTile electronics system acts to process and interpret the signals coming from the detectors and calculate electron and proton count rates in each of the four energy channels. A block diagram of the signal chain is depicted in Figure 2, showing the stages the signal passes through before count rates are calculated. The chain is duplicated for each of the four detectors.

When a particle hits a detector, it produces a shower of electrons in the silicon. This charge pulse is collected on the anode and passed to a charge sensitive amplifier (CSA), which acts to amplify the signal and convert it to a shaped voltage pulse. The CSA selected was the A225 from Amptek Inc., which is a space grade component but very sensitive to noise and other environmental factors. Due to this sensitivity, a number of measures were taken to remove background signals and noise from its signal. Details on the testing and correction methodologies are discussed in Section 3.2.

Following the CSA, a secondary amplification is performed by a pulse-shaping amplifier (PSA), which amplifies the signal by 3.4x and further shapes it. The output of this stage ranges from ∼0-4V depending on the species and energy of the incident particle. These voltages are passed into a three-stage discriminator chain, which is used to identify whether the particle is an electron or proton based on the voltage measured. Each discriminator compares the output of the PSA to a predefined reference voltage. The reference voltages are set to 0.29, 1.35, and 3.88V, equivalent to energy deposition in the detectors of 0.25, 1.5, and 4.5MeV respectively, and are adjustable from the ground during operations. The first discriminator in the chain returns a 1 if the input voltage exceeds the equivalent of 0.25MeV deposited in the detector, and a 0 otherwise. The second returns a 1 when the second voltage threshold is exceeded, and similarly for the final discriminator and third threshold. Thus a discriminator chain output of 100 indicates a particle has deposited 0.25-1.5MeV in a given detector.

In the final signal processing stage, the Complex Programmable Logic Device (CPLD) interprets the discriminator values and classifies the particle by species and energy. Particles depositing between 0.25 and 1.5MeV in a detector (a discriminator output of 100) are classified as electrons, and those depositing > 4.5MeV (discriminator output 111) as protons. Discriminator outputs of 110 are discarded as noise, as this energy range (1.5 to 4.5MeV) is contaminated by both electrons and protons. The number of detectors a particle hits determines the energy of the particle, as described by the binning logic applied by the CPLD (see Section 4). 6-second count rates are calculated for each energy channel for both electrons and protons, and these rates are passed on to the Command and Data Handling (C&DH) system to be stored and transmitted down to the ground.

The REPTile electronics board is also responsible for providing the 350V bias across each detector and for containing housekeeping sensors to track temperatures, voltages, and currents of the system. Housekeeping information includes the detector temperatures as well as the electronics board temperature, as the performance of these components is temperature sensitive. Due to the small sizes of the signals being measured, a number of the instrument and electronic components are very sensitive to noise. Careful testing and calibration of the system must be performed to ensure reliability in the data retrieved from the measurements.

3. Component-Level Testing

The first step in characterizing REPTile's performance was to test each component individually, followed by integrated testing of the system. Components were thoroughly tested to understand and quantify their behavior, and unacceptable performance warranted mitigation. The most sensitive components include the silicon detectors and the CSAs. The detectors were tested both with and without a radioactive source (Section 3.1), and the A225s were characterized over temperature, input signal amplitude, and input signal rate (Sections 3.2.1, 3.2.2, and 3.2.3 respectively).

3.1 Single Detector Testing

Each Micron detector was subject to a number of acceptability tests to characterize its performance and determine the limits of its operability. Testing results are shown below for six different detectors — four flight model (FM) detectors and two engineering models (EMs).

First, the leakage current of each detector was measured. Leakage current is a measure of the performance and inherent noise of the detector, as simply biasing a detector can release electrons from the silicon. Large bias voltages release more electrons, producing larger leakage currents and thus more system noise. The background current produced by each detector was measured to determine how leakage current values vary. Leakage currents should be roughly constant over the operating range so that data processing does not need to incorporate any variations due to increased leakage current. Figure 3 shows the current measured on each flight and engineering model detector for varying voltage biases. The system is designed to operate with 350V across each detector, with an assumed error in the high voltage supply of ± 15V. Thus, in this voltage range, we look for the leakage current to remain relatively constant and below the system requirement of 2μA. Detector EM40 was selected as an engineering model rather than flight detector since the leakage current begins to rise again beyond a bias of 300V, rather than remaining flat. Leakage current is proportional to the area of the detector, so the two 20mm detectors produce $\sim 1/4$ the current of the 40mms.

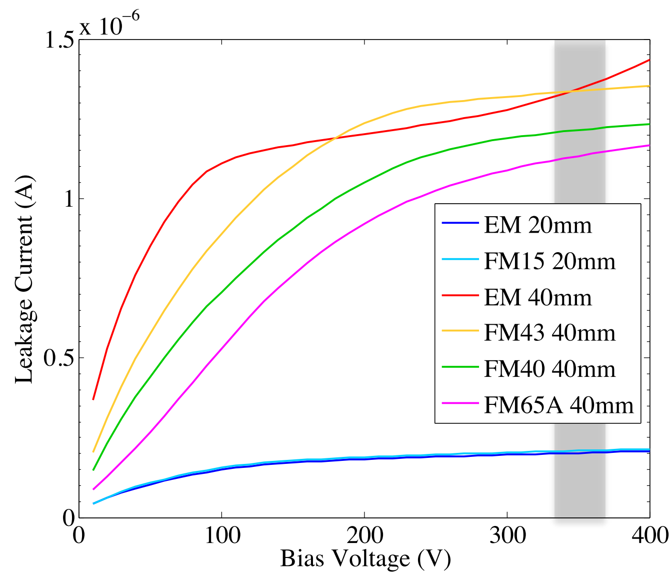

Figure 3. Detector leakage current versus bias voltage.

A second test was performed to determine the depletion voltage of each detector. The depletion voltage is a measure of the voltage at which the silicon detector is fully biased. The bias voltage across the detector is intended to collect all electrons produced by incident particles, creating a charge pulse proportional in size to the magnitude of the energy deposited in the detector. If the bias voltage is too low, all of the electrons released by an incident particle will not be swept from the detector on a timescale readable by the electronics, and the complete charge may not be collected. The voltage at which all the loose charge is collected as one pulse, and at which the pulse magnitude no longer increases with increasing bias, is known as the depletion voltage. Detectors should be operated above this depletion voltage to ensure pulse magnitude is proportional to incident particle energy. A radioactive alpha source, americium 241 (^{241}Am), was placed directly in front of single detectors, and the pulse magnitudes were measured by a multichannel analyzer (MCA), where channel number scales linearly with pulse size. ^{241}Am has a half-life of 432 years and releases 5.5MeV alpha particles. Figure 4 shows the magnitude of the charge pulses collected (as measured by MCA channel, plotted on the y-axis) versus detector bias voltage.

While ideally all four detectors would be biased at 350V, the output of the high voltage converters varies from component to component. Only three achieved a bias of 350V, with the fourth reaching a maximum of 300V. Based on the depletion voltage measurements shown above, as well as the leakage currents from Figure 3, flight model FM15 was selected to receive a bias of only 300V. This still allows for ±15V variation on each detector bias without affecting the noise or output pulse amplitude.

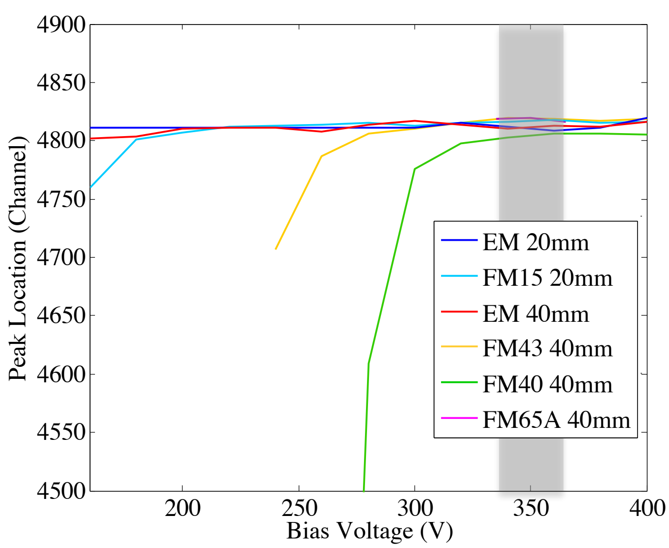

Figure 4. Detector pulse magnitude (as measured by a multichannel analyzer) versus bias voltage. Incident particles were generated by an ^{241}Am alpha source. Curves flatten out beyond the depletion voltage, and remain roughly constant in the operating range (shaded in grey).

3.2 Testing the Charge Sensitive Amplifier

The function of the CSA is twofold: to 1) amplify the signal and 2) standardize the signal shape, as each particle-detector interaction is not uniform. Ideally, the CSA output signal amplitude is proportional to the input amplitude, which is determined by the amount of energy deposited into the detector from an incident particle.

The reality of measuring very small amounts of charge deposited by a single particle is extremely challenging, and due to the significant amplification required, the CSA output signal is very sensitive to noise. To mitigate board-level noise sources, a copper ground plane is included on the REPTile electronics board, and the plane is grounded to the spacecraft chassis multiple times. Additionally, the board layout is arranged in a way to minimize electro-magnetic interference (EMI) from wiring loops or noisy components. Filtering is applied to the high voltage converters, which bias the detectors at 350V, as they are especially noisy. However, despite the care taken to eliminate electronics noise, the A225 is still inherently sensitive to temperature, input signal rate, and input signal amplitude.

With additional resources, the output of the CSA would be filtered so that variations in noise are removed from the signal in flight. However, due to the mass, volume, and power constraints intrinsic to CubeSat missions, there are not enough resources to address every level of noise. Instead, the performance of the CSA must be characterized in detail to understand which features must be actively corrected, and how the science is affected by those that are not. The following sections will describe the details of characterizing the CSA's performance under various conditions: temperature, input signal amplitude, and input signal rate.

3.2.1 A225 Temperature Sensitivity

As a result of mass and power restrictions, CSSWE implements a primarily passive thermal system. The satellite uses radiator windows covered in silver-coated Teflon tape, which possesses the desired emission properties, to maintain internal temperatures within the operational range of all components. Using Thermal Desktop, a design environment that creates thermal models, the expected range of the REPTile electronics board is modeled to be -4 to 19°C. All of the components onboard, including the Amptek A225 CSA, are rated to operate over this temperature range. However, the CSA's output is not consistent over this range, so its variations due to temperature are tested to be fully understood and accounted for.

The baseline output of the A225, that is, the steady-state output with no input signals, is inversely propor-

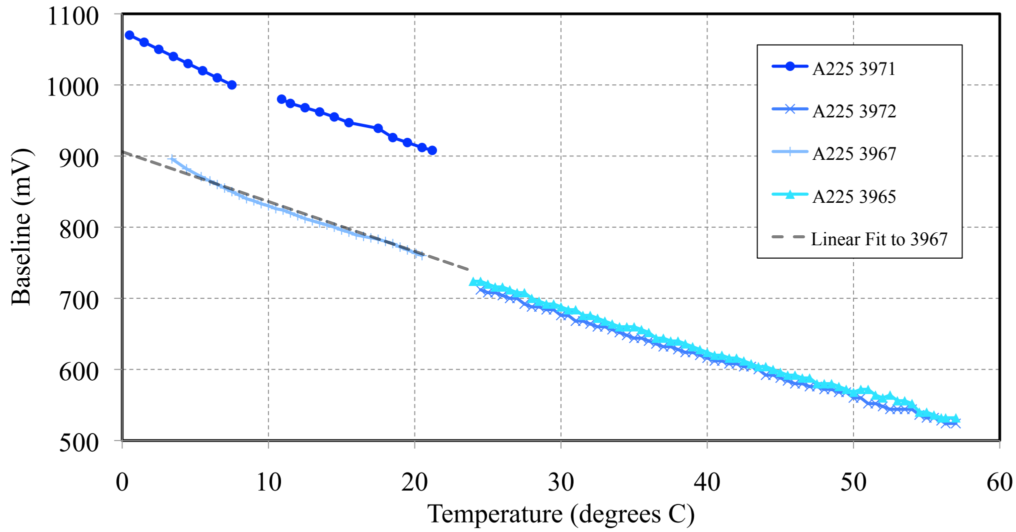

Figure 5. The response of the Amptek A225 CSA's baseline over temperature. The response is approximated as -7mV/C and removed from the output signal. The operational range of the satellite is ∼-4 to 19°C.

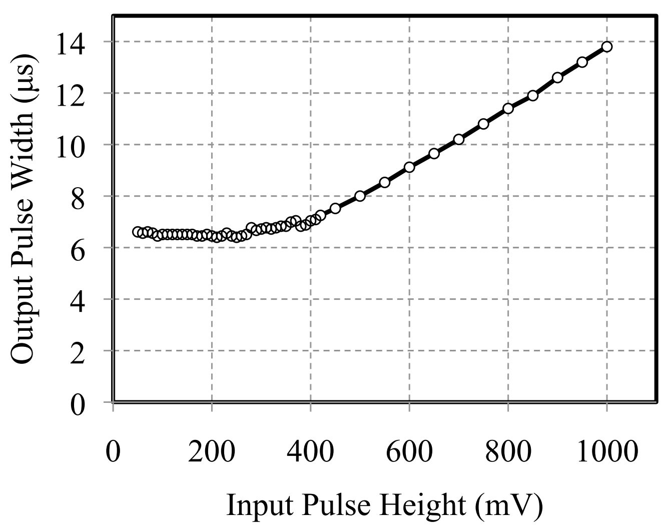

Figure 6. The effect of the amount of energy deposited in a detector on the A225 output pulse width. The pulse width is relatively constant at ∼ 7μs below 15MeV deposition in the detector. A single particle depositing 15MeV in a detector is an extremely rare event.

tional to temperature, as shown in Figure 5. The A225 baseline varies significantly over the operational range, by ∼200mV, which is a large enough fluctuation to significantly affect the science results without active removal. Thus, a simple subtraction circuit is developed to remove a linear approximation of the variation over temperature for each A225. Although the curve is exponential due to internal components of the A225, to first order between -4 and 19°C the response is linear. The baseline of each A225 is approximated to have a slope of -7mV/°C, with each component having a unique offset. However, over temperature extremes the linear approximation of the A225s' response breaks down. This fact is addressed in post processing of the science data.

3.2.2 A225 Dependence on Input Signal Amplitude

The A225's pile-up time is ∼ μ7s; that is, the output signal pulse is ∼ μ7s wide, during which time the component cannot accurately respond to additional signals. However, the pile-up time is dependent on the amplitude of the input signals. In other words, if a particle deposits energy into a detector above a certain threshold, the A225 lag time is proportional to the deposition energy. An inconsistent lag time decreases the reliability of the data, as particles are not registered during the lag, so the response of the A225 pile-up time is critical to understand in order to determine if a mitigation scheme is necessary.

The relationship between the input pulse amplitude and the output pulse width (which defines pile-up time)

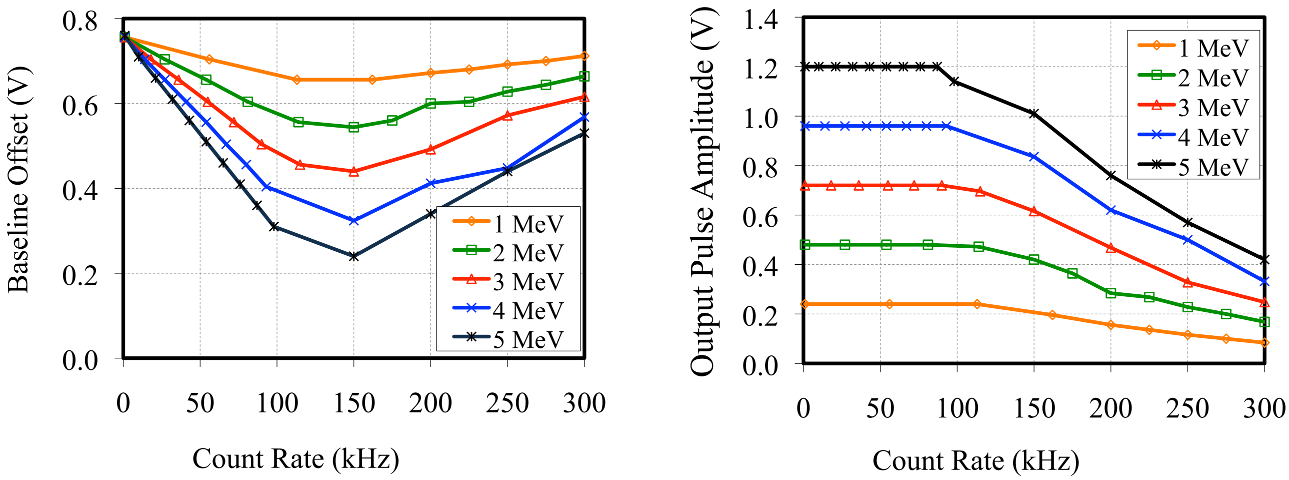

Figure 7. Response of the A225 to particle incident rate. The colored lines correspond to the energy deposited in the detector. The left panel depicts the variation in baseline and the right panel illustrates the decrease in signal amplitude.

Detector	Maximum Expected Electron Count Rate [kHz]	Maximum Expected Proton Count Rate [kHz]
1	427	30
2	72	14
3	37	8
4	22	5

Table 1. Expected Count Rates for both species based on worst-case energy spectra.

is depicted in Figure 6. It shows that the output pulse width is relatively constant for deposited energies below 15MeV. Based on Geant4 analysis and a worst-case SEP particle spectrum,[7] there is a sharp decrease in the number of particles depositing >15MeV in a detector. It is very rare for particles to deposit more than 15MeV in a single detector. Therefore, the A225 pile-up time can be treated as constant for all particle populations.

3.2.3 A225 Dependence on Particle Flux Rate

On orbit, CSSWE will encounter high signal rates (>400kHz) when passing through the outer radiation belts during geomagnetic storm times. Since the A225 also has features that depend on flux rate, characterizing how the component behaves over count rates is required to achieve accurate science data.

As the signal rate increases, both the A225 baseline and the output signal amplitude are affected. The left panel of Figure 7 depicts the effect of count rate on the baseline. At low count rates (<10kHz), neither the baseline nor the output signal is affected. However, between 10kHz and 150kHz the baseline falls to ∼30% of its nominal value (for particles depositing 5MeV). Above 150kHz, the baseline rises, recovering to ∼70% of the nominal value at 300kHz (for particles depositing 5MeV). However, as seen in Table 1, only electrons exhibit high enough count rates to significantly affect the baseline. Electrons deposit between 0.25 and 1.5MeV in a detector, so the baseline effect for electrons is negligible. The values in Table 1 are based on an electron storm-time energy spectrum derived from the AE8 Max model (http://modelweb.gsfc.nasa.gov/models/trap.html), an extremely large solar particle event of October-November 2003,[7] and the Geant4 software.

The right panel of Figure 7 shows the response of the output signal to count rate. For the output signal amplitude, there is no variation for count rates less than ∼80kHz. However, above this value the amplitude begins to drop. For particles depositing 5MeV, the amplitude decreases quasi-linearly to ∼70% of the nominal amplitude from 80kHz to 300kHz.

As demonstrated in Figure 7, the A225 does not produce consistently sized output pulses above 80kHz, yet REPTile expects a count rate up to 460kHz on the first detector. Thus, an onboard processing technique is re-

		Detector											
		1			2			3			4		
Species	**Energy (MeV)**	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
Electron	0.5-1.5	1	0	0	0	0	0	0	0	0	0	0	0
Electron	1.5-2.2	X	0	0	1	0	0	0	0	0	0	0	0
Electron	2.2-2.9	X	0	0	1	0	0	1	0	0	0	0	0
Electron	>2.9	X	0	0	1	0	0	1	0	0	1	0	0
Proton	8.5-18.5	1	1	1	0	0	0	0	0	0	0	0	0
Proton	18.5-25	1	X	X	1	1	1	0	0	0	0	0	0
Proton	25-30.5	1	X	X	1	1	1	1	1	1	0	0	0
Proton	30.5-40	1	X	X	1	1	1	1	1	1	1	1	1

Figure 8. Coincidence logic for particle binning. D1, D2, and D3 represent the discriminators referencing 0.25, 1.5, and 4.5MeV respectively. A 1 signifies the threshold must be achieved, a 0 signifies the threshold must not be achieved, and an X signifies that either a 1 or a 0 satisfies the logic in order to bin the particle in the corresponding energy and species.

quired to retain accurate science despite an overload of the first detector chain. We address the saturation by a modified coincidence binning scheme in the CPLD, as discussed in the next section.

4. Binning Logic in the Complex Programmable Logic Device

As described above, the A225 output signal amplitude is reduced significantly during periods of count rates greater than 100kHz. Particles incident on a detector during these periods will not be properly measured. Only particles that deposit a large amount of energy in a detector (e.g. high energy protons) will be able to trip the first discriminator, and their amplitudes will inaccurately be reduced significantly. More often, the signal chain will constantly show that no particles are incident on the detector, as more abundant particles (e.g. lower energy electrons) will not deposit enough energy to compensate for the decrease in signal size. This error will only be encountered during high count rate events, such as geomagnetic storms in the outer radiation belt. Additionally, it will only affect the first detector, as higher energy particles are less abundant and the beryllium window and first detector shield the remaining detectors from the largest fluence of particles.

The binning logic in the CPLD takes the discriminator signal and increments the electron counter, proton counter, or discards the input as noise. A binning logic where the signal from the first detector, which is prone to saturation, will not affect the binning logic of the remaining detectors is used to mitigate the flux-dependent effect. The augmented binning logic can be seen in Figure 8, where the detectors are in order from left to right. D1, D2, and D3 represent the discriminators, which compare the particle signal to the adjustable reference voltages corresponding to 0.25, 1.5, and 4.5MeV respectively. The appropriate differential energy channels for both electrons and protons are outlined in the second column. Here a 0 represents that the particular discriminator for that detector was not tripped and the particle deposited less than the reference energy corresponding to that discriminator. A 1 represents the particular discriminator for that detector was tripped and the particle deposited more than the reference energy. An X represents that either a 0 or 1 will satisfy the logic for the particle to be binned in the energy range. The X logic is present on only the the first detector, where saturation-level count rates are expected. This scheme permits the binning logic to continue to operate even if the first detector becomes saturated and returns no signals.

Detector	Average Measured Muon Countrate [$\frac{\#}{6s}$]	Average Measured Muon Flux [$\frac{\#}{cm^2 s}$]
1 (20mm)	1.07	0.057
2 (40mm)	4.10	0.054
3 (40mm)	3.49	0.046
4 (40mm)	3.42	0.045

Table 2. Muon count rate and flux as measured by the CSSWE satellite.

5. Fully Integrated Spacecraft Testing

The previously described analyses were done at component-level or subsystem-level tests. Further testing was done with the fully integrated spacecraft to verify the functionality of the entire signal chain, including the interface between REPTile and Command and Data Handling (C&DH), as well as the ability of the spacecraft to store, access, and transmit data. The data from the following tests were received through radio communication with the satellite and post processed for analysis.

5.1 Cosmic Ray Muon Testing

The first fully integrated spacecraft test presented here involved measuring muon counts at the surface of the earth. When a very high-energy (>100MeV) galactic cosmic ray (GCR) interacts with the atmosphere, it produces a shower of particles that dissipate its energy in the atmosphere. The majority of the secondary particles are very short lived and quickly decay or collide with neutrals. Muons are one of the secondary particles, but they have a very low interaction cross-section so they are unlikely to interact with atmospheric particles. Furthermore, their mean lifetime is 2.2μs, long enough for the relativistic particles to reach the Earth's surface. At the surface of the Earth they typically have energies of 4GeV, which is enough energy to pass through buildings and organic tissue, as well as all four of REPTile's detectors. 4GeV muons at the Earth's surface deposit ~0.6MeV in the silicon detectors when perpendicularly incident, which is enough energy to trip the first reference voltage and thus can be measured by the instrument.

To measure muon flux, the integrated spacecraft is positioned with the look direction of the instrument oriented vertically. The spacecraft is then commanded into science mode, in which the REPTile instrument is activated and begins to store count rate data. For this specific test, the CubeSat took muon data for 30 minutes, and then the data was requested and downloaded through the radio frequency (RF) link and analyzed. Since the muon flux is proportional to the receiving area of the detector, we expect to have 4x more counts on the 40mm detectors than the 20mm. As expected, outlined in Table 2, the larger detectors do see ~4x higher counts. This test confirms the basic functionality of all four detectors.

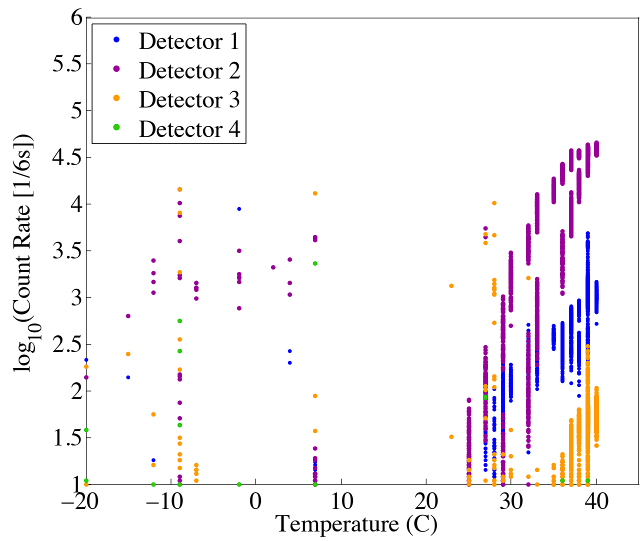

Figure 9. Measured singles count rate as a function of detector temperature for all four detectors. The maximum operational temperature is 25°C, at which point system noise potentially overwhelms science data.

5.2 Thermal Vacuum Testing

A passive thermal control system is well suited to CubeSat missions as it is a simple, no power, and low mass approach to internal temperature control. However, these benefits are at the cost of performance, as the temperature of specific components cannot be precisely controlled. As presented in previous sections, the REPTile payload is extremely sensitive to various parameters, especially temperature. The detector signal becomes noisy with increased temperature, as valence electrons have a lower potential to overcome to be released from the silicon. As the noise rate becomes significant, it affects the A225 baseline and output signal. Clearly, there are many coupled factors that will affect the data quality as the temperature of the instrument varies. For this reason, it is critical to verify that the instrument, as well as the entire system, behaves acceptably over the operational temperature range.

To make this verification, the fully integrated CSSWE

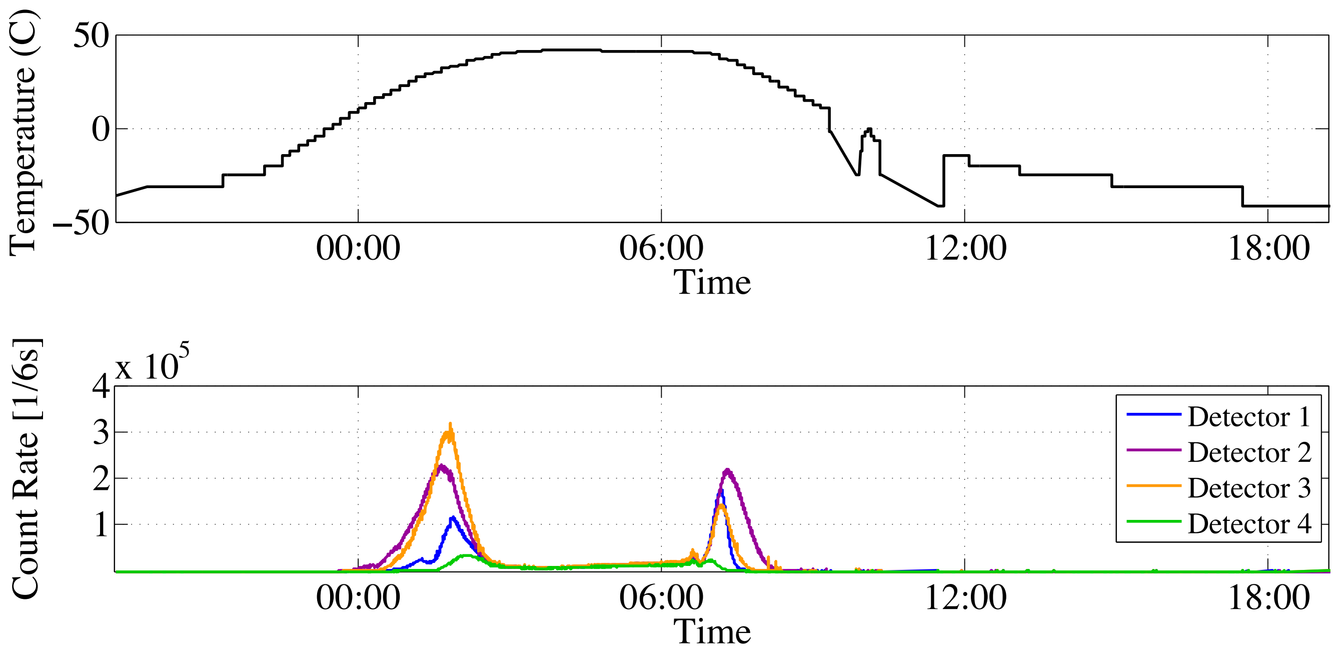

Figure 10. The top panel shows detector temperature over time. The noise threshold (reference voltage 1) was lowered from 0.29 to 0.16V. Data gaps between 09:00 and 12:00 are due to unrelated testing procedures. The bottom panel shows the measured noise singles counts in all four detectors. The noise increases with temperature, but the electronics become saturated between ∼02:00 and 07:00 and do not register counts.

spacecraft is installed in a thermal vacuum chamber, with no particle beam or radiation source for the instrument to measure. The chamber evacuates the air to a pressure of $\sim 2\times10^{-7}$torr ($\sim 2.6\times10^{-10}$atm) and uses a chiller-controlled platen to cycle between -25 and 40°C approximately once a day, dwelling at the extremes for 4 hours. Housekeeping information and spacecraft vitals are monitored through the RF link established with the spacecraft inside of the chamber. When possible, the system enters science mode to best simulate on-orbit operations. The data is requested approximately once every 8 hours, as it will be on orbit.

The performance of the system over temperature determines two important items: 1) the temperature at which detector noise overwhelms the system and 2) the count rate that saturates the electronics. The first point, diagnosing the maximum temperature for nominal operations, can be derived from Figure 9. The figure depicts the amount of system noise at a temperature range from -20 to 40°C. For this figure, no binning logic was applied; that is, the plot depicts individual hits on a detector large enough to trip any of the reference voltages. The individual hit data are also known as singles counts.

The singles count noise increases dramatically above 25°C, at which point it could potentially overwhelm science data. Thus, 25°C represents the highest reliable operating temperature of the instrument. Although periods of temperature greater than 19°C are not expected, science data received above 25°C will be flagged with a warning and undergo additional processing to attempt to remove this component of system noise. Component and detector temperatures will be monitored on orbit to verify their operating temperatures.

The second point, to determine the count rate at which the combination of factors prevents signals from tripping the first reference voltage, is addressed in Figure 10. For this figure, the noise threshold limit (specifically, the reference voltage for the first discriminator) was reduced from 0.29V to 0.16V. As seen in the figure, the noise becomes significant at ∼10°C due to the lower threshold. Additionally, the saturation becomes apparent at a count rate of 300kHz, when the count rate is expected to increase since the detector temperature is still rising, but there is an unexpected sharp decrease in counts. As previously discussed, this interesting saturation effect is due to the A225 output dependence on incident count rate. On orbit, since we expect for some saturation to occur in the outer radiation belt, especially during storm time activity, we will recognize this characteristic feature representing saturation and apply a warning flag to the

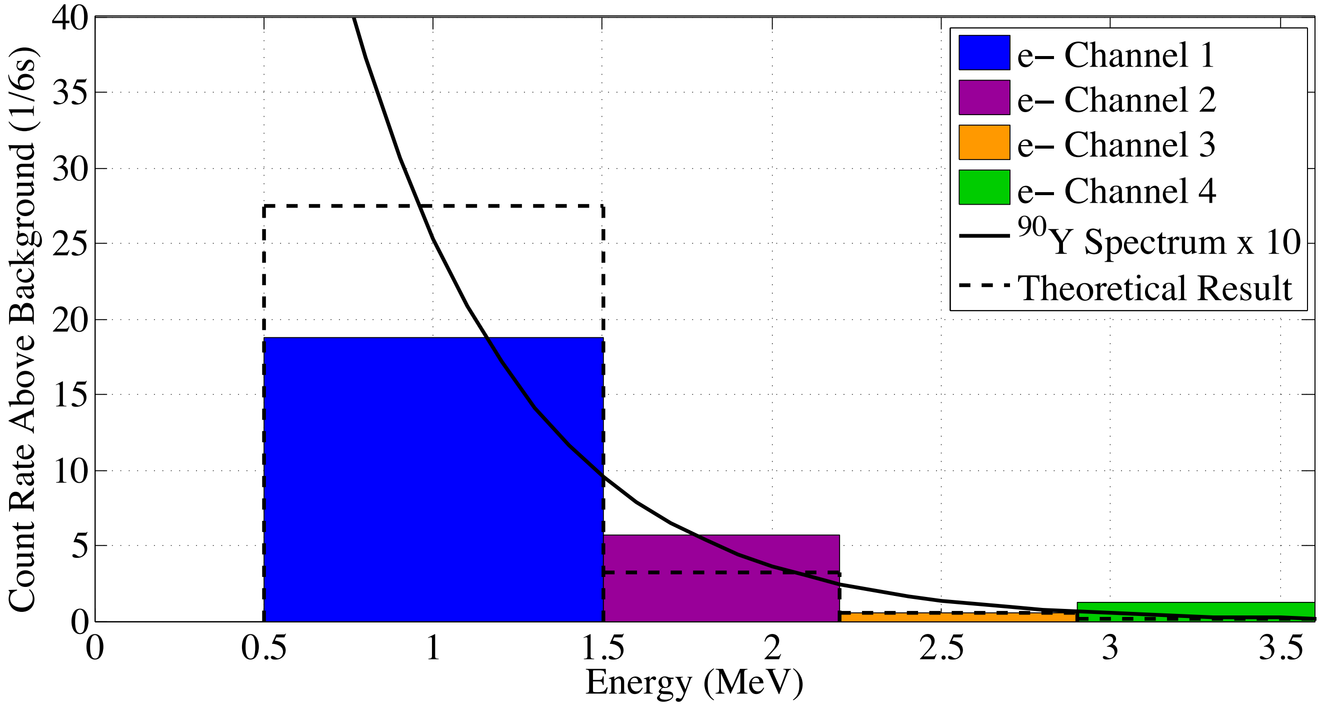

Figure 11. The ^{90}Y spectrum (amplified by 10 for reference) plotted over the measured electrons from REPTile in the fully integrated CSSWE test. The theoretical result for each energy bin is plotted with dashed lines.

data.

5.3 Radioactive Source (Strontium 90) Testing

As a NSF funded CubeSat mission, CSSWE has been designed, built, and tested for a budget well under that of other space weather projects. As a result, energetic particle beam tests are out of the scope of the REPTile budget. This fact motivates the extensive Geant4 simulation of the REPTile instrument discussed in detail in Schiller and Mahendrakumar.[6] Without beam test capabilities, the most extensive system level test available is with a radioactive source. The source test is performed using a strontium 90 (^{90}Sr) source fitted close to the bore sight of the instrument to prevent attenuation in air. ^{90}Sr has a half-life of 28 years and decays into yttrium 90 (^{90}Y), emitting an electron with maximum energy of 0.546MeV. ^{90}Y has a half-life of 2.7 days and decays into Zirconium 90 (^{90}Zr), emitting an electron with maximum energy of 2.28MeV. Both isotopes emit electrons in a continuous kinetic energy spectrum from zero to the maximum.

Based on Geant4 simulations, very few of the electrons originating from the ^{90}Sr propagate through the beryllium window with enough energy remaining to deposit >0.25 MeV on the first detector. Thus, an assumption is made that all measured particles from the ^{90}Sr source originate from the ^{90}Y decay.

From independent measurements, the energy spectrum for the ^{90}Y source is derived and is equal to $798.3\mathrm{e}^{-1.937E}$. Using the instrument response function, the ^{90}Y spectrum is integrated to determine the theoretical count rate in each energy bin. The results are shown in Figure 11, where the ^{90}Y spectrum has been amplified 10x to enhance its features on this scale. The background count rate is subtracted and instrument dead time is corrected for each differential energy bin. The measurements agree to theoretical results within expectation, despite the challenges of designing such a sensitive payload with strict CubeSat requirements.

6. Summary

This paper describes the *R*elativistic *E*lectron and *P*roton *T*elescope *i*ntegrated *l*ittle *e*xperiment (REPTile) instrument onboard the Colorado Student Space Weather Experiment (CSSWE) CubeSat, which has been fully built and tested and is scheduled to launch in August, 2012. For a cost of less than $1M, the CSSWE mission will provide valuable differential energetic electron and proton measurements from a simple and robust payload to help understand the dynamic near-Earth space environment.

Making such measurements from a CubeSat platform poses a number of challenges for both instrument design, as well as data calibration and analysis. Due to the simple, miniaturized design of the REPTile instrument and onboard data processing, the instrument must be thoroughly characterized to determine the quality of the measurements returned under a variety of conditions. Only through comprehensive testing and calibration are we able to understand the limitations of the instrument and correctly interpret the data received.

The REPTile instrument has undergone extensive testing to confirm detector operability and measure inherent system noise over temperature, energy deposition in the detectors, and incident particle flux. We have characterized REPTile's performance through instrument-level tests of the detectors and charge sensitive amplifiers, and have determined which aspects require correction from valuable onboard resources and which can be addressed in ground processing. This step is critical to ensure accurate data is retrieved from the CSSWE CubeSat mission. As a result, adjustments have been made to the onboard data processing to account for issues like temperature variations, detector saturation, and increasing noise floors. We have also verified instrument functionality in completely integrated spacecraft tests, examining noise levels in a thermal vacuum chamber and count rates from cosmic ray muons and a radioactive source.

The successful comprehensive system tests fully validate REPTile's ability to provide reliable and accurate measurements. Such rigorous testing confirms that valuable scientific data will be returned from the CSSWE mission, and that legitimate and valuable science can be conducted as a CubeSat payload. Despite the restrictions inherent in CubeSats, REPTile — an innovative, affordable, robust, and simple instrument — will supply critical measurements which will enhance our ability to understand and predict the dangerous effects of energetic particles on space assets.

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