REPTile: A Miniaturized Detector for a CubeSat Mission to Measure Relativistic Particles in Near-Earth Space

Quintin G. Schiller
University of Colorado, Boulder, CO 80309

Abhishek Mahendrakumar
University of Colorado, Boulder, CO 80309

Xinlin Li
Advisor, University of Colorado, Boulder, CO 80309

The *R*elativistic *E*lectron and *P*roton *T*elescope *i*ntegrated *l*ittle *e*xperiment (REPTile) is a solid-state particle detector designed to measure solar energetic protons and relativistic electrons in Earth's outer radiation belt. These particles pose a radiation threat to both spacecraft and astronauts in space, and developing a better understanding of these particles has been identified as a critical area of research by NASA's Living With a Star program. REPTile has been designed specifically to meet the requirements for a CubeSat mission, namely the Colorado Student Space Weather Experiment, which is an example of how CubeSats can be employed to provide important scientific measurements for very low cost. This paper focuses on the REPTile design and functionality. The particular difficulties of energetic particle detection are introduced to provide a full understanding of the REPTile design, and then the design itself is covered in detail, including both mechanical and electronic aspects. The paper finishes with a detailed discussion of the various simulations that have been conducted to develop accurate estimates of the detector performance followed by a discussion of the instrument test plan.

Introduction

IN the solar system, the Sun acts as the ultimate driver of space weather, the study of the dynamics of particles and fields that make up space plasmas, which can have serious implications for manmade systems both in space and on the ground. The Sun is continually spewing forth a turbulent stream of magnetic field tied with mostly low-energy ions and electrons called the solar wind. This solar wind serves to tie the solar system together since through it energy can be transported from events on the solar surface to every planet and body in the solar system. Near the Earth, the space environment is a vast and highly dynamic region consisting of a plethora of different plasmas primarily split into two categories: those in the solar wind and those in the magnetosphere. Earth's magnetosphere, the region of plasmas and energetic particles whose dynamics are governed by the magnetic fields generated within the Earth, is home to the processes that cause such spectacles as the aurora. Anyone lucky enough to catch a glimpse of these spectacular light shows in the night sky is witness to the fascination of space weather.

In recent decades, scientists and engineers have realized that space weather is extremely important to understand and forecast as society becomes more and more dependent on space-based technology. They have found that events on the Sun, such as solar flares or coronal mass ejections, can have serious effects on Earth's magnetosphere, atmosphere, and even on ground-currents within the Earth itself. For example, a high magnitude solar flare on the Sun can send a blast of highly energetic photons (X-rays) and relativistic protons and electrons moving nearly the speed of light (solar energetic particles, SEPs) at the Earth. SEPs arrive at the Earth less than ten minutes after the flare is generated on the Sun, almost simultaneously with the light that warns us that there has been a flare at all. They are guided by Earth's magnetosphere to the poles, where they interact with the atmosphere and result in reduced transmission of radio signals from spacecraft and increased levels of radiation for any person at high latitudes at the time. Events also associated with a solar flare are coronal mass ejections (CMEs), which are the explosive releases of a massive amount of solar material into the solar wind. When Earth's magnetosphere is impacted by a CME, the result is often a magnetospheric storm that can have further negative effects on manmade systems. During such a storm, spacecraft are at risk from an enhancement of the intensity and fluxes of the outer radiation belt, which is composed primarily of relativistic electrons that have been known to embed themselves in sensitive electronic components and fatally disable spacecraft in the region. Also, an enhanced ring current associated with geomagnetic storms can induce intense ground-currents on Earth, overloading power grid systems to cause power outages on a continental scale.[1]

Currently, there are still several outstanding questions concerning some of the physical processes that can result in negative space weather effects on manmade systems; such as, the source, loss, and transport processes of Earth's outer radiation belt electrons. Earth's outer radiation belt is a system of relativistic electrons that are trapped within Earth's magnetosphere and form a torus shaped region with variable equatorial plane boundaries from 3 to 7 Earth Radii (R_E) with peak intensities around 4 to 5 R_E, as seen in Figure 1. These electrons can be potentially fatal to spacecraft and astronauts in the region since they carry enough energy to penetrate into electronics boxes and through spacesuits. Energetic electrons can bury themselves in electronic components, and when fluxes are high enough, they can build up enough charge to result in dielectric breakdown and discharge through the material, which can be critically fatal to spacecraft systems.[2] With a better understanding of the source, loss, and transport of energetic electrons, it will be possible to improve the forecast and provide a warning system for spaceflight operations in the region.

Another outstanding question concerning the serious implications of space weather is: how do solar flare location, magnitude, and frequency relate to the timing, duration, and energy spectrum of SEPs reaching Earth? Developing a better understanding of the answer to this question is critical for mitigating the risks of airline flight crews and passengers, loss of navigation capabilities due to increased error in GPS, and loss or degradation of radio communications. Solar flares can occur anywhere on the solar surface during any time in the solar cycle. However, they occur most frequently in mid to low solar latitudes around solar maximum, that is, when solar activity is high. Despite their significance, there is no existing model to determine how powerful an SEP event will be based on the type and location of the accompanying flare.

To address these critical space weather questions, it is necessary to make in-situ measurements of the energetic particles, namely relativistic electrons from Earth's outer radiation belt and the energetic particles associated with solar flares. This work serves as a detailed

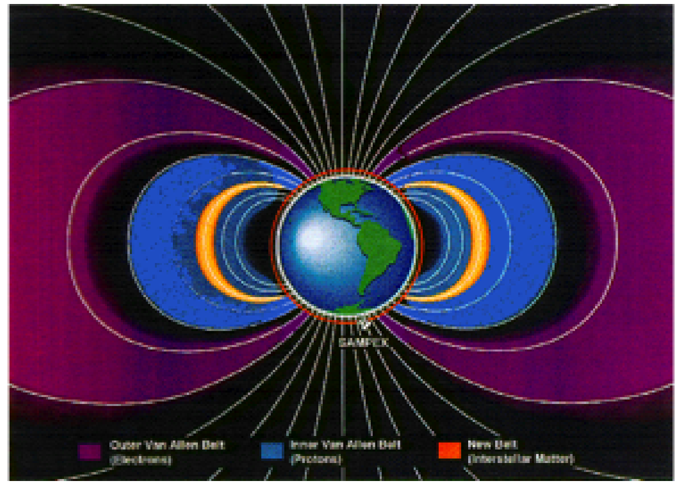

Figure 1. An artistic representation of the Inner and Outer Radiation Belts.[3]

description of an instrument that has been developed specifically to make these measurements for very low cost from a low-Earth orbit (LEO) CubeSat mission [cubesat.calpoly.edu/index.php/about-us]. In the following sections, a general background of energetic particle detection is provided, followed by a detailed discussion of the University of Colorado's Relativistic Electron and Proton Telescope integrated little experiment (REPTile) instrument. REPTile has been designed primarily by engineering graduate students to measure outer belt electrons with energies ranging from 500 keV to >3 MeV and SEP protons from 10-40 MeV, and will be incorporated as the principle science instrument on the NSF-funded Colorado Student Space Weather Experiment (CSSWE). The following sections are initiated with a discussion on the difficulties in designing an instrument to measure energetic particles. Despite the inherent challenges, a review of the unique mitigation techniques incorporated in the design of the REPTile instrument is presented. Details on simulations of the performance of the instrument follows the design section, and the work is concluded by discussing the importance of taking important scientific measurements from small, low-cost spacecraft in conjunction with larger, more expensive missions.

Measuring Energetic Particles

As discussed thoroughly by Vampola,[4] measuring energetic particles of particular incident energies accurately is no trivial task. Due to the complex behavior of individual particles interacting in matter, energetic electrons and protons behave quite differently as they pass through a material. Being relatively massive, protons are well behaved with respect to electrons. Protons pass through solid matter with trajectories that are not greatly diverted and their deposited energy is inversely proportional to their velocity. However, very high-energy protons are able to penetrate through any reasonable amounts of instrument shielding and will appear as noise in a particle detector's signal.

Electrons, on the other hand, behave in practically the opposite way. Electrons up to ~10 MeV in energy are easily stopped by properly designed shielding. Statistically, their trajectories scatter to the point that a beam of electrons incident on any material will result in some significant percentage of fully backscattered electrons (i.e. reflected by the material itself). For example, up to 25% of electrons incident on aluminum will be diffusely backscattered upon encountering its surface.[4] This phenomena is caused by a wide range of electron interactions with matter including atomic excitation and ionization, bremsstrahlung radiation (i.e. the generation of high-energy photons caused by an electron accelerated in a curved trajectory), dissociation of molecules, and material lattice excitation. Any of these processes can result in a large deviation to electrons' incident trajectories and, due to this significant scattering in matter, energetic electrons do not deposit consistent amounts of measurable energy. A statistical understanding of an instrument's response to incident electrons at various energies is critical to developing an accurate electron-detecting instrument.

The design of a relativistic particle telescope must consider both the scattering properties of electrons as well as the shield-penetrating capabilities of energetic protons. As Vampola states: "Few investigators who have flown energetic electron spectrometers have really understood the behavior of their instruments" primarily due to a lack of understanding or proper simulations of the instrument's response to electron scattering and shield penetrating particles.[4] Vampola and Leo discuss different types of instruments and the strengths and shortcomings of each.[4,5] Of these, collimated and shielded solid-state detector stacks are the most common type of energetic particle instruments used for indirect energy measurement. However, instrument designers often overlook, disregard, or simply misunderstand the response of their design to electron scattering and shield-penetrating particles.

Poor instrument design allows for electron scattering in a collimating chamber where shielding paths are thin, while electron reflection occurs in the collimating chamber where incidence occurs at oblique angles. An instrument is most susceptible to noise from shield-penetrating particles through large areas of shielding, which become transparent to certain energies of protons and electrons. The instrument is most sensitive to this source of noise in the shielding around the detector stack. Large thicknesses of shield surrounding the detector stack will minimize shield-penetrating particles. However, due to mass restrictions, a balance between shield thickness and noise must be accommodated and accounted for in the resulting data. The generation of secondary particles in shield alloys must also be taken into account. High-Z materials, when bombarded by incident radiation, produce larger amounts of energetic secondary particles when compared to low-Z materials. However, dense materials, which serve as the best shields for blocking high-energy particles, tend to also be high-Z materials. Thus, an adequate shield design must take thickness, mass, density, and nuclear charge into account, but also the noise from any secondary particles generated in the shields.

The most common types of detectors used to measure energetic particles are made of a semiconducting material, such as doped silicon.[5] When an incoming energetic particle hits such a detector, it results in an electron-hole pair generation in the doped silicon. A bias voltage must be applied across the detector to accelerate these loose electrons to an anode on which they can be measured and amplified by sensitive electronics. This amplified electronic signal can then be analyzed further to determine particle type and approximate incident energy in incremental counting bins, which are the raw data produced by an instrument.

In the following section, an innovative new instrument design, which accounts for all of the above-mentioned difficulties, yet is small enough to be incorporated onto a CubeSat, is introduced. In addition, it's mechanical assembly and electronic signal chain are described in detail.

REPTile Design

The following sections demonstrate the design of the REPTile instrument, specifics regarding it's assembly, and details on the electronic system used to process data.

Instrument Geometry

The geometry of the REPTile instrument, shown in Figure 2, is designed to meet a required signal to noise ratio of at least 2 when the complications mentioned above are taken into account. To do so, REPTile is a loaded-disc collimated telescope design incorporating layered shielding and a beryllium window to block lower-energy particles from entering the detector stack. In the collimator, tantalum baffles prevent electrons from scattering off of the collimator walls and into the detector stack. This affect is demonstrated superbly in panel d) of Figure 7, where a beam of 2 MeV electrons are fired into

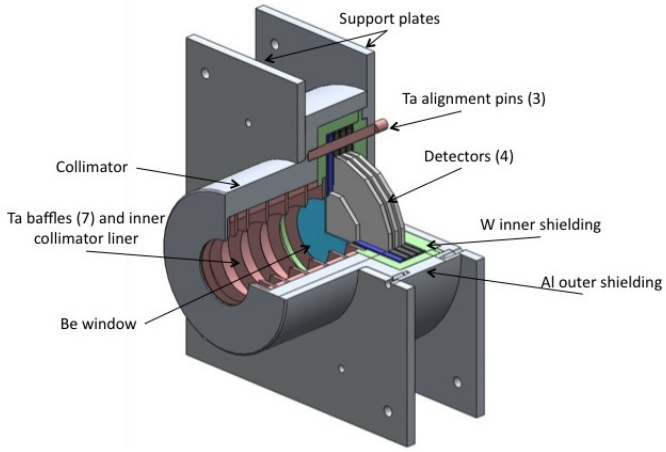

Figure 2. Cross-sectional view of REPTile.

the collimator but out of the instrument's field of view. The baffles effectively cause the particles to back-scatter, thus preventing them from entering the detector stack. The spacing of the baffles is designed to maintain a 50° field of view such that an out-of-field electron cannot directly enter the detector stack without impacting at least one baffle after its initial scattering. Additionally, the baffles also incorporate knife-edges to decrease the number of particles reflecting off the baffle edge and into the detectors. Tantalum is used for the collimator lining and baffle material due to its high density but reasonably low secondary particle generation.

As can also be seen in Figure 2, the main shielding of the instrument consists of an outer aluminum shell with a smaller chamber of heavy tungsten shielding within it. Due to the large area of the instrument's end cap, additional heavy shielding is applied to further reduce the noise from particles penetrating the rear of the instrument. Tungsten is used for the inner shielding due to it's high density; however, tungsten behaves poorly in regards to secondary particles. The layered shield design accommodates this with an aluminum outer layer, which serves to soften incoming particles before they encounter the tungsten. This layered shielding configuration stops all electrons with energy (E) less than 10 MeV and all protons with E $\leq$ 85 MeV.

The beryllium window at the front of the detector stack acts as a high-pass filter for incoming field of view particles. Despite a thickness of 0.5 mm, the beryllium foil effectively stops electrons up to 400 keV and protons up to 8 MeV. This window sets the lower limit for the instrument energy range. It also limits the count rate the electronics handle since there are increasingly more particles at lower energies, as seen in Figure 5.

For the detector stack, Micron Semiconductor solid-state doped silicon detectors are employed. The front detector in the stack (i.e. immediately behind the Be-window) has an effective area with a 20mm diameter, while detectors 2 through 4 have effective areas of 40mm in diameter. The design uses the same detectors used on the Relativistic Electron and Proton Telescope (REPT) instrument, which is being designed for NASA's Radiation Belt Storm Probes mission. This is no coincidence; the REPTile and REPT design teams have worked closely together on the REPTile design, it is quite advantageous to use the same detectors given the strict time and monetary budgets for REPTile. The final REPTile design results in a total instrument mass of 1.25 kg (including structural supports) with a cylindrical envelope of 7.6 cm (diameter) $\times$ 6.0 cm (length).

Mechanical Assembly

Figure 3 shows an exploded view of REPTile's components. To assemble the instrument, the outer aluminum shielding serves as the base for the assembly stack. The collimator discs are loaded into the collimator and are press fit by the inner tungsten shielding. These discs are free to rotate, though since they are held under compression, any rotation will be minimal and they will not rattle. The last collimator baffle has the Be-window adhered to its inner face. It is press fit between the tungsten shield and the PCB-casing on the first (20mm) detector. A spacer is included between the Be-window and the first detector. The thickness of this spacer (as well as that of the one behind the fourth detector) is dependent on the measured thicknesses of the actual manufactured parts to conform to the design requirements. Detectors 2 through 4 (40mm) are installed after the first detector. The PCB casings ensure that the sensitive material is isolated from other parts. Finally, the tungsten and aluminum end caps are used to close and seal the detector chamber. Fasteners and alignment pins hold the entire assembly together. Three threaded tantalum pins insert through the holes in the end caps, spacers, detectors, and tungsten shields. These align the detector stack and restrict rotation, which could shear the detector electronic cables. The alignment pins screw into the inside of the outer aluminum shield and will be held in place with nuts on the outside of the aluminum end cap.

The cables from the detectors are flex-circuits with a built-in ground plane ending in 10-pin connectors that interface with the instrument electronics board residing behind the instrument in the spacecraft. Housing and breakout points for these cables have been incorporated in the design of each detector and in the bottoms of the tungsten and aluminum end caps through a system of slots and notches. The wire breakouts have been de-

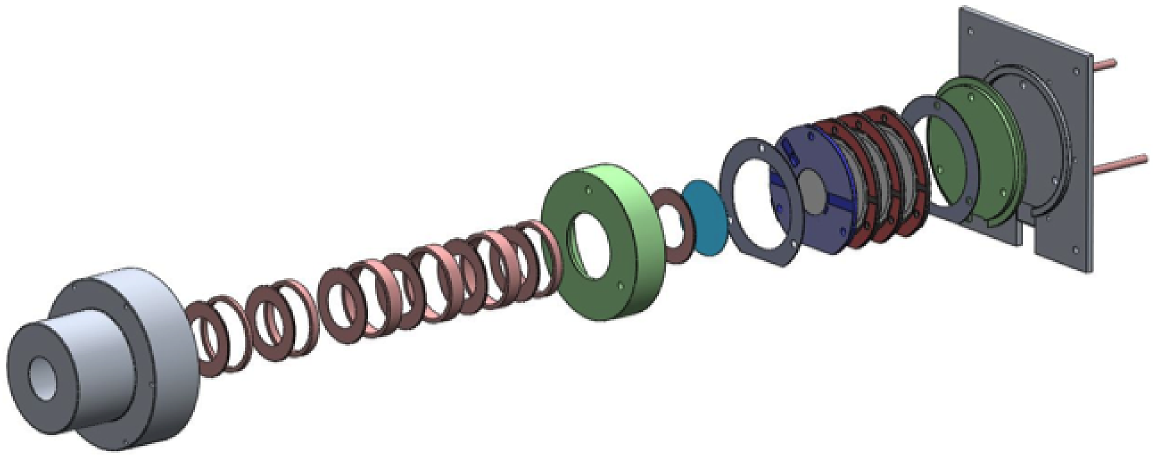

Figure 3. Exploded view of the REPTile assembly.

signed in such a way that there is no line-of-sight directly into the sensitive areas on the detectors, and thus, noise through this weak part of the shielding is highly reduced.

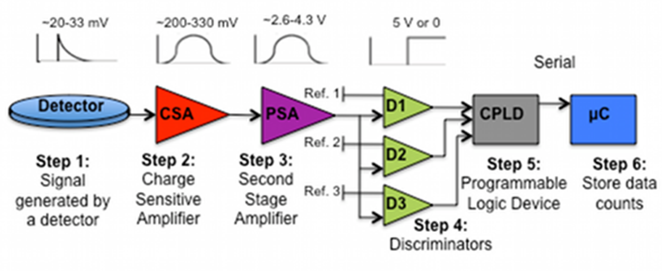

Figure 4. REPTile electronics block diagram.

Electronics Design

REPTile electronics have three major roles to play in the mission, namely: 1) to identify particles that hit the detectors; 2) to find the approximate energy of these particles; 3) convert the analog data to digital data for transmission to Command and Data Handling (C&DH). The signal chain block diagram is shown in Figure 4.

When a particle hits a silicon detector the response is a very small voltage spike on the order of 20 to 33mV. These signals are highly sensitive to noise since the amplitude of the signal is very low. There are two stages of amplification in the circuit. In the first stage, the voltage spikes are converted to a pulse which is amplified to a similar pulse of approximately ten times higher amplitude. This amplifier is called a charge sensitive amplifier (CSA). An IC A225 from Amptek Inc. is used as the CSA in the design. The A225 is a space graded IC and very sensitive to noise. Due to this sensitivity, the A225 is placed very close to the detectors reducing the effect of noise.

The second stage amplification is thirteen times amplification of the output of the CSA. The purpose of this stage of amplification is to have clearly distinguishable voltage bands for electrons and protons. Amplification is performed by a generic OpAmp and the approximate voltage level for electrons and protons would be from 2.6V to 4.3V.

The stage where the analog signal is converted to digital is at a three level discriminator chain. An analog to digital converter (ADC) can be used in place of the discriminators; however, the rate at which the particles hit the detector exceeds the ADC operational margins. The discriminators used are simply OpAmp comparators and they compare a predefined reference voltage with the output of the second stage amplification. The reference voltages for the discriminators represent deposited energy of 0.25, 1.5, and 4.5 MeV and are provided by digital to analog converters (DACs) from C&DH. The first discriminator returns a 1 if the voltage exceeds the equivalent of 0.25 MeV deposited on the detector. The second discriminator in the chain returns a 1 if the input voltage exceeds the equivalent of 1.5 MeV deposited in the detector. The final discriminator outputs 0 unless the input voltage exceeds the equivalent of 4.5 MeV deposited. Thus, a return of 100 signifies energy deposited between 0.25 and 1.5 MeV, 110 signifies energy deposited between 1.5 and 4.5 MeV, and 111 signifies energy deposited greater than 4.5 MeV. The reference energies are determined by detailed simulations discussed in the next section.

A discriminator chain output of 100 indicates a particle has deposited $0.25 < E < 1.5$ MeV in an individual detector. The binning logic incorporated in the Complex Programmable Logic Device (CPLD), the next stage in

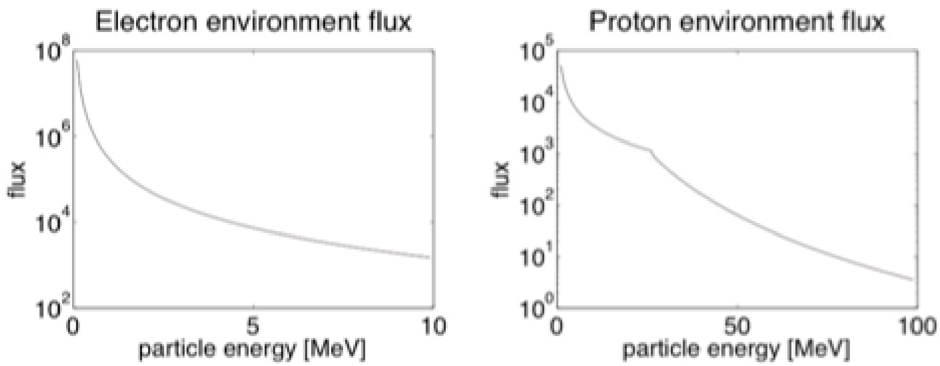

Figure 5. The spectral power laws used for protons and electrons. The units of flux are $\left[\frac{\#}{s\ MeV\ Sr\ cm^2}\right]$.

the signal chain, classifies this type of incident particle as an electron. A discriminator chain output of 110 indicates a particle deposited $1.5 < E < 4.5$. These particles' data are discarded. Finally, a discriminator chain output of 111 indicates deposited $E \geq 4.5$ MeV and classifies the hit as a proton. Depending on the number of detectors a particle hits, the incident energy of the particle can be estimated, and the incident energy ranges are described in Table 1.

The reference voltages can be varied by software in the C&DH module. This design provides the versatility to adjust the reference voltages of each discriminator throughout the mission, in case; for example, of a detector malfunction. The exact reference voltage values will be found through testing as described later.

The final stage in the electronics chain, the CPLD, filters the data received by the discriminators to send the valid data to C&DH and discards the invalid data. The CPLD and DACs are connected to the C&DH subsystem through an I2C bus, in which the CPLD and DAC are slaves. Additionally, there are housekeeping sensors on the electronic board which keeps the track of temperature, voltage and, current of the whole system. All the sensors communicate with the master using an I2C bus.

Performance Simulations

To test the performance of the instrument, the REPTile team uses the Geant4 software tool. Geant4, developed by physicists at the European Organization for Nuclear Research (CERN), is used to simulate the performance of the Large Hadron Collider (LHC), the Tevatron at FermiLab, and the Gamma Ray Large Area Space Telescope (GLAST). The simulation code uses Monte Carlo methods to model the passage of particles through matter, and it is ideal for simulating an instrument's response to the relativistic electrons and protons found in Low Earth Orbit (LEO) (geant4.web.cern.ch).

Table 1. Detector Energy Bin Ranges (MeV)

Particle	D1	D2	D3	D4
Electrons	$0.5-1.5$	$1.5-2.2$	$2.2-2.9$	> 2.9
Protons	$10-18$	$18-25$	$25-30$	$30-40$

Geant4 Modeling

Geant4 creates a software environment in which the instrument is assembled and bombarded with particles. The simulation results are analyzed to determine specific design constraints of REPTile geometric features. For example, the collimator and heavy shielding chambers went through multiple design iterations to confirm the required performance efficiency.

The analyzed Geant4 output is a series of numbers corresponding to the energy deposited by individual particles in each of the four detectors. The particles are then logically binned based on the energy deposited as described in previous sections. To determine the binning efficiency, each detector is integrated over energy for particles incident on the instrument:

$$C_i = \int_0^\infty I(E)\,\gamma\,\alpha_i(E)\,dE \tag{1}$$

where C is the count rate $\left[\frac{\#}{\text{sec}}\right]$, i is the index $(1-4)$ of the detector, I is the environmental flux of the particle, γ is the geometric factor for the incident particles, α is the binning efficiency of the detector, and E is the energy of the particle. These quantities are described below.

The incident electron spectral flux is determined to be $3.003 \times 10^5 \times E^{-2.3028}$ using solar max AE8 for L=4 and $B/B_o = 27.1$ (model-web.gsfc.nasa.gov/models/trap.html) . This incidence

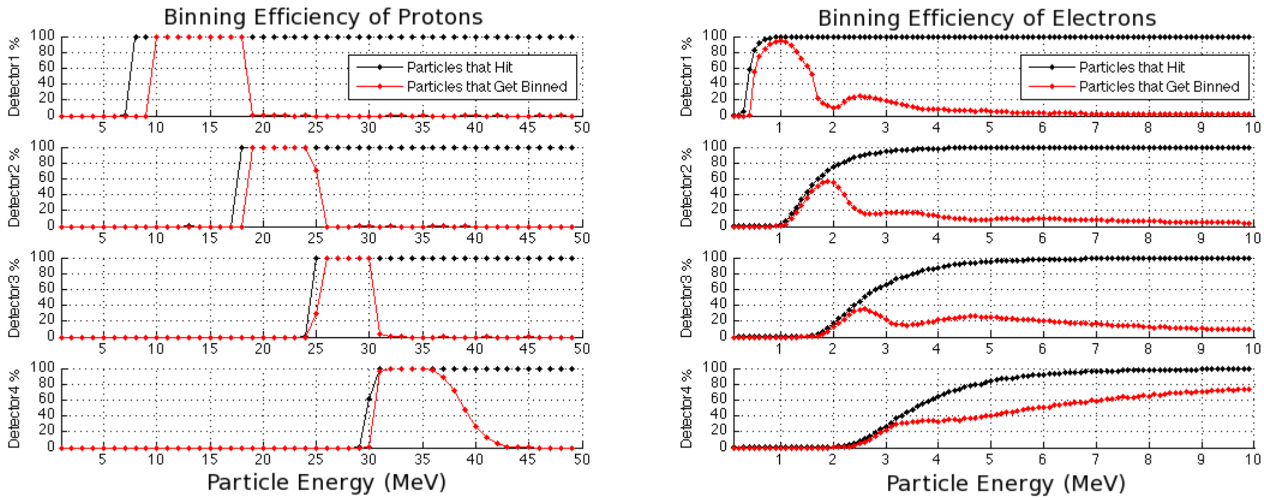

Figure 6. REPTile binning effeciencies for signal particles through the instrument's field of view.

is used for all simulations as it represents higher-than-average fluxes. Similarly, we determine the incident proton spectral flux using GOES-11 storm condition data analyzed in Mewaldt et al.[6] The result is a spectral power law with a knee such that I(E)= $5.2008 \times 10^4 \times \mathrm{E}^{-1.1682}$ for $0.1 \leq \mathrm{E} \leq 26$ MeV and $9.6489 \times 10^8 \times \mathrm{E}^{-4.2261}$ for $26 < \mathrm{E} < 1000$. These power laws can be seen in Figure 5.

The geometric factor γ describes the number of particles incident at one surface that will penetrate a second. Configuration factor algebra is used to find γ through summing infinite nonoverlapping surfaces both completely covering a surface as well as enclosing the surface. The geometric factors for various REPTile surfaces are found in the Howell Catalog (me.utexas.edu/∼howell/index.html), which provides geometric factors for a series of different surface shapes and configurations. For example, the geometric factor for the instrument field of view is

$$\gamma_{FOV} = \frac{1}{2}\left(X - \left[X^2 - 4\left(\frac{R_2}{R_1}\right)^2\right]\right)^{\frac{1}{2}} \tag{2}$$

where a is the distance in cm from the front of the instrument to the first detector, r_1 is the radius of the boresight, r_2 is the radius of the first detector, $R_1 = \frac{r_1}{a}$, $R_2 = \frac{r_2}{a}$, and $X = 1 + \frac{1+R_2^2}{R_1^2}$.

Statistical analyses of Geant4 simulations are done using MATLAB codes created by Quintin Schiller and Jainbao Tao. The result, α, ascertains the binning efficiency for each detector and every energy step for protons ($1 \leq$E≤ 350 MeV) and electrons ($0.1 \leq$E≤ 9.9 MeV). The field of view binning efficiencies are shown in Figure 6, where the panels, from top to bottom, represent detectors 1 through 4 respectively. In each panel, the y-axis represents the percentage of particles and the x-axis represents the specified particle energy. The black line corresponds to particles depositing energy into the detector and the red line signifies particles depositing the required energies to bin the particle as either electrons or protons. These plots aid in determining the energy binning ranges of the detectors as described in Table 1.

In total, ten particle beams are shot from various incidence angles at the instrument in the Geant4 environment. The data from each beam are classified into signal (particles depositing energy after entering from the instruments field of view) and noise (particles depositing energy without entering from the instruments field of view). Particles that entered from the instrument's field of view are classified as signal particles, such as panels a) and c) in Figure 7. Signal particles are represented with a single particle beam through the center of the collimator. All particles that contacted shielding prior to entering the detector stack are classified as noise, such as panel b) in Figure 7.

Figure 7 panel a) provides an example of 40 MeV protons fired down the instrument's field of view. These protons are of high enough energy to pass through all four detectors and embed themselves in the rear of the instrument. Observe how, even after impacting the Be window and all four Si detectors, the protons' deviations from their path are extremely small. Another noteworthy component of Figure 7 can be seen in panel c), where a beam of 9 MeV electrons are fired down the instrument's boresight. Upon impact with the first detector, the electrons immediately begin to diverge into a scatter-cone, where they interact with the remaining detectors and the rear of the shielding, releasing additional particles and electromagnetic radiation. Note the back-scattering which occurs in addition to the scatter-cone. In particular, one particle rebounds off the rear of the chamber, travels backward through the detectors and Be foil, and embeds itself in a collimator baffle. The chaotic nature of relativistic electrons interacting with matter is an excellent example of the importance of performing this type of analysis on high-energy particle detectors.

In addition to the field of view particles, nine particle beams are chosen to represent the most basic noise estimates. Panel b) in Figure 7, an example of simulated noise, displays 250 MeV protons fired through the shielding. These particles pass through the entire instrument and exit the rear shielding with little trajectory deviation, yet they deposit enough energy in all four detectors to be logically binned as bin 4 protons. Analysis of noise particles such as these is critical to understand how the REPTile will interact with the ambient environment in LEO, and how those interactions affect the data.

To determine the geometric factor of this particular shot, or any particle vector, the instrument is broken up into a variety of surfaces. The geometric factor γ is calculated for each surface and a single beam directed toward the detector stack is fired through each surface, similar to the examples seen in Figure 7. The resulting nine beams represent all particles penetrating the instrument classified as noise, and the sum of the nine geometric factors total to the entire surface of the instrument shielding. The geometric factors of all ten beams combined result in the geometric factor of the instrument as a whole.

A large geometric factor indicates that a large number of incident particles may penetrate the surface and impact the detector stack. To reduce noise from surfaces with large geometric factors, such as the rear of the instrument, additional shielding is implemented. In this way, a balance is created between different aspects of Equation 1. That is, if a large geometric factor, γ, indicates a high particle countrate through an aspect of shielding, additional shielding is applied to decrease the binning efficiency, α. This analysis allows shielding to be applied to only necessary areas of the instrument where significant noise originates from. Thus, for small spacecraft under a strict mass budget, superfluous shielding can be avoided.

The resulting signal to noise ratios are outlined in Table 2. As per defined by the mission requirements, the signal to noise ratio for each detector and particle type is confirmed to be > 2.

The modeled signal to noise ratio is lower than expected to observe in orbit due to a variety of factors not included in the Geant4 simulation. For example, in the REPTile flight structure, the collimator baffles are knife-edged to reduce particle reflectance, an aspect not included in the model. Additionally, the incident particle flux used in the simulations is a spectral power law estimated during periods of storm or sub-storm activity. It is likely that the majority of the mission will observe a particle flux at non-storm levels. Finally, in addition to the instrument shielding included in the simulations, there will be supplemental shielding from other components of the spacecraft; such as the spacecraft chassis and batteries. These components are not included in the Geant4 simulations.

Table 2. Simulated Signal to Noise Ratio

Particle	D1	D2	D3	D4
Electrons	87.9	42.2	28.9	23.8
Protons	13.6	8.5	6.4	2.2

Passive Attitude Control Interaction

The attitude control system (ACS) used in this mission is, like many previous small spacecraft missions, passive magnetic. A permanent bar magnet will be used to orient the structure so the instrument's field of view is nearly perpendicular to the local magnetic field lines. A series of hysteresis rods will damp angular oscillations and torques caused by the magnet and Earth's geomagnetic field. The result of the magnetic ACS system is permanent alignment with the local magnetic field to within ±10 degrees. (For further details see presentations by David Gerhardt and Dr. Scott Palo.[7,8])

A permanent magnet aboard the spacecraft can potentially interfere with the science objectives of the mission. Simulations of energetic particle interactions with an appropriate constant magnetic field (from the magnetic ACS) are conducted to determine the effect of the permanent magnet on the instrument's data. Relativistic test-particle simulations are run using a simple force model employing the magnetic component of the relativistic Lorentz force:

$$\vec{F} = \frac{q}{\gamma} \cdot (\vec{v} \times \vec{B}) \qquad (3)$$

where γ is the relativistic Lorentz factor, q is the particle's charge, v is the particle's velocity, and B is the local magnetic field vector. The local magnetic field at each point in the simulation space is calculated using a constant value for Earth's field at LEO and a dipole field using a magnetic moment identical to that which

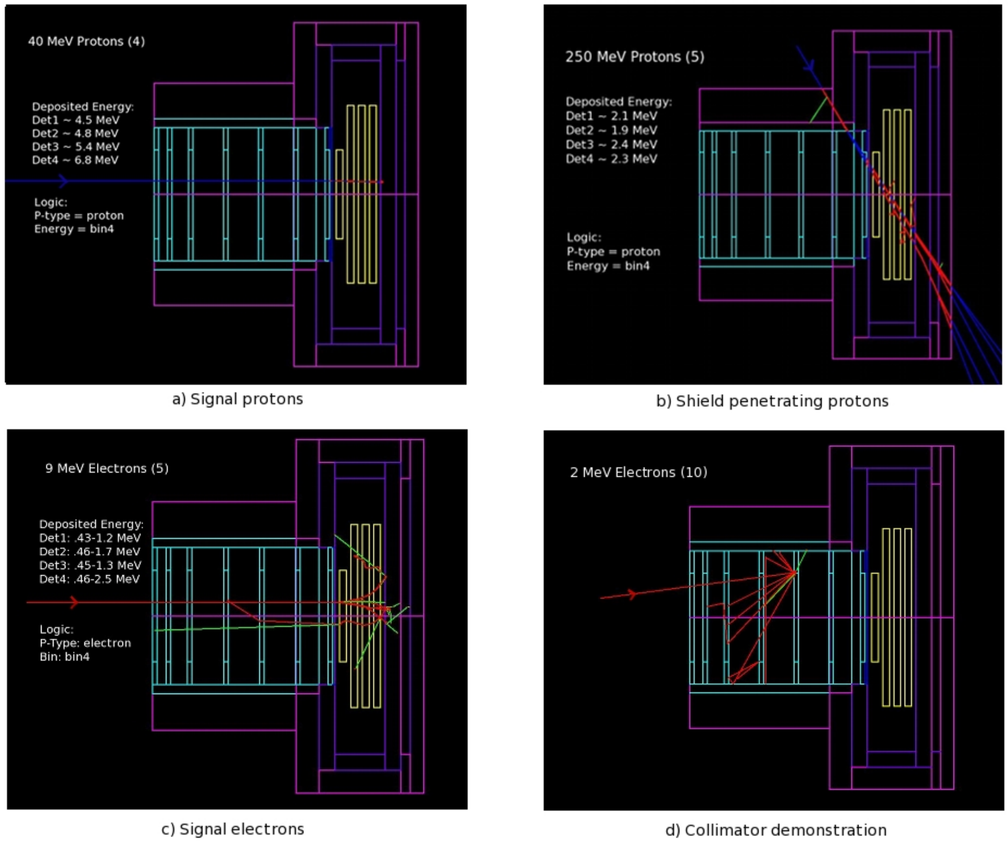

Figure 7. Geant4 simulations of the REPTile instrument. Protons can be seen in blue, electrons in red, and high energy photons in green. Protons inside of a material are hidden due to the cascade of electrons caused by their interaction with the substance, resulting in a red path. The incident energy, type, and number of each particle can be seen in the upper left of each panel. On the left of panels a-c is displayed the average particle energy deposited in each detector, as well as the binning logic for the particles as would be sent to C&DH.

will be used for CSSWE. The initial position of the test-particle beam is one meter away from the magnet, which is small compared to an energetic particle's gyro-radius but large with respect to the strength of the permanent magnet on the spacecraft. The initial velocities are dependent on the incoming test-particle's energy and are directed down the instrument bore-sight. Particle trajectories of various energy and species are integrated to determine the effect of the passive magnetic ACS.

The result of this analysis, as seen in Figure 8, confirm that the use of a small onboard permanent magnet will affect the trajectories of the ambient relativistic particles, but not significantly for the energies REPTile is required to measure. The magnetic field from the onboard permanent magnet for the passive ACS is weak enough that it will not interfere with energetic particles' trajectories until after the particles have passed through the detector stack. Particles of high energy entering the detector chamber from the field of view do not markedly change their trajectory until after they have left the rear of the instrument. Additionally, in the model, the magnetic dipole is placed at the nearest possible location to the instrument. Current design places the magnet further away than shown in this analysis, which results in even less affect on ambient particles. Thus, the passive magnetic ACS will not have a negative effect on CSSWE's science objectives.

Instrument Test Plan

Without access to a particle beam facility, the REPTile team must find alternative methods to test the performance of the detectors. The current test plan for the detectors involves two sources of radiation: atmospheric sources, resulting from galactic cosmic rays, and radioactive materials. Initially, atmospheric source tests will confirm the functionality of the detectors and their ability to respond to energies higher than those available in a laboratory environment. The atmospheric particles occur in a broad spectrum of energies and these tests will validate the detectors response to relativistic particles, though the incident energy values will be unknown.

Unlike cosmic rays, the radioactive sources will emit alpha or beta radiation at known discrete energy values. For example, a trinucleide source of Americium, Polonium, and Curium emit α and β decay at a variety of precise energies between 2 and 6 MeV. By confirming the detector's linear response to known particle energies, these tests will calibrate the detectors response to energetic radiation observed in space. Additionally, both the atmospheric and radioactive tests can be simulated in Geant4 to confirm the behavior of the detectors.

In addition to the detectors, the electronics shall also undergo rigorous testing. Specific voltage pulses shall be injected into each stage of the signal chain to ensure that each component operates as specified, starting with the digital end of the signal chain. The digital inputs to the CPLD will verify the data stream through the CPLD and discriminators. An analog input into the discriminators will test their performance and aid in establishing reference voltages. Digital inputs into the pulse shaper and discriminators will simulate the output of the charge-sensitive amplifier and pulse shaper respectively. Analog inputs to the charge-sensitive amplifier designed to simulate the output from the detectors will be propagated through the circuit to test the signal chain.

Conjunctive Science

Small spacecraft, like CubeSats, have a variety of distinctive benefits; low cost, small mass, and ease of launch, to name a few. In addition to these conveniences, they are capable of magnifying their mission goals through conjunctive science; that is, taking measurements in parallel with instruments aboard other spacecraft. For example, REPTile's data could be enhanced through congruent measurements made by REPT. REPTile, which is on a highly inclined, low altitude orbit, is capable of measuring electrons whose equatorial crossing point is $\sim$5 R_E: the heart of the outer radiation belt. Likewise, the REPT instrument aboard NASA's Radiation Belt Storm Probes (RBSP) mission, a pair of spacecraft on a highly elliptical, low inclination orbit, is also designed to measure outer belt electrons. From that orbit, REPT passes through the outer radiation belt to $R_E \sim 6$ at 10° inclination to measure the same particles available to REPTile, but at lower latitudes and further from Earth.[9] REPTile will measure the outer radiation belt electrons observed by REPT, but close to Earth at high latitudes. Additionally, REPTile measurements will be simultaneous with data from the GOES and SAMPEX spacecraft, potentially amplifying it's scientific significance further.

Conclusions

This paper has introduced the Relativistic Electron and Proton Telescope integrated little experiment, REPTile, which is currently being designed and manufactured by graduate students at the University of Colorado at Boulder. REPTile will serve as the primary instrument aboard the Colorado Student Space Weather Experiment, CSSWE, a CubeSat mission which has been fully funded through the NSF and will be launching late 2011 or early 2012, depending on the availability of a launch vehicle-of-opportunity.

REPTile will be studying Earth's outer radiation belt electrons and solar energetic protons associated with solar flares, both of which have outstanding questions concerning their nature and behavior in near-Earth space, from a platform that cost less than $1M to design and manufacture. By measuring 0.5 to >3 MeV electrons from its low-Earth orbit, REPTile will be able to address relativistic electron precipitation and loss from the outer radiation belt, which is a key part of the delicate balance between source, loss, and transport that governs the extreme variability in outer belt intensities. Also, by measuring protons with $10 \leq E \leq 40$, REPTile measurements during SEP events associated with solar flares will be used to determine properties of the events, measured from Earth, based on the original flare location and magnitude at the Sun.

Analyses presented in this paper represent the vanguard for energetic particle detector designs. The Geant4 simulations are an exceptionally thorough approach to instrument design, and its applications to space radiation are only just beginning to become realized. Using Geant4 to constrain the instrument and electronics design, as well as to address the critical issues normally ingnored or overlooked in energetic particle instrument design (i.e. electron scattering and shield-penetrating particles), further establishes the CSSWE mission as a unique method of undertaking space radiation studies. Additionally, this mission and the REPTile instrument provide an opportunity to represent the massive potential of small spacecraft, like CubeSats, to perform important science for a fraction of the cost of larger missions.

If this mission is successful, it will exemplify how small satellite missions can be used to greatly complement larger, more expensive missions in addressing critical science questions. For example, NASA's Radiation Belt Storm Probes mission, scheduled to launch in 2012, is being developed for the sole purpose of measuring the

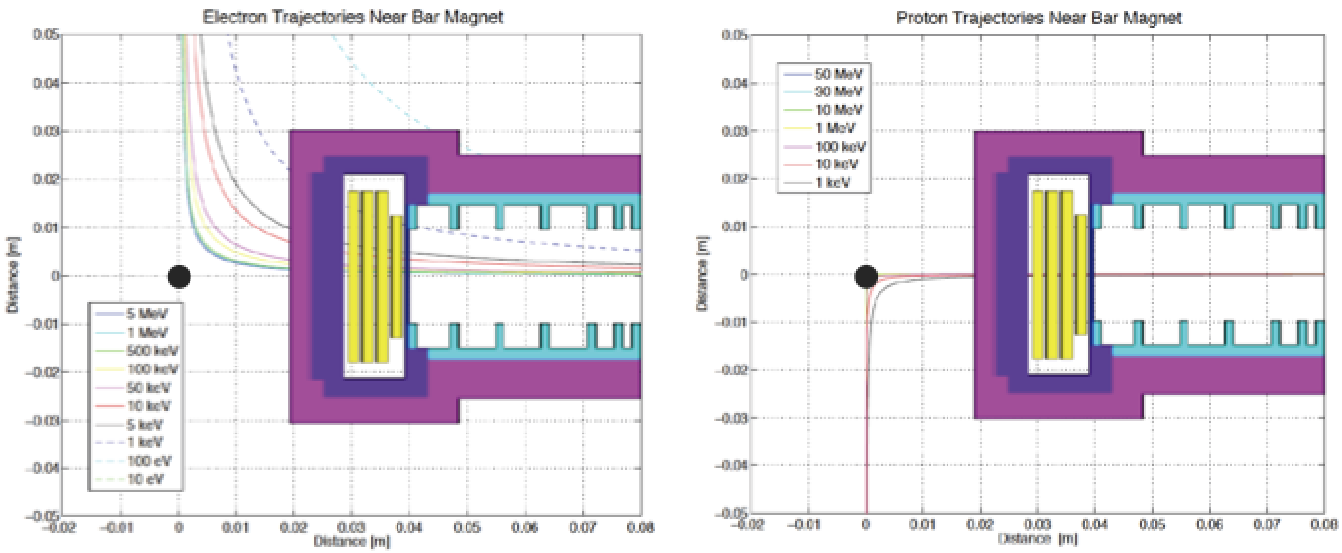

Figure 8. Particle deflection distances due to the instrument proximity to the permanent magnet of ACS.

particles and fields believed to be important to outer radiation belt electron dynamics. RBSP will be in a low-inclination, GEO-transfer orbit, which leaves it unable to measure precipitating electrons at high latitudes very close to Earth. CSSWE with REPTile, however, will have some overlap in mission operations with RBSP, and will be able to measure these electrons. This leads to the possibility of conjunctive science, where RBSP and CSSWE data are used from the same observation times to provide a better understanding of key outer belt loss processes, like enhanced precipitation of electrons to high-latitudes near LEO. In general, CubeSats and small spacecraft missions can complement larger, vastly more expensive missions by providing additional simultaneous measurements at different yet critical locations, which allows for a more comprehensive snapshot of the system being observed.

Acknowledgements

A most gracious acknowledgement to Drew Turner, without whom this paper would not have been written. The authors would also like to thank the CSSWE team, current and past, for their input to REPTile design and testing. Leading the team is Dr. Xinlin Li and Dr. Scott Palo, who also have our thanks. Additionally, engineers at the Laboratory for Atmospheric and Space Physics who have been instrumental in providing insight to the project: Rick Kohnert, Vaughn Hoxie, and Susan Batiste. The authors would also like to recognize the National Science Foundation for funding this, and other, student projects; most notably, the NSF-AGS0940277 grant which provides funding for CSSWE mission.

References

[1]Kappenman, J. G., "An Introduction to Power Grid Impacts and Vulnerabilities from Space Weather," *Space Storms and Space Weather Hazards*, edited by I. A. Daglis, Kluwer Academic, Dordrecht, Netherlands, 2001, pp. 335–361.

[2]Baker, D. N., "How to Cope with Space Weather," *Science*, Vol. 297, 2002, pp. 1486–1487.

[3]Mewaldt, R. A., Cummings, A. C., Cummings, J., Leske, R. A., Selesnick, R. S., Stone, E. C., and von Rosenvinge, T. T., "Anomalous Cosmic Ray Studies Using the Earth's Field as a Magnetic Rigidity Filter," *Bull. Am. Phys. Soc.*, Vol. 39, 1140, 1994.

[4]Vampola, A. L., "Measuring Energetic Electrons," *Measurement Techniques in Space Plasmas: Particles*, edited by R. F. Pfaff, J. E. Borovsky, and D. T. Young, Geophysical Monograph, American Geophysical Union, 1998, p. 102.

[5]Leo, W. R., *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag, New York, 1987.

[6]Mewaldt, R. A., Cohen, C. M. S., Labrador, A. W., Leske, R. A., Mason, G. M., Desai, M. I., Looper, M. D., Mazur, J. E., Selesnick, R. S., and Haggerty, D. K., "Proton, Helium, and Electron Spectra During the Large Solar Particle Events of October-November 2003," *Journal of Geophysical Research*, Vol. 110, 2005.

[7]Gerhardt, D. T., "Passive Magnetic Attitude Control for CubeSat Spacecraft," *SmallSat Conference*, AIAA/USU, 2010.

[8]Palo, S., "Conducting Science with a Cubesat: The

Colorado Student Space Weather Experiment," *Small-Sat Conference*, No. SSC10-XII-8, AIAA/USU, 2010.

[9]Mauk, B. H., Fox, N. J., Sibeck, D. G., and Grebowsky, J. M., "NASA's Radiation Belt Storm Probes (RBSP) Mission," *American Geophysical Union Fall Meeting*, No. SM21B-03, AGU, 2009.