Relationship between solar flares and energetic particles

Satellite studied for this purpose – **CSSWE**

CSSWE was a student satellite of University of Colorado at Boulder(with the help of Laboratory for Atmospheric & Space Physics).

cost	**<1 million**
Type	3U cube satellite
Reference system	Geocentric
Perigee	472 km
Apogee	777 km
Inclination	64.6 deg.
Period	97.19 min.
Size	10 * 10 * 34 cm^3
Mass	4 kg
Launch date	22/12/2014

The science goals of the CSSWE mission are to study

- How flare location, magnitude, and frequency relate to the timing, duration, and energy spectrum of SEPs reaching Earth?
- How the energy spectrum of radiation belt electrons evolve and how this evolution relates to the acceleration mechanism.

Why?

Understanding near-Earth space 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. Electrons can penetrate through spacecraft shielding, causing dielectric breakdown and discharging within sensitive electronics.

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.

To accomplish our goal we need to measure differential fluxes of relativistic electrons in the energy range of 0.58-3.8 MeV and protons in 9-40 MeV. Mission life of atleast 3 months is required.(based on expected flare and geomagnetic storm frequency)

SCIENCE BEHIND SEPs

CMEs (Coronal Mass Ejections) are very large structures (billions of tons of particles) containing plasma and magnetic fields that are occasionally expelled from the sun into the heliosphere. This violent solar activity is the cause of major geomagnetic disturbances, reflected by the space weather, during which the trapped radiation belt electrons have their largest variations. There is a strong correlation between CMEs and solar flares, but the correlation does not appear to be a causal one. Rather, solar flares and CMEs appear to be separate phenomena, both resulting from relatively rapid changes in the magnetic structure of the solar atmosphere.

Solar flares are very violent processes in the solar atmosphere that are associated with large energy releases ranging from 10^{22} J for sub-flares, to more than 10^{32} J for the largest flares. The strongest support for the onset of the impulsive phase is due to magnetic reconnection of existing or recently emerged magnetic flux loops. Reconnection accelerates particles, producing proton and electron beams that travel along flaring coronal loops.

Some of the high-energy solar particles, referred to as SEPs (Solar Energetic Particles), escape from the sun to produce solar energetic particle events. The CCCWE mission will measure these SEPs with the **REPTile** (Relativistic Electron and Proton Telescope integrated little experiment) instrument.

CSSWE is a LEO (Low Earth Orbit) nanosatellite mission to measure outer belt electrons and SEP protons to study outer belt processes, the relationship between events and solar flares, and these particles' effects on the lower thermosphere.

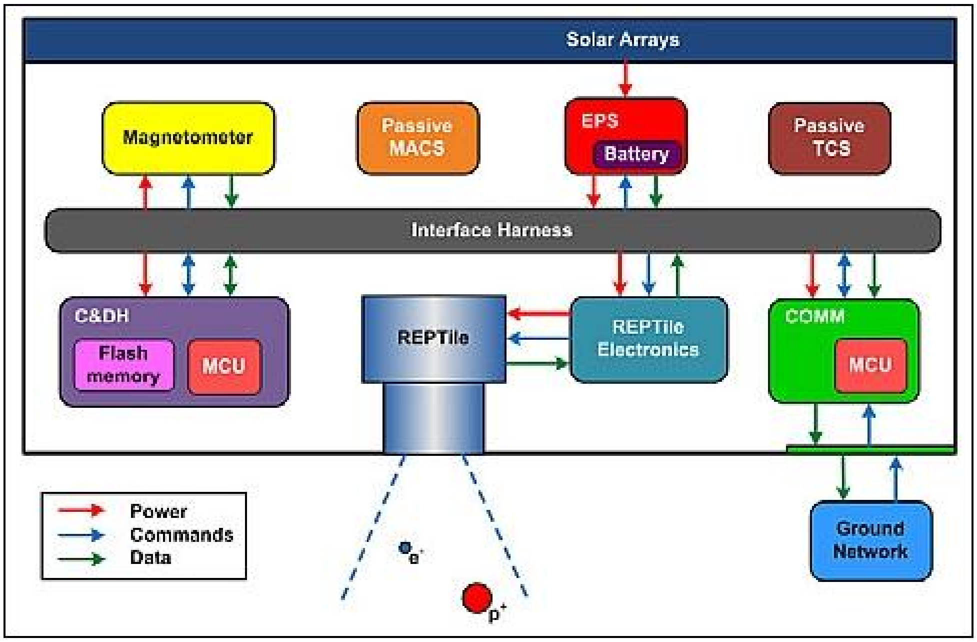
Details about satellite

The design uses surface-mounted triple junction solar cells of Emcore with 28% efficiency. Eight cells are located on two of the 3U sides, and six cells are located on the remaining two 3U sides, with no cells on the two 1U sides on the ends of the CubeSat. effective area of solar panel was 763 cm^2

The CSSWE team opted to use the 3U solid wall structure provided by Pumpkin Inc., San Francisco, CA.

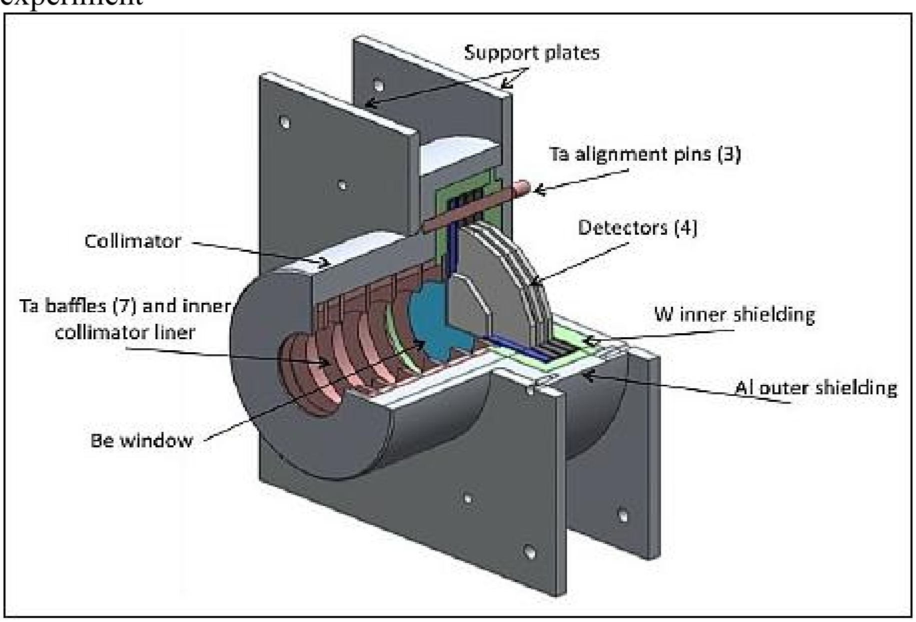
The spacecraft uses a measuring tape as an antenna to communicate with ground stations - two deployable steel-tape monopole antennas.

All the sensors communicate with the master using an I2C bus.



Instrument used

REPTile - Relativistic Electron and Proton Telescope integrated little experiment



The REPTile instrument provides the following functions:

- It measures the outer belt electrons, both trapped and precipitating to study how the low rate and energy spectrum of the Earth's outer radiation belt electrons evolves.

- It monitors the SEP protons associated with solar flares to study how flare location, magnitude, and frequency relate to the timing, duration, and energy spectrum of SEP protons that reach Earth.

- It measures electrons in 3 differential and 1 integral energy channel. Protons are measured in 4 differential channels.

Details about REPtile

Length	6.05 cm
Diameter	6 cm
FOV	52 degree
Temperature range	-4 to 19 deg Celsius
Mass	1.25 kg

Particle detection sequence of the REPTile instrument electronics:

1) Particle produces signal in detector

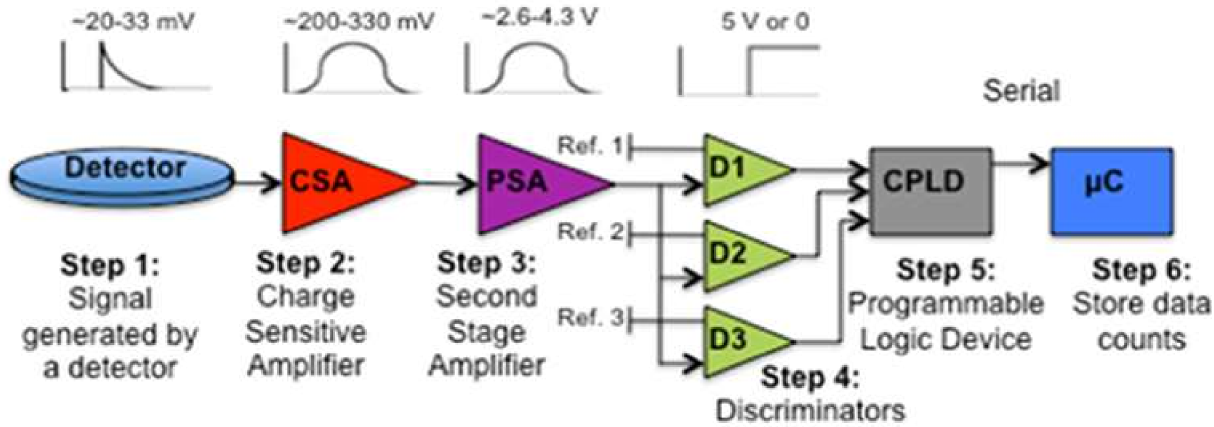
2) Detector signal amplified by CSA (Charge Sensitive Amplifier)

3) Signal further amplified by NIA (Non-Inverting Amplifier)

4) Signal is compared to references to determine if electron or proton

5) CPLD (Complex Programmable Logic Device) determines the energy bin

6) Store bin counts at given temporal resolution in PIC (Peripheral Interface Controller).



Mechanical Aspects

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 in the stack is immediately behind the Be-window. The front detector has a diameter of 20 mm, while the following three are 40 mm across. Higher energy particles penetrate deeper into the detector stack and, as they do, they generate electron-hole pairs in the doped silicon. 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.

The detector stack is housed in a tungsten (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 degree FOV and give the instrument a geometric factor of 0.52 sr cm^2. Tantalum is used because it strikes a balance between stopping power and relatively low secondary particle generation.

The spacing of the baffles is designed to maintain a 50 degree 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 produced by the baffle edge and entering into the detectors. Tantalum is used for the collimator lining and baffle material due to its high density but reasonably low secondary particle generation.

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.

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. 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. 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.

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 pressed 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 pressed between the tungsten shield and the PCB-casing on the _rst (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 ex-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 designed 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.

The current instrument shielding has been shown in GEANT4 to stop all electrons with energies < 10 MeV and protons up to 85 MeV from penetrating through the outer casing and reaching the detectors from directions other than the collimator aperture. The 0.5 mm thick beryllium foil at the front of the detector stack acts as a high-pass filter, stopping all electrons < 400 keV and protons < 8 MeV. 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.

GEANT4 is used to simulate particle behavior in instrument materials:

- Used to obtain a detector efficiency

- Used to determine energy thresholds for particle determination

- When combined with geometric factors and expected particle fluxes (e.g. AE8-max or empirical flux data), efficiencies are used to determine signal and noise count rates.

Electrical Aspects

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 most common types of detectors used to measure energetic particles are made of a semiconducting material, such as doped silicon. 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 passed to a charge sensitive amplifier (CSA), which acts to amplify the signal and convert it to a shaped voltage pulse. 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 CSA selected was the A225 from Amptek Inc., which is a space grade component but very sensitive to noise and other environmental factors.

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. 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. 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, 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 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.

Challenges & Remedial Action taken

On orbit, CSSWE will encounter high signal rates (>400kHz) when passing through the outer radiation Belt, 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.

1) At low count rates (<10kHz), neither the baseline nor the output signal is affected. 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.
2) For the output signal amplitude, there is no variation for count rates less than 80kHz. However, above this value the amplitude begins to drop. 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 required 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.

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.

		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

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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 altered so that variations in noise are removed from the signal in flight.

The baseline output of the A225, that is, the steadystate output with no input signals, is inversely proportional to temperature. 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.

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. After different tests it is found that the A225 pile-up time can be treated as constant for all particle populations.

Tests performed on detectors

1) 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. Leakage current is proportional to the area of the detector, so the 20mm detectors produce 1/4 the current of the 40mms.

2) 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.

Summary

The clean measurements from REPTile reveal the detailed structures and dynamic variations of MeV electrons in both outer ($L = 3$–8) and inner ($L = 1$–2) radiation belts. The measurements show that (1) outer belt electrons are dynamic with continuous pitch angle scattering, (2) inner belt electrons are more stable, mostly confined to the equatorial region, and (3) lower energy electrons (0.5–1.7 MeV) can penetrate deep into the radiation belt slot region ($L = 2$–3) and even the inner belt region during geomagnetically active times (there was a geomagnetic storm during 8–9 October, 2012). REPTile also provides clean measurements of energetic protons.