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A Compact Gamma and X-Ray Detector for Cube Satellites

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ABSTRACT

Cosmic radiation continues to be a constant threat to any prolonged space mission. Harboring biological or non-biological payloads aboard a spacecraft traveling in space, cosmic radiation showers ionizing particles such as gamma and x-ray particles from our neighboring stars in our solar system and galaxy clusters. These ionizing particles create extensive issues for extended space missions such as traveling to Mars due to their degrading radiation effects on the human body and spacecraft electronics. Although precise instruments give more accurate results, they are presented as expensive, bulky, and heavy for space missions.

This paper presents the background, capabilities, and opportunity of a small, low-cost particle detector aimed to (1) measure directional originating sources of the formation of cosmic radiation (2) narrow and establish a gamma and x-ray radiation shielding material used to protect spacecraft electronics, and (3) offer an open-source economical and educational solution used to inform and educate the populace on cosmic radiation activities.

This paper is intended for the use and operation in small cube satellites operating within the PC-104 form factor architecture; but can be rearranged for specific intended use.

INTRODUCTION

As the space industry continues to grow and access to orbital flight expands, the community of academia and student-focused CubeSat programs is likewise rapidly growing. With this development, there comes a perceived need for lower cost and faster turnaround science instruments. These instruments would ideally have dual roles as on-orbit explorers and classroom or hobbyist class laboratory equipment for training the future generation of the space industry. The selection of a cosmic ray detector as the basis for this dual-role science instrument is supported by both the scientific value of expanding observations of cosmic radiation and the relatively simple deployment of such an instrument in a space environment learning ecosystem. Cosmic Rays profuse throughout our universe with no definitive knowledge of their origin despite best estimates ranging from neighboring stars and distant galaxies that travel faster than the speed of light across the universe. Because cosmic rays are composed of ionizing particles ranging across the standard model of elementary particles, they can potentially damage onboard electronics during flight. To mitigate exposure, a particle detector can be used to detect and identify possible sources that produce cosmic rays as well as determine suitable materials used to shield against cosmic radiation.

PHYSICS BACKGROUND

To properly understand the operations of the Cosmic Watch it is important to first have a better understanding of the general physics behind it. The following topics are essential as a background to better understand the Cosmic Watch; what are cosmic rays, gamma rays and the Van Allen Belt? As well as how is it possible to detect these particles and what can occur if particles such as cosmic rays or gamma rays interact with electronics onboard a spacecraft and how might they be shielded.

Cosmic rays are high-energy particles that are constantly hitting the Earth. The mass of this flux of cosmic rays that are constantly hitting the Earth are made up of approximately 74% free protons from ionized hydrogen and 18% from helium nuclei, with the remaining 8% being made up of heavier elements [1].

Gamma rays are also high-energy particles that can be found constantly bombarding the Earth, however unlike cosmic rays they are massless and in Low Earth Orbit (LEO) are not as commonly detected as cosmic rays due to the Earth's atmosphere. While gamma rays can have extremely high energies, most are either absorbed or scattered by the oxygen in the atmosphere as a result of the intrinsic wavelength of gamma rays.

Although it is impossible to know the precise origin of these particles it is known that the majority of cosmic rays originate from the solar winds generated by the Sun and most gamma rays are emitted from sources such as supernovae explosions, pulsars and neutron stars. Once these cosmic rays reach the Earth many of them become trapped in a region of the Earth's magnetosphere known as the Van Allen Belt. These particles become trapped in the Van Allen Belt due to a physical phenomenon known as the Lorentz Force which acts in a direction perpendicular to that of a charged particle's motion and the magnetic field it is in [2]. As a result of cosmic rays being trapped within the Van Allen Belt it is important to then discover how particles can be measured by instruments such as the Cosmic Watch while in LEO.

Regarding gamma and cosmic particles, the mean rate of energy lost via interactions with particles in the medium is given by the Bethe equation [3], where $\beta = v/c$ is the ratio of the velocity of the particle to that of light, Z and A are atomic number and atomic weight of the absorbing medium respectively, $m_0$is the mass of the particle, I is the mean excitation

$$-\frac{dE}{dx} = (\frac{0.307}{\beta^2})(\frac{Z}{A}) \times (ln(\frac{2m_0c^2}{I}) +$$

$$ln(\beta^2) + ln(\gamma^2) - \beta^2) \times MeV g^{-1} cm^2 \quad (1)$$

energy corresponding to the absorbing medium, γ is the Lorentz Factor of the gamma or cosmic particle, and dE/dx is the change in energy of the gamma or cosmic particle per the path length of the medium.

Detected gamma rays may come either directly from a celestial body such as a star or by scattering from a charged particle such as an electron interacting with the detector. The measured energy is deposited into the scintillator and may depend on the type of interaction between each single gamma ray and the scintillator. There are three primary ways that gamma rays interact with matter: photoelectric absorption, Compton scattering, and pair production. Photoelectric absorption dominates the low-energy gamma rays (up to several hundred keV) and pair production dominates the high-energy gamma rays (above 5-10 MeV). Compton scattering dominates in between these two extreme ranges[4]. For the Cosmic Watch, it is more likely that any particles passing through the scintillator will fall in the energy range for Compton scattering. Due to this, Compton scattering is the most probable process over a range of energies. Using the law of conservation of energy and the equation 2,

$$E_0 = m_0c^2 \quad (2)$$

the energy given during Compton scattering can be calculated by

$$E_f = E_0[1 - \frac{1}{1+\frac{E_0}{m_0c^2}(1-cos(\theta))}] \quad (3)$$

where E_f is the energy of the scattered photon.

Since the maximum kinetic energy transferred occurs when the scattering angle is $180°$, the maximum energy transferred is given by

$$E_{f,max} = E_0[1 - \frac{1}{1+2\frac{E_0}{m_0c^2}}] \quad (4)$$

The Cosmic Watch can measure the rate at which particles travel through the scintillator rather than the number of particles inside the scintillator. A key way to study the detected particles is to measure the differential intensities. When measuring, it is standard to not refer to all the particles coming in from different directions, but instead coming from one steradian of the solid angle. This gives the differential intensity of

$$j_T = \frac{vU_T}{8\pi} \quad (5)$$

where U_T is the differential density with respect to kinetic energy per nucleon[5].

Shielding is an important aspect of this mission, as it can improve the longevity of the mission. With any shielding material, it is pertinent to understand the attenuation when the shield is placed between a scintillator and a point source of rays. The attenuation can be calculated by:

$$D = D_0e^{-\mu x} \quad (6)$$

where D is the intensity with shielding, D_0 is the intensity without shielding, x is the thickness of shielding, and μ is the linear attenuation coefficient. The linear attenuation coefficient is strongly contingent on the shield composition. However, particles such as beta particles and free protons are more strongly affected by shielding because they have both charge and mass. The computation is much more complex for these particles and hence will require future experiments to see their effects with a chosen shielding material.

The scintillation detector volume is a luminescent material that can be solid, liquid, or gas. Energies that are deposited into it are viewed by a device, such as a photomultiplier tube (PMT) or Silicon Photomultiplier (SiPM), that transforms detected gamma and cosmic ray emissions into an electrical pulse. A common inorganic scintillation material are cesium iodide (CSI) crystals.

When gamma and cosmic rays interact inside the scintillator material, the excited electrons in the scintillator drop back to the ground state and emit photons. However, in a pure inorganic scintillator crystal, this process is inefficient. The emitted photons will usually have too high of an energy that does not lie in the range of wavelengths for the PMT. To resolve this, small amounts of activators are added to all scintillators to enhance the emission of photons. This activation leads to the photons that can activate the PMT. A common activation example is thallium-doped sodium iodide [NaI(T1)].

However, for the coming PROVES-X CubeSat mission that will be equipped with a Cosmic Watch, an organic unpolished plastic scintillator was chosen primarily due to its ability to withstand an LEO environment as well as its low cost and extensive use in previous missions and experiments. There was concern that changing the exposed surface area of the scintillator may result in inaccurate measurements as the scintillator was required to be smaller than in previous missions and experiments. However, further research concluded that a variation of the scintillator's exposed surface does not drastically change the accuracy of the particles detected using the Cosmic Watch. This is assuming that the attached SiPM can measure significant signals produced by particles across the full surface area of the scintillator. This has been shown by muon detection experiments conducted by Dr. Richard T. Kouzes and his colleagues at PNNL who used multiple SiPMs to detect signals across a significantly larger polymer scintillator [6].

In order to improve the longevity of the Satellite's mission, various materials for shielding the internal electronics against radiation were considered and compared with one another. The criteria under which the various considered materials were compared are the cost of the material, the weight, the installation feasibility, its availability in the required dimensions and lastly the interference it may cause in detecting particles while the Cosmic Watch is in operation.

The possible shielding materials that were considered and compared with one another are Aluminum, Tantalum, Polypropylene (PP), Polyethylene (PE), and Kapton polyimide Tape. While all five materials each had their own strengths and weaknesses in the considered criteria, Kapton was ultimately chosen as the primary contender for use in the SmallSat. Kapton, like PP and PE, is a polymer that is efficient at shielding against the free protons found in LEO. However, as past experiments and studies have shown, such as NASA's MISSE Project, PP and PE do not tolerate the varying temperatures of space effectively without another form of an insulating coating such as aluminum or carbon fiber [7]. This is different from Kapton, which has been shown to withstand a wide range of temperatures without additional protective coating. Another, originally unforeseen factor that was considered in the selection of Kapton was the considerable presence and ill effects of atomic oxygen on electronics in LEO. While polymers are prone to erosion more than metals in LEO [8], Kapton is still a viable choice for shielding important electrical components on the internals of a SmallSat due to its low weight.

Table 1: Potential Shielding Materials Comparison

Criteria	Aluminum	Tantalum	PP	PE	Kapton
	Score	Score	Score	Score	Score
Cost	15	3	15	15	15
Detection Interference	5	15	10	10	15
Installation Feasibility	8	6	10	10	10
Weight	12	8	20	20	20
Dimensions	15	9	12	12	15
Effectiveness	25	25	5	5	15
Total:	80	66	72	72	**90**

Kapton in numerous studies has been shown to shield against free protons, gamma rays, and in some cases neutrons, but future testing will still be required in order to observe how it may or may not interfere in the detection of particles while using the Cosmic Watch. As the Cosmic Watch will be equipped with a BC-412 scintillator, it is crucial to test whether gathered data will be affected by any form of Kapton shielding.

THE COSMIC WATCH

During his dissertation, Dr. Spencer Axani initially developed the design and concept of the Cosmic Watch from MIT, Massachusetts Institute of Technology [9]. The instrument was originally three separate PCBs attached with pin headers and sockets.

On the original Cosmic Watch, Dr. Axani used the Arduino Nano due to its simplicity and familiarity with developers. The primary PCB is called the main PCB, known as the motherboard for the other two PCBs, SiPM PCB and SD Card PCB. Besides housing the Arduino Nano and the other two boards, the main PCB contains the 5V to 16V boost converter and OP amp, with the latter driving the SiPM.

Mounted onto the main board is the SiPM, silicon photomultiplier, PCB. The PCB utilized a scintillator block coupled with a SiPM to detect the cosmic rays and amplify the voltage to be read and recorded, passed a certain threshold by the Arduino Nano.

The third PCB contains the SD card and a buffer to manage the inputs and outputs from the MCU, main controlling unit, and the card, respectively.

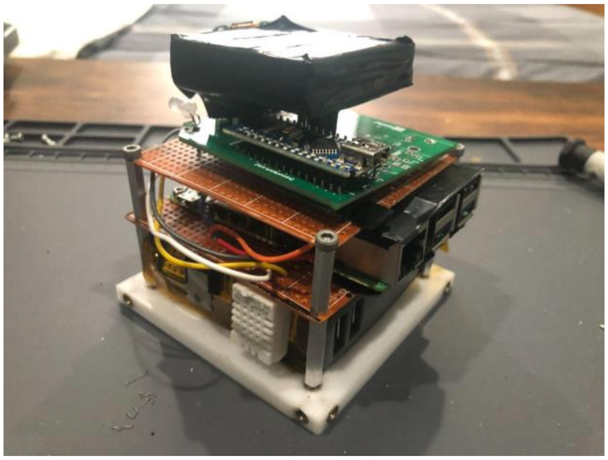

Figure 1: AIRSAT Fully Stacked

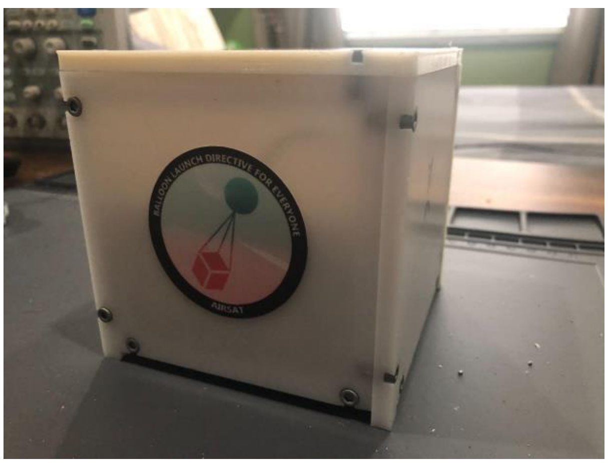

Figure 2: AIRSAT Fully Enclosed

Table 2: Cosmic Watch muon particle data collected

Time since started (ms)	ADC (0-1023)	SiPM (mV)
1545	0	34.76
2127	14	0.27
2346	31	30.24
3066	49	52.8
3101	66	45.07
3198	84	26.05
3466	113	0.69
3586	130	9.62

Before the current group, there was AIRSAT, Atmospheric Infrared Radiation Satellite. This group utilized the original Cosmic Watch design developed by Dr. Axani from open-source information from his website and Github. AIRSAT successfully flew the Cosmic Watch to an altitude of 105,000ft to detect muon particles (see Figure 3 and Figure 4).

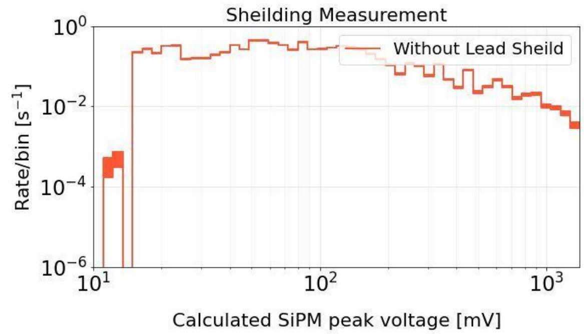

Figure 3: Calculated SiPM Peak Voltage

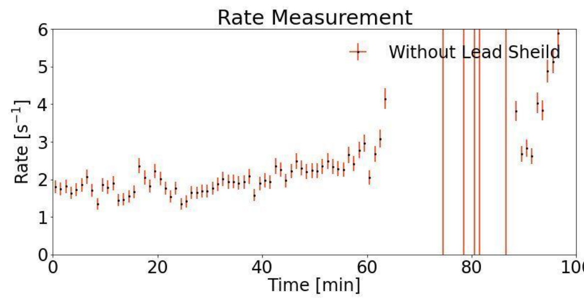

Figure 4: Measured Count Rate

WITHIN THE CUBESAT FORM FACTOR: PC-104

For further ease of use for future and current missions for the Cosmic Watch, its form factor was redesigned to fit within the PC-104 standard set out by the PC-104 Consortium. This standard is defined as 3.550x3.775 inches or 90x96mm with mounting holes offset from each other (See Figure 6).

All the components of the Cosmic Watch were laid out to one side of the PCB as several manufacturers offer SMT, surface mount technology, and assembly. The Arduino Nano served as a great starter to ensure the team understood the methodology behind the Cosmic Watch; however, to further streamline the process for future teams, a Raspberry Pi Pico was substituted in its place. The switch to all surface mount components besides the testing components for troubleshooting during integration (see Figure 6).

The first adjustment to the Cosmic Watch along with the initial form factor change was integrating the SD card PCB within the main PCB (see Figure 5). Along with this, the Arduino Nano was swapped out for the Arduino Nano Every due to its ATMega4809 capabilities compared to the ATMega328 on the original Arduino Nano. Initially, this configuration was the final iteration of the Cosmic Watch Rev 5, however, the Raspberry Pi Pico shortly replaced the Nano Every. (see Figure 6).

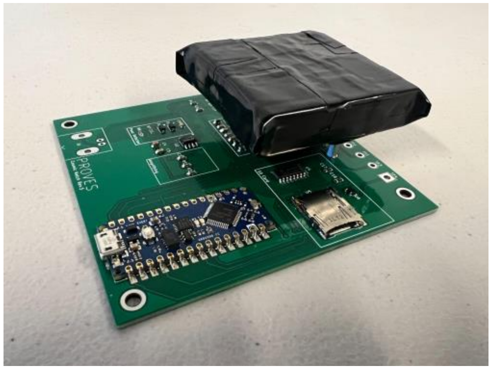

Figure 5: Cosmic Watch with Arduino Nano Every

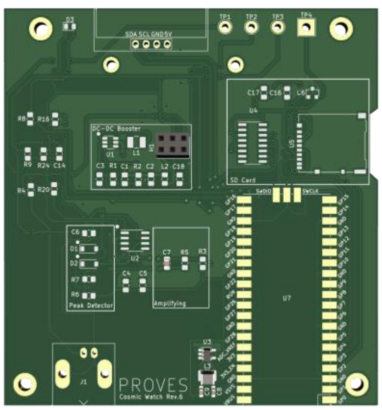

Figure 6: Cosmic Watch 2D View

The THT, through-hole technology, components were swapped out with the Arduino Nano and replaced by the Raspberry Pi Pico (see Figure 7). With this switch, a 5V boost converter, RP402N501F, was incorporated into the design to boost the Pico's 3.3V pin into the power plane. The Pico utilizes the RP2040, a dual ARM Cortex-M0+ processor, allowing faster process time and better integration to the PROVES architecture.

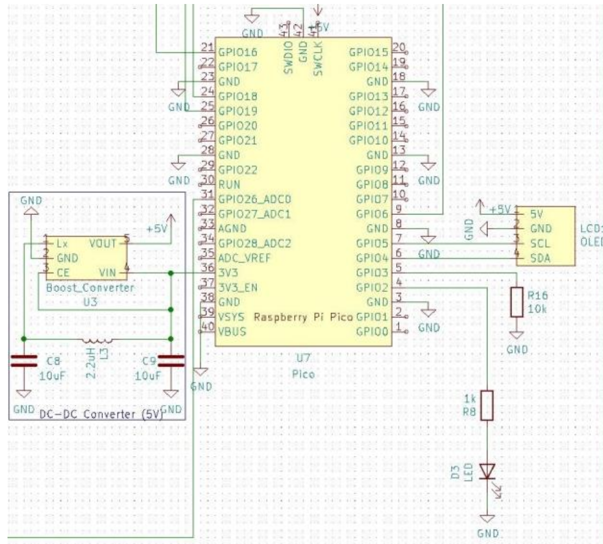

Figure 7: Cosmic Watch Schematic

FUTURE DEPLOYMENTS AND FINAL WORDS

The PROVE's, Pleiades Rapid Orbital Verification Experiment, architecture is currently in development by the Bronco Space CubeSat Laboratory located in California Polytechnic State University, Pomona. The architecture shall be a low-cost kit for educators and university CubeSat programs to give them a head start in developing their mission using a modular and open-source flight-proven platform.

The switch to the Raspberry Pi Pico allowed the Cosmic Watch to be based in Python over C++ utilizing the MicroPython libraries. Mainly this shall allow for the software to be simplified, and ease of additional complexity in future missions as Python is the most commonly known computer programming language.

Although the PC-104 Cosmic Watch is still in current development, it shall be the primary payload utilizing the PROVES architecture slated to launch in January 2023 into LEO, low earth orbit. For this mission, the Cosmic Watch shall be detecting gamma rays throughout the satellite's life span and downlinking collected data to the ground station.

Acknowledgments

The Cosmic Watch group works within an organization called Bronco Space CubeSat Laboratory, which provided an atmosphere and location to develop and refine the instrument and give the launch vehicle for this instrument's first flight. The Cosmic Watch group developed the concept upon Dr. Axani's initial design from MIT, and Dr. Axani gave initial guidance on the first assembly of the Cosmic Watch. Further advice and assistance were provided by the Bronco Space CubeSat Laboratory members and references from Adafruit.

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