Development of a Universal Small-Satellite Payload for On-Orbit Characterization and Evaluation of Novel Radiation-Shielding Materials

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ABSTRACT

There is a need for novel lightweight radiation shielding materials for small satellites operating in LEO and beyond. Current commonly used shielding materials include aluminum and polyethylene, though often no additional shielding than that provided by structure is used due to mass and dimensional constraints. New materials are being developed which may offer advantages over these current solutions. These materials include novel lightweight composites impregnated with metallic nanoparticles, chitin-derived bioplastics, and aerogel-family materials. A compact CubeSat experiment payload that allows the simultaneous testing of numerus potential shielding materials would be useful to enable material comparison and efficacy validation. An effort currently underway seeks to develop such a miniaturized modularized payload, which will enable the testing of materials in 1U CubeSat form factor modules, with each module hosting four scintillator radiation detectors arrayed behind four sample material windows exposed to space. The first proposed mission will utilize a 2U payload volume to host two test quartets enabling eight materials to be tested. Such a test platform can potentially be used as a hosted payload on a variety of spacecraft to test additional materials in the future.

I. INTRODUCTION

As NASA expands space exploration with new missions requiring a larger variety of assets, small platforms promise to enable data collection in ways inaccessible to larger platforms. As the dimensions of space-faring assets and the equipment they carry shrink, and exploration locations increase in number and become more distant, the high radiation environment of space increasingly puts the long-term operation of missions at risk due to radiation damage to sensor, communication, data processing, and general electronic systems infrastructure.

Traditional monolithic shielding materials for space applications, such as aluminum and polyethylene, tend to require layer thickness and overall mass budgets infeasible or not worthwhile for use on small satellites such as CubeSats. Therefore, CubeSats frequently fly with little shielding aside from their structure, particularly in short duration low-Earth orbit (LEO) missions. If the lifetime of small satellites can be increased by providing mass-effective radiation shielding for components, it will become possible to expand the duration and impact of CubeSat missions, reducing the cost and schedule of exploration. Additionally, as propulsion systems for small satellites continue to be developed, mission ranges will expand to new locations further from Earth, increasing the importance of radiation shielding for instrumentation and control systems on small satellites. The increased complexity of new planned space missions would be well-served by having increased variety and choices in radiation shielding material so that the longest possible mission that serves the greatest science needs can be planned, built, and flown at the lowest cost and mass.

Still other uses for novel composite shielding material are in the studies of high-energy ions that comprise part of the radiation environment of space. Different layers of different types of shielding can be used to preferentially shield against the large number of low mass, low energy particles in space such as protons, helium ions, and electrons, or to moderate the energies of high-energy ions in space so that their presence can be detected more readily. Also, currently available software for modeling the reactions of energetic ions with matter are best suited to reactions with single materials, or thick layers of uniform materials. Composite materials that contain a mixture of substances in a complex structure are difficult to model. Data from exposure to actual radiation environments is essential to create models that accommodate composite materials.

NASA's Small Spacecraft Technology program, and the Small Business Innovation Research (SBIR) programs it hosts, develop novel technologies at a low technology readiness level (TRL) that hold great promise for advancing the capabilities of small spacecraft. A critical hurdle for these technologies is raising their TRL via an initial flight demonstration or environmental test, which can oftentimes be done concurrently if acceptable to a mission's risk posture. Recent efforts have developed a suite of composite and non-traditional radiation shielding materials suitable for small spacecraft use, for which a payload is being developed to gather in-situ performance metrics as to the shielding performance of candidate materials. This payload is being developed in a manner enabling the easy integration and testing of a wide variety of materials on a wide variety of spacecraft to promote repeated material testing missions.

II. NEAR EARTH RADIATION AND SMALLSATS: THE SPACE WEATHER ENVIRONMENT

There are a variety of radiation sources in space which can produce a greater range of radiation than is found or feasibly produced on Earth, both in energy and type. Ionizing radiation is comprised of a variety of energetic particles and electromagnetic waves of various energies. For example, the sun produces particulate radiation in the form of high energy electrons, protons, and heavy ions cast off by stellar processes including the solar wind, solar flares, and coronal mass ejections. Cosmic rays or galactic cosmic rays (GCRs) are radiation from deep space sources outside the solar system and are comprised mainly of protons, heavy ions, electrons, x-rays, and gamma rays, and are generally understood to be produced by deep space stellar processes such as supernovae. The radiation that comprises GCRs is generally thought to be mostly protons (83%), followed by alpha particles (13%) and electrons (3% abundance), with about 1% of GCR makeup thought to be elements heavier than helium [Barth, Dever, Howell, Leske, Mewaldt, Reames (2022), Reames (2019), Schmelz, Wiedenbeck, Wrbanek]. High energy neutrons can also be a component of radiation in space if they are generated from the interaction of space radiation with random atoms in space. Ionizing radiation also comes in the form of electromagnetic waves such as high energy x-rays and gamma rays released by stellar processes [Barth, Nwankwo].

Within the solar system, the sun is a major contributor to ionizing radiation. The changing activity level of the sun, known as the solar cycle, generally increases and decreases over a roughly 11-year cycle. This cycle correlates with the number of sunspots on the surface of the sun. During periods of increased solar activity there is an increased number of solar flares, high-speed solar wind streams, and coronal mass ejections (CME) [Nwankwo]. Solar flares can erupt, generating coronal mass ejections that hurl charged particles and accompanying x-rays into space. The coronal mass ejections contain solar energetic particles (SEP), charged particles consisting of mostly energetic protons. The increased solar output can contribute to increases in the amount of trapped radiation near the earth and other planets with magnetic fields. Even during times when the sun is in its quiet phase there are streams of charged particles sent into space with the solar wind.

Radiation in space in the vicinity of planets is present in multiple forms. Transient radiation is radiation that travels through space after escaping the source that generated the radiation, such as supernovae, high energy jets, exchange of mass between massive objects such as stars, etcetera. Both particle and electromagnetic wave radiation can be part of the transient radiation which interacts with and modifies planetary atmospheres, surfaces, satellites, and spacecraft.

Charged particles, both electrons and positive ions, can become part of trapped radiation belts contained by the magnetic fields of planets that produce such a field [Nwanko, Wrbanek]. The trapped charged particles follow planetary magnetic field lines from one pole to another, spiraling around the field lines as they travel. These trapped particles form their own radiation belts around planets with a magnetic field. The Earth is known to have trapped radiation belts, comprised mainly of electrons and protons, known as the Van Allen Belts. The Van Allen Belts are generally present in two regions of trapped particles. The inner Van Allen belt, located in a region above the earth's atmosphere to approximately 2.5 Earth radii, holds mostly protons with energies beginning in the tens of MeV range and higher [Baker]. The outer belt, located between 3 and 10 Earth radii, is generally made up of trapped electrons with lower energies from 1 to 10 MeV [Phys. Today]. Sources of trapped radiation in the Earth's Van Allen belts include particles generated by solar plasma captured during geomagnetic storms, charged particles that escape Jupiter's magnetosphere and are captured from interplanetary magnetic field lines, and so-called anomalous cosmic rays [Baker]. Sources of particles for both trapped and transient radiation comes from coronal mass ejections and deep space stellar processes that can send energetic particles at high energies through space. Additionally, x-rays and gamma rays produced by solar and stellar processes add to the transient ionizing radiation found in space. The energies of charged particles in solar storms can easily reach the MeV and GeV range, which can be hazardous to satellite electronics [Lloyd's]. Additionally, in the vicinity of planets with atmospheres, such as the earth, the upper atmosphere expands when the ionization rate of the upper atmosphere increases due to increased radiation received from space. This expanded and increasingly charged upper atmosphere contributes to satellite drag and creates position uncertainty. As a result, more fuel is needed to keep satellites in orbit and the added position uncertainty can force satellite operators to use precious fuel resources to prevent collisions amongst satellites as they experience unpredictable drag from the expanded atmosphere [Berger].

In recent years there has been an increased demand to use small satellites for a variety of applications [Caspi, Helvijian, Lanzerotti, Wrbanek]. Though small satellites began as temporary short-lived assets generally used for educational purposes, small satellites have increasingly taken on new roles in science, communications, and observing operations, and have been proposed for significant research and exploration roles. Small satellites take advantage of the shrinking dimensions of complex electronics. This makes it possible to put meaningful scientific, communications, and monitoring equipment on a small satellite. However, as the feature size of the active electronic components become smaller, they become increasingly vulnerable to damage from space radiation as smaller silicon features are more easily subject to damage. These new increased roles for small satellites will put the electronics at greater risk for damage from radiation in space, possibly risking loss of the small satellite's mission.

Much of space radiation has sufficient energy to penetrate electronic components on satellites and is capable of causing physical damage. Single Event Upsets (SEUs) such as gate latch-up and bit flips can be caused by penetrating particles adding charge where it is not wanted within silicon structures, or even causing material transmutation and sputtering of semiconductor materials when incident energy levels are sufficient to damage the atomic bonds within the material. This damage can accumulate over time and lead to missing or incorrect data from spacecraft instruments and electronics or even render the device inoperable. Catastrophic damage from sufficiently high-energy particles can induce events such as single event gate rupture and single event burnout, rendering electrical components useless long before the planned end-of-mission for a spacecraft [Bedingfield, Rax, Lee, Shea, Summers, Wrbanek].

Because of their small size, it is difficult to shield electronics on small satellites. Adding shielding to a small satellite to reduce the energy of incoming radiation takes up valuable space and mass, often leaving insufficient space for the necessary equipment to accomplish the mission. Therefore, small satellites often fly with insufficient shielding or no shielding whatsoever, accepting the risk of loss due to radiation damage for reduced cost and schedule. As the variety of applications for which small space-faring assets are used increases, more choices in passive radiation shielding become necessary.

A. CURRENT SHIELDING TECHNIQUES

Aluminum has generally been the material of choice for radiation shielding in space as it is a cheap light-weight metal that can be formed into rigid structures. However, aluminum and other metals are known to produce secondary radiation that includes both positively charged ions and neutrons when exposed to galactic cosmic radiation [Gohel]. Generally, dense materials with high atomic numbers such as lead, steel, tungsten, iron, or concrete have been used for shielding in terrestrial applications against energetic protons, ions, x-rays, and gamma rays, but such dense materials add significant mass to a small spacecraft and may also be a source of secondary radiation or contain some activated impurities [Knoll, Lee]. However, materials of low atomic number (Z) are generally better at shielding against inelastic scattering of electrons, while materials with high Z are known to be better at shielding against elastically scattered electrons [Fan]. Thermal neutrons generated as secondary radiation from shielding and active satellite components are typically best shielded by low Z materials. Because of the wide variety of radiation in both particle and photon form, no single material can provide completely adequate radiation shielding for electronics in space.

Historically, a 100 mil (0.10 inch or 2.54 mm) thick layer of aluminum has been used as a standard shielding material with risk acceptance of secondary emission effects so long as charging effects remained less than 100 fA/cm^2 [Zheng]. In addition to aluminum, polyethylene has also become a standard radiation shielding material for use in space. It's protective characteristics, second only to liquid hydrogen, make it a very effective option in shielding both satellites and human missions.

In order to produce lightweight shielding suitable for flight that maximizes shielding against primary radiation and minimizes secondary radiation effects, investigations into layered and composite materials comprised of carefully chosen materials of different atomic numbers are under investigation to maximize protection for electronic components while minimizing the mass and space required for shielding of satellites [Atwell, Baumann, Daneshvar, Fan, Gohel, Packer, Telegin]. Composite materials are thought to be a superior form of radiation shielding as the layers of a composite material can be chosen to stop multiple forms of radiation. Recent ISS experiments on the use of woven Kevlar as a radiation shielding material show its efficacy to be similar to that of polyethylene [Narici]. The variety of layers in a composite shielding material decrease the likelihood of secondary radiation penetrating through to valuable equipment below. If composite radiation shielding can be developed that is lightweight enough to be used with small satellites, it will increase their useful lifetimes and enable small satellites to be used in more ways in more locations.

Further investigation into improved shielding methods is essential to ensure successful missions on small satellites and to improve the useful lifetimes of all electronic systems used in space. Space experiments performed in LEO with sample shielding materials exposed to the space weather environment would advance the state of the art in understanding the shielding potential of such materials, especially when done with a multi material testing system for direct comparison.

B. NOVEL RADIATION SHIELDING: NANOSONIC COMPOSITES

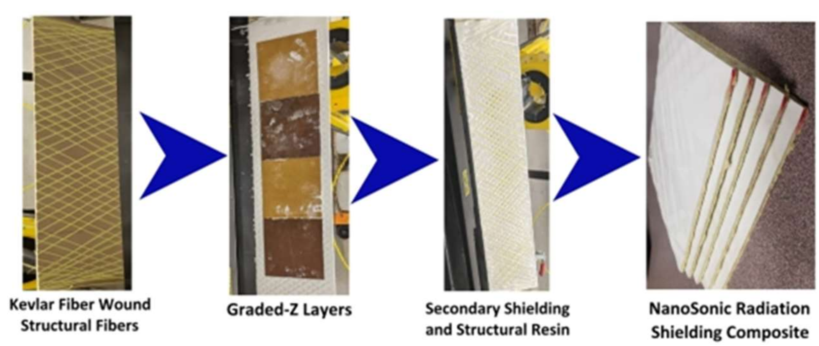

Figure 1: NanoSonic radiation shielding composite fabrication overview.

NanoSonic has successfully demonstrated a production method that is reliable and scalable for producing 'graded-Z shielding' using their experience designing, developing, and manufacturing innovative materials with engineered properties. Testing during their participation in the NASA SBIR program demonstrated a composite material that offered significant dose reduction at less shielding mass compared to more traditional shielding materials such as tungsten, aluminum, and polyethylene. The shielding is comprised of a wound Kevlar and Boron Nitride composite which provides not just radiation shielding, but also impact protection and structural support. An overview of the composite material construction is shown in figure 1 above. NanoSonic's materials have demonstrated shielding of electrons, protons, and iron ions during ground testing. Exposure tests were conducted at the Department of Environmental and Radiological Health Sciences at Colorado State University (CSU), and at the NASA Space Radiation Laboratory at Brookhaven National Laboratory (NSRL/BNL), shown in Figure 2,

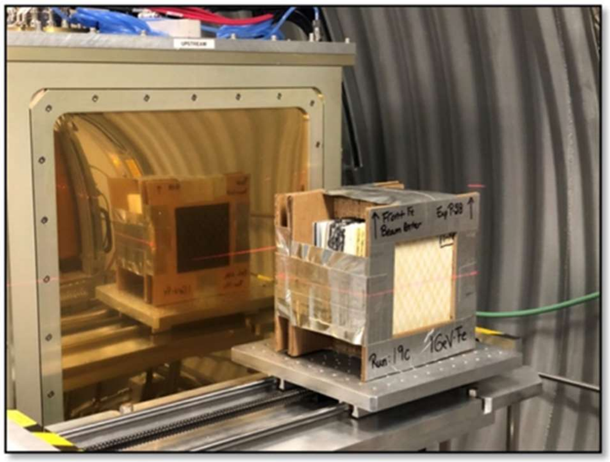

Figure 2: NanoSonic radiation shielding composite under test at NSRL/BNL.

as part of the SBIR effort. These tests have demonstrated the composite shielding material significantly attenuates X-rays and gamma rays with a radiation attenuation 71% higher than polyethylene as a function of areal density without secondary radiation, and structurally survives simulated 50-year exposure to solar energetic particles (SEP) and galactic cosmic rays (GCR) [https://techport.nasa.gov/projects/102828].

C. NOVEL RADIATION SHIELDING: AEROGELS

Newly developed specialized polymer aerogels from NASA show promise for potential radiation shielding that is customizable and conformable with a potential for material inclusion during the curing process. A sample of novel polymer aerogel material will be included as one of the shielding coupons in the proposed payload, with proprietary material details to be released at a later date.

D. NOVEL RADIATION SHIELDING: CHITIN

Chitin is a useful and versatile biopolymer very similar in chemical composition to polyethylene. Long duration space missions and habitats that utilize insect and crustacean farms for efficient and compact protein generation will produce excess exoskeleton waste material, primarily composed of chitin, via molting and harvesting processes. Chitin products are currently used in pharmaceuticals, nanomaterial creation, food preservation, biomaterials, plastics, and for radiation protection and mitigation. In closed loop or limited-input life support systems, chitin that would otherwise be a waste product or fed back into the system could be instead compressed into high density bricks able to be efficiently stored as a raw material stock for later use.

The payload development described in this effort will provide a direct comparison between current state of the art radiation shielding materials such as aluminum and polyethylene with novel materials like the NanoSonic composite and compressed chitin material. Compressed chitin material will be cut into shape corresponding to the sample windows on the payload and will be compared at the same surface area and thickness to the other candidate shielding materials. Results of this testing will determine if a chitin based shielding material can play a role in space missions of the future and provide a renewable ISRU based option for LEO and, potentially, for deep space missions as well.

III. PAYLOAD DEVELOPMENT

To maximize the usefulness of the developed payload, the overall design approach is focused on making a material sample testbed able to host the widest variety of materials possible on the widest variety of spacecraft possible. Given the nature of the NASA SST program, building a payload conforming to a 1U CubeSat standard that can be hosted in a generic 1U volume or in a traditional CubeSat PC/104 stack was made a physical requirement. From this decision, several radiation measurement options and sensors were considered and downselected to produce the most beneficial science payload.

A. INITIAL RADIATION SHIELDING MATERIAL SELECTION

The materials selected for the first flight of this payload center around NASA and NASA SBIR developed technologies with conventional shielding materials as a test reference and control. The test materials for this first demonstration will consist of:

- NanoSonic 'graded-Z' lightweight woven composite structural materials developed under a NASA SBIR. Three variants of this composite material will be tested. The material is designed to greatly attenuate ionizing radiation as well as offering structural capability and impact protection without secondary emissions. Current material is assessed at TRL 5-6.
- A bio-plastic composite material derived from heat melt compacted exoskeleton chitin developed at NASA Ames.
- An aerogel-composite material developed by NASA.
- One sample each of polyethylene and aluminum alongside a sample-less control, with all three used as a performance and model references.

As each material presents different manufacturing and structural limitations, the test system must be able to accommodate materials of various thickness and physical properties in a simple manner to ease integration.

B. RADIATION DETECTOR SELECTION

The radiation environment for the first LEO-based test mission targeting launch in 2026 is expected to consist mostly of solar energetic particles (SEPs) such as protons, helium ions (alpha particles), and electrons, ranging in energy from keV to GeV. Galactic Cosmic Radiation (GCR) is expected to also be a component of the radiation encountered, which consists primarily of protons (~85%), helium ions (~14%), and heavier ions (~1%). GRCs are less prevalent during periods of high solar activity but may still be a component of the radiation that will be encountered by this CubeSat payload. GCRs peak in energy between 10 MeV/u and 10 GeV/u. Both SEPs and GRCs may be present in the environment, however the ratio of SEPs to GRCs cannot be predicted in advance. This payload is expected to be in orbit during a timeframe that may be the most active portion of Solar Cycle 25. Currently, Solar Cycle 25 has been more active than previous predictions.

Initial payload designs contemplated several standard radiation detection methods, with the original design utilizing a PIN-diode Geiger counter and a silicon-sample dosimeter placed in each sample chamber. Realizing that such sensors would not provide the energy spectrum needed to truly evaluate each material and possible secondary emissions, a low-cost custom scintillation detector was identified and manufactured for this payload by CapeScint of Natick, Massachusetts. Each scintillator module is fully integrated with a multichannel analyzer (MCA) unit that is radiation-tolerant and spaceflight-proven. For this payload, Cesium-Iodide crystals of a 20mm cubic geometry were selected, with the chemistry selected to maximize radiation response, and the geometry selected to provide a symmetric probability of incident particle direction. To enhance the low-energy readout capability of each scintillator detector, each detector's sample-facing aperture is constructed of a metalized mylar film, providing the necessary optical shielding the detector requires but offering better low-energy particle transmission than a traditional purely aluminum enclosure. To better understand the test environment, additional sensors will be present to characterize the solar environment. These will include temperature sensors located in each detector quadrant to track sample temperature, a sun-angle sensor based on a duo-lateral position sensing optical detector located in a separate payload control module, and a silicon PIN photodiode in the same housing to measure incident energetic particles. This information is expected to lead to better understanding of how new composite shielding material may be used in future missions. Additionally, this will be the first exposure of the shielding materials under test on this CubeSat to x-rays and gamma rays in space. The results of this test are also expected to inform on the feasibility of using lightweight shielding to better distinguish between lower energy ions and electrons and higher energy particles even during times of increased solar activity. This should provide new tools that may inform predictions of future solar activity.

C. SELECTED RADIATION SENSOR BACKGROUND

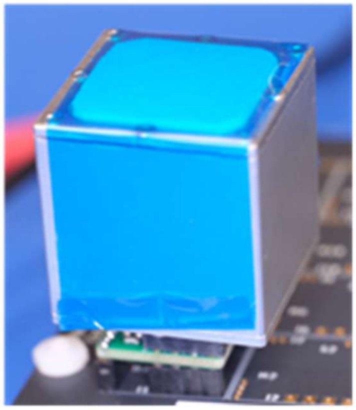

Figure 3. CapeScint CsI-20c-SiPM Custom Scintillation Detector with CapeMCA 1.5.7

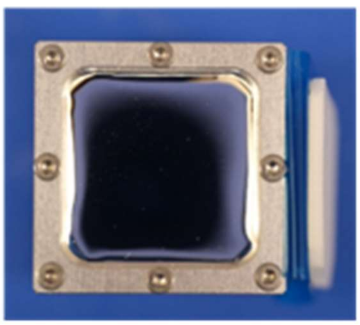

Figure 4. Metalized Mylar Film Window on Custom Scintillation Detector Sample Face.

For this payload, CapeSym, conducting scintillation crystal related business as CapeScint, has delivered high-performance, space environment worthy spectroscopic detector modules with miniaturized multichannel analyzer (CapeMCA) electronics to be used as building blocks for the next-generation radiation shielding evaluation instrument developed by NASA Ames. All the electronics for light collection, digitization and accumulation of energy spectra are contained within each small sensor module. The modules are easily configurable into large arrays with high detection sensitivity, capable of identifying, locating, and tracking sources of gamma radiation.

Each module (Fig. 3) consists of a scintillation detector containing a 20mm cube single crystal of CsI:Tl attached to a 3x3 array of 6mm^2 silicon photomultipliers (SiPM) produced by ON Semiconductor. This assembly is hermetically packaged inside an aluminum housing with Mylar window (Fig. 4), and a single-board CapeMCA v1.5.7 (17x17x10mm) developed by CapeSym under an SBIR program supported by DoE NNSA for radiation environment monitoring in space. Each assembled module is only 28x28x40mm and 75g. The module draws 30 mA of current from a USB 5V supply, for 150 mW power consumption. High-resolution gamma energy spectra over a configurable 5 keV to 12 MeV range are transmitted by USB to a host processor at a rate of 0.1 to 10 Hz. The module was verified to operate over -50ºC to 50ºC and proven resilient to high-intensity gamma and neutron radiation.

The CapeMCA v1.5.7 design itself (Fig. 5) is a paragon of simplicity. A single chip microcontroller performs digitization, real-time pulse processing, temperature-stabilized energy correction, pulse pileup rejection, gamma spectral analysis, directional computations, and communication with both host and neighboring MCAs. A small amount of additional circuitry is required for the 30V SiPM bias supply, pulse over-voltage and electrostatic discharge protection, temperature feedback, and parameter storage. Only three integrated circuit chips are used per MCA: the microcontroller, a DC-DC converter chip, and a ferro-electric random-access memory (FRAM) used for radiation-hard parameter storage.

The detector module can operate as a standalone instrument, sending its gamma energy spectrum to a host computer up to 10 times a second via the microcontroller's USB data lines. When multiple MCAs are plugged into one backplane, the array mode of operation is automatically enabled through the SPI communication fabric. The SPI fabric allows the MCAs to synchronize and share their gamma energy information, while one MCA configures itself to communicate this information to the host computer.

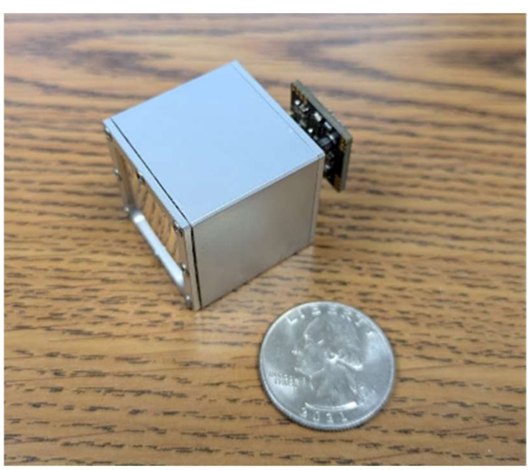

Figure 5. CsI-20x-SiPM-T scintillation detector coupled with CapeMCA v1.5.7 digital readout.

IV. PAYLOAD DESIGN

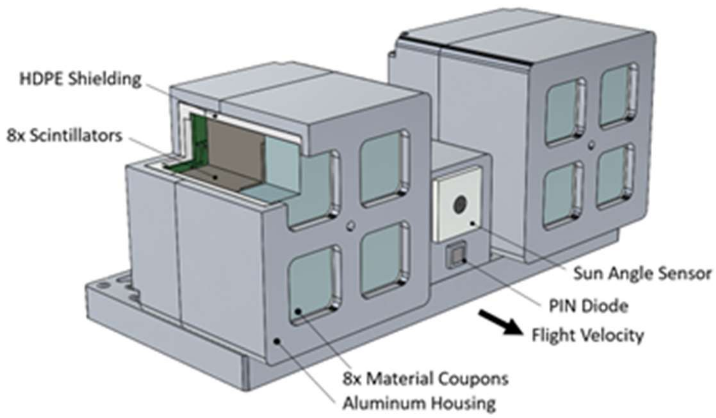

Figure 6. Payload CAD model showing internal shielding and external shell construction. Four detector/sample pairs are contained in each 'quartet'. For integration in the 12U Exoterra spacecraft's 2U payload bay, two quartets are arranged on an adapter plate to occupy the full volume, with PIN diode sun sensors and the payload computer located in the center section.

The material characterization testbed in development contains eight scintillator detectors packaged in two modular quartets, with each quartet housing a 2x2 grid of detector/sample pairs. Each quartet consists of a machined aluminum housing and a nested, additively manufactured polyetherimide (PEI) insert to shield against secondary effects from the aluminum shell. The PEI inserts contain cavities for detector and sample insertion. Square material coupons 2.8cmx2.8cm of varying thicknesses are situated inside the PEI housing, exposing a 2.2cmx2.2cm square surface area to the radiation environment. A pair of quartets are integrated to the hosting spacecraft via an aluminum adapter plate with the material sample faces ported through cut windows in the spacecraft exterior shell, providing an unobstructed view of space, with the scintillator's field of regard inevitably varying with the sample's thickness. An individual quartet is sufficiently small such that a single module can be contained in a traditional nanosatellite PC/104 stack, allowing for modular reconfigurability across common CubeSat form-factors. The detector housing geometry attempts to preserve symmetry in the shielding material, such that each detector receives comparable effective shielding, though the necessary surrounding bus structure will also influence the shielding that each sample receives.

From an electronics perspective, the 2U payload requires no more than 5W of power and is designed to operate from a 6-28VDC bus with communication to the host over standard RS-485. Each scintillator can be placed in an SPI-chain to form a sensor network supported by the CapeMCA firmware, or individually addressed via USB 2.0 for configuration updates and individual readout. This design enables power cycling and data addressing of each sensor individually to increase overall mission success should a single sensor fail. All harnessing is comprised of flexible printed circuit boards with shielding layers and differential pairs to reduce the impact of potential electromagnetic interference from the targeted host spacecraft's experimental ion thruster. An embedded Linux microprocessor will operate the payload and perform initial data processing on orbit.

A. PLANNED MISSION OPERATIONS AND DATA VALIDATION

To continue the theme of increasing TRL and interaction with NASA business investments, the first flight of this detector payload is nominally planned for integration within a novel 12U spacecraft bus developed and funded in part by a NASA Tipping Point program. This spacecraft will primarily test a Xenon thruster system and host the detector payload in an exposed 2U forebody compartment as it performs orbital maneuvers out to 800km. The host spacecraft will provide power and radio communications for the payload, as well as attitude and altitude positional data. Such data will better enable radiation source identification. Integration of the payload is currently scheduled for late 2025, with launch provided by a Transporter mission shortly thereafter. During spaceflight operations, the payload's scintillator detectors will integrate energy spectra counts over commanded time periods, which will then be downlinked for analysis. This data will be correlated with the spacecraft's location and attitude data, along with input from the sun sensors on the payload. Each detector can operate independently or as a two-dimensional array, offering the ability to roughly determine 2D particle velocity from side-impacting radiation. It is expected that as the experiment progresses, optimal integration times and sensor settings will be determined, especially given the unpredictable nature of the current solar cycle. This data will be compared to models and data from existing spacecraft to provide a means of validation.

Material sample effectiveness will be determined by comparison of resultant energy spectra from each detector set compared to the unshielded, aluminum, and polyethylene control samples. From these spectra, the attenuation versus incident energy relationship for each sample can be ascertained. This data, along with material specifications and relative performance, will be the primary topic of a follow-up publication after flight operations have concluded or reached a significant data milestone.

Prior to spacecraft integration, the scintillation detectors must be calibrated against known particles to some degree so that sensor bias and error does not produce an erroneous material performance conclusion. While initial sensor calibration with a 10uCi^{137}Cs source was performed by CapeScint for each detector, testing with higher energy particles and gamma radiation is desired. Discussion is ongoing with various NASA sites to arrange for beamtime for calibrating and validating operation of the completed payload.

B. CURRENT STATUS

The mechanical CAD model for the payload is now complete and initial hardware prototyping has been performed. All scintillator and PIN diode sensors to be used have been acquired. An SLA 3D-printed mock housing for fitment testing has been created at the NASA Ames rapid prototyping shop, and the scintillator sensor and associated circuit boards and connectors have been integrated and installed successfully. The fit check and test assembly were performed at NASA Ames in late November 2024 and served to validate the current CAD model and component selection. Lessons were learned about how to best insert the four sensors and connectors in order to create assembly procedures for the flight build. Pending design assessments with the host vehicle team, the Ames team is now ready to send out drawing files for fabrication of the flight housings. Once machining is complete, the build of the payload will commence after functional testing of the electronic components. Functional testing after payload assembly will be performed as well, including thermal-vacuum and vibration testing. Beam exposure testing will then be performed to characterize the sensors chosen for flight.

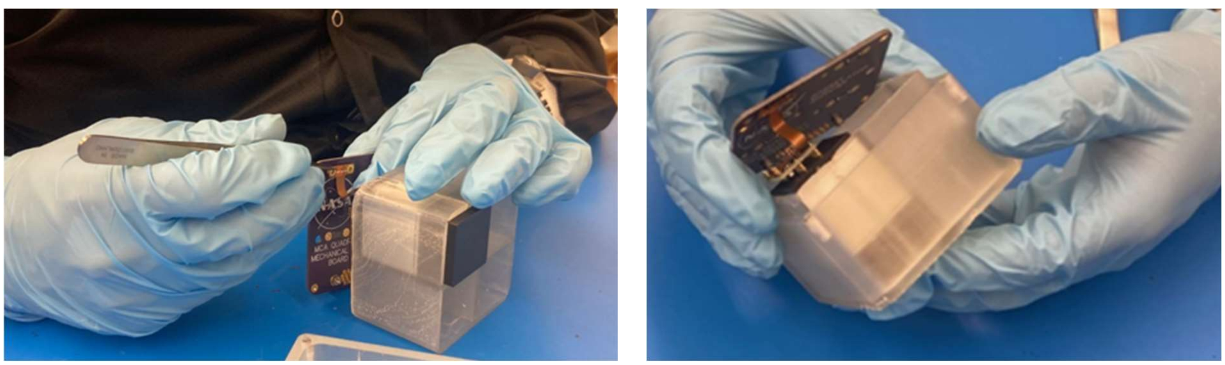

Figure 7. Images from test-fit integration of mechanical fit-check circuit cards and flex harness assemblies with resin SLA printed prototype structure and flight-spare scintillator unit.

C. PAYLOAD DESIGN: TESTING AND CALIBRATION

TVAC and vibration testing of the completed hardware will be performed at the NASA Ames Engineering Evaluation Laboratory, with beam testing of the completed payload to be completed at the GSFC radiation source facility with results to be documented and published in a following publication.

V. CONCLUSION

The CubeSat payload project described will provide foundational data that can be used to develop predictions about the shielding capabilities of composite materials and will inform future efforts to measure high energy ions in space, as well as provide an in-situ test of lightweight shielding materials potentially enabling longer distance and duration small satellite missions. Materials developed in the future, including a variety of bio-inspired polymers and plant and fungal-based composites, will benefit from a flight-tested experimental payload testbed that is modular and reconfigurable, based on the 1U CubeSat form factor, and with the ability to be integrated into a diverse range of host spacecraft.

REFERENCES

Atwell, W., Rojdev, K., Aghara, S., & Sriprisan, S. (2013). Mitigating the effects of the Space Radiation Environment: A novel approach of using graded-Z materials. *AIAA SPACE 2013 Conference and Exposition*. https://doi.org/10.2514/6.2013-5385

Baker, D. N., & Panasyuk, M. I. (2017). Discovering Earth's radiation belts. *Physics Today*, *70*(12), 46–51. https://doi.org/10.1063/pt.3.3791

Barth, Janet L, "Space and Atmospheric Environments: From Low Earth Orbits to Deep Space," in Proceedings of the 9thInternational Symposium on Materials in a Space Environment, European Space Agency, ESA SP-540, September 2003 pp. 17-30

Bedingfield, K.L.; Leach, R.D. and Alexander, M.B.; Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment, NASA Reference Publication 1390, August 1996

Berger, T. E., Holzinger, M. J., Sutton, E. K., & Thayer, J. P. (2020b). Flying through uncertainty. *Space Weather*, *18*(1). https://doi.org/10.1029/2019sw002373

Baumann, N., Diaz, K. M., Simmons-Potter, K., Potter, B. G., & Bucay, J. (2022). Particle loading as a design parameter for composite radiation shielding. *Nuclear Engineering and Technology*, *54*(10), 3855–3863. https://doi.org/10.1016/j.net.2022.05.029

Caspi, A., Barthelemy, M., Bussy-Virat, C. D., Cohen, I. J., DeForest, C. E., Jackson, D. R., Vourlidas, A., & Nieves-Chinchilla, T. (2022). Small satellite mission concepts for space weather research and as Pathfinders for Operations. *Space Weather*, *20*(2). https://doi.org/10.1029/2020sw002554

Daneshvar, H., Milan, K. G., Sadr, A., Sedighy, S. H., Malekie, S., & Mosayebi, A. (2021). Multilayer radiation shield for satellite electronic components protection. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-99739-2

Dever, J., Banks, B., de Groh, K., & Miller, S. (2013). Degradation of Spacecraft Materials. In *Handbook of Environmental Degradation of Materials* (Second). essay, Elsevier, Inc.

Fan, W. C., Drumm, C. R., Roeske, S. B., & Scrivner, G. J. (1996). Shielding considerations for satellite microelectronics. *IEEE Transactions on Nuclear Science*, *43*(6), 2790–2796. https://doi.org/10.1109/23.556868

Gohel, A., & Makwana, R. (2022). Multi-layered shielding materials for high energy space radiation. *Radiation Physics and Chemistry*, *197*, 110131. https://doi.org/10.1016/j.radphyschem.2022.110131

Helvajian, Henry, & Janson, S. W. (2023). *The nanosatellite revolution: 30 years and continuing*. SPIE / International Society for Optical Engineering. Howell, E. (2018, May 11). *What are cosmic rays?*. Space.com. https://www.space.com/32644-cosmic-rays.html

Hugo Sanchez, James Chartres, Robert Hanel, Sharmila Bhattacharya, Antonio Ricco, et al., "BioSentinel A 6U Nanosatellite for Deep Space Biological Science," 13thAnnual Summer CubeSat Developers' Workshop, Logan, UT, USA, August 6, 2016, URL:http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3453&context=smallsat

Lucci, N., Levitin, A. E., Belov, A. V., Eroshenko, E. A., Ptitsyna, N. G., Villoresi, G., Chizhenkov, G. V., Dorman, L. I., Gromova, L. I., Parisi, M., Tyasto, M. I., & Yanke, V. G. (2005a). Space weather conditions and spacecraft anomalies in different orbits. *Space Weather*, *3*(1). https://doi.org/10.1029/2003sw000056

Knoll, G. F. (2000). Background and Detector shielding. In *Radiation Detection and Measurement* (Third, pp. 767–774). essay, John Wiley & Sons, Inc.

Lanzerotti, Louis J. chair (2006) "Report of the Assessment Committee for the National Space Weather Program," FCM-R24-2006 , Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), Silver Spring, MD

Lee, J., Kim, H., Jeong, H., & Cho, S. (2020). Optimization of shielding to reduce cosmic radiation damage to packaged semiconductors during air transport using Monte Carlo Simulation. *Nuclear Engineering and Technology*, *52*(8), 1817–1825. https://doi.org/10.1016/j.net.2020.01.016

Leske, R. A. (1993). The elemental and isotopic composition of galactic cosmic-ray nuclei from scandium through nickel. *The Astrophysical Journal*, *405*, 567. https://doi.org/10.1086/172388

Lloyd's. (n.d.). *Space Weather Its impact on Earth and implications for business*. London; RAL Space.

Mewaldt, R. A. (1994). Galactic Cosmic Ray Composition and energy spectra. *Advances in Space Research*, *14*(10), 737–747. https://doi.org/10.1016/0273-1177(94)90536-3

Narici, L., Casolino, M., Di Fino, L. et al. Performances of Kevlar and Polyethylene as radiation shielding on-board the International Space Station in high latitude radiation environment. Sci Rep 7, 1644 (2017). https://doi.org/10.1038/s41598-017-01707-2 NASA. (2020, September 1). *NASA TechPort*. NASA. https://techport.nasa.gov/projects/102828

Nwankwo, V. U. J., Jibiri, N. N., & Kio, M. T. (n.d.). In *The Impcact of Space Radiation Environment on Satellites Operation in Near-Earth Space*. essay, Web of Science.

Packer, Brinley "Effectiveness of Multilayer Graded-Z Forms of Radiation Shielding," Senior Thesis, Utah State University, Logan, UT, May 2023

Rax, B. G., Johnston, A. H., & Lee, C. I. (1998). Proton damage effects in linear integrated circuits. *IEEE Transactions on Nuclear Science*, *45*(6), 2632–2637. https://doi.org/10.1109/23.736507

Reames, D.V. Solar Energetic Particles: Spatial Extent and Implications of the H and He Abundances. *Space Sci Rev* **218**, 48 (2022). https://doi.org/10.1007/s11214-022-00917-z

Reames, D. V. (2019). Hydrogen and the abundances of elements in gradual solar energetic-particle events. *Solar Physics*, *294*(6). https://doi.org/10.1007/s11207-019-1460-4

Schmelz, J. T., Reames, D. V., von Steiger, R., & Basu, S. (2012). Composition of the solar corona, solar wind, and solar energetic particles. *The Astrophysical Journal*, *755*(1), 33. https://doi.org/10.1088/0004-637x/755/1/33

Shea, M. S., Smart, D. F., Allen, J. H., & Wilkinson, D. C. (1992). Spacecraft Problems in association with episodes of intense solar activity and related terrestrial phenomena during March 1991. *IEEE Transactions on Nuclear Science*, *39*(6), 1754–1760. https://doi.org/10.1109/23.211363

Simpson, J. A. (1983). Elemental and isotopic composition of the Galactic Cosmic Rays. *Annual Review of Nuclear and Particle Science*, *33*(1), 323–382. https://doi.org/10.1146/annurev.ns.33.120183.001543

Summers, G. P., Burke, E. A., Shapiro, P., Messenger, S. R., & Walters, R. J. (1993). Damage correlations in semiconductors exposed to gamma, electron and proton radiations. *IEEE Transactions on Nuclear Science*, *40*(6), 1372–1379. https://doi.org/10.1109/23.273529

Telegin, S. V., & Draganyuk, O. N. (2016). The heterogeneous anti-radiation Shield for spacecraft*. *IOP Conference Series: Materials Science and Engineering*, *122*, 012033. https://doi.org/10.1088/1757-899x/122/1/012033

Wiedenbeck, M. E. (2013). Elemental and isotopic composition measurements of Galactic Cosmic Rays. *AIP Conference Proceedings*, 150–155. https://doi.org/10.1063/1.4792559

Wrbanek, J. D., & Wrbanek, S. Y. (2023). Multi-Aspect Cosmic Ray Ion Detectors for Deep-Space CubeSats. In *The Nanosatellite Revolution: 30 Years and Continuing* (pp. 505–536). essay, SPIE Press.

Zheng, Y., Ganushkina, N. Y., Jiggens, P., Jun, I., Meier, M., Minow, J. I., O'Brien, T. P., Pitchford, D., Shprits, Y., Tobiska, W. K., Xapsos, M. A., Guild, T. B., Mazur, J. E., & Kuznetsova, M. M. (2019). Space radiation and plasma effects on satellites and Aviation: Quantities and metrics for tracking performance of Space Weather Environment Models. *Space Weather*, *17*(10), 1384–1403. https://doi.org/10.1029/2018sw002042