Experimental Payload Analysis Concerning Known Radiation Effects and Degradations

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E-PACK-RED evaluates radiation shielding as an alternative to traditional radiation-hardened electronics for space environments. This paper details the structural, thermal, and electrical design of a test payload intended for launch on NASA's High Altitude Student Platform (HASP), which provides a high-altitude stratospheric testing environment. The experiment compares two NVIDIA Jetson Orin Nano processors: one coated with a proprietary metal-oxide infused conformal coating (MOICC) and an uncoated control. During flight, the processors will execute Double-Precision General Matrix Multiplication stress tests to detect radiation-induced interference, while an onboard photovoltaic sensor correlates these single-event upsets to local particle flux. Ultimately, the E-PACK-RED mission aims to increase the technological readiness level of the MOICC, supporting future space missions seeking to implement high-performance Commercial Off-The-Shelf processors.

Nomenclature

A	= original matrix A
A_c	= computed matrix A vector ($v^T A$)
B	= original matrix B
B_r	= computed matrix B vector (Bw)
$C_{compute}$	= computed matrix
C_{input}	= input matrix
F	= force, N
Q_{albedo}	= heat transferred from Earth's albedo, W
Q_{earth}	= heat emitted from Earth, W
Q_{gen}	= heat generated by payload, W
Q_{in}	= heat transferred into the payload, W
Q_{out}	= heat transferred out of the payload via IR radiation, W
Q_{stored}	= heat stored by payload, W
T	= payload temperature, °C
r	= residual
α	= scalar multiplier for matrix product
β	= scalar multiplier for input matrix
ϵ_{mach}	= machine epsilon
ρ_{solar}	= heat emitted from the Sun, W
σ	= stress, MPa

1. Introduction

Computational technology developed for terrestrial applications requires few environmental considerations. However, once projects go beyond Earth's atmosphere and magnetosphere, the effects that solar and cosmic radiation have technology must be evaluated. Due to the nature and design, complex electronics like computer processors are extremely susceptible to high radiation exposure, which can lead to performance degradation and potential failure.

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Of course, projects including electrical components have been completed in space for many years now, but the solution to radiation exposure has remained the same since its inception. Although rad-hard processors and other components do work in space experiments, these techniques are known to limit the productivity of electronics by interfering with their composition. To target the outdated use of older processors configured with rad-hard materials, evaluating radiation exposure and prevention with newer, more accessible processors should be pursued. North Carolina State University (NCSU) has developed the Metal Oxide Infused Conformal Coating (MOICC) to be an applicable radiation protection for contemporary commercial electronics.

The nature of testing in space can be quite inaccessible due to the resources and extended timeline required to get a project into orbit. To manage this, tests can be conducted with high altitude vehicles to produce a space-like environment. The High Altitude Student Platform (HASP) is a program founded by NASA that allows the use of student research payloads to be tested in use with a high-altitude balloon. To combat the time constraint required by launching a space-related project, intermediary projects such as HASP are utilized to collect reasonable data to further verify any mission parameters before actually testing with orbital vehicles such as a CubeSat.

The space industry needs to find a way to ensure the efficiency of their electronics while also protecting electronics from the harmful effects of radiation due to the space environment. In order to improve future space projects, a new solution should be developed to address the computational losses of rad-hard electronics. The technique of radiation shielding should be analyzed and tested as it could potentially protect electronics without interfering with their individual components, thus preserving computational efficiency. To test the capabilities of radiation shielding in comparison to current radiation prevention methods, a project will be developed in which an unshielded and a novel NCSU shielded processor will be exposed to radiation. By conducting this experiment to validate the usefulness of radiation shielding, E-PACK-RED will increase the technological readiness level of the NCSU conformal coating and serve as a low cost verification for the Computation in Low Earth Orbit Satellite for Radiation Assessment (CLEOSATRA) mission.

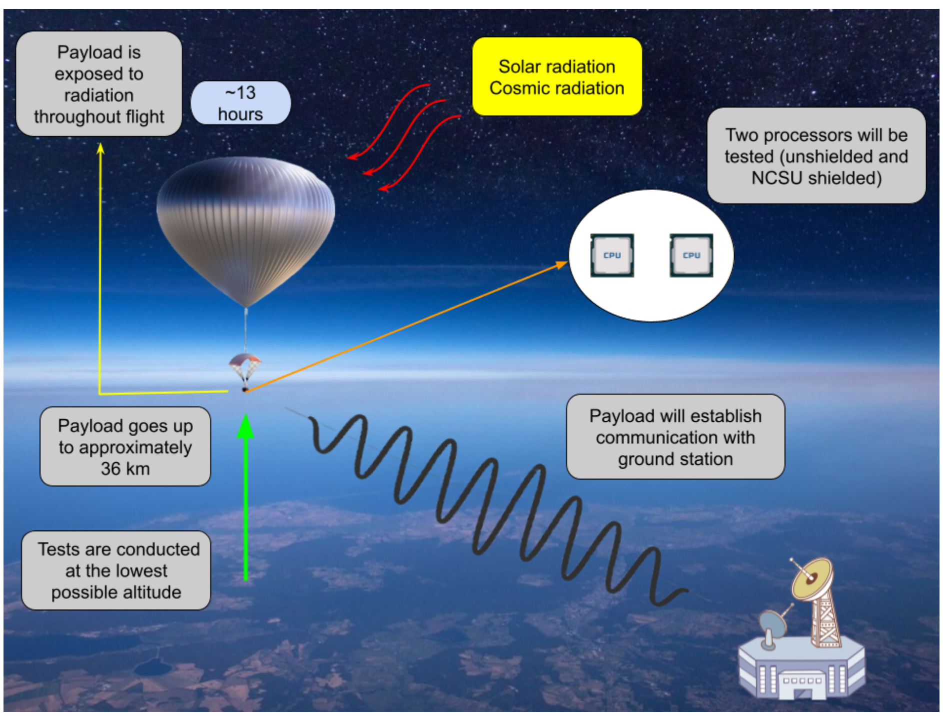

Fig. 1 Visual and Graphic Concept of Operations

2. Experimental Design

E-PACK-RED is a CubeSat-like payload to be launched on NASA's HASP in August 2026. The platform will rise through the atmosphere before coming to rest at an altitude of approximately 36 km where the altitude will fluctuate for nearly a day. Radiation environments in Low Earth Orbit and high altitude conditions are significantly different, but such altitudes provide a microcosm of the radiation profile faced by satellite computers. The spectrum of radiation is predicted by the EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum (EXPACS). The program uses a PHITS based Analytical Radiation Model in the Atmosphere to predict radiative fluxes at a given altitude, latitude, and longitude [1]. The following graphic displays the average particle flux at the specified test altitude.

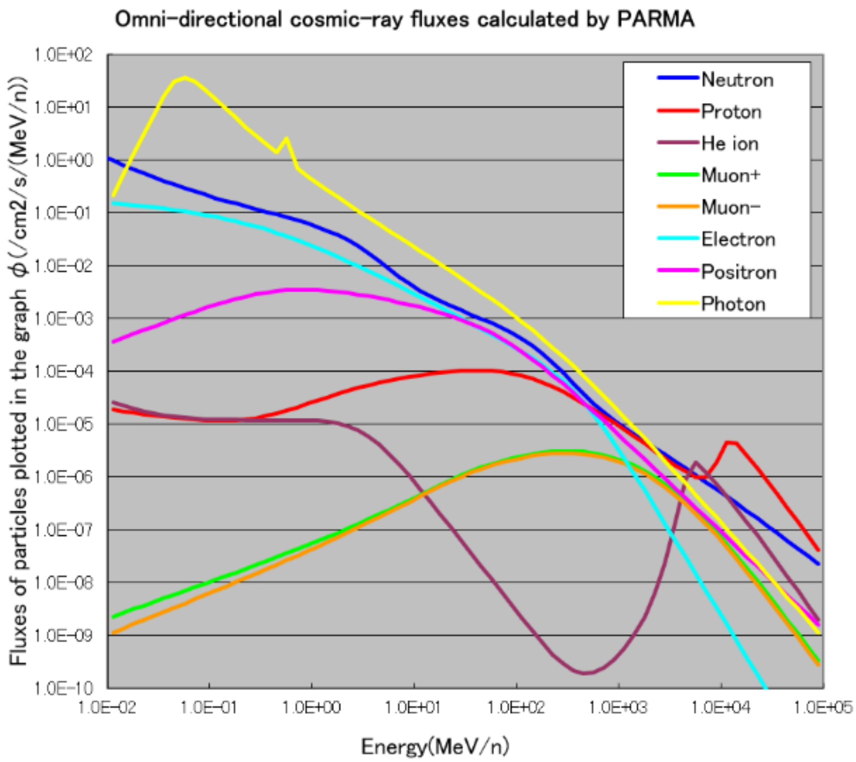

Fig. 2 Particle Flux at HASP Design Altitude, Latitude, and Longitude

The indicated flux peaks around the 1E2 counts range, which is quite low compared to the more damaging radiation associated with Low Earth Orbit. The high energy particles that are more likely to cause radiation damage are even more infrequent. During the payload's ascent, its pass through the Pfotzer maximum will introduce a high density of scattered neutrons and high energy particles by cosmic ray shower effects. Ray shower effects are most likely to introduce the high energy particles that harm electronics. There are several types of damage to computer electronics associated with the listed radiation, including single event effects, displacement damage, and total ionizing dose. Both of the latter damages are largely time dependent, making them challenging to demonstrate with low flight time. With the limited time-span in the irradiated environment, and the weak flux of radiation, it is desirable to maximize the single event upsets experienced by the computer processors to demonstrate significant shielding by the MOICC.

The experimental payload will house two NVIDIA Jetson Orin Nanos, which are commercially available modern chips. One of the two will be coated with the MOICC radiation shielding, using a 66 % WO_3 (tungsten oxide) mass ratio. The two processors will each run DGEMM benchmark tests to occupy the GPU and CPU of the processors. The operations are known to be susceptible to single event upsets [2]. Below is the form of the test run by the computer, and the associated residuals that will measure the incidence of upsets.

$$C_{compute} = \alpha AB + \beta C_{input} \tag{1}$$

$$r = \frac{||C_{computed} - (\alpha AB + \beta C_{input})||}{(||\alpha A|| \ |\beta| \ ||C_{input}||)\epsilon_{mach} max(m,n)} \tag{2}$$

The experiment is interested in creating a time-stamped feed of test results within the payload's aluminum-sheilded Raspberry Pi 5 control computer. Usage of a time-sensitive data feed will allow data analysis to demonstrate that errors are associated with radiation damage. E-PACK-RED includes a HAMAMATSU PIN detector to record radiation data of the experiment with its own timestamps. Residuals checking is a common and "light-weight" error detection software [3]. Another common methodology of error detection is Algorithm Based Fault Tolerance (ABFT) [4]. Such algorithms are common due to their ability to locate and correct errors when they occur [3]. The equations for which are listed below.

$$A \rightarrow \begin{pmatrix} A \\ A_c \end{pmatrix}, \quad \text{where} \quad A_c = v^T A \tag{3}$$

$$B \rightarrow (BB_r), \quad \text{where} \quad B_r = Bw \tag{4}$$

The Raspberry PI 5 will act as the control computer, shielded by the industry standard aluminum, and will issue commands to the test processors, the power control systems, and the thermal regulation systems. The PI 5 will store relevant data from tests onboard and send packets of system data to the HASP ground station transmission system. The data will be analyzed after the experiment to determine the efficacy of the MOICC. With the test method of choice, E-PACK-RED will be able to measure the rate at which the test processors undergo single event upsets, and determine if the MOICC had a significant effect in shielding. The radiation detection will ensure that computational error spikes are due to radiation instead of outside effects. The following sections describe the payload that supports the test conducted by E-PACK-RED.

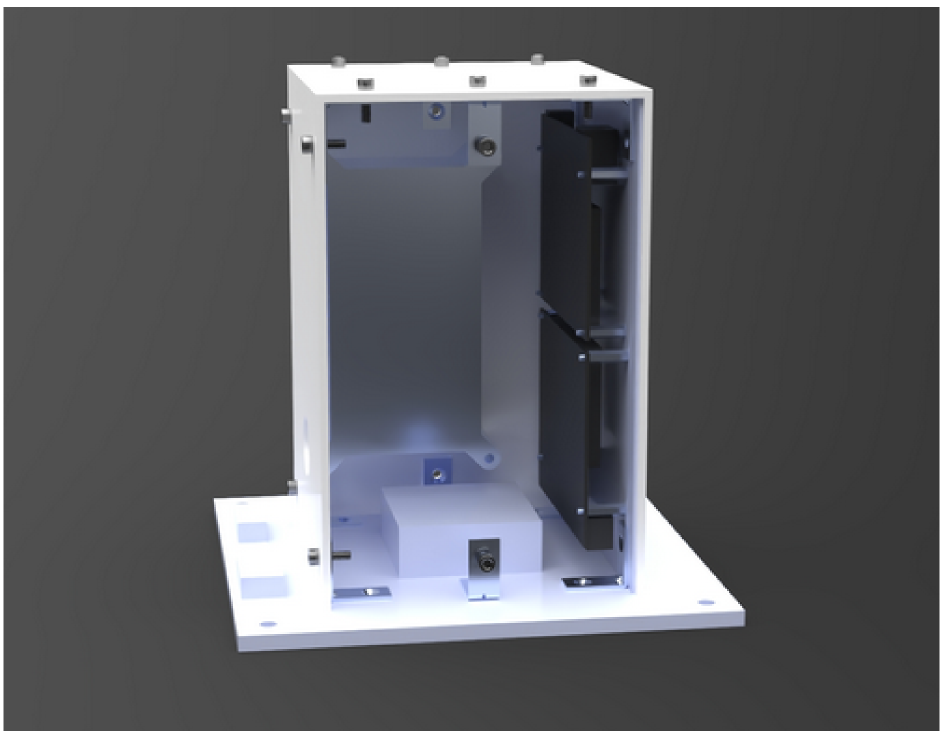

Fig. 3 Visualization of Overall Payload Design, Internal View

3. Structural Design and Analysis

A. Design Requirements

The structural subsystem is designed to provide a structurally stable environment for critical system components to survive the harsh conditions at high altitudes and the forces of landing. Previous HASP missions have laid bounds of the physical requirements we are expected to ensure our payload meets. As defined by HASP in their student payload interface manual, the small payload may be no greater than 15 cm x 15 cm x 30 cm and weigh no more than 3 kg. The payload structure is also required to survive 10 G's of vertical acceleration and 5 G's of horizontal acceleration. The HASP payload is expected to be at 36 km for approximately 15 hours in temperatures of +40°C to -60°C.

B. Structural Configuration

To begin designing the structure of the payload, a solid concept of the forces on the structure needs to be calculated. Using Newton's second law of motion a rough estimate of the overall force can be calculated.

$$F = 3(10 \times 9.81) = 294.3\,\mathrm{N} \tag{5}$$

Seeing as the magnitude of the overall force is relatively small for the payload a simple concept can be created with a rectangular box made of thin panels bolted together with angle brackets. Next the size is constrained by HASP and by the overall mass budget, utilizing these bounds overall payload dimensions of 130 mm by 140 mm by 200 mm were utilized. PVC was selected to be the primary structure due to it's comparatively low density, ease of manufacturing and adequate yield strength for the expected loading.

$$\sigma = \frac{F}{A} \tag{6}$$

The given g forces the HASP payload must survive allows for calculation of the total forces that must be designed for. In the vertical direction, compressive, the force of 10 g is multiplied by gravity and mass to get a total force of 294.3 N. The area that this is acting on is a hollow box with the dimensions of 15 cm by 13 cm by 20 cm with a thickness of 1/8 inch. This results in an area of 1737.7 mm^2. Dividing the force over area results in 0.169 MPa. PVC shows compressive forces around 66 MPa in some tests. [5] This shows that PVC is more than strong enough to handle this force. The shear forces are done with a similar calculation, the cross sectional area does not change, just the direction of the test. HASP requires that the payload withstand 5 g of force in the horizontal direction, which translates to 147.15 N of force. Dividing this by the same area results in a strength of 0.0846 MPa. PVC is weaker in shear tests, having a strength of 51 MPa, however this is still significantly higher than the predicted forces.[5]

C. Verification

Aerospace structures are made up of many shapes including various complex geometries. While an analysis completed by hand is capable of modeling the performance of a structure; finite element analysis is the optimal method for E-PACK-RED. By breaking down each individual component into tiny parts, computer software can calculate the sum of the products creating models that can predict the performance of complex parts with greater accuracy. To complete the design solution each component had to be modeled in SOLIDWORKS. Using this, 3D model simulations were run in which the expected loads were simulated. HASP requires the payload to be capable of surviving a 10 g vertical impact and a 5 g horizontal impact. These forces were applied as distributed loads assuming a mass of 3 kg which is the maximum allowed by HASP. These forces were applied to a static system where the static simulation calculated stress, strain, displacement and the factor of safety. As shown below in the factor of safety plots the current structural design is more than adequate for the guidelines laid out by HASP.

D. Mass Budget

NASA's HASP imposes a strict mass budget for the payload of 3 kg. To ensure E-PACK-RED's payload is inside of this limit a mass budget is created as shown below. Mass of all key components was weighed inside of North Carolina State University's Senior Design Lab on a digital scale. The mass budget does not include wiring and paint at this time due to the electrical system being currently still in the manufacturing process but a 1 kg buffer for these components is adequate.

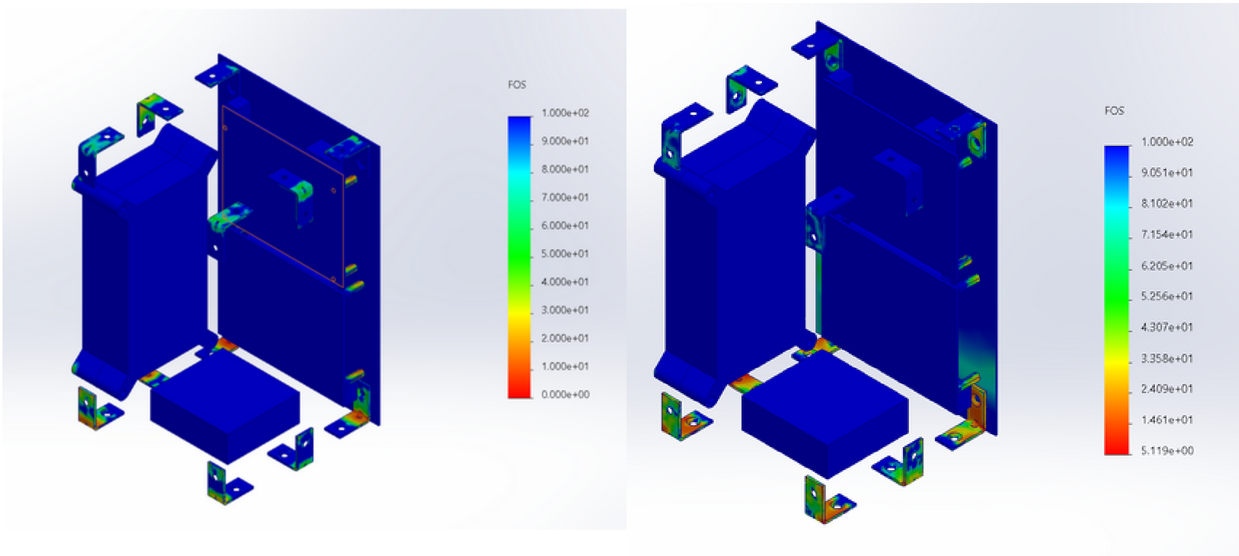

Fig. 4 Factor of Safety Plots, Left: Vertical Loading with Minimum FOS: 2.8. Right: Horizontal Loading with Minimum FOS: 5.1

List Item	Weight (kg)
Nvidia Jetson Orin x2	0.254
Raspberry Pi 5	0.045
SSD x3	0.030
PVC Panels	0.584
Mounting Brackets	0.154
Mounting Hardware	0.319
Radiation Sensor	0.005
Temperature Sensor	0.005
Thermal Heating Panels	0.00104
Conformal Coating	0.145
Aluminum Sheet	0.100
Aluminum Shielding	0.180
USB to Ethernet Adapter	0.040
DC/DC Converter	0.113
TOTAL	**1.97504**

Table 1 System Mass/Weight Budget

4. Thermal Analysis

Based on data from HASP and previous HASP missions [6], ambient outside temperatures are expected to change from -60°C to 20°C throughout the mission timeline. At the parked altitude of 36 km, the temperature is expected to stay around -40°C. However, it should be noted that these outside temperatures can differ by tens of degrees depending on weather, time of day, sun exposure, and heat radiation from surrounding payloads.

The electrical components within the payload all have recommended temperature ranges from their respective manufacturers. The Jetson processors actually produce heat during operation, requiring this heat to be removed to prevent overheating. These thermal concerns require a complete and thorough analysis of the thermal subsystem.

A. Verification

The following equation is an energy balance equation for the heat energy that the payload will experience. This equation will serve as the governing equation to determine how much heat will be added and removed from the payload, which will be helpful in determining the expected temperature of the entire payload. To do this, Q_{stored} can be set equal to zero.

$$Q_{stored} = Q_{in} - Q_{out} + Q_{gen} \tag{7}$$

The heat transferred into the payload can be derived by considering all possible heat sources the payload will be exposed to. This would include the heat emitted from the Sun, Q_{solar}, the heat emitted from Earth, Q_{earth}, and the heat emitted from the Sun that is reflected by the Earth, Q_{albedo}. Notice this does not include heat transferred via conduction because at the expected altitudes, the air pressure is low enough to make this form of heat transfer negligible. Due to the lack of convection at the mission altitude, the only reliable way to transfer heat out of the payload is through IR radiation. This heat would be transferred out through the outermost portion of the payload.

The primary thermal concern with the payload is the heat generated by the Jetson processors during operation. The SoC (System on a Chip) produces 20.20 W of heat if operating at 25 W of power. The processor RAM produces 1.5 W of heat. This means that each processor must have 21.7 W of heat removed to keep from overheating. To accomplish this, both Jetson processors will have a copper thermal strap attached to the SoC and RAM with a gel TIM (Thermal Interface Material) between the connection. The other end of the copper strap will be connected to an aluminum plate serving as a heat sink. This aluminum plate will be attached inside the payload and will span the wall face. This will maximize the heat transferred into the payload walls without completely shielding the processors from radiation flux. For the analysis, this means that Q_{gen} = 50 W, representing the heat produced by the Jetsons, plus any unexpected, extra heat produced by other electronics.

Now, the payload temperature, T, from $Q_{out} = \epsilon\sigma AT^4$, can be solved for by solving and plugging in Q_{in} and setting $Q_{stored} = 0$. The payload temperature is determined for a "hot case" and a "cold case". The "hot case" assumes the Jetson processors are running ($Q_{gen} = 50W$), whereas the "cold case" assumes the Jetson processors are not running ($Q_{gen} = 0W$). The corresponding payload temperatures are $T_{hot} = 65°C$ and $T_{cold} = 10°C$, which are both within the operating temperature ranges of the on-board electronics.

5. Electrical

The electrical subsystem of the E-PACK-RED payload is engineered to provide constant, regulated power to all onboard components while strictly adhering to the HASP constraints. Early iterations of the electrical design considered incorporating an external, supplementary batteries to ensure energy margins. However, upon further investigation and implementation of optimization strategies, it was verified that the total payload power consumption lies safely beneath the 70 W maximum allocation provided by the HASP power source. Therefore, the external battery was eliminated from the final design, reducing system complexity, integration time, and overall payload mass while preserving an adequate power margin for all mission functions.

A. Power Source and Budget Constraints

HASP provides small student payloads with a 26-30 V DC supply, fluctuating based on temperature and duration of the mission, which is capable of supplying 0.5 A. Since E-PACK-RED expects a power consumption of approximately 60.8 W during peak operations, a special request was fulfilled by the HASP team, agreeing to supply the E-PACK-RED payload with 2.5 A. This additional supply allowed for the mission to continue as planned, now with a top end budget of 70 W. The peak load that the payload will experience accounts for two NVIDIA Jetson Orin Nano modules locked into a 15 W power mode, a Raspberry Pi 5 flight controller, solid-state drives (SSDs), GPIO (General-Purpose Input/Output) relay modules, polyimide heaters, and the onboard radiation sensor. This nominal consumption leaves an operational safety margin of approximately 11.3 W (when assuming a 70 W total).

List Items	Quantity	Voltage	Current	Power (W)	Notes
Nvidia Jetson Orins	2	12	1.25 A	30	Switched Jetsons to 15 W mode
Raspberry Pi 5	1	5	3 A	15	
Radiation Sensor	1	42	Very small	0.1	
2 Channel Relay	1	5	70–80 mA	0.35	
4 Channel Relay	1	5	70–80 mA	0.35	If all on then 1.4 W
Heaters	3	5	0.2 A	3	1 W each
Pi SSD	1	Internal 3.3 V	~1.5 A	5	Approx 5 on avg
Jetson SSDs	2	3.3 V rail	~1 A	7	Approx 3.5 each on avg
HASP Provided Power		28	2.5 A	70	
Total Power				**60.8**	Within range

Table 2 System Power Budget

B. Distribution Architecture

To efficiently utilize the incoming 28 V DC power, the electrical distribution network relies on a parallel converter architecture. Incoming power is split using modular WAGO lever-nut connectors, routing the 28 V supply to two separate, non-isolated DC/DC converters. One converter outputs a regulated 12 V bus, dedicated primarily to the high-current computing loads, specifically the two Jetson Orin Nano modules and their associated peripheral devices. The second converter steps the voltage down to a 5 V bus, which power the lower-current control electronics, including the Raspberry Pi 5, relay modules, and thermal heaters. Lower secondary voltages, such as the 3.3 V required by the RS-232 to UART (Universal Asynchronous Receiver-Transmitter) converter and storage devices(SSDs), are handled internally by onboard regulators within the components themselves. Furthermore, the radiation sensor demands a specific, higher bias voltage to operate correctly. This is achieved by using a specialized high-voltage step-up transformer that draws from the regulated supply to generate the necessary 42 V bias with a low current load.

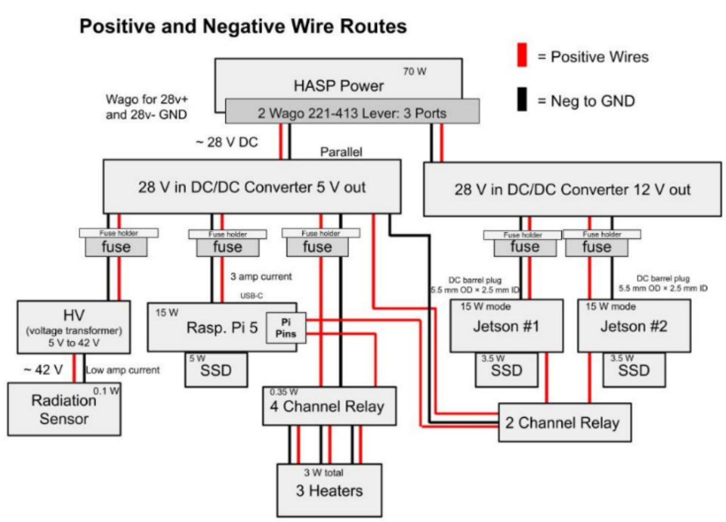

Fig. 5 Electrical distribution architecture, demonstrating the parallel conversion of the 28 V HASP supply into isolated 5 V and 12 V rails with localized fault protection.

C. Fault Protection and Isolation

Robust fault protection is critical for mission survival. Independent inline fusing is strategically placed on each primary power branch stemming from the converters. This provides localized fault protection, guaranteeing that an electrical short or thermal runaway in a single subsystem (such as a single Jetson module or heater) does not cascade and disable the entire payload.

Additionally, the dual-rail power distribution scheme physically segregates the high-current computing loads from the sensitive electronics. This electrical isolation minimizes the risk of electrical noise from the processors coupling into the control and data handling circuits, improving the integrity of sensor readings and serial communications. All circuits share a common ground reference that is directly tied to the HASP return line.

6. Communication

The Communication and Data Handling (CDH) subsystem is the central nervous system of E-PACK-RED. It is responsible for orchestrating scientific experiments, logging experimental and housekeeping data, and interfacing with the HASP platform for telemetry downlink and command uplink.

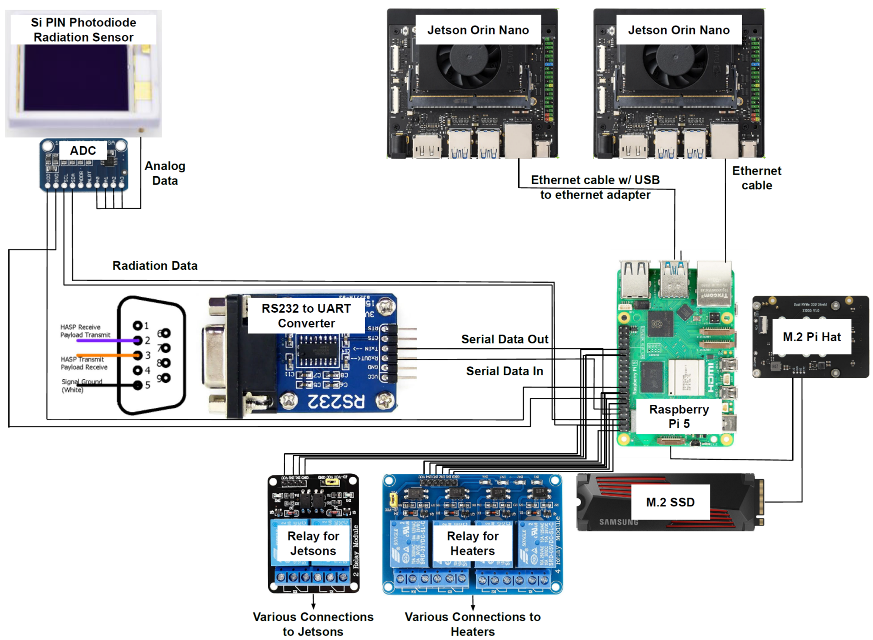

Fig. 6 CDH system architecture, highlighting the Raspberry Pi 5 as the central router between the NVIDIA Jetson modules, environmental sensors, and the HASP serial interface.

A. Internal Communication and Data Handling

Embedded payloads frequently utilize heterogeneous computing architectures to isolate tasks and optimize energy usage. E-PACK-RED employs a Raspberry Pi 5 as the central master controller, tasking it with routing data, interacting with sensors, and managing the subordinate NVIDIA Jetson modules.

Data generated by the Double-Precision General Matrix Multiplication (DGEMM) stress tests on the Jetsons is streamed to the Raspberry Pi via high-speed Ethernet. The unshielded Jetson interfaces via a native 2.5 Gbps Ethernet connection, while the shielded Jetson uses a USB 3.0-to-Ethernet adapter capable of practical throughput of 3-4 Gbps. Simulation analysis shows that even at a maximum throughput of 200 GFLOPS (Giga Floating Point Operations Per Second), the required bandwidth is only 1.49 Mbps per Jetson. Therefore, the peak data rates consume less than 0.05% of the available interface capacity, entirely eliminating internal bandwidth bottlenecks.

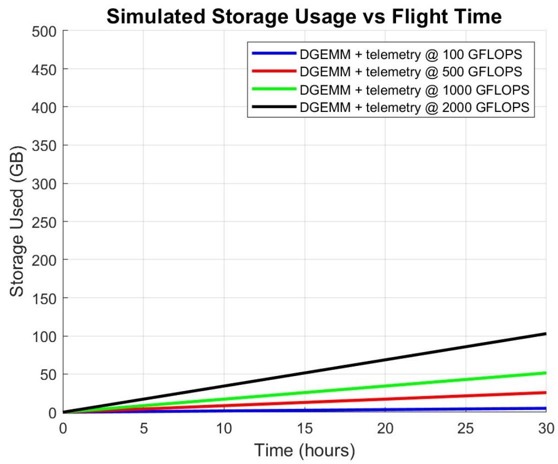

Fig. 7 Simulated cumulative onboard storage usage over a 30-hour HASP flight duration, demonstrating sufficient SSD capacity for DGEMM residuals and telemetry data across multiple performance scenarios.

B. Onboard Data Archival

Given the potential for communication dropouts during the flight, non-volatile onboard storage is mandatory. The payload houses a 1 TB NVME (Non-Volatile Memory Express) M.2 SSD connected via an M.2 HAT on the Raspberry Pi. The SSD archives all DGEMM metadata (run ID, matrix size, GFLOPS, checksum results), aggregated radiation counts, and housekeeping metrics.

To demonstrate feasibility, a MATLAB simulation was performed to evaluate cumulative data usage over a 30-hour flight. Assuming two Jetsons generated 64 KiB of residual data per run, alongside redundant telemetry and housekeeping data, the total data accumulation falls drastically below the 1 TB capacity. Furthermore, all files are stored in a chronological directory hierarchy (e.g. run_<timestamp>_<id>.json) accompanied by a CSC32 checksum for post-flight data verification.

C. Serial Interface and Telemetry Downlink

The payload interfaces with the HASP ground station, utilizing the RS-232 serial protocol through a DB9 connector. The communication is configured to 8 data bits, no parity, 1 stop bit, at a rate of 4800 baud. Because the Raspberry Pi 5 operates on 3.3 V logic and the RS-232 standard uses negative logic voltages (-5 V to -15 V logic "1", +5 V to +15 V for logic "0"), a MAX232 level shifter is employed. This chip acts as a bridge, successfully converting the RS-232 signals into standard TTL levels compatible with the Pi's Universal Asynchronous Receiver-Transmitter (UART).

Real-time telemetry acts as a health monitor for the payload. The Pi packages crucial status metrics, including Jetson Processor states, CPU and GPU temperatures, payload altitude, and radiation levels, into fixed 66 byte telemetry packets. These packets are downlinked to the ground station every 5 seconds to provide the monitoring team with insights into the payload's status.

D. Command Uplink and Failsafes

To allow for responsive mission control, the CDH system accepts 7-byte uplink command strings from the HASP ground station. These string strictly define the payload's operational state. Byte 3 contains the hexadecimal command code (e.g., 0X71 for HEATING_ON or 0x74 for JETSONS_OFF), while Byte 4 serves as a checksum to ensure that the uplink data has not been corrupted.

Upon receiving a command, the Pi executes a bitwise XOR operation against the command byte (with 0XAA) and compares the result to the checksum byte. If the Checksum verifies successfully, the command is executed via the GPIO-driven relay modules, and a confirmation string (e.g., "JETSONS OFF") is transmitted back down in the next downlink packet. If verification fails, an error message is returned, preventing the execution of corrupted instructions. This robust architecture allows ground operators to manually override payload states, such as shutting down an overheating processor or activating backup thermal systems. This ensures the survivability of the payload in the volatile and varying stratospheric environment.

7. Conclusion

E-PACK-RED was developed as a continuation of the CLEOSATRA project at North Carolina State University to evaluate the effectiveness of radiation shielding as an alternative to traditional radiation-hardened electronics for in space computation. The mission is designed to compare an uncoated NVIDIA Jetson Orin Nano with an identical unit coated with a proprietary metal-oxide infused conformal coating.

The various subsystems were designed to meet HASP requirements while maintaining specific performance guidelines. Structural and finite element analysis ensures that the structure of the payload will survive the impact loading constraints. Thermal modeling predicts that internal temperatures will stay within operational limits for all possible cases. The electrical subsystem distributes the 28V HASP power through various electronic components while remaining within the 70 W power budget. The communication and data handling system ensures reliable communication with the experiment and reliable archival of experimental data.

This mission will increase the technological readiness level of the metal-oxide infused conformal coating and provide data supporting its application in LEO missions. If validated, conformal radiation shielding approaches like the metal-oxide infused conformal coating may lead to developments in more capable and cost effective satellite computation.

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