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Computation in Low-Earth Orbit Satellite for Reliable Accessibility (CLEOSATRA)

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The demand for on-orbit computational power far exceeds what is available by current means, necessitating the development of more efficient and reliable electronic systems able to withstand the orbital environment. This study aims to explore and address the the need for increased on-orbit computational power in satellites, to be done via the testing of new rad-hard techniques on Commercial Off-The-Shelf (COTS) electronics through the deployment of a CubeSat platform. This research establishes a new rad-hard technique that will allow for the deployment of newer and more efficient electronic equipment into space at a fraction of the current cost and weight.

I. Introduction

Traditional electronics used in space applications require expensive radiation shielding and testing to ensure that the space environment does not materially affect the performance of the mission. The need for radiation-hardened (rad-hard) electronics has limited the electronic components available for on-orbit computing [1]. As such, innovation and efficiency are sacrificed for a reliable and known entity, leading to a stagnation in computational power and thermal management [2]. The mission outline of CLEOSATRA is included in this paper, including mission and orbit characteristics and expected radiation received by the CubeSat.

The primary objective of this research is to evaluate and demonstrate new rad-hard techniques on Commercial Off-The-Shelf (COTS) electronics. This will be done via an economical CubeSat platform, which will carry a payload of electronics and subject them to low Earth orbit (LEO) radiation. The CubeSat will have radiation detectors to measure the radiation levels of the payload, and a telemetry system to relay the payload condition back to Earth. The payload includes two Raspberry Pi computers, one protected by the rad-hard technique and another without radiation protection. The rad-hard technique used is a Metal Oxide Impregnated Conformal Coating, Patent No. 11887743, developed by Dr. Robert Hayes and Michael DeVanzo of the North Carolina State University Nuclear Engineering Department. The coating will be tested as an alternative means of radiation protection, one that is cheaper and much lighter than traditional rad-hard techniques.

This paper presents the design, analysis, and manufacturing of a prototype for the CLEOSATRA mission, including mission objectives, system requirements, design implementation, and verification strategies. The findings contribute to the broader field of on-orbit computation, supporting future LEO missions requiring autonomous processing capabilities. The study will comprehensively detail the mission's objectives, success criteria, and concept of operations, including mission phases from launch through on-orbit testing and the de-orbit process. An outline of the rigorous research effort focused on radiation shielding and computational experimentation, as well as supporting NASA research in areas such as SMA-based solar array deployment and miniaturized radiation detection. This approach ensures that every aspect of the mission is thoroughly addressed, ensuring that CLEOSATRA will be a pivotal step forward in the advance of affordable, high-performance space technology.

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The expected outcome of this research includes a further understanding and testing of new rad-hard techniques and their implementation with COTS electronics. Success will result in a cheaper and lighter means of radiation protection, allowing for the widespread use of COTS electronics and the expansion of on-orbit computing power. The data provided by this research will allow the integration of next-generation electronics in future space missions, thereby improving performance, efficiency, and the availability of affordable technology in space.

II. Literature Review

The demand for on-orbit computational power far exceeds what is available by current means, necessitating the development of more efficient and reliable electronic systems able to withstand the orbital environment. Traditional electronics used in space applications require expensive radiation shielding and testing to ensure that the space environment does not materially affect the performance of the mission. This need for radiation-hardened (rad-hard) electronics has limited the electronic components available for on-orbit computing [1]. As such, innovation and efficiency are sacrificed for a reliable and known entity, leading to a stagnation in computational power and thermal management [2]. The objective of this research is to design, fabricate, and deploy a CubeSat to test new rad-hard techniques that will allow for the deployment of newer and more efficient electronic equipment into space at a fraction of the current cost and weight.

The primary technical challenge involves the effects of ionizing radiation on commercial off-the-shelf (COTS) computing hardware, necessitating robust shielding and error mitigation strategies. The team has conducted extensive radiation analysis based on predicted orbital flux using ESA's Space Environment Information System (SPENVIS) to model the total ionizing dose (TID) and single-event effects (SEE) in the target LEO environment [3]. Prior studies on radiation-hardened electronics guided the selection of computational components, incorporating redundancy and radiation-aware fault tolerance to balance performance with power efficiency constraints [2].

CLEOSATRA's design encompasses a comprehensive trade study evaluating power sources, mobility and attitude control, thermal regulation, and communication subsystems. A key innovation includes adaptive shielding using tungsten oxide conformal coatings to mitigate radiation effects while maintaining mass efficiency [4]. The thermal management system leverages deployable radiators to dissipate excess heat, ensuring optimal processor performance within operational limits [5]. The communications subsystem utilizes a UHF transceiver and LoRa-based telemetry for robust data downlink and command execution.

The CLEOSATRA project aims to develop and deploy a computational platform aboard a Low Earth Orbit (LEO) satellite designed to enhance reliability and accessibility in space-based processing. This study addresses the increasing demand for computational autonomy in space systems, mitigating latency and dependence on terrestrial networks. The platform integrates radiation-hardened and fault-tolerant processing methodologies to ensure sustained operation in the harsh space environment.

III. Methodology

The project methodology integrates analytical modeling, hardware-in-the-loop simulations, and iterative design validation. Preliminary results indicate that the proposed architecture effectively mitigates radiation-induced errors while maintaining computational throughput. The power management system, modeled on established CubeSat designs, ensures adequate energy storage and consumption throughout the mission [6]. The baseline design reflects the design decisions made by the CLEOSATRA team through the trade study, literature reviews, evidence of feasibility, and simulation or testing. Future work includes hardware testing in a controlled radiation environment and in-orbit validation of the deployed system.

A. Payload: Radiation Shielding

The primary research objective will be to demonstrate the ability to decouple the radiation protection method from the electronic design using a conformal coating instead of rad-hard electronic design. CLEOSATRA will quantify the effectiveness of a novel conformal coating to shield Commercial-Off-the-Shelf electronics from the radiation fluxes present in LEO.

Protecting electronics from radiation typically involves an entire redesign of the electronics. However, employing a radiation shield that is not dependent on the electronics design would enable COTS components to be used widely. CLEOSATRA will be a test platform to establish the feasibility of using a metal oxide impregnated polymer to shield electronics from the gamut of radiation sources present in space. To accurately measure the effectiveness of decoupling the radiation protection from the electronics design CLEOSATRA will use a conformal coating developed by North Carolina State University's Nuclear Engineering Department. This coating will be applied to a commercially available processor, a Raspberry Pi. An unshielded Raspberry Pi will be used as the control processor in the experiment.

Solutions for radiation shielding on the structure include a multi-layer shield made of aluminum, copper, molybdenum, and tin which showed an ability to provide protection in LEO conditions in experimental and computational analysis [7]. MIT has worked on 3D printed composite shielding using both high and low z materials as a means to provide a rapidly configurable and direct deposit on COTS electronics [8]. The results showed that their coating outperformed the aluminum blocks that are standard for space missions by reducing the radiation effects by 50 percent. Dr. Rob Hayes in the nuclear engineering department at North Carolina State University has developed a coating that provides radiation protection for radiation under 10 keV [9]. The coating is made of acrylic and a metal oxide and conforms to the geometry it is applied to, allowing for this coating to be installed on the outer CubeSat structure or on the electronics themselves. Additional work has been done to show the effectiveness of the metal oxide in a polyurethane matrix which has protection from 123 eV to 1.2 keV, and was further improved to 247 keV when a tungsten oxide was incorporated [10].

B. Payload: Processors

Computing resources in orbit have been typically confined to radiation-hardened electronics such as the industry standard RTG4 FBGA board [11]. Radiation effects on electronics take form in three main ways: Total Ionizing Dose (TID), Displacement Damage (DD), and Single-Event Effects (SEE) [3]. Using COTS components presents a great challenge when attempting to mitigate these effects as their resistance to radiation damage varies significantly across manufacturers and between lots [12]. A typical shield for electronics in current space systems is an aluminum block strategically placed to help absorb and modify the spectra of energy coming both from inside the spacecraft and the space environment. CLEOSATRA will perform computational checks on data loss and corruption to estimate the radiation effects on a coated Raspberry PI and a control Raspberry PI.

CLEOSATRA will employ a multitude of radiation fault detection techniques at both the system and component levels [13]. A dual processor architecture, split into two computers, where one acts as a shielded reference and the other as an experimental unshielded computer will be utilized to determine shield effectiveness. The conformal coating will be applied directly to electronic surfaces, drying to create a protective rubber-like shell. A radiation sensor will be placed at the heart of the payload, between the two processors to directly measure the incident radiation over time. Both computers will have symmetric connections to all sensors, thus the sensor data will be monitored for single event errors and bit flips. All communications will have check-sums to ensure information is correctly transmitted between subsystems. The CPU health-status and memory storage will be parsed for errors and logged between processors to measure error rates, effectively measuring shield functionality. Finally, both internal and external watchdogs will monitor both CPU functions to determine when a hardware reset is necessary. The Raspberry Pi Zero2W has the capability to internally reboot the processor if it becomes frozen, this function will act as the internal watchdog [14]. A separate Arduino Beetle will act as the external watchdog, which will power-rest either computer if it becomes unresponsive. The logging of damage accumulation and error rates, in combination with the direct measurement of incident radiation, will aid in the determination of shield efficiency in space. If successful, the shielding and processor architecture enables state-of-the-art non-radiation-hardened computing electronics to be placed in space missions, bringing AI, advanced computation power, and on-demand computing to orbit and beyond.

C. Structure

Through a trade study, it was determined that the primary structure should be made of aluminum alloys 6061, 6082, or, most preferably, 7075, due to their favorable mechanical, thermal, and physical properties. This determination then helped to narrow down the options for commercially available structures. In the end, the 3U CubeSat chassis and panels manufactured by Gran Systems was selected to be CLEOSATRA's primary structure, due to its low pricing and high potential for customization.

D. Power

Deployed solar arrays using Spectrolab XTJ cells were selected for their industry-standard performance, increased surface area, and ability to power the satellite at full capacity for 50% of the mission; facilitating flexible radiation effect testing and generating data to validate the novel radiation shielding. Lithium-ion batteries were chosen over Nickel-Cd and Nickel-Hydrogen for their high specific energy, wide availability, and superior cycle life. Four LG MJ1

18650 cells, each providing 12.74 Wh and already flown on NASA's Pace mission, will be used to allow the satellite to avoid exceeding 80% depth of discharge and tolerate the failure of two cells without compromising operations. To manage power, a COTS Nano-plus EPS from AAC Clyde. The EPS was selected for its proven flight heritage, compatibility with deployable solar panels, and absence of an integrated battery. It was decided to use a COTS solution as specialized electrical design falls outside the aerospace team's scope.

E. Thermal Control

Thermal control of a spacecraft utilizes a multitude of system in order to obtain the balancing of the orbiting spacecraft equation. Three major systems were chosen to achieve thermal control of CLEOSATRA. These include thermal coatings, an electric heater, and a deployable radiator system. The thermal coatings, specifically, Z306 Polyurethan was chosen as the matte black paint and A276 Polyurethan was chosen as the matte white paint to reflect or absorp radiated heat as need [5]. The CubeSat required some heat dissipation, so deployable radiators were selected in combination with a heat sink to dissipate excess heat. An electric heater was required for the Power subsystem's battery package, a typical Omega KHLVA-103 series heater was chosen to fit the thermal needs of the battery. Additional PT-100 Temperature Sensors were selected to measure internal temperature and adjust the electric heater as needed. Testing, simulation, and historical data provided a required internal temperature range of 15-35 Celsius, which was achieved through simulation of the chosen systems.

F. Mobility and Altitude Control

The mission's attitude control and determination system will utilize magnetorquers, reaction wheels, magnetometers, and sun sensors due to their proven performance in precise, low-power operations. Magnetorquers leverage Earth's magnetic field for fuel-free attitude adjustments, while reaction wheels provide fine orientation control through stored angular momentum. Magnetometers measure the magnetic field to guide magnetorquer activity, and sun sensors offer a reliable external reference for attitude determination. These components are lightweight, cost-effective, and widely used in small satellite missions operating in low Earth orbit. An Inertial Measurement Unit (IMU) will also be included for increased precision.

For three-axis control and stabilization, the system will use three RocketLab RW-0.003 reaction wheels, each aligned with the satellite's x, y, or z-axis. These wheels provide a nominal torque of 0.003 Newton-meters and can reach a peak torque of 0.005 Newton-meters at 5 volts. To manage excess angular momentum, each reaction wheel will be paired with an EXA MT01 Compact Magnetorquer, which generates a nominal magnetic moment greater than 0.19 Amperes-square-meter. Attitude determination will rely on three Space Inventor IMU-P4 units, eight TensorTech CSS-10 coarse sun sensors, and four TensorTech FSS-15 fine sun sensors. The IMUs measure angular velocity, acceleration, and magnetic field strength, while the sun sensors provide sun-angle measurements with accuracies of ±5 degrees (coarse) and ±0.1 degrees (fine). These components will be housed in compact aluminum frames, with three frames integrated into a single U of the CubeSat, ensuring balanced torque application and optimal performance.

G. Data and Communications

The UHF frequency band was chosen for CLEOSATRA's communication system due to its reliability and effectiveness in CubeSat operations. UHF offers a lower data rate than other choices, however, the mission will not require large volumes of data to be transmitted to the ground station. This frequency band is largely used in CubeSat communications and has a simple licensing process and large options for ground support. By selecting the UHF frequency band, CLEOSATRA can use existing infrastructure and simplify the overall communication strategy. This choice will also allow for effective communication in LEO, where the mission will occur, ensuring connection with the ground station.

A dipole antenna was selected for CLEOSATRA due to its simplicity, effectiveness, and reliable performance in the UHF frequency range. This antenna will provide an omnidirectional radiation pattern, this will allow for easier communication with ground station and simple pointing for the control system. The dipole antenna is compact and lightweight, making this an ideal fit for the limited space constraints of the CubeSat. The deployment system of the dipole antenna is less complex than other choices and will allow for a reliable deployment during the mission. The dipole antenna will meet the mission requirements and allow for effective communication.

The half-duplex UHF transceiver was chosen for its cost-effectiveness, effective power consumption, and integration simplicity. This transceiver type allows for the transmission and reception of signals on a single channel, which will reduce the complexity of the communication system. This design will be useful for the data transmission mission requirements, as it will manage the transfer of telemetry data without the need for a complex design. The half-duplex transceiver will align the power budget, ensuring that communication can occur without having a significant effect on the CubeSat's energy resources. This selection will support the operational needs of CLEOSATRA while being reliable and efficient.

H. Ground Station

Through the trade study process, the UHF frequency was selected for ground station-to-satellite communication due to its favorable characteristics for CubeSat missions, including lower power consumption and reduced atmospheric interference, making it ideal for long-range communication in space. For cloud-based commercial networks, such as InfoStellar and KSAT, UHF provides compatibility with existing ground stations and satellites, offering global coverage and flexibility. AWS Ground Station Network was particularly advantageous due to its on-demand scalability, lower costs for intermittent communication, and integration with AWS cloud services, making it a cost-effective solution for managing satellite data and operations. The ground station for CLEOSATRA's mission will involve the use of AWS Ground Station's various locations across the globe.

IV. Results

CLEOSATRA will serve as a 3U computational satellite which demonstrates the use of a novel radiation-shielding technique and characterizes its effectiveness. CLEOSATRA's Orbit is targeted for 1000 km altitude, an inclination of 43°, and passing over the South Atlantic Anomaly, enabling optimal communication coverage and radiation incidence. Over the year-long mission CLEOSATRA must sustain the critical radiation bands: Protons from 0.1-0.3 MeV, Electrons from 0.04-0.2 MeV, and Galactic-Cosmic Rays from 10-500 MeV/nuc. CLEOSATRA shall employ a shielded reference and an experimental unshielded computer, to monitor and compare shield functionality.

A. Payload: Radiation Sensing

The Mini Gamma, electronic scintillator, radiation sensor was selected as the radiation detector best suited for CLEOSATRA's mission. The Mini Gamma detects x-rays and gamma rays from 30keV to up to 3MeV. The sensor is connected to a custom discriminator circuit with an LM311P comparator. The sensor is connected to both processor through the communications Arduino onboard. During the following experiment to characterize the sensing capabilities of the Mini Gamma sensor a low-level radiation source (a household banana) was exposed to the sensor. As the radiation sample sat under the sensor, there were seen to be both small and large spike in radiation.

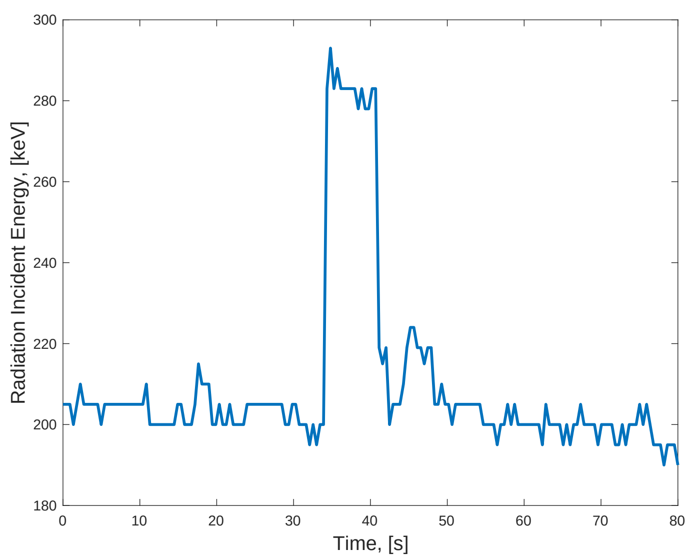

Figure 1. Plot of Mini Gamma radiation sensor and circuit data over time.

CLEOSATRA's radiation detection algorithm, "Detection.py," incorporates system health checks on the Raspberry Pi's CPU to determine if the computer has experienced memory latch or single error events have occurred. The algorithm logs the occurrence to the error log file, which will be parsed and sent down to the ground station via the transceiver. This detection algorithm, eventually the communication and watchdog circuit, needs to be tested thoroughly before launch. The detection-logging python script written by the CLEOSATRA design team is the Appendix, and was used to stream data over WIFI and log data to the error file. The error log file will be streamed over UHF frequencies instead of WIFI and the WIFI unit will be toggled off for the mission duration to save on power consumption. Figure 2 shows a snippet of the error detection working and subsequently increasing in count. This excerpt contains timestamps for all detections for tracking over time and position.

```
2024-11-14 00:05:00,766 - WARNING - Detected 1789 error(s) in system logs.
2024-11-14 00:05:00,874 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:11,927 - WARNING - Detected 2760 error(s) in system logs.
2024-11-14 00:05:12,011 - CRITICAL - Potential radiation-induced error detected!

2024-11-14 00:05:23,064 - WARNING - Detected 2760 error(s) in system logs.
2024-11-14 00:05:23,152 - CRITICAL - Potential radiation-induced error detected!
```

Figure 2. Excerpt from radiation detection log that will be sent to ground station.

B. Payload: Radiation Shield

Bulk aluminum shielding is the industry standard for a direct shielding material, due to the relatively light mass of aluminum compared to other metals [15]. The mass and volume are a major downside of utilizing aluminum block shielding. Modern shielding developments use engineered coatings to solve radiation penetration. Dr. Hayes' work designing a conformal coating doped with heavy metals offers a competitive design alternative to bulk aluminum shielding [4]. The conformal coating offers custom shielding with selective levels of radiation tolerance. Discussion with the PhD student developing the coating, with Dr. Hayes, is being established to obtain direct Total Ionizing Dose ratings per thickness measurements and other specifications of the conformal coating. The mass attenuation's for the different shield material is given in Figure 3. It shows how the NCSU-developed coatings doped with heavy metal oxides of gadolinium and tungsten. The tungsten oxide coating attenuated slightly more mass flux across the tested energy range. Where, the range is specifically tuned to the frequencies that are most common in LEO.

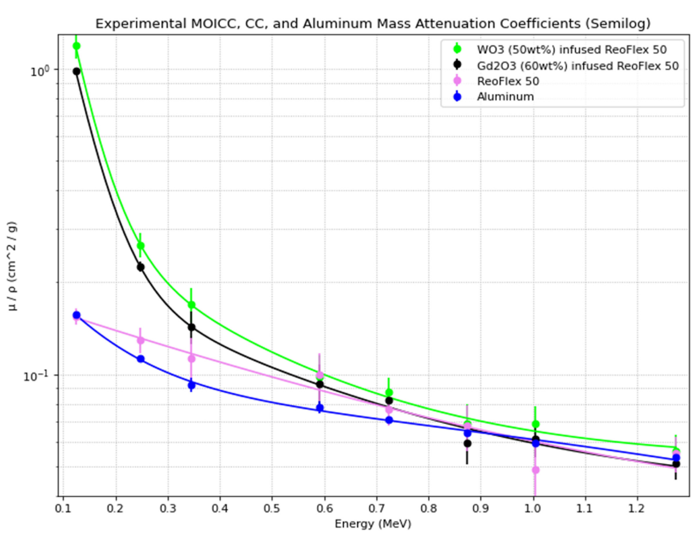

Figure 3. Mass attenuation of typical shield materials along a span of energies.

Figure 4 details the tungsten oxide coatings results separated from the others, as this oxide is specifically mentioned as the preferred option for spacecraft systems. There is high mass attenuation at energy levels of less than 150 keV, and exponentially drops off to similar levels as aluminum block shielding at 800 keV. The electron and proton flux are highest in LEO at 0.1 to 1MeV energy levels, which implies this is the best option for radiation shielding available. Future testing of the payload system with the coating applied will be exposed to a nuclear reactor at NCSU's Nuclear

Engineering Department with Dr. Hayes.

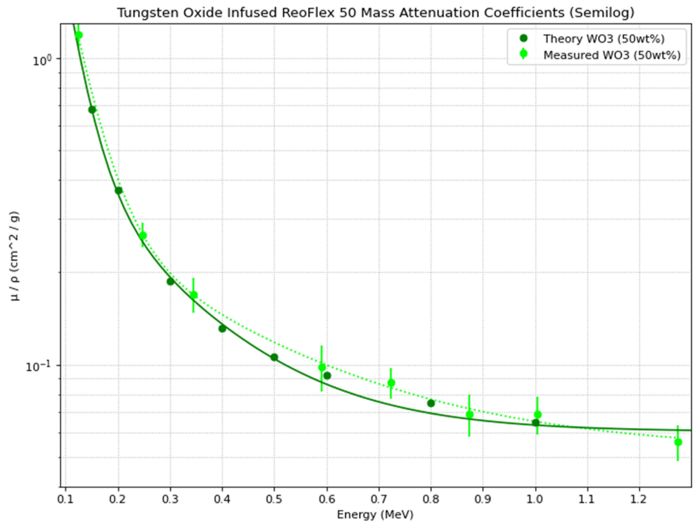

Figure 4. Tungsten oxide mass attenuation along typical energy levels.

C. CONOPS

The concept of operations, or CONOPS, describes the different phases that CLEOSATRA will undergo in order to carry out its mission. The first phase of the CONOPS includes the rideshare launch into LEO on a commercial rocket. The second phase encompasses the initial ejection from the P-POD system into the designed orbit along with a satellite de-tumbling procedure. From there, CLEOSTRA will deploy both the RF antenna and solar panel arrays. Upon the battery being charged for the first time, the CubeSat will begin its subsequent power-up sequence. This is the start of mission phase 4, when CLEOSATRA will log radiation-based data loss or corruption and communication failures. The bulk of the experimentation is then utilized to determine the effectiveness of the conformal coating shield in response to the LEO environment. The final, post-experimentation, mission phase will include the end-of-life plan for CLEOSTRA where a dragsail will be deployed to lead the satellite to succumb to atmospheric drag and burn up upon reentry. The CONOPS diagram can be found in Figure 5.

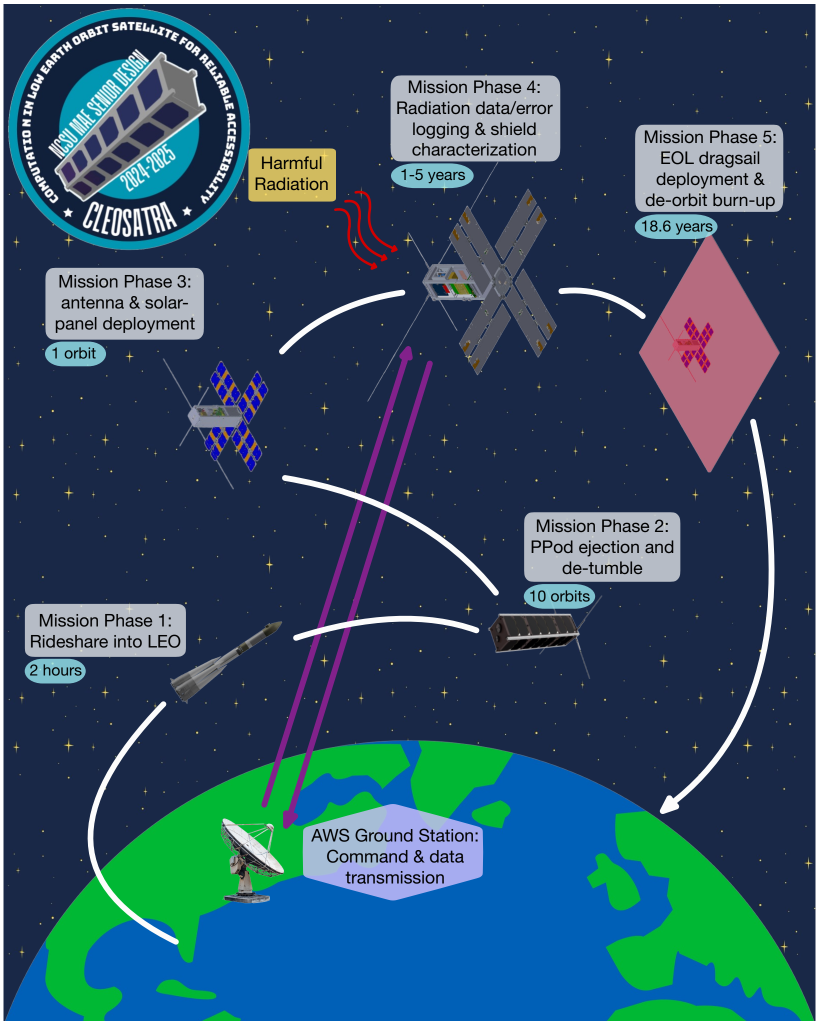

Figure 5. CONOPS Diagram showcasing the different phases of CLEOSATRA's mission.

D. Functional Block Diagram

The functional block diagram dictates the communication bridges inside CLEOSATRA. The CubeSat will house all subsystems except for the ground station, which will be communicated with via RF transmissions from the C&DH subsystem. The block diagram shows the relationship between each subsystem, specifically how they communicate, how power is provided, and how control is directed between the subsystems. Data collected by the each subsystem's sensors is parsed for losses and corruption in the payload and processing system. This information is logged and streamed down to the ground station for analysis. Power is provided from the solar panels and charging system through the power-network bridge to each subsystem. The processor will alter the CubeSat's orientation or activate thermal adaptation if either sensors indicate the necessity for control or if the ground station does. The central payload processor branch will have full command over the spacecraft's subsystems. The functional block diagram for CLEOSATRA can be found in Figure 6.

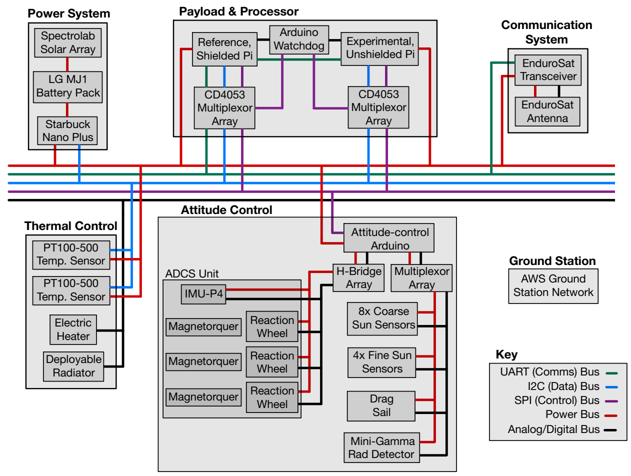

Figure 6. The functional block diagram, representing CLEOSATRA's design at the subsystem level.

V. Discussion

Radiation can have consequential effects on satellites, from data malfunctions to mission critical component failure. One way to protect satellite electronics against radiation is to use rad-hard designs, which can be costly and time consuming [2]. Although these designs do succeed in protecting electronics from degradation, they reduce the computing capacity and processing speed of the components, making them inefficient compared to the widely available ones used on Earth [3].

The space industry needs a way to provide reliable radiation protection for electronics without changing the underlying electronic components from their COTS design. CLEOSATRA's mission is to find a way to accomplish this task and will do so by testing the reliability of an alternate form of radiation protection in-situ. The data that will be gathered from this mission would revolutionize the current industry by exponentially increasing the computational capability of satellites and other orbiting vehicles. Additionally, the ability to use high-level electronics in space will inherently prompt technological advancement of space-grade equipment across many fields.

Many groups, including the Airforce Research Laboratory (AFRL), NASA, and the DoD are conducting research to determine ways to increase computing power available for electronic components in space. Specifically, the Air Force Research Laboratory (AFRL) is actively researching the deployment of cutting-edge AI workloads that require advanced chipsets capable of high-performance computing in space environments [4]. Success of the CLEOSATRA mission would lead to the advancement of computing power in space by allowing for COTS electronics to be widely used for various missions.

Some potential limitations include the method of creation of the rad-hard technique, as it must be created to target a specific amount of radiation exposure. Any significant change in the orbit path or radiation exposure outside the intended level could result in the coating not protecting the COTS electronics, leading to radiation damage. Additionally, there can be issues with the most efficient way to coat the electronic, as there must be a specific coating layer based on the radiation level expected. The coating can either encase a specified volume with the electronic inside, or could be sprayed directly onto the electronic depending on its function. Overall, volume constraints must be included in discussion about what the coating will protect or where it will sit inside the satellite.

Beyond CubeSats, developing methods of radiation hardening is an important components for all space activities and nuclear capabilities on Earth. Successful testing and validation of the conformal coating will allow for the widespread use of COTS electronics in all space-faring vehicles, allowing for the use of modern electronic equipment and more powerful on-orbit computation. Additionally, the coating is much lighter and cheaper than traditional rad-hard techniques, allowing for more less weight restriction, more affordable designs, and increased accessibility.

VI. Conclusion

The CLEOSATRA CubeSat mission will allow for the initial testing of new rad-hard techniques, such as the NCSU Metal-Oxide Impregnated conformal coating, in orbit. It will demonstrate a feasible step toward less expensive and lighter radiation hardening techniques. The integration of a COTS computing payload, shielded by the experimental NCSU conformal coating, highlights CLEOSATRA's unique contribution to radiation-tolerant systems in space. Analyzing the effectiveness of a low mass penalty radiation shield will allow for more powerful electronics in space, along with providing the widespread use of COTS electronics in space and a more accessible satellite.

Further research could focus on the most effective means of protection and refinement of the use of newer rad-hard techniques like the conformal coating described in this study. Specifically, the best way to house the electronic, should it be a skin-layer coating of each part or a container that houses multiple electronics. Further testing of new rad-hard techniques will be needed to validate on-Earth testing values and address concerns surrounding the containment of the electronics.

Appendix

A. CAD Model

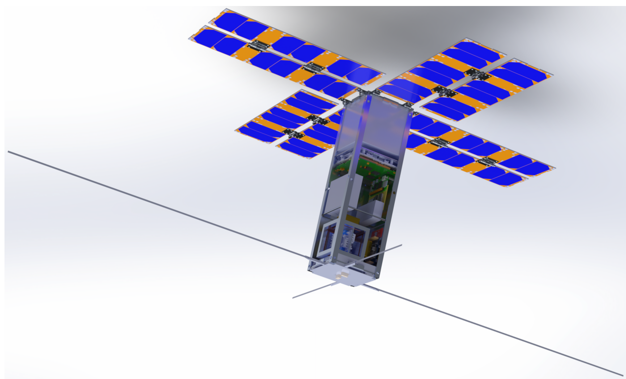

Figure 7. CLEOSATRA isometric view (side panels removed)

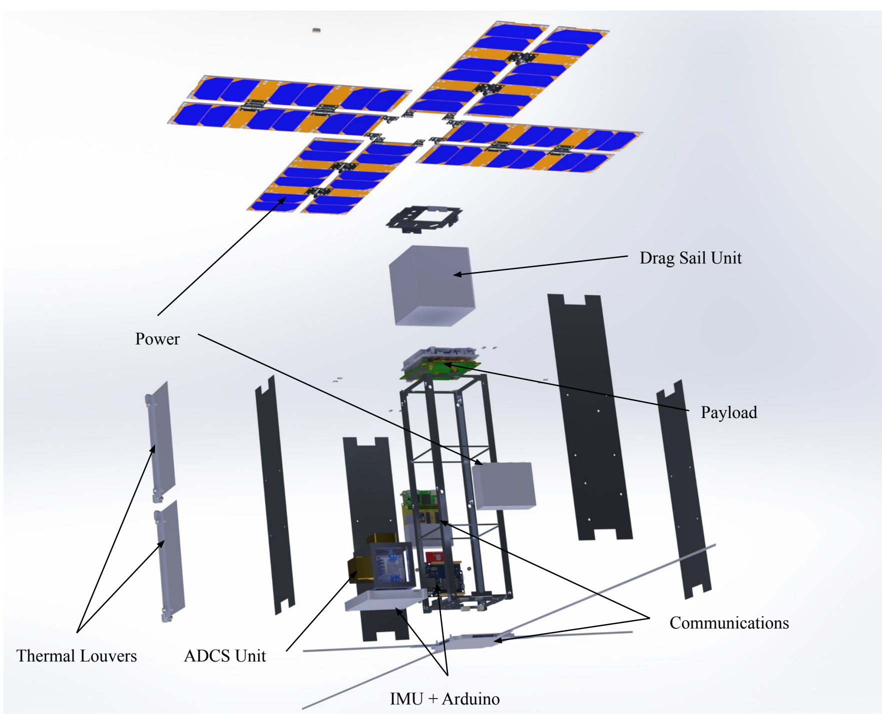

Figure 8. CLEOSATRA Components

Acknowledgments

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