NASA CSLI Proposal: FluxSat

Submission in Response to Announcement of Partnership Opportunity CubeSat Launch Initiative

Submitted by:

Canyon Crest Academy Aerospace Club % San Diego Air and Space Museum

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Cubesat Mission Parameters

CubeSat Mission Parameters	Value	
CubeSat Mission Name	FluxSat	
Mass (kg)	1.25 kg	
Cube Size (ex., 1U, 2U, 3U, 4U, 6U)	1U	
Rail/Tab Length (mm) (ex., 340.5 mm, 366 mm)	113.5 mm	
Readiness Date for Integration to Dispenser	09-01-2026	
Desired Orbital Lifetime after Deployment (years)	1	
Designated Operational Lifetime (years)	1	
Is an ISS deployment acceptable (~400 km @ 51.6 degree inclination)? Yes or or No	Yes	
Is a Sun Synchronous Orbit (SSO) acceptable? Yes or No	Yes	
Sun Synchronous Orbit (SSO) required? Yes or No	No	
Is the proposed mission compliant with the limitations in Section 5.1, or is an exception requested for consideration?	Yes	
Orbital Parameters	**Desired/Preferred Range**	**Acceptable Range**
Altitude (km)	400 km	325-450 km
Inclination (degrees)	45°	45-75°
Mean Local Time of the Ascending Node (MLTAN). N/A as SSO is not acceptable.	10:00-14:00	8:00-16:00

Table 1: Mission Parameters

CubeSat Project Details Table

CubeSat Project Details							
		NASA Funding		*Sponsoring Organization(s)*	*Collaborating Organization(s)*		
Focus Area(s) Note: Select as applicable per requirements fo Appendix A or B.		*Yes or No*	*Organization*		*List*	*International* Yes or No*	
Education	☑	No	NA	Canyon Crest Academy	None	No	
Science	☑	No	NA	San Diego Air and Space Museum	• Reuben H Fleet Science Center • San Diego Air and Space Museum	No	
Technology	☑	No	NA	Wswan Inc.	None	No	

Table 2: Project Details Table

Points of Contact

Team Contact Information				
Name	*Title*	*Email*	*Phone Number*	*Address*
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 3: Contact Information

Proposal Abstract

The students of the Canyon Crest Academy Aerospace Club, under the supervision of Dvora Celniker, the San Diego Air and Space Museum, and the Reuben H. Fleet Science Center have developed a design proposal for the NASA CSLI AoPO. FluxSat will test an innovative energy-harvesting concept, leveraging the principles of Faraday's Law to generate electric current through a loop of wire by electromagnetic induction. By orbiting Earth with a rotating loop of conductive wire, FluxSat intends to measure magnetic flux variations and induced current and potentially charge onboard capacitors. Through this proof-of-concept mission, FluxSat will assess the practicality and feasibility of using Earth's magnetic field to power CubeSats and other low-power satellites, potentially paving the way for future missions with greater autonomy from traditional power sources such as batteries and solar panels.

To execute its mission, FluxSat will be equipped with precise instruments to measure the induced current and an onboard capacitor to attempt energy storage. The satellite will monitor changes in magnetic flux as it traverses Earth's magnetic field, recording data on orbital variations, position, and orientation to optimize current induction. This data will provide valuable insights into how consistently the Earth's magnetic field can yield usable power, and if the technology can scale for future applications. By examining these aspects, FluxSat aims to contribute significantly to the field of space energy technologies, with the potential to support extended missions into regions where traditional power sources are insufficient, such as the soon-to-be launched JPL INSPIRE mission or other deep space missions orbiting around planets or moons with a strong magnetic field.

In addition to its primary mission, FluxSat will also attempt to evaluate the suitability of Polyetheretherketone (PEEK), a high-performance thermoplastic, as a material for CubeSat structures. This secondary mission addresses a growing interest in lightweight, durable, and cost-effective materials that can be 3D printed in space. FluxSat's PEEK structural frame will be exposed to space conditions for the duration of the mission, and data on performance, longevity, and resilience will be collected. If successful, this experiment could introduce PEEK as a viable alternative to traditional metals like aluminum and titanium, offering benefits in manufacturing flexibility, repairability, and cost-efficiency.

FluxSat is designed with the FCC's "5-year rule" for Deorbiting Satellites in mind and will use the satellites own drag decay to bring it down to the earth. Along with FCC compliance, FluxSat is compliant with NASA's Strategic goals. The Primary Mission is compliant with goals 3.1, 1.1 and 4.2 which focus on novel technologies, and fostering technological innovation. Our

secondary mission is complaint with goals 2.2, 2.4, and 4.2 which focus on sustainability and cost-effectiveness

With a focus on sustainable energy sourcing and innovative materials, FluxSat aligns with NASA's objectives to advance technology, address the challenges of long-duration missions, and explore alternative resources for space exploration. By evaluating both energy generation through electromagnetic induction and the use of space-grade thermoplastics, FluxSat represents a forward-looking approach to enhancing CubeSat capabilities.

Proposal Details

1. Primary Mission:

Earth's magnetic field is an incredibly variable and complex body that protects the planet from solar wind and cosmic radiation. These variations are influenced by various factors, including solar activity, Earth's core dynamics, and atmospheric processes. While the field is relatively stable, turbulent and highly dynamic regions exist, especially near the polar regions, where the interaction with solar radiation induces significant variations. The primary goal of this mission is to measure the current generated across a conductive loop in response to the variable magnetic fields present around the Earth. This data could shed light on magnetic turbulence patterns and evaluate the feasibility of utilizing such geomagnetic interactions as a potential alternative power source for small, low-energy space instruments.

The European Space Agency (ESA) launched the Swarm mission in November 2013, consisting of three identical satellites that monitor and map Earth's magnetic field with unprecedented accuracy in near-polar orbit. These satellites have provided crucial insights into the magnetic field strength originating from various parts of the Earth. However, due to the larger scale and complexity of the Swarm mission, smaller satellites have yet to replicate or extend this observational ability on a cost-effective scale. Inspired by Swarm, this mission helps demonstrate how a CubeSat could contribute to similar research at a much lower cost, mainly focusing on turbulent magnetic field regions that might offer insights into Earth's magnetic field fluctuations.

Earth's magnetic field varies due to solar activity and the internal motion of Earth's liquid core. This variability is most notable near the polar regions, where channeled solar winds interact with the field and the atmosphere. Understanding these variations may help inform space weather models, improving predictions for geomagnetic storms, which have implications in satellite communications and other infrastructure. This understanding may also benefit research on energy generation utilizing motion through the field. Prior research suggests that current can be induced across a conductive path when there is time-varying magnetic flux, which is the basis of the proposed CubeSat experiment.

Power generation from Earth's geomagnetic field is centered around Faraday's Law of Electromagnetic Induction. A time-varying magnetic field will lead to the induction of an electromotive force in a conductive loop. While this method of power generation is impractical for higher-power applications, this mission aims to explore the feasibility of lower-power energy for small electronics in missions where constraints limit other alternatives.

The satellite aims to measure current generated by magnetic flux across multiple points within its orbit, providing data on how effectively electromagnetic energy from Earth's field can be converted into usable power. The spacecraft is equipped with a large conductive loop of wire, which, in combination with the rotational motion of FluxSat as it orbits Earth, is designed to generate an electric current by leveraging Faraday's Law. According to Faraday's Law, a change in magnetic flux through a closed loop induces a current within that loop; in this context, as FluxSat's wire loop moves through varying strengths of Earth's magnetic field, it experiences changing magnetic flux, which should induce a measurable current. The mission seeks to quantify these effects to determine if sufficient power could be generated to support spacecraft systems, potentially reducing reliance on traditional power sources like batteries or solar panels.

To test this concept, FluxSat will be fitted with instruments to measure the induced current, as well as an onboard system capable of attempting to store this energy in a capacitor. This capacitor serves as a proof of concept, demonstrating that energy captured from Earth's magnetic field can be accumulated and stored. Data collected by the satellite will be analyzed to understand fluctuations in current due to orbital position, speed, and orientation relative to the Earth's magnetic field. The mission will also assess how efficiently this harvested energy can be stored and if it can be scaled for practical use.

Should FluxSat succeed, this new approach could pave the way for a new generation of CubeSats, enabling long-duration missions with more autonomy and reduced dependency on finite energy reserves or solar power, especially for missions venturing into regions where solar energy is less accessible.

1.1 Viability of Induction

The viability of electromagnetic induction for energy generation in space, as proposed for FluxSat, depends largely on the ability of a rotating conductive loop to consistently generate a measurable current through the Earth's magnetic field. According to Faraday's Law, a time-varying magnetic flux through a closed loop induces an electromotive force, or EMF. In this context, FluxSat's orbit through regions with variable magnetic flux, such as those near the poles and equator, offers promising conditions for current induction. Although the magnetic field strength is relatively weak, continuous movement and the carefully engineered alignment of the conductive loop could yield low but usable levels of power. This proof-of-concept mission seeks to demonstrate that even modest current levels, if reliably produced, could be captured and stored in onboard capacitors, potentially sustaining low-energy satellite operations without traditional energy sources like solar panels or batteries.

However, challenges to this approach remain. The induced current is expected to be small, making it difficult to harvest without highly sensitive instrumentation. FluxSat's design incorporates a silver coil to minimize resistance, improving the efficiency of current generation despite the low intensity of Earth's magnetic field. Additionally, the satellite's rotation must be precisely controlled to maximize flux variation across the loop, aligning with the magnetic field direction to induce the greatest EMF. If successful, the mission would validate this approach as a supplementary power source for small, low-power satellites and could serve as a pioneering step toward self-sustaining satellite missions in regions where traditional energy sources are unreliable or inaccessible.

1.2 Data Collection

The spacecraft will collect data on the magnetic field throughout its orbit using a magnetometer to measure the vector quantity of the Earth's magnetic field at a specific point in the orbit. As the Earth's magnetic field is relatively uniform over a very small distance it can be assumed that the magnetic field vector passing through one point on the spacecraft is roughly equivalent to the magnetic field vector over the entire surface of the spacecraft. From this the spacecraft will be able to calculate the magnetic flux through the coil by integrating the magnetic field vector with respect to the entire spacecraft's surface area. This will allow a single magnetometer placed within the CubeSat to extrapolate the magnetic flux through the spacecraft when rotating.

The procedure for acquiring the information will have the spacecraft record data about the magnetic field prior to giving the spacecraft any significant angular momentum by using a 3-axis magnetorquer system. This is the most reliable procedure that the spacecraft can have as recording the direction of the Earth's magnetic field, while rotating is likely to introduce small errors in the calculation. This will also allow for the spacecraft to determine the axis in which it will rotate. By determining the direction of the field line the spacecraft will be able to spin itself and the coil within the field line which will ensure that the maximum current is generated by having the component of orientation that leads to induced current directly aligned with the field line.

1.3 Component Standards

In order to realize the greatest amount of current from the magnetic flux of the Earth's magnetic field, it is necessary to minimize the resistance of the coil material. A silver coil, while it would increase the cost of the overall project, would increase the odds of a significant finding, as the very low resistance of the material would increase the chance of a noticeable EMF with a less precise ammeter. However the application of this case will still require a reasonably accurate ammeter (sensitive to least 10^{-6} amperes), as the expected current generated is very small, and thus greatly precise and sensitive equipment will be required.

1.4 Mathematical Theory

Applying Faraday's law:

$$\varepsilon = -\frac{\delta\Phi}{\delta t} \Rightarrow I = \frac{\varepsilon}{R}$$

Where:

ε is the electromotive force

R is the resistance of the coil

I is the induced current

$\Phi = \int_L \int_A B \bullet dA$ is the electromagnetic flux through the coil

L is the length of the coil

A is the cross sectional area of the coil

B is the experimentally determined magnetic field vector of earth

The magnetic flux Φ can be expanded to account for the directionality of the cross sectionally orthogonal vector and the vector of the magnetic field B:

$$\Phi = \int_L \int_A B \cdot dA \cdot cos(\theta)$$

Where θ is the angle between the orthogonal vector to the cross section and the magnetic field vector

Which can be simplified:

$$\Phi = \int_L (B \cdot cos(\theta) \int_A dA)$$

$$\Phi = \int_L B \cdot A \cdot cos(\theta)$$

$\Phi = L \cdot B \cdot A \cdot cos(\theta)$

Accounting for the angular velocity, $\theta = \omega \cdot t$:

$\Phi = L \cdot B \cdot A \cdot cos(\omega \cdot t)$

Plugging in:

$\varepsilon = -\frac{\Delta\Phi}{\Delta t} = L \cdot B \cdot A \cdot \omega(sin(\omega t))$

Thus:

$I = \frac{\varepsilon}{R} \Rightarrow \frac{L \cdot B \cdot A \cdot \omega(sin(\omega t))}{R}$

2. Secondary Mission:

FluxSat's Secondary Mission is to assess the viability of Polyetheretherketone (PEEK) as a space-grade material for CubeSats in Earth orbit. PEEK is a high-performance thermoplastic that has started to be used in the fields of aerospace and astronautics, specifically in the field of small satellites including CubeSats. With a low density, high tensile strength, excellent thermal insulation, and the ability to be 3D-printed in space, PEEK has the potential to replace conventional space materials such as aluminum and titanium with a much greener solution.

As FluxSat's Secondary Mission, we will use PEEK material as the structural frame of FluxSat, exposing the material to the space environment. Through FluxSat's operational lifetime and a detailed scenario evaluation table, we will evaluate the potential of PEEK as a material for future cube satellite missions.

2.1 Current Space Materials

Spacecraft materials have to meet very strict requirements due to extreme conditions such as high radiation, extreme temperatures, and vacuum exposure. Key materials are traditionally titanium alloys and aluminum alloys, given their lightweight and resilient nature. As the research in space materials continues to advance, thermoplastics like PEEK begin to be more viable options.

There are fundamental issues with the space materials used today. Materials like titanium and aluminum require very specialized and complex machinery to be manufactured properly, and while the field of 3D design and printing is advancing, the current technology is not enough to be able to viably produce satellites on board the ISS as they are slow and have a marginally high fail rate. Additionally, replacing or repairing these metal parts in space is challenging, while a material like PEEK would be much easier to replace, given the ability to 3D print on board the ISS. Titanium and aluminum are not as expensive as raw materials, but the high costs of machining and transporting them due to their being heavier make PEEK a much more affordable alternative, allowing for more performance on a tighter budget.

Currently, there are no PEEK CubeSats in space today. Titanium and aluminum have a well documented history in space applications, and known performance allows for reduced mission risk. Titanium and aluminum are also much more impact resistant, yet this is less of a problem as the chance for any debris impact is negligible. Thermoplastics like PEEK are able to withstand the everyday conditions of operating in space with ease. While the price for PEEK material is high, the manufacturing costs are far less than traditional materials. The increasing accessibility of in-space manufacturing via 3D printing of polymers may drive the industry to widespread adoption of PEEK, and our CubeSat mission aims to demonstrate the feasibility of the material.

Material Properties Comparison:

	Aluminum Alloys (7075)	Titanium Alloys (TI-6AI-4V)	PEEK
Density (g/cm^3)	2.81	4.43	1.3
Tensile Strength (MPa)	510-540	880-950	170
Thermal Conductivity (6.7-7.5W/m*K)	130	6.7-7.5	0.295
Thermal Expansion Coefficient (µm/m*K)	23.5	8.6	47
Cost ($/kg)	5-10	60-80	150-300
Advantages	Lightweight, medium ease of machining, good thermal and electrical conductivity	High strength-to-weight ratio, excellent corrosion resistance, and good thermal stability	High temperature resistance, chemical resistance, very easy to manufacture
Disadvantages	Lower strength compared to titanium and steels, susceptible to oxidation and stress corrosion cracking	Expensive and difficult to machine, especially in complex shapes; requires careful processing to avoid cracking	Lower tensile strength, reduced thermal conductivity

Table 4: Material Properties Comparison

2.2 Potential of PEEK as a Space Material

The integration of PEEK into CubeSat structures would conserve weight, serve multiple purposes, and minimize the overall cost. PEEK has a variety of properties that make it suitable for use in space, including the ability to withstand the vacuum conditions and temperature fluctuations that occur in space. Additionally, it has recently been used to incorporate electrical pathways directly into the structure of the satellite itself. Overall, PEEK is a material that can serve as a potential replacement to typical aluminum structures with a host of added benefits.

One of the most important characteristics when considering a material for use in satellites is its mechanical strength. The minimum requirement recommended for use in satellites is the ability to withstand 1200N of applied force. PEEK has a tensile strength of 95.52 MPa, meaning the minimum cross sectional area for each part of the structure would be 12.6 mm^2. The actual stress distribution is not just tensile however, which must be considered when evaluating a material to use. Typical spacecraft aluminum does display higher tensile strength, yet PEEK has a lower overall mass and exceptional chemical and thermal resistance, as well as being able to be manufactured easily using 3D printers. Currently, Portuguese company Orion Additive Manufacturing is looking to launch their AMCUBE mission, which is a 3D printed PEEK cubesat.

Thermoplastics propose an exciting new way of manufacturing CubeSat and other satellite structures. A very powerful benefit is the ability to potentially manufacture these structures on board the ISS with a 3D printer. As PEEK can be manufactured in space, with the materials needed being light and taking up relatively little space, this poses a new avenue for both manufacturing new satellites and parts needed to use in the ISS. PEEK also reduces the cost, especially on the small scale of cubesat missions, being around half of the cost. Additionally, there is current research on the feasibility of incorporating the wiring of electronic systems directly into the structure, reducing the points of failure for the CubeSat.

2.3 Mission Execution and Scenario Evaluation

We will use PEEK for FluxSat's structural frame. Through FluxSat's exposure to the space environment for the duration of our mission, we will evaluate the viability of PEEK as a structural material for cube satellite missions. The form of evaluation will be a detailed table correlating each possible end-of-lifetime scenario with an assessment on PEEK performance (C.2.1 Scenario Evaluation Table). The factors we will consider are sensor data including altitude, power level, and temperature, and the operational lifetime of FluxSat based on our last received transmission. We are also looking into potentially incorporating a strain gauge sensor for a more quantifiable evaluation of PEEK over the mission lifetime.

The operational lifetime of FluxSat will be our main factor of consideration. If FluxSat meets or exceeds the average CubeSat lifetime of 1.1 years, then we can conclude that FluxSat's PEEK structure had the durability to withstand space conditions until FluxSat re-entered the atmosphere, thus showing that PEEK is highly viable for future cube satellite missions. However, if FluxSat falls significantly below the average CubeSat lifetime, then sensor data will be used to assess if FluxSat's end-of-lifetime was due to a compromise in the PEEK structure or electronic failure.

If we determine a high likelihood that FluxSat's early end-of-life was due to electronic failure, then we are unable to accurately assess the performance of PEEK and make a conclusion on its viability for future missions. Thus, we have comprehensively determined our failure scenarios and planned mitigation for electronic failure (C.9 Failure Scenarios).

2.4 PEEK Compliance with Primary Mission

A key criterion of FluxSat's secondary mission is that it does not interfere with the primary mission. If our PEEK structure fails early in the mission, it may compromise FluxSat's scientific payload and result in an insufficient amount of data collected to accomplish the primary mission.

To ensure full PEEK compliance with the primary mission, we will conduct intensive testing of FluxSat's PEEK structure prior to integration. We will assess the ability of FluxSat's structure to withstand space conditions through vibration, stress, and thermal tests. We will design our structural frame using CAD (Computer Aided Design) and run simulations to ensure structural integrity, insulation, and protection of our electronics. If at any point in our testing we determine that FluxSat's PEEK structure is not viable, we will use an alternative material such as aluminum to not compromise our primary mission.

3. Compliance with NASA Strategic Goals

The FluxSat is designed with full compliance with Launch Services Program Requirements Document (LSP-REQ-317.01B) and The Cal Poly CubeSat Design Specification (CDS).

3.1 Primary Mission Compliance

FluxSat's Primary Mission directly targets NASA's Strategic Goal Objectives 3.1, 1.1 and 4.2

Objective 3.1 focuses on NASA's goal to foster innovation and push forward transformational space technologies through the development of novel approaches and the reimagining of existing technologies to expand NASA's technical expertise. FluxSat aligns with this objective by pioneering the concept of electromagnetic induction as a new potential power source in long-term small spaceflight, using Earth's magnetic field to induce electric current. This approach, centered on Faraday's Law of Electromagnetic Induction, represents a significant step in power generation technology for spacecraft, especially small satellites. If successful, FluxSat will contribute to NASA's technological toolkit by showcasing the feasibility of using natural interactions as a renewable, cost-effective energy source for low-power, long-duration space missions.

Objective 1.1 calls for an increased understanding of the Earth system, including its climate and magnetic dynamics. FluxSat directly contributes to this objective by collecting and analyzing data on magnetic flux variations across different orbital locations around Earth. Through precise measurements of magnetic field strengths at multiple points, FluxSat will contribute to a better understanding of Earth's magnetosphere and the influence of solar activity on magnetic turbulence, particularly in high-variability regions like the polar and equatorial zones. This data will provide valuable insights into Earth's dynamic magnetic environment and contribute to broader climate and space weather models, supporting NASA's goal of enhanced Earth system understanding.

Objective 4.2 emphasizes NASA's commitment to advancing mission-support capabilities for future space exploration by encouraging the development of transformative technologies. FluxSat embodies this principle by exploring a fundamentally new paradigm in on-orbit power generation, utilizing Earth's magnetic field as an energy source. By investigating the practicality of geomagnetic energy harvesting, FluxSat may lay the groundwork for small-scale power systems that enable greater independence from traditional energy sources, such as batteries and solar panels. This capability is especially critical for missions to the many distant stars and planets, paving the way for self-sustaining CubeSats and small satellite missions that are capable of extended operations with minimal energy resupply.

3.2 Secondary Mission Compliance

FluxSat's Secondary Mission directly targets NASA's Strategic Goal Objectives 2.2, 2.4, and 4.2.

Objective 4.2 outlines NASA's goal to support "environmental stewardship, sustainability, and enhancing resource conservation efforts" for the next era of aerospace. PEEK is a promising space material that would meet the sustainability and resource conservation requirements set by NASA. Resource conservation is crucial with the cost and complexity of sending a payload to space, especially for deep space missions. As a thermoplastic, PEEK can be reshaped under heating, allowing the material to be recycled and reused for new applications. With the ability for the same material to be used multiple times without a downgrade in performance, PEEK increases the productivity of in-space manufacturing and enhances the production of crucial replacement parts. In addition, it has exceptional durability and resistance to extreme temperatures and radiation and has longer lifetimes than traditional material components. Components would require fewer replacements over the life cycle of a space mission, making PEEK a sustainable option that conserves resources and minimizes waste. Combined with the fact that PEEK can be recycled and reused, PEEK is an extremely viable material to address NASA's goal of sustainability and resource conservation.

Objective 2.4 outlines the need to "provide cost-effective, mission-essential services … for America's human and robotic missions." With plans for more in-orbit spacecraft and deep space missions, cost-effective and replaceable components are crucial to mission feasibility and success. PEEK can be 3D-printed, which is an extremely cost-effective and efficient manufacturing tool for space applications. PEEK costs roughly $150-300 per kilogram, compared to $2,000-$3,000 per kilogram for a payload on the Falcon 9 to LEO. The drastic advantage in cost makes 3D printing with PEEK a viable alternative compared to conventional payload delivery. PEEK can also be used to replace components onboard spacecraft. This is especially crucial for future deep space missions where the feasibility of sending a payload supply is extremely low. A crewed mission needs in-space manufacturing for a variety of applications including part replacements, and with excellent strength-to-weight ratio, thermal insulation, and chemical resistance, PEEK is a promising material to be used to provide these services.

Objective 2.2 outlines the need to "develop a human spaceflight economy enabled by a commercial market", specifically through in-space manufacturing facilities. With 21 commercial facilities operating onboard the ISS including a 3D printer, PEEK has wide accessibility to be used to manufacture CubeSats and other crucial components in space. Following a demonstration of PEEK used for space applications, the commercial demand for PEEK 3D printing services and raw materials has the potential to increase, leading to a resultant increase in commercial supply. This would be especially prevalent in the area of civilian cube satellites, where developers will buy these services and materials from distributors at a higher unit price. With an increase in supply and demand for PEEK in cube satellite missions, the introduction of the material has the potential to help grow the space economy.

Through FluxSat, we will assess the viability of PEEK as a space-grade material for cube satellites in orbit. If FluxSat maintains structural integrity throughout its lifetime, then we determine that PEEK is a viable alternative to conventional materials for future cube satellite missions, with the potential to eventually be used for larger spacecraft applications.

3.3 Additional Compliance

The FluxSat Team will work towards NASA's Objective 4.3 to inspire and engage the next generation of students in space. We will recruit more students from our school to work on the development of FluxSat, exposing them to advanced space science and engineering. We will utilize our outreach involvement in our community to share about FluxSat at other schools to inspire students, incorporating presentations on CubeSats and demonstrations of electromagnetic induction. Through our partnership with the San Diego Air and Space Museum and the Fleet Science Center, we will use the opportunity to teach students of all grade levels about space and science.

4. Schedule and Budget

4.1 Schedule

The FluxSat will be making progress on a weekly basis including routine checkup meetings every Wednesday. The Gantt chart shown in the appendix provides a more accurate timeline for the project. The Gantt chart includes all times including flight testing, ground test, PEEK printing and shipping time, and more. Our current timeline projects us to be ready for launch by April 2027. As this is the first time we are working on CubeSats, the timeline may be slightly inaccurate due to over or underestimation of how long certain tasks take. The life expectancy of the CubeSat we are aiming for is 1-2 years. This gives our sensor array the time to be operational for multiple orbits around the earth and also around the sun. This allows our sensors to assess the variation currently generated based on orientation and altitude.

4.2 Budget

This project is being financed by multiple sources, including public institutions, private companies, and parent support. We have secured $26,000, which exceeds our total budget of $24,516. We are securing more financial support, and we project to receive $10,000 more in financial commitments, manufacturing and testing services, and components discounts by March 2025. The condensed budget is shown below, and the full financial budget can be viewed in the appendix. Please reference the appendix for letters of financial commitment.

System	Component(s)	Qty.	Price	Ext.
Power	Solar Panels, Electric Power System, Battery Pack	1	$6550	$6550
Avionics	Flight Computer	1	$3000	$3000
Comms	Radio Transceiver	1	$5,000	$5,000
Structure	PEEK Plastic & Manufacturing	1	$608	$608
Mission	Magnetorquer, Wire Coil, Current Sensor	1	$3855	$3855
Testing	Environmental Testing	1	$500	$500
Miscellaneous	Contingency Funds	1	$5000	$5000
Total Budget				**$24,516**

Table 5: Condensed Budget Table

5. Project Organization

The FluxSat Team is comprised of three subdivisions: Scientific Payload, Structures, and Power Avionics & Communications. Leadership on the team includes subdivision leads, project co-leads, and advisors, who work together with the subdivisions to ensure smooth development of all the FluxSat subsystems. The FluxSat team has prior experience working with CubeSats, particularly in the MIT BeaverWorks CubeSat Challenge where they built a CubeSat to detect power outages from space and received a 3rd Place award in the national competition. Outside of CubeSats, the team has experience working with aerospace vehicles including rockets, high-altitude balloons, drones, and RC planes.

The FluxSat Team has access to a wide range of industry experts, notably from the San Diego Air and Space Museum and the San Diego Fleet Science Center. The team has acquired support of Canyon Crest Academy faculty, notably mentioning the physics department who have conducted the merit and feasibility reviews. Additionally, Terry Himes, a retired NASA JPL spacecraft and software engineer, has offered to provide mentorship to the team for the development of FluxSat. Charlotte Raymond and Brandon Lozano, students at the Rice University OwlSat CubeSat team have conducted a Merit and Feasibility Review as well. If accepted, the team also intends to reach out to faculty and student organizations at universities such as UC San Diego and Cal Poly SLO faculty for mentorship and advisory services.

Since the leadership of FluxSat is comprised of high school seniors, the team plans on recruiting new FluxSat team members early on from Canyon Crest Academy and potentially neighboring schools as part of their sustainability plan. The leadership will ensure that each member has the necessary skills to contribute to the development of FluxSat so that the transition between years will not affect the projected timeline. The FluxSat team, operating under the Canyon Crest Academy Aerospace Club, will also work to obtain the partnership of other related student organizations such as the Proxima Rocketry Club to aid in the development of FluxSat.

- Mrs. Dvora Celniker, Canyon Crest Academy's Computer Science and Engineering Department Chair, serves as the faculty advisor for the Aerospace Club and the FluxSat Team. She has her Bachelor's in Aerospace Engineering from Rutgers University and teaches higher level engineering courses such as Digital Electronics. Mrs. Celniker contributes to the project as our faculty liaison and helps us with some basic issues.

6. Merit and Feasibility Reviews

For the Merit and Feasibility Reviews, we asked professionals to review our proposal and complete an evaluation document. The document consisted of specific questions evaluating the alignment of the Primary and Secondary Missions to NASA's Strategic Goals, as well as the feasibility of developing the FluxSat systems. For each question, we asked for a rating from 0 to 5 on the scale of “Does Not Comply” to “Fully Complies” respectfully. We also asked evaluators to provide comments for their rating of each question and general feedback at the end of the review.

For our review panel, we asked the physics department of Canyon Crest Academy to conduct our reviews. They had no association with the development of the proposal, so they were able to give a fair and unbiased evaluation. Additionally, we asked Terry Himes, a retired JPL Spacecraft and Software Engineer, to conduct our review. Terry has worked on numerous JPL missions including Mars Odyssey, Dawn, and InSight, so he was able to give a professional assessment of our FluxSat mission according to NASA's mission standards. Finally, we asked the project managers of Rice University's OwlSat mission. OwlSat was a 1U CubeSat measuring EUV radiation that was accepted into NASA CSLI and launched in 2022. With their experience developing OwlSat, Brandon and Charlotte were able to provide valuable feedback and evaluation. The Merit and Feasibility Reviews comprised of the following evaluators:

1. Evan Fisher, AP Physics Teacher, Canyon Crest Academy
2. Andrew Corman, AP Physics Teacher, Canyon Crest Academy

3. Riley Dunne, AP Physics Teacher, Canyon Crest Academy
4. Terry Himes, retired JPL Spacecraft and Software Engineer
5. Brandon Lozano, Rice University OwlSat Project Manager
6. Charlotte Raymond, Rice University OwlSat Project Manager

6.1 Merit Review of Primary Mission

The average rating for FluxSat's primary mission merit review was 4.73 out of 5. All reviewers agree that FluxSat's primary mission of electromagnetic power generation is novel, sound, and fully complies with NASA's goal to innovate transformational space technologies. The primary concern was whether the magnetorquer will impact EM (electromagnetic) readings. The solution to address this is to only read EM data when the magnetorquer is not correcting FluxSat's attitude, although we will look further into other ideas that allow for more frequent and accurate EM readings. The appendix contains the list of questions asked, a breakdown of the average rating for each question, and reviewer comments.

6.2 Merit Review of Secondary Mission

The average rating for FluxSat's secondary mission merit review was 4.5 out of 5. The general consensus among reviewers is that PEEK has the potential to be a viable space material for CubeSats that would help grow the space economy. All reviewers agree that FluxSat helps inspire and engage the next generation of students in space. The main feedback is to create a quantifiable calculation for PEEK assessment based on the scenario evaluation table. To address this, the FluxSat team is looking into implementing a small strain gauge sensor in the PEEK structure as numerical data to aid in the PEEK assessment. Additional research into PEEK properties and the CubeSat lifetime will be done to determine a more accurate target lifetime for FluxSat and future PEEK CubeSats. The appendix contains the list of questions asked, a breakdown of the average rating for each question, and reviewer comments.

6.3 FluxSat Feasibility Review

The average rating for FluxSat's feasibility review was 4.78 out of 5. The general consensus among reviewers is that all FluxSat systems address the needs of the Primary Mission. The reviewers agree that the FluxSat team is technologically capable of developing the Scientific Payload, Structure, Avionics, Power, and Communication Systems. The main feedback is more engineering testing and further Integration & Test Requirements, which will be thoroughly written and implemented after CSLI notification. The appendix contains the list of questions asked, a breakdown of the average rating for each question, and reviewer comments.

Proposal Appendices

A. Resumes

A.1 FluxSat Leads

A.2 Review Panel

B. Compliance Documentation

The Canyon Crest Academy Aerospace Club is fiscally sponsored by The Hack Foundation (dba. Hack Club). Supporting documentation for the EIN-Sharing

INTERNAL REVENUE SERVICE
P. O. BOX 2508
CINCINNATI, OH 45201

DEPARTMENT OF THE TREASURY

Date: JAN 06 2017

THE HACK FOUNDATION
C/O KENT E SETON
269 S BEVERLY DR STE 338
BEVERLY HILLS, CA 90212

Employer Identification Number:
81-2908499
DLN:
17053286341006
Contact Person:
RONALD D BELL ID# 31185
Contact Telephone Number:
(877) 829-5500
Accounting Period Ending:
December 31
Public Charity Status:
170(b)(1)(A)(vi)
Form 990/990-EZ/990-N Required:
Yes
Effective Date of Exemption:
June 1, 2016
Contribution Deductibility:
Yes
Addendum Applies:
No

Dear Applicant:

We're pleased to tell you we determined you're exempt from federal income tax under Internal Revenue Code (IRC) Section 501(c)(3). Donors can deduct contributions they make to you under IRC Section 170. You're also qualified to receive tax deductible bequests, devises, transfers or gifts under Section 2055, 2106, or 2522. This letter could help resolve questions on your exempt status. Please keep it for your records.

Organizations exempt under IRC Section 501(c)(3) are further classified as either public charities or private foundations. We determined you're a public charity under the IRC Section listed at the top of this letter.

If we indicated at the top of this letter that you're required to file Form 990/990-EZ/990-N, our records show you're required to file an annual information return (Form 990 or Form 990-EZ) or electronic notice (Form 990-N, the e-Postcard). If you don't file a required return or notice for three consecutive years, your exempt status will be automatically revoked.

If we indicated at the top of this letter that an addendum applies, the enclosed addendum is an integral part of this letter.

For important information about your responsibilities as a tax-exempt organization, go to www.irs.gov/charities. Enter "4221-PC" in the search bar to view Publication 4221-PC, Compliance Guide for 501(c)(3) Public Charities, which describes your recordkeeping, reporting, and disclosure requirements.

Letter 947

Hack Club

Hack Club
8605 Santa Monica Boulevard #86294
West Hollywood, CA 90069
hcb@hackclub.com

November 15th, 2024

CCA Aerospace Club Subsidiary Confirmation

To whom it may concern,

This letter is to verify that The Hack Foundation (d.b.a. Hack Club) is acting as the nonprofit fiscal sponsor for CCA Aerospace Club since October 10th, 2023.

We have established a restricted fund within our foundation to support their organization and are receiving donations and other funds on their behalf. The Hack Foundation is a 501(c)(3) public charity with the EIN 81-2908499.

Please don't hesitate to contact us with any additional questions. Our team can be reached at hcb@hackclub.com.

Best,

Melanie Smith
Fiscal Sponsorship Director of Operations
Hack Club

C. Additional Documentation

C.1 Technical Details: Scientific Payload

The primary scientific payload's design philosophy is similar to that of the avionics. It will be built for redundancy with nonspace-grade electronic hardware to minimize costs due to the project's budget constraints. All materials that can be made redundant without severe associated costs will be utilized to avoid the primary mission's premature failure due to the hardware.

As the magnetorquer is the only single-point failure of the system, it is necessary to ensure that the hardware is made from radiation-hardened material to minimize failure in orbit. Since this component is inherently expensive yet crucial to attitude control, we have budgeted accordingly with conservative estimates on the mass and power budget. With a magnetorquer, the satellite can complete attitude control during the mission. We will use three CubeTorquerCR0002 magnetometers oriented on three perpendicular axes to provide a full range of motion. These three components enable complete control of the spacecraft's angular momentum in orbit. Data will not be recorded while the magnetorquers are active to minimize skewed measurements of the induced current.

In the pursuit of redundancy, we will use three Texas Instruments INA190 chips with pico-amperage resolution. This chip will measure the induced current in the coil, as the chip is capable of monitoring both AC and DC current, which is essential considering we plan to induce current with a harmonic pattern. The direction of the induced current will constantly be swapping as the spacecraft rotates through multiple different angular displacements through the magnetic field lines. The directionality and magnitude of these lines will be determined experimentally for each point in orbit by an onboard boomless magnetometer.

The spacecraft will contain four single microfarad capacitors, which will be charged by the ammeter's DC out functionality, allowing the spacecraft to charge small capacitors while inducing current in the coil. The demonstration will serve as a proof of concept for the viability of using electromagnetic induction and Earth's magnetic field as a power source in orbit. The capacitors will be wired back into the ammeter's Vin pin after being placed through several resistors to ensure a low current. This discharging method will facilitate the multiple experiment iterations for the primary mission.

Due to its low resistance, silver wire will be used in the coil that retains the induced current. As the experiment hopes to minimize losses and have maximum efficiency, the wire coil will enable the most significant probability of a meaningful electrical potential differential being measured by the ammeter. Since these coils are not readily available, we plan to construct our own by manually coiling silver wire and then integrating it into the FluxSat.

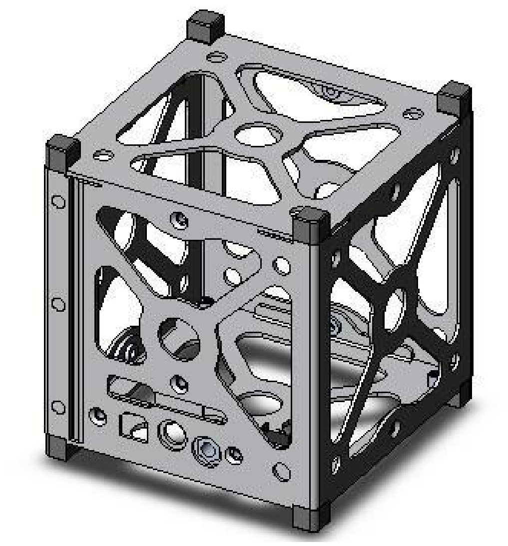
C.2 Technical Details: Structure

C.2.1 Scenario Evaluation Table

Sc.	CubeSat Lifetime (% of 1.1 yrs)	Last Known Altitude	Last known power level	Last temperature reading	PEEK Assessment (Y/N/M/U)	PEEK Assessment (0-100)
1	>100%	Normal	Normal	Normal	Yes	95
2	90-100%	Normal	Normal	Normal	Yes	90
3	40-80%	Normal	Normal	Normal	Maybe	75
4	0-30%	Normal	Normal	Normal	No	30
5	0-50%	Below	Normal	Normal	Unsure	N/A
6	0-50%	Normal	Below	Normal	Unsure	N/A
7	0-50%	Normal	Normal	Below	Unsure	N/A
8	0-30%	Below	Below	Normal	No	20
9	0-30%	Normal	Below	Below	No	15
10	0-30%	Normal	Normal	Normal	Yes	85
11	80-90%	Below	Normal	Below	No	25
12	0-50%	Normal	Normal	Above	Maybe	70
13	>100%	Normal	Normal	Below	Yes	95
14	60-90%	Normal	Below	Normal	Maybe	65
15	0-50%	Below	Below	Below	No	10
16	100%	Normal	Normal	Above	Yes	90
17	70-90%	Normal	Normal	Normal	Maybe	70
18	90-100%	Normal	Normal	Above	Yes	92
19	0-40%	Normal	Below	Below	No	20
20	0-40%	Below	Normal	Normal	No	15

Table 6: PEEK Scenario Evaluation Table

C.2.2 CubeSat Structure



The above structure, sourced from CubeSat Kit 1U CubeSat Skeleton CAD Model [73] | Download Scientific Diagram , has a modular frame and a rigid skeleton, designed to support the physical needs of the mission. The 1U structure offers high durability and stability, crucial to supporting the primary mission requirements. It has strong support for the core electronic components such as electronic components, solar panels, antennas, and sensors. Additionally, the structure shown above would comply with our secondary missions of evaluating the use of PEEK thermoplastics as a structural material for cubesats.

Our components will be integrated into the cubesat in a way that maximizes space efficiency and does not interfere with our primary missions. Our power system will contain a battery pack positioned centrally to maintain a balanced center of gravity, with solar panels on the outer faces of the cubesat. Our antenna ray would be attached to the outer structure, with the transceiver located near the antenna for efficient data transfer, placed also to minimize interference with other electronic components. The onboard computer would be positional close to the battery for reliable power access and thermal stability. The magnetorquers would be mounted on the interior of the side panels, away from our experiment to reduce interference.

C.2.3 Mass Budget

System	Component	Qty.	Mass (g)	Ext. (g)
Power	EXA DMSA/1 3-panel Solar Arrays	2	92	184
Power	EXA BA0x Battery Array	1	210	210
Avionics	Main PCB	1	120	120
Avionics	Sun Sensors	6	2	12
Communications	Transceiver	1	75	75
Structure	PEEK Structure	1	75	75
Primary Mission	Ammeter	3	0.07	0.21
Primary Mission	Capacitor	4	6	24
Primary Mission	Coil	1	20	20
Primary Mission	Magnetometer	1	85	85
Primary Mission	Magnetorquer	3	16.5	49.5
Miscellaneous	Contingency			395
Total Mass				**1250g**

Table 7: Condensed Mass Budget Table

C.3 Technical Details: Avionics

The avionics were designed with the following design philosophy: rather than trying to buy highly expensive radiation-hardened electronics for every part we needed, we would instead design an "error-robust" system that, while susceptible to radiation-caused errors, is able to at best continue functioning and at worst recover in short notice.

The core of the avionics system will consist of a trio of ATmega328P microcontrollers in lockstep. They will run off of the same clock signal, and run identical code that minimizes branching. In the event of a branch, they will verify with each other that it's okay first. No modification is needed for input pins, as the peripheral signals can just be fed into all three ATmegas at once. For outputs, a hardware voting system will be implemented through ATF22V10C programmable logic devices (PLD). This will be implemented on a per-pin basis, meaning the three ATmegas will interact with the rest of the avionics as if they were one unit. For output pins that deal with fault-tolerance signals (i.e. "reboot request"), 74xx series logic chips will be used for voting logic instead, as the outputs of the PLDs have unused latches that might be more susceptible to errors from radiation. Henceforth, the ATmegas will be referred to as processors.

Rather than keeping the entire mission profile in RAM, or in the microcontroller's FLASH program storage, current satellite functions will be performed to accomplish a series of "tasks", uploaded from a ground station and stored in an external EEPROM. Examples of tasks include adjusting attitude to a specific direction, performing a more thorough system diagnostics test, or beginning a data-collection session for a desired length of time. To reduce the effects of radiation changing the stored instructions, each value will be repeated 4 times in the EEPROM, by having said storage device be split into 4 identical segments. Upon each power cycle event, or through request via a task, the processors will verify the integrity of the data, and if a single bad copy is found it will be rectified with the other three. If two or more bad copies are found, the ground station will be notified and FluxSat will return itself to a safe state to await further instructions.

The processors will occasionally perform checkups on each other, adapted to lockstep operation by way of dedicated hardware latches used for inter-microcontroller communication. If a fault is detected in either of its two partners, a dedicated "reboot request" pin will be set to high. If two microcontrollers request a reboot (voting hardware), the system will perform a power cycle. Thus, a glitch resulting in a reboot request in a single microcontroller won't affect the system. A pair of watchdog timers will be used, in case either one is incapacitated by unlucky radiation effects. The processors will occasionally check on the status of the watchdogs, and if errors are detected the system will perform a power cycle.

To get orientation information, FluxSat will incorporate at least 6 simple sun sensors, one per side. These can be photoresistors or phototransistors, depending on which one is most price-effective while still being within spec for the space environment. The sun sensors can also be used to test for solar panel failures, as if a panel isn't collecting energy despite being in the sun the satellite will notify ground control before rotating itself towards a safer orientation. The sun sensors will also be used as a last-ditch reboot initiator: if every single other system somehow fails (i.e. a particularly harsh CME) and the entire system bus is catatonic, the transition from low to high on any of the sun sensors will trigger a reboot of the entire system. Of course, this is only of any use if launched from the ISS.

A side-effect of the voting hardware is that serial communication is much more difficult to implement, aside from which the serial libraries have an unknown (thus uncontrollable) branch structure. This means that all peripherals are restricted to parallel communication. This is not an issue, because it can easily be solved with “chip select”-style signals that select the current active peripheral - the limit of one peripheral active at once also allows us to use current sensors to forcefully reboot the system should an unusual amount of current be drawn, as we now know the exact maximum current it should be able to draw.

Multiple Analog to Digital Converters (ADC) will be used. A high-accuracy ADC will be used to read the current sensor, and a lower-accuracy ADC will be used for the PEEK strain gauge. Additional lower-accuracy ADCs will be used for miscellaneous system monitoring: solar cell power, battery levels, internal temperature, etc.

To allow for adjustments in attitude as well as spin up/down, magnetorquers will be employed. If other parameters make it a reasonable limitation to enforce, we might limit magnetorquer operation to when other components are fully disabled to limit peak power consumption.

A summary list of the components we use to achieve “error-robustness”:

- Triply-redundant lockstep processors that vote on outputs
- Inter-processor checkups
- External, repeated-data EEPROM for task storage
- Dual watchdog timers
- Sun-sensor boot signal

C.4 Technical Details: Communication Systems

We will be using UHF waves of 450-470MHz to communicate with our ground station. We would use these frequencies for both downlink and uplink. For downlink we would be sending down our scientific data and other critical information about the status of the CubeSat. Uplink would be used to update the software of the cubesat as needed and to provide instructions to the CubeSat if necessary. We chose to use UHF waves as the data being sent does not require high-data-rate communication. The licenses required to operate on these frequencies are also easier to obtain, allowing us to focus on more critical aspects of our mission.

For a transceiver, we have selected the ISIS VHF uplink/UHF downlink Full Duplex Transceiver. We chose this transceiver for a variety of reasons. Some reasons are that it operates in the frequencies we want, it is small, it is compatible with a variety of ground station solutions, and it is low power. It supports full duplex communication, allowing for real-time two way communication. It is also high sensitivity, providing stable signal reception even at low signal strength. It is tailored for CubeSat missions and has built in fault tolerant systems. It is also compatible with a variety of antennas, allowing us to be flexible with our designs. These strengths make it the ideal transceiver for our CubeSat.

C.5 Technical Details: Power Systems

Flat solar panels will be included on at least 3 of the 6 sides, or if deployable panels on 2 of the 6 sides, arranged such that there is always an orientation that allows for energy collection. These will most likely be DHV-CS-10 panels if flat, or EXA DMSA/1 panels if deployable.

The battery will be the EXA BA0x battery array. Either the 22.2 Whr or 50 Whr option will be chosen once the power budget is finalized. A battery board will be used to adjust the 3.7V or 7.4V output of the battery array to the voltages required by the various other components.

Power Budget

System	**Component**	**Qty.**	**Wh**	**Ext. (Wh)**
Avionics	ATmega328P	3	100 mWh	300 mWh
Avionics	ATF22V10C	6	140 mWh	840 mWh
Avionics	Glue logic 74xx chips	12	50 mWh	600 mWh
Avionics	ADC, high accuracy	1	250 mWh	250 mWh
Avionics	ADC, low accuracy	8	50 mWh	400 mWh
Communications	Transceiver	1	4 Wh	4 Wh
Primary Mission	CubeTorquerCR0002	3	500 mWh	1.5 Wh
Primary Mission	ADA4523	3	15.6 mWh	46.8 mWh
Primary Mission	PEGASUS Magnetometer	1	750 mWh	750 mWh
Miscellaneous	Contingency	1	2 Wh	2 Wh
Total Power				**10.68 Wh**

Table 8: Condensed Power Budget Table

C.6 Technical Details: Ground Station

For receiving data we are going to use the SATNOGS network. The SATNOGS network has a variety of stations that are compatible with the frequencies that we will operate in (450-470

MHz). We are using this network because it allows us to receive data from a variety of locations across the globe, ensuring near-continuous data downlink. This allows us to only worry about building up our uplink infrastructure, and also eliminates the need to create or maintain any downlink infrastructure.

We will also need the ability to uplink with our CubeSat, to provide software updates and instructions. To uplink with our CubeSat we will use our own radios and antennas, as SATNOGS does not support uplink. We will need to obtain an AZ-EL rotor system and use software, such as Gpredict, to account for doppler-shift, and provide strong, clear signals to our CubeSat.

We are considering building a permanent CubeSat Ground Station with a Raspberry Pi development board and installing it in our club's meeting space. We should be able to access this ground station via a virtual viewer such as VNC, enabling us to convert any laptop with the VNC Viewer App to become a potential ground station.

C.7 Technical Details: Software

Software for FluxSat will be written following the "Power of 10" rules created by NASA to make programs more reliable. For example: dynamic memory allocation will be minimized, if not outright unused; variables are declared in the lowest possible level; use of pointers is minimized; and all loops will have a strict upper limit, with the exception of the top-level loop. This will reduce complexity and allow for robust unit testing.

The software will also be written following additional constraints imposed by the hardware, as well as rules set to improve error-robustness. For example, conditional branching will be kept to a minimum to reduce the odds of a bit-flip in a processor propagating into a misalignment of its program counter. Instead, bitwise operations will be used, with said boolean logic achieving the same end result of the if-statement. For example, through use of the inter-processor checkup latches described in C.3, said checkups can be performed using entirely sequential software. A processor will assert its "checkup ok" output, either on its own or if some sanity-checking code runs successfully. Then it will add the value of the two input pins corresponding to the other two processor's checkup latches. It subtracts 2 (b/c 1 + 1) from this value and outputs the result to the (binary) "reset request" pin. If the result is non-zero, then the "reset request" pin is asserted. Thus, not a single conditional branch needs to be used for effective inter-processor checkups. Jump vectors will be strictly prohibited- the possibility of an erroneous value being introduced to the vector means a processor could jump into an undefined entry point in the code, or at worse begin executing data as code. Each function that does not return anything will return a boolean value indicating success or failure. This allows for the main loop to handle errors gracefully. For example, a “Transmit Data” function will return a boolean stating its success or failure, whereas a “Receive Data” function will return actual values.

The RAM will be split into 3 mirrored segments, and a 4th input buffer segment. While this limits the effective RAM size to 512 bytes, our data isn’t expected to generate at a rate that exceeds the ability of the operating system to shuttle said data to the EEPROM.

To simplify mission operations and assist somewhat in navigating the programming paradigm, we will develop an in-house simple operating system for the hardware. This was done for two main purposes: we wanted to be able to schedule “tasks” from the ground in a flexible manner, and no such operating system exists for ATmega328p, lockstep or not. The operating system will be designed to be modular enough for potential use in other spacecraft. The core of the operating system will be a top-level “scheduling loop” whose job is to execute “tasks”. These tasks may be built-in to the OS (attitude adjustment, system check, data-collection session description, etc.) or custom tasks (such as telling the processors to assert specific pins, or adding additional steps to the routine system checks). When not performing tasks, the OS will perform simple house-keeping duties such as fixing deviations in attitude or performing error correction on the RAM and EEPROM. Additionally, the OS will perform inter-processor checks after every task and routine system checks every so often. FluxSat can also be manually be ordered into Standby (lowers power consumption, orients itself for maximum solar collection) and an emergency Safe State (minimal power consumption,transmitting the heartbeat ping only while listening to further instructions only at a specific timing offset from the heartbeat ping). A forced power cycle will most likely be an option invokable in a worst-case scenario. Tasks are given a priority level from 1 to 16, with 2, 6, 10, 14 being the ones intended to be used most often to provide room for nuance when needed. The scheduling loop simply begins the task with the current highest priority. If multiple of the same priority exist, the oldest one is run first.

C.8 Merit and Feasibility Review Questions and Results

C.8.1 Merit Review

Primary Mission Questions	**Average Rating (0-5)**
Does FluxSat contribute to NASA's mission to innovate and advance transformational space technologies? (Objective 3.1)	5
Does FluxSat contribute to NASA's mission to conduct scientific studies of the Earth from space? (Objective 1.2)	4.2
Does FluxSat contribute to NASA's goal to provide mission support capabilities to enable the next generation of spaceflight vehicles? (Objective 4.2)	5
Average Primary Mission Rating	**4.73**

Secondary Mission Questions	**Average Rating (0-5)**
Does FluxSat help create a commercial space economy for in-space manufacturing and new space materials? (Objective 2.2)	4.6
Does FluxSat help support NASA's next era of aerospace through environmental stewardship, sustainability, and resource conservation? (Objective 4.2)	4
Does FluxSat help lay the foundation for cost-effective and mission-essential services for America's human and robotic missions? (Objective 2.4)	4.4
Does FluxSat help inspire and engage the next generation of students in aeronautics, space, and science? (Objective 4.3)	5
Average Secondary Mission Rating	**4.5**

C.8.2 Merit Review Comments

- The premise of the primary mission is sound – a clearly identified proposed solution (novel means of providing power to electrical components) to an existing problem.
- Interesting and feasible power source, great experimental design
- Using the Earth's magnetic field as a source of energy for space missions is a very novel idea.
- Flux Sat creates a commercial space economy but doesn't create new space material. They use existing material in an innovative way as well as seeing if they are space compatible.
- By exploring novel ways of energy generation and storage, FluxSat could help improve power systems for a range of space applications.
- I'm not sure if they have determined a theoretical energy output value or if they know what the energy demands are for a mission, however I am a fan of incremental change and every little bit helps.
- FluxSat seems well-positioned to contribute to NASA's broader goals of advancing energy

technology and earth studies from space. Its impact on mission support for next-gen space vehicles and potentially aiding Earth science through enhanced energy systems could support NASA's objectives.
- The proposal makes a compelling case for the FluxSat mission's value and feasibility.
- The concept itself is forward-thinking and showcases the kind of cutting-edge, real-world problem-solving that can inspire future generations of scientists, engineers, and astronauts.

C.8.3 Feasibility Review

FluxSat System	Average Rating (0-5)
Is the FluxSat Scientific Payload capable of addressing the Primary Mission?	4.4
Is the FluxSat Team technologically capable of developing and testing the FluxSat Scientific Payload?	5
Is the FluxSat Structure capable of addressing the Secondary Mission?	5
Is the FluxSat Team technologically capable of developing and testing the FluxSat Structure?	4.8
Does the FluxSat Avionics System address the needs of the Primary Mission?	4.8
Does the FluxSat Power System address the needs of the Primary Mission?	4.8
Does the FluxSat Communication System address the needs of the Primary Mission?	4.4
Is the FluxSat Team technologically capable of developing and testing the Avionics, Power, and Communication Systems?	5
Is the FluxSat Team financially capable of developing and testing the FluxSat CubeSat?	4.8
Does the FluxSat Team have the organizational structure, experience, and expertise to develop the FluxSat CubeSat?	4.8
Does the FluxSat Team assess and mitigate failure scenarios of the FluxSat CubeSat?	4.8
Average	**4.78**

C.8.4 Feasibility Review Comments

- A well-written FluxSat feasibility proposal. It clearly assesses the practicality of the mission, addressing both technical and operational challenges.
- Structure requires further Integration & Test (I&T) Requirements
- Received funding for first proposal. More funding will be required after approval.
- "Error-robust" avionics system helps to optimize cost-benefit of materials usage
- Very solid hardware plan. Some more engineering testing may be beneficial.
- Concerns with the magnetorquer impacting EM readings
- By minimizing complexity, the system is likely to reduce points of failure, increase mission longevity, and improve overall system performance—critical factors for any space mission.
- The failure scenario mitigation is an ongoing challenge that every space mission faces. While the team is likely aware of potential risks, further documentation of failure modes and

contingencies would help strengthen their preparedness.

- The FluxSat project demonstrates strong potential, with a capable and well-rounded team addressing key technical areas such as avionics, power systems, and structure. The team's expertise in developing and testing the CubeSat, as well as their financial and organizational readiness, bodes well for the project's success.

C.9 Failure Scenarios

The FluxSat team has created a Failure Scenarios and Analysis Table to assess and mitigate critical failure points of the cube satellite. This is crucial for the success of our Primary and Secondary Mission. The Primary Mission requires key onboard electronics to be functional to collect, process, and transmit our sensor data, and the Secondary Mission requires no permanent electronic failure to accurately assess the viability of PEEK through FluxSat's lifetime. Thus, we have determined the failure scenarios below and outlined a mitigation plan to ensure the success of our Primary and Secondary Missions. A Risk Index was used for each failure scenario which combined both the probability of occurrence and the severity. The Risk Index table was inspired by Rice University's OwlSat proposal.

Risk Index

		Probability of Occurrence				
		1	2	3	4	5
Severity	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Table 9: Risk Index Table

Failure Scenarios and Analysis

Potential Failure Scenario	Cause(s)	Effect(s)	Probability (1-5)	Severity (1-5)	Risk Index	Mitigation Plan
Failure of an Ammeter	Destruction of the IC due to radiation	The mission tasks will be placed onto a space ammeter	3	1	3	There will be several amateurs on the vehicle all wired into the circuit such that the failure of one does not mean the failure of the mission
Failure of the magnetorquer	Power loss; inability to get enough current to the system loss of system computer controlling the part	The spacecraft will be unable to orient itself and create the necessary spin	1	5	5	The operation of the magnetorquer will be tested before launch such that the group is confident the magnetorquer will work; The magnetorquer will be space grade;
Failure of magnetometer	Destruction of the IC due to radiation	The spacecraft will be unable to orient itself in the correct direction to execute the primary mission	3	5	15	The magnetometer will be aerospace grade and radiation hardened. The team will also ensure the IC is operational prior to integration onto the cubesat as well as after integrated on the cubesat to ensure the part works prior to launch
Failure of PEEK structure	LEO radiation, extreme temperatures, space debris, launch vibration and stress	Electronics exposed to space environment, potential end of mission	2	5	10	Intensive ground testing of PEEK prior to integration. Vibration, stress, and thermal tests; simulations and structural analysis to ensure full PEEK compliance with the space environment.
EEPROM double data corruption	LEO radiation	Task data is irrecoverable	2	2	4	System will go into a safe state and notify ground stations. No immediate danger, however satellites will be unable to respond to some issues.
Faulty checkup latches - fixable	LEO radiation	If stuck at 1, checkup will say safe despite issues. If stuck at 0, it makes the system prone to reset.	2	3	6	The following self-initiated power cycle should reset the latches.
Dual faulty checkup latches at 0 - not fixable	LEO radiation, adverse solar events	If two faulty latches are stuck at 0, and power cycling doesn't fix, the system will endlessly reboot.	1	5	5	During programming, we will perform a further risk analysis to see if it should be possible to disable the checkup system. If so, we would send this task repeatedly to FluxSat in the hopes that it receives it before the next reboot.

Total failure of 1 processor	Adverse solar events	One processor is wholly unusable.	1	5	5	Voting hardware will keep working with 2 processors online, but no longer protected from errors.
Total failure of 2 processors	Adverse solar events	Mission termination.	1	5	5	Voting hardware can't work with both processors. Most likely, if this happens multiple other components are fried anyhow.
Solar sensor failure	Extreme temperatures	More difficult, or impossible, to determine orientation. Last-ditch reboot diminished.	2	2	4	Tasks given will have to take into account this fault. Code will include "turn relative to sun" and "turn relative to initial" tasks.
Faulty transceiver	LEO radiation, adverse solar events	Faulty electronics may lead to transceiver not broadcasting at the right specifications or lead to broadcasting failure.	1	3	3	We will add Error Correction Code to our software to check for bit errors. If a bit error is detected, the CubeSat system will reset the transceiver.
Total transceiver failure	Space debris, acts of god	Failure to transmit data without any way to repair the transceiver will lead to mission failure.	1	5	5	In the unlikely event that the transceiver fails with no known cause and in an irreparable state, the transceiver will switch to a "beacon mode". In this state, the CubeSat will only attempt to transmit information on system health. This information could help the team on the ground diagnose and fix the issue.

Table 10: Failure Scenarios and Analysis Table

C.10 Detailed Financial Budget

System	Component	Qty.	Price	Ext.
Power	Solar Panel	3	$850	$2550
	Electric Power System	1	$2500	$2500
	Battery Pack	1	$1500	$1500
Avionics	Flight Computer	1	$3000	$3000
Communications	Radio Transceiver	1	$5000	$5000

Structure	PEEK Manufacturing	1	$400	$400
	PEEK Plastic	1	$158	$158
	Wiring, fasteners, etc.	1	$50	$50
Mission	Silver Wire Coil	2	$50	$100
	Ammeter(s)	3	$1.26	$3.78
	Capacitor(s)	4	$0.50	$2
	Magnetometer	1	$1500	$1500
	Magnetorquer(s)	3	$750	$2250
Testing	Environmental Testing	1	$500	$500
Miscellaneous	Contingency	1	$5000	$5000
Total Cost				**$24,513.78**

Table 11: Full Budget Table

C.11 Gantt Chart