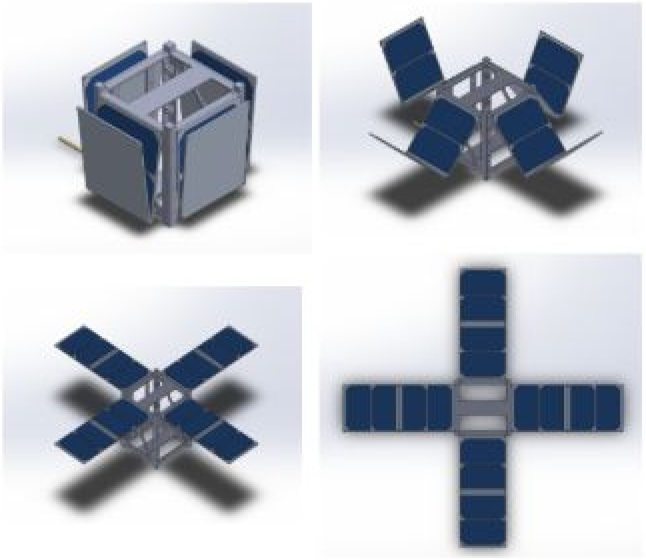
NASA CSLI Application

In Response to Solicitation NNH19ZCQ001O

OwlSat: Space City's First CubeSat

November 4, 2019



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CubeSat Mission Parameters

Mission Name	Mass (kg)	Cube Size	Desired Orbit		Acceptable Orbit Range	400 km @ 51.6 degree incl. Acceptable- Yes or No	Readiness Date	Desired Mission Life
OwlSat	0.987	1U	Altitude	400 km	325-450 km	Yes	Jan. 2022	1 Year
			Inclination	45°	45-75°			

CubeSat Project Details

Focus Area	Student Involvement- Yes or No	NASA Funding		Sponsoring Organization(s)	Collaborating Organization(s)	
		Yes or No	Organization		List	International- Yes or No
Science	Yes	No	N/A	Rice Space Institute Rice Eng. Alumni Oshman Eng. Design Kitchen	None	No

Points of Contact

Name	Title	Address	Phone	Email
Dr. David Alexander	OwlSat Team Mentor	[redacted]	[redacted]	[redacted]
Paul Glenski	OwlSat Team Lead	[redacted]	[redacted]	[redacted]
Ryan Udell	SEDS Rice President	[redacted]	[redacted]	[redacted]

Proposal Abstract

The 2019 Students for the Exploration and Development of Space (SEDS) Chapter of Rice University has developed a design proposal for a CubeSat platform to analyze the relationship between solar activity and the Earth's lower atmosphere.

Energetic emissions from the sun can have tangible effects upon the Earth's atmosphere. Increased EUV radiation caused by solar activity adds energy to the particles that compose the atmosphere, causing the atmosphere to expand. This movement increases the amount of atmospheric drag satellites encounter and subsequently raises their rate of orbital decay.

The proposal describes the **OwlSat CubeSat** (referred to as OwlSat), a 1U (10x10x11 cm) CubeSat Satellite that will record EUV (extreme ultraviolet) radiation measurements of the Sun, the satellite's orbital velocity, and the satellite's orbital position (altitude) to characterize how varying EUV values modulate the orbital decay rate of a Low Earth Orbit (LEO) CubeSat over time. This comparison will serve as the basis for a new linear regression orbital propagation model created and updated via an iterative Deep-Layered Neural Networks (DNN) that will enable future scientists and engineers to make more comprehensive predictions for orbiting bodies, such as space debris and small satellites.

Additionally, the charged particles emitted by the sun contribute primarily to the lethality of ionizing radiation, a danger that must be studied further if humans are to make a prolonged presence in LEO. The OwlSat CubeSat will measure the levels of ionizing radiation at LEO and use that data to synthesize a second linear regression model capable of predicting the altitudes of maximum radiation pressure, helping mission planners plan for the physical health of astronauts during extreme solar weather events.

The OwlSat CubeSat includes 4 EUV radiation sensors that measure solar activity, 3 heavy-particle detectors used to determine levels of harmful ionized particles found within LEO, 3 accelerometers used to monitor the velocity of the satellite, and a GPS receiver used to determine the location and altitude of the satellite.

Proposal Details

OwlSat has 2 primary goals:

1. OwlSat's Primary Mission is to investigate the atmospheric response to EUV solar radiation and create a linear regression model predicting the orbital behavior of satellites
2. OwlSat's Secondary Mission is to study the profile of ionized particles found at different . altitudes within LEO and create a linear regression model estimating their values (as a function of solar variability) across a specific range of LEO

1. Primary Mission: Modeling the Atmospheric Response to EUV Radiation

OwlSat's Primary Mission is to develop a Deep-Layered Neural Network (DNN) that correlates measured atmospheric responses to solar EUV radiation and the orbital drag force experienced by the OwlSat CubeSat in order to create a new linear regression model capable of advanced orbital predictions. By synthesizing a model of this relationship, organizations such as NASA will have the ability to further understand and maximize the many benefits satellites have to offer in addition to proactively predicting the orbital behavior of any small object in LEO.

1.1 The Emerging Importance of CubeSat Satellites

In comparison to their much heavier and larger siblings, CubeSat Satellites have a shorter development lifecycle and are much cheaper to manufacture and launch [15]. This economical alternative to traditional satellites has the potential to make possible advancements such as a global internet and is quickly becoming the scientific "go-to" when it comes to performing space-based measurements and operations, such as those conducted by NASA.

To give context, the global marketplace for CubeSats is growing at a compound annual growth rate of more than 33 percent and is expected to surpass $550 million by [16]. Additionally, SpaceX has recently announced plans to construct 30,000 new small satellites within the next 10 years, Amazon plans to launch 3,236 satellites, and OneWeb will send 1,976 new satellites into orbit, vastly dwarfing the 2,200 active traditional satellites currently in orbit [10, 23, 24].

These developments in the CubeSat Satellite Industry have the potential to contribute to space debris problems unless a proactive deorbiting plan can be developed. The OwlSat CubeSat will generate the appropriate scientific knowledge needed to aid in the future mitigation of space debris.

1.2 Solar Radiation and its Atmospheric Effects

EUV radiation and ionized particles originate in the corona and chromosphere of the Sun's atmosphere. The solar EUV spectrum, between 10 and 124 nm, is dominated by spectral lines from hydrogen (H), helium (He), oxygen (O), sodium (Na), magnesium (Mg), silicon (Si), and iron (Fe) [8]. The EUV radiation and ionized particles reach Earth and are absorbed by the atmosphere, primarily above 80 km. The thermosphere of the Earth is heated predominantly by these EUV inputs and the radiation serves to create and structure the ionosphere [8].

EUV radiation irradiance varies wildly on timescales from minutes to hours (solar flares), days to months (solar rotation), and years to decades (solar cycle). The varying nature of incoming radiation causes the thermosphere and ionosphere to fluctuate greatly over similar magnitude and time scales in addition to the diurnal variations due to the Earth’s rotation, affecting satellite communications as well as the orbits of natural and artificial satellites [12].

1.3 The Aggravating Nature of Satellite Collisions

During the geomagnetic storm of March 1989, the North American Aerospace Defense Command (NORAD) lost track of 1000’s of satellites, increasing the likelihood for satellite collisions with other satellites or orbiting space debris [28]. In 2009, such a collision occurred between an Iridium communications satellite and a Russian Cosmos 2251 satellite, generating 10,000 pieces of debris that varied in size from a few millimeters to centimeters in diameter [25].

The consequences of such satellite collisions can range from performance degradation to complete failure and satellite fragmentation. In Low Earth Orbit (LEO), debris as small as a few millimeters in diameter can puncture unprotected fuel lines and damage sensitive components, while debris smaller than 1 mm in diameter can erode thermal surfaces and damage optics [3]. Although smaller objects can partly be mitigated through the use of meteor bumpers, such as on the ISS, the only way to mitigate the impact of larger objects is to maneuver the spacecraft to avoid collision. Such maneuvers are expensive, impact the operation of sensitive experiments on board, and ideally should only be done if the chance of collision is high [3]. However, these maneuvers are impossible to conduct with smaller satellites that do not have propulsion systems, such as most CubeSats.

Furthermore, these problems appear to compound as the number of satellites in orbit increases. As mentioned in Section 1.2, the quantity of orbiting satellites increased by a factor of 6 from 2012 to 2018. This statistic only appears to worsen as private companies such as SpaceX, Amazon, and OneWeb plan to boost the current numbers of orbiting satellites by an additional factor of 10, which greatly increases the likelihood for subsequent satellite collisions.

1.4 The Science of Orbital Estimation

As of now, the future paths of orbiting satellites can only be predicted to within a 98% confidence level in a weekly period [15]. This accuracy decreases with larger time periods and has fostered great consternation for satellite and space debris managers.

The difficulty of satellite orbit estimation is primarily due to miniscule changes present in the Earth’s atmosphere caused by solar radiation, especially EUV (Extreme Ultraviolet) radiation. EUV radiation is absorbed by the atmosphere and heats up the atmosphere in return, causing it to expand and affect the drag forces satellites subsequently encounter [28].

Ultimately, it is this drag force that creates the largest uncertainty in satellite orbital predictions. In order to calculate drag forces ($\boldsymbol{D}$), the density of the atmosphere(ϱ), the drag coefficient of the satellite($\boldsymbol{C}$), and the satellite's velocity ($\boldsymbol{v}$) need to be used according to Equation 1 [8].

$$D = \frac{1}{2}CAv^2 \qquad \text{Equation 1}$$

Varying levels of EUV radiation can directly affect the values of atmospheric density and drag coefficients. Thus, an orbital estimation model must take into account varying EUV levels in addition to the satellite's orientation in order to correctly calculate the force of drag acting upon a satellite.

Unfortunately, this relationship between EUV intensity and its atmospheric responses has not been identified with physics-based models. While the F10.7 cm Solar Radiation Index is currently used to provide the estimated EUV effect on the atmosphere for orbital calculations [7], this data can only be derived on a daily basis, whereas EUV and atmospheric properties change minute by minute. Additionally, most of the F10.7 Indices are based on interpolated estimation models that are not accurate enough for the estimation of longtime orbital change, requiring constant monitoring of satellite positions.

The OwlSat Satellite's EUV sensors will be able to collect more accurate and continuous EUV data than what is currently available with the F10.7 cm Solar Radiation Index. Due to the extensive cost and its failure to get relationship between EUV and atmospheric change with physics-based models, we will use empirical models based on Deep-Layered Neural Networks (DNN) to estimate satellite trajectories [9].

Currently there are several attempts to predict satellite trajectories by using DNN [32]. One such method was developed by Amber Yang, a high school student who was able to predict orbit accuracy to a confidence level of 98% within 3 days using the widely used commercial software MATLAB [33].

However, this example and others like it included a DNN that only utilised the historical data of previous satellite orbits. In those cases, it is generally well-known that a DNN would have provided an easier, more effective method for predicting the future paths of orbits by creating an algorithm based off of past data, but none of them have incorporated real-time or future measurements of solar radiation when constructing their orbital estimations.

OwlSat would be the first to incorporate actual EUV sensor data with position and orientation data from the satellite into a DNN to try to identify the hidden relationship between EUV radiation and the satellite's orbit variation. If this model is a success, Cubesats with EUV sensors can be tracked with a higher accuracy and at a much lower cost to in order prevent space collisions as well as predict future scenarios resulting from extreme solar weather events.

1.5 How the OwlSat Orbital Propagation Model Will Be Created

The OwlSat Satellite makes use of 4 EUV sensors to measure solar EUV radiation levels directly. To optimize this data, the sensors will be pointed directly at the sun at all times (excluding eclipse) using the onboard active attitude system. Furthermore, 4 additional science instruments (3 accelerometer sensors and a GPS transceiver) will be used to record the orbital velocity, altitude, and position of OwlSat.

The EUV radiation, positional, and orientation data would be used as inputs for a new Deep-Layered Neural Network (DNN). Furthermore, these data points will also be inputs to more-traditional physical models such as orbital, drag, and perturbation equations as well as conventional atmospheric density models. We could also incorporate X-ray and F10.7 spectrum data to possibly increase the accuracy or efficiency of our linear regression model.

To add to this, the availability of solar EUV radiation data from government funded science missions, such as the Solar Dynamics Observatory (SDO), will allow our team to validate recorded radiation levels and serve as a control for OwlSat. In the unlikely event that our EUV sensors become inoperable, this data will still allow our team to make correlations between the publicly-available reference data and the positional data being provided by OwlSat. While the public data will likely not be optimal as a reference for our new orbital propagation model, it will still allow us to create a model that takes into account the atmospheric response to EUV radiation, which fulfills our mission’s primary goal.

1.6 The OwlSat Ground Station

One of the ambitions of this team is to operate a ground station of our own. Nonetheless, there have also been ongoing communication with other universities regarding combined ground communication operations. These operations would be based loosely on both the open source Satellite Networked Operational Ground Systems (SatNOGS) project and the experiences of other university-based CubeSat projects. The end goal would be a collaborative network of university ground stations; the University of Illinois at Urbana-Champaign, Virginia Polytechnic Institute and State University, and Portland State University have already taken the first collaborative steps on this project.

Technical details of the OwlSat Ground Station can be found in the appendix.

2. Secondary Mission: Predicting the Levels of Harmful Radiation in LEO

OwlSat’s secondary mission focuses on the ionized (heavy) particles emitted by the sun. These particles contribute largely to the lethality of radiation and are of primary concern to humans operating in an environment outside the protection of the Earth’s inner atmosphere [27].

The rate of ionizing radiation in the atmosphere cannot be modeled as a function purely of altitude, which is shown by the existence of an ionospheric structure known as the Chapman layer [27]. The specific height at which the pressure due to ionizing radiation is maximized can be found with the following equation: (Equation 2)

$$P = P_o e^{-z/\lambda_p(T)} \qquad \text{Equation 2}$$

where P represents the pressure due to ionizing radiation, P_o is the pressure at some arbitrary base height (usually sea level), z is the height of the satellite, and $\lambda_P(T)$ is the scale height as a function of temperature. The scale height, $\lambda_P(T)$ is defined by the following: (Equation 3)

$$\lambda_p(T) = \frac{kT}{mg} \qquad \text{Equation 3}$$

where k is the Boltzmann constant ($1.38*10^{-23} JK^{-1}$), T is the mean atmospheric temperature, m is the mean mass of a molecule (predominantly nitrogen and oxygen), and g is the acceleration due to gravity.

By using the data collected by OwlSat's 3 heavy particle detectors to correlate the observed interaction between ionizing (heavy particle) radiation and the thermal expansion of the atmosphere due to EUV radiation, our secondary mission will be able to develop a linear regression model via a DNN used to determine the altitudes of the atmosphere where the pressure due to ionized radiation is maximized.

When the atmosphere changes drastically due to extreme solar weather events, mission planners will be able to determine the altitudes at which radiation becomes most concentrated and change the orbits of humans working in LEO in order to decrease their exposure to radiation. This will help mitigate the detrimental effects of solar radiation to our astronauts and will aid in humanity's quest to live sustainably beyond the confines of the Earth's inner atmosphere.

3. Project Organization

The SEDS Rice OwlSat Project is lead by Paul Glenski, an undergraduate electrical engineering major. The leadership structure further includes 5 sub-team leads who independently have authority over their particular teams. This balanced matrixed approach to project organization allows the different sub-teams to customize their meeting and work structures in addition to providing a single point of contact responsible for the managerial duties the project requires to function.

Under the aforementioned project lead, there are 5 sub-team leads: Eric Yang, Scientific Payload Engineering; Alp Yakici, Avionics and Communications: Lianne Johnson, Power; Douglas Steinbach, Structures; and Juan De La Garza, Systems Integration. Additionally, due to the complicated scientific research that must be researched and thoroughly understood, Hoik Jang, a graduate student at Rice University, was chosen to serve as the Team's Head Science Advisor.

Within the team, there are 17 undergraduate students and 3 graduate students. These graduate students are studying subjects such as material science, space studies, and business while the undergraduate students are mostly pursuing STEM degrees, though there are several team members who are studying the social and natural sciences.

When interviewing for subteam leads, the OwlSat recruiting team recognized the value that a diverse set of subteam leads would bring to the team. With those considerations in mind, all 5 of the chosen subteam leads represent commonly underrepresented minorities in STEM. Our group displays various backgrounds, such as a student of immigrant-descent, a first-generation student, an international student from Turkey, and a woman in STEM.

Since OwlSat is Rice's first CubeSat, the OwlSat team is actively recruiting experienced advisors to help with the project management and technologies. A few of OwlSat's project and technical advisors include:

- Dr. David Alexander, a Physics and Astro-Physics Professor at Rice University who serves as the Director of the Rice Space Institute and is SEDS Rice's sponsor. He performs research on solar physics, exoplanetary physics, and remote sensing capabilities. He also serves on the board of t he American Astronautical Society. Dr. Alexander will contribute to all aspects of the project and will also provide additional expertise in EUV sensor development and deployment. He can also contribute to marketing, outreach, and engineering capability.

- Dr. Stephen Bradshaw, another Physics and Astro-Physics Professor at Rice University, serves as the Associate Chair for Rice University's Undergraduate Physics and Astro-Physics Departments. His primary research is focused on developing a better understanding of heating mechanisms that occur in the solar corona of Sun-like stars. Due to his expertise, Dr. Bradshaw will be contributing to the EUV sensor payload development, deployment, and research. He will also help the team map the data received from the EUV sensors and explain its impact on aerospace environments and future satellite missions in the same orbit.

- Nick Espinosa is a Deputy Life Support Component Manager of the Exploration Extravehicular Mobility Unit (xEMU) within Jacobs Engineering. He received his bachelor's degree in aerospace engineering from the University of Texas-Austin in 2002. Prior to joining industry, he served in the United States Army, where his group management skills were refined and he learned the importance of producing deliverables on an ordered time frame. Since Mr. Espinosa has a large amount of experience working with NASA as a contractor, he will contribute to delivering government regulatory documents and NanoRacks/NASA integration documents.

- Dr. Jeffery Chancellor is an Assistant Professor of Physics at Louisiana State University. His primary research studies the nature of heavy particle radiation with soft and condensed matter. This will be used to influence the design of manned spaceflight vehicle structure, its shielding, and clinical healthcare. Dr. Chancellor will be contributing heavily to OwlSat's Secondary Mission of measuring the profile of heavy particle radiation across LEO by guiding the team with the assembly, retrieval, and evaluation of mission data.

4. CSLI Applicability

OwlSat's mission plan is in keeping with the 2018 NASA Strategic Plan [20] and is directly applicable to objectives 1.1, 1.2, 2.1, 3.3, and 4.3. Specifically, OwlSat's mission objectives are aimed at developing a relationship between solar EUV radiation and the drag inflicted on LEO-based satellites, which will provide NASA with important data on solar radiation levels as well as the Earth's atmospheric response to it.

NASA's strategic objective 1.1 specifically outlines the need to "Conduct scientific studies of the Sun and Earth from space". As time progresses, NASA will "…expand the use of lower-cost CubeSat and SmallSats to accomplish (their) scientific goals" and due to NASA's position as the primary data-collecting entity for federal, private, and international agencies, the importance of correctly configuring CubeSat orbits will become increasingly critical to NASA and their ancillary organizations. CubeSats and SmallSats are becoming the cost-effective backbone of many modern scientific experiments and it is thus crucial for NASA to fully understand the factors influencing their successful operation. The linear regression orbital propagation model for small satellites proposed as part of our effort can be extrapolated to serve as an important tool in the management of space debris, aligning with strategic objective 4 "NASA (will) demonstrate standards of best practice for civil and commercial activities such as orbital debris mitigation…"

Additionally, the ionized particle data gathered from OwlSat will provide time-varying data about the levels of harmful radiation found at different altitudes sampled by the Owlsat mission. In alignment with strategic objective 1.2, this data would be useful for researchers attempting to better “Understand (the) Responses of Physical and Biological Systems to Spaceflight, … including space radiation”. It would also yield a better understanding and methodology to predict the radiation environment humans would face during a prolonged stay in LEO. This is in accordance with objective 2.1, which plans to “ Lay the Foundation for America to Maintain a Constant Human Presence in Low Earth Orbit…” and serves to enhance the safety of NASA’s Missions (objective 4.3).

Finally, this direct scientific research will yield itself to better inform the public about the atmosphere and the sun’s effect upon it, increasing its prominence in the public sphere and satisfying objective 3.3 “(To) Inspire and Engage the Public in Aeronautics, Space, and Science.” Furthermore, SEDS Rice will implant a small chip containing the engraved names of local community members into OwlSat, further satisfying this NASA objective.

5. Compliance Requirements

The OwlSat design is in full compliance with:

- The Cal Poly CubeSat Design Specification (CDS) version 13 [18]
- NanoRacks CubeSat Deployer Interface Control Document (NR-NRCSD-S0003) revised on 06/04/2018 [19]
- Launch Services Program Requirements Document (LSP-REQ-317.01) [14]

As part of OwlSat’s development schedule, a full complement of thermal, vibration, and vacuum testing will be implemented in accordance with Table 1 of the Launch Services Program Requirements Document (LSP-REQ-317.01). Testing is currently set to be performed at the Ryon Engineering Laboratory and the Oshman Engineering Design Kitchen at Rice University.

All known regulatory compliance documents have already been completed and are awaiting the outcome of this application. These documents include:

- An International Amateur Radio Union (IARU) Satellite Frequency Coordination Request, which will be submitted upon proposal acceptance. This coordination needs to be completed several months prior to the launch manifest and can take up to a year, so the request will be submitted once a response to this proposal is received.
- A notice of intent to operate will be submitted to the Federal Communications Commission (FCC) with the coordinated frequency and emission designation, after coordination with the International Amateur Radio Union (IARU).

6. Merit and Feasibility Reviews

For each review, we gathered a group of subject matter experts and asked them to review our proposal and submit their feedback via a Google Survey Form. Each Google Survey Form was populated with questions specific to the mission it was covering. For each question we asked for a rating from 1 to 5 on the scale of “Does Not Comply” to “Fully Complies”. Additionally, we asked for comments and concerns at the end of the questionnaire. A summary for each review and a list of reviewers is given below. The Merit and Feasibility Reviews comprised of the following reviewers:

1. Joe Figura, Systems Engineer, Astranis
2. Dr. David Alexander, Director Rice Space Institute, Physics & Astronomy Professor, Rice University
3. Sumayya Abukhalil, Systems Engineer, Northrop Grumman
4. Matthew Hawkins, Project Engineer, Lockheed Martin
5. Dr. Andrew Meade, Mechanical Engineering Professor, Rice University
6. Conor Brown, Director of Payloads, NanoRacks, LLC
7. Mike Lewis, Chief Innovation Officer, NanoRacks, LLC

6.1. Merit Review of Primary Mission: Atmospheric Modeling of Solar Radiation

The average rating for OwlSat's primary mission merit review was 4.57 out of 5. Please see the appendix for a list of the questions posed and a breakdown of the average rating for each question. The general consensus among reviewers is that OwlSat's primary mission of atmospheric modeling is in keeping with NASA strategic goals and by that measure has merit. They believed the mission to be very relevant to the development of the satellite industry, though they were less certain that this mission would aid in providing for humanity's long term habitation of space. Due to that, we modified OwlSat's secondary mission to focus more on the human response to solar radiation

6.2. Merit Review of Secondary Mission: Predicting Harmful Radiation in LEO

The average rating for OwlSat's secondary mission merit review was 3.95 out of 5. Please see the appendix for a list of the questions posed and a breakdown of the average rating for each question. The main concern is that this mission has already been done before and will not contribute much new science; however, the judges did note that the number one concern for deep space and interplanetary human missions is space radiation. Thus, OwlSat will help to provide more data in this field.

6.3. OwlSat Feasibility Review

For the feasibility review we asked our subject matter experts to review each subsystem of OwlSat and rate it on feasibility and also provided a comments section for each system to elaborate on any concerns they might have. The average rating for the feasibility review was 4.76 out of 5. Please see the appendix for a list of the questions posed and a breakdown of the average rating for each question. The feasibility reviews of the OwlSat systems were varied in their feedback, but the general consensus is that each system is feasible. This said, clearly more explanation and a more thorough systems analysis needs to be addressed prior to launch. Examples of concerns were primarily directed towards the OwlSat ground station. Due to those concerns, the OwlSat Team added many technical specifics to our ground station design and acknowledged the possibility of working with other universities on this manner.

6.3 Astranis SEDS Sat-2 Competition

SEDS Rice competed in the SEDS Sat-2 Competition with a similar CubeSat Proposal. The Astranis SEDS SAT-2 competition called on SEDS chapters from universities across the country to submit a design for a novel 1U CubeSat to be launched and deployed by NanoRacks, LLC, with Astranis donating the cost of the launch. In total, there were 18 teams that participated, with over 75% of the universities having had previous satellite and launch experience. Rice University tied for second place with a team from MIT/Tufts/Northeastern, an impressive achievement given that SEDS Rice did not have a CubeSat Team until 5 months before the deadline. OwlSat's average rating for the SEDS Sat-2 Competition was 86 points out of 100 total points. Please see the appendix for a list of teams, a list of judging criteria, and a breakdown of the average rating for each question.

The SEDS Sat-2 Judges were:

1. Conor Brown, Director of Payloads, NanoRacks, LLC
2. Mike Lewis, Chief Innovation Officer, NanoRacks, LLC
3. Joe Figura, Systems Engineer, Astranis
4. Marc Dahlberg, Guidance, Navigation and Control Engineer, Astranis
5. Cory Whiltshire, Senior Software Engineer Astranis
6. Sumayya Abukhalil, Systems Engineer, Northrop Grumman

Overall, the SEDS Sat-2 Judges noted that the team was capable of developing OwlSat from a technical and non-technical perspective. That said, the judges noted that SEDS needs to take into account other scientific results when collecting the data, which is the reason why novelty was scored the lowest. Since space radiation is the largest hinderance to manned missions and unpredictable radiation can cause large adverse effects on satellites, the International Space Station and a few satellites currently monitor radiation. The OwlSat team will utilize this additional data to compare with its own data for greater accuracy results.

7. OwlSat Development Schedule

OwlSat progress is being managed on a weekly basis, with a routine status meeting held every week. The current project management timeline being used is a Gantt Chart that tracks OwlSat's critical path (see appendix).

The Gantt Chart considers time for testing of the FlatSat, for ground use only, a medium-fidelity 3-D prototype, to be tested via high-powered rocket flights, and 2 models of the actual CubeSat itself, to be flown in space (1 will serve as a contingency). With the current chart, OwlSat is scheduled for launch in January of 2022. SEDS Rice will be able to complete the main construction and testing of the FlatSat during the 2020 Spring Semester.

Following a post-Flat-Sat Design Review, the 3-D medium fidelity prototype will be built and tested during the 2020 Fall Semester. After that, the first high-fidelity, launch-ready CubeSat will be constructed and tested in the Spring Semester of 2021, with its second contingency being built and tested during the following Fall Semester of 2021. This will conclude with both flight-ready CubeSats being ready for launch by January 2022.

The proposed lifetime of OwlSat is 1 year. This time will allow the EUV sensors to be operational over a complete orbit of the Earth around the Sun, allowing us to assess the effect of the variability on EUV radiation between perihelion and aphelion. Furthermore, the projected 2022 launch date of this mission enables OwlSat to sample solar radiation levels as the sun enters a more active phase of its solar cycle, increasing the likelihood that OwlSat will have the opportunity to collect data on extreme solar weather events [28]. The Project Life Cycle will come to an end at the beginning of the 2023 Spring Semester.

Table 1: OwlSat Schedule

Task/Event	Start	End
Design, low-fidelity prototypes, proposal writing	Now	Feb 2020
CSLI Announcement	-	Feb 2020
Preliminary Design Review	-	Feb 2020
Full FlatSat Built, Including Integration Testing	Feb 2020	May 2020
Critical Design Review	-	May 2020
First 3-D Medium-Fidelity Prototype Built, Rocket Tests	Aug 2020	Dec 2020
First 3-D High-Fidelity (Launch-Ready) Prototype Built	Jan 2021	Mar 2021
Environmental Testing on First High-Fidelity Prototype	Mar 2021	May 2021
Second 3-D High-Fidelity (Launch-Ready) Protoype Built	Aug 2021	Oct 2021
Environmental Testing on Second High-Fidelity Prototype	Oct 2021	Dec 2021
Ready for Launch	-	Dec 2021
Launch	Jan 2022	Jan 2023
In Orbit Operations	Launch	Launch + 12m

8. Budget

This budget is based on constructing 4 OwlSat prototypes, with the components from 3 being reused for subsequent prototypes. This will result in 2 final CubeSats capable of being launched into space.

The first unit is the FlatSat prototype, which will be used for component and system testing. A 3-D, medium-fidelity prototype will then follow and will undergo flight testing on high-powered rocket flights. The final prototypes are the high-fidelity prototypes, scheduled for preflight environmental testing.

Table 2: Financial Budget

System	Components	Qty.	Price	Ext.
OwlSat Bus	Structure, Power, Avionics, etc.	2	$15,757	$31,514
Primary Mission	EUV, Accelerometer, and GPS Sensors, Magnetorquer	2	$1,755	$3,510
Secondary Mission	Heavy Particle Detector	2	$450	$900
Ground Station	Primary and Secondary Ground Stations	2	$2,500	$5,000
Testing	Environmental Testing	1	$1,000	$1,000
Miscellaneous	Contingency	1	$3,000	$3,000
Total Budget				**$44,994**

For a more detailed budget, please see the appendix.

9. Funding

OwlSat is being enthusiastically funded by over 12 Rice University Institutions, organizations and companies. Please see the appendix for the list of current funding sources. These funding sources total $58,000 worth of in-kind service donations and proceeds, which exceeds the projected budget of $44,994.

Proposal Appendix

A. Resumes

Resumes of OwlSat's leadership team:

- Paul Glenski, Overall Project Lead
- Ryan Udell, President of SEDS Rice
- Hoik Jang, Head Science Advisor
- Eric Yang, Payload Development Sub-Team Lead
- Alp Yakici, Avionics and Communications Sub-Team Lead
- Lianne Johnson, Power Sub-Team Lead
- Douglas Steinbach, Structures Sub-Team Lead
- Juan De La Garza, Systems Integration Sub-Team Lead

B. Compliance Documentation

The OwlSat team understands the importance of dealing with regulatory requirements as early as possible. Detailed here is the current state of our regulatory compliance for the OwlSat project.

B.1.1. International Amateur Radio Union (IARU)

OwlSat has already filled out the IARU Amateur Satellite Frequency Coordination Request form for the S Band communication system and the 70 cm Low Gain Radio. Once a flight opportunity has been announced, the form will be submitted to the IARU Satellite Advisor to request an amateur frequency coordination.

B.1.2. Federal Communications Commission (FCC)

The Notice of Intent to Operate will be filed with the FCC as soon as the IARU has coordinated OwlSat's frequencies and OwlSat has been manifested.

C. Letters of Support

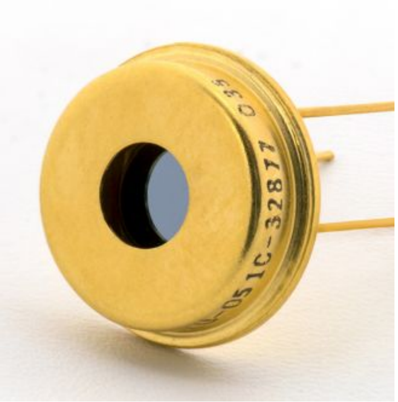
Note that SEDS Rice is fully financially capable of building OwlSat. These letters were able to be obtained before the submission deadline. SEDS Rice was able to obtain written confirmation from other contributors, but unable to secure the Financial Support Letter in time of proposal submittal.

D. Additional Project Documentation

D. 1. Technical Details: OwlSat Scientific Payload

D.1.1 Primary Mission

Figure 1: EUV Sensor



Our primary mission concept under development makes use of 4 SXUV20C photodetectors to measure solar EUV (Extreme UltraViolet) radiation directly (Figure 1). These sensors are produced by Opto Diode and are capable of EUV measurements over the entire EUV spectrum (1nm to 190nm). This range also allows us to measure vacuum ultraviolet radiation, which is known to be very strongly absorbed by atmospheric oxygen in the ionosphere and provides us with more data to analyze thermal expansion of the upper atmosphere. Combined, the 4 EUV sensors draw 1.60 Watts/hour of power and weigh 200 grams, falling within our desired power and mass allocations. To optimize our data collection, the EUV sensors will be pointed directly at the Sun at all times (except when in eclipse). This requires external apertures to be located outside of the satellite structure and controlled by an attitude control system (see D.1. 3. Attitude Control System).

The primary mission of OwlSat employs 4 additional science instruments: 3 KX022-1020 accelerometer chips (Figure 2) and a Venus838FLPx-L GPS Chip (Figure 3). The accelerometers consume a combined wattage of .06 Watts, weigh 6 grams, and will take repeated measurements of OwlSat's orbital velocity while the GPS chip needs .09 Watts of power, weighs about 1 gram, and will monitor the location and altitude of OwlSat.

Figure 2: KX022-1020
Accelerometer Chip

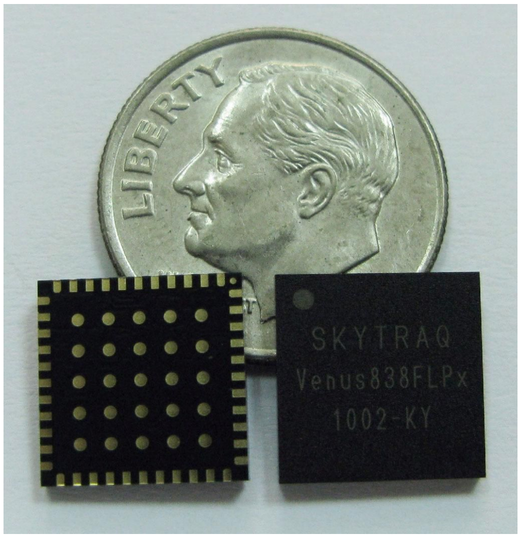


Figure 3: Venus838FLPx-L
GPS Chip

Each of the 4 EUV scientific instruments are connected to a single science board using soldered wire connections, where it is stored on an external memory drive until it can be downlinked to Earth. The other 4 positional science instruments are connected to a second communications board, which is likewise connected to a radiation-tolerant external memory drive until it can be downlinked to Earth. We elected to use 4 EUV sensors and 3 accelerometer chips because our power and mass budgets can afford it and the multiple data points provided by the various instruments will provide redundancy to our results. The GPS chip has its own redundancy mechanisms built into it, thus eliminating the need to collect multiple GPS data points.

Preliminary analysis of the communications subsystem indicates that OwlSat is capable of downlinking a maximum of about 1 megabyte of science data per fly-over. This is based on one ground station of a similar nature to the ground stations of previous CubeSat missions. A data downlink region consisting of +/-10° of latitude, corresponding to about 11 minutes of data downlink time per orbit, was chosen to fit within the downlink capability.

D.1.2 Secondary Mission

OwlSat's secondary mission objective relates to recording data pertaining to the levels of charged particles found within LEO. This data will be collected through 3 MiniPIX TPX3 Heavy Particle Detectors (Figure 4), which are small sensors capable of measuring the heavy particles that make up the vast lethality of ionizing radiation. They draw 4.5 combined Watts of power and collectively weigh 90 grams.

Figure 4: MiniPIX TPX3 Heavy Particle Detector

Since these measuring devices do not require an unobstructed aperture into space, they will be internally located and connected directly to the second CubeSat science board. Once the levels of heavy particle radiation are recorded by these chips, the data will be sent to OwlSat's external memory drive and subsequently downlinked down to Earth during its next available opportunity.

D.1.3 Attitude Control System

An active attitude control system is needed to ensure OwlSat's success because the EUV sensors of its primary mission and the main power collection method (solar panels) should be pointed towards the sun in order to most-optimally function. This magnetorquer board fulfills these requirements by inducing torques on the 3 axes relevant to the satellite's orientation in free space. In order to most efficiently utilize the torque generated by this system and to adhere to NanoRacks specifications regarding the center of mass of OwlSat, the attitude system will be placed at the center of the structure.

The attitude control system of OwlSat will be the ISIS Magnetorquer board, produced by ISIS Space Systems (Figure 5). It provides attitude control via a 3-axis magnetic torquer system capable of providing actuation of up to 0.2Am^2. It draws 1.2 watts of power during peak operation and weighs .176 kg, both of which fit within our desired contingencies. A 3-axis magnetometer detects the interaction between Earth's magnetic field and the field created by the magnetorquer coil. The board also includes a detumbling algorithm, which can be tested and modified to suit our satellite's needs. This attitude control system was chosen because it was specifically designed for CubeSat applications and provides a reasonable amount of actuation specific to this mission's needs.

Figure 5: Magnetorquer

The magnetorquer board can act as a standalone detumbling system, but it can also be integrated into more advanced attitude determination and control system (ADCS). This allows the team flexibility for the future, since we have discussed potentially using reaction wheels in addition to this magnetorquer board to provide greater torque for attitude control. While the current plan and design will only include the magnetorquer board, we acknowledge the possibility of needing additional components to provide higher torque onto the system if the magnetorquer board proves to be too weak during testing.

Additionally, in the unlikely event that our active attitude control system fails, a passive attitude control system using the forces of the Earth's magnetic field will provide an adequate orientation system to the satellite.

D.1.4 Future Prototyping and Tests

As mentioned, the vast majority of the components of OwlSat will be bought off-the-shelf. This is because professionally made products are of a higher quality and precision than similar products produced by our own team. Therefore, the process of prototyping individual components that we intend to purchase is not necessary.

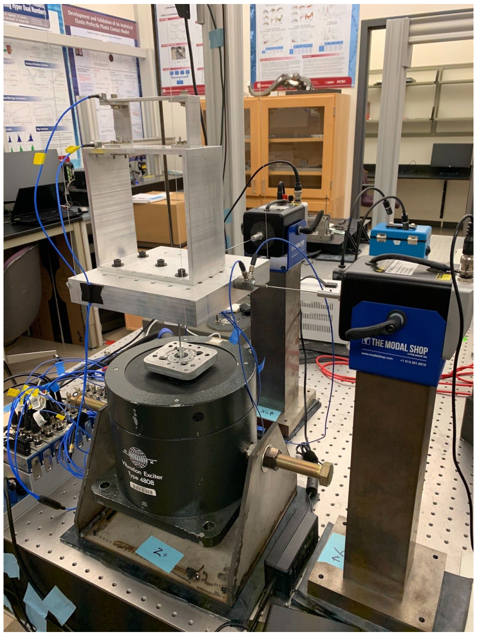


Figure 6: Vibrational Tester with 3 Freedom Degrees

The primary testing of these components, in addition to the testing conducted by the manufacturer, will be done through thermal vacuum and vibration testing at the component, subsystem, and spacecraft level. A FlatSat (2-Dimensional prototype) and traditional 3-Dimensional prototypes will be created to perform component, subsystem, and integrated system tests in the lab and on high-power rocket tests.

A great resource that we are fortunate to have is access and support from the Oshman Engineering Design Kitchen (OEDK), an undergraduate engineering facility that provides students with access to design tools, prototyping equipment, computational facilities, meeting rooms, and ample space for prototype design and development. The OEDK has served our team as the primary space for our meeting and design sessions, in which we have been able to bring this project to life. We plan on continuing our relationship with the OEDK for the remainder of our project.

Additionally, the Ryon Engineering Laboratory of Rice University houses various types of machinery that will be of great use to OwlSat once testing commences. This laboratory houses the only vibrational tester with 3 degrees of freedom in the United States and is immediately available for use by SEDS Rice free of cost. This piece of machinery already has code in place for random vibrations and rocket simulations, making it very easy to operate (Figure 6). Further, there is extensive liquid helium infrastructure at Rice University that will enable us to thermally test OwlSat down to -100 °C, in addition to numerous vacuum chambers available to us at Rice.

D.2 Technical Details: OwlSat Structure and Mass Budget

D.2.1 External and Internal Geometry

The external components of OwlSat include the cube structure, 4 deployable solar panel wings (with sun sensors and 2 solar cells each), and a deployable antenna array.

The internal components of OwlSat include 4 EUV sensors, 3 accelerometer chips, 1 GPS chip, 3 heavy particle detector chips, 2 microcontroller science boards, 1 transceiver module to transmit data to the ground station, 1 external memory to store data on-board, 1 magnetorquer, and 1 power system module (Figure 7).

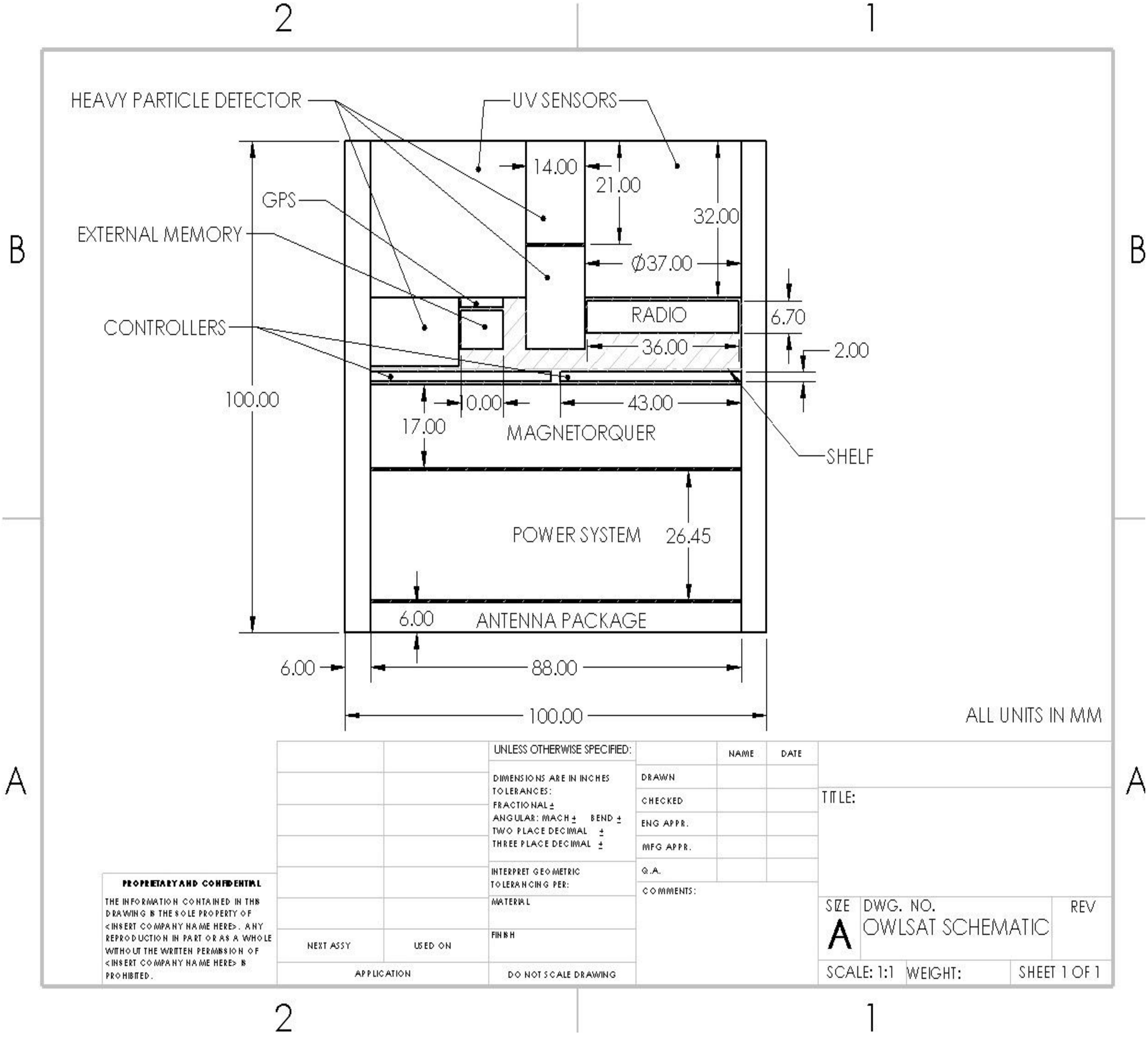


Figure 7: Internal Schematic of OwlSat

When designing the internal configuration of the satellite, it is important to consider the Center of Mass (CM). Per NanoRacks launch guidelines, the CM, relative to the geometric center of the satellite, must be within 20 mm on all axes. During satellite construction, SEDS will be using the center of mass equations to properly orient all materials within the satellite. The equation will take into account the CM of each material and overlay them in OwlSat to properly orient each material within the satellite. Calculations for the CM will be completed during the final design process and confirmed with the physical components to ensure that the team meets the NanoRacks Requirement.

D.2.2 CubeSat Bus

The primary structure of the spacecraft will transmit loads throughout the spacecraft to the interface of the deployment system. Secondary structures, such as solar panels and the antenna array, will be attached to this structure. It is essential the primary structure performs as expected, since a failure of the primary structure can have dramatic consequences that are difficult to overcome after the spacecraft has launched.


Figure 8: ISIS's 1U CubeSat Structure

We plan to use ISIS Space System's 1-U CubeSat Structure as the final structure for OwlSat. It adheres to NanoRack's CubeSat Launch Interface, weighs 87 grams, and includes a shelving mechanism that will make it easy for us to customize the internal layout of the CubeSat (Figure 8).

However, SEDS Rice is also interested in gaining technical experience in the manufacturing of satellite components. As such, the structure of our 3-D medium fidelity prototype will be constructed in-house by SEDS Rice.

When beginning design, material selection is a necessary and highly important step for the structure. We first begin by referencing materials that have already shown the capabilities to withstand space flight. Properties that we will take into consideration when building our prototype are strength, operational temperatures, weight, and cost. OwlSat must withstand the loads experienced during launch and withstand the thermal stresses that may exceed 93 °C when operating. The ideal material will exhibit properties surpassing the requirements, giving a safety factor to our structure, and have the lowest density possible to maintain our mass budget. Taking these into consideration, our material of choice is Aluminum 6061.

With the material decided, the focus moves into the design requirements of the primary structure. First, the design should satisfy the requirements placed by the Nanoracks CubeSat Launch Interface. These are to provide adequate interfaces to each subsystem to ensure safe passage through all phases of the mission. In addition, an ability to accommodate the scientific payload without large modification of the design is a strong driver. Alongside these requirements, the frame should be designed in such a way to maximize volume efficiency. The structure will carry loads in the external shell to increase internal volume, such as solar panels and the antenna array. This design will allow us to add extra EUV Sensors, accelerometers, and heavy particle detectors in OwlSat, affording us redundancy in our measurements.

Some of the requirements listed by Nanoracks are explained here. The primary structure must have external rails that are the only mechanical interface between OwlSat and the NanoRacks CubeSat Deployer (NRCSD). The rails make up 4 parallel edges of the CubeSat and their dimensions are defined by the NanoRacks launch interface. The rails will have a length of 113.5mm (+/- 0.1mm) along the Z axis. The +Z rail ends will have a minimum area of 6mm x 6mm and be bare as well to ensure OwlSat will provide no issues within the NRCSD. Other rail characteristics include edge radii of 0.5mm (+/- 0.1mm), minimum extensions from the +/- Z planes of 2mm, and smoothness and proper alignment of the rails with one another (+/-0.1mm). The structure must also abide by NASA's LSP Dispenser Requirements.

The prototype frame will be machined with multiple mounting locations on the exterior that will allow for the addition of solar panels and antenna array. The antenna array will be mounted on the -Z face while the solar panels will be mounted on the +/- X and Y faces. The +Y face will contain the access port Nanoracks requires that will allow the interior of OwlSat to be reached when the outer shell is in place. A preliminary design is shown in Figure 10.

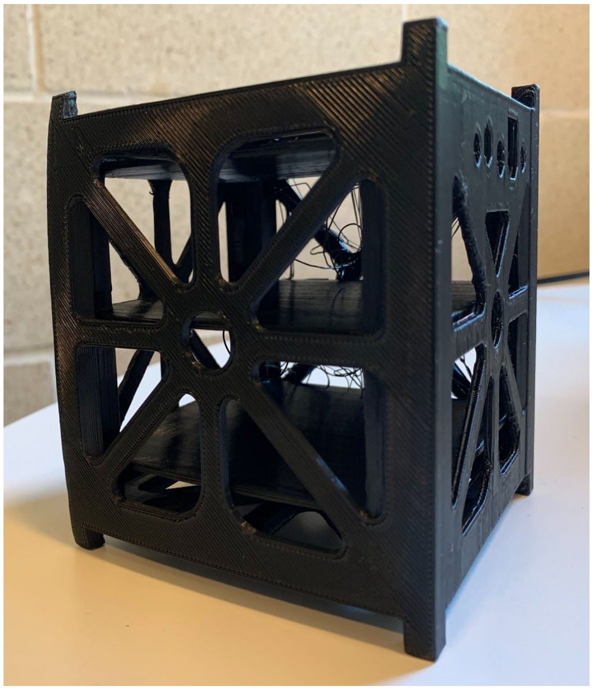


Figure 9: Initial 3-D Prototype of the Medium-Fidelity Prototype

Internally, the components will be fastened to the structure as a single package using brackets and fasteners, keeping in mind that the structural load is on the external shell. Not only does this create maximum volume efficiency, but it also keeps the internal components away from stress concerns. The 6 faces covering the sides of OwlSat are attached to the structure base with screws, enabling easy removal should access to the internal components of OwlSat be desired. All of these basic construction materials and the tools needed to use them are available to us free of charge at Rice University's Oshman Engineering Design Kitchen. An initial 3-D printed prototype of our eventual prototype is shown in Figure 9.

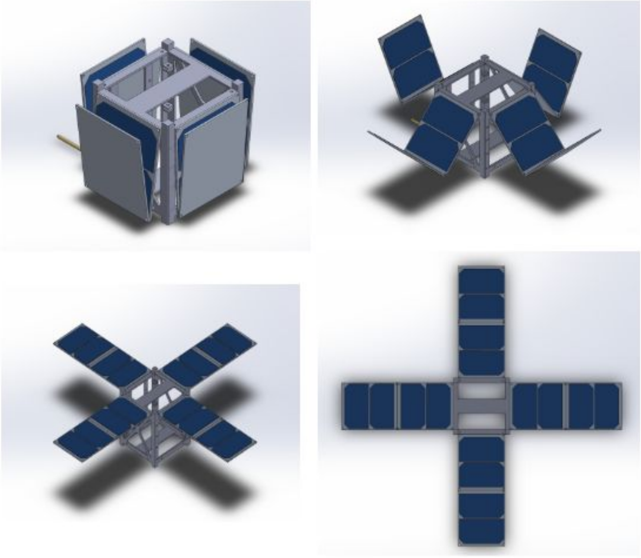


Figure 10: CAD Model of the OwlSat Structure

Table 3: OwlSat Mass Budget

System	**Component**	**Qty.**	**Mass (g)**	**Ext.(g)**
OwlSat Bus	Structure	1	87	87
	Solar Module	4	25	100
	Power System	1	184	184
	System controller	2	42	84
	Radio	1	18	18
	70 cm antenna	1	100	100
	External memory	1	5	5
	Wiring, fasteners, etc.	-	50	50
Primary Mission	EUV Sensors	4	50	200
	GPS chip	1	5	5
	Accelerometer chips	3	2	6
	Magnetorquer	1	8	8
Secondary Mission	Heavy Particle Detector	3	30	90
Miscellaneous	Contingency	-	50	987
Total Mass				**987 Grams**

D.3 Technical Details: OwlSat Avionics

The Avionics subsystem consists of the onboard microcontroller science boards with an external memory drive,as well as data interfaces for science, telemetry, and communications.

Figure 11: ATSAMD21J18 Microcontroller Science Board

The microcontrollers of choice are the ATSAMD21J18 controllers, which provide the necessary interfaces for our auxiliary sensors and modules, such as SPI, I2C, and USB (Fig. 11). In addition to their internal 256KB flash memory and 32KB SRAM, we will be using 1 magneto-resistant MR25H10 4 MB external memory drive to store applications and log experiment results. Both the microcontrollers and external memory drive have been previously used in a variety of CubeSat missions, and MR25H10 is proven to be resistant to extreme environmental conditions, including severe space radiation. Additionally, we estimate that each data-collection period will only require around 20KB of memory, well within our memory storages.

The microcontrollers will be running an open-source operating system, FreeRTOS. This is a suitable operating system for a space mission as it adheres to a strict structure and ensures events are responded to in a timely and deterministic manner. All applications will be written as independent tasks and will be executed according to the priority assigned to them. FreeRTOS comes with an open-source IDE - Atmel Studio - which we will be utilizing. All applications will be programmed in low-level programming languages, such as C and Assembly, to ensure efficiency.

There are various different functions within the software that perform different tasks given different needs. The science function is called when the GPS indicates that the satellite is within the appropriate data taking region. This function collects and records science data for a length of time determined by the mission’s region of interest. The science function also periodically monitors the health sensors and can call the fault response function if necessary.

The communications function is called when the transceiver indicates that it has received a beacon signal from a ground station. The function sends science data to the ground until all of the stored data has been sent or the function determines that the beacon signal has been lost, indicating that the satellite has passed out of communication range. As with the science function, the communications function monitors satellite health and can call the fault response function if needed.

The fault response function is activated if any other functions detect abnormal health readings. The fault function examines the abnormal reading and calls an appropriate health function, for example, a “too hot” function or a “too cold” function.

D.4 Technical Details: OwlSat Communication System

An S-band communications system is planned for OwlSat for 3 reasons. First, there are fewer regulatory constraints in attaining the frequency bands. Second, commercial off the shelf parts can be used for the flight system. Third, other universities can be coordinated such that there is more ground station access.

We will be using the SATELLINE-M3-TR4 UHF data transceiver module for radio communication with the ground station (Fig. 12). This specific transceiver has a low power consumption, which makes it suitable for our needs. The module comes with configuration software, making it rather easy to deploy in our mission, and has also been deployed in previous CubeSat missions, proving that it is capable of performing in the environment of outer-space.

The antenna array of choice is the Deployable Turnstile Antenna Array System from ISIS Space Systems, specifically its dipole antenna array variant. A dipole antenna array was chosen because it has a larger beam width than a monopole antenna, allowing for longer communication windows (more science data) and easier attitude control requirements. The system made by ISIS Space Systems is also easily compatible with our data transceiver module, has low mass and power requirements, and operates in various amateur radio bandwidth.

Table 4: Communication Systems

System	Specification	Qty.
Communication Link	Frequency	438.0 MHz
	Link Margin (25.0 dB)	25.0 dB
	Specified B.E.R.	1.00E-05
	Demodulator Type	BPSK
Primary Mission	Eb/No Threshold	10.6 dB
	BW bpf	12.0 MHz
	Bit Rate	9,600 bps
	Lp (Loss Due to Free Space)	148.6 dB
	Total Link Losses	150.9 dB
Secondary Mission	EIRP Ground Station	22.3 dBW
Miscellaneous	Tx Antenna Gain	16.0 dB (Helix)
	Polarization	RHCP
	Loss Total Line	3.62 dB
	Loss PBF	1.0 dB
	Power Tx (RF)	10.0 Watts

Figure 12: SATELLINE-M3-TR4 UHF Data Transceiver Module

D.5 Technical Details: Power Systems Budget

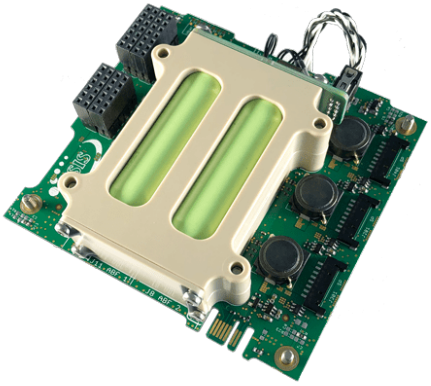


Figure 13: ISIS' iEPS Electrical Power System

The Power subsystem is made up of the integration of deployable GaAs Triple-junction solar panel arrays and an iEPS Electrical Power System from ISIS Space Solutions.

Each solar panel array will consist of 2 solar cells that use an expanding mechanism to extend. There will be 4 arrays total, all of which will deploy in a parallel plane coinciding with the +Z plane (Fig 13). Each solar panel array will include sun sensors that will be linked to the attitude control system in order to orient the solar panels and EUV sensors towards the Sun. The combined power output of the solar panel arrays is 18.4 Wh in full sunlight, aligninging with OwlSat's power requirements.

The solar panel arrays will deploy once OwlSat has reached an operable distance away from the CubeSat deployer mechanism. A deploy signal is sent through a control module, which releases and extends the solar arrays to our pre-programmed final position. The release sequence takes 10 seconds and the deployment takes 10 seconds, ensuring a smooth transition with no backlash.

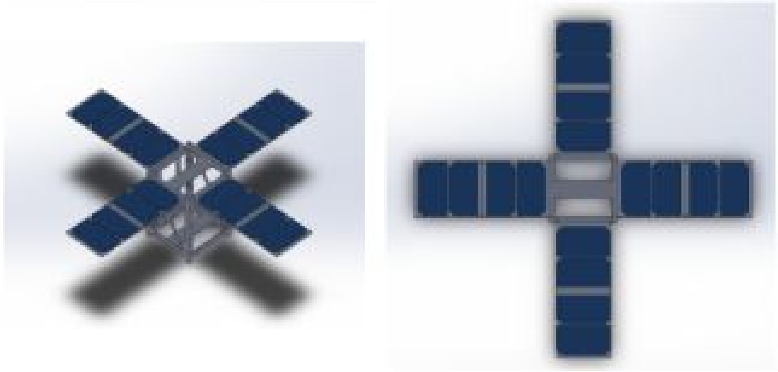


Figure 14: Solar Panel Orientation

The power system will be used to store and deliver power to our electrical components. This system was specifically chosen because its design is designed to couple with the solar arrays that will be mounted into our system. The power system will ensure that we have a continuous source of power at all times and includes a heating element, which will become particularly useful when our satellite is in solar eclipse.

There are multiple redundant solar cells within the power system to ensure that power will always be available. The solar power system can supply up 6300 mAh and 22.5 Wh and its components have been environmentally tested in space before.

OwlSat's power system will go through a full test simulation, including parameterizing orbital variables, cell efficiencies, cell temperatures, battery efficiencies at temperature, etc., in order to better predict the power system's behavior in orbit. In the meantime,Table 5 is the estimated power budget allocated for the OwlSat mission. The values derived are the power values correlated to each component’s peak power consumption, which would not be realistically in place while the mission is underway. With this contingency in place, the mission requires a max power allotment of 15.21 Watts/hour. Of the 15.21 W/h power requirement, a contingency of 10%, or 1.52 Watts is to be reserved, resulting in a total power budget of 16.73 W/h. After taking the power budget into account, the solar power system will be capable of generating 18.4 W/h, surpassing the power budget by ~10%.

Table 5: OwlSat Power Budget

System	**Component**	**Qty.**	**Maximum W/h at 3.6V**	**Ext.(W/h)**
OwlSat Bus	Science Board Controller	2	0.26	0.52
	Radio	1	4.70	4.70
	70 cm Antenna Array	1	2.0	2.0
Primary Mission	EUV Sensors	4	0.40	1.60
	GPS Chip	1	0.09	0.09
	Accelerometer Chips	3	0.02	0.06
	Magnetorquer	1	0.20	0.20
Secondary Mission	Heavy Particle Detector	3	2.0	6.0
Miscellaneous	Contingency	-	1.52	1.52
Total Power				**16.96 W/h**

D.6 Technical Details: Ground Station

OwlSat will utilize 2 ground stations for this project, a primary station, and a fully-capable secondary station. The primary station will be constructed by the students involved in the project and located on the Rice University campus. The secondary station will be an existing amateur satellite ground station located at a different location for spatial diversity. It can be used to help verify and check out the primary station as construction progresses, and serve as a backup to the primary station. The 2 stations are identical.

The ground station infrastructure provides 2 communications functions between the ground and the spacecraft, (1) up and down communications on UHF for the Telemetry and Command (T&C) subsystem onboard the spacecraft, and (2) downlink communications on S-band for mission payload and camera data.

The UHF component is centered in the 435 to 438 MHz amateur spacecraft band and utilizes both a RHCP and LHCP directional helix antennas mounted on an azimuth/elevation antenna positioner. Coax switches connect one of the antennas to either a Low Noise Amplifier (LNA) for receiving, or a Power Amplifier (PA) for transmitting. The LNA and PA are then connected to a Software Defined Radio (SDR) that provides both UHF RF input and output signals.

The SDR used is the LimeSDR from LimeMicro, which utilizes GnuRadio for modulation and demodulation. The emission type is BPSK at 9600 bps, and was chosen because of the capability of the T&C transceiver radio on the spacecraft, an acceptable performance indicated in the link budget, and is somewhat common in the amateur satellite community.

An antenna positioner controller is used to aim the antenna array and is interfaced serially using the EasyComm control protocol accessible through the HamLib control library. The positioner controller is based on the Open Source hardware/software project of SatNOGS, and provides the ability for tracking control locally using GPredict, or by the SatNOGS Network software across the Internet. Data is passed into/out of the ground station radio through GnuRadio ModCod blocks and can provide raw IQ sample files from the payload data. Doppler shift can be compensated for in real time using the tracking software and an interface into GnuRadio.

The T&C subsystem provides telemetry data to the ground in two forms, a BPSK modulated data frame in response to a command request, and a very short Morse code modulated telemetry sequence and satellite ID if no activity is present for a given period of time. This Morse code ID allows the satellite to be heard by the general amateur radio community and will help with identifying the satellite once on orbit. There are several satellite housekeeping commands that can be sent up from the ground to control power, attitude and payload functions, and most importantly a command to reliably shut off all RF transmissions if required. All commands up to the satellite are encrypted for security.

D.7 Merit and Feasibility Review Results

D.7.1.1. Merit Review

Primary Mission Questions	**Average Rating (0-5)**
Does OwlSat contribute to NASA’s mission to conduct scientific studies of the Sun and Earth from space?	4.71
Does OwlSat's primary mission contribute to NASA's mission to understand the responses of physical and biological systems to spaceflight including space radiation?	4.71
Does OwlSat's primary mission contribute to advance knowledge about space radiation?	4.29
Average Primary Mission Rating	**4.57, 91.4%**
Secondary Mission Questions	**Average Rating (0-5)**
Does OwlSat help to lay the foundation for America to maintain a constant human presence in LEOt?	3.86
Does OwlSat help to inspire and engage the public in aeronautics, space, or science?	4.14
Does OwlSat help to enhance the safety of NASA's human spaceflight program?	3.86
Average Secondary Mission Rating	**3.95, 79.0%**

D.7.1.2. Merit Review Comments

- Solid radiation/solar studies, orbit determination is applicable to physical systems and robotic exploration.
- I think the primary and secondary mission objectives of OwlSat both align directly with NASA's Strategic Objectives. The scientific outcomes will aid in humanity's understanding of the LEO environment, and thus will foster a safer and more reliable LEO satellite industry.
- Very scientifically sound and valid.
- Not fully sold on whether this mission actually is applicable to human spaceflight.
- Details of public engagement plans were limited.

D.7.2.1. Feasibility Review

OwlSat System	**Average Rating (0-5)**
Is the OwlSat Team technologically capable of developing the OwlSat Structure?	5
Is the OwlSat Team technologically capable of developing the OwlSat Power System and Solar Module?	5
Is the OwlSat Team technologically capable of developing the OwlSat Avionics Systems?	5
Is the OwlSat Team technologically capable of developing the OwlSat Payload Systems?	4.71
Is the OwlSat Team technologically capable to develop the OwlSat Ground Station?	3.86
Is the OwlSat Team technologically capable to design and test the OwlSat CubeSat?	4.86
Is the OwlSat Team financially capable of funding the OwlSat CubeSat?	4.86
Is the OwlSat Team and proposal organized and structured in a professional manner?	4.86
Does the OwlSat team set realistic goals and timelines for OwlSat completion?	4.71
Average	**4.76, 95.2%**

D.7.2.2. Feasibility Review Comments

- Ground Station component needs more explanation.
- Ground station is only technical aspect that is a little risky, but very reasonable amount of risk and lots of educational value.
- Overall the proposal is great. Avionics, comms, power, and mechanical subsystems are detailed thoroughly. Margins on mass and power as well as fault management are well thought out. The team has clearly already started on working out business/fundraising partnerships, including partnerships that will support testing of the cubesat (really great that you guys already have that locked down). The only thing I would have loved to see more of is development or ideas for the ground station.
- It is good that you have looked into ground stations, though specifics would make your argument more sound. However, you have plenty of time to do that and I'm assuming that you will just use the existing ground station infrastructure of your university/other universities/NASA to communicate with OwlSat.

D.7.3. SEDS Sat-2 Competition Review

Engineering Capability	**Scoring Weight**	**Category Description / Competition Notes**	**Average Rating (0 - 3)**
Technical Ability	20%	Design, testing, and launch plans are detailed thoroughly	2.58
Practicality	15%	Very realistic goal set considering the outlined plans/schedule	2.83
Non-Technical Capability			
Finances / Fundraising	10%	Thorough detailing of how the team will raise needed funds	2.50
Outreach / PR	10%	Thorough detailing of how team will raise awareness, recruit members, and receive public support	2.67
Professionalism	15%	The proposal resembles a company-written proposal	2.58
Mission Novelty	10%	High scientific novelty / No one has experimented on this yet	1.54
Mentorship	10%	Developed multiple beneficial mentor relationships	3.00
Undergraduate / Graduate Student Ratio	5%	Majority of the team are undergraduate students	3.00
Team Diversity	5%	Over 50% of the team is comprised of minorities	2.50
Total Score			**85.83%**

D.7.4. SEDS Sat-2 List of Competing Teams

1. Arizona State University
2. Embry-Riddle Aeronautical University
3. Florida Institute of Technology
4. MIT/Tufts/Northeastern
5. Ohio State University
6. Purdue University
7. Rice University
8. Texas A&M University
9. University of Arizona
10. University of California San Diego
11. University of Central Florida
12. University of Colorado Boulder

13. University of North Carolina at Chapel Hill
14. University of North Texas
15. University of Tennessee at Chattanooga
16. University of Texas at Arlington
17. Utah State University
18. Virginia Tech

D.8. Minimum Mission

The primary mission of OwlSat is to characterize the relationship between solar EUV radiation and atmospheric drag in LEO conditions. This requires our system to measure EUV irradiance, together with satellite position and acceleration. In order to ensure mission success, redundancies have been built into the system. This section will show what OwlSat components can fail without jeopardizing mission success.

OwlSat will have 4 EUV sensors, each of which will measure EUV radiation of greatly overlapping wavelengths. This means that we can lose up to 3 sensors and still collect a significant amount of EUV radiation data. If 1 or 2 EUV sensors produce false data, we can compare data sets across all 4 sensors to determine which sensors are faulty. Additionally, in the extremely unlikely event that we lose all 4 EUV sensors, our team plans on using EUV radiation data collected by public satellites such as those operated by NASA and use this data as an estimation of the EUV radiation affecting the OwlSat orbit.

OwlSat will also have multiple sun sensors, which will be referenced by the attitude system to orient OwlSat towards the sun. If one of these sensors fail, the system will still be able to detect the sun. If all of the sun sensors fail, an integrated passive attitude system will work to use the Earth’s magnetic field to orient OwlSat orthogonal to the Earth’s magnetic field. While this means that OwlSat will no longer be pointed directly at the sun, the passive attitude system will allow it to still be pointing outwards, orthogonally to its orbital path, allowing some EUV data to still be collected. These data points will be augmented by EUV data from previous NASA solar space missions.

OwlSat’s GPS system will allow our ground station to locate the satellite’s position and it can also be used to approximate the acceleration of the satellite. If this system fails, tracking of the satellite will be done by simulation and the acceleration data needed will still be collected through the accelerometer.

OwlSat’s accelerometers are the primary source of acceleration data, used to characterize the atmospheric drag effect on the satellite. In the very unlikely event that 2 accelerometers fail, the GPS system will allow us to approximate the satellite’s acceleration by using position data points.

Overall, our primary mission can still be accomplished if we lose all 4 EUV sensors, all of our sun sensors, and either the GPS system or 2 accelerometers. Our secondary mission of outlining heavy particle radiation profile across LEO can still be performed in the event that 2 of OwlSat’s heavy particle detectors fail.

Nevertheless, our critical components include the solar panels, power system, antenna array, and microcontrollers. If any of these complete systems break, our mission will result in failure.

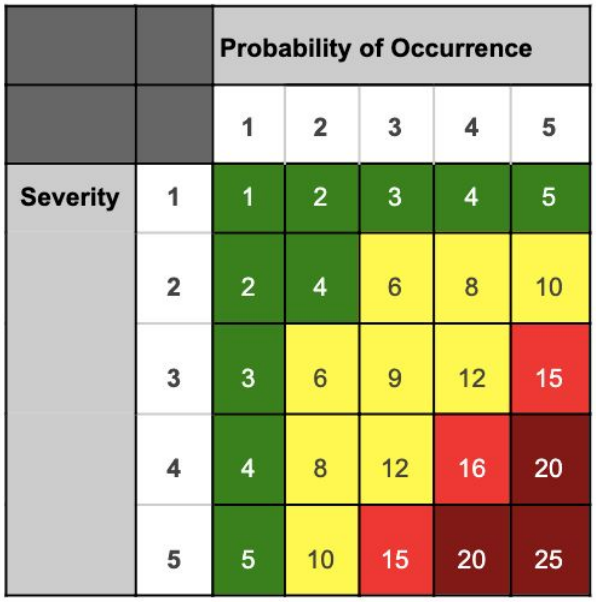
D.9. Failure Scenarios

The OwlSat Team has created a Failure Modes Effects and Analysis (FMEA) to assess the potential failure points of the proposed design, highlight the causes and effects of these failure points, predict the probability of occurrence and severity, and establish a mitigation plan for each point (Table 7). This analysis helped inform the team on which systems are the most critical and also serves as a tool to ensure that there is an established plan to minimize the risk of failure of the mission.

The FMEA shows that our most critical components are the solar panel arrays, the antenna array deployment system, and the power system. While we plan on doing extensive testing on all components and systems, identifying these systems as the most critical ensures that special attention is given to them throughout the engineering process.

Although there is a significant number of potential failure modes that will result in the overall failure of the entire mission, the likelihood of any of them happening is extremely low. We have designed redundancy into various subsystems by having more than one of the same component, such that the failure of one of these components will not lead to the failure of the mission. Some examples of this include having multiple solar panel arrays, EUV sensors, sun sensors, accelerometers, and heavy particle detectors. The entire system was designed by prioritizing the insurance that our minimum mission will be met, as will be discussed in the next section. Testing will also be a very large part of our engineering process, as explained in our previous section.

Table 6: 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 7: Failure Modes Effects and Analysis (FMEA)

Potential Failure Mode	Cause(s)	Effect(s)	Probability (1-5)	Severity (1-5)	Risk Index	Acceptable?	Mitigation Plan
Solar Panel Array Fails to Deploy	Antenna Misalignment or the Panels become Jammed	Lack of Power to CubeSat	2	5	10	Yes	Test deployment methods of the solar panels and antenna. Include multiple solar panel arrays to provide redundancy
Antenna Array Fails to Deploy	Antenna becomes Jammed or Fails to Operate Correctly	Data Cannot be Received from CubeSat	2	5	10	Yes	Test deployment method of the antenna array. Include multiple antennae in antenna array
EUV Sensor Failure	Too Much or Too Little Power, Bad Calibration, Temperature/Radiation Exposure	EUV Data Cannot be Measured	1	3	3	Yes	Test EUV sensors with multiple EUV wavelengths, temperatures, and radiation levels. Have 4 sensors for redundancy and use public EUV data for verification
GPS Failure	Too Much or Too Little Power, Antenna Misalignment	CubeSat Position Cannot be Measured	1	3	3	Yes	Test GPS to ensure compatibility with communications system. Use accelerometer data to estimate position
Sun Sensor Failure	Too Much or Too Little Power, Bad Calibration, Faulty Sensor	Sun Cannot be Located, Resulting in EUV Sensor and Solar Panel Inefficiency	1	2	2	Yes	Test sun sensor functionality. Have multiple sun sensors to ensure redundancy.

Accelerometer Failure	Too Much or Too Little Power, Bad Calibration, Faulty Sensor	CubeSat Acceleration and Velocity Cannot be Measured	1	3	3	Yes	Test accelerometer before integration. Include 3 accelerometers for redundancy. Use the GPS to estimate acceleration and velocity.
Attitude System Failure	Too Much or Too Little Power, Magnetic Field Interference	CubeSat Orientation Cannot be Controlled	1	5	5	Yes	Test altitude system using simulations to mimic LEO
Communications Failure	Antenna or Ground Station Misalignment	Data Cannot be Downloaded from CubeSat	2	5	10	Yes	Test communications system using environmental testing, have multiple antennas in antenna array to ensure redundancy.
Losing Track of CubeSat	Antenna or Ground Station Misalignment	Data Cannot be Downloaded from CubeSat	1	5	5	Yes	GPS and communication systems tested beforehand.
Radiation Degradation of Electronics	Materials Not Suited for LEO Radiation Levels	Electronics Stop Functioning	1	5	5	Yes	Ensure all components can withstand LEO radiation levels or coat uncertified electronics with radiation protection.
Radiation Degradation of CubeSat Structure	Materials Not suited for LEO Radiation Levels	Structure Fails	1	5	5	Yes	Ensure all components can withstand LEO radiation levels or coat the structure with radiation protection.

D.10. Detailed Financial Budget

The OwlSat budget assumes building 2 complete satellites and having 1 component spare. The components from the FlatSat prototype will be incorporated into the first CubeSat prototype, so we would only need to order a duplicate of every component. Numbers are approximate and depend heavily on purchasing COTS vs space rated components.

Table 8: Detailed Financial Budget

System	**Component**	**Qty.**	**Price**	**Ext.**
OwlSat Bus	Structure	2	$2,400.00	$4,800.00
	Solar Module	8	$2,375.00	$11,000.00
	Power System	2	$2,500.00	$5,000.00
	System controller	4	$25.00	$100.00
	Radio	2	$275.00	$550.00
	70 cm antenna array	2	$5,000.00	$10,000.00
	External memory	2	$7.00	$14.00
	Wiring, fasteners, etc.	-	$50.00	$50.00
Primary Mission	EUV Sensors	8	$200.00	$1,600.00
	GPS chip	2	$35.00	$70.00
	Accelerometer chips	6	$5.00	$30.00
	Magnetorquer	2	$905.00	$1,810.00
Secondary Mission	Heavy Particle Detector	6	$150.00	$900.00
Ground Station	Primary / Secondary Ground Stations	2	$2,500.00	$5,000.00
Testing	Environmental Testing	2	$500.00	$1,000.00
Miscellaneous	Contingency	1	$3,000.00	$3,000.00
Total Cost				**$44,994.00**

D.11. Detailed list of Funding Sources

Members of the OwlSat project are enthusiastically raising money and services to ensure the project's success. Current funding sources include:

- The OEDK Machine Shop and Design Kitchen is allowing access to the machine shop, environmental testing support, and professional engineering services. These services are estimated to be about $7,500.
- The Rice Tribomechadynamics Laboratory is allowing access to the 3 degree of freedom vibration tester suited for random rocket vibration testing. These services are estimated to be about $2,000.
- Rice Eclipse Rocket Club is donating a rocket launch on their high powered rocket which is estimated to be about $2,000 in services for vibration and high altitude testing.
- The Moody Center Design and Prototyping Shop is allowing access to their prototyping laboratory and professional services. These services are estimated to be about $2,500.
- The Rice Space Institute has provided $1,000 towards the development of OwlSat and has agreed to support the program with an additional $3,000 toward the project.
- The Oshman Engineering Design Kitchen has already provided $1,000 towards the development of OwlSat and has agreed to support the project with an additional $3,000 over 3 years with an opportunity for an additional $5,000.
- The Rice George R. Brown School of Engineering has agreed to provide $2,000 towards building the satellite and SEDS Rice estimates that the School of Engineering will provide an additional $3,000 over the next 3 years.
- The Wiess School of Natural Sciences has agreed to provide $3,000 towards the OwlSat project.
- SEDS Rice estimates that the Rice Center for Engineering Leadership will provide $5,000 towards building the satellite.
- The Rice Department of Physics & Astronomy has agreed to provide $3,000 towards the OwlSat project.
- The Rice Engineering Alumni has agreed to provide $5,000 towards the OwlSat project.
- SEDS Rice estimates to raise approximately $5,000 from corporate giving programs through the Rice University Corporate Relations Office with a goal to raise $10,000.
- SEDS Rice aims to start a Crowdfunding Campaign for the OwlSat CubeSat. With the ability to submit your name to a chip on the satellite, SEDS will provide several options to submit your name and help support the project. While all person’s will be able to submit their name for free, they will also have the option to financially support the project. SEDS Rice estimates to raise $5,000 from the CrowdFunding Campaign with a goal to raise $10,000.

In total, monetary and in-kind donations is approximately $58,000.

D.12. OwlSat Heritage: Rice University’s Prosperous Relationship with NASA

Rice University first began research collaborations with NASA in 1959, but as early as 1958, Rice alumnus and board chairman George R. Brown played a pivotal role to make sure that Houston and Rice University would play a pivotal role in the space race. Additionally, Brown’s friend and former roommate, Congressman Albert Thomas, helped transform Houston into “Space City USA” which officially began when the city was named as the future site of the Manned Spacecraft Center, which is known today as NASA’s Johnson Space Center.

On September 12, 1962, President John F. Kennedy gave his “We Choose to Go to the Moon” speech at Rice Stadium. His words challenged the United States to become the “world’s greatest space-faring nation.” In director response to President Kennedy’s speech, Rice University established the nation’s first dedicated Space Science department in 1963. On July 20, 1969, when Neil Armstrong and Buzz Aldrin became the first humans to walk on the moon, they carried the Apollo Lunar Dust Detector designed by Rice Professor Brian O’Brien. The Apollo Lunar Dust Detector flew on Apollo 11, 12, 14, and 15. Additionally, the Suprathermal Ion Detector Experiment and the Charged Particle Lunar Environment Experiment were built by Rice scientists and flew on Apollo 12,14, and 15 and Apollo 13 and 14 respectively.

Today, the Space Sciences, Physics, Space Physics, and Astrophysics/Astronomy departments are now part of the Physics and Astronomy Department. The Rice Space Institute was created in 2000 which coordinates commercial space activities and ties to Johnson Space Center. Rice also has a Space Studies Masters program and hosts numerous aerospace events through the Baker Institute for Public Policy with policy researcher and “astronaut maker” George Abbey. To date, Rice University has 14 astronaut graduates and the current NASA Administrator is a rice alumnus.

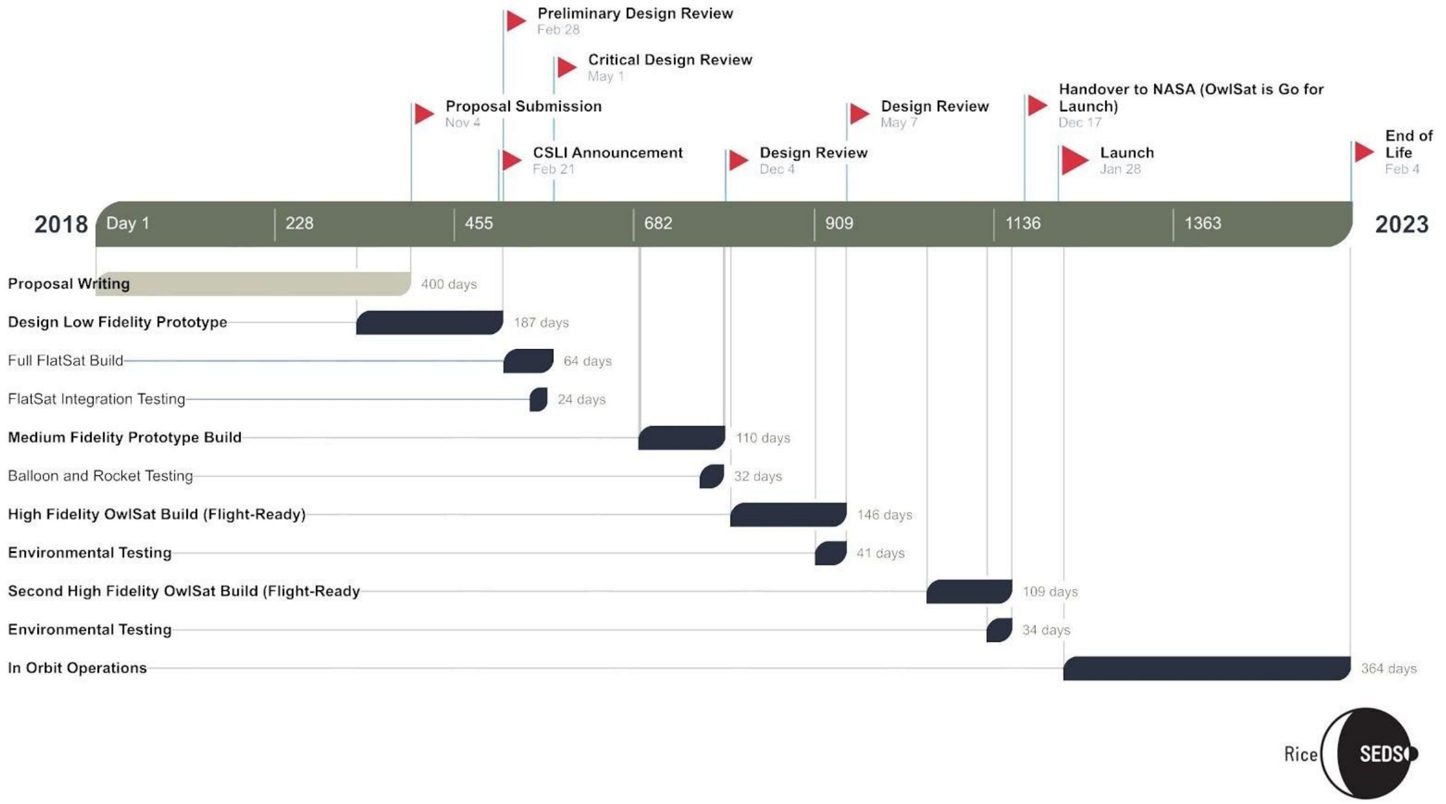
In the past few years, undergraduate and graduate students have helped to rekindle aerospace engineering and space sciences at Rice starting in 2014 with the creation of the Rice Eclipse Rocket Club and the Students for the Exploration and Development of Space (SEDS) Rice. Rice Eclipse Rocket Club has successfully tested many 10,000 ft launch vehicles and 50 lb thrust and 800 lb thrust hybrid rocket engines.

SEDS Rice was revamped in 2018 with the goal of connecting undergraduate and graduate students to the space industry at Rice and abroad. SEDS Rice hosted the first Owls in Space Symposium on April 13, 2019 with over 45 aerospace industry professionals including NASA Administrator Jim Bridenstine and Astronaut Dr. Peggy Whitson. Throughout the day, over 250 students and faculty attended the event with tremendous positive feedback. SEDS Rice is currently planning for the second Owls in Space Symposium to be held in February of 2020.

SEDS Rice also started developing OwlSat in 2018 for the SEDS Sat-2 Competition sponsored by Astranis and NanoRacks. While SEDS Rice did not receive a ride to space, the judges believed that the organization was technically and non-technically competent to develop a spacecraft. Additionally, SEDS Rice is pursuing the NASA Micro-G challenge to develop a Lunar Dust Collector for the next Artemis missions building on the heritage of the Apollo missions.

D.13. Gantt Chart

Figure 15: OwlSat Gantt Chart



Additional Tasks and Milestones	Start	End
Interface Control Agreement Start	Aug 2022	Sep 2022
Customer Safety Data Call Start	Aug 2022	Aug 2022
Safety Initial Assessment by NanoRacks	Aug 2022	Aug 2022
Baseline Interface Control Agreement	Sep 2022	Sep 2022
Phase 0 Safety Package Submitted to NASA	Sep 2022	Sep 2022
Phase 0 Safety Review	Sep 2022	Sep 2022
Technical Interchange Meeting	Sep 2022	Sep 2022
Phase 1 Safety Data Package Submittal to NASA	Oct 2022	Oct 2022
Phase 1 Safety Review	Oct 2022	Oct 2022
Phase 2 Safety Data Package Submittal to NASA	Oct 2022	Oct 2022
Phase 2 Safety Review	Oct 2022	Oct 2022
Satellite-Separation System Fit Check	Nov 2022	Nov 2022
Ground Safety Support Data Package	Nov 2022	Nov 2022
Phase 3 Data Package Submittal to NASA	Dec 2022	Dec 2022
Phase 3 Safety Review	Dec 2022	Dec 2022
Ground Safety Data Package Delivery	Dec 2022	Dec 2022

D.14. References

1. Chobotov (2002). “*Orbital Mechanics”*, AIAA Education Series, *pp191*

2. Connolly, Ryan, The P-POD Payload Planner’s Guide, Revision C, June 5, 2000.

3. Crowther, R. (2003). “*Orbital debris: A growing threat to space operations*”, Philos. Trans. R. Soc. London, Ser. A, 361

4. Forsberg, K., Mooz, H. (1998). "*System Engineering for Faster, Cheaper, Better*" (PDF). Center of Systems Management.

5. Fuller-Rowell, T. J., and S. C. Solomon (2010), “*Flares, coronal mass ejections, and atmospheric responses, in Space Storms and Radiation: Causes and Effects*”, edited by C. J. Schrijver and G. L. Siscoe, pp. 321–357, Cambridge Univ. Press, New York.

6. Global CubeSat Market. “Focus on Sizes(1U, 2U, 3U, 6U and other sizes), Subsystems, and End Users(Academic, Commercial, Government, Defense, and Non-Profit Organization)-Analysis and Forecast: 2018-2022, 2018”, BIS Research.

7. Guide to Reference and Standard Atmosphere Model (2010). “*Guide: Guide to Reference and Standard Atmosphere Models”,* AIAA.

8. Haigh, Joanna D. (2007). "*The Sun and the Earth's Climate: Absorption of solar spectral radiation by the atmosphere*". *Living Reviews in Solar Physics*.

9. Hardesty, L. (2017, April 14). Explained: Neural networks. Retrieved from http://news.mit.edu/2017/explained-neural-networks-deep-learning-0414.

10. Henry, C., & Henry, C. (2019, October 16). SpaceX submits paperwork for 30,000 more Starlink satellites. Retrieved from https://spacenews.com/spacex-submits-paperwork-for-30000-more-starlink-satellites/.

11. IEEE. “*IEEE Guide--Adoption of the Project Management Institute (PMI) Standard A Guide to the Project Management Body of Knowledge (PMBOK Guide)”,* Fourth Edition. p. 452.

12. Kelley, Michael C. “*The Earth’s Ionosphere, Plasma, Physics and Electrodynamics*”, Academic Press, San Diego, 1989.

13. Kilic, C. (2015). Mission analysis of a 2U CubeSat, BeEagleSat. *2015 7th International Conference on Recent Advances in Space Technologies (RAST)*.

14. Launch Services Program Level Dispenser and CubeSat Requirements Document. (2014, January 30). *Nasa.gov*. Retrieved from https://www.nasa.gov/pdf/627972main_LSP-REQ-317_01A.pdf

15. Marcos, F., B. R. Bowman, and R. E. Sheehan (2006). “*Accuracy of Earth’s thermospheric neutral density models*”, paper presented at AIAA 2006–6167, AIAA/AAS Astrodynamics Specialist Conference, Am. Inst. of Aeronautics. and Astronautics.

16. Marcus, B. (2019, February 20). Small Satellites, Big Market: Sky's the Limit for CubeSats. Retrieved from https://www.protolabs.com/resources/blog/small-satellites-big-market-sky-s-the-limit-for-cubesats/.

17. Marshall, B. (2018, November 19). Build a CubeSat Satellite that actually works, Part 1: Make it Resilient. Retrieved from https://www.rs-online.com/designspark/build-a-cubesat-satellite-that-actually-works-part-1-make-it-resilient.

18. Mehrparvar, A. (2014, February 20). CubeSat Design Specification . Retrieved November 3, 2019, from http://www.cubesat.org/resources.

19. Nanoracks CubeSat Deployer. (2018, June 4). Retrieved from http://nanoracks.com/wp-content/uploads/NanoRacks-CubeSat-Deployer-NRCSD-Interface-Definition-Document.pdf

20. NASA Strategic Plan 2018. (2018, February 12). *Nasa.gov*. Retrieved from https://www.nasa.gov/sites/default/files/atoms/files/nasa_2018_strategic_plan.pdf

21. National Aeronautics and Space Administration. “*CubeSat 101: Basic Concepts and Processes for First-Time*”. Washington, D.C.

22. *Orbital debris: A growing threat to space operations*”, Philos. Trans. R. Soc. London, Ser. A, 361

23. Porter, J. (2019, April 4). Amazon will launch thousands of satellites to provide internet around the world. Retrieved from https://www.theverge.com/2019/4/4/18295310/amazon-project-kuiper-satellite-internet-low-earth-orbit-facebook-spacex-starlink.

24. Pultarova, T., Henry, C., Pultarova, T., & Henry, C. (2017, February 24). OneWeb weighing 2,000 more satellites. Retrieved from https://spacenews.com/oneweb-weighing-2000-more-satellites/.

25. Satellite Collision Leaves Significant Debris Clouds. (2009). *Orbital Debris Quarterly News*, *13*(2). Retrieved from https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv13i2.pdf

26. Shishko, R., Aster, R., & Cassingham, R. C. (1995). “*NASA systems engineering handbook*.”, Washington, D.C.: National Aeronautics and Space Administration.

27. Solar Radiation Basics. (2013, August 21). Retrieved November 3, 2019, from https://www.energy.gov/eere/solar/articles/solar-radiation-basics.

28. Solomon (2010), “*Flares, coronal mass ejections, and atmospheric*

responses, in Space Storms and Radiation: Causes and Effects", edited by C. J. Schrijver and G. L. Siscoe, pp. 321–357, Cambridge Univ. Press, New York.

29. Turner, Martin J. L. (2004), "*Rocket and Spacecraft Propulsion: Principles, Practice, and New Developments*", Springer

30. Vallado (2008).*"A Critical Assessment of Satellite Drag and Atmospheric Density Modeling"*, AIAA/AAS Astrodynamics Specialist Conference.

31. Vourlidas (2018). "*EUV Irradiance Inputs to Thermospheric Density Models: Open Issues and Path Forward*", Space Weather, AGU, Vol 16 Issue 1, pp5-

32. Xiaoli Bai (2018). "Using Artificial Neural Network in Machine Learning Approach to Improve Orbit Prediction Accuracy", Space Flight Mechanics Meeting, AIAA SciTech Forum.

33. Page, T. (2018, January 26). Meet Amber Yang. She's trying to prevent a space debris catastrophe. Retrieved November 4, 2019, from https://www.cnn.com/2018/01/15/health/amber-yang-tomorrows-hero/index.html.