Solar Sail Utilizing Radiative Forces Examining Radio-waves (SolarSURFER)

Mission Background

First conceptualized over 50 years ago, solar sailing has been an attractive form of a low-thrust system for satellite orientation. Developed upon the principle of light reflection, where thrust is generated by the momentum of photons bouncing off a surface, solar sailing serves as a low-cost and energy-efficient method of long-distance propulsion, with no theoretical limit on the upper-speed satellites can attain.

While many missions have attempted to solar sail, successful solar sails are few and far between, with the technology only being effectively demonstrated by JAXA's IKAROS probe in 2010. Further solar sail satellites have been launched since, including The Planetary Society's LightSail missions as well as NASA's ASC3 satellite, but all have failed at a crucial point in their deployment or detumbling process. To date, there has not been a successful solar sailing mission that started in Low Earth Orbit and traveled across interplanetary space under pure solar sail propulsion. We aim to change this.

Mission Summary

Our team will seek to pioneer the next generation of solar sailing technology, utilizing the prior innovations in solar sailing technology in conjunction with in-situ data from other solar sailing projects. SolarSURFER (Solar Sail Utilizing Radiative Forces Examining Radio-waves) is a joint Johns Hopkins University, Olin College of Engineering, and University of Maryland College Park Cube Satellite (CubeSat) that aims to explore technological advances in the realm of Solar Sailing. The mission is set to be built in a 6U form factor (30cm x 20cm x 10cm) with a 15m x 15m solar sail (compressed volume: 4U (20cm x 20cm x 10cm)) and the other flight dynamics and communications systems filling the other 2U.

SolarSURFER will explore many new technologies to fulfill its mission requirements, including experimentation with sail composition, the utilization of the sail as a High Gain Antenna, and the integration of the science instruments with the shape memory alloy powered booms of the sail, among other developments.

Mission Objectives

Engineering:

1. Demonstrate the feasibility of Solar Sailing out of Low Earth Orbit (LEO)
    - Design a sail where radiation pressure exceeds atmospheric drag

2. Demonstrate the feasibility of inflating sail technology
    - Use shape memory to allow for solid booms, implement safe inflation methods, and make the sail micrometeoroid-resistant
3. Demonstrate the feasibility of a High Gain Antenna (HGA) Sail
    - Create a horn extension mechanism
    - Determine sail composition necessary for X band communication
4. Demonstrate the feasibility of Solar Sail Solar Cells
    - Research composition of thin film, quantum dot, and spray on solar cells
        i. Integrate solar cells on the sail without drastically reducing thrust
    - Create the best sail alloy for maximum solar cell efficiency while maintaining sail flexibility
5. Explore the possibility of Laser-Assisted Solar Sailing
    - Test to see if lasers can be used to increase the sail acceleration

Science:

- Measurement of Solar dust particles
    - In a system similar to JAXA IKAROS ALDN
- Measurement of Earth's Ionosphere
    - Utilizing the Earth's ionosphere for testing & calibration of instruments
- Measurement of the Interplanetary magnetic field out to deep space
    - In-situ 3-dimensional magnetic field measurements with a coarse measurement range of 2-dimensional electric field measurements at VLF and HF frequencies

Cubesat Subsections

Sail Composition

The propulsion of spacecraft using solar sails has gained mass attention due to its ability to harness solar radiation pressure for propulsion. This allows spacecraft to travel through space without the need for traditional fuel, offering a low-cost, long-duration propulsion method. The CubeSat's solar sail must be designed utilizing a combination of lightweight materials, crucial to meeting CubeSat weight and size limitations. The sail's primary structural backbone is designed with a thickness of 2.5–4 microns using CP1 or Kapton films. Both materials are chosen for their excellent thermal stability, high tensile strength, and low outgassing properties. These materials are already extensively used in spacecraft due to their ability to withstand extreme temperatures and resist atomic oxygen degradation.

CP1 is a colorless polyimide with high optical clarity and superior mechanical performance in the space environment. It has been tested in previous solar sail missions, where its ability to retain its properties even under prolonged exposure to UV radiation and atomic oxygen has been well-documented. Kapton has light history and has been extensively used in NASA's solar sail missions, such as the NanoSail-D mission, where it demonstrated excellent durability and flexibility. In both cases, the thinness of the film (2.5-4 microns) is key to minimizing the sail's mass, which directly affects its acceleration.

The sun-facing side of the sail is coated with a 2.5-micron aluminum layer followed by a 0.5-micron gold layer. Aluminum is selected for its high reflectivity in both the visible and near-infrared spectrum, which enhances photon momentum transfer and thus provides efficient propulsion. However, Al oxidizes over time, which diminishes its reflective properties. The addition of a gold layer mitigates this by protecting the Al from oxidation and further enhancing reflectivity, particularly in the infrared spectrum. This dual-layer coating system has been successfully employed in prior solar sail designs, such as the Advanced Composite Solar Sail System (ACS3), where it demonstrated improved reflectivity and resistance to environmental degradation.

The side of the sail facing away from the sun is coated with a highly black pigment, which is used to reduce emissivity and manage the thermal load. In the space environment, managing heat absorption and dissipation is crucial to maintaining the structural integrity of the sail. By reducing emissivity, the black pigment allows the sail to radiate excess heat more efficiently, preventing overheating that could lead to material degradation.

The total thickness of the sail will be approximately 7 microns. This configuration includes the backbone (CP1 or Kapton), the Al and Au reflective layers on the sun-facing side, and the emissivity-reducing black coating on the anti-sun side. The reduced thickness compared to previous solar sails, such as those made from Mylar, provides a lightweight yet durable structure, capable of withstanding the mechanical stresses of deployment and operation. Sails used in missions like the Alpha CubeSat have demonstrated the importance of minimizing mass to maximize acceleration, particularly in deep space missions. By opting for a 7-micron thickness, the design seeks to enhance thrust without compromising on structural integrity.

The sail will be folded and stowed within the CubeSat, with a deployment mechanism similar to those employed in ACS3 and NanoSail-D. In these missions, deployment involved spring-loaded booms that extended the sail into its operational configuration. The proposed sail will use Mylar as an analogous material for testing folding patterns and deployment mechanisms due to its similar mechanical properties to polyimides but at a lower cost. The folding pattern will be optimized for compact stowage, with tests conducted to ensure that the sail can be deployed smoothly without snagging or tearing. Previous designs, such as the Miura fold used in Alpha CubeSat, allow for rapid deployment and effective packing within the CubeSat form factor.

The sail materials must be able to withstand the harsh environment of space, including temperature fluctuations, micrometeoroid impacts, and solar radiation. CP1 and Kapton are well-suited for this, with high resistance to UV degradation and atomic oxygen erosion. The reflective coatings also help to mitigate the effects of solar radiation, while the black pigment on the anti-sun side aids in dissipating absorbed heat. Studies from the NASA TVIW 2016 Interstellar Probe Study highlight the importance of these mechanical and thermal properties in ensuring long-term mission success. The sail design will be tested under simulated space conditions to verify its durability and performance.

The CubeSail mission, developed at the Surrey Space Centre, successfully demonstrated the use of solar sails for CubeSats, with a sail made from 5 x 5 m Mylar film deployed using a novel boom mechanism. Similarly, the NanoSail-D mission, which utilized a Kapton sail, provided valuable data on the deployment and operational challenges associated with solar sails in Low Earth Orbit. Both missions highlighted the importance of material selection and deployment reliability in the success of solar sail missions. These lessons inform the current sail design, which seeks to improve on past designs by utilizing a thinner, more efficient material composition.

In addition to the metallic layers, this solar sail incorporates a dielectric reflectarray in specific regions of the sail to further enhance its reflectance and control the direction of reflected solar radiation. (Figure 1) The reflectarray is composed of Dielectric Layers (Copper/Gold/Aluminum): Thin dielectric films (approximately 0.25 microns) are deposited over select areas of the sail to form a reflectarray. This array consists of patterns that control the phase and direction of the reflected light, optimizing the propulsion force by concentrating solar radiation in targeted directions.

Reflectarrays have been used in NASA’s ACS3 solar sail system, where they were deployed to manipulate the reflection angles and enhance the propulsion efficiency of the sail by creating controlled photon redirection. These arrays act as optical antennas, adjusting the sail’s thrust vector without needing to reorient the entire spacecraft. The addition of dielectric layers over the reflective coatings allows for precise control of photon reflection, maximizing the efficiency of photon momentum transfer and improving the sail's overall performance. The concept is similar to phased arrays used in radar systems but adapted for light.

The use of CP1 or Kapton for the backbone, along with aluminum and gold reflective coatings, offers a lightweight yet robust solution. The design balances the need for high reflectivity with thermal management, ensuring long-term durability in space. Lessons from previous missions, including CubeSail and ACS3, provide a foundation for optimizing the sail's performance and deployment mechanisms. Future work will involve experimental validation of the sail’s material properties and deployment tests using Mylar prototypes.

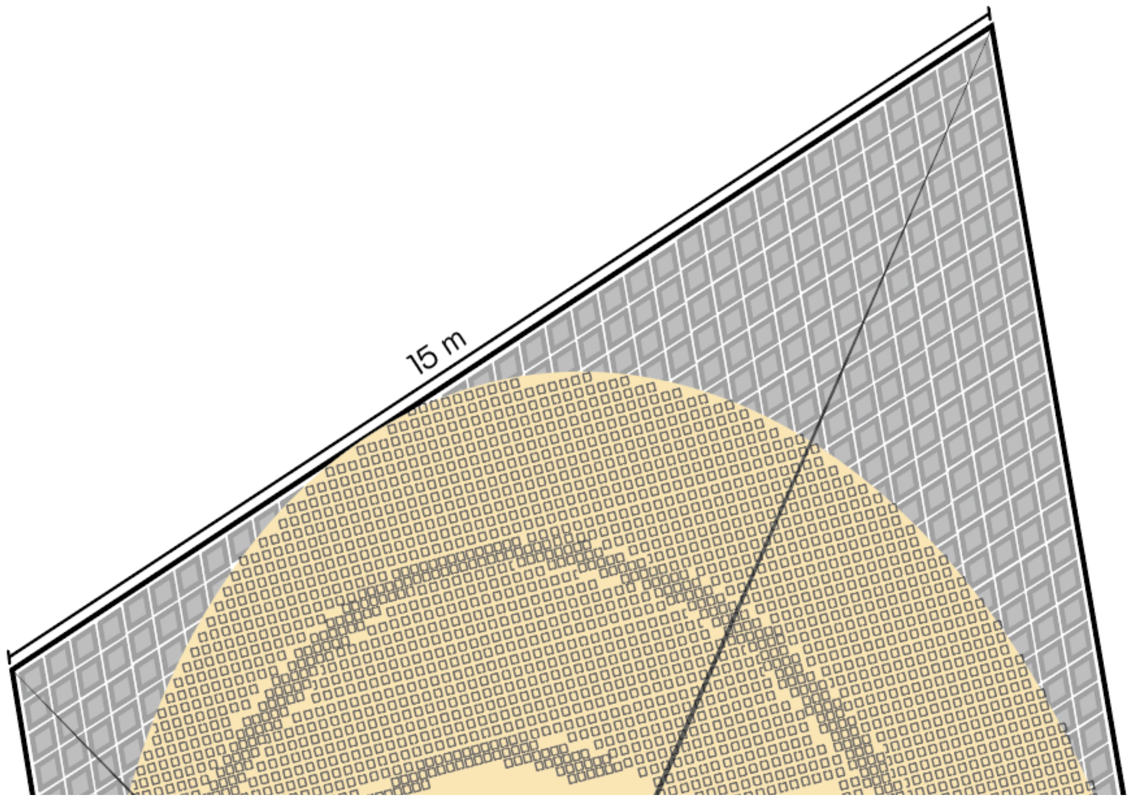
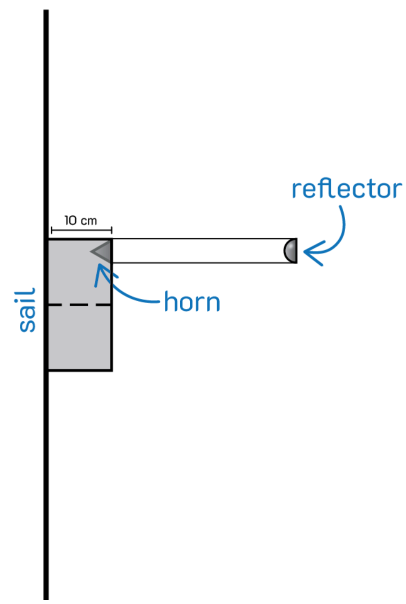


Figure 1. Cross section of the sail. The solar cells are in gray and the reflectarray is in gold.

High Gain Antenna System



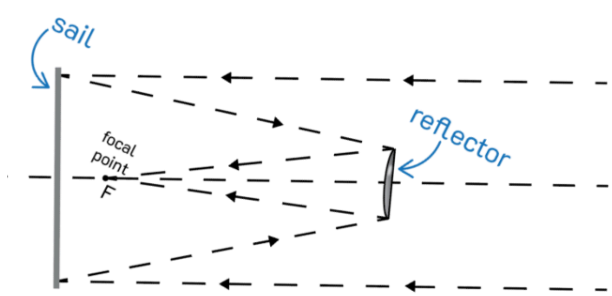
The solar sail will also be used as a high gain antenna (HGA), employing a reflectarray antenna design. A reflectarray antenna is a planar array of reflecting unit cell elements combined with a corresponding feed antenna. The planar array focuses the waves from the feed in a way analogous to a parabolic dish. This allows for an exceptionally high gain to be achieved, optimal for a solar sailing CubeSat intended to leave LEO. For this reason, reflectarray antennas have become an increasingly popular solution for space applications such as CubeSat missions.[1] By combining a deployable reflectarray antenna with a solar sail, we can increase the amount of space used by our CubeSat to stow our solar sail. As a result, our solar sail can be designed to have larger dimensions than previous solar sailing CubeSats, allowing us to increase the thrust of our CubeSat while simultaneously

[1]Imaz-Lueje, B., Prado, D.R., Arrebola, M. et al. Reflectarray antennas: a smart solution for new generation satellite mega-constellations in space communications. Sci Rep 10, 21554 (2020). https://doi.org/10.1038/s41598-020-78501-0

increasing our antenna gain and allowing us to transmit and receive stronger signals. Both of these factors should improve the feasibility of a solar sailing satellite leaving LEO while still transmitting and receiving strong signals.

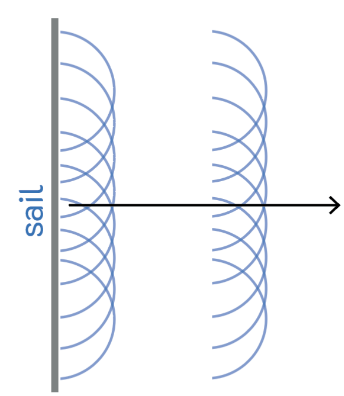
A horn will function as our feed antenna. Given that our solar sail will take up 4U of space and our other subsystems will take up another 1U of space, the remaining 1U of space will be used to house this feed antenna. With the solar sail facing the Sun side, the opening of the feed antenna shall face the Earth side, away from the main body of the CubeSat. A lens mirror will be attached to the bottom of the CubeSat in the interior of this 1U space. This bottom will be detached and then deployed a static distance away from the feed antenna using nitinol wires, which is a shape memory alloy. Deployed like this, the radio waves will be propagated off the lens mirror and through the reflectarray antenna to simulate a parabolic dish in the manner of either a Cassegrain or Gregorian reflector depending on whether the mirror is designed to be concave or convex, whichever is found to be more optimal for our purposes (see Cassegrain Reflector figure below).

The use of a mirror system to reflect waves onto the reflectarray is what allows us to house the feed antenna in the interior of the CubeSat while still focusing waves onto the reflectarray, allowing us to more easily heat the feed antenna for proper functionality. Deploying a feed antenna away from the CubeSat to directly face the reflectarray would make heating the feed antenna much harder. Additionally, heating the feed antenna will cause the antenna to produce excess waste heat that can help heat the satellite as a whole.



Cassegrain reflector
with concave mirror

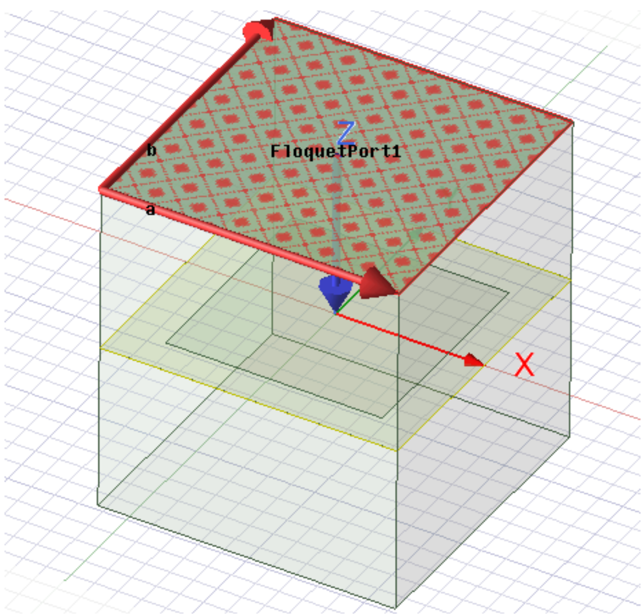
The reflectarray design itself on the solar sail will consist of a pattern of unit cells, whose shapes and rotations will vary depending on the necessary phase shift determined such that the spherical waves emitted by the reflectarray interfere with each other in a way that makes them directional. There should be no perceivable peaks or troughs from the individual spherical waves. This ensures the signal sent and received by the reflectarray antenna is clear and can transmit information with minimal noise. The actual reflectarray design on the solar sail will be circular with a 20 m diameter. The sections of the solar sail not taken up by the reflectarray will be allocated to the thin film solar cells (see Solar Sail Solar Cells).



We have determined that the system will use S band frequencies, which is about 2 to 4 GHz, due to the availability of amateur radio bands in that frequency range.[2] As the probe gets further from Earth, the data rate will decrease, and science modes will be selectively activated based on high-importance targets. There is some promise in changing coding as the distance from Earth increases in an attempt to increase data throughput. Additionally, we want to employ hyperspectral imaging through a 9-camera system that records images at different frequencies along the electromagnetic spectrum (e.g. RGB, infrared, etc.).

As the CubeSat is being launched into orbit and is orienting itself toward the Earth, it will rely on a patch antenna attached to the bottom of the other 1U space on the exterior of the CubeSat. Our reflectarray antenna signal will be strong, so it is necessary to rely on a weaker patch antenna closer to the Earth to not interfere with the signals of other satellites occupying an S-band frequency.

Progress wise, we have designed a simulation of a unit cell of our reflectarray using ANSYS HFSS, constructing two 2.5 micron-thick boxes with variable-assigned dimensions and kapton material properties. The top box has dimensions that are a fraction of the bottom box's dimensions. Additional rectangle objects are applied to the bottom of the bottom box and the top of the top box to have reflective boundaries assigned to them, meant to simulate the aluminized sides of the kapton sheets. The bottom aluminized side serves as the ground plane, while the top aluminized side serves as our patch element. We used a Floquet port excitation to analyze this unit cell as a periodic element of an infinite array.



[2] NASA, "Chapter 6: Electromagnetics - NASA Science." *NASA*, NASA, science.nasa.gov/learn/basics-of-space-flight/chapter6-3/.

We aim to use HFSS to analyze this unit cell, generating graphs that will help us optimize the shape such that assigning different dimensions to the patch element will yield the same phase responses across different incident angles, as seen in reflectarray design literature.[3] We then plan to automate the generation of the entire reflectarray in HFSS with a MATLAB or python script using the optimized phase response data to more efficiently simulate our reflectarray as a finite array.

Once we have a successful simulation of our proposed reflectarray, we plan to develop a 1 m by 1 m prototype of our sail to test the effect of folds or creases on the integrity of our signal.

Pneumatics System

The pneumatics system serves to deploy a framework to support and connect the sail with the CubeSat body, to deploy the solar sails in a timely fashion, and to provide a rigid support beam (booms) for the sail.

A pneumatic system will be applied to the satellite as opposed to the traditional mechanical pulley deployment, as inflatable structures offer the potential of compactly stowing lightweight structures, which assume a fully deployed state in space. An important category of space inflatables is cylindrical booms, which may form the structural members of trusses or the support structure for solar sails[4].

In this design, the team hopes to use inflatables to deploy an external metal truss, and since the post-deployment boom undergoes much less stress when in space, this not only allows greater payload for other components but also cuts down satellite weight by a significant amount, which is crucial for solar sailing[5].

Ridgidization:

The major deployment system comprises an air reservoir, a customized four-way nozzle for air release (with a threaded influx nozzle and a pressure release), and four cylindrical air booms, each roughly 11 meters.

For post-deployment structure, the team also developed an integrated rigid metal truss system composed of alloy ring bands and rigid wires of a shape memory alloy, to maintain a rigid truss(boom) to continue to support the sail tension and connect the sail to the CubeSat

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[3] Ye, Qi-Cheng, et al. “Development of Microstrip Reflectarray Based Monostatic STAR Antenna.” AEU - International Journal of Electronics and Communications, vol. 137, Urban & Fischer, May 2021, p. 153827, https://doi.org/10.1016/j.aeue.2021.153827.

[4] Schenk, Mark, Andrew D. Viquerat, Keith A. Seffen, and Simon D. Guest. "Title of the Paper." In Journal Name, Year. https://www3.eng.cam.ac.uk/~sdg/preprint/inflatable.pdf.

[5] Bernasconi, Marco C. "Going Elsewhere – Adapting Structures for Use in Space through Rigidizing Materials" Adaptables2006, TU/e, International Conference On Adaptable Building Structures Eindhoven [The Netherlands] 03-05 July 2006 https://www.irbnet.de/daten/iconda/CIB10915.pdf.

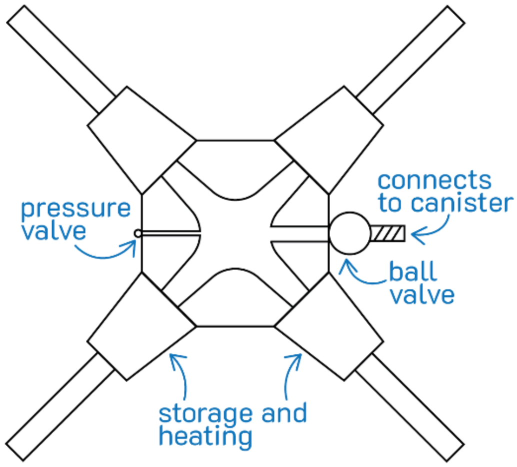
body, initially the truss will be collapsed into the allotted space in the body during takeoff. Still, it will be altered into its rigid shape during deployment[6].

In addition, four individual heating coils will installed on the end of the nozzles to alter the collapsable truss into a rigid and straight truss that can continue to support the sail as the Cubesat moves into the stage of solar sailing,

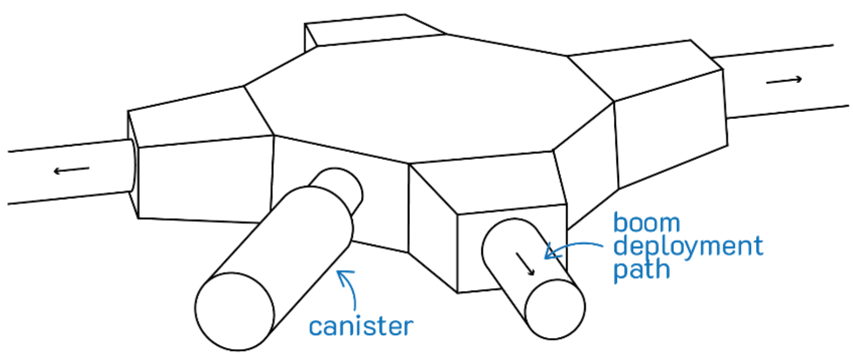
The pneumatics system is composed of many different parts that come together to facilitate the deployment and rigidization of the sail. A compact pressurized tank that holds the air needed to deploy the pneumatic system; typical composition can be either steel, aluminum, or carbon, for this design, a small canister similar to the size of a metered-dose inhaler can be installed for the purpose as an air reservoir. An octagonal prism that is welded onto the back of the Cubesat body, its main priority is to join the deployed sail to the body, with an inner cavity that can allow even air dispersion in four directions. This component is to be made of steel alloy and will be machined in a CNC mill. The cylindrical booms are molded by an air-tight membrane that can be easily inflated and collapsed, the composition of the material will be a thermoplastic polymer, notably polyethylene[7]. Alloy ring bands, small ring-sized bands, are molded into cylindrical booms, composed of light alloys, possibly derived from aluminum alloy. Finally, collapsible truss wires composed of shape memory alloy (SMA), namely Nitinol wires, would be preferred, but the design would still be viable with either iron-based or copper-based SMA[8]. The heating coils are thin strands of conductive wire that are used to heat up and restore the SMA into the form of a long rigid truss. The wire demands high heat/electric conductivity, and commercialized components can be applied for this purpose if they are found to be reliable.

Schematics:
Nozzle/Junction(internal cavity view):

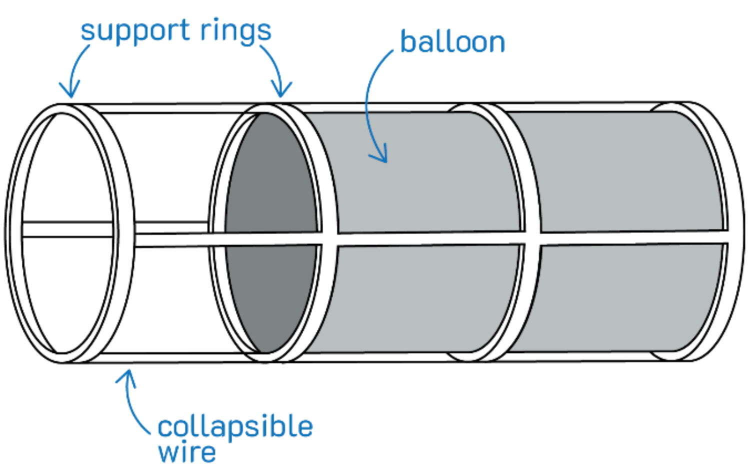
[6] Defoort, B., et al. "Rigidization Techniques." In Structures and Materials, pp. 34-42. Shanghai Jiao Tong University, 2023. https://structures.dhu.edu.cn/_upload/article/files/65/01/14dd0cb04034939ecb00d1cf6d9d/4b27f861-2724-4337-b427-a3f58948c5bc.pdf#:~:text=of%20rigidization%20techniques%20can%20be%20proposed:%20chemical,integrated%20light%20sources)%2C%20thermal%20curing%20(using%20so.
[7] Schnell, Andrew R., Larry M. Leigh Jr., and Michael L. Tinker. "Deployment, Foam Rigidization, and Structural Characterization of Inflatable Thin-Film Booms" In NASA Technical Reports, 2003.
[8] Rastogi, Vikas, S. H. Upadhyay, and Kripa Sankar Singh. "Self-rigidizable Kapton-SMA conical booms: A comprehensive numerical and experimental study" ScienceDirect, vol. 73, no. 8, 2024, pp. 3936-3962. https://www.sciencedirect.com/science/article/abs/pii/S0273117724000048#:~:text=Further%20advancing%2C%20thermosetting%20resins%20evolved,overcome%20the%20hurdles%20mentioned%20above.



Outer design:



Deployed truss:



System Architecture:

The aim is to use pneumatics to deploy a collapsible truss through the utilization of air booms, seeking to innovate and derive a more payload-efficient and energy-efficient approach to spacecraft structures than the traditional method of solid metal scaffolding.

For the mission, this system seeks to deploy four air booms through inflation to unfold the solar sails and alloy truss, then seek to permanently stabilize rigid and straight trusses formed by alloy ring bands and SMA wires that can provide support for the sail to be fully stretched and under tension.

Further, the system holds a deflation outlet at the junction with a ball valve controlled by the onboard computer to slowly deflate the air booms post-deployment, to solely use pneumatics for collapsible truss deployment, with the final overall structure being composed of four strengthened trusses to connect and support the solar sail for the duration of the mission.

Solar Sail Solar Cells

A fundamental condition for a CubeSat is the availability of onboard power. The power system of this CubeSat comprises a battery system, mainframe solar cell arrays, and a photovoltaic array fitted onto the sail. On the sun-facing side of the solar sail, there will be a thin-film solar sail that utilizes amorphous silicon or quantum dots as the concluding sheet. The solar sail's thrust vector is halved in areas where photons are absorbed. Thus the size and placement of the solar cells must be strategic. Additionally, solar cells have an operational temperature limit that must be considered when creating the sheet.

Multiple photovoltaic (PV) cells will harness photons from the sun. These cells, placed on the sail, will generate energy for the CubeSat in conjunction with a deployable array attached to its frame. A photovoltaic cell consists of multiple layers such as semiconductors, conductors, and anti-reflective material.[9] When the sun hits a photovoltaic cell, photons release electrons from a semiconducting material's atoms. The typical diode has two semiconducting layers, a positive and negative type, in which electrons are donated from negative to positive to create charge [See Figure A]. This electron exchange happens continuously during a constant stream of photon impact. The photovoltaic also includes different buffer aspects for resistance to optimize voltage without overloading the PV system. This repetition creates a system of electrons moving about holes in the semiconductor layers.[10] This generates an electrical current.

A photovoltaic cell's power output is characterized by its open circuit voltage. The voltage of a PV cell is proportional to its short circuit current as the electrons flow between layers versus

[9] Thomas, Nathan. (October 2017). How Solar Panels Work.
[10] Moon, Md. Mahabub Alam & Rahman, Md & Hossain, Jaker & Ismail, Abu Bakar Md. (2019). Comparative Study of the Second Generation a-Si: H, CdTe, and CIGS Thin-Film Solar Cells. Advanced Materials Research. 1154. 102-111. 10.4028/www.scientific.net/AMR.1154.102. Ibid 10

the resistance offered by buffer layers of the cell.[11] A certain energy (band) gap, or minimum energy required to excite a semiconductor electron to transition between the valence band and the conduction band in insulators and semiconductors, is crucial for photon absorption. Higher energy promotes higher output to the other subsystems within the scope of this mission. A greater band gap can produce a higher voltage at the cost of current.[12] A balance of about 1.2-1.5eV band gap was determined to be a working efficiency for this CubeSat mission.

This CubeSat mission will include multi-junction photovoltaic cells. The distinction between heterojunction and multijunction is the amount of p-n junctions, the region of contact between the positive and negative layers of the cell. A single-junction cell has one in series. By contrast, a multijunction cell includes multiple layers of light-absorbing substance. Because of its multi-layered nature, triple-junction cells can take in various frequencies and thus have higher absorption rates, increasing efficiency.[13] The heightened efficiency, combined with a higher temperature coefficient and radiation resistance, are beneficial beyond the capabilities of a single-junction solar cell.[14]

We will utilize thin-film solar cells for the CubeSat wall array. Many manufacturers have been developing small-scale photovoltaic cells for small satellite projects.[15] Thus, there are readily available thin-film solar cells that will be useful to this mission. These diverge from traditional silicon solar cells in the way they minimize wasted energy.[16] This occurs due to thin-film cells' composition, which allows them to absorb different wavelengths. Amorphous Silicon (A-Si) [See Figure B] and Gallium Arsenide (GaAs) [See Figure C] are optimal choices for fixed array semiconductors. Amorphous silicon has been a major semiconductor for thin-film solar cells for almost two decades.[17] Efficiency for amorphous silicon semiconductors drastically increased with the introduction of hydrogenated A-Si (A-Si: H) cells.[18] In A-Si: H cells, hydrogen atoms help close bonds in the A-Si to perpetuate energy circulation.[19] These differ from regular A-Si cells because the closed bonds aid in light trapping and circuit continuation as a result.

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[11] Aghaei, Mohammadreza. (2012). A Review on Comparison between Traditional Silicon Solar Cells and Thin-Film CdTe Solar Cells. Ibid 5
[12] Brandon R. Sutherland, Solar Materials Find Their Band Gap, Joule, Volume 4, Issue 5, 2020, Pages 984-985, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2020.05.001.
[13] T. Takamoto, H. Washio, and H. Juso, "Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic," in Proceedings of the 40th IEEE PVSC, Denver, CO (IEEE, 2014), pp. 0001–0005
[14] Assiya Lemmassi, Aziz Derouich, Ahmed Hanafi, Abdelilah Byou, Mounir Benmessaoud, Najib El Ouanjli, Low-cost MPPT for triple-junction solar cells used in nanosatellites: A comparative study between P&O and INC algorithms, e-Prime - Advances in Electrical Engineering, Electronics and Energy, Volume 7, 2024, 100426, ISSN 2772-6711, https://doi.org/10.1016/j.prime.2024.100426.
[15] F. Santoni, F. Piergentili, Analysis of the UNISAT-3 solar array in-orbit performance, J. Spacecr. Rockets 45 (N1) (2008), https://arc.aiaa.org/doi/10.2514/1.32392.
[16] See Cite 3
[17] Imamzai, M., Aghaei, M., Hanum Md Thayoob, Y. and Forouzanfar, M. (2012) A Review on Comparison between Traditional Silicon Solar Cells and Thin-Film CdTe Solar Cells. Proceedings of National Graduate Conference (NatGrad 2012), Tenaga Nasional Universiti, Putrajaya Campus.
[18] Kenu, Eguono & Uhunmwangho, Roland & Okafor, Ephraim. (2024). A Review of Solar Photovoltaic Technologies. 09. 741-749.
[19]S.C. Bhatia, 5 - Solar photovoltaic systems, S.C. Bhatia, Advanced Renewable Energy Systems, Woodhead Publishing India, 2014, Pages 144-157, ISBN 9781782422693, https://doi.org/10.1016/B978-1-78242-269-3.50005-X.

Hydrogenated amorphous silicon cells offer a high voltage in relation to cell temperature, making them useful for this CubeSat mission.[20] The array on the body of the CubeSat will most likely utilize amorphous silicon for its semiconducting layers due to the increased endurance compared to crystalline silicon which has considerable physical drawbacks such as inflexibility. A thin-film array is useful for space applications due to its lightweight nature. This allows for greater thermal and damage resistance.[21] These qualities are integral to our CubeSat mission.

Our solar cell arrays will include a substrate to enhance circulation and give physical support through the semiconducting layers of the cells. Various flight-grade options are for sale from current vendors and Gallium Arsenide may be the most optimal for energy circulation. The implementation of GaAs as a substrate differs from Gallium Arsenide as a semiconductor because it will not be used directly for energy flow, but as a foundation for the layers to be fixed onto. Therefore, the GaAs can support active PV material rather than being used as a semiconductor. This substrate will also hold the electrical contacts of the arrays. These contacts allow the charge generated by the solar arrays to be transported to applicable areas in the Cubesat. This includes front, back, and interconnection contacts, each located at different points of the cell. The front and back are situated as such on the panels, and the interconnection contact is what allows the cells to come together to form a PV array.[22]

To attach the solar arrays to the CubeSat's body, we will use layers of Kapton Tape. Kapton coverlay is a polyamide film that has adhesive properties that will bond the panel substrate to the CubeSat chassis. This film has a very high resistance to extreme temperature conditions; thus its condition and longevity are optimal for this mission.[23] One issue that may hinder this material from bonding the array to the wall of the satellite is the instance of air pockets which will ruin the link between the materials. To prevent air pockets from ruining the attachment and causing different issues due to vacuum conditions in space, we can add stitching onto the panels' substrate or use double-sided kapton layers to solidify the pieces.[24]

The body-mounted solar arrays will be fixed on five walls of the CubeSat [See Figure D], three 10cm x 20cm, and two 20cm x 20cm (sides 1,3,5,7,9 see Structural). Once the sail deploys, the sides will fold out to capture photons at an optimal angle. The increased surface area of a panel is beneficial to energy capturing, hence the panels are to be bought and fitted to take up as much space on the sides as possible.[25] This particular mission configuration will point the panels

[20] See 2
[21] Ho-Baillie, A.W.Y., Bremner, S., Brenner, C. et al. Emerging photovoltaics for onboard space applications. Nat Rev Mater (2024). https://doi.org/10.1038/s41578-024-00723-9
[22] Borgers, T., Govaerts, J., Voroshazi, E., Jambaldinni, S., O'Sullivan, B., Singh, S., Debucquoy, M., Szlufcik, J., and Poortmans, J. (2017) A woven fabric for interconnecting back-contact solar cells. *Prog. Photovolt: Res. Appl.*, 25: 569–582.
[23] P. Karuza and D. A. Hinkley, "Solar Cell Installation Using Double Sided Polysiloxane Pressure Sensitive Adhesive (PSA) Polyimide
[24] Sorensen, Nicholas & Halliwell, Erik. (2024). Open-Source CubeSat Solar Panels: Design, Assembly, Testing, and On-Orbit Demonstration. 10.48550/arXiv.2407.19356.
Film," Cal Poly. The Aerosp. Corp. Web. 23 Dec. 2015 (2009).
[25] Santoni, Fabio & Piergentili, Fabrizio & Donati, Serena & Perelli, Massimo & Negri, Andrea & Marino, Michele. (2014). An innovative deployable solar panel system for Cubesats. Acta Astronautica. 95. 210–217. 10.1016/j.actaastro.2013.11.011.

in a manner such that they should be able to harness solar radiation at the cells' intended capacity; the satellite-fixed array will be extended forward to achieve maximum photon collection. The amount of energy generation is dependent on the panel situation and other factors that determine light capturing and perpetuation of the current. Thus, optimization of the panel angle and situation increases onboard power and allows the CubeSat subsystems to sustain and function.[26]

Typically, CubeSat missions implement photovoltaic cells for primary power generation and a battery for energy storage and launch. A battery is integral to providing sufficient power to the different subsystems and instrumentation within the craft because space-applicable solar cells are not wholly sufficient for the scope of this mission. Considerations for the battery include temperature constraints, mission life, and orbit energy requirement. A pivotal instance for the battery is during and right after launch. Here, the battery must self-sustain as well as power the conjoining subsystems. Self-consumption and external usage factor into the initial powering of the system. Then, the battery needs to sustain the CubeSat.[27] A lithium-ion (Li-Ion) cell seems to be the most favorable for a secondary energy-storing battery for this mission as they have a dramatically increased power density than other current chemistries offer.[28] These batteries can be enhanced with a low-temperature electrolyte which allows them to withstand intense temperatures while in orbit.[29]

Each component of the CubeSat Power System is pivotal to this mission; thus, we are taking into careful consideration the different limitations we must abide by for this subsystem to operate successfully in Low Earth Orbit and beyond.

Power Systems Diagram Appendix:

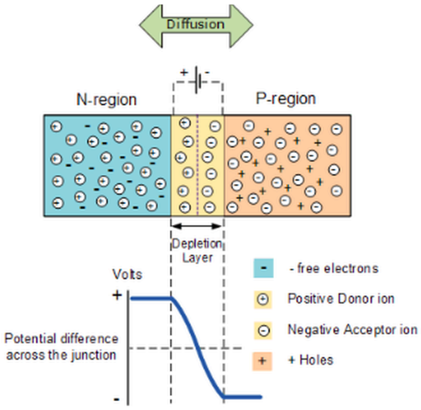
[A] The different parts of a p-n junction. Source: electronics-tutorials.

[26] F. Santoni, M. Ferrante, F. Graziani, F. Ferrazza, In orbit performance of the UNISAT terrestrial technology solar panels, in: 2001 IEEEAerospace Conference Proceedings, Big Sky, MT, vol. 1, 10–17 March2001

[27] Knap, Vaclav & Vestergaard, Lars & Stroe, Daniel-Ioan. (2020). A Review of Battery Technology in CubeSats and Small Satellite Solutions. Energies. 13. 4097. 10.3390/en13164097.

[28] Joseph R. Kopacz, Roman Herschitz, Jason Roney, Small satellites an overview and assessment, Acta Astronautica, Volume 170, 2020, Pages 93-105, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2020.01.034.

[29]Chin,K.B.;Smart,M.C.;Brandon,E.J.;Bolotin,G.S.;Palmer,N.K.;Katz,S.;Flynn,J.A.Li‐IonBatteryandSuper‐CapacitorHybridEnergySystemforLowTemperatureSmallSatApplicationsConferenceonSmallSatellites.InProceedingsoftheProceedingsofthe28thAIAA/USUConferenceonSmallSatellites,Logan,UT,USA,4–7August2014;pp.1–



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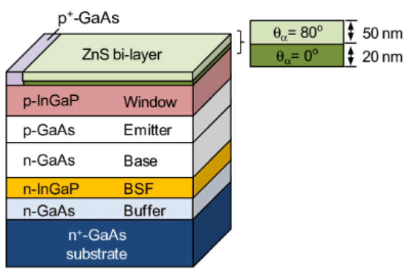
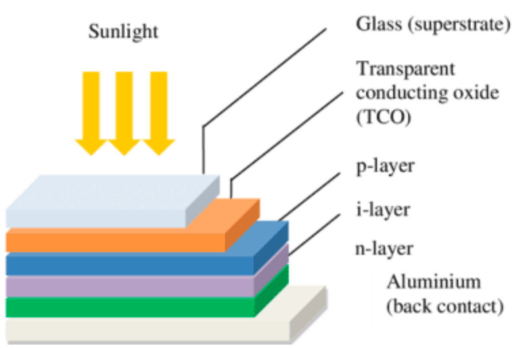
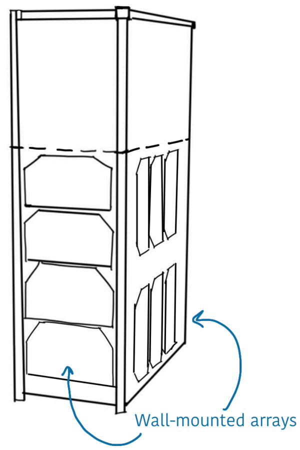
[B] GaAs Solar Cell Example. Source: Single-material zinc sulfide bi-layer antireflection coatings for GaAs solar cells by Woo, J. et al.



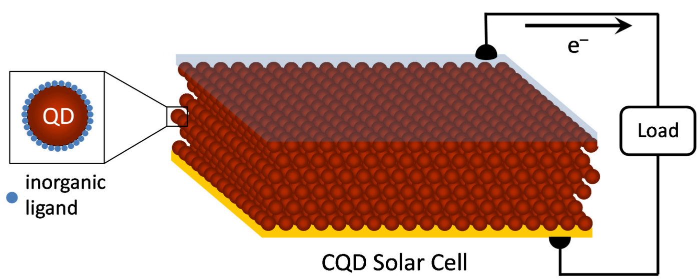
[C] Schematic of amorphous silicon (a-Si) cell structure. Source: Inorganic photovoltaic cells: Operating principles, technologies, and efficiencies - review by Karzazi, Y. and Arbouch, I.



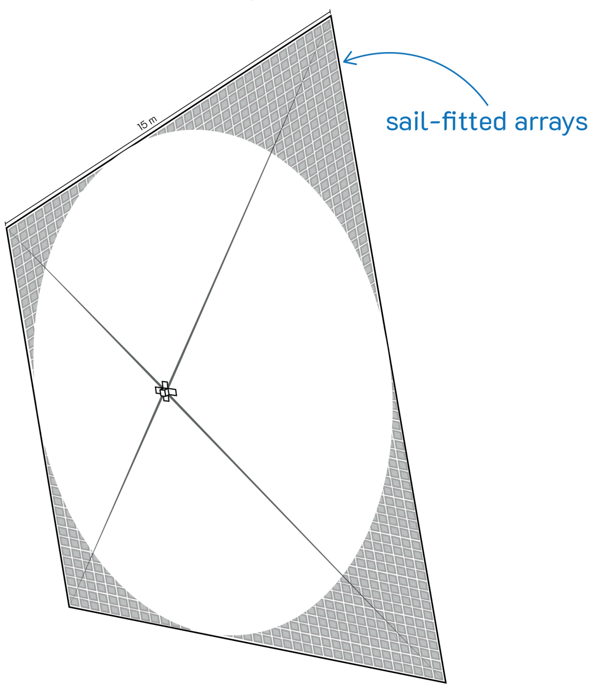
[D] Wall-Mounted Solar Array Diagram. Source: HopSat Power Systems Team.



[E] Colloidal (Perovskite) Quantum Dot solar array. Source: John Asbury lab, Penn State University.



[F] Sail-Fitted Array (modeled to have Perovskite film). Source: HopSat Power Systems Team.



On Board Computer

Rust:

Traditionally, the development of aerospace systems is dominated by the C programming language[30]. C, however, is often riddled with memory safety issues. This is because the programmer themself has to manage memory, which makes it simple to introduce unknown vulnerabilities or bugs causing the program not to operate at full capacity. Rust, on the other hand, has systems in place that force programs to be memory-safe. In Rust, the compiler abides by a system of rules which all stem from the concept of ownership. Ownership requires that every piece of data has only one owner and that every piece is immediately dropped when it goes out of scope. The combination of these two traits ensures that memory can be recycled as soon as possible and that common bugs such as attempting to access memory that has already been cleared or double-clearing portions of memory never happen. This system of ownership, in which principles propagate to create safer methods of programming across the entire language, minimizes vulnerabilities and squashes many bugs before they apply. For over a decade, memory safety vulnerabilities have "consistently represented" more than 65% of vulnerabilities."[31] At the date of the article's writing, despite accounting for 21% of all new native code, there still had been "zero memory safety vulnerabilities" discovered in Android's Rust code. Given the volume of new Rust code, this is a massive vouch for Rust's application in code that needs to be robust. So, the benefits of rust, previously proven in Android programs, will ensure that solarSURFER is robust in the space domain, where the safety and reliability of computing are of the utmost importance.

Hardware:

While Rust's benefits are enumerable at a minimum, they are only as good at the hardware that executes it. For this mission, we plan to use the LEON3 Scalable Processor Architecture (SPARC) developed with the principles of Reduced Instruction Set Computing (RISC) architecture. When considering processors, our team evaluated potential options on 3 main criteria: technical mission synergy (space, power, speed constraints), compatibility with Field-Programmable Gate Arrays (FPGAs), and prevalence in the aerospace sector with respect to community usage and support. The following is a treatise to our research and is subject to change with evolving mission needs.

The LEON3 architecture drew our interest first due to its speed and high capacity for computations. It permits us to perform signal analysis very quickly, even with complex filters such as Kalman filters for the Altitude Determination System all implemented on FPGAs. Additionally, our application requires a mid-level clock frequency and moderate logic utilization. While this could be solved on traditional Cortex processors, using an FPGA would allow us to use a single chip for multiple tasks without interference or extra space. This is not to say that FPGAs are a solution for every problem as they consume power, chip space, and time to implement, however, a reconfigurable system can save time and weight when its power is

[30] Seidel, L., & Beier, J. (2024). Bringing Rust to Safety-Critical Systems in Space. *arXiv preprint arXiv:2405.18135*.

[31] https://security.googleblog.com/2022/12/memory-safe-languages-in-android-13.html

distributed among the systems that use it. Examples include an altitude determination system implemented on a Xilinx Spartan6 XC6LX16-C324 chip on a Digilent Nexys 3 board.[32] Other processors that were considered did not leave us computational flexibility, especially as we are early in the project and the computational needs of a given component will continue to evolve.

One consideration with using an FPGA is the fact that they can be expensive in terms of power. Hence, we will likely implement different modes during which we can batch perform computations and compressions to ease the strain on our power cycle. While FPGAs are heavy consumers of power, their efficiencies are unmatched in many ways, so batching calculations can allow them to save power.[33] Kovac used a fully-pipelined very large scale integration (VLSI) architecture to compress a JPEG image at a rate of 100 million pixels per second, or 30 1024x1024 pixel frames in one-second [34]. However, it was shown that an FPGA implementation of SAR afforded a 6x speedup and a 50% reduction in energy consumption as compared to a software implementation.[35] We plan to use an IGLOO2 FPGA for its cost efficiency and radiation hardening for aerospace applications paired with an IGLOO2 development board. The board allows us multiple interfaces, enabling us to develop an efficient and comprehensive embedded hardware-compatible solution.

With the LEON3 processor architecture implemented on a Microchip IGLOO2 FPGA, the Onboard Computer (OBC) will manage inputs from various subsystems efficiently, using a single, integrated chip. The Attitude Determination and Control System (ADCS) inputs, such as data from gyroscopes, magnetometers, and sun sensors, are fed into the FPGA via I2C or SPI interfaces. Analog signals from sun sensors are processed through analog-to-digital converters (ADCs), and the FPGA directly handles the sensor data, while the LEON3 processor processes the combined sensor inputs to calculate and adjust the CubeSat's orientation for optimal solar sail positioning. High-resolution star tracker data is stored in external memory, interfaced via the FPGA, and further analyzed by the LEON3 for precision orientation control.

The power management system (PMS) provides critical data from solar panels and battery monitors, which are also fed through ADCs. The FPGA handles real-time monitoring of power levels, while the LEON3 uses this data to regulate power distribution across subsystems, ensuring balanced energy use. The OBC continuously monitors power generation and battery status to maintain operation even during shadow periods or low sunlight conditions.

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[32] Aboelaze, Mokhtar & El_Debb, Osama & Mansour, Ahmed & Ghazy, Mohamed. (2014). FPGA Implementation of a Satellite Attitude Control using Variable Structure Control. 10.13140/RG.2.1.4462.5448.
[33] S. S. Arnold, R. Nuzzaci and A. Gordon-Ross, "Energy budgeting for CubeSats with an integrated FPGA," 2012 IEEE Aerospace Conference, Big Sky, MT, USA, 2012, pp. 1-14, doi: 10.1109/AERO.2012.6187240.
[34] M. Kovac, N. Ranganathan, "JAGUAR: a fully pipelined VLSI architecture for JPEG image compression standard," in Proceedings of the IEEE, vol.83, no.2, pp.247-258, Feb 1995
[35] A. Jacobs, C. Conger, A.D. George, "Multiparadigm Space Processing for Hyperspectral Imaging," in Aerospace Conference, 2008 IEEE, Big Sky, MT, March 2008

For the communication system, data from the CubeSat's radio transceivers enters the FPGA through UART or similar communication protocols. The FPGA takes care of low-level tasks like packet assembly and data buffering, while the LEON3 handles high-level decision-making, such as decoding ground station commands or transmitting telemetry data. Additionally, the FPGA monitors antenna deployment via GPIO inputs, ensuring the communication subsystem remains functional throughout the mission.

The solar sail deployment and health are critical inputs for the OBC. Tension sensors, providing analog signals processed by ADCs, monitor the sail's condition during and after deployment. The FPGA handles real-time control of the sail's position, while the LEON3 evaluates the data and ensures the sail remains optimally aligned with the Sun to generate propulsion from solar radiation. Actuators for deploying or adjusting the sail send digital signals to the FPGA for precise control.

Environmental data from thermal sensors and radiation sensors are also input into the FPGA through ADCs or digital interfaces. The FPGA monitors these inputs in real time, triggering interrupts for the LEON3 if thresholds are exceeded. The LEON3 can make adjustments, such as rotating the sail to control temperature or reducing power consumption to prevent component damage from excessive heat or radiation.

The navigation and propulsion systems provide inputs such as GPS data, which is fed through UART interfaces to the FPGA. The LEON3 processes this data to make real-time adjustments to the CubeSat's trajectory. If propulsion systems are present, data from thruster controllers (e.g., fuel levels) is managed through digital inputs on the FPGA, enabling the LEON3 to coordinate small corrective maneuvers.

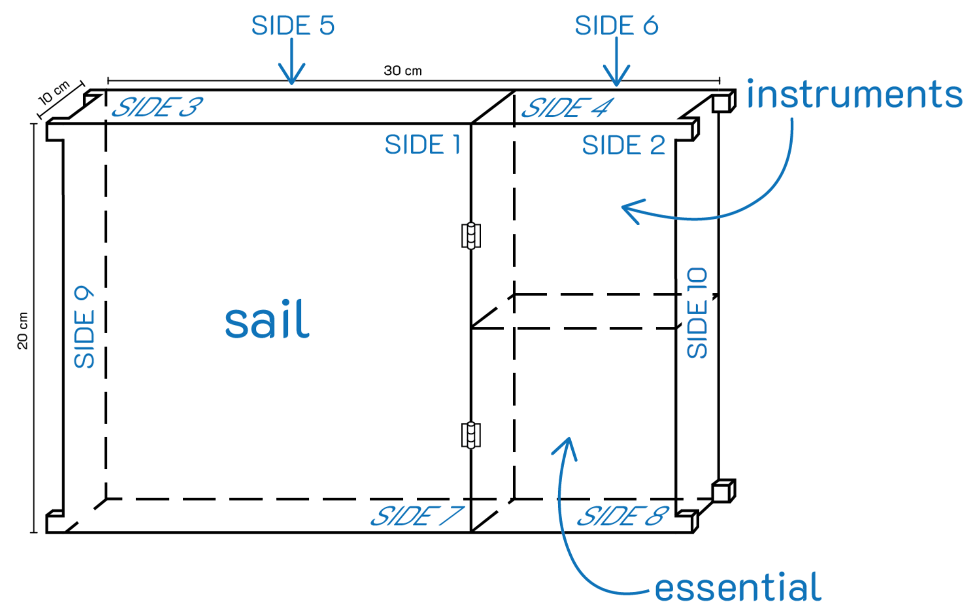
Commands from ground stations are received through the communication system and buffered in the FPGA before being passed to the LEON3 for execution. The FPGA ensures proper error correction and packet handling, while the LEON3 focuses on interpreting the commands and adjusting the mission parameters as needed, such as altering the sail's orientation or updating the CubeSat's trajectory.

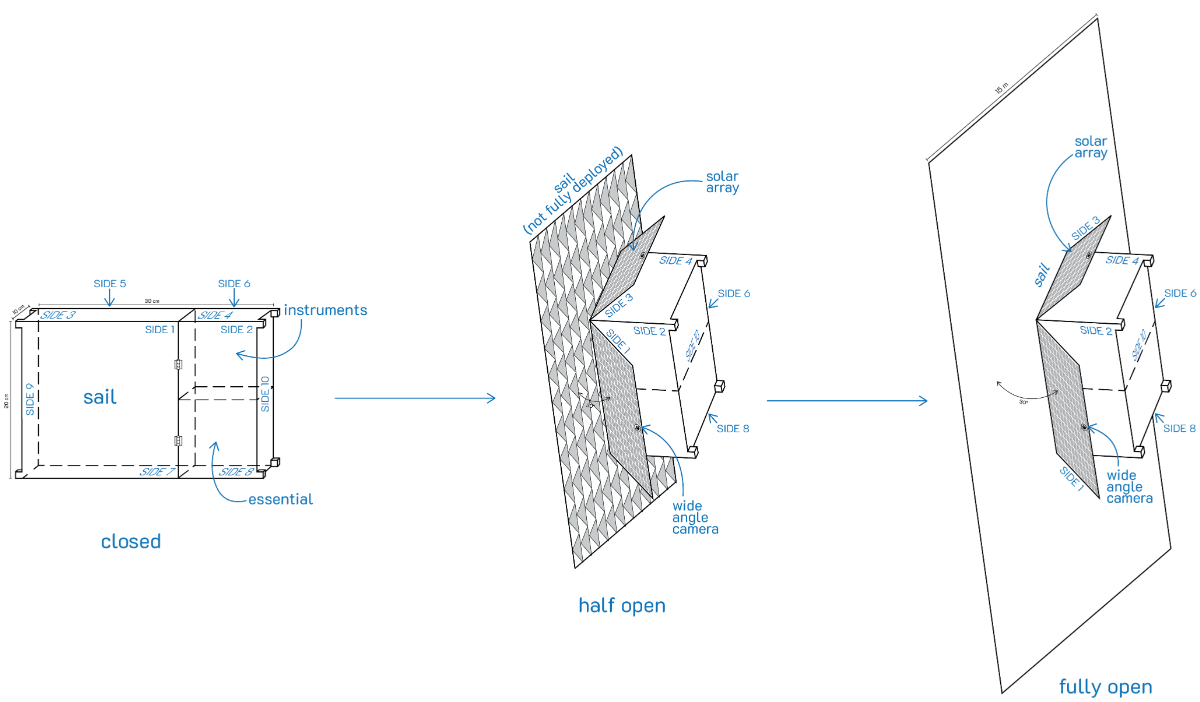
Data storage inputs, such as sensor readings or sail performance logs, are handled through SPI interfaces to non-volatile memory like flash or SD cards. The FPGA manages low-level read and write operations, while the LEON3 oversees higher-level data management tasks, including data compression, organization, and scheduled transmission to Earth.

In this fully integrated system, the LEON3 architecture on the IGLOO2 FPGA provides both real-time control and higher-level processing capabilities. The FPGA handles the fast, real-time inputs from sensors and subsystems, while the LEON3 ensures mission-level decisions are made efficiently. This combination allows the CubeSat to optimize its solar sail, manage power distribution, communicate with ground stations, and monitor system health, all within a single-chip solution ideal for the power and space constraints of a CubeSat platform.

Structural

The construction, integration, and testing of the satellite body fall under the purview of Structural.



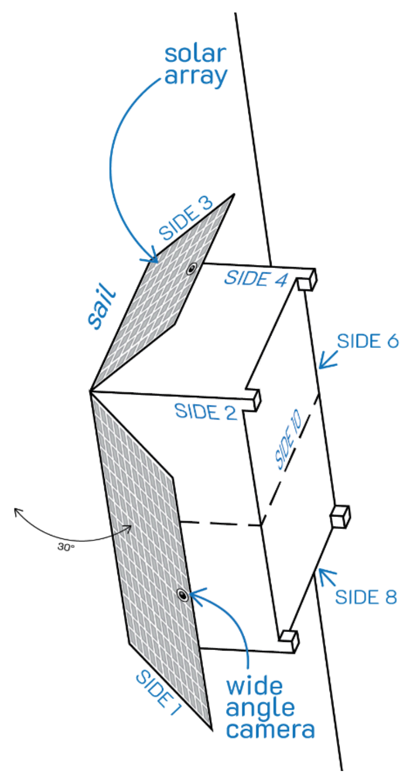


The design of the chassis is standardized. NASA's CubeSat form factor has stringent requirements for the sizing and mass of allowed nanosatellites—the relevant 6U form is arranged in a 2U x 3U configuration. This configuration satisfies the ISIS Space and Tyvak nanosatellite deployer systems, which are the usual contracted deployers for ride-share launches. These deployer systems are also designed to maximize space. The satellite also includes two “tuna-can” pods on the front panel, which are used for additional space. We have not yet determined whether the extra pods have utility, planning suggests we may use these volumes for horn extension and array instrument deployment systems.

The outer structure of the CubeSat will be machined Aluminum 6061. This is the standard metal utilized in nanosatellite construction primarily because of its mechanical properties, affordability, and ease of manufacturing. 6061 is easily machined and extruded, readily available from mills, and not expensive to purchase, especially in thinner sheets as needed for the CubeSat. CubeSat wall thickness will most likely be 2mm, as data models show good radiative blocking and strength characteristics in 6061 at that thickness. Aluminum 6061 also satisfies space technology outgassing requirements, with a Total Mass Loss (TML) of less than 0.15% and a Collected Volatile Condensable Materials (CVCM) percentage of 0.00. These are well within the bounds, specifically that TML is less than 1% and CVCM is less than 0.1%. Additionally, the critical components of the chassis will be hardened or impervious to expected radiation damage. The use of off-the-shelf components (COTS) will aid this, as space-grade hardware is readily available for purchase. Radiation-proof COTS also satisfies outgassing regulations.

The payload will be split into three major components: 4U dedicated to the solar sail, 1U for instrumentation, antenna deployment, and camera arrays, and 1U for essential satellite life support such as batteries, onboard computers, magnetorquers, transceivers, and communications modems. Electronics and communications busing will run through a separation panel between the sail deployment actuators and the onboard computing 1U.

The solar sail is contained in 4U by panels 9, 1, 3, 5, and 7. Side 9 is an explosively jettisoned panel. The bolt connections to Sides 1, 3, 5, and 7 will be constructed with frangible nuts, which will be detonated after launch deployment via a signal from the onboard transceiver. After removing panel 9, sides 1, 3, 5, and 7 will hinge outwards, allowing the solar sail to deploy outwards (for solar sail deployment, see [Boomless Sail]).



The high-efficiency solar cell arrays for powering mission-critical components will be deployed first. On the exterior of each side panel (1,3,5, and 7) will be a sized stack of solar cells, held via tensioned hinges and burn wires. During deployment, each of the burn wires holding a stack flush to its panel will be ignited and melted by an OBC instruction to flow current through the burn resistor. The panels will swing out, 30 degrees forward from the perpendicular, to minimize induced shade (as the panels will be sunward). Further signals from OBC will melt the secondary burn wires and deploy the triple stack of solar cells.

On the interior of panels 1, 3, 5, and 7 will be a small mounted wide-angle camera in the visual spectrum. After the panels have deployed forward, the wide-angle cameras will capture the solar sail deployment process. During this stage, communications to Earth will happen on a low-powered transceiver to allow the ground station team to monitor the sail deployment. Photos will provide visual confirmation that the sail has fully deployed and provide insight into how the sail fares over the mission. Any change in the satellite status, for example from micro-meteors, will be able to be spotted by the ground team through daily sail photographs.

Integration and full-scale mock testing are expected to occur from Q1 2027 to the 2028 launch date. Once CAD models of the full satellite are complete and the simulations work as expected, we will integrate the critical components on a “FlatSat” first. This will be a simple sheet of Al 6061 acting as a backplate for a full test run of the mission components, from location and motion sensing to communications and instrumentation. After iterating designs and finding conclusive successes from the FlatSat, a full-scale integration will take place in a clean warehouse located on Johns Hopkins’ Homewood campus. The sail will be stowed via the origami plans [See Sail Composition] in the CubeSat and put through a mock deployment of all critical systems including the sail. Once cleared, the CubeSat will undergo rigorous pre-launch testing to certify that the satellite will survive launch undamaged. These tests include a shock test and a vibration test done at a nanosatellite testing facility, and after successful completion of the tests the satellite will not be modified. System components will not be modified, and the satellite will be cleared for launch.

Attitude Determination Control System

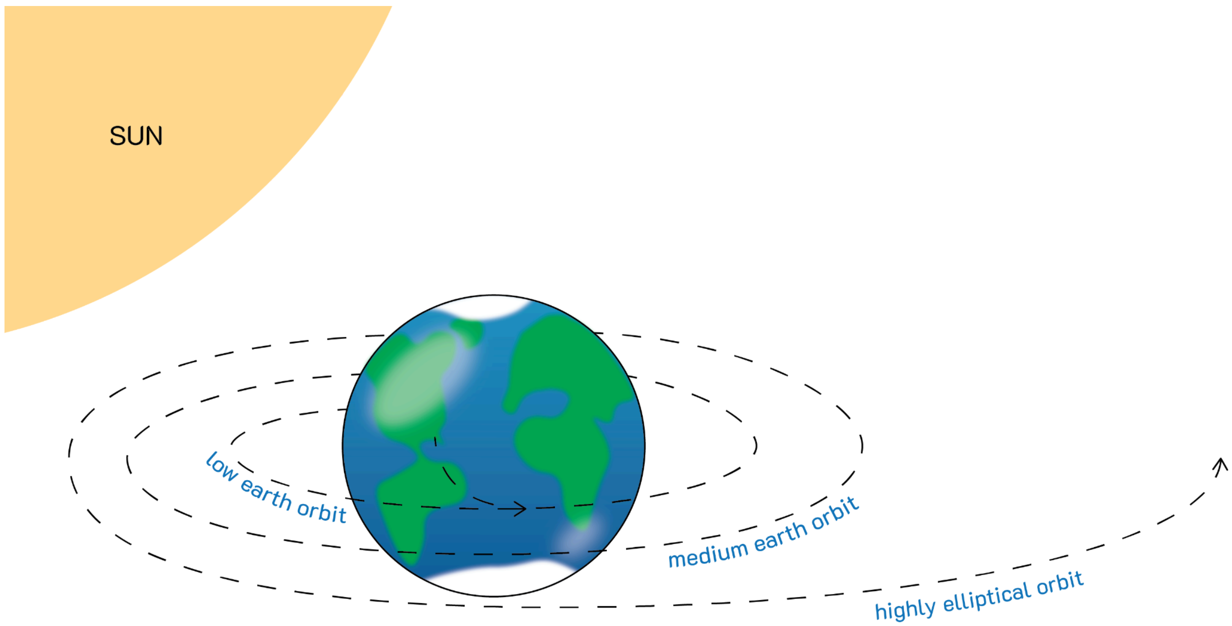
ADCS Overview:

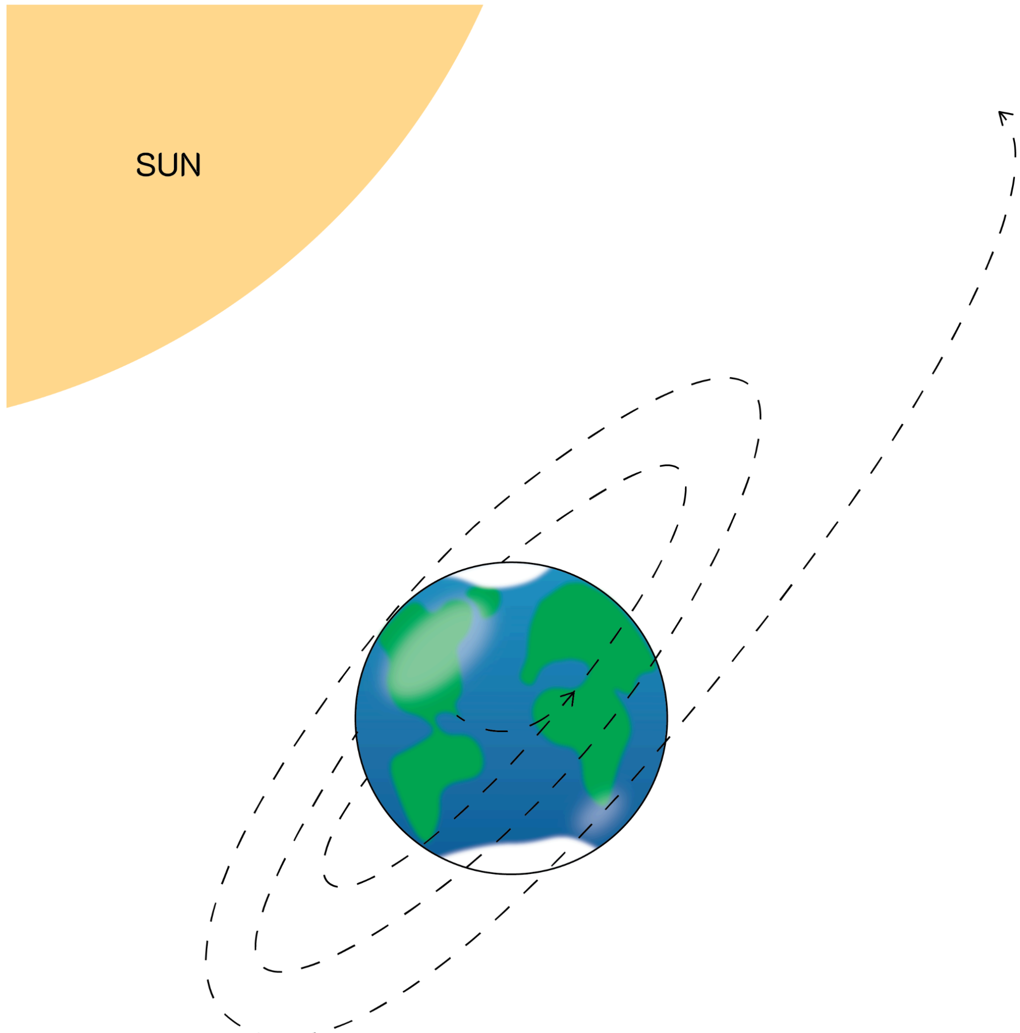
The Attitude Determination and Control System of the HopSat SolarSURFER, in addition to maintaining the orbit ‘transition’ pathway below, has multiple goals in mind. These include optimizing communication between the satellite and the ground, navigating through orbits best suited for data-collection related to the scientific goals of the mission, and most importantly, maintaining orientation to optimize solar ray exposure to both longevity and immediate power needs.

- ADCS Overview; outline goal orbit
- Input: detail sensors needed
- Data processing
- Calculating error using PID
- Actuators to correct error in a feedback loop
- Orbit Raising: Need live data on all nearby objects to avoid collision

Orbit Path:

The CubeSat will be launched into Low Earth Orbit and the momentum gained from photons hitting the solar sail will gradually lead to an increase in eccentricity until the CubeSat breaks from orbit. We have identified two orbit paths that would provide the expected result: equatorial and polar orbits. In the polar orbit, the CubeSat will experience the highest levels of radiation pressure and will spiral out faster. In the equatorial orbit, the CubeSat will be able to take a more direct path to other planets in the solar system, which will be useful in reducing ration exposure outside of the Earth's protective magnetosphere.





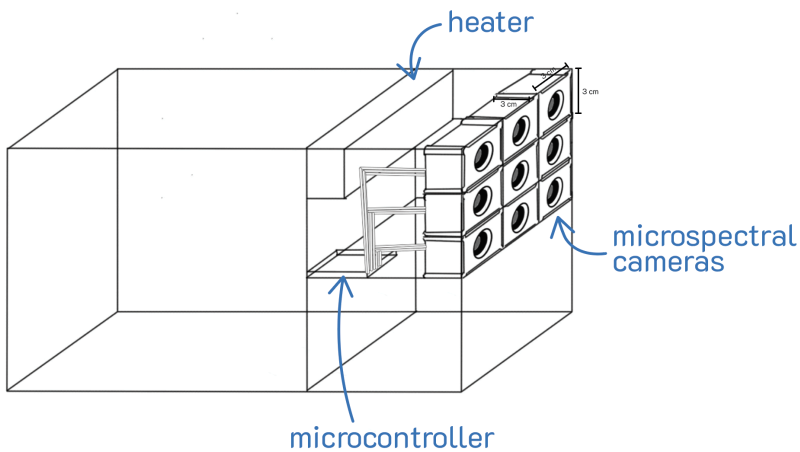
Main Components of the Navigation System:

The main components of the navigation system are sensors, actuators (for torque), and software. For navigation, the goal is to implement both a sun sensor for the sake of power and a star sensor to plot the overall trajectory of the satellite, especially as it leaves Earth's orbit and away from the sun. Regarding satellite data, a 3-axis magnetometer and a 3-axis gyroscope will be used to monitor the magnetic dipoles and angular momentum of the system. Communication with the structural sub-team will be key to identifying key sources of torque disturbances. Both magnetic torquers and reaction wheels will be used as torque actuators to provide 3-axis control of the system. Magnetic torquers will lose efficiency as the satellite moves away from Earth's magnetic field, thus reaction wheels are crucial for control at further distances. However, magnetic torquers, with their low power requirements, can be used to offset torque disturbances and prevent angular momentum overload of the reaction wheels and overall satellite.

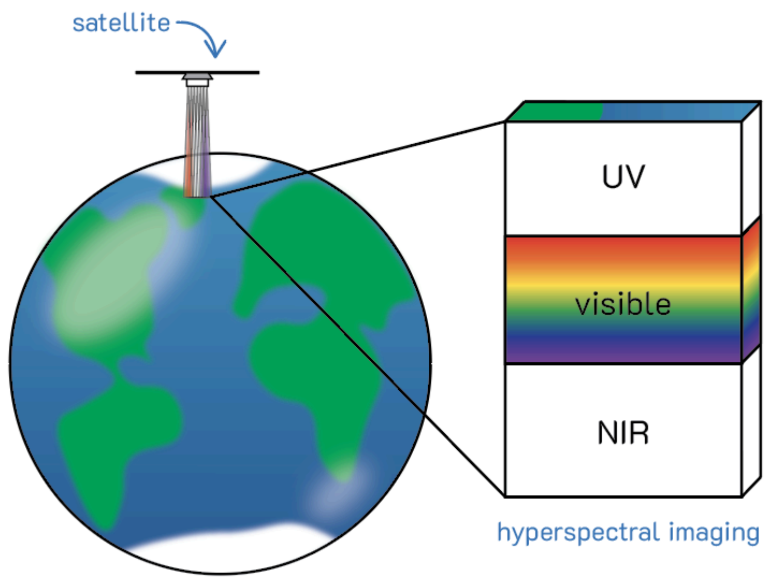
Science Payload & Boom Membrane Instruments

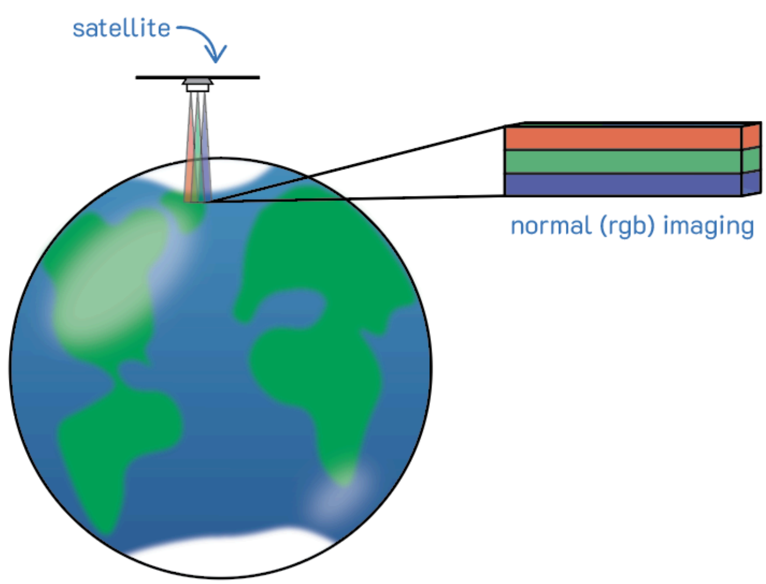
Hyperspectral imaging:

There will be a 9-camera array situated on side 10 of the chassis. This instrumentation will perform a sweep on various targets in the NIR-V-UV (Near Infrared - Visible - UltraViolet or 400 nm to 2000nm) regime to collect high amounts of information regarding many points of interest. As the CubeSat points towards the Earth, the camera array will have a high degree of visibility to many Earth targets, allowing it to collect scans of the surface. Additionally, in a sun-synchronous polar orbit, the Earth will remain lit and in view. This continuous visibility will allow for the creation of a global reconstruction image. In a classic RGB photo, there is only a composite of the classic 3 color channels (R, G, B) or 4 color channels (C, M, Y, K). However, in hyperspectral imaging, a sweep is performed over a high range of frequencies with narrow bandwidth gaps, allowing for the formation of an image cube and the extrapolation of large amounts of data. Because of the high-powered communications system in the X band regime, there is ample bandwidth to send such large images even when the CubeSat enters Geosynchronous orbit and beyond.



Check out this:
https://www.harvardmagazine.com/2024/12/seeing-methane-from-space





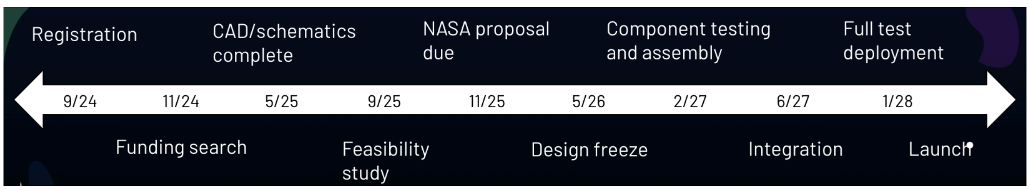
Magnetometers:

There will be four tip weights on the sail to help the sail deploy correctly, pulling it taut before the balloons are inflated. These tip weights will consist of high-fidelity heated magnetometers for the observation of the Earth's magnetic field. The data collected can be used to observe trends in the Earth's Ionosphere. The scans taken by SolarSURFER can be used to reconstruct the magnetic field and its flux around the Earth. As the CubeSat travels further away, it will have the ability to take measurements of the Interplanetary Magnetic Field (IMF), which would add to the sparse data we have on this area of magnetic exploration.

Boom Membrane Instruments:

In addition to the magnetometers, each boom will be electrically isolated and treated as a monopole antenna with the ability to receive High-frequency (HF) and VHF (Very Low-frequency) waves, which can be used to interpret the flux of magnetic and electric fields, as well as performing studies on plasma emitted by the sun. We can formulate a comprehensive understanding of the Magnetosphere and Ionosphere by utilizing magnetometers and high-fidelity readings of the IMF.

Mission Timeline:



Budget:

Item	Cost (USD)
Communications	4,000.00
Onboard Computer	12,000.00
Deployment	8,000.00
Structural	18,000.00
Guidance Navigation and Control	26,000.00
Material	
Science Sensors	15,000.00
Solar Sails	17,000.00
Electrical	2,000.00
Thermal	16,000.00
Testing & Incidentals	7,000.00
Total	125,000.00