Hypersonic ReEntry Deployable Glider Experiment (HEDGE): A CubeSAT Approach to Low-Cost Hypersonic Research

2024 - 2025 Academic Year Report

MAE 4800 Aerospace Design II

Department of Mechanical and Aerospace Engineering

School of Engineering and Applied Sciences

University of Virginia

ADVISOR:

Prof. Christopher Goyne, Department of Mechanical and Aerospace Engineering

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TEAM MEMBERS:

Sydney Bakir	Franklin Escobar	Benjamin Petsopoulos
Cole Bixby	Nathan Kaczka	Cade Shaw
Max Cristinzio	Jason Morefield	Michael Wennemer
Luke Dropulic	Zachary Morris	Caleb White
	Arooj Nasir	

Approved by: C.P. Goyne

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Introduction

Background and Context

Hypersonic technology represents a frontier in aerospace innovation with significant implications for scientific, commercial, and defense sectors (Persons, 2019). However, access to hypersonic research is constrained by the high costs and technical challenges of sustaining hypersonic speeds, limiting accessibility for academic and smaller research institutions (Button, 2023). The Hypersonic ReEntry Deployable Glider Experiment (HEDGE) seeks to overcome these barriers by using a CubeSAT framework to provide a cost-effective, scalable solution for gathering essential data on hypersonic reentry and flight dynamics. By deploying a glider from an exo-atmospheric sounding rocket, HEDGE aims to capture real-time telemetry on structural, thermal, and aerodynamic performance during reentry, addressing critical gaps in hypersonic research.

Mission and Project Overview

Mission Statement

The purpose of this mission is to demonstrate the affordability and accessibility of CubeSat technology for hypersonic flight test research through a RockSat-X launch from NASA Wallops Flight Facility.

Mission Objectives

The HEDGE team's primary goals center on advancing hypersonic research while creating meaningful educational opportunities for undergraduate students:

1. Demonstrate a low-cost hypersonic flight experiment using an exo-atmospheric rocket launch.
2. Validate the operation of avionics, data acquisition, and telemetry systems to reduce risk in future hypersonic experiments.
3. Provide undergraduates with hands-on experience in design-build-fly projects relevant to hypersonics.

In addition to its primary mission, HEDGE also supports broader educational and professional development aims:

1. Introduce students to industry-standard engineering design practices.
2. Facilitate connections between undergraduate students and aerospace professionals.
3. Offer experience working in an engineering team that simulates a professional workplace environment.

Concept of Operations

The concept of operations for HEDGE's sub-orbital flight is detailed in Figure 1. The figure outlines the full flight profile of the Hypersonic ReEntry Deployable Glider Experiment (HEDGE), from launch to splashdown. HEDGE is launched aboard a two-stage sounding rocket from NASA Wallops Flight Facility, following a suborbital trajectory that enables data collection during hypersonic reentry.

1. Launch and Ascent: At t = 0s, Stage 1 ignites, initiating the vehicle's ascent. Following the burnout of Stage 1, the rocket undergoes Stage 1 separation at approximately t = 20s. Stage 2 ignition and burn occurs immediately after, continuing the vehicle's climb.

2. Mid-Flight Events: At t = 31.7s, Stage 2 burn begins, and by t = 79s, the skin and nose cone separate to prepare for payload deployment. At t = 85s, HEDGE is deployed near apogee, which occurs between 150–170 km altitude.

3. Onboard Communication and Data Transmission: After deployment, HEDGE begins transmitting telemetry. At t = 95s, the payload establishes a connection with the Iridium satellite constellation to ensure continuous communication. Telemetry is subsequently sent to the UVA Ground Station for real-time monitoring and post-mission analysis.

4. Reentry and Splashdown: HEDGE re-enters the atmosphere and continues its descent. The vehicle experiences hypersonic conditions during this phase, enabling critical data collection on flight dynamics and thermal environments. Finally, at approximately t = 348s, HEDGE splashes down, concluding the mission.

This trajectory and deployment timeline are designed to maximize the experiment's exposure to hypersonic conditions while ensuring the safe return of hardware for post-flight inspection. The inclusion of satellite telemetry via Iridium is a key feature that distinguishes HEDGE, providing real-time communication capabilities even beyond line-of-sight from the launch range.

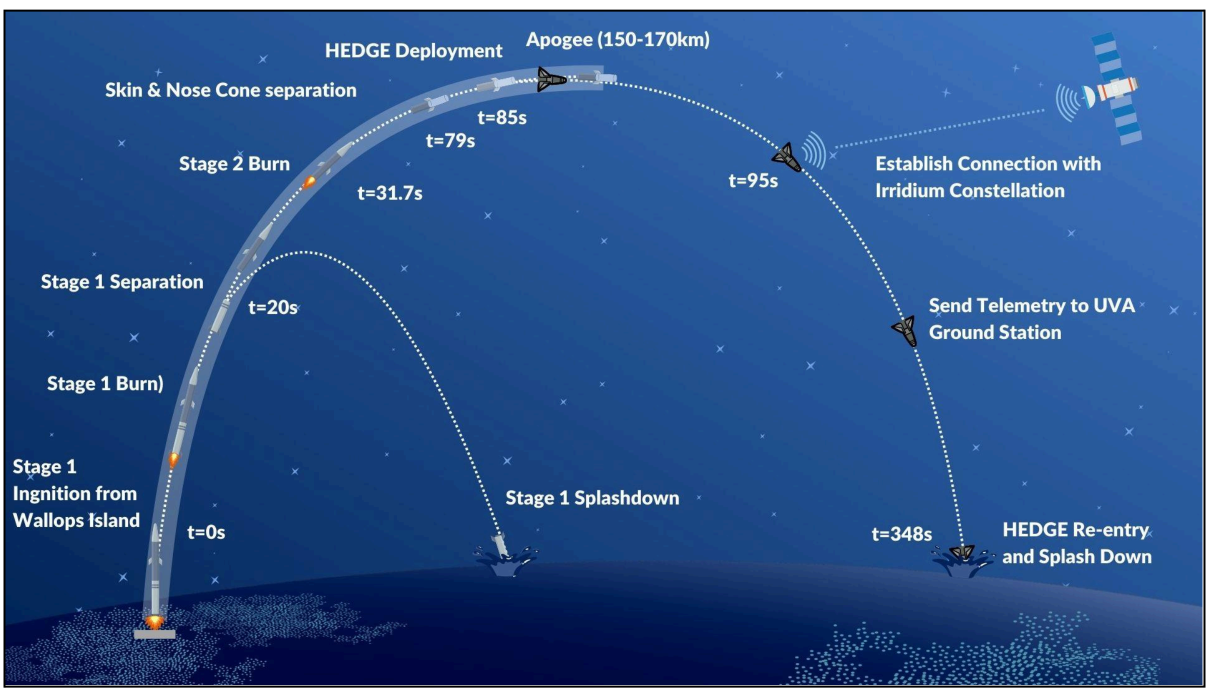

Figure 1: HEDGE Concept of Operations adapted from "RockSat-X User Guide", 2025

Design Requirements and Constraints

Tables 1, 2, and 3 outline the key quantitative metrics that guide the design, development, and validation of the HEDGE system. These include functional performance requirements (Table 1), operational performance requirements (Table 2), and mission-specific constraints (Table 3). Together, these requirements define the engineering boundaries within which HEDGE must operate to ensure a successful flight, reliable data collection, and safe deployment within the RockSat-X launch platform.

Functional Performance Requirements

Table 1: HEDGE Quantitative Functional Performance Requirements

F1	Withstand RockSat-X Launch Loads of 25 g's in all directions with occasional impulses of 50 g's in the z-direction
F2	CubeSat deployment mechanism opens in <1 second and ejects CubeSat with velocity of 0.1 - 0.5 m/s.
F3	Fins must fully deploy and lock into place within 5 seconds after activation, and must remain locked throughout flight despite aerodynamic forces.
F4	HEDGE must endure reentry vibrations, vacuum, reentry temperatures up to 500°F (260°C), and microgravity.

Operational Performance Requirements

Table 2: HEDGE Quantitative Operational Performance Requirements

O1	HEDGE must be able to survive a total mission length of 10 minutes in suborbital flight.
O2	Separation mechanism activates within 1 second of command, with a force sufficient to ensure clean separation.
O3	Iridium modem establishes connection autonomously within 10 seconds post-separation. Signal strength $\geq$ 15 dB.
O4	Data packet size of $\geq$ 1 KB transmitted. Frequency of 2 data packets per second. At least 90% of expected packets received at the ground station.

Mission Constraints

Table 3: HEDGE Quantitative Mission Constraints

C1	Diameter must be < 12in (minus keep-out zone)
C2	Height < 5.13in
C3	Experiment and deck must be 15+/-0.5 lbf
C4	Center of gravity must lie within a 1in square in the plane of the deck
C5	Speed of the deployable must be < 10in/s

Ethical and Professional Considerations

The Hypersonic ReEntry Deployable Glider Experiment (HEDGE) project requires a strong commitment to ethical responsibility and professional standards, particularly in launch safety, regulatory compliance, spectrum management, and responsible research practices. Adhering to the Federal Aviation Administration (FAA), Federal Communications Commission (FCC), National Aeronautics and Space Administration (NASA), and RockSat-X program guidelines. We ensure that all aspects of the mission, from vehicle integration to flight testing, meet safety protocols and do not pose risks to other experiments. Our design complies with RockSat-X safety standards, prioritizing structural integrity, proper deployment mechanisms, and safeguarding against harm to other experiments.

Additionally, spectrum management is an essential consideration due to our affiliation with the Iridium satellite network. Compliance with FCC licensing ensures efficient frequency allocation and prevents signal interference. Ethical collaboration of knowledge necessitates open research balanced against security issues to permit our findings to advance science without compromising sensitive technology developments. Sustainability activities support NASA's Sustainability Policy, which governs the responsible selection of materials and operational planning. By being transparent, professionally honest, and following the best practices in aerospace and telecommunications, we establish the highest levels of ethics and professionalism during the mission.

Program Management

Management Approach

The Program Management team is responsible for ensuring HEDGE the best chance of achieving all mission objectives through smooth and efficient communication and cooperation between functional teams. This is achieved through proactive coordination, transparent communication, and structured oversight across all five functional sub-teams, including Structures & Integration, Software & Avionics, Communications, Attitude, Stability & Trajectory, and Power, Thermal & Environment as shown in Appendix A: Figure 1A. The management team establishes cross-functional meeting schedules, tracks action items, and monitors dependencies to minimize roadblocks and ensure cohesion between design, testing, and integration phases. Key responsibilities include milestone tracking, donor coordination, documentation upkeep, and facilitating decision-making processes that balance technical feasibility, schedule, and risk.

Budget

The HEDGE budget was constructed with a focus on affordability and strategic allocation of funds to maximize the probability of the best outcome to achieve our mission objectives. The project is funded through a combination of the University of Virginia (UVA) capstone budget, donations from Systems, Planning & Analysis (SPA) and the School of Engineering, as well as funding from Jefferson Trust, and the UVA Student Council Contracted Independent Organizations (CIO) budget. A detailed description of these partnerships can be found in Table 1B in Appendix B. Major expenditures include manufacturing materials for the glider structure, avionics components, and payment for a spot on the Summer 2025 RockSat-X Mission. The Program Management team monitors spending through regular audits and budget reviews to ensure adherence to financial constraints and identify opportunities for cost savings or reallocation. See Table 2B in Appendix B for a detailed breakdown of the HEDGE budget.

Schedule

A detailed project schedule was developed using Google Sheets and milestone planning to ensure timely progress toward the expected launch in Summer 2025. The schedule includes capstone deadlines, RockSat-X presentations, subsystem reviews, procurement deadlines, integration checkpoints, and testing campaigns. The Program Management team leads twice weekly coordination meetings to update the schedule based on real-time progress, resource availability, and technical challenges. Built-in slack time accommodates for delays in procurement or unexpected rework, ensuring that critical path items remain on track.

FCC Licensing

HEDGE requires radio frequency communication capabilities to transmit flight telemetry during and after deployment. To comply with regulatory requirements, the Program Management team is responsible for securing the necessary licensing through the Federal Communications Commission (FCC). This includes coordinating with university representatives and external advisors to ensure that the application process aligns with spectrum allocation and regulatory standards.

HEDGE utilizes an Iridium 9603 modem to establish a communication link with the Iridium satellite constellation shortly after deployment. This satellite-based communication allows for real-time data transmission beyond line-of-sight, including while the vehicle is in space or during reentry when ground-based line-of-sight systems are not viable. The team has outlined specific frequency usage, transmission power, and antenna specifications in its FCC documentation to ensure compliance and minimize interference. Securing timely approval of the licensing is a critical milestone in preparation for flight.

Risk Management

Risk management was performed using a risk assessment matrix created by the HEDGE team. This matrix can be seen in Appendix C: Table 1C. Using this matrix, the team identified eight modes of failure that posed a high likelihood of failure, critical importance to the mission, or both. A chart that lists each of these failures, their assigned risk value, a description of the failure, and our reasoning and mitigation plans, can be found in Appendix C: Table 2C.

Structures and Integration

Subsystem Level Constraints

The structures and integration team is responsible for the design, testing, and manufacturing of the physical HEDGE body and cage system, as well as any prototype. The design and testing of HEDGE as seen by the Structures team was subject to several constraints in accordance with the NASA Wallops RockSat X launch requirements. Most notably, this included a limited circular deck space provided by NASA, measuring about 14 inches in diameter with only 12 inches being usable due to NASA reserving some space for their own devices and electronics. This deck space can be seen in Figures 4H and 5H in Appendix H. Additionally, there were roughly 5 inches of height allowed in the experiment space due to the experiment above HEDGE. The next constraint imposed by NASA was a limitation on launch speed. Initially, HEDGE was only allowed to exit the exit with a speed of 1 in/s, but after a request by the Structures team, this was increased to 10 in/s. HEDGE also faced a constraint on its allowable mass. In total, both the HEDGE deployable and its cage must be exactly 6.8 kg, +/- 0.23 kg to allow for small deviation. This is to ensure that the Wallops rocket is not overweight upon launch.

Lastly, HEDGE has two constraints regarding its center of gravity and center of pressure as well, the first being the location of the center of gravity for the entire experiment. The center of gravity must be located in the center of the deck plate within a 1 square inch box to allow for slight deviation. This is to ensure the weight of the rocket is not thrown off. Additionally, the center of gravity must be forward of the center of pressure to allow for aerodynamic stability when reentering the atmosphere.

Component Overview

Figure 2 shows the three distinct primary sections that HEDGE is composed of: the forebody, avionics cubesat, and the fins. The forebody is 7.3” long, 4” wide, 4” tall, and is responsible for reducing the aerodynamic drag experienced by HEDGE. HEDGE is composed of stainless steel, weighing at approximately 6 lbs. Each face of the forebody has four cut-outs to accommodate the protrusions on the fins when HEDGE is in its stowed position. A 2.5” deep internal cavity houses the pressure transducers and thermal couples, while also helping to shift the center of gravity forward. Last are the four pressure taps, one on each face of the forebody, to allow the pressure transducers to collect data. The avionics structure was purchased from Pumpkin Space Systems. It is a 4” x 4” x 4” hollow cube made of 5052 aluminum. It has 4 threaded holes for rods, which pass through each internal PCB and are secured in place with nuts. It is attached to the forebody via four ¼ -20” screws located near each corner of the CubeSat. The final component is the fins. Each fin is 7” long, 4” wide, and 1.8” tall, weighing approximately 0.5 lbs. There are 4 protrusions at the front of each fin that serve as mounting bases for two spring hinges. These spring hinges are responsible for the deployment of the fins following ejection from RockSat-X. On the rear is the main fin panel, which is responsible for the aerodynamic stability of HEDGE during reentry.

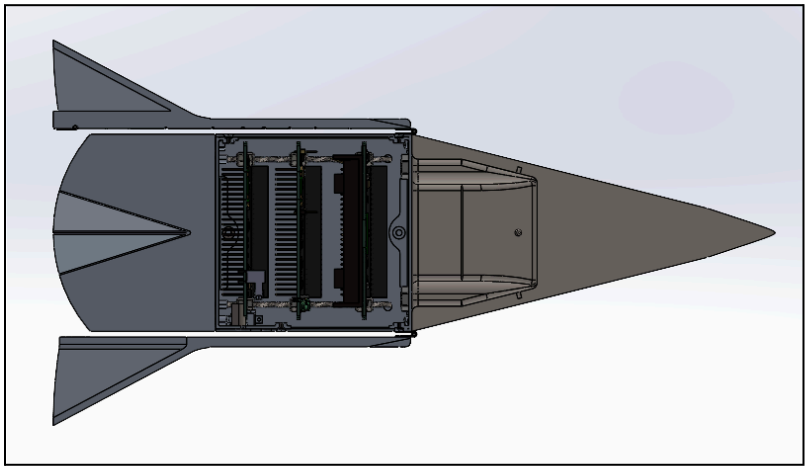

Figure 2: Cross section view of HEDGE

Deployment Mechanisms

Deployment consists of two distinct mechanisms that combine together to form the full deployment process for HEDGE. The first mechanism is the bungee system, whose earliest design can be seen in Figure 1G of Appendix G. This mechanism is responsible for deploying HEDGE from the cage, out of the rocket deck space, and into space. In its most up-to-date design, its primary method of achieving this is via an elastic paracord, which is threaded through two pulleys to maintain a constant impulse on HEDGE as it pushes it out of the cage. The elastic cord can further be adjusted by increasing or decreasing the slack allowed via two plates on both sides of HEDGE that can be loosened and tightened. Images containing these components can be found in Figures 4H, 5H, and 6H. Visuals of the earlier deployment designs and testing of those designs can be found in Figures 1G, 2G, and 3G in Appendix G.

The second mechanism involved in deployment is the latching system, which will keep HEDGE secured in the cage and only open when triggered. This system can be seen in Figures 1K and 2K of Appendix K, and it consists of a spring hinge attached to an aluminum bar placed in front of HEDGE. This bar is held on the other side of HEDGE by a fishing line that is wrapped around the side plate and clamped to the side plate by another small aluminum clamp and screws. A burn wire mechanism is set up, which involves wrapping copper wires around the fishing line so that when a voltage is passed through the wires they heat up and melt the fishing line, breaking the hold it has on the bar and allowing the spring hinge to open the aluminum bar and make way for HEDGE to be pushed out by the bungee system.

Prototyping and Analysis

Both the ejectable and deployment system of HEDGE are a combination of stock parts from major manufacturers and stock parts machined in-house and outsourced to manufacturing facilities. After a suitable design concept was created and approved, ABS plastic 3D printing was used as a method of rapid prototyping to visualize design changes and begin testing. Images of this early-stage testing and the completed plastic model can be found in Appendix F. Through rapid prototyping, major design flaws were identified and addressed, accordingly. For example, the cage system was originally designed to have aluminum crossbar supports connecting and supporting the angle brackets. After assembling the first prototype, the cage system was noticeably unstable and would not be able to withstand extreme loading conditions, even when made out of aluminum. These crossbar supports were then exchanged for skeletonized plate supports.

The 3D printed prototypes were also used to test early stages of the bungee deployment mechanism and served as a proof of concept for future testing procedures. In order to conform with the RockSat-X program's low-speed deployment regulation, the HEDGE deployment system must be carefully designed to ensure full deployment without exceeding the given restrictions. To test this precise deployment, an elastic bungee cord was tied to the ends of both of the front cage plates. The HEDGE ejectable was then placed in the cage and restrained until its simulated deployment. To analyze the deployment speed, video footage was recorded as HEDGE was ejected from the deck plate. This footage was then uploaded into a PASCO capstone, a video-analysis software for kinematic applications. This software was used to show the change in the deployable's velocity over time, and mark the speed at ejection. Figure 3 depicts the vehicle's velocity over the course of deployment.

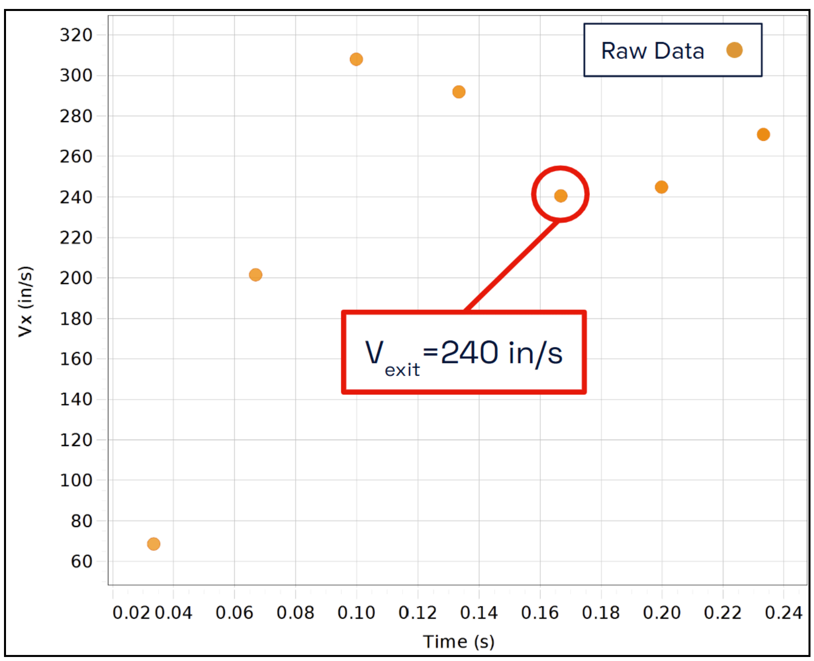

Figure 3: HEDGE deployment speed (in/s) vs. time (s)

The highlighted velocity in Figure 3 is noticeably high, but the bungee cord could be secured with varying tensions, allowing the deployment speed of the HEDGE vehicle to be adjusted accordingly. Images from this testing are shown in Appendix G.

After multiple iterations of the rapid prototyping and testing process, metal parts were machined individually to replace their plastic counterparts. Images of this prototyping and machining can be found in Appendix H. The majority of the on-deck components were manufactured in-house using a drill press, bandsaw, and vertical mill. The skeletonized deck plates were cut using a water jet, and a drill press was used for the components' through holes and tapped holes. The angle brackets were cut to size, and a vertical mill was used to ensure holes were drilled in precise locations along its length to ensure the parts would fit as designed. This was particularly important as the HEDGE ejectable was designed for a running clearance fit and needed to be properly secured by the cage mechanism while still allowing unhindered motion. All of the pulley mounts were made using ABS plastic 3D printing, as they are not considered major structural components. Lastly, the deckplate from the RockSat-X program was cut using a water jet and tapped to secure the cage system.

On the other hand, the components of the ejectable had complex designs that were not machinable with UVA's available machinery and with undergraduate students' experience level with machining. As a result, these parts were outsourced to professional manufacturers. The steel forebody was created using CNC milling, and its design was altered slightly to conform to the requirements of the machine. The fins were 3D printed out of Aluminum using direct metal laser sintering, as their design was more complex and could not accommodate for the changes necessary to use a CNC mill. These components have not yet been received, but they will be received, assembled, and tested before the experiment's integration into the RockSat-X rocket.

In order to test the deployment mechanism after adding the pulleys and elastic rope, a similar test was conducted to the one that was performed using the plastic model. The 1U cubesat frame was placed in the cage system and held until its deployment. Video footage was recorded as the tension in the bungee was released and the 1U frame was ejected. In this analysis, bungee positions were marked using a permanent marker after each trial. An example of these markings is shown in Figure 6H in Appendix H. This, in combination with a simpler method of securing the bungee to the cage system, improved the accuracy of the testing and identified a valid procedure for securing and adjusting the deployment of the bungee cord during the integration. Overall, rapid prototyping and simple testing procedures enhanced the design process and identified necessary changes in HEDGE's components and mechanisms.

Mass Budget

In order to conform to the rules and regulations set by NASA's RockSat-X program, HEDGE's components were carefully selected and designed to meet a mass constraint of 6.80 ± 0.23 kg (15.00 ± 0.50 lb). In its current design, HEDGE's necessary components have an approximate mass of 5.49 kg. A complete inventory of components and their associated mass can be found in Table 1I in Appendix I. Additional masses can be secured to the experiment space to make up for any margin, so the system was designed to be as lightweight as possible without compromising structural integrity. As the mass of the experiment is noticeably under weight, having a margin of 1.31 kg, a 1.25 kg mass will be secured on the deck plate upon integration. This mass can be strategically placed to influence the center of mass of the entire system to fall within a one-inch square at the center of the deck plate, as per NASA's regulations. Overall, HEDGE's design conforms to the RockSat-X guidelines and seeks to optimize its functionality. The mass of the experiment is divided into two subcategories: the ejectable and the on-deck components.

In total, the ejectable has a mass of 4.11 kg, accounting for the majority of the system's functional mass. As a reentry glider, HEDGE must be aerodynamically stable to reach hypersonic conditions and ensure proper data collection. In order to shift the center of gravity forward of the center of pressure, it is designed to be front-heavy. The forebody of the ejectable is made of stainless steel, which is a heavier and stronger alternative to the 6061 aluminum that makes up most of the other components. The fins and 1U structure, including all of the ejectable's avionics and hardware, have a combined mass of 1.40 kg, compared to the forebody's 2.71 kg mass. Currently, the center of gravity of the ejectable is 0.168 from the tip of the forebody.

The structural components on the deck plate are relatively light, having a mass of 1.39 kg, but they still account for a significant amount of the system's mass. The plates that support the cage system are skeletonized to minimize weight while providing ample support for the ejectable under extreme loading launch conditions. Likewise, many of the attachments for the bungee deployment system have been 3D printed out of ABS plastic to reduce mass and improve manufacturability. Additionally the deployment system does not use any major mechanical components or motors, so it does not contribute any major sources of mass. The deck plate PCB and its resin coating are the most massive components on the deck plate. Even so, HEDGE's integration and deployment system has little mass, and the system as a whole will fall comfortably within the required mass range.

Software and Avionics

Subsystem Level Constraints

The Software and Avionics subteam is responsible for the timely and accurate collection and storage of data regarding HEDGE's temperature, pressure, and position throughout the duration of the experiment. The design of the Software & Avionics subsystem is subject to several constraints, listed as follows. Firstly, the system must be capable of collecting four temperature values, two pressure values, altitude, and velocity every four seconds to ensure statistically significant results. Secondly, the software must be capable of tagging and storing the data in between regular packages sent to the Iridium satellite constellation, which operates at a rate notably slower than data is collected. Thirdly, the software must be capable of minimizing damage in scenarios where data congestion or temporary loss of connection to the Iridium satellite constellation prevents a portion of the data from being sent on time. This ensures that such complications have minimal effect on the variety and spacing of data points collected. Fourthly, the avionics and all related hardware must be capable of surviving the ascent conditions, including frequent vibrations and 25G of acceleration in all directions, in working condition. Finally, the software should be developed in conjunction with the Communications team to ensure full operating compatibility with the Iridium satellite network. Should the Software and Avionics subsystem, upon construction and assembly, be found to satisfy all above requirements, it shall be considered fully operational.

Component Overview

The Software and Avionics system is comprised mainly of the electronic components that collect, store, and transmit the temperature and pressure data that is collected during near-hypersonic flight. However, it is also made up of the software that fulfills the processing duties. In terms of collecting the data, the primary devices involved are thermocouples, pressure transducers, and a GNSS receiver.

The thermocouples collect temperature data, and, in conjunction with the ADS 1015 temperature module, convert that information into a voltage which can be stored. The thermocouples chosen for this task are the Omega 5TC-TT-K-40-36, primarily due to the high temperatures that this thermocouple can withstand, balanced by its relatively low cost. Additionally, type K thermocouples work well with the ADS 1015 ADC. In total, there are four thermocouples and one ADC.

In addition, two pressure transducers are also used to measure the pressure while the vehicle experiences near-hypersonic speeds. The pressure transducers chosen are Kulite XCQ-080, which are miniature pressure transducers designed to measure pressures below 5 PSIG, at a clear resolution and within the range calculated for this mission. These transducers were chosen because of their small size, which is important as space inside the forebody is limited, and their quick turn-around time, as other similar options had lead times close to six months, which were not feasible.

Finally, a GNSS receiver is used to collect positioning and movement information, including latitude, longitude, and velocity, which will help us to know exactly where and how quickly HEDGE traveled (and how close to hypersonic speeds it came). This will be vital for us to correlate the temperature and pressure data by time for future generations of HEDGE. The GNSS receiver chosen for this project is the Adafruit Ultimate GPS, mainly due to its low cost and ability to function at a high frequency, allowing data collection significantly faster than most other GNSS types.

Each of the above-mentioned devices is directly connected to the DATA/OBC PCB, where data is packaged by software run on a Raspberry Pi Pico microprocessor. Additionally, the Pico is directly connected to a 1 GB solid state drive (SSD), allowing for the saving of data in the case that connection to Iridium is lost throughout the flight. Once data is packaged, it is sent through direct wire connection to the RADIO PCB, which holds the RockBLOCK 9603 Iridium Transceiver, allowing for short messages to be sent from HEDGE to the Iridium constellation, and eventually onward to the UVA ground station, where the data can be post-processed. More information regarding the RockBLOCK will be covered in the Communications section of this thesis. A picture of the full Software & Avionics setup is shown in Appendix J, first in the flatsat setup (Figure 1J) and then where all PCBs and components are properly attached and showcased in the 1U structure (Figure 2J). An FBD of the system is shown in Figure 3J.

Prototyping and Analysis

Like most software, all of HEDGE’s necessary code is run through the main.py class. This class combines three larger classes to create a fully functioning data acquisition, processing, and transmission system. The first is DataHandling which was written by the Software and Avionics team and takes care of the initialization and manipulation of the temperature, pressure, and GNSS data frames throughout the duration of the flight. Next is the ADS1015 class which allows for direct interaction with the thermocouples and provides a temperature value based on the reference provided as the cold junction. Lastly is the ADS1115 class which allows HEDGE to interact with the pressure transducers. However, the ADS1115 class returns a voltage rather than pressure value, so a calibration formula is required to extract the corresponding pressures for each reading.

In order to perform adequate testing on HEDGE's software as a whole, each component and behavior first had to be tested on its own. This involved checking each thermocouple and pressure transducer one by one to ensure that they could accurately collect data. Additionally, not only did each component need to be able to collect data, but they needed to be able to record at a rate of 2 hz while storing each value in their respective data frame. Working in conjunction with the Communications team, we then ensured that these values could be successfully transmitted to Iridium before erasing them.

Arguably the most important part of software testing, there were many edge cases that needed to be accounted for. These included but were not limited to losing connection with a thermocouple, pressure transducer, or GNSS, losing connection with Iridium, and running out of storage space on the OBC. In each scenario, we had to ensure that one undesired behavior would not bring down the whole system. To do so, we implemented exception handling throughout the entirety of the main.py class, allowing us to lose some functionality without ruining all prior and future data. In the scenario that the OBC runs out of storage space, we made the executive decision to prioritize the most recent data by removing the oldest entries to free up memory.

Communications

Subsystem Level Constraints

The Communications subteam is responsible for transmitting all collected data taken during the mission in real time. Messages are sent via the Iridium satellite network and consist of temperature, pressure, and GNSS data at four second intervals. Throughout the conceptualizing, designing, and testing processes of HEDGE's communication system, several constraints are in place. The most significant constraint is satellite positioning at any given time. The transceiver in use, RockBLOCK 9603N, does not consistently maintain a strong connection to the Iridium constellation. During testing, the antenna was stationary with a 180° field of view. Even with ideal conditions, the transceiver took approximately 2 minutes to establish a signal strength greater than 0. After connection was established, average signal strength was 3 out of 5, and transmitted a message 50-75% of the time. This can hopefully be mitigated by gaining approval from Iridium for priority transmission. In this case, the transceiver should establish a strong and consistent connection almost immediately after powering on. Second, the RockBLOCK can only transmit messages less than 360 bytes. If packages can be compressed efficiently and consistently then this shouldn't be a pressing issue. Third, messages can only be sent every 30 seconds at quickest, with a 60 second average during ideal condition testing. However, an accurate buffer system could bypass this constraint. We are also awaiting permission from Iridium to send messages quicker than this. Fourth, the RockBLOCK requires a minimum of 100mA at 5V to operate. This also shouldn't be an issue as long as the power supply functions correctly. Lastly, HEDGE must modify the required FCC Iridium license to be approved for suborbital flight. If this license is unattainable, then no data can be transmitted during flight. Additionally, HEDGE communication relies directly on the Software and Avionics team to be able to transmit the correct sensor data. Should the Communications subsystem, upon construction, assembly, and testing, be found to satisfy all above requirements, it shall be considered fully operational.

Component Overview

The Communications subsystem integrates four major components.

1. RockBLOCK 9603N Transceiver, acting as a transmitter and receiver in one. The transmitter sends radio frequency (RF) signals to the antenna after encoding data using a modulator.
2. 2JP0133BGFz Iridium-GPS Screw Mount Embedded Dual Antenna, used to propagate, direct, and strengthen signal being transmitted and capture signal being received. The antenna is used for communication via Iridium and acquiring positional data via GNSS. The antenna is connected to the RockBLOCK via SMA cables, allowing for ideal antenna positioning on the HEDGE structure (as the RockBLOCK is located inside HEDGE, out of range of Iridium satellites).
3. Raspberry Pi Pico is the microcontroller board designed for all electronic computing on HEDGE. The RockBLOCK relies on the Pico to power on and receive directional code when transmitting and buffering. The Pico is directly connected to a 1 GB solid state drive (SSD), allowing for the saving of data in the case that connection to Iridium is lost throughout flight. Once data is packaged, it is sent through direct wire connection to the Radio PCB, which holds the RockBLOCK.
4. The Iridium Satellite Constellation is the communication network used by the RockBLOCK. It is capable of receiving data signals and transmitting them to receivers elsewhere, providing global telecommunications coverage. Data transmitted via the RockBLOCK will travel via Iridium to eventually reach the UVA ground station, where data can be post-processed.

Prototyping and Analysis

Thanks to HEDGE's previous Communications subteam, all components were chosen prior to the start of this year's mission planning. Once the transceiver and antenna were ordered and received, the first connection test commenced on December 11, 2024. The test was a success; a sample Iridium message with simulated data was transmitted to UVA's ground station on the third attempt, each attempt occurring at 30-second intervals.

In February and March, 2025, the Communications subteam worked with Structures and Integration to identify the ideal placement for the dual antenna. In HEDGE's first prototypes, the antenna was placed on the bottom plate facing outwards. After some consideration, this was deemed inefficient because the wings of HEDGE served as walls that obstructed the antenna's field of view to less than 90°. To resolve this issue, a new antenna apparatus was constructed on the base of one of the wings, allowing for a full 180° field of view. This required SMA cable extenders because the antenna's current cables were too short, so cable tracks were indented on the side of HEDGE so the antenna could be connected to the RockBLOCK by cables that did not obstruct HEDGE's aerodynamic efficiency.

In April 2025, the integration between the software and avionics system and the communications system was tested. After numerous setbacks involving sensor probe shipping times and electronics malfunctions (both hardware and software), communication testing was a success. The Communications subteam wrote three sets of code, each to be testing sequentially (as the results of one test was necessary for the next code to be tested):

1. Connection testing: After all hardware issues were resolved, a test was run that would tell the microprocessor to supply power to the RockBLOCK, turning on the transceiver and preparing it for use. This test was simple and succeeded after the first trial
2. Signal testing: Once the RockBLOCK powered on, its connection to Iridium was tested. The signal strength is rated out of 5; message transmission should only be attempted if the signal test returns a value of 3 or greater. The code for this test was a loop that attempted connection every 30 seconds. Even with the antenna in ideal conditions, it took the RockBLOCK 2 minutes on average to connect to Iridium. At 60 seconds after initial connection, on average, the RockBLOCK established a connection with signal strength between 3 and 5 for 6 continuous cycles (3 minutes), deeming this test a success.
3. Transmission testing: Because HEDGE's sensor probes were experiencing malfunctions and not able to collect data, this test was run using dummy temperature and pressure data that was simulated every 12 seconds. Due to imperfect signal connection, data updates were sent to the ground station every 60 seconds. After 20 minutes of testing, the ground station received 3 consecutive updates, each containing all data collected during buffer times. This is not consistent, however, as transmission seemed to have a 50% success rate. This is simply due to a weaker signal strength governed by conditions out of our control. Nonetheless, the test was deemed successful and HEDGE is now able to transmit data at intervals.

Future testing will involve refinement of the transmission and buffer tests. After data compression is perfected, the RockBLOCK will be able to send data at 4 second intervals and transmit data at 60 second intervals. Data collection during this past test was limited to 12 second intervals simply due to the 340 byte message limit implemented by RockBLOCK. Code also needs to be updated to perform buffer transmission in the case RockBLOCK loses signal for a cycle, which is very likely. As soon as our main.py software is perfected and sensor probes are working consistently, mission-simulated conditions will be tested (temperature, pressure data, and GNSS data at 4 second intervals, transmitted to ground station every 60 seconds).

Attitude, Stability and Trajectory

Component Overview

Attitude, Stability and Trajectory was tasked with verifying that HEDGE would be aerodynamically stable in flight under near-hypersonic conditions it will experience in August of this year. This task required the calculation of the boundary conditions necessary for the successful convergence of two-dimensional and three-dimensional CFD models that were run on Ansys Fluent as well as OpenFoam platforms, respectively. The boundary conditions were calculated using the MATLAB programming language and the calculations are explained below. For the two-dimensional CFD analysis, the center of pressure was estimated and compared with the center of gravity to verify static stability in flight. Additionally, the three-dimensional CFD model on OpenFoam was run on UVA's HPC cluster in order to maximize the accuracy of the drag coefficient estimation as well as the underlying physics that are inherent to near-hypersonic flight. Further, in order to investigate how HEDGE would withstand near-hypersonic speed thermal analysis was conducted using oblique shock theory to estimate the temperature of the walls of HEDGE.

Initial Reentry Trajectory Simulation

A MATLAB script was written to simulate the one-dimensional vertical reentry trajectory of HEDGE, which gave us flight environment data for subsequent analyses. The simulation uses an Euler forward integration method with a time step dt to solve the equation of motion listed as Equation 1, where g is gravitational acceleration, m is the vehicle mass, and D is the aerodynamic drag force. The drag force is calculated using the standard aerodynamic equation for drag (Equation 2) where u is the instantaneous velocity, A is the reference frontal area, and ρ is the atmospheric density. The density ρ and static temperature T are determined at each altitude h by interpolating tabulated data from the U.S. Standard Atmosphere 1976 model. The drag coefficient c_d is approximated using Newtonian impact theory for the vehicle's conical forebody, shown in Equation 3, where θ_{rad} is the cone half-angle in radians. The altitude values are updated using the relationship found in Equation 4.

$$\frac{dv}{dt} = g - \frac{D}{m} \quad (1)$$

$$D = \frac{1}{2}\rho u^2 c_d A \quad (2)$$

$$c_d = 2sin^2(\theta) \quad (3)$$

$$h_{new} = h_{old} - u * dt \quad (4)$$

Within the simulation loop, derived aerodynamic and thermal parameters are calculated. The local speed of sound a is found using Equation 5, where γ is the specific heat ratio and R is the specific gas constant for air. This allows for the calculation of the Mach number shown in Equation 6. The stagnation temperature T_0, representing the adiabatic temperature rise at the vehicle's stagnation point, is calculated using the energy equation (Equation 7), where c_p is the specific heat at constant pressure. After the simulation completes, key parameters are extracted at specific altitudes (75, 50, and 15 km) via linear interpolation. At these points, static pressure P_{static} is obtained from the atmospheric model, total pressure P_{total} is calculated using the isentropic relation in Equation 8, and the Reynolds number Re is computed with Equation 9, using the vehicle length L and dynamic viscosity μ obtained from Sutherland's formula based on T_{static}. These discrete condition points provide essential boundary conditions and validation data for CFD and analysis of HEDGE's aerodynamic stability.

$$a = \sqrt{\gamma R T} \quad (5)$$

$$M = \frac{v}{a} \quad (6)$$

$$T_0 = T + \frac{v^2}{2c_p} \quad (7)$$

$$P_{total} = P_{static}\left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}} \quad (8)$$

$$Re = \frac{\rho v L}{\mu} \quad (9)$$

Fluid Analysis and Results

The goal for two-dimensional CFD was to obtain an accurate estimate of the center of pressure and compare it with the already known location of the center of gravity to ensure HEDGE's aerodynamic stability. The location of the center of gravity was calculated by the Structures and Integration Team to be a distance of 0.168 m from the tip of the nose of HEDGE. So, as long as the center of pressure is behind the center of gravity HEDGE will have positive static stability regardless of whether HEDGE pitches up or down during flight. Table 1E communicates the center of pressure calculated by Ansys Fluent software at three discrete heights: 15, 50 and 75 km which can be found in Appendix E. These results show that the center of pressure moves farther away from the nose as HEDGE approaches the surface of the earth and that the vehicle will have positive static stability at these discrete heights. As a note, the center of gravity is 0.168 m from the nose which is ahead of the center of pressure at each altitude in HEDGE's flight. Further, the center of pressure calculated by this two-dimensional CFD model differed from calculations made by three-dimensional CFD which will be discussed later. Next, in order to calculate what the center of pressure would be at heights in between 15, 50 and 75 km, spline interpolation was used to create Figure 1E which reinforces that HEDGE will have positive static stability throughout its entire flight.

In order to determine how the nose and fins would react to the extreme conditions that come with near-hypersonic speed the temperature of these materials was modeled using oblique shock theory. Firstly, in order to find the shock wave angle which will form on the nose of HEDGE the Θ-□-M relation was solved for the shock wave angle β, from John D. Anderson's *Fundamentals of Aerodynamics* and is shown in Equation 10. As a note, θ is the nose half-angle and M is the mach number of the freestream flow before the shock wave. In Equation 11, the total temperature after the oblique shock is a function of the mach number of the flow and static temperature after the wave. This value of the recovery factor r was found using the fact that the flow of air around HEDGE is turbulent. Due to this, the Prandtl number, originally assumed to be 0.72, was raised to the one-third power which leaves r with a value of 0.896 calculated using Equation 12. In order to find the wall temperature of HEDGE Equation 13 was used. In Equation 13, r relates the total temperature after the shock wave to the temperature of HEDGE's exterior T_{wall}. Graphs of the altitude h, mach number of HEDGE (M) and adiabatic wall temperature (T_{wall}) can be found in Appendix E: Figure 2E.

$$tan(\theta) = 2cot(\beta)\frac{M_1^2 sin^2(\beta)-1}{M_1^2(\gamma+cos(2\beta))+2} \quad (10)$$

$$T_{02} = T_2(1 + \frac{\gamma-1}{2}M_2^2) \quad (11)$$

$$r = (Pr)^{1/3} \quad (12)$$

$$T_{wall} = rT_{02} \quad (13)$$

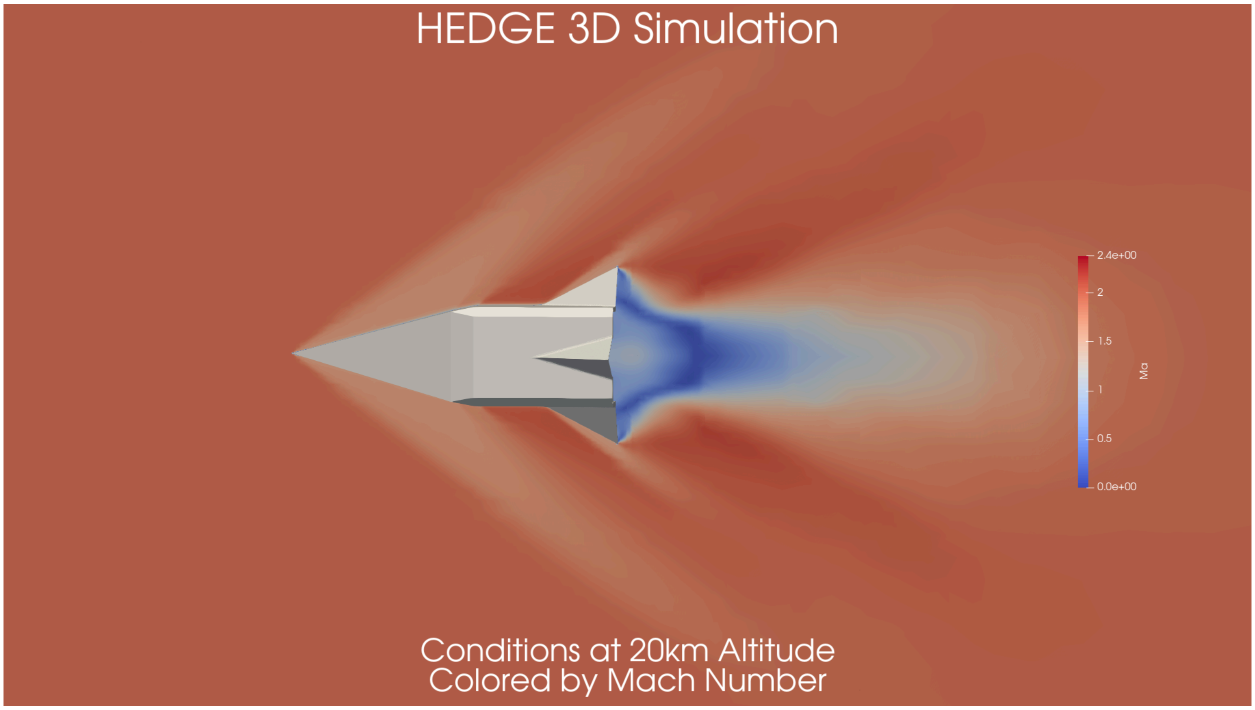

Figure 4: 3D CFD results for HEDGE
(Background color scheme: Mach number)

Computational fluid dynamics simulations in 3D were conducted using OpenFOAM 12, an open-source CFD suite which is widely used in academia and industry. The initial simulation was conducted with freestream conditions calculated by a Jupyter notebook derived from the Matlab predictor script referenced earlier, which implemented an RK4 ODE scheme instead of the Euler scheme in the MATLAB script. This resulted in the selection of 20 km as the initial 3D altitude, picked instead of 15km because, under the predicted drag coefficient, 20km was the lowest altitude at which HEDGE was supersonic. The HEDGE drag coefficient resulting from the first simulation was then used to set the freestream conditions for later simulations.

Our CFD solver, boundary conditions, turbulence parameters, and mesh setup were then validated by simulating the flow over a sphere under the same freestream conditions. These results were then compared with experimental data based on empirical formulas calculated by Loth et al [2], listed below, and found to agree to within 5% of their predicted values. The sphere was then replaced with a simplified version of HEDGE, simulated to convergence, and post-processed using Paraview. A grid-convergence study is in progress but has been hampered by numerical instability at higher Mach numbers.

The empirical drag coefficient of a sphere was calculated using the following formulas from Loth et al. [2] from the compression-dominated regime section. First, C_M represents a ratio which shows the effects of Mach number on drag at high Reynolds numbers. Its equations are as follows:

$$C_M = 1.65 + 0.65 tanh(4M_p - 3.4) \text{ for } M_p < 1.5$$

$$C_M = 2.18 - 0.13tanh(0.9M_p - 2.7) \text{ for } M_p > 1.5$$

where M_p represents the particle mach number (The subscript p in this paper denotes particle, or the sphere). The calculated value of C_M is then inserted into the equation for C_D below along with G_M and H_M, which are two model coefficients used to pass different polynomial values of M_p into the C_D equation. $Re_{p,crit}$ varies, but increases with Mach number, and is above 2,000,000 for Mach numbers above 2.

$$C_D = \frac{24}{Re_p}(1 + 0.15Re_p^{0.687})H_M + \frac{0.42C_M}{1+(42,500/Re_p^{1.16C_M})+(G_M/Re_p^{0.5})} \quad \text{for} \quad 45 < Re_p < Re_{p,crit}$$

$$G_M = 166M_p^3 + 3.29M_p^3 - 10.9M_p + 20 \quad \text{for} \quad M_p < 0.8$$

$$G_M = 5 + 40M_p^{-3} \quad \text{for} \quad M_p > 0.8$$

$$H_M = 0.0239M_p^3 + 0.212M_p^2 - 0.074M_p + 1 \quad \text{for} \quad M_p < 1$$

$$H_M = 0.93 + \frac{1}{3.5+M_p^5} \quad \text{for} \quad M_p > 1$$

For the initial predicted freestream conditions at 15km (Re = 1,330,000 and M = 1.96), these equations predict the sphere to have a drag coefficient of 0.989. Our CFD simulation produced a value of 0.949, which is within 5% of the empirical value. After validating the case setup against empirical data, we replaced the sphere with a simplified HEDGE geometry and ran the case to convergence. Our predicted drag coefficient was 0.194, which was lower than we had used for our flight simulation scripts, leading us to slightly upwardly revise our velocity and Mach number estimates, as seen in Appendix E: Figure 6E. One of the potential challenges when running a supersonic or hypersonic CFD simulation is proper capturing of shockwaves. Seen in Figure 5 are the results of the same case as in Figure 4, but colored by pressure gradient to highlight shockwaves. Note the strong bow shock along with shockwaves at each sharp feature on HEDGE; this indicates that the mesh is fine enough to properly resolve shockwaves and their effects on drag are properly modelled. Additionally, all residuals for each time step were converged to a maximum of 10^{-6}, indicating numerical convergence of the model. The center of pressure was calculated at 0.149 meters from the nose, which is ahead of the center of gravity, calculated at 0.168 meters from the nose. This may be due to the simulation having been run on a quartered fluid domain; a full-domain simulation is in progress.

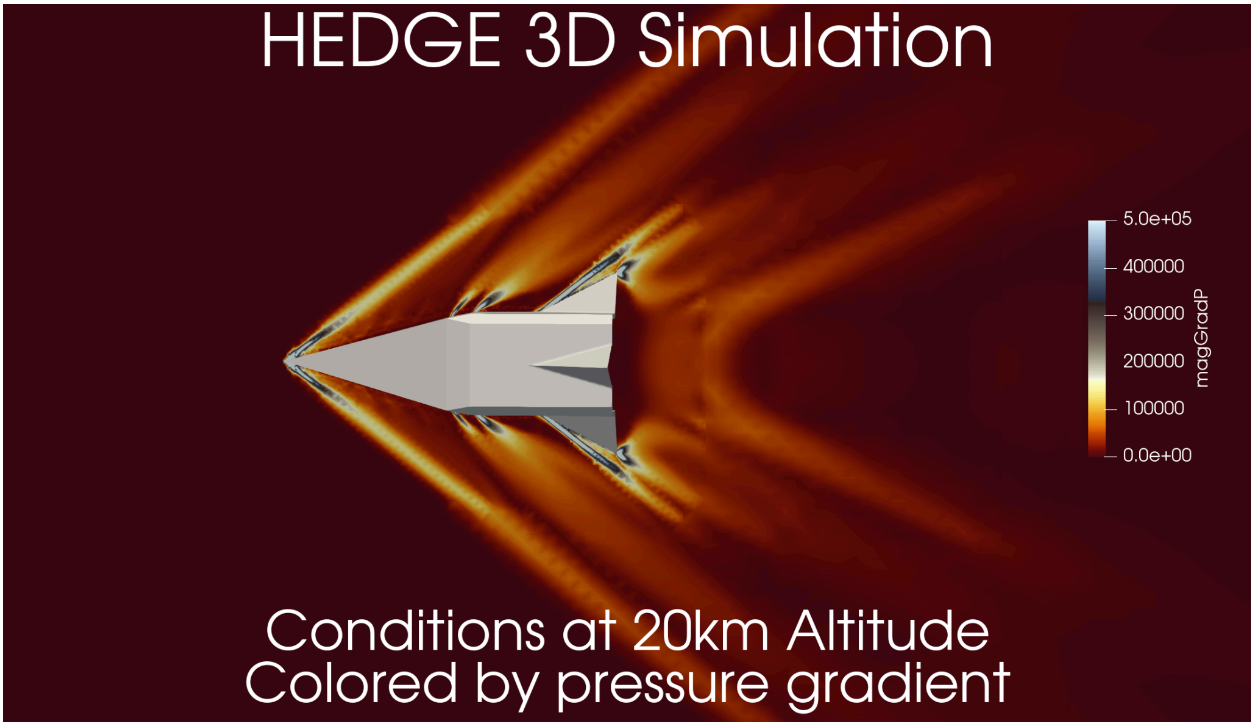

Figure 5: 3D CFD results colored by pressure gradient

Future steps include simulating HEDGE at various nonzero angles of attack and finalizing the grid convergence study.

Power, Thermal and Environment

Subsystem Level Constraints

The Power Thermal and Environment team has multiple responsibilities that are split into three activities. The Power portion focuses on ensuring that the satellite's power generation and consumption are accurately accounted for, as well as making sure that there is sufficient power for HEDGE for the duration of the mission. Thermal portion focuses on the satellite's heat management during reentry, calculating burn-up times for sensitive areas and running simulations to analyze thermal effects. The environmental portion handles simulations for random vibration testing to ensure that the satellite remains intact during launch. Their work involves setting up modal and random vibration analyses in ANSYS, verifying the structural integrity against vibrational forces during rocket launch.

Component Overview

The RockSat-X GSE-1 system includes the DECK PCB, which handles power distribution and signal routing, and the HEDGE OBC/DATA PCB, which serves as the onboard computer for data handling and mission control. Together, they manage core payload operations and ensure stable electrical interfacing.

In RockSat-X TE-1, the primary component is a sense resistor, used for monitoring current and ensuring safe operation by detecting overcurrent conditions. For TE-2, the key component is a deployment stepper motor, which enables controlled mechanical deployment of payload elements.

The RockSat-X power budget must account for all these systems, with a recommended margin (typically 20–30%) to ensure reliability under variable conditions and thermal loads.

Internally, the HEDGE power system includes the HEDGE OBC/DATA PCB and the HEDGE COMM PCB. The latter supports Iridium satellite telemetry and requires careful power management due to its burst transmission demands. Maintaining an adequate power margin is critical for both continuous data operations and communication reliability. The Power flow chart replicates the components' flow, and is found in Appendix D: Figure 1D.

The Thermal team ensures that HEDGE components remain within safe temperature limits throughout all mission phases, including reentry. Simulations model heat transfer to identify hotspots and predict burn-up times for sensitive areas.

The Environment team focuses on mechanical survivability during launch. Using ANSYS, they perform modal and random vibration analyses to verify structural integrity under launch conditions. These simulations ensure that critical components like the stepper motor and sense resistor can withstand vibrational loads, with adjustments made to mounting or damping where necessary.

Prototyping and Analysis

Power system prototyping involved a series of ground tests to verify safe and reliable operation under mission-like conditions. A Power Consumption Test was conducted to confirm that each component received appropriate voltage and current. The Combined Stress Test simulated extended full-load operation, monitoring both thermal behavior and power stability. Battery Charge Testing validated proper charging and discharging cycles, ensuring long-term reliability and safe operation. An Endurance Test assessed the battery's ability to sustain variable loads over time, measuring total discharge capacity to confirm the system meets mission duration requirements. These tests informed design refinements and confirmed operational readiness under expected conditions.

Power Budget

Our analysis of our power budget ensures that RockSat-X and HEDGE remain within power limits. The power budget demonstrates strong efficiency, with a total consumption of just 9.85 watt-hours out of 500 available, leaving a large margin of 490.15 watt-hours. All components operate well within limits, even those with high short-term draw like the stepper motor. The total HEDGE system consumes 30.83 watt-hours, with a margin of 1169.17. These values can be seen in Appendix D: Table 1D. This ensures that all systems are well within power limits, thus ensuring their reliability.

Plan For FMSR, Integration, and Launch

As we work toward the Full Mission Simulation Review (FMSR) on May 13th, 2025, the Structures and Integration team is actively replacing all ABS plastic parts with metal parts. They are also integrating the avionics inside of the 1U structure and performing deployment tests of HEDGE. The Software and Avionics and Communications teams are finishing up buffer and rate testing, as well as preparing to run a final test through the entire system—ensuring that all data will be delivered from the beginning to the end of HEDGE's mission. The Attitude, Stability, and Trajectory team is currently conducting vibration testing to ensure aerodynamic stability during flight. Finally, the Power, Thermal, and Environment team is conducting heat transfer calculations to ensure that HEDGE will not experience any complications on the thermal end.

At the Full Mission Simulation Review (FMSR), we will have completed the fabrication, integrated-system testing, as well as a full mission simulation of HEDGE. In June, an integration team will travel to Wallops Flight Facility for Visual Verification Test and a full integration of HEDGE onto the RockSat-X sounding rocket. HEDGE will remain stowed on the sounding rocket until the mid-August 2025 launch window.

Conclusion

HEDGE aims to provide a low-cost solution for conducting hypersonic experiments in hopes of contributing to further advancements in the field. Through the development of HEDGE and with its successful mission in August 2025, we will prove the feasibility of low-cost hypersonic experiments using CubeSat technology. Advancing hypersonic technology through cost effective experiments is of quintessential importance to further understand reentry dynamics in an effort to contribute to research on hypersonic vehicles. This research may offer potential benefits in commercial flight, spacecraft design, and defense and national security. While the relatively small size of the 1U CubeSat within HEDGE limits the types of sensors and payloads carried on experimental missions, the low-cost nature of these experiments gives way to more frequent flights—leading to more hypersonic data collection overall. Future research could implement heat flux sensors or Langmuir probes to learn more about the heat flux and characterize ionized gas behavior respectively on the forebody of HEDGE upon reentry. Understanding how reentry vehicles perform at hypersonic speeds is not only critical for advancing hypersonic research, but also for developing real-world applications of hypersonic technology to further advance transportation and defense capabilities.

References

[1] Anderson, John D., and Chris Cadou. *Fundamentals of Aerodynamics*. McGraw-Hill, 2024.

[2] Eric Loth, John Tyler Daspit, Michael Jeong, Takayuki Nagata, and Taku Nonomura AIAA Journal 2021 59:8, 3261-3274 Supersonic and Hypersonic Drag Coefficients for a Sphere

Appendices

Appendix A: Teams and Roles

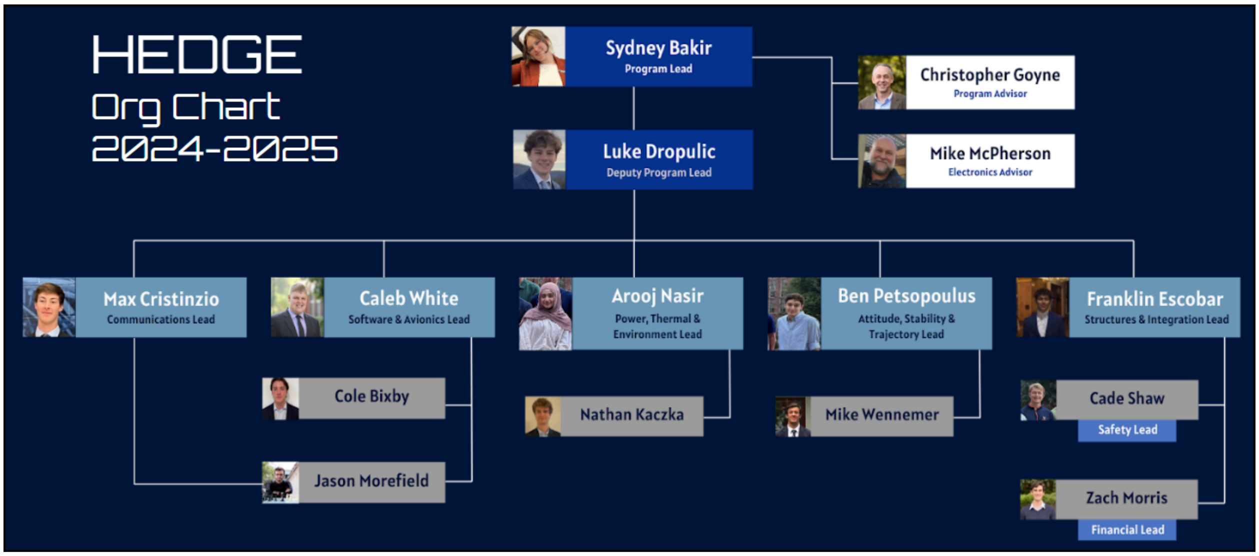

Figure 1A: Team structure and roles of HEDGE broken down

Appendix B: Description of Financial Partnerships and Financial Budget

Table 1B: Description of Financial Partnerships

Partnership	Description	Amount
Systems, Planning & Analysis (SPA)	$80,000 donation split over two academic years for support of HEDGE research	$40,000.00
Jefferson Trust	Grant for university projects that enrich the University of Virginia community and student experience	$10,000.00
UVA Capstone Budget	Undergraduate engineering capstone projects are allotted $200 per student on the project team	$2,800.00
School of Engineering	Donation from Dr. Jennifer West (Dean of the School of Engineering and Applied Science)	$2,600.00
	TOTAL SUPPORT	**$55,400.00**

Table 2B: Detailed Financial Budget for HEDGE Components

Category	Component	Qty	Cost/Unit	Total Cost
Communications	Iridium 9063 Transceiver	1	$188.00	$188.00
	Iridium-GPS Patch Antenna	1	$45.00	$45.00
	Iridium Satellite Constellation License and Data Payment	7	$113.00	$791.00
	Communications Total		$1,024.00	
Avionics	5TC-TT-K-40-36 Insulated Thermocouples (Pack of 5)	1	$130.20	$130.20
	Kulite XCQ-080D Pressure Transducer	2	$1,461.00	$2,922.00
	Custom OBC (Equivalent to EnduroSat OBC)	1	$300.00	$300.00
	Custom A to D card	1	$300.00	$300.00
	Custom Power Supply (Equivalent to EnduroSat EPS I+)	1	$500.00	$500.00
	Custom Deck Plate PCB	1	$200.00	$200.00
	Avionics Total		$4,352.20	
Structures & Integration	Machining Forebody Estimation	1	$5,000.00	$5,000.00
	Machining Fins Estimation	4	$1,500.00	$6,000.00
	15205A214 304 Stainless Steel Spring Hinge	8	$4.10	$32.80
	Pumpkin Space 1U CubeSat Structure	1	$1,215.00	$1,215.00
	Pumpkin Space CubeSat Kit Cover Plate Assembly	1	$495.00	$495.00
	GNSS Receiver	1	$5,000.00	$5,000.00
	Pumpkin Space CubeSat Kit Base Plate Assembly	1	$690.00	$690.00
	8982K112 Multipurpose 6061 Aluminum 90 Degree Angle	1	$1.66	$1.66
	2024 Aluminum Sheet .1"x12"x12"	2	$28.63	$57.26
	8982K1 Multipurpose 6061 Aluminum 90 Degree Angle	1	$5.27	$5.27
	8982K501 Multipurpose 6061 Aluminum 90 Degree Angle	1	$3.43	$3.43
	4490T181 Architectural 6063 Aluminum Bar	1	$7.04	$7.04
	6627T111 Stepper Motor	2	$83.98	$167.96
	Structures and Integration Total		$18,675.42	
Miscellaneous	FCC License Applicaion Fee	1	$140.00	$140.00
	RocksatX Payment (0.5 Experiment Space)	1	$15,000.00	$15,000.00
	Materials and Supplies	1	$5,000.00	$5,000.00
	Shipping Estimation	1	$2,000.00	$2,000.00
	Travel	1	$9,208.38	$9,208.38
	Miscellaneous Total		$31,348.38	
			TOTAL BUDGET	**$55,400.00**

Appendix C: Risk Management

Table 1C: HEDGE Risk Value Assignments

	Negligible (1)	Minor (2)	Moderate (3)	Major (4)	Total Mission Failure (5)
Certain (5)	Medium (7)	Dangerous (16)	Very Dangerous (20)	Very Dangerous (23)	Critical (25)
Likely (4)	Medium (6)	Urgent (13)	Dangerous (18)	Dangerous (22)	Very Dangerous (24)
Possible (3)	Low (4)	Urgent (10)	Dangerous (15)	Dangerous (19)	Very Dangerous (21)

Unlikely (2)	Low (2)	Medium (8)	Urgent (11)	Urgent (14)	Dangerous (17)
Rare (1)	Low (1)	Low (3)	Medium (5)	Medium (9)	Urgent (12)

Table 2C: Risk Analysis of HEDGE Subsystems

Type of Failure	Risk Value Assigned	Description	Reasoning	Mitigation
Temperature Failure	**9**	HEDGE chassis structure fails and burns up in the atmosphere or leads to damage to vital parts	Rare to occur and poses major threat to the mission	Ensure selected material has adequate heat resistance and properly test it
Structural Failure	**9**	HEDGE chassis structure fails and breaks down under reentry or launch forces	Rare but poses a major threat to the mission	Multiple rounds of testing the chassis through aerodynamic forces
Integration Failure	**12**	HEDGE comes loose during flight and deploys early or in the rocket	Rare but could lead to total mission failure and damage to the rocket if it occurs	Multiple stepper motors for redundancy and backstop to prevent backwards deployment
Approval Failure	**12**	Cannot gain approval for launch	Rare and would lead to complete mission failure	Ensure we fulfill all RockSAT-X requests and requirements in a timely manner
Fin Failure	**9**	Spring-loaded fins do not deploy upon ejection, making HEDGE unable to reorient into a nose down position	Unlikely chance of occurrence and poses a major risk to mission	Ensure tests can withstand expected forces, and add magnets for redundancy if needed
Deployment Failure	**17**	HEDGE is unable to eject from the rocket	Possible chance of occurrence and poses greatest threat to mission	Add teflon to interior cage to prevent friction or jamming. Reduced amount of stepper motors to 1 to reduce malfunction chances. New pulley system to reduce necessary impulse for bungee cord

Communication Failure	22	HEDGE is unable to connect with the Iridium Satellite Constellation to relay data	Likely and could pose a major threat to the mission if it occurs	Working with Iridium to mitigate risks
Licensure Failure	14	Cannot acquire necessary licences	Unlikely but could pose a major threat to data acquisition	Currently in process of securing FCC license

Appendix D: Power Budget and Flow Chart

Table 1D: Total HEDGE power budget.

RockSat-X GSE-1						
Component	**Component Voltage**	**Max current draw (mA)**	**Max Power Draw (W)**	**Time active**	**Total Power Consumption (Watt-Hours)**	**Total Power Consumption (mAHr@28VDC)**
DECK PCB	5	120	0.6	463	4.63	8.04
HEDGE OBC/DATA PCB	5	240	1.2	40	0.80	1.39
RockSat-X TE-1						
Component	**Component Voltage**	**Max current draw (mA)**	**Max Power Draw (W)**	**Time active**	**Total Power Consumption (Watt-Hours)**	**Total Power Consumption (mAHr@28VDC)**
Sense resistor	28	0.03	0.00084	420	0.01	0.01
RockSat-X TE-2						
Component	**Component Voltage**	**Max current draw (mA)**	**Max Power Draw (W)**	**Time active**	**Total Power Consumption (Watt-Hours)**	**Total Power Consumption (mAHr@28VDC)**
Deployment stepper motor	10	1440	14.4	1	0.24	0.42
RockSat-X Total Consumption						**9.85**
RockSat-X Total Available						**500.00**
RockSat-X Margin						**490.15**
HEDGE INTERNAL POWER						
Component	**Component Voltage (V)**	**Max current draw (mA)**	**Max Power Draw (W)**	**Time active (seconds)**	**Total Power Consumption (Watt-Hours)**	**Total Power Consumption (mAHr@9.6VDC)**
HEDGE OBC/DATA PCB	5	168	0.84	423	5.92	10.28
HEDGE COMM PCB	5	540	2.7	263	11.84	20.55
HEDGE Total Consumption						**30.83**
HEDGE Total Available						**1,200.00**
HEDGE Margin						**1,169.17**

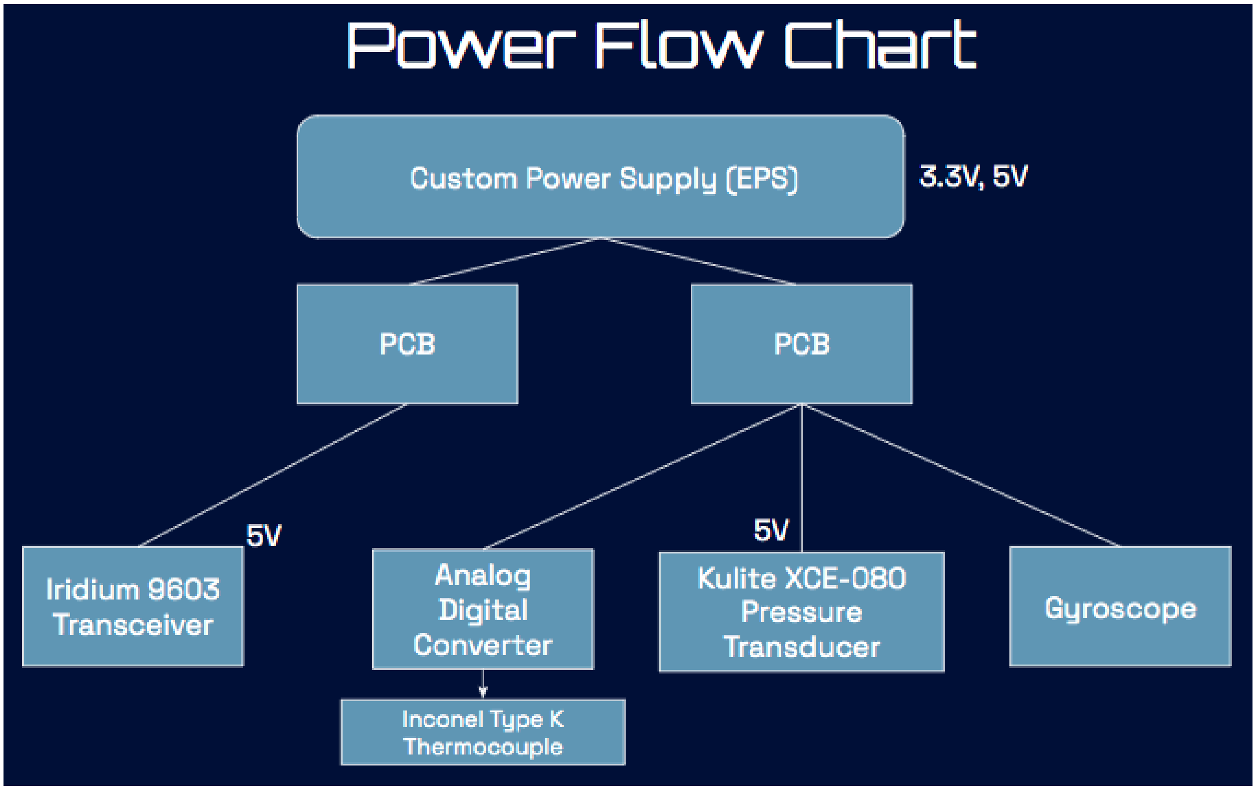

Figure 1D: Power Flow Chart

Appendix E: Attitude Determination Algorithm and Center of Pressure Results

Table 1E: Center of Pressure and Height of HEDGE

Height of HEDGE (km)	Center of Pressure (m)
15	0.1994
50	0.1967
75	0.1829

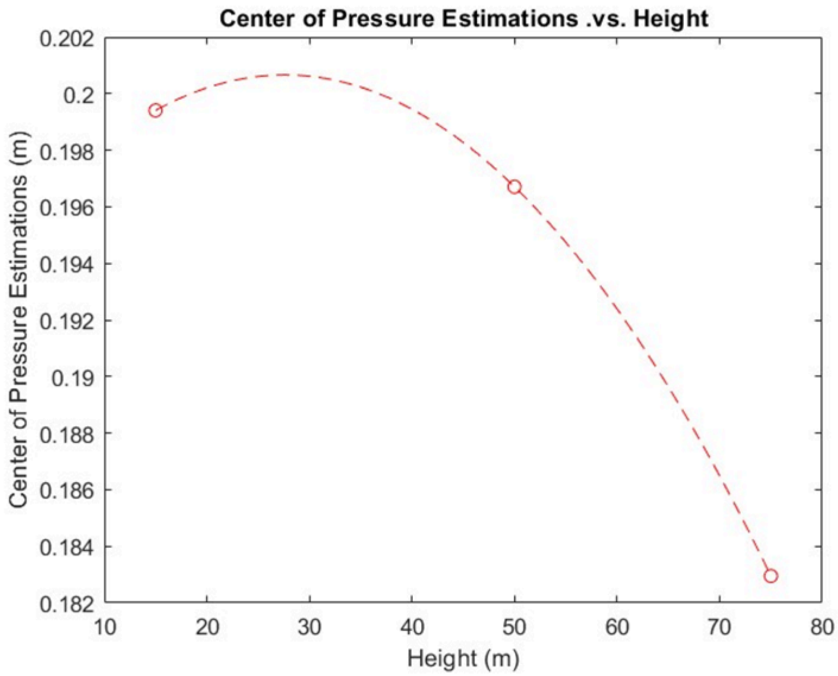

Figure 1E: Center of Pressure Estimations at Given Heights Using Spline Interpolation

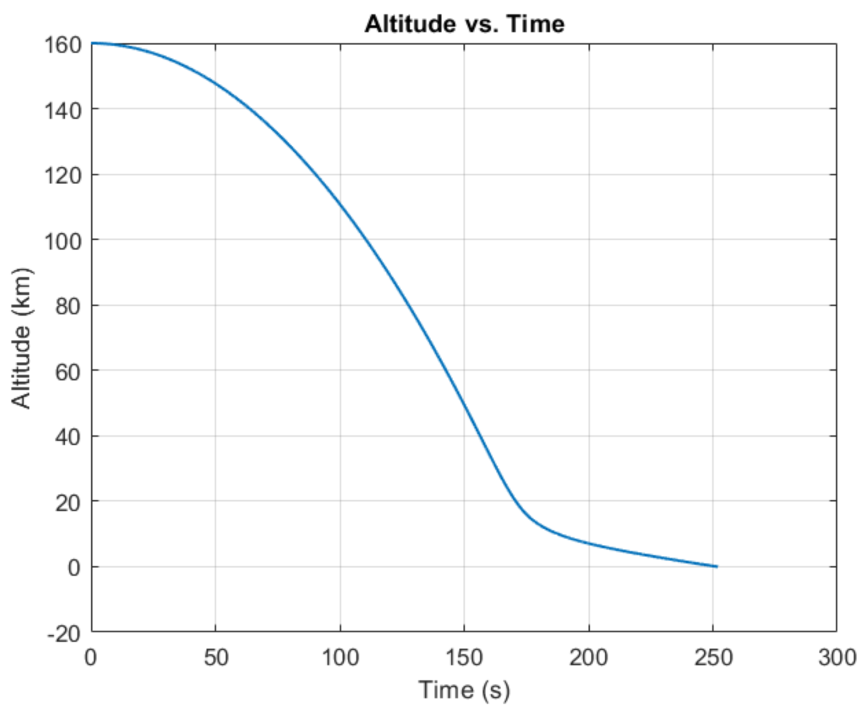

Figure 2E: Altitude vs. Time

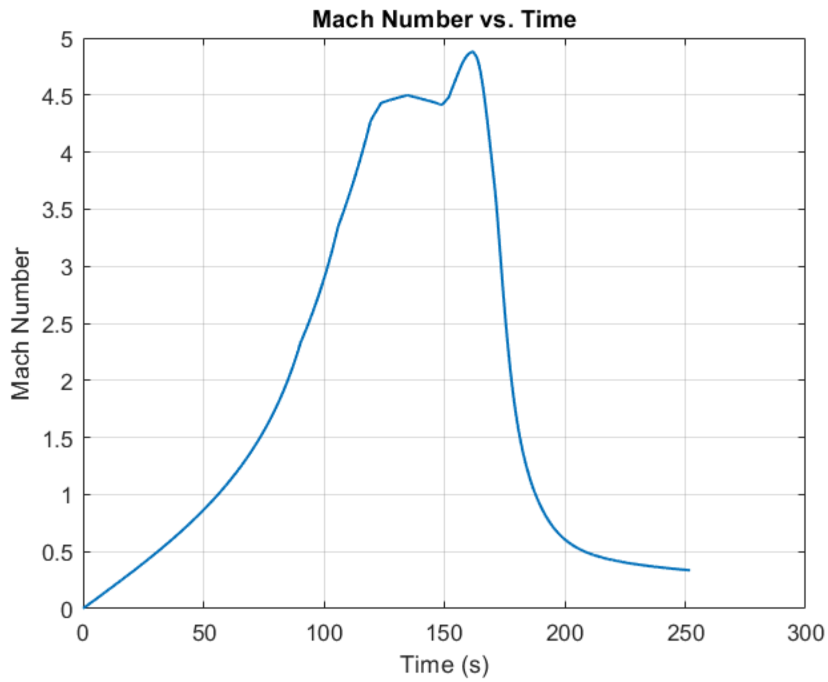

Figure 3E: Mach Number vs. Time

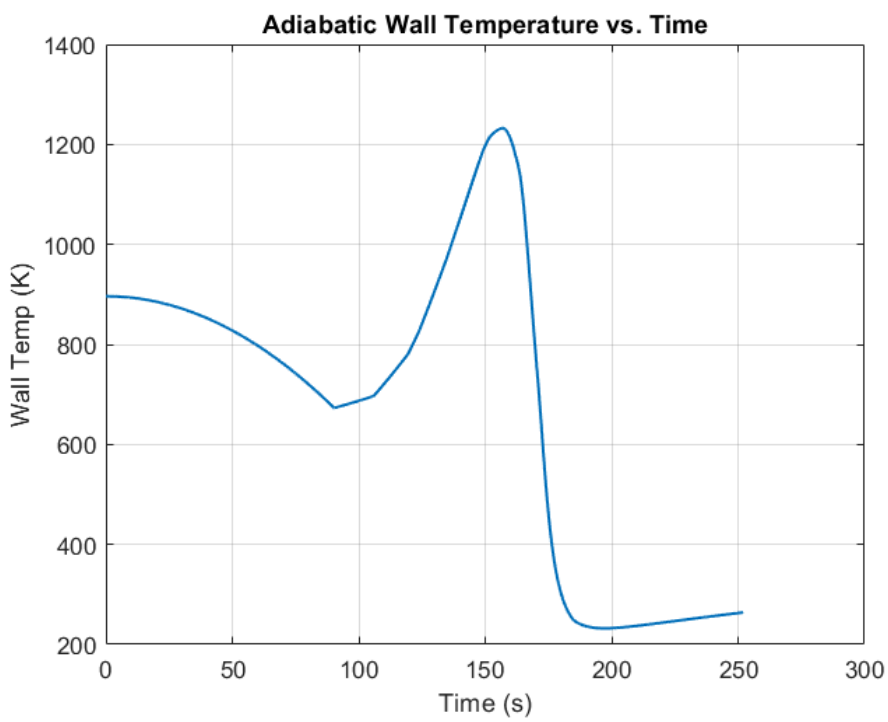

Figure 4E: Adiabatic Wall Temperature vs. Time

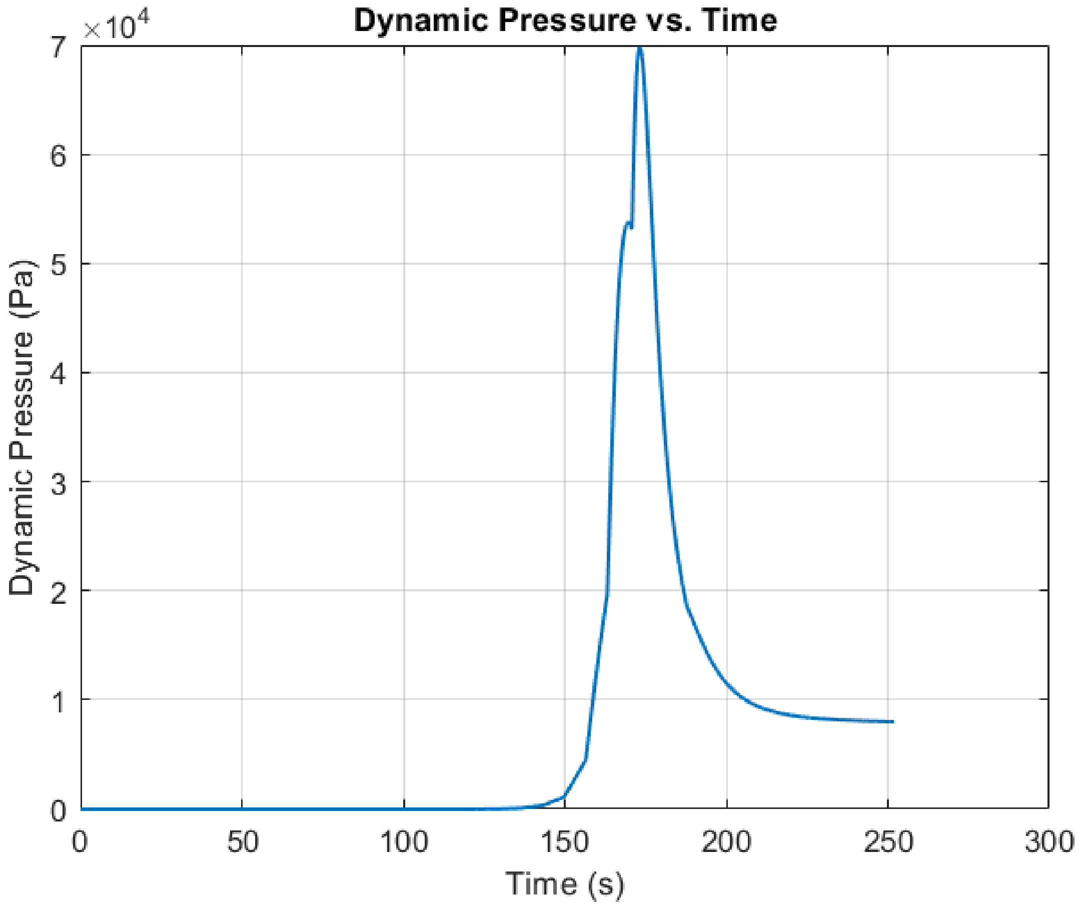

Figure 5E: Dynamic Pressure vs. Time

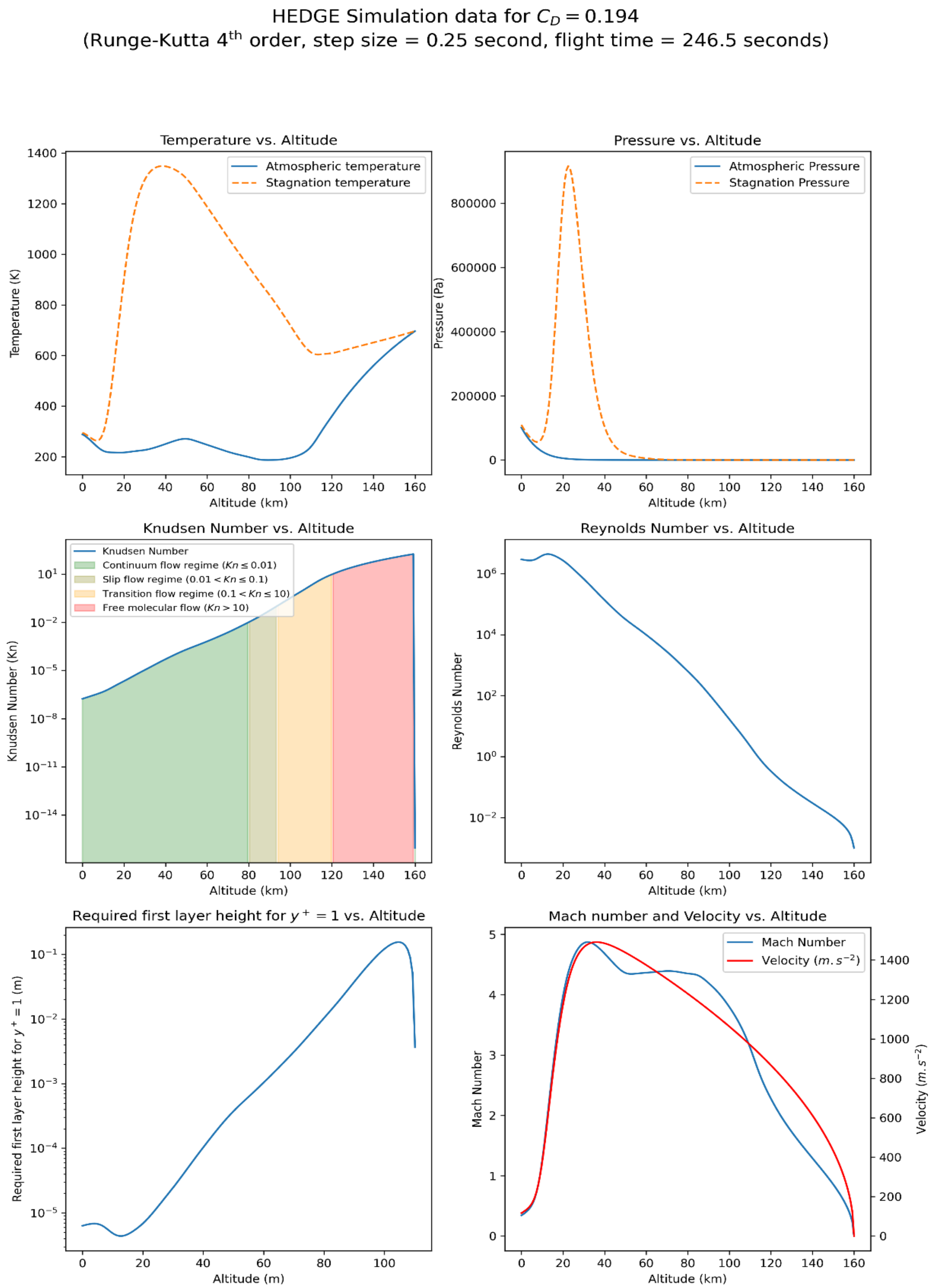

Figure 6E: Freestream conditions with updated $C_D = 0.194$

Appendix F: Images of Early Stage Prototyping and Testing

Figure 1F shows early testing of the fin deployment system using the 3D printed parts. This was used to prove, conceptually, that spring hinges could function as the main fin deployment mechanism. This mechanism was assembled on all sides of the HEDGE ejectable and was tested as an entire system. Figure 2J depicts the first, fully-assembled ejectable prototype.

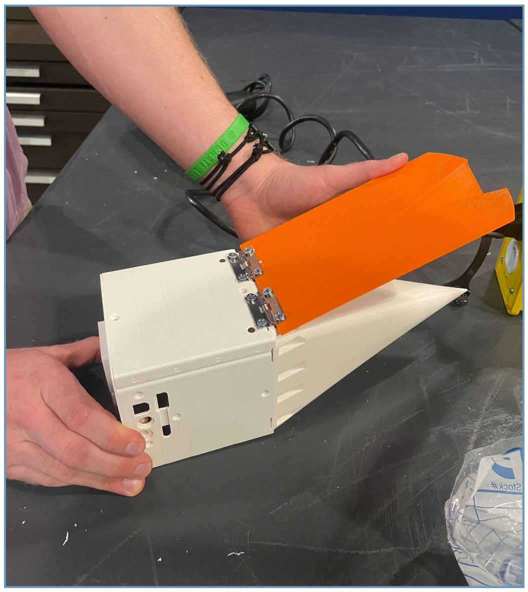

Figure 1F: Using plastic prototyping to test fin deployment

Figure 2F: Fully assembled ABS prototype

As previously stated, using rapid prototyping to test the assembly and functionality of the cage led us to notice design flaws and make adequate modifications. Figure 3F shows the original cage design, which was not structurally sound during testing. After designing new cage supports, the cage was reassembled on a model deck plate. Figures 4F and 5F are isometric and top views of the newly-designed cage demonstrating spacing and early designs of the bungee deployment system.

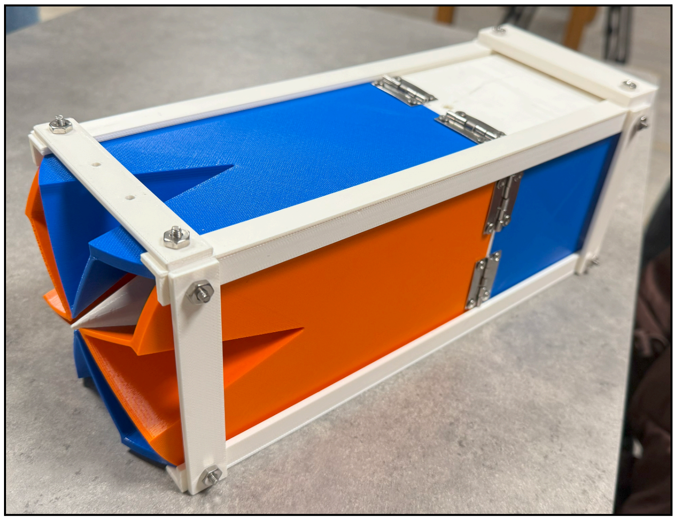

Figure 3F: Original cage design for HEDGE

Figure 4F: Isometric view of deck plate

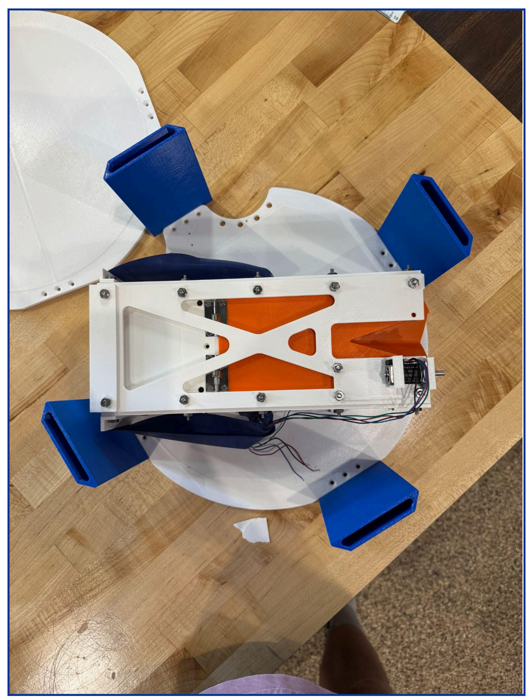

Figure 5F: Top view of deck plate

After the original prototype, the ejectable's components were redesigned to mimic manufacturing of the metal components. These components are depicted in figures 6F and 7F.

Figure 6F: ABS forebody in drill press

Figure 7F: ABS fin in drill press

Appendix G: Images of Deployment Testing and Analysis Results

Early testing of HEDGE's deployment served to validate the use of an elastic band as a mechanism. As a result, a simplified version of the deployment mechanism was used. In this case, the main component in the mechanism was an elastic exercise band, and the ejectable was constrained in the cage with a hand. This design and testing setup is shown in Figure 1G. Figures 2G and 3G show the full experimental setup and HEDGE's deployment.

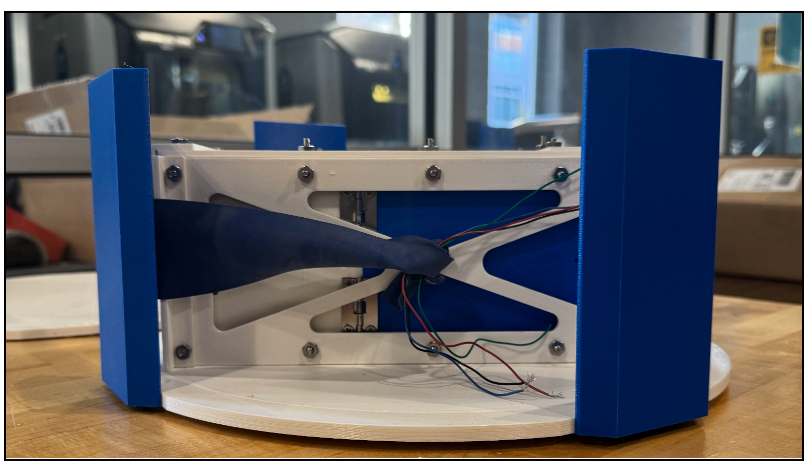

Figure 1G: Early elastic bungee deployment mechanism

Figure 2G: Deployment experimental setup

Figure 3G: HEDGE in mid-deployment

Appendix H: Images of Metal Prototyping and Testing

As the designs of the cage components were finalized, the plastic parts were replaced with metal components. These components were fabricated using a drill press, bandsaw, and vertical milling machine, as shown in figures 1H, 2H, and 3H.

Figure 1H: Top deck plate in drill press

Figure 2H: Angle brackets cut with bandsaw

Figure 3H: Angle brackets in vertical milling machine

As the metal parts were machined and completed, we assembled them on the deck plate given to us by the RockSat-X program. The ABS parts making up the pulley system were also attached to the cage and the deployment system was tested by deploying the 1U avionics structures at various levels of tension. Figures 4I and 5I show side and isometric views of the completed cage system on the deck plate. Figure 6I also depicts the markings on the bungee to indicate the levels at which deployment was tested.

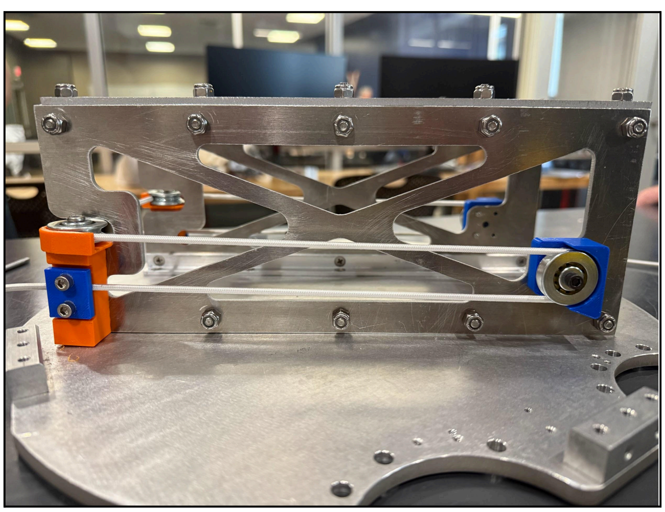

Figure 4H: Side view of metal cage on deck plate

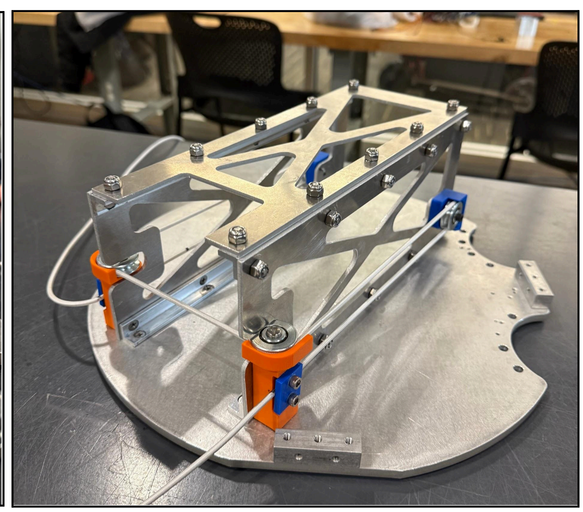

Figure 5H: Isometric view of metal cage

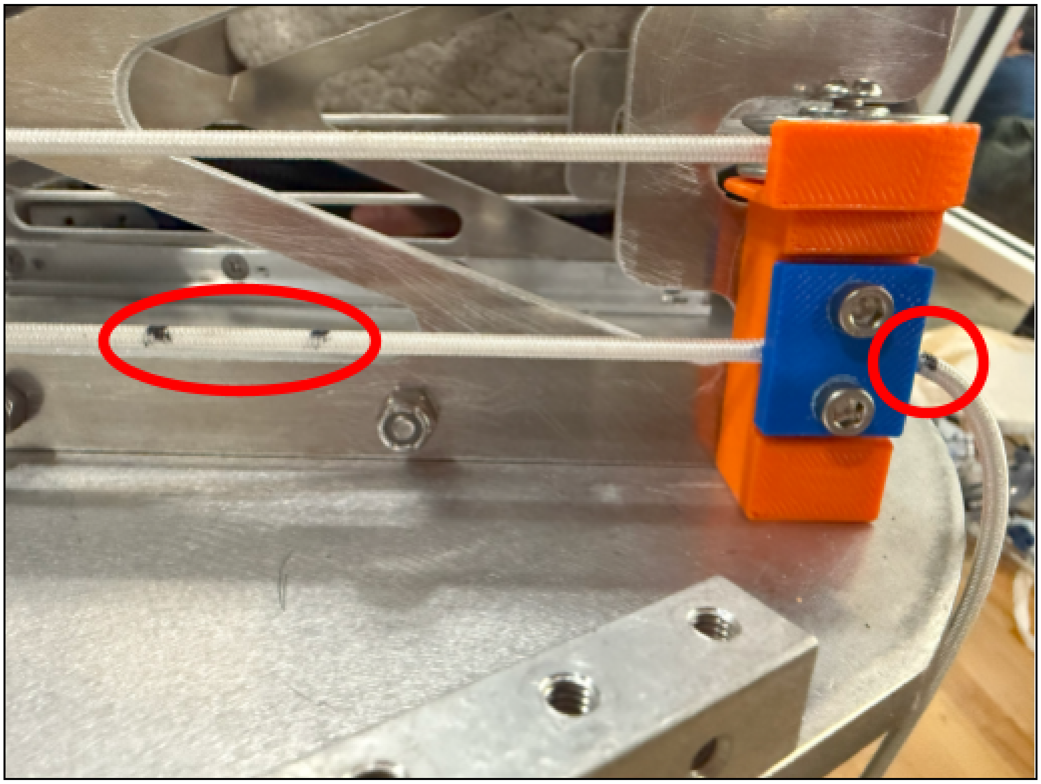

Figure 6H: Bungee deployment system with marks to indicate various levels of tension
The red circles indicate how and where the levels were marked.

Appendix I: Mass Budget

Table 1I: HEDGE Mass Budget

	Sub Assembly	Part Name	Mass (kg)	Qty	Total Mass (kg)
Deployable	HEDGE	Main Forebody	2.71	1	2.71
		Fin	0.21	2	0.42
		Antenna/Opposite Fin	0.24	2	0.48
		Spring Hinge	0.00	9	0.04
		1/4-20 3/4" Screws	0.00	4	0.02
		5-40 1/2" Screws	0.00	34	0.00
		5-40 Nut	0.00	16	0.00
		Pumpkin Space 1U Frame	0.13	1	0.13
		Electrical Contacts	0.00	2	0.00
	Data Collection	18650 Rechargeable Battery	0.05	3	0.15
		M3 Threaded Rod	0.01	4	0.02
		M3-48 Locknut	0.00	32	0.03
		Electrical Power Supply	0.04	1	0.04
		Data PCB	0.02	1	0.02
		Comm PCB	0.03	1	0.03
		Iridium-GPS Patch Antenna	0.02	1	0.02
				Total Mass of Deployable	4.11
On-Deck Components	Integration and Deployment	Cage Corner Angles	0.05	4	0.20
		Cage Support Angles	0.02	2	0.04
		Cage Back Stop	0.04	1	0.04
		Cage Side Plate	0.14	2	0.28
		Cage Top Plate	0.13	1	0.13
		4-40 7/16" Screws	0.00	8	0.00
		8-32 1/2" Screws	0.00	48	0.01
		1/4-20 1/2" Screws	0.01	8	0.07
		Bungee	0.05	1	0.05
		Pulleys	0.00	4	0.01
		Pulley Covers	0.01	2	0.02
		Pulley Holders	0.01	2	0.03
	Electronics	Camera	0.03	1	0.03
		Camera Mount	0.00	1	0.00
		External PCB	0.03	1	0.03
		Protective Resin	0.45	1	0.45
				Total Mass of On-Deck Components	1.39
				Total Mass	5.49
				Constraint	6.80 ± 0.23
				Margin	1.31

Appendix J: Stackup of Electronics (PCB's) in 1U Structure & Avionics Block Diagram

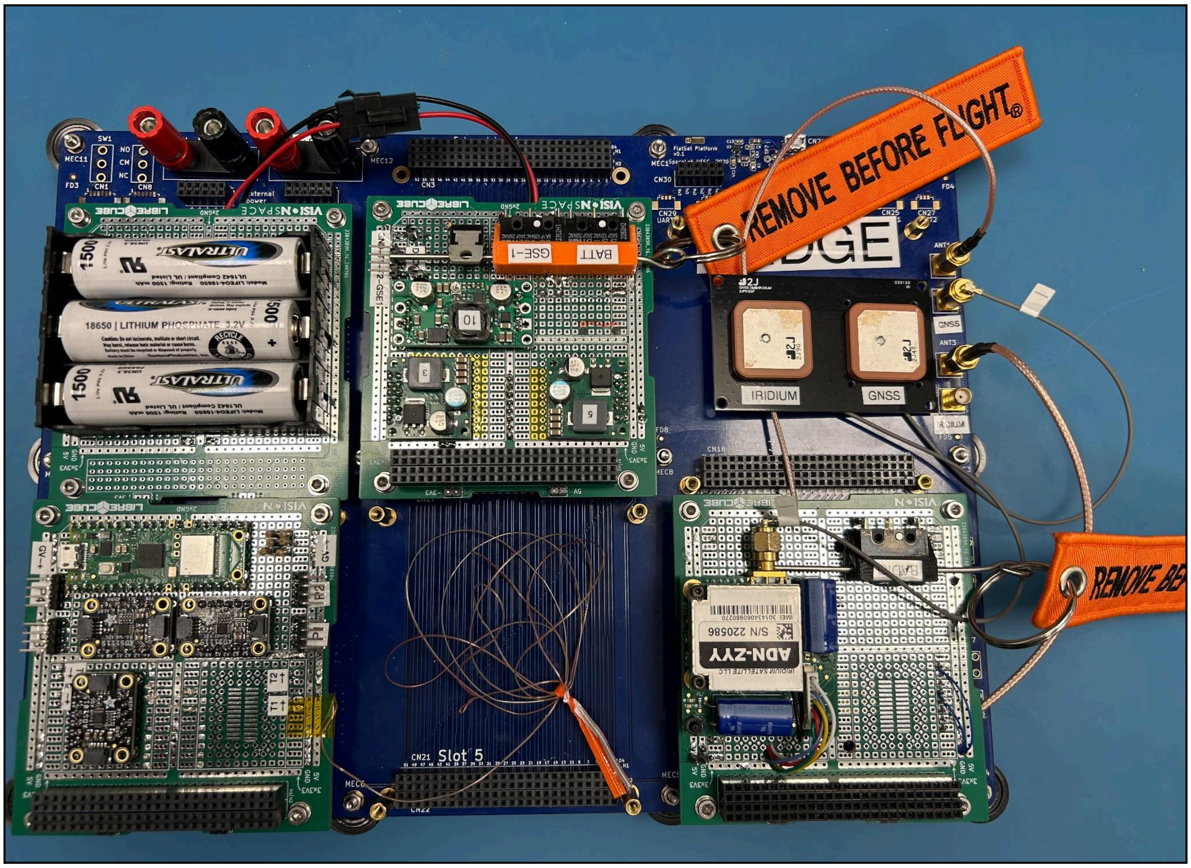

Figure 1J: Avionics Setup on Flatsat

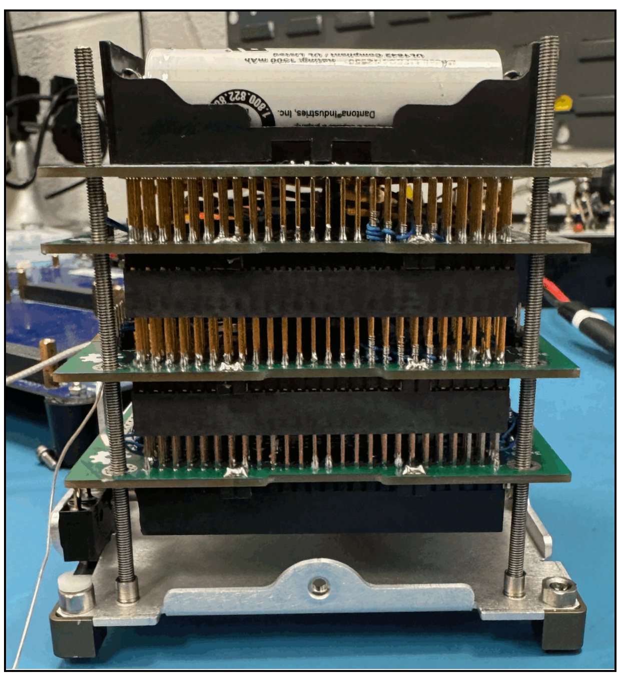

Figure 2J: PCB Stackup in 1U Structure

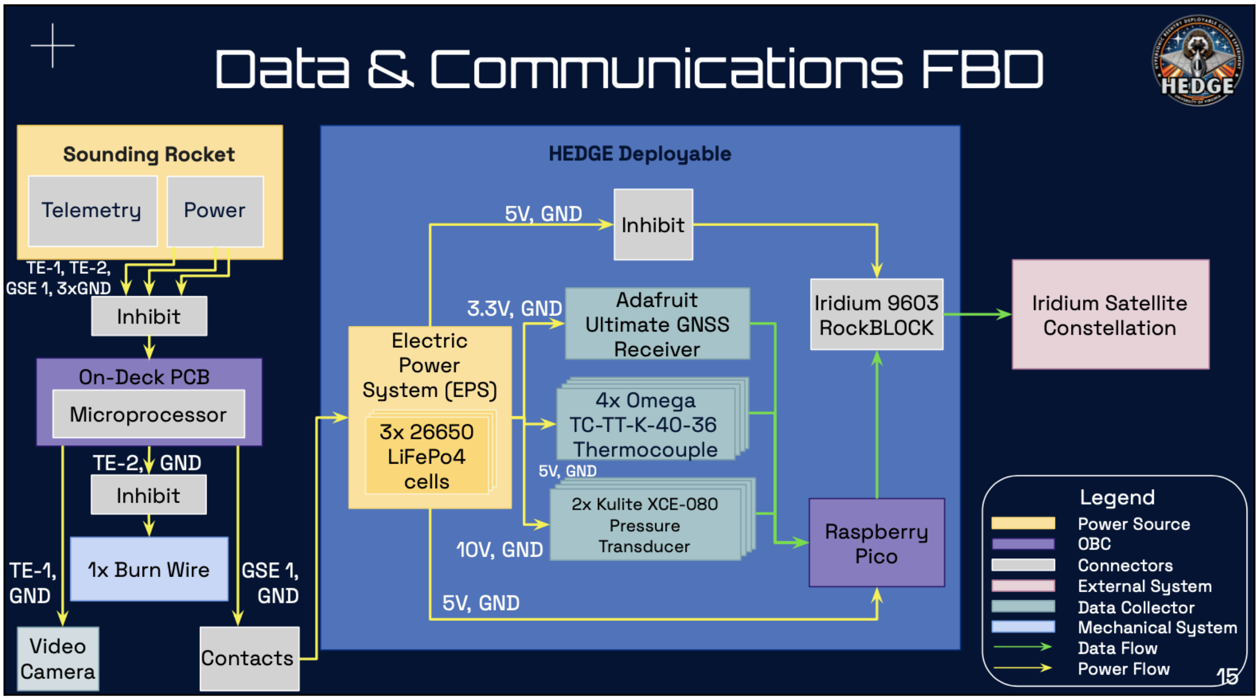

Figure 3J: Avionics Block Diagram

Appendix K: Conceptual Design of Containment Mechanism

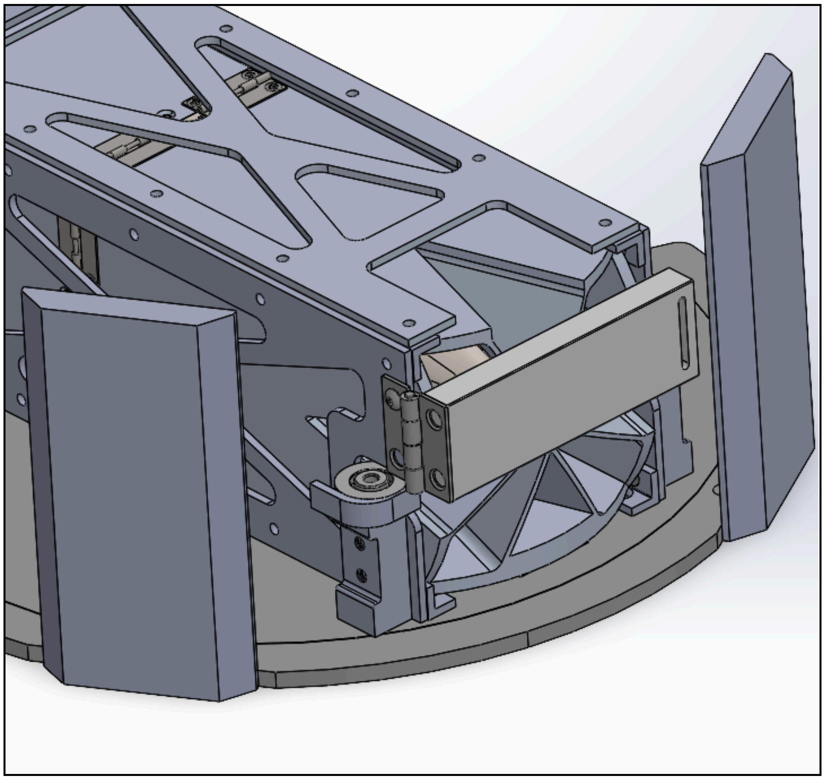

Figure 1K: Isometric view of containment mechanism

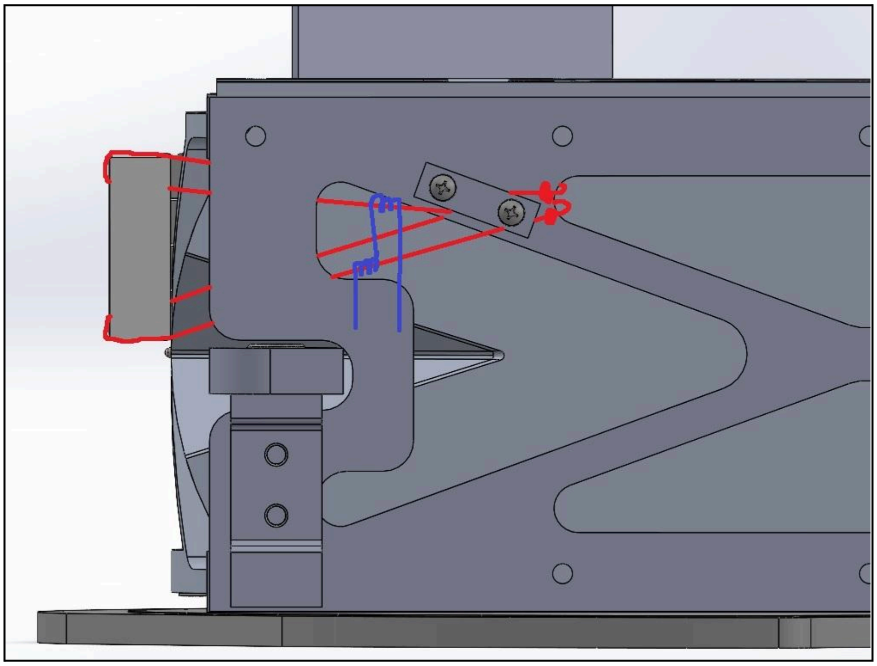

Figure 2K: Side view of containment mechanism
The red lines indicate burnable fishing lines. The blue lines represent burn wire.