UCCS DemoSat

AMERGINT Technologies

Alondra Hauser, Edward Lundberg, Ian Heinrich, Isaac Remington, Lauren Uebel, Maxwell Albrecht

UCCS Senior Design Final Report

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Executive Summary

The goal for project CubeSat was to evaluate a low power data link from an edge of space payload with the help of AMERGINT Technologies. The project was based off the DemoSat program through Colorado Space Grant Consortium criteria which lays out the basic requirements for the size and weight of the structure, what type of sensors and data it will need to collect, as well as a personal mission. The mission selected for the UCCS payload was to demonstrate communications throughout the entire flight.

There were three design processes for the project that are covered in the report: the mission for the payload, a mechanical portion that was responsible for the structure and the mounting components, and an electrical portion that was responsible for all the hardware and software. It started out with 9 different missions that were filtered down to a low power communications demonstration. The structure had gone through three distinctive design changes starting out with a 3d printed CubeSat design but after testing eventually got a change for a foam core structure. The electrical components had a similar design process, with several possible communications and computer systems examined before a final decision was made.

The structure was designed to be a 150mm cube made all out of foam core that had 45-degree corners to have proper adhesion with itself. The process of deciding the structure with other CubeSat but during every test the structure would break under its own weight, eventually a solid foam core structure was the best design because there wasn’t a worry to add any insulation as the foam already is a good insulator and is nonconductive so there would be no interference with the electrical components.

The design for the electrical portion was contingent on which type of mission was decided. The chosen mission, a communications demonstration, was accomplished using two systems: an automatic Very High Frequency (VHF) transmit-only beacon, and a half-duplex data link utilizing an off the shelf (OTS) transceiver chip at Ultra High Frequency (UHF). A mixture of open-source and custom written software was included to control these systems.

Flight operations conducted on 1 APR concluded with complete mission success. During a flight that reached over 105,000 feet in altitude, the payload continuously received and sent data to a mobile ground station. Data consisted of in-flight telemetry from onboard sensors, outbound message traffic to an external station, and photos from an onboard camera. Primary datalink was accomplished using the UHF link. VHF signals from the beacon were successfully received shortly after takeoff and after landing. The payload was recovered after the 2 hour and 18-minute flight fully intact, powered on, and capable of transmitting.

Introduction

Objective

The Primary objective of this project was to design, test, and manufacture a DemoSat which will be launched attached to a high-altitude weather balloon as part of the COSGC DemoSat Design Challenge program on April 1st, 2023. This DemoSat is intended to demonstrate communication throughout the entire flight so that the aspirations of communication that AMERGINT has are encompassed. By having a successful flight, the feasibility of low-cost, low-weight communications payload in satellites can be further developed.

The secondary objective of this project is to create interest in utilizing the CubeSat designed for the DemoSat Design Challenge program as demonstration units for future students within the newly founded Aerospace Engineering program at UCCS. The purpose for this is to generate interest for CubeSat programs among students who are just beginning their academic career at UCCS.

Problem Statement

CubeSat are small satellites that can allow automatic collection of data for a bigger objective. Colorado is one of the best locations where the aerospace industry conducts business. That is why CU boulder is the number one launcher of CubeSats in the country. The University of Colorado in Colorado Springs is seeking to be part of that exciting field and have a CubeSat on orbit. This project is an investigation of the communications system and the automation of telemetry relay from edge of space payload. The low power data links in this investigation should provide us with a basis for a more complex system for the future of a CubeSat program at this institution.

Project Planning and Management

The project was planned during the senior seminar portion and executed in the senior design semester. The senior seminar timeline of August 22, 2022- December 17, 2022, allowed for five students to research and select experimentation for the payload. By gathering all the requirements from sponsors (AMERGINT) and launch provider (CSGC) the team was able to evaluate any obstacles that might arise in implementation. The team also evaluated an agile technique to pass down specific tasks for team members using Jira as a host. In this preliminary phase of the project, the main concern was dealing with FCC rules for communicating at certain frequencies. The team quickly learned that the operations from the launch provider were more complex and needed to collaborate with the recovery team at Edge of Space Sciences (EOSS) to coordinate radio communications. By the end of the semester the team had two additional members. A master student that is an experienced HAM radio operator to mitigate with FCC rules.

The project was divided into three phases from January 17, 2023-May 13, 2023, to ensure the deadlines were met for Colorado Space Grant Consortium where met. A preliminary design review (PDR), a conceptual design review (CDR), and a final readiness review (FRR) presentations of the project process had to be presented to be able to launch. The team divided these deadlines that worked in phases.

Phase 1: Design/Execute – To design structure, calibrate and learn electrical components selected for system. Mitigate and anticipate problems with materials, power budget, link budget estimations.

Phase 2: Testing/Validation- To learn about structural deficiencies and strong points by rapid prototyping. Integrating sensors and validating links to main board and increase complexity in automation of system. To evaluate communication links (both downlink and uplink) to mitigate protocol problems with EOSS.

Phase 3: Integration/Verification: To do a complete system integration and verify that all specifications placed by sponsors and space grant were followed.

Project planning was easy to implement to meet clear deadlines placed by Space Grant. It was an effective way to guide teams to success. Gantt charts made for this project are in the appendix.

The management part of this project was mentored by the sponsors (AMERGINT). The budget provided by the sponsor was $2500, which the team was able to stay under. Meetings with sponsors were done every week and every two weeks close to launch day (April 1st, 2023).

This team was an interdisciplinary effort which gave some difficulties with scheduling and many assignments and due dates coming from different departments. The mechanical engineering department is excellent in showcasing documentation compared to the electrical engineering and DASE curriculum. It would benefit everyone to combine the senior seminar and senior design classes to create a pipeline of information and responsibility sharing.

Problem Specifications

Project Requirements

The communications requirements were derived from a combination of COSGC DemoSat requirements, FCC regulations, and sponsor developed constraints. Some major driving requirements that contributed to the final design of the DemoSat were COM-1,2,7 and 8. These requirements helped to shape how the payload would function as it relayed information and data between itself and the ground station. Other major requirements such as COM-6 played key roles in the logistics of the launch day, ensuring all regulations and safety measures were met.

Communications Requirements List:

COM-1: Communication systems shall have uplink capability.

COM-2: The telecom system shall be capable of supporting a data volume of 1200bps.

COM-3: Antennas shall not interfere with sensors.

COM-4: System transmission power shall remain within limits of power budget allocation.

COM-5: The communications subsystem shall be compliant with restrictions set by the FCC.

COM-6: The payload shall implement its own unique satellite ID in the telemetry downstream.

COM-7: The EIRP (Effective Isotropic Radiated Power) limits.

COM-8: The communications subsystem shall be capable of interfacing with ground station operations and support 1200bps.

COM-9: Communications Subsystem shall be able to function in simulated environment.

The power sub-system requirements were all derived from the needs of the hardware for the payload to function. POW-1 is responsible for determining how much power is needed for the overall system. Pow-2 and Pow-3 are then implemented to reduce risk in power drops and surges.

Power Requirements List:

POW-1: Power sub-system shall supply sufficient current to all other systems at a minimum of 5 V DC.

POW-2: Power sub-system shall provide sufficient voltage regulation from variable power source (Batteries).

POW-3: Power sub-system shall include overcurrent and overvoltage protection.

The telemetry and control sub-system requirements help to dictate how the process of data collection and transmission within the payload is executed. In Tel-1 and Tel-4, it talks about where the data is being collected from and how/when it should be downlinked. In Con-1, it talks about how to facilitation of the data is managed throughout the payload.

Telemetry and Control Requirements List:

TEL-1: Data collected from sensors package shall be downlinked every 5 minutes.

TEL-2: Telemetry data collected shall be exported to the memory in a readable configuration.

TEL-3: Telemetry data shall be stored locally as back-up in case of failure.

TEL-4: Telemetry data shall consist of 9-axis position data, current reading, internal temperature, external temperature.

CON-1: The control System shall manage telemetry and comms integration by implementing a data down-link algorithm.

The mechanical sub-system requirements focus on ensuring that the payload structure does not compromise any other system and in turn, no other system impedes the structure. In addition to protecting the payload, requirements such as ME-1 were required by balloon launch personnel to ensure a safe launch and flight. These launch constraints determined what the mechanical structure looked like and behaved like under the flight environment.

Mechanical Requirements List:

ME-1: Total system shall weigh 800 g or less.

ME-2: Frame shall maintain functional integrity at –40 C.

ME-3: Frame shall protect and ensure functional integrity after impact tests.

ME-4: Frame shall ensure functional integrity after jerk test.

The thermal sub-system requirements were based off the flight environment that the payload was exposed to during the mission. The main environmental factor that derived these requirements was temperature change. The batteries on board the payload began to lose power when they reached – 40 degrees Celsius so TH-1,2, and 3 were created to help retain heat.

Thermal Requirements List:

TH-1: Batteries maintained between operational temperatures.

TH-2: Batteries maintained between non-operational temperatures.

TH-3: Electrical components maintained between operational temperatures.

A more detailed description and verification method for all requirements can be found in appendix C.

Conceptual Design

Missions

A variety of mission concepts were evaluated for this payload. The mission is crucial in determining how the payload will function, what components will be needed, and how large the payload needs to be.

Mission Concept 1: Cybersecurity Communication Test

This mission concept involves utilizing homo-morphic encryption of images as a cybersecurity communication demonstration. This encryption requires the people with clearances (allowed) to have access in a way of a key with no decryption needed. This would allow for this experiment to use little computing power. This concept would demonstrate secure data transmission and would be cost effective. The concept was well investigated but would require more expertise from the team.

Mission Concept 2: Telemetry and Communications Demonstration

Sends live telemetry data of the payload regarding altitude, acceleration, temperature, pressure, spin rate, moisture, and images.To demonstrates communication throughout entire flight, easy to produce, cost effective, compact, and lightweight. The downside to this concept was that it does not generate any majorly useful data for future experimentation.

Mission Concept 4: Lunar Dust experiment using Carbon Nanotubes

To design an experiment that would evaluate lunar dust using carbon nanotubes to repel the electrostatic properties of carbon nanotubes. The experiment would also allow for analyzing the behavior of lunar dust at 120,000 feet. One of the most complex concepts for an investigation is that would last only one semester. It was voted to be one of the most complex concepts due to the time and effort designing a control system that would allow the team to operate during harsh environmental conditions.

Mission Concept 5: Autonomous Robotic Communication and Performance

Allows for control of a robot on the ground from a signal sent from the Payload. Signals will be sending a robot on the ground to activate a command. The robot on the ground would then relay a signal to confirm the operation performed. This concept would highlight a communication system protocol for autonomous vehicles on other planets. Timeline would not permit a complex communication system. However, this was one of the lightest options for the payload and it generates useful data for future experimentation. Some of other difficulties with this concept was that it may be exceedingly difficult to maintain communication throughout the flight, requires an additional robot in addition to the payload, and difficult to accurately give GPS guided instructions, along with doppler effected of communication downlink and uplink.

Mission Concept 6: Flash Lidar

Using flash lidar to map the trajectory of the flight and analyze ground statistics. Effective flash lidar requires a high-power budget and is mostly heavy. The topological trajectory path of the high-altitude balloon does not highlight enough ground points that the team can focus on or study. The payload would require an attitude control system which would be complex to implement on a high-altitude balloon. Overall, this concept would break one of the most important requirements, which is weight.

Mission Concept 6: Stardust Collector

To take advantage of high altitude in Colorado, the team was proposing to investigate stardust collection deposits in the area. Using aerogel and an opening closing mechanism, the team would plan the automatic release of a valve to suck in the particles in the air. The aerogel would trap particles collected to later examine them using an electron microscope. This concept offered the most intense after flight investigation and requires students to learn how to operate, rent time with electron microscope and know what they were looking for. Time wise this concept would take dedication along the time of finals and reports due. The materials were not easily accessible and costly.

Mission Concept 7: Deployable Radio Astronomy

In addition to the radio communication demonstration, the concept of a deployable radio astronomy was proposed. The team quicky realized it would require an obnoxious antenna sticking out of the payload and that the time of flight would be mostly in the day. It would also require an attitude control system for accuracy of pointing. The components alone would break the weight budget of 1kg. Being able to identify a celestial object by bouncing frequencies and pointing at something in the sky sounds fascinating but the components and added complexity to the system would not be a task to take within the amount of time given.

Mission Concept 8: Radiation protection

The mission of this concept was to evaluate varied materials or substances to measure the amount of radiation penetrated or repelled by the material. This investigation was an often sought out one by anyone interested in radiation. The problem with the specifications is that the payload would only go to a max of 120,000 feet and the duration at that altitude would only be counted in minutes. By cross-examining the investigations done in the past. The team concluded that the experiment would not have enough exposure to have conclusive or relevant data.

Mission Concept 9: Solar Sails

Finally, solar sails to navigate a space craft have been proposed in the past. The payload would not go to space and the payload would not be able to navigate using solar wind because it would not be in outer space. Any solar sail device would have to be deployable which would disrupt the balloon transition and possible other experiments on the string.

Electrical

A variety of electrical systems were investigated for this payload. Regardless of mission profile or structural design, the internal electrical and computer systems must be capable of communicating with the ground station (uplink and downlink), logging any sensor or other measured data during the flight, and supplying power to all necessary components.

Main Computer

For the main computer, an Arduino-based development board, and two raspberry pi development boards were considered. These options were initially chosen based on the wide range of compatible software, ease of development, and availability.

The Arduino based system would be the cheapest and simplest option, as well as the most limited of the suggested computers. The AtMEGA328p processor is not capable of running a full operating system and would require a significant amount of software being written to handle both communications and sensor control. This would be difficult to accomplish considering the limited computational resources of the computer. The Arduino would, however, draw the least amount of power and occupy the least amount of space in the structure.

The raspberry pi options were to use a full-size pi 4 b+, or a pi zero W. Both options can run a full operating system, have large aftermarket support, and are readily available. The full-size pi 4 has the greatest computational resources of the three options by a significant margin. The pi 4 has a large amount of I/O, making development and writing software even easier than the other options. This is also the most expensive choice, as well as taking up the most space in the structure and requiring the largest amount of power. The pi zero W represents a middle ground, having decent computational power while still requiring less power and space than the pi 4. The pi zero W is priced in between the 4 and the Arduino.

Sensor Package

Additional sensors beyond the primary payload should be included to provide additional context to the data from the primary payload. Numerous OTS sensors, both analog and digital, are cheap, readily available, and simple to integrate with the above computer systems. Data sources initially suggested are listed below:

- Temperature probes (internal, external, per-component)
- Gyroscopes (attitude, multi-axis acceleration, positional magnetometer)
- Pressure Altimeters
- Humidity sensors
- Visible-Light and infrared cameras
- Gas transducers (O_2, CO_2, CO)

Communications

Current FCC regulations regarding the use of certain RF bands at the power levels required for bi-directional communications at the expected distances limits the legal options for communications systems; consequently, all suggested solutions were within the hobbyist ham radio domain. Specifically, three packet ham radio systems were investigated.

APRS (Automatic Packet Reporting System), a community-driven network of receivers and transmitters, was initially investigated. This system would allow for a network of ground stations to be able to send, receive, and forward data packets to and from the payload on the 144 MHz band. Operating using the AX.25 specification at the data-link layer, integrated with the community stations to provide a higher network layer and integration with the wider internet. This solution would be simple and cost-effective to implement, owing to the large amount of hardware and software available to implement APRS capability. A key limitation with APRS is the limited frequency of transmissions. 144.39MHz is a busy channel, and especially at high altitude and transmit power could become congested with other traffic. A transmission interval of not less than 5 minutes was recommended by the launch provider, significantly limiting the effective throughput of the system.

A SDR (software defined radio) implementation was also initially suggested. This solution would entail a custom point-to-point SDR system developed using an open-source SDR package such as GNU radio. This would allow for precise fine-tuning of transmission parameters to provide the maximum possible throughput and minimum power draw. This solution would be the most work intensive, requiring an extensive test and development cycle potentially beyond what was available during the project. This would require virtually all software to be custom-built and integrated with a variety of external hardware. Integration with a higher-level network protocol (such as TCP/IP) would further increase the development overhead. The SDR would require a substantial number of computational resources to implement.

The final communications system investigated was to integrate an OTS transceiver chip out of a hobbyist VHF/UHF radio with an existing software modem, such as DIREWOLF. This solution would be significantly cheaper than, but potentially more difficult to implement than the APRS solution. It would, however, provide some significant advantages. DIREWOLF implements AX.25 v2.2, which includes forward error correction. The carrier frequency could be set to a less-congested band, allowing for more frequent transmissions. While this would be a point-to-point system, a network layer could be easily integrated with DIREWOLF, allowing for more complex downlinked data.

Onboard hardware was contingent on which of the above systems were implemented. Each system would at minimum require an antenna. Due to internal space constraints, two types of external antenna were considered: J-pole and a ¼ wave dipole. The dipole antenna would take up much less space than the J-pole (especially when tuned for UHF frequencies) but has an undesirable horizontal radiation pattern and horizontal polarization, making transmission reception more difficult. The J-pole has a better radiation pattern and (when dangling from the payload) has a vertical polarization. For the ground station, a high-gain antenna such as a Yagi was found to be desirable, with manual and self-tracking solutions investigated. Packet radio traffic could then be received using another ham VHF/UHF receiver, with packets being decoded by an additional computer running DIREWOLF.

Power System

The primary power source for a payload such as the one described here is stored battery power. A variety of energy storage technologies were researched, including Lithium-ion, lithium-polymer, and disposable alkaline batteries. For the case of rechargeable batteries, the usage of a PV (Photovoltaic) system was investigated. This would reduce both the mass and dimensional footprint of the required energy storage but entail a more complex onboard balance charging system, as well as external PV panels.

Power regulation could be done either via DC-DC switching converters, or linear regulators. DC-DC converters are much more efficient and generate less heat but occupy more space and are less physically robust compared to linear regulators. Protective elements such as relays, fuses, and a physical on/off switch were also investigated as suggested by the launch provider.

Structure

A variety of different structure designs were investigated for this payload. Regardless of the mission chosen, it is crucial that the structure can hold and protect the internal components, surviving landing and other flight scenarios, preventing water from reaching the interior, being lightweight, and being easily replicable.

Design Concept 1: 3D Printed Design

When deciding what structure to use for this project, many unique designs were considered. The first design was a 3D printer structure which can be seen in Figure 5 below. When evaluating this structure, PETG were used. In the design there are four pillars that stick out on both the top and the bottom. These pillars were intended to function as crumple zones and absorb some of the impact from landing before it was transferred to the remainder of the structure. This design would also allow for extremely easy modifications to be made and allow for extremely easy replication as it would just need to be reprinted for extra structures. However, there were two significant issues with this structure. The first was that each wall of the structure was held together with screws which caused large stress concentrations. The second was that this structure was not waterproof or insulated and would require extra material to be layered around the structure to achieve the desired insulation and waterproofing.

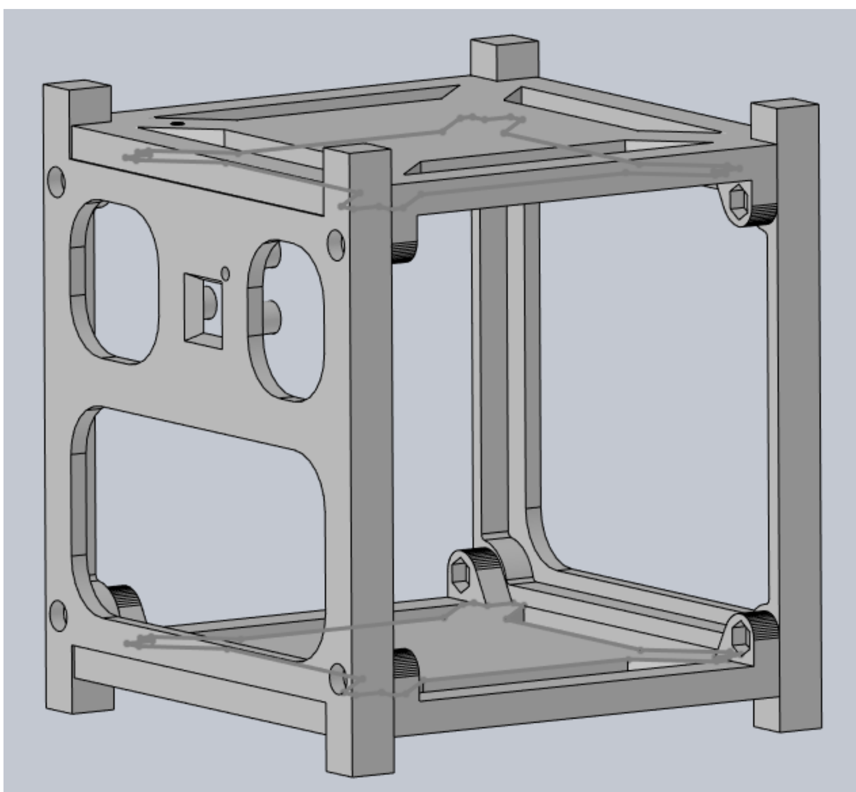


Figure 1: 3D Printed Structure Design

Design Concept 2: Foam Core and Plexiglass

Another design evaluated utilized a combination of foam core and plexiglass which can be seen in Figure 6 below. In this design, the main enclosed area is made up of foam core walls with pillars on each corner and a top and bottom made from laser cut plexiglass. These were held together using hot glue that was rated for cold temperatures. This design allowed for a rigid interior area which allowed for easy mounting of all internal components as well as the interior to be waterproof. The foam core pillars were intended to function as crumple zones and absorb some of the impact from landing before it was transferred to the plexiglass and interior components. This design had two issues with it. The first was that it was time consuming to recreate as the plexiglass needed to be laser cut. The second is that the plexiglass provided little insulation for the internal components and would require another material to be layered on top to achieve the desired amount of insulation.

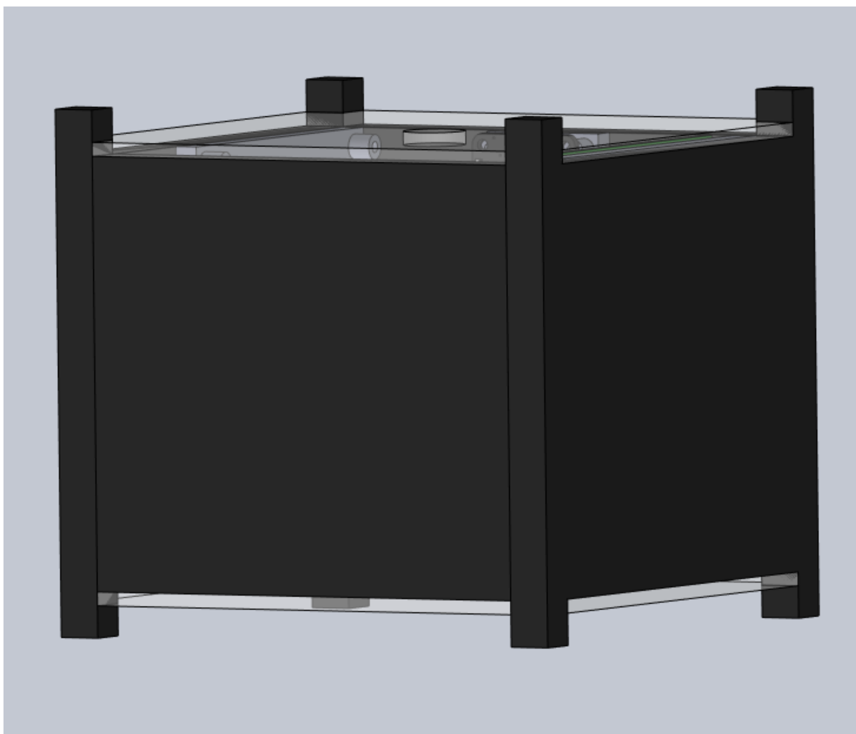


Figure 2: Foam Core and Plexiglass Design

Design Concept 3: Foam Core Cube

The final design evaluated utilized ½ inch foam core with 45º cuts on every wall which can be seen in Figure 7 below. In this design, the entire structure is made of foam core and utilizes hot glue, rated for cold temperatures, to hold the walls together. This design allowed for a rigid interior which allowed for components to be mounted relatively easily. This design also allowed for the interior to be well insulated and waterproofed very easily. The large ½ inch thickness of the foam core allowed for some impact to be absorbed before transferring the rest to the interior components. This design was easily replicable with a 45º cutting tool being the only special tool needed for manufacturing.

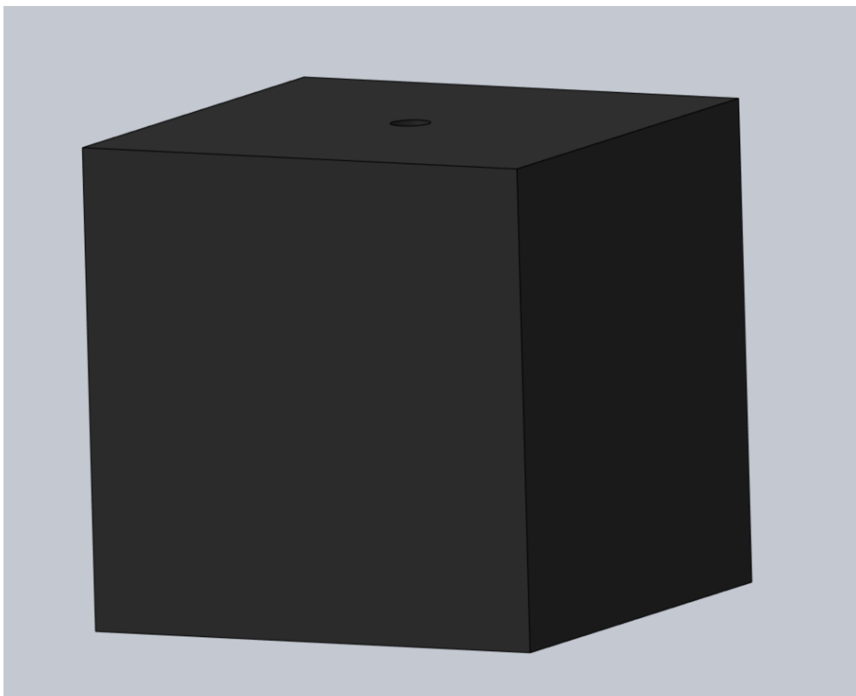


Figure 3: Foam Core Cube

Testing and Analysis Summary

A variety of tests were performed on electrical components that were planned to be used within the payload. These tests are crucial to ensure that the electrical components used are working properly and are capable of withstanding flight scenarios.

Electrical Testing Methods and Results

Sensor Integration & Calibration

An initial test of sensors to assess rudimentary functionality and calibration in a controlled environment was conducted. The preliminary sensors identified as being mission critical were connected to a preliminary computer system running simplified software. The complete test system included a BME280 temperature/humidity/pressure alt. combination sensor, an INA219 current & voltage sensor, and a raspberry pi zero W connected to bench power. The preliminary software was run for approximately 5 seconds, generating 5 data points for each of the sensors (software polling each sensor at 1 Hz and recording). The collected data was compiled in table 1.

Table 1. Results of Sensor Integration & Calibration

Instrument	Measured Value (Average of 5)	Actual Ambient Conditions
BME280, Temperature	21.5855 C	20 C
BME280, Humidity	11.135 %	~ 10 %
BME280, Pressure Altitude	1882.494 m	1889.76 m
INA219, RPI logic voltage	3.291 V	3.3 V
DS18B20, Temperature	20.9748 C	20 C

This test successfully verified that data could be reliably recorded and saved in a human-readable format to the computer system. This test also verified that the sensor payload was calibrated to a reasonable degree at low altitude (~6200 ft) and at room temperature.

Cold Testing, Electrical

A test of the preliminary sensors, computer system, and power system in significantly worse than expected environmental conditions was conducted. This test was conducted simultaneously with the initial structural cold test. The purpose of this test was to assess battery and electronic component performance in adverse conditions.

The preliminary system consisted of the same BME280 and INA219 sensors, with the addition of a ds18b20 temperature probe acting as an external temperature sensor. An early design of the power system consisting of two 18650 li-ion cells and two DC-DC buck converters supplied power to the sensors and a full-size raspberry pi running the same preliminary software as above. The entire system was placed in an early design for the casing, powered on, and left in a -80° C freezer for 2 hours.

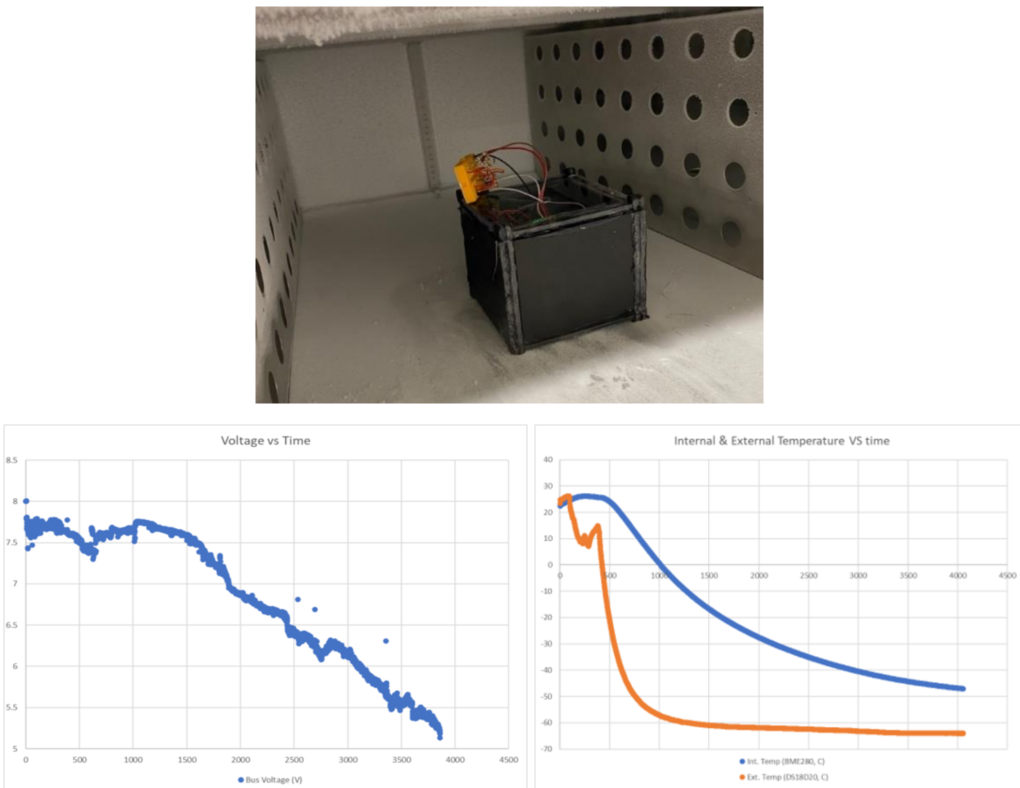


Figure 4: Top: Early payload in freezer. Bottom left: Freezer test voltage. Bottom right: Freezer test internal and external temperature.

At approximately 1 hour into the test, the temperature of the batteries dropped low enough to halt their internal chemical reaction, causing the entire system to shut down. It was determined that, while the payload did suffer a failure during the tests, this failure was under extreme conditions significantly worse than expected during the flight. The system was able to log data for a full hour before this failure, indicating that it will likely function for the entire flight duration. The only major change to the design to come from this test was to improve the insulation capability of the structure, with no significant alterations to the power system.

Spurious Transmission Evaluation

The OTS transceiver chip selected as a possible communications component, the DRA818, generates significant harmonics and spurious transmissions. A test of the unfiltered transceiver, and with two integrated lowpass filters was conducted.

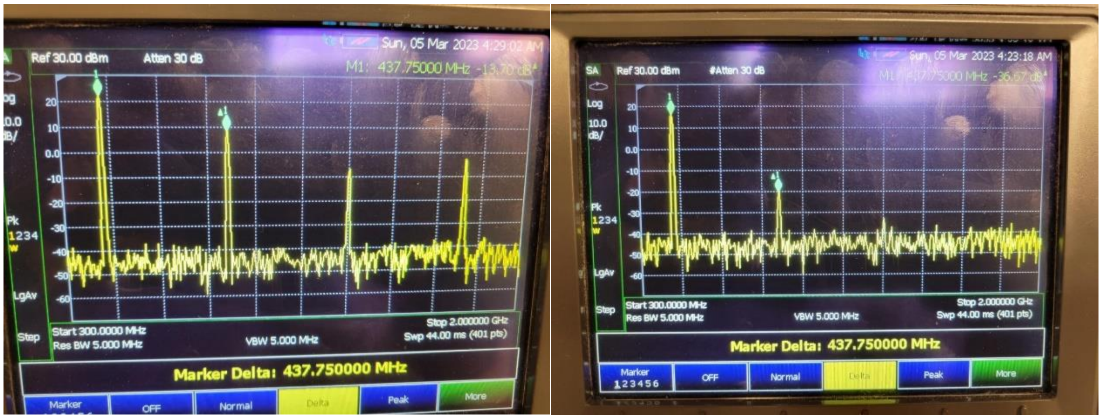


Figure 5: Left: Transmission harmonics without filter. Right: With filter.

The test compared each filter individually, as well as cascaded, with the unfiltered transceiver. Figure X shows the frequency response of the best suited filter configuration, a single LCFN-400+ low pass filter.

Initial 2C Verification

A test verifying the functionality of remote command & control was conducted. The test apparatus consisted of a preliminary communications configuration consisting of an OTS transceiver and an automated APRS beacon connected to a full-size raspberry pi. The pi was running preliminary software consisting of a web server attached to a DIREWOLF modem allowing for on-demand downlinks of example data and HTML content, as well as start/stop commands for the APRS beacon and the raspberry pi itself. The transceiver was configured in the UHF band and duplexed with the APRS unit into a single antenna. A simplified ground station was set up in the same room as the preliminary payload.

Figure 6: Left: Antenna hanging up during initial comms test. Right: APRS traffic decoded by mobile ground station, showing GPS altitude and example voltage, internal, and external temperature data.

Start/stop of the beacon, downlink of example text data, and loading of a sample webpage from the payload was demonstrated. Proper startup and operation of the APRS beacon was also verified. This test confirmed the capability of half-duplex communications between the payload and a ground station.

Complete System Bench Test

A test covering all major functionalities of the near-finalized payload was conducted. The payload consisted of a preliminary power system, completed computer system with 99% software implemented, full sensor payload, and a communications system consisting of the DRA818 OTS transceiver and APRS beacon.

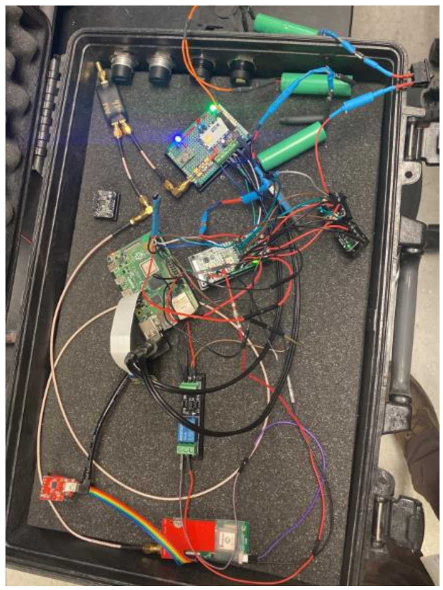


Figure 7: Near-complete bench assembled system.

The payload was assembled on a bench and initialized under its own power. A full-dress rehearsal of the preflight procedure was conducted, consisting of starting up the web server, initializing DIREWOLF with the correct audio port information, startup of sensor data collection, and an initial 'echo' command to verify communications on the UHF link. The ground station was also initialized as described above. The beacon system was powered on and initially could not acquire GPS lock. After remotely power cycling, the beacon successfully powered up and achieved GPS lock.

In-flight functions were then verified, including downlinking text data, downscaled images, and relaying text messages to a separate station. Startup and shutdown of the APRS beacon was again verified, and finally a shutdown command was issued. This test confirmed that the complete system was capable of all required mission functions.

Real Power Draw Test

The above test was repeated, except for the battery power being replaced by a bench supply connected to a multimeter. Power draw was measured throughout the startup and operation of the payload, allowing for a more accurate estimate of the payload's energy usage during flight operations.

The results of this test showed significant energy demand and voltage sag when transmitting. This test also revealed that the current power system does not include a significant safety margin. The amount of stored energy (batteries) brought on the flight should be increased, weight and internal volume allowing.

Long-Range Communications Verification

A final test consisting of the finalized payload assembled in its housing was conducted under long-range conditions. The payload was assembled and placed on top of the Osborne Center for Science & Engineering at the University of Colorado, Colorado Springs. The preflight procedure was conducted, and a mobile ground station was set up out of a team member's truck.

The mobile ground station was then driven 16 miles to the south, with echo and data downlink commands issued throughout the drive sent through arial antennas on the truck roof. The station was then parked on a hill such that minimal blockage existed between the station and the payload. A tripod-mounted Yagi antenna was set up and pointed roughly in the direction of the university.

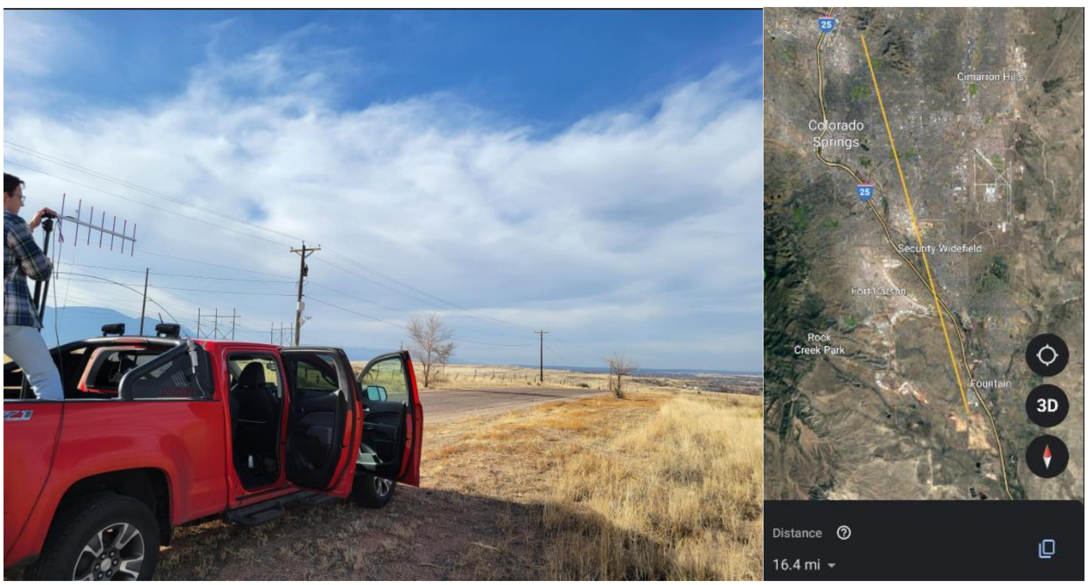


Figure 8: Left: Mobile ground station configured with Yagi antenna. Right: Distance measurement of long-range comms test.

During the drive, communication was intermittent. This was likely due to the significant number of obstructions between the station and the payload (hills, buildings, etc.). Once the station was configured with the high gain antenna, communications were consistent even with direct obstructions consisting of a natural ridge and light foliage. This test determined that, during flight conditions, line of sight will be guaranteed, and that the payload will be able to communicate with the ground station for most of, if not the entire duration of flight.

Structural Testing Methods and Results

There were multiple tests that were performed on each design structure to verify the integrity of the structure and the adhesives holding it together. These tests were dropped testing, whip testing, cold testing, and pitch testing. These tests were intended to simulate the scenarios that the payload would encounter during the flight. Before these tests were conducted, simulation components were installed around the structure in the locations where flight ready components would be installed.

Drop Testing:

During the drop testing, the payload was dropped from approximately 20ft in elevation onto concrete. To conduct this test, the balcony attached to the Osborne building at the University of Colorado, Colorado Springs was used. This test simulated the impact that the payload would encounter during landing and verified that the structure and connection methods used could withstand this impact. For this test all the conceptual designs were used.

The first structure evaluated was the PETG 3D printed design. This structure failed this test as the location where the structure was screwed together snapped upon impact which can be seen in Figure 8 below. Due to this, this design was no longer being considered as it was determined that this design was not capable of withstanding the flight even with heavy modification.

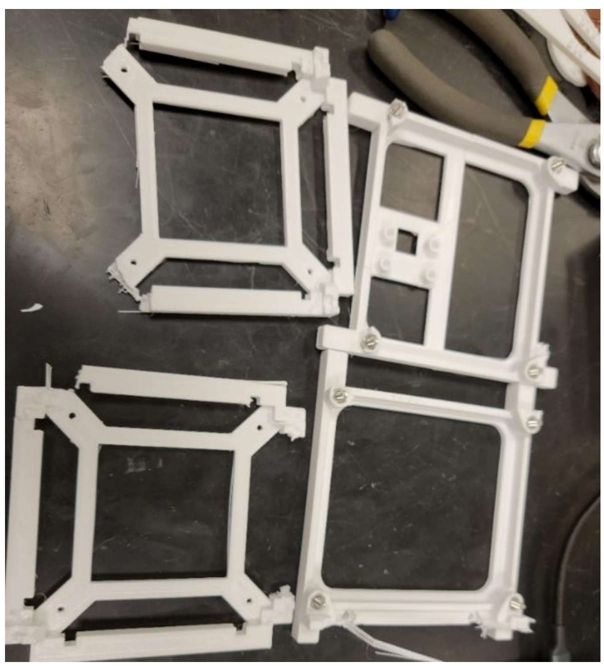


Figure 9: PETG 3D Printed Structure Following Drop Test

The second structure to be drop tested was the foam core and plexiglass design. This design did survive drop testing, however, the plexiglass on the bottom of the structure did crack upon impact which can be seen in Figure 10 below.

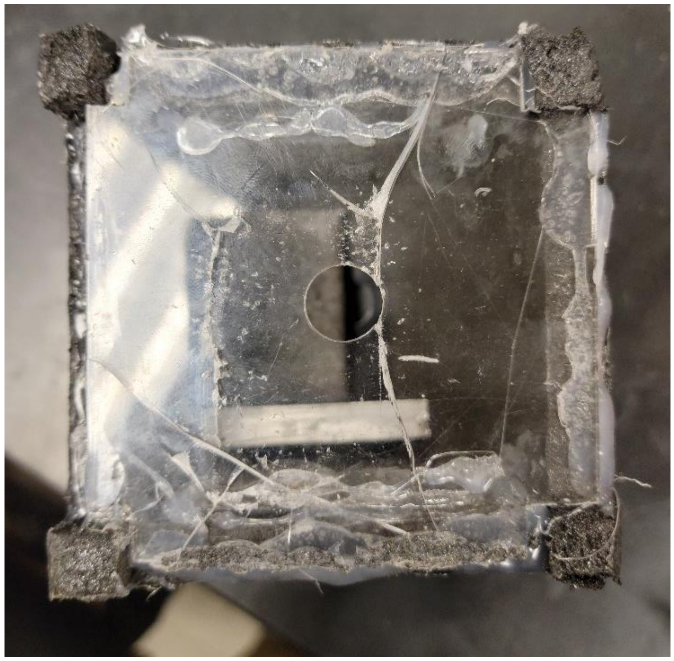


Figure 10: Foam Core and Plexiglass Design Following Drop Test

The final structure to be drop tested was the foam core cube connected with 45º angles. This structure was superior to the other two designs drop evaluated with the only damage being that the corner of the structure where impact occurred was crumpled. Seen in Figure 11 below.

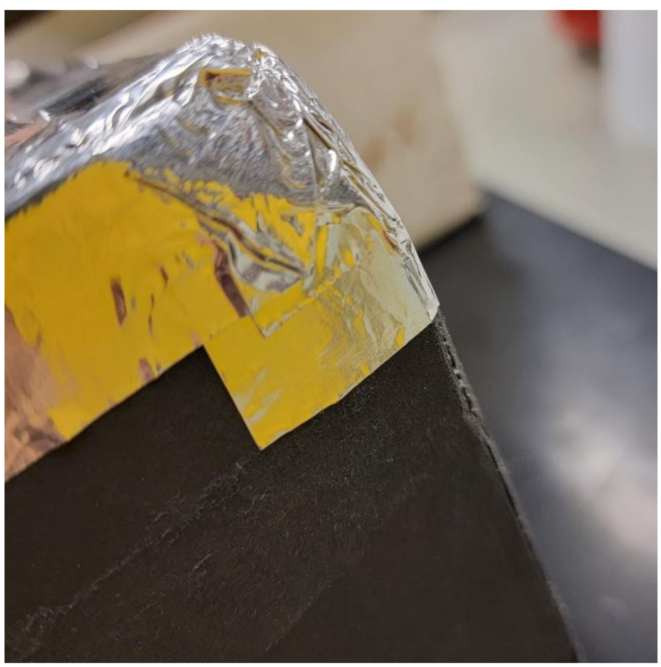


Figure 11: Foam Core Cube Connected with 45º Angles.

Following this test, the PETG 3D printed structure was ruled out as it was not able to survive the drop test. The foam core and plexiglass design were allowed to move onto following testing with the cracked plexiglass as it was still intact.

Cold Testing, Structural:

During the cold test, the payload designs were placed in a –80ºC freezer with a thermometer placed inside and was allowed to sit for 2 hours. The freezer used was found inside the biology lab found inside of the Centennial building at the University of Colorado, Colorado Springs. This test simulated extremely cold temperatures, which would exceed the temperature that the payload would encounter at the extremely high elevations it would reach. This test primarily ensured that the interior of the structure was able to maintain enough internal temperature to allow for the electronics and batteries to maintain function. This test also made sure that the structure materials and adhesive used could withstand these temperatures and would keep everything secure during the flight. For this test only the foam core and plexiglass design and foam core cube were evaluated.

The first design that was cold tested was the foam core and plexiglass design. This design had no issues with the materials used as the plexiglass, foam core, and hot glue were all intact with no noticeable issues following the test. However, this design did not provide good insulation as the internal temperature reached -68ºC after being in the freezer for 2 hours. This would be too cold or the electronics and batteries inside to properly work. This is most likely due to the plexiglass lid and bottom not providing much insulation to the interior.

The second design that was cold tested was the foam core cube. This design also had no issues with the materials used as the foam core and hot glue were all intact with no noticeable issues following the test. This design, however, was superior to the foam core and plexiglass design as it provided significantly better insulation as the internal temperature on reached -42ºC after being in the freezer for 2 hours. This, while still being extremely cold, would still allow for the electronics and batteries inside to be able to work. This was most likely due to the entire structure being made from thick foam core all around which allowed for significantly more internal temperature kept.

After this test, the foam core and plexiglass design were ruled out as it did not provide enough insulation to the interior electronics and batteries. This left only the foam core cube design to move onto following testing.

Whip and Pitch Testing:

The whip and pitch tests were conducted together as the main purpose of these tests were to validate that the internal components would remain secure. To secure components to the structure, PLA printed mounts were made for all components and secured to the structure using cold temperature rated hot glue. During the whip test, a string like the flight string used to connect the payload to the high-altitude weather balloon was connected to the structure with 4ft of excess string. Using the excess string, the structure was swung as fast as possible**,** then the direction of the spin was abruptly switched. This was repeated two times. This test simulated abrupt rotation caused by the popping of the high-altitude weather balloon once it reached its peak elevation and verified that the structure and adhesive used could withstand this intense rotation. During the pitch test, the payload was rolled down two flights of concrete stairs. The concrete stairs used for this test were the stairs between the third and fourth floor of the Osborne building at the University of Colorado, Colorado Springs. This simulated the situation where after landing the wind dragged the payloads along the ground and verified that the structure and adhesive used were capable of withstanding this dragging motion. The only design used for this test was the foam core cube design.

Upon completion of these tests, the structure was opened to verify that the internal components were still intact and secure which can be seen in Figure 12 below. All components were still securely connected to the structure demonstrating no issues with the securing methods. All wires attached between test components were also still intact verifying that the connections between components survived with no issues.

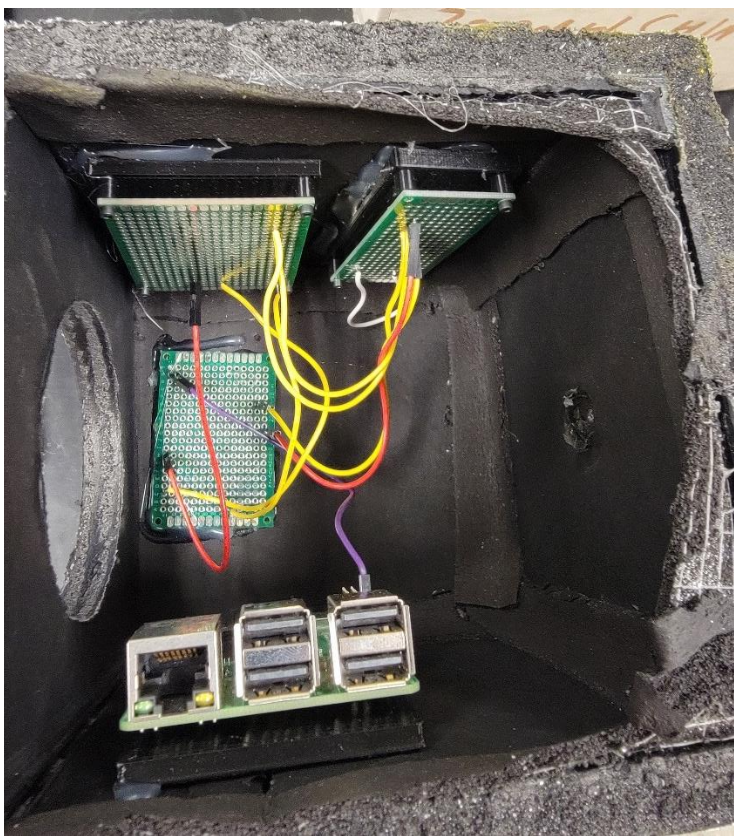


Figure 12: Foam Core Cube Design Following Whip and Pitch Tests

Final Design

Mission

The Finalized mission was, Mission 2: Telemetry and Communications Demonstration. This mission was decided before any testing of the electrical system was done due to not knowing what hardware was needed to successfully complete the mission. This mission had to be chosen because this was the only requirement given to the team from AMERGINT. No other mission was chosen due to either it being too much extra weight or the execution of the mission being too complicated to demonstrate in a 2–3-hour flight.

Electrical

A complete circuit diagram can be found in Appendix B.

Main Computer

The primary computer system chosen for the payload was a raspberry pi 4 model B 2Gb. This device was chosen due to the massive amount of computing power, ease of integration, and large catalog of open-source software. This device served as the only major piece of control hardware onboard the payload.

A full-operating system, Raspbian, was installed on the device. The operating system is manufacturer recommended for the raspberry pi and is a feature-complete port of the Debian distribution of Linux. Running an operating system significantly simplified the development of software and flight operations for the payload. The next major software component was DIREWOLF, an open-source packet modem and virtual 'soundcard' implementing AX.25 v2.2. This package manages the encoding and decoding of digital information to and from an audio signal, like a dial-up modem. DIREWOLF was configured to communicate at 2400 baud using phase-shift keying (PSK) and with forward error correction enabled.

An open-source program, TNCAttach, was used to connect DIREWOLF to the operating system as a standard network interface. This allows for data communications as if the payload was a TCP/IP device operating on a local area network. A LightTPD web server was installed on the device to facilitate data transfer, with a simple PHP file allowing for image and sensor data to be loaded on a web page.

In addition to the web page, a method of direct command was developed to interact with the payload. This program allowed for an 'echo' test (like a ping test), on-demand sensor data downlink, text message relaying, and a shutdown command. FastCGI was used to allow this program to interface with the web server during flight operations.

Simple Python scripts were written to facilitate sensor and image data acquisition, storage, and retrieval. Sensors were polled at 1 Hz, while images were taken at 10 second intervals. While full-resolution images were taken and saved locally, transmitted image data was downscaled before being downlinked.

A final set of programs were written in python to initially configure the communications equipment. This software also runs automated processes for certain equipment during the flight.

Sensor Package

Based on the chosen mission profile, sensors that describe the status of the payload and especially the power system were prioritized. A summary of sensors used can be found in table 2.

Table 2: Summary of included sensors.

Name	Measurement	Interface	Notes
INA219	Voltage	I2C	Measures voltage at battery pack
BME280	Altitude, Humidity, Internal Temperature	I2C	Onboard altimeter and primary internal temperature sensor
DS18B20	External Temperature	1W	External temperature probe
BCM2711	CPU Temperature	Proprietary	Built-in temperature probe on Pi CPU
Pi-Cam	Visual	Proprietary	External Camera

Sensors were connected directly to the raspberry pi using their respective interfaces, with I2C data and clock routed through the power/data bus board. The Pi-Cam and DS18B20 were attached externally, while the remainder of the sensors were attached along the internal surface of the structure.

Communications

Two communications platforms were implemented: an OTS transceiver chip DRA818, and an OTS automatic APRS beacon BigRedBee.

The BigRedBee is a community sourced APRS transmitter designed specifically for applications like high altitude balloon missions. The system was powered by the main power system and interfaced to the computer using USB. The beacon was configured to automatically transmit GPS coordinates, internal temperature, external temperature, and battery voltage every 5 minutes. The beacon was only capable of sending APRS packets and could only be controlled through the main computer. The beacon operated on the 144.39 MHz band using standard APRS protocols at 1 W transmit power.

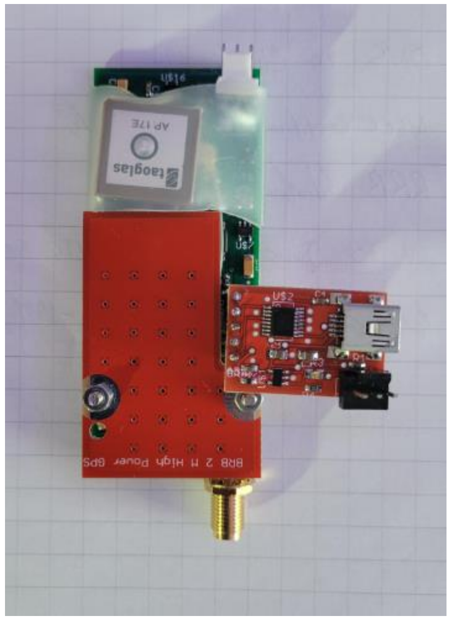


Figure 13: BigRedBee APRS Beacon

The DRA818 was integrated with a specific circuit board that included LED indicators for power, Push-To-Talk enable, and receive enable. The device had a dedicated buck converter for power, fed directly off the main batteries. A single LCFN-400+ low pass filter was connected to the output of the chip. Initial configuration of the DRA818 was done over a UART interface from the raspberry pi GPIO. Squelch, power enable, and push to talk were also controlled via the raspberry pi GPIO. The audio in and out lines were connected to an OTS USB digital to analog converter connected to the raspberry pi. The transceiver operated on 441.00 MHz band using DIREWOLF and the software described above at 1 W transmit power.

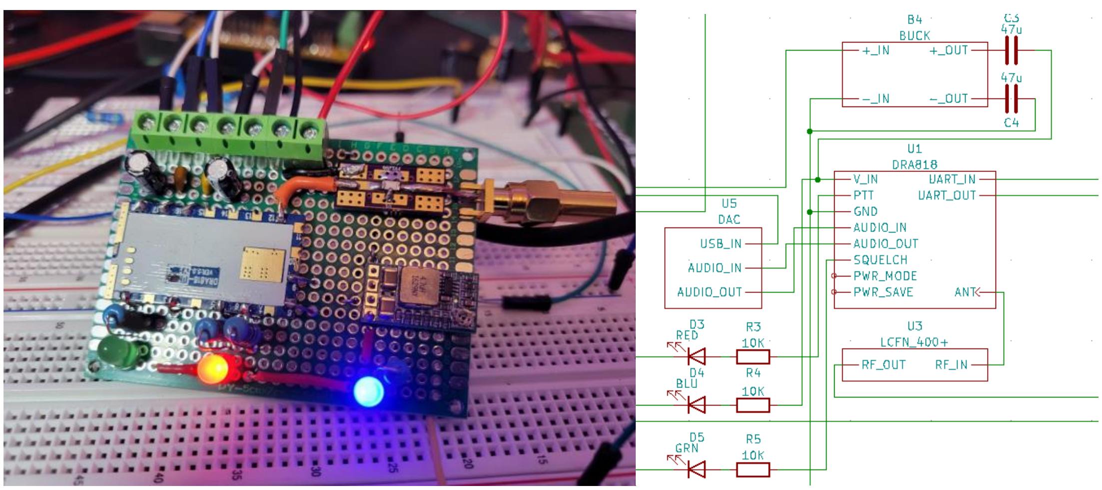


Figure 14: Left: Assembled & powered up transceiver board. Right: Circuit diagram of transceiver board

To simplify the antenna design, a J-pole antenna was selected. The antenna was custom-cut in the 'Slim Jim' configuration to ensure that the ½ - ¼ relationship in the antenna wire length matched the UHF and VHF frequencies selected. Both the UHF and VHF systems were diplexed into the single antenna, which then would hang below the payload during flight.

The mobile ground station was mounted in a team member's truck. The system was built around a Kenwood TM-D710G dual-band transceiver tied to a laptop running DIREWOLF and the ground-station component of the above software. Two antenna systems were used: whip antennas mounted to the roof of the truck, and a manually aimed Yagi. The Yagi required for the truck to be stationary, while the whip antennas could be utilized while the truck was moving.

Power System

Based on both initial power budget calculations and the electrical freezer test, a main battery component consisting of four 18650 lithium-ion cells in a 2-parallel, 2-series (2P-2S) configuration was selected. At sea level and room temperature, the batteries provided 10.4 amp-hours of current at a nominal 7.2 V. The batteries were connected directly to the transceiver board described above and separate integrated power/data bus board. The only protective device included was an external single-pole, single-throw toggle switch breaking connection with the batteries at the positive terminal.

Solar power was determined to be not worth implementing, owing to the large internal volume of the final structure and simplicity of a battery-only solution.

The power/data bus board consisted of three DC-DC buck converters, an indicator LED, smoothing capacitors, and four breakaway buses: +5 V, GND, I2C-DATA, and I2C-CLK. The power rails on the breakaways were connected to the first buck converter and provided power to all sensors and the computer. An additional buck converter was configured specifically to power the BigRedBee at 5.5 V.

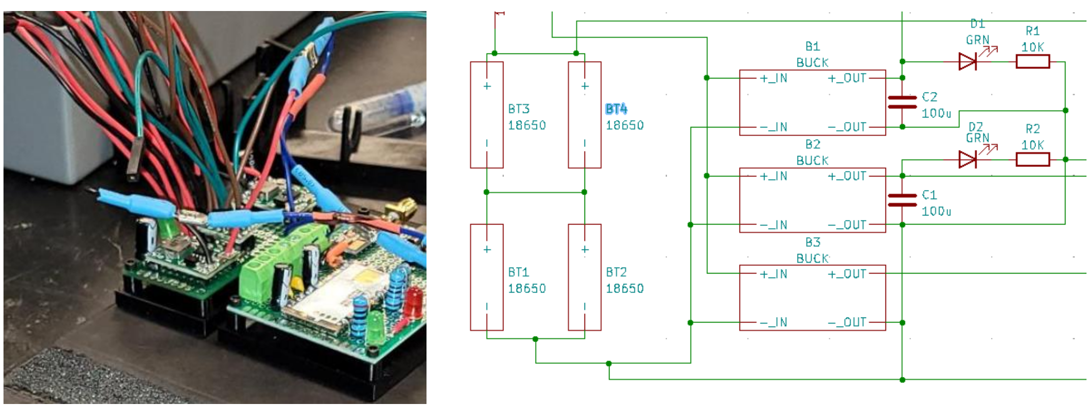


Figure 15: Left: Assembled power/data bus board. Right: Circuit diagram of power section of power/data bus board with batteries.

In addition to a dedicated buck converter, the startup process of the beacon required complete power isolation. A 3.3 V relay was added for this purpose, controlled via the raspberry pi GPIO and coil current supplied from a third buck converter at 2.2 V. The input sides of all three converters were connected to the battery pack.

DC-DC converters were utilized extensively, as they provide excellent voltage regulation and efficiency. Switching converters, however, typically generate high-frequency noise undesirable for sensitive RF equipment. To rectify this, smoothing capacitors were utilized where necessary. In addition, each sensor, communications device, and the main computer have built-in linear regulators, further improving the quality of power delivered.

Structure

The final design chosen for the structure was the foam core cube design. This design was chosen due to it being superior to the PETG 3D printed and foam core and plexiglass design in both drop and cold testing. This design also passed the whip and pitch testing without any issues.

This design utilized a 48inX24in sheet of ½ inch black foam core board which was cut into 6 150mmX150mm section. The reason black foam core was chosen was so that it would absorb significantly more heat from radiation from the sun than lighter color foam core. Once the foam core was cut to size, a 45^{o} angle cutting tool was used to cut 45^{o} angles onto all sides of each section which can be seen in Figure 16 below. Once this was complete, two of the sections would have a 12.5mm diameter hole drilled into the center of the section. These two sections would be the top and the bottom of the structure.

Figure 16: Foam Core Section with 45^{o} angle cut into it.

To mount all electrical components to the foam core sections, mounts for each component were designed in SOLIDWORKS after taking measurements of each component. The mounts were then printed using a 1kg spool of PLA filament. The mounts designed for the Raspberry Pi 4 and batteries can be seen in Figures 17 and 18 below (Mounts for all other components and drawings of each mount can be found inside of Appendix A).

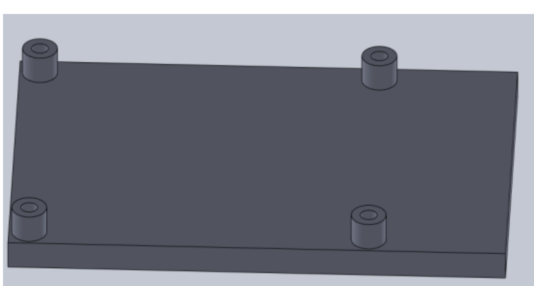


Figure 17: Raspberry Pi4 Mount Model

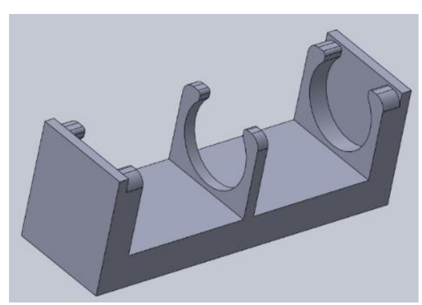


Figure 18: Battery Mount Model

Once mounts for all of the electrical components were made, the mounts that held circuit boards were screwed together using 10mm length M2 screws and 5mm M2 nuts and the batteries were clipped into their mounts. The foam core sections were then laid out in a grid pattern and electrical components began being connected which can be seen in Figure 19 below.

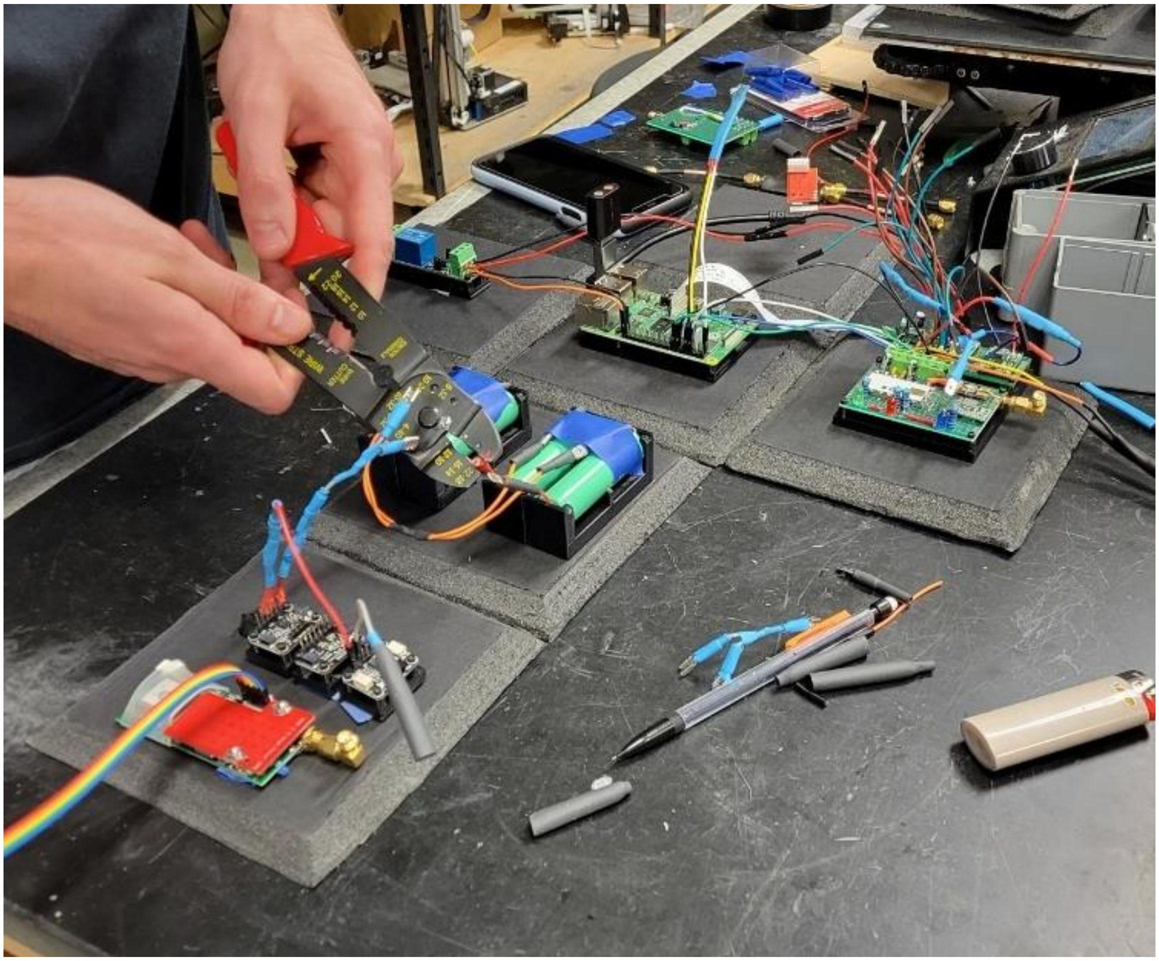
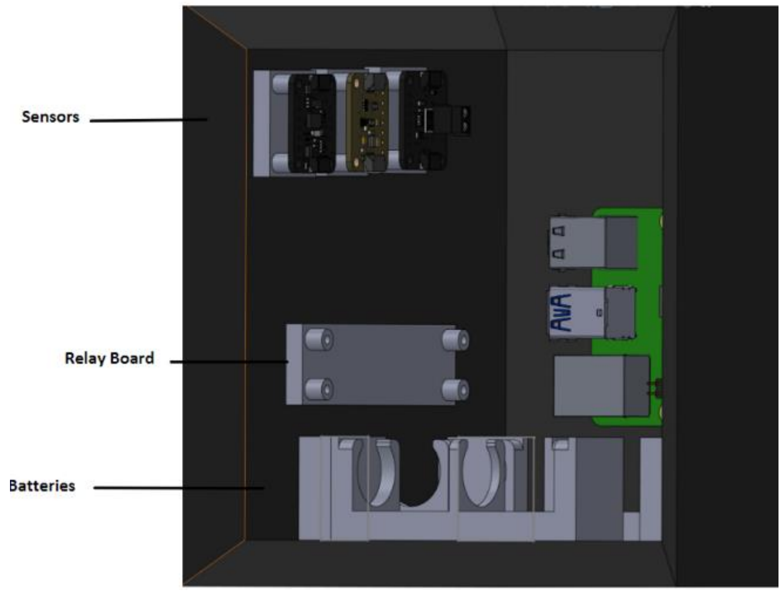
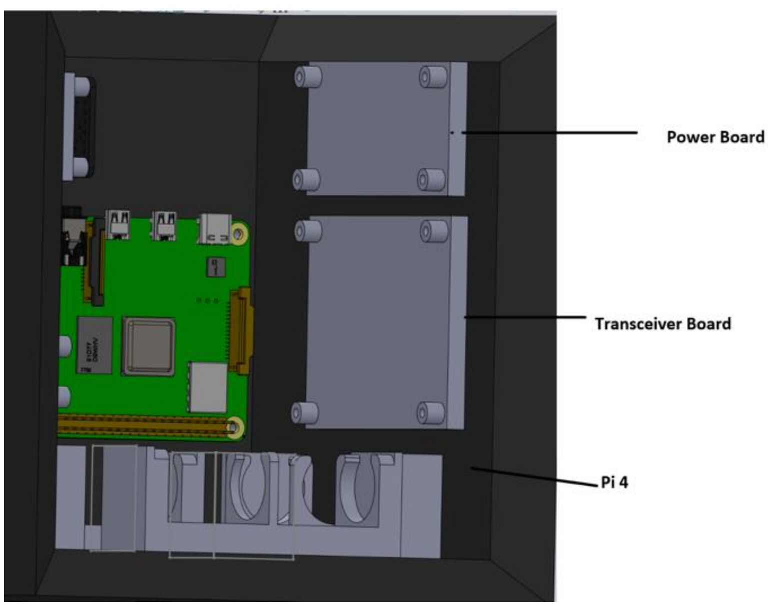


Figure 19: Components Being Attached to Foam Core Sections

Once all the electrical components were connected, the mounts were then adhered to their designated locations within the structure which can be seen in the model in Figures 20 and 21 below.



Figures 20: Component Mounting Locations in Model



Figures 21: Component Mounting Locations in Model Continued

Once each component was adhered to their designated location within the structure, the structure was assembled in the shape of a cube and held together temporarily using a roll of painter's tape which can be seen in Figure 22 below.

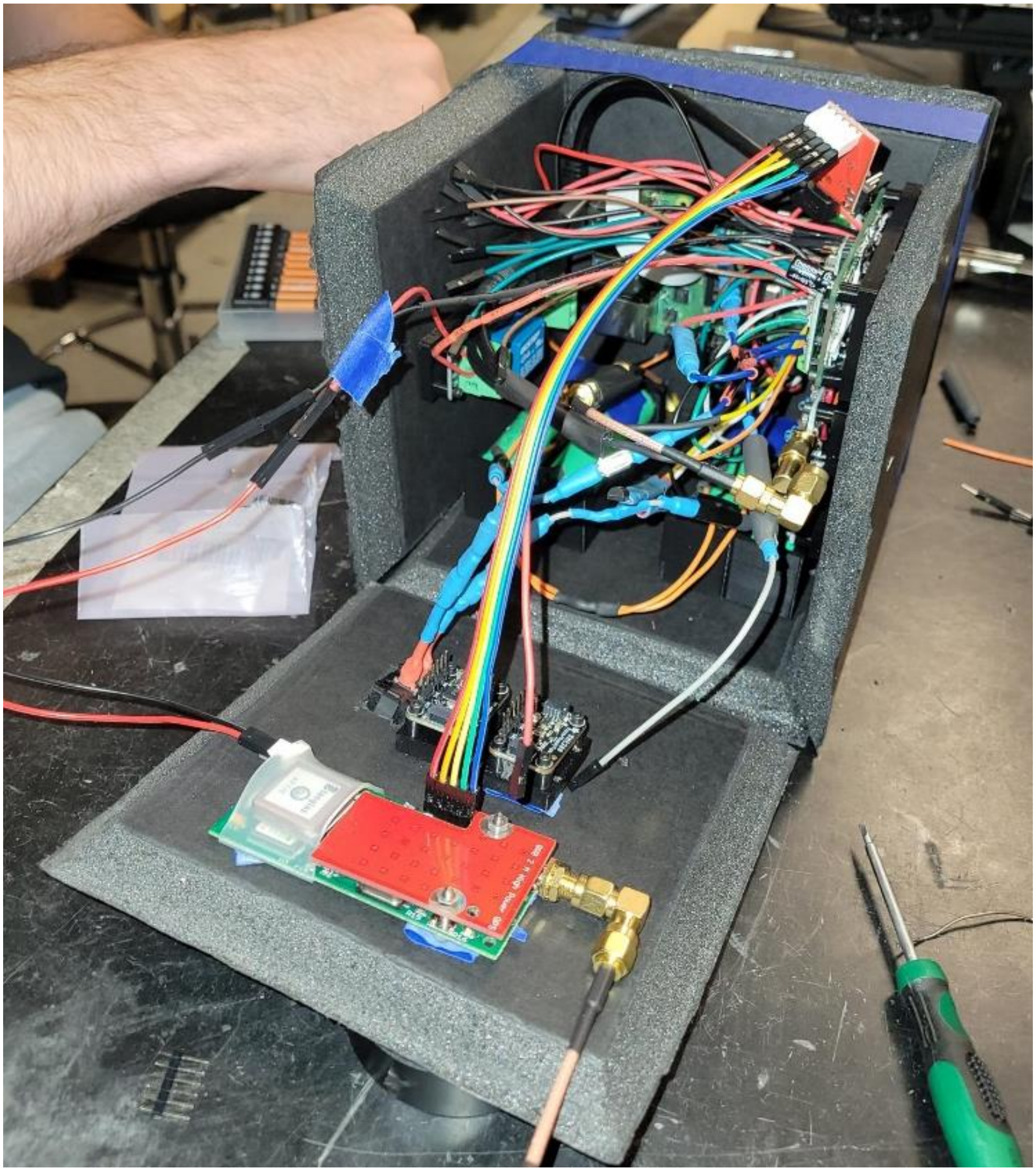


Figure 22: Structure Held Together with Painter's Tape

Carefully with one section off at a time, four sticks of hot glue were used to adhere each section of the foam core to the other section. ½ inch washers were then adhered around the hole drilled into the top and bottom sections of foam core. Carefully, a 1ft long section of ½ inch opaque plastic tubing was inserted into the holes drilled into the top and bottom sections of the foam core. The tubing was held in place using a paperclip at both the top and bottom. Finally, aluminum tape was wrapped around every corner of the structure. The final assembly and its weight can be seen in Figures 23.

Figure 23: Final Assembly and Weight of Payload

Concept of Operations

The CONOPS diagram seen in Figure 1 below walks through how the payload should function throughout the duration of a successful mission. In step 1, the balloon is launched with the power on. This is activated by an external switch. This then activates all the sub-systems inside the payload as seen in step 2. In step 3, the sensor package starts to gather data such as temperature, voltage, and pictures. This data is pulled in repetitive intervals so that memory and power can be conserved. In step 4, the data retrieved is then sent to storage and then step 5 pulls the data to begin a downlink. In step 6, data moves from the control package to the comms package and the data is injected. In step 7, that data is then broadcast down to the ground station. A loop starting at step 3 and going to step 7 is maintained until the payload is powered off. This provides a steady flow of data collecting and downlink. To maintain a viable connection for downlink capabilities during flight, the ground station must follow the balloon. After the mission is complete, the payload is powered off.

CONOPS Diagram

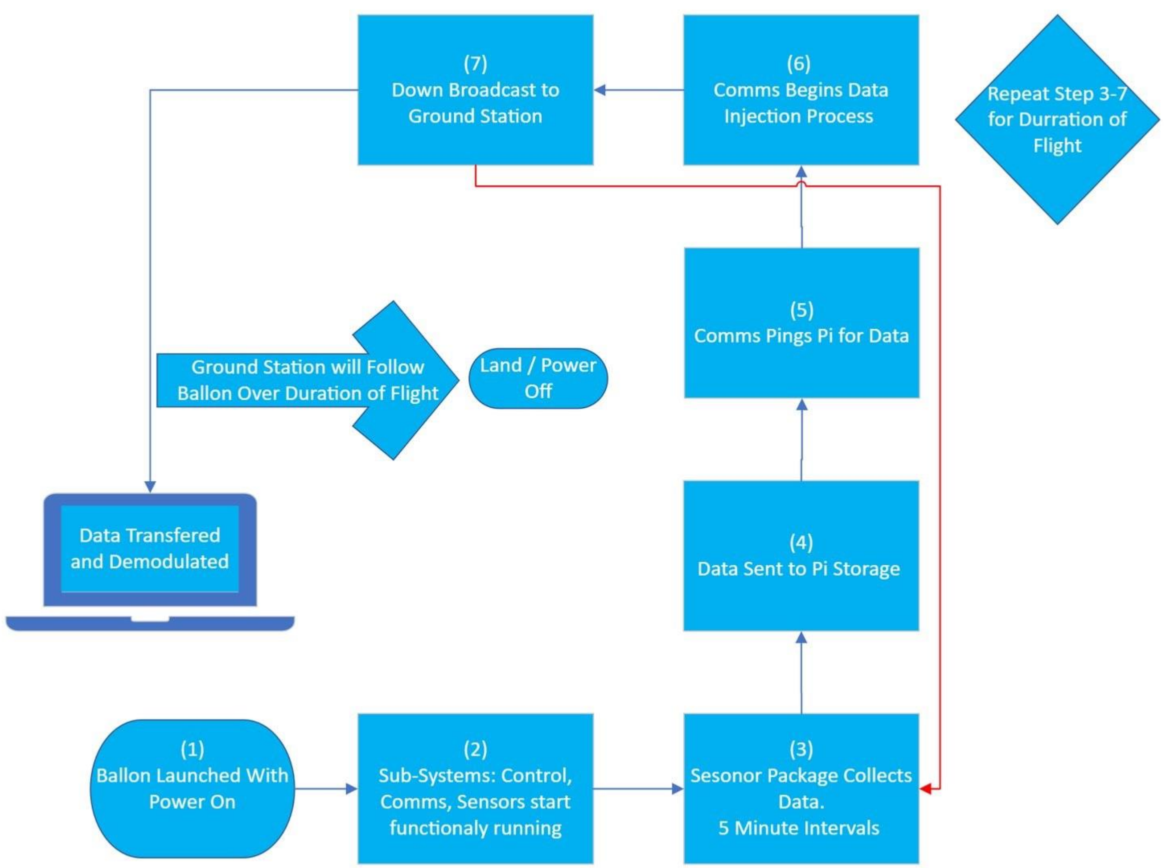


Figure 24: Concept of Operations (CONOPS) Diagram

System Block Definitions Diagram

The external system diagram seen in Figure 2 below illustrates the hierarchy of subsystems that make up the mission environment. Everything that is responsible for the mission to be conducted is attached to the high-altitude balloon. Attached to the balloon then is the DemoSat system and the system is made up of payload. The payload is then made up of 4 main branches: structural, power, control, and comms. Structure is then further connected to thermal. Power is connected to both control and comms along with their remaining subsections also. Control consists of the sensor package and the storage for the data. Comms consists of telemetry hardware and the down broadcast information. Control and comms are both connected as well.

External System Diagram

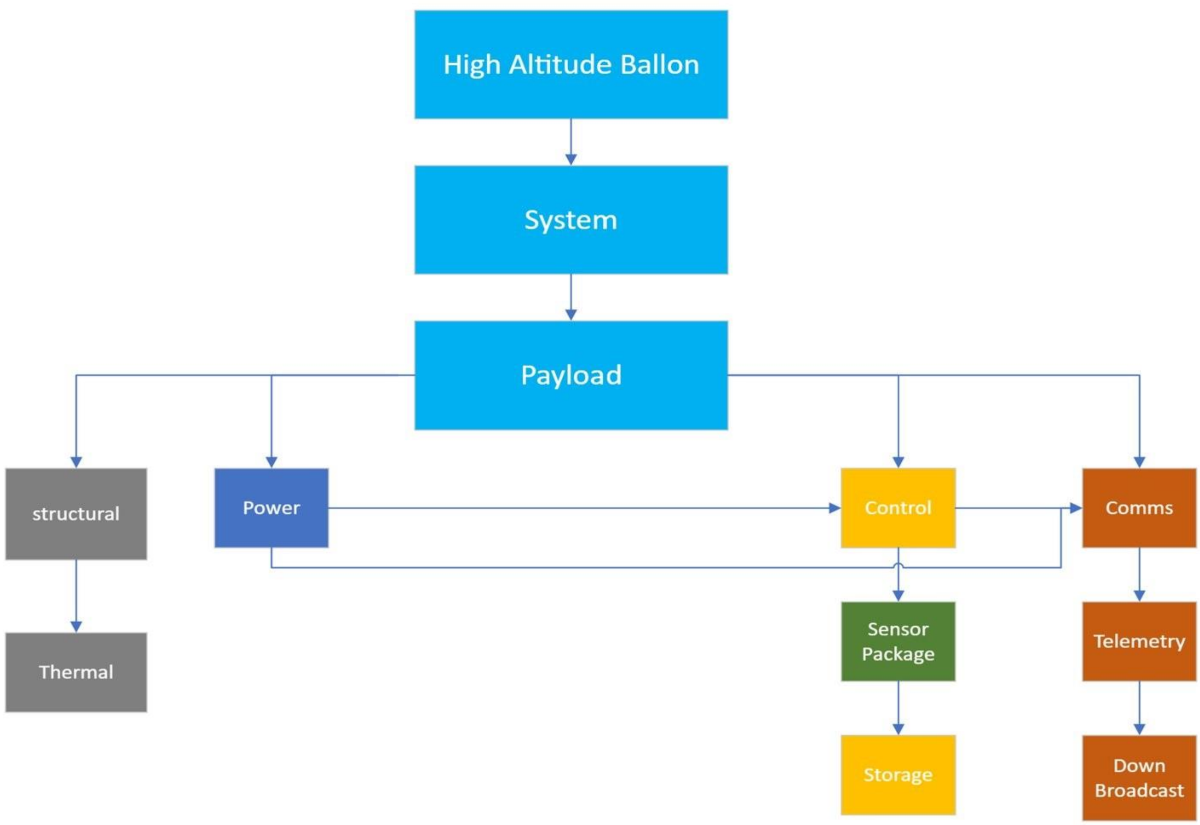


Figure 25: External System Diagram

The internal system diagram seen in Figure 3 below provides a view of how the different subsystems within the payload are connected. Starting with the power button, which is connected to the battery pack and that power is sent to a buck converter. The buck converter then goes to the sensors, Raspberry Pi, and the transmitter. This allows all 5 sensors and the Pi camera to gather data. That data is then directed into the storage system managed by the control system. That data is then pulled by the control system and sent to the comms system for data injection. Is it then sent to the transmitter and relayed to the ground station. The comms system also has a digital on/off switch onboard.

Internal System Diagram

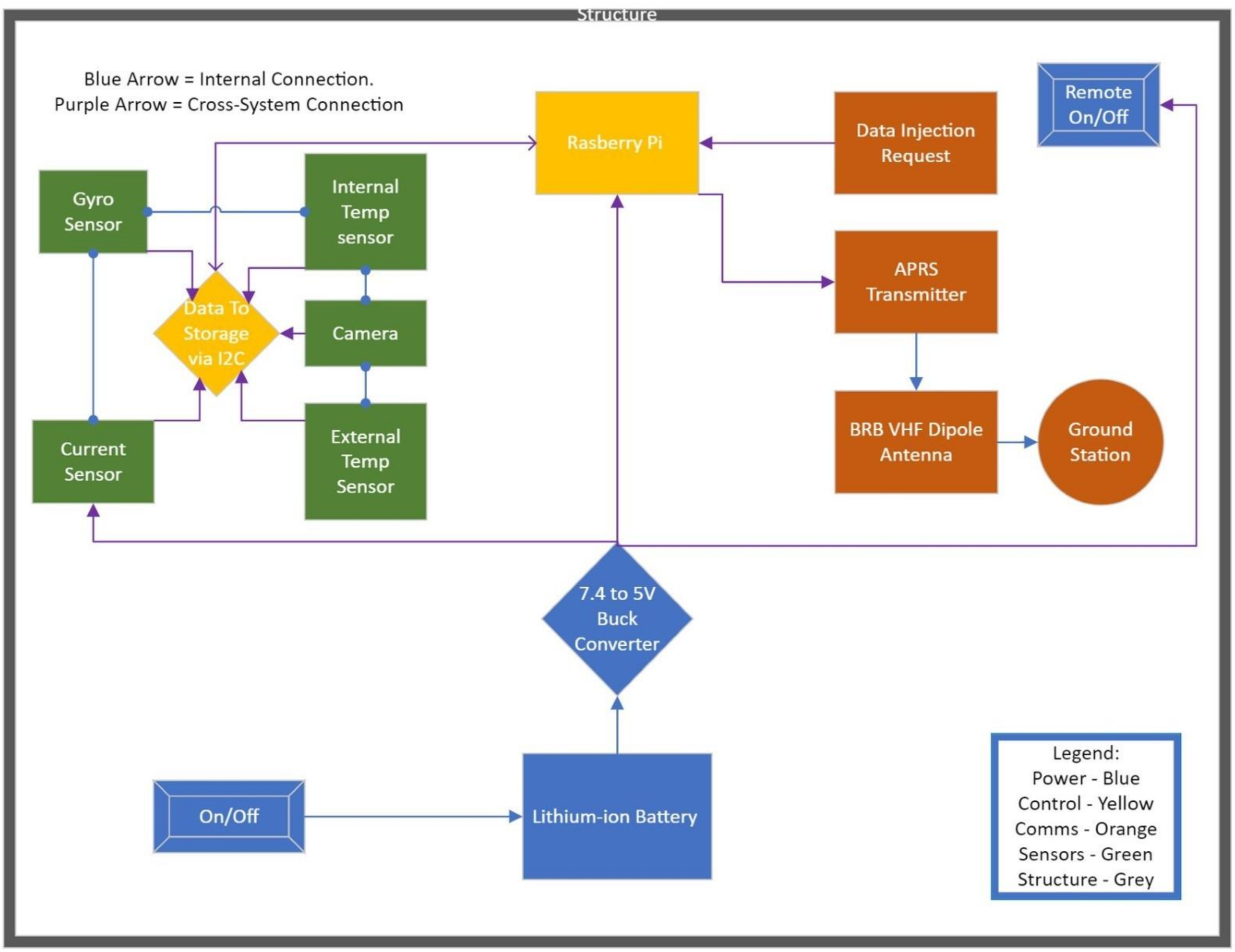


Figure 26: Internal System Diagram

The functional system diagram seen in Figure 4 below serves as a visual to depict how the transfer of information is conducted across the different subsystems to complete the mission objectives. Like the other views, the power source is applied to the entire system. The power applied to the control system is then used to communicate with the sensors and camera. Each one of those data mediums is then incrementally written to a respective file via the Raspberry Pi for data storage.

While the data is being collected and stored, the transmitter and comms system pings the Raspberry Pi with a command to request data. The Raspberry Pi then sends back a command for approval and the data injection is conducted. The data pull is then carried through the transmitter and on to the antenna where the down broadcast takes place. The destination for this data is then the ground station.

The ground station works as a relay as seen in the diagram being able to downlink and uplink information. Uplinked information was completed by having the antenna and transmitter connected to the DIREWOLF software modem via the Raspberry Pi control system.

Functional System Diagram

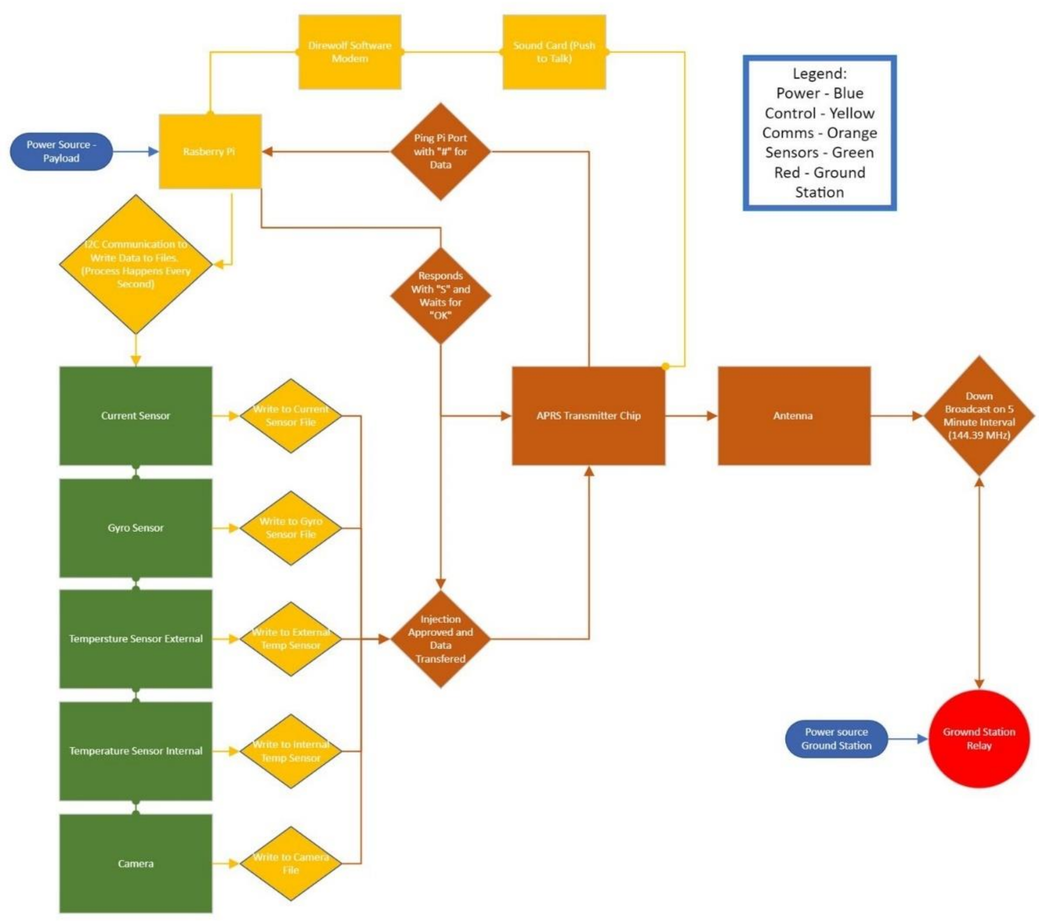


Figure 27: Functional System Diagram

Flight Results

The location for flight lift-off was Deer Trail Colorado at 7 am the day of April 1st, 2023. The 3,000-gallon (hydrogen) balloon carried multiple student payloads from different institutions. The high-altitude balloon reached 107,835 feet and landed in the Stratton Colorado area. Travel time was 2 hours, 18 minutes.

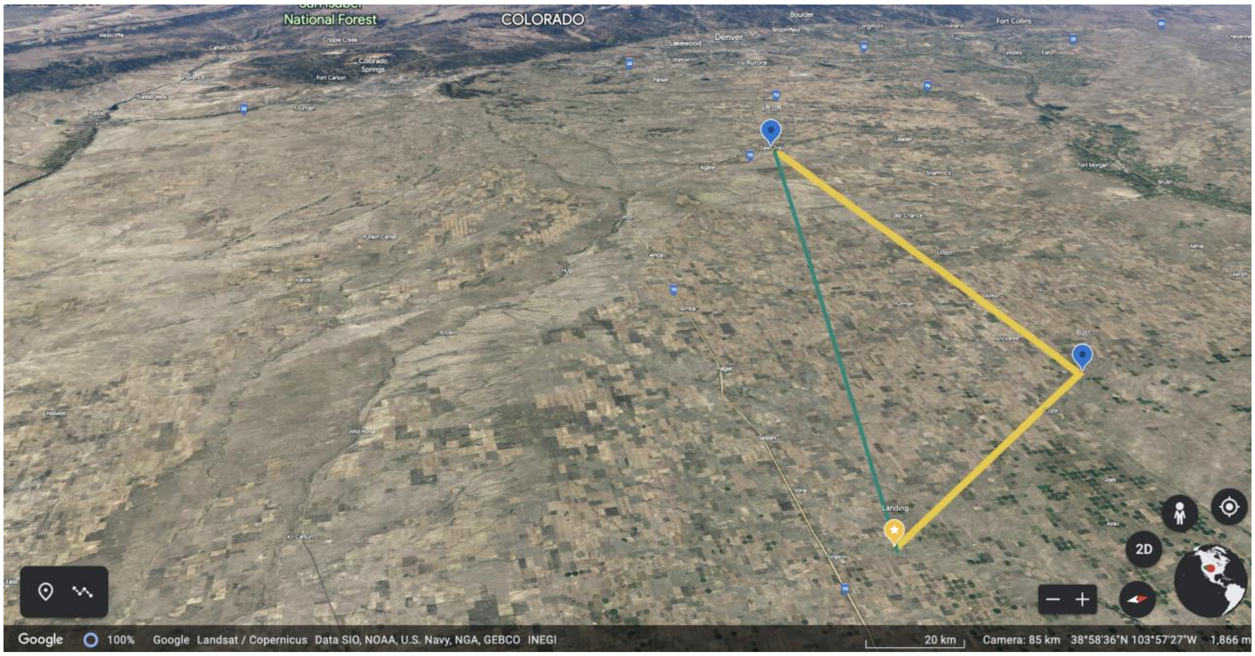


Figure 28: yellow line from Deer Trail CO. line shows the trajectory of the balloon to its final location in Stratton CO. (Image/data provided by Edge of Space Science and Google Earth)

Environmental factors guided the team to successfully implement a design to survive the conditions. The sensor package captures these environmental factors to support the survival of the payload. The data collected from the SD card onboard the Raspberry Pi 4 was analyzed. The temperature specification that the team was given was -40℃, and the trajectory took the payload to only to a low external temperature of -31.6℃. The image bellow also shows the lowest internal temperature of -13℃. The electrical components produced a small amount of heat during flight that allowed the system to stay functional. The insulation properties of foam core were enough to keep internal temperature from lowering any further than most electronics were rated for. Internal temperature was the most crucial to electrical system and the lowest temperature occurred before 1 hour had passed.

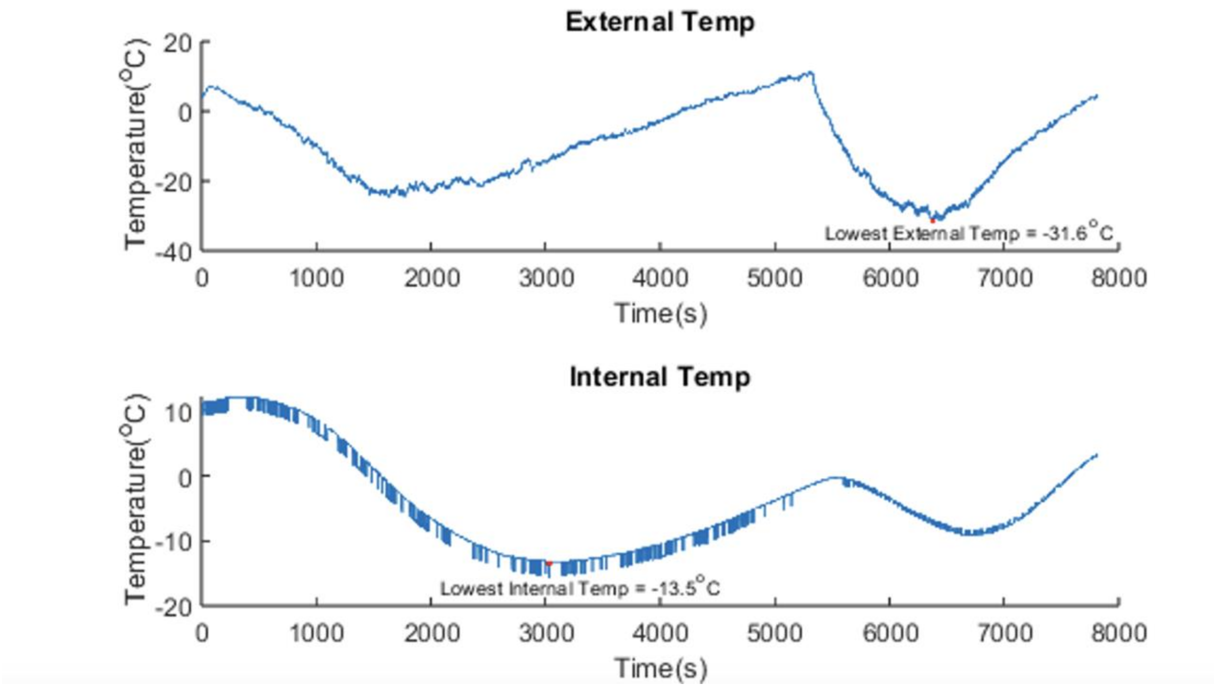


Figure 29: External and internal temperature noted minimum.

The voltage sensor gave a visual of the non-linearity of discharge from the lithium-ion batteries most likely due to temperature and dragging movement of payload. Batteries show stability during the 5000 second mark that is also the time of highest altitude, which is also the most serene in terms of movement. It can be determined that the batteries became stable in terms of chemical reaction and most likely the system was the most stable. The final voltage drop of batteries was 0.51 Volts. This power budget would have allowed the payload to run for significantly longer than the flown mission.

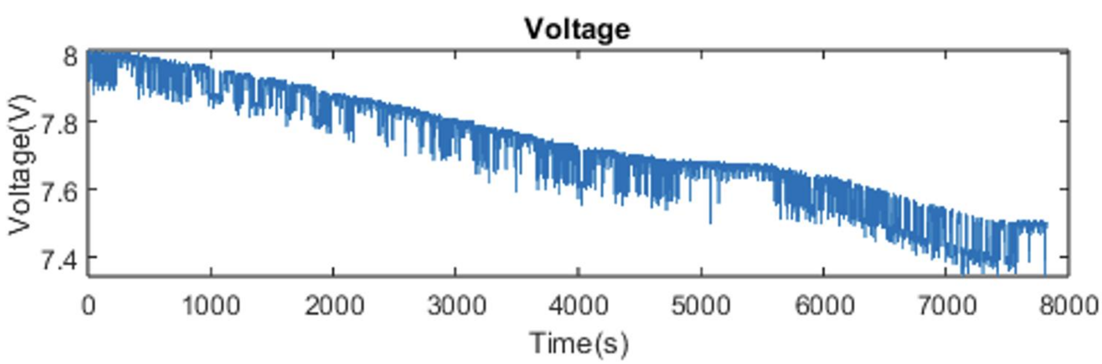


Figure 30: Voltage drop during flight.

The testing of low power data links was achieved with the final low effective isotropic radiated power (EIRP) of 80mW from antenna. System echoes were received, and system data downlinked on-demand throughout the flight. Seven photographs were also transmitted (again, on-demand) during the flight, the last one broadcasted at near maximum altitude shortly before balloon burst.

Primary datalink was accomplished using the UHF system, which performed as expected. The VHF system proved less reliable. Data was initially received once during preflight and once after takeoff. After the 2nd transmission, the balloon had climbed above a few thousand feet AGL and transmissions were no longer received by either the mobile ground station or the greater APRS network (APRS.fi). This would continue until after the payload had landed, when traffic was received by the larger network.

This represents the only major anomaly encountered in-flight. While the primary objective was accomplished via the UHF link, the failure to receive APRS traffic from the beacon meant that the payload itself was not transmitting GPS coordinates. To track the balloon, the team operating the ground station had to rely on separate beacons attached to the balloon operated by the launch provider. These updated less frequently than the 5-minute interval configured at the payload and made manual tracking more difficult.

Because traffic was received without incident before and after the flight, but not during the flight, the beacon likely experienced a failure in maintaining GPS lock. The device requires a good GPS signal before sending a packet; if the balloon were moving too fast, the device might have had trouble measuring its position. This is consistent with early testing, where the BigRedBee would occasionally not acquire GPS and need a reset before properly functioning.

All transmissions followed federal communications commission (FCC) protocols, with a licensed ham radio operator brought on to supervise and operate the communications equipment.

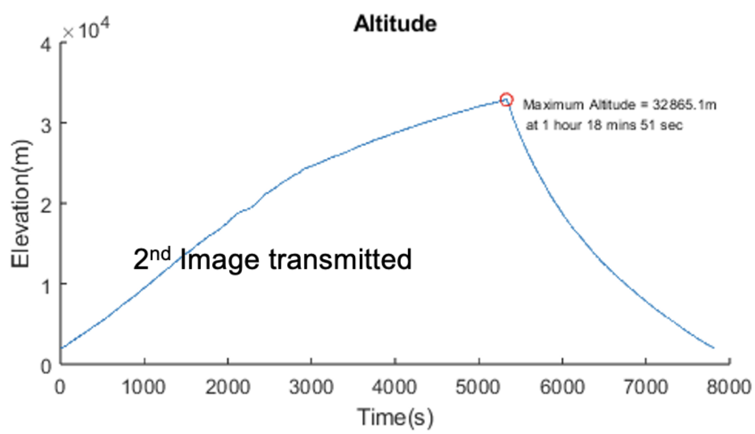


Figure 31: Altitude vs time

1st Image transmitted

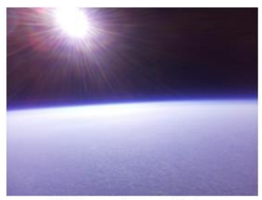
2nd Image transmitted

3rd Image transmitted

4th Image transmitted

5th Image transmitted

6th Image transmitted



7th Image transmitted

Figure 32: Seven images transmitted in real time from payload.

An experiment was performed, and two radio operators were able to relay messages using the payload. The image below shows that about one hour into flight the radio operator was able to send a message to the payload. The message was relayed to another radio operator at a different location, as if both were connected via a LAN. The command line printout at the ground station is shown below, where the message "this is a test message from Caleb…through the high-altitude balloon" was sent to another ham radio operator. The other operator replies, "Hello World!".

```
2023-04-01 07:33:10.237768 - RECEIVED: relay 10.10.10.31: this is a test message from
caleb [redacted] through the high altitude balloon

2023-04-01 07:33:10.238256 - RELAYED TO 10.10.10.31: RELAY FROM 10.10.10.2: THIS IS A
TEST MESSAGE FROM CALEB [redacted] THROUGH THE HIGH ALTITUDE BALLOON

2023-04-01 07:33:10.238378 - SENT: message relayed to 10.10.10.31
2023-04-01 07:35:07.561447 - RECEIVED: echo
2023-04-01 07:35:07.561968 - SENT: echo reply
2023-04-01 07:35:11.896090 - RECEIVED: relay 10.10.10.2: hello world! KX4TH
2023-04-01 07:35:11.896834 - RELAYED TO 10.10.10.2: RELAY FROM 10.10.10.31: HELLO
WORLD! [redacted]

2023-04-01 07:35:11.897184 - SENT: message relayed to 10.10.10.2
```

The payload was recovered structurally intact and with a functional electrical system that can be reused.

Figure 33: Team members at recovery site. Left to right (Caleb, Edward, Lauren, Maxwell, Ian, Alondra, Isaac)

Conclusion

The CubeSat team designed, evaluated, and flew a payload that was able to show reliable and consistent communication from and to a ground station that had a Yagi antenna through a DRA818 transceiver that was mounted in the payload. The only requirement for the project was to be able to communicate with a payload at 120,000 feet in elevation. There were multiple designs for the structure of the but the structures that eventually won out was a 150m cube made all out of foam core due to its impact resistance and its low thermal conductivity. All the mounts for the electrical sensors, power boards and batteries were all 3d printed from PLA. The electrical parts were bolted to the mounts and the mounts were hot glued to the structure, the entire structure was all hot glued together due to it being the strongest and the fastest drying adhesive.

As the flight went very smoothly there are a few considerations if the project was done again. Firstly, is to plan out the wiring for the electrical components as even though there were no problems with the wiring it can get very messy and hard to trouble shoot if there is anything wrong with it such as a short or a wire gets disconnected. Another would be to design a structure after the electrical components are already chosen due to the case needing to be increased in size multiple times to make sure the electrical components can fit. As well with the communication even though the performed as intended it would be much easier if a SDR system was used it would've allowed for precise tuning of transmission parameters to provide the maximum possible throughput and minimum power draw.

Sponsor Interactions

For the duration of the project the meeting with the sponsor was online or in person every two weeks. While communication with the sponsor occurred at least once a week. The main contact Jon Gomez often came to the machine shop to deliver parts for the project and conduct meetings. Email communications happened often mainly pertaining to ordering and receiving parts. The frequency of communication and meetings worked well for the project. AMERGINT supplied all needed resources and supported the team when needed. No issues noted and no changes needed.

Team Interactions

Finally, communication between team members were done using a Discord server and Microsoft teams. Communication was constant throughout the week for questions, problem solving, and assignment adjustments. The team including Caleb Hill, who worked on the project as an independent study, met every Friday to do work in person. Occasionally in person meetings were conducted online, typically in cases of harsh weather. During spring break, the week before launch, the team met every day to assemble and fix any problems that arise.

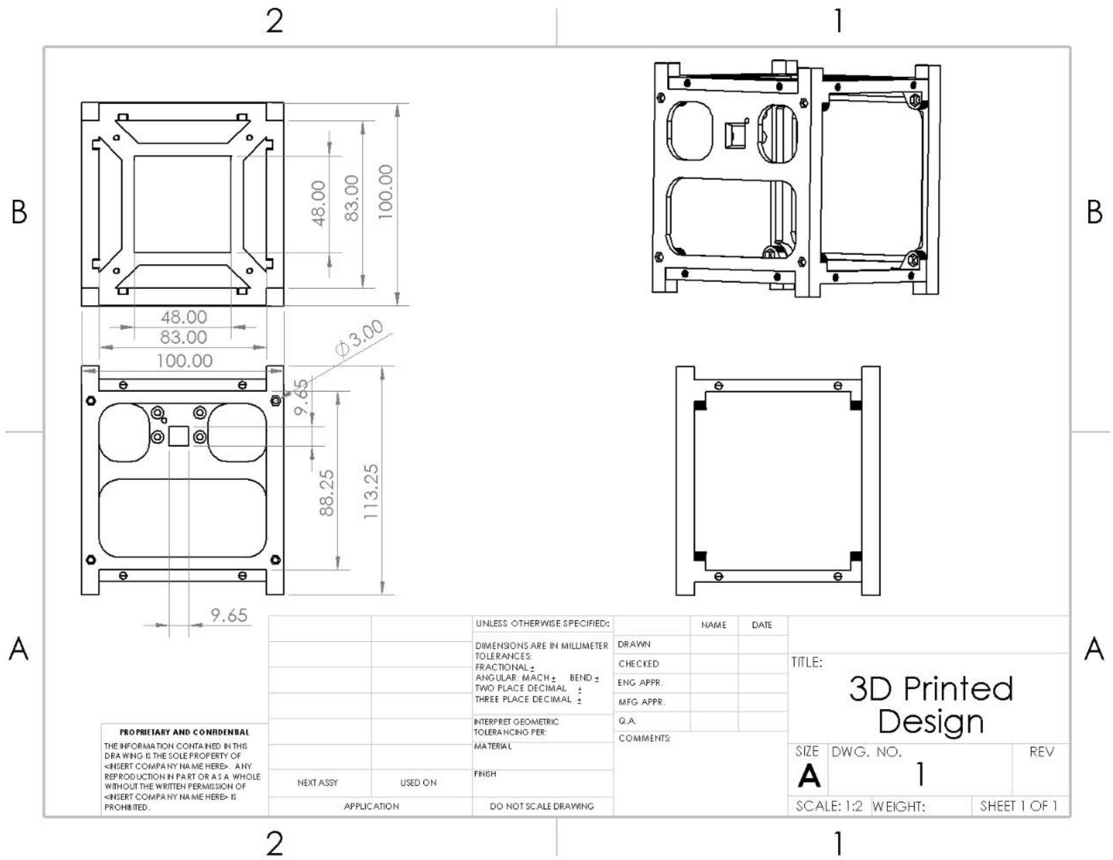
The weekly team meetings were beneficial, it was a day most team members set aside solely for the project. Having a day when everyone could meet made it easy for a lot of work to get done in one day. The frequency of the meetings is something that would not need to be changed if the project were to be restarted but the organization of them would. Meetings would occur but would lack structure. To improve structure a single team member could be appointed to delegate tasks with a more specific schedule. When it comes to communication using two platforms could be confusing at times when information was conveyed on one and not the other.

Appendices

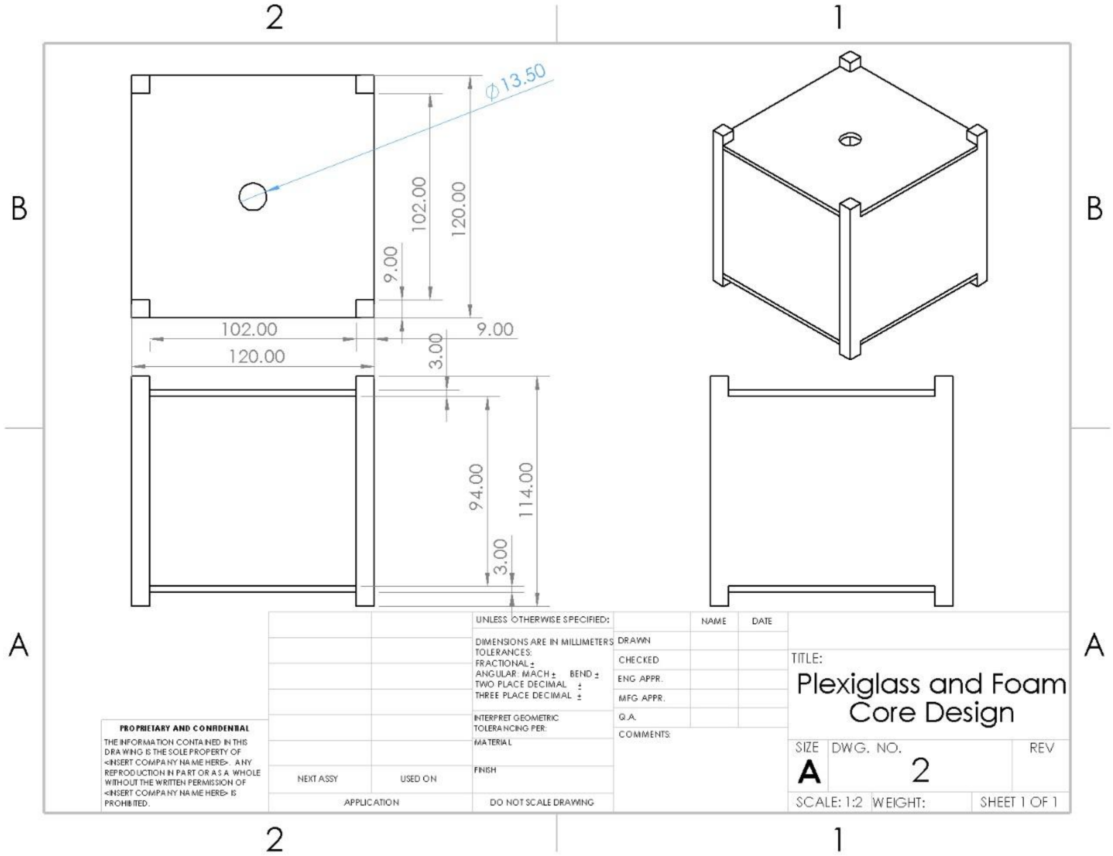
Appendix A – SOLIDWORKS Drawings

Assembly Drawings:

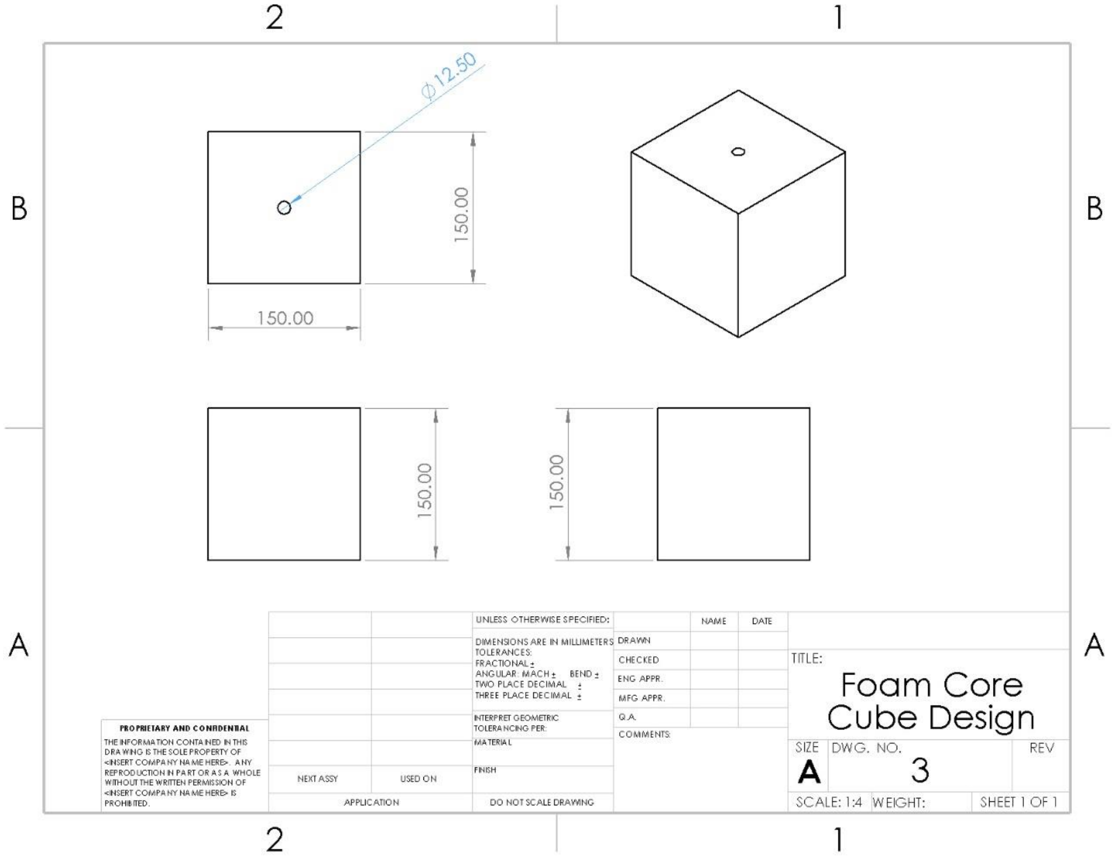
3D Printed Design



Foam Core and Plexiglass Design

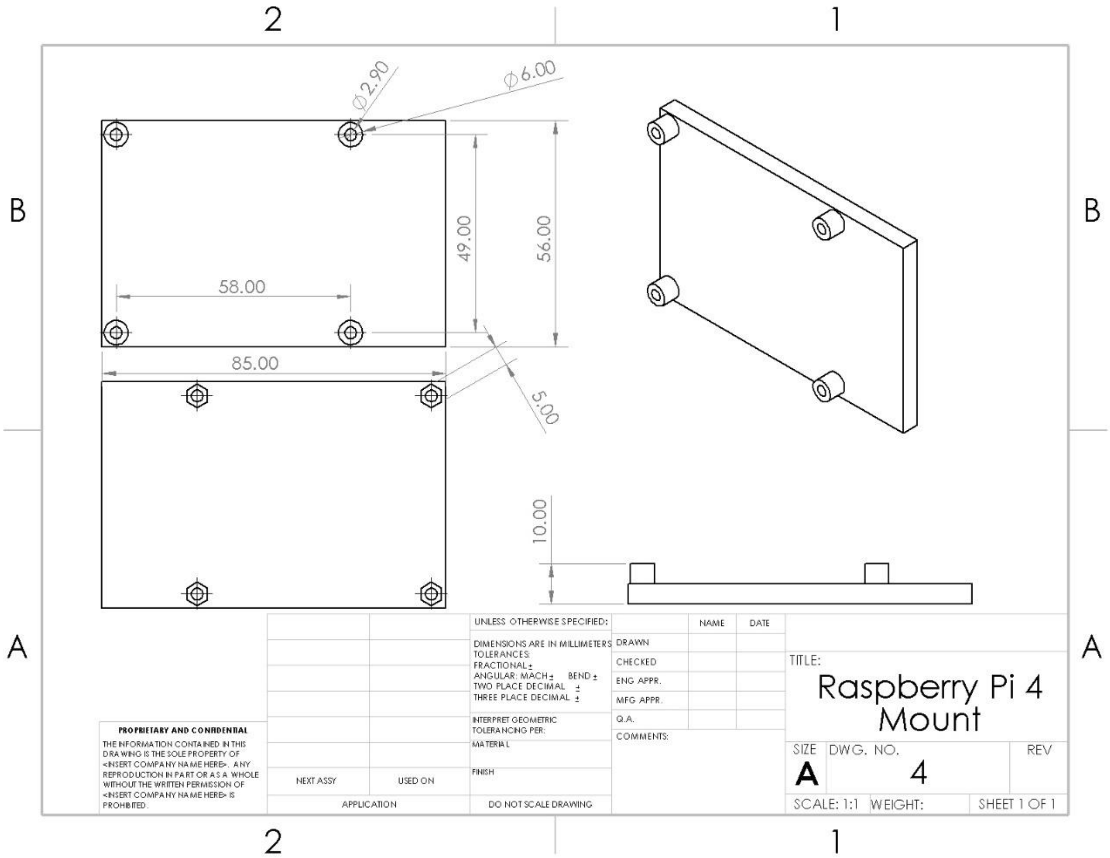


Foam Core Cube Design

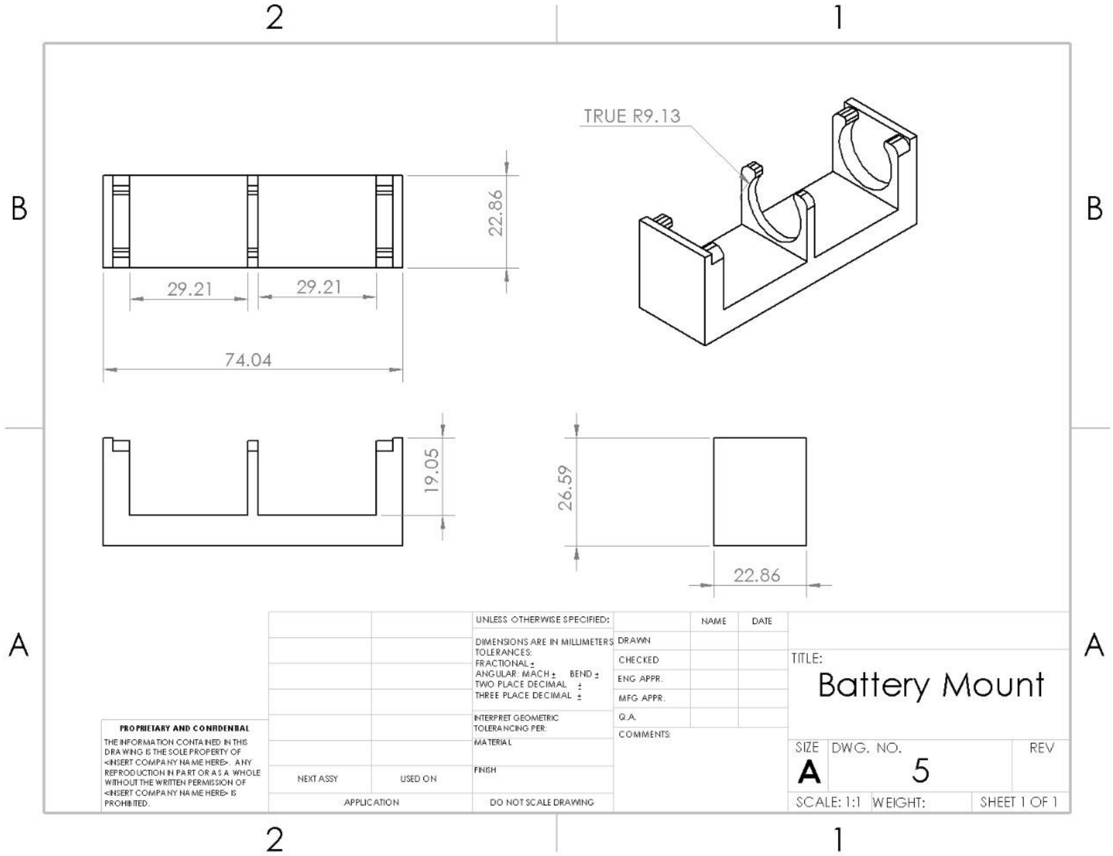


<u>Part Drawings:</u>

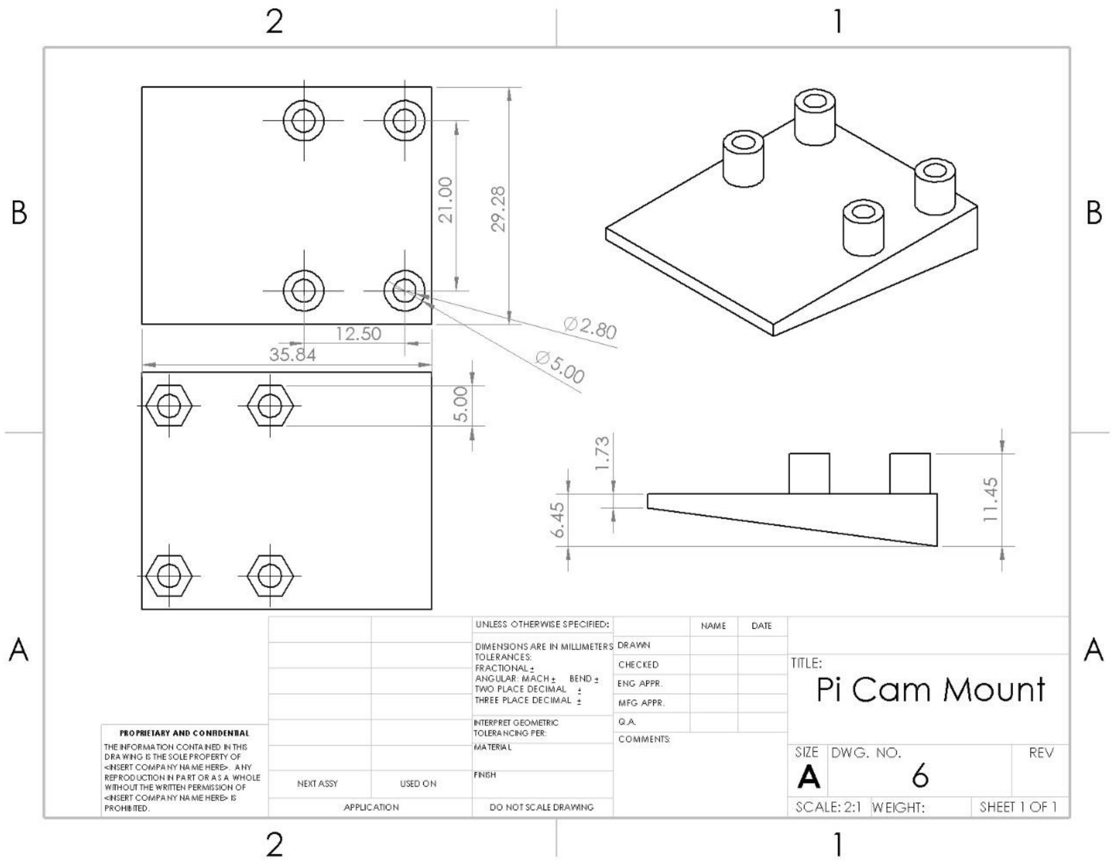
Raspberry Pi 4 Mount



Battery Mount

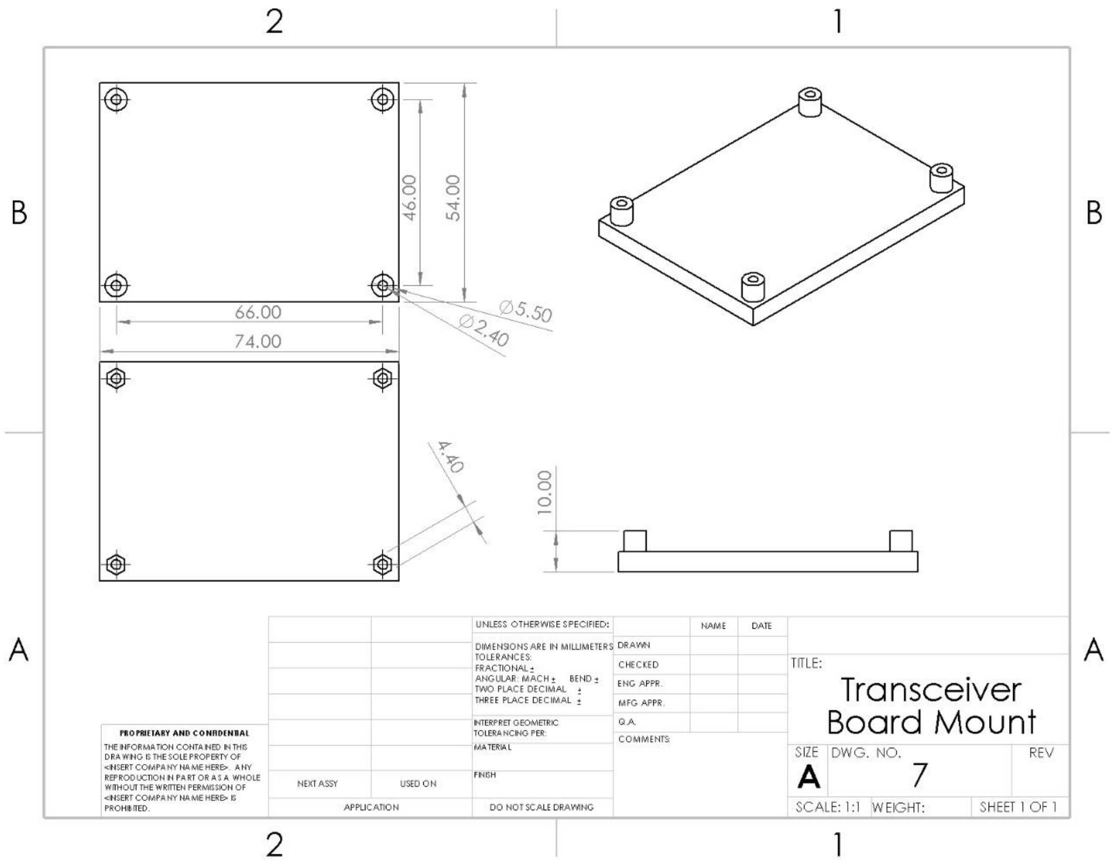


Pi Cam Mount

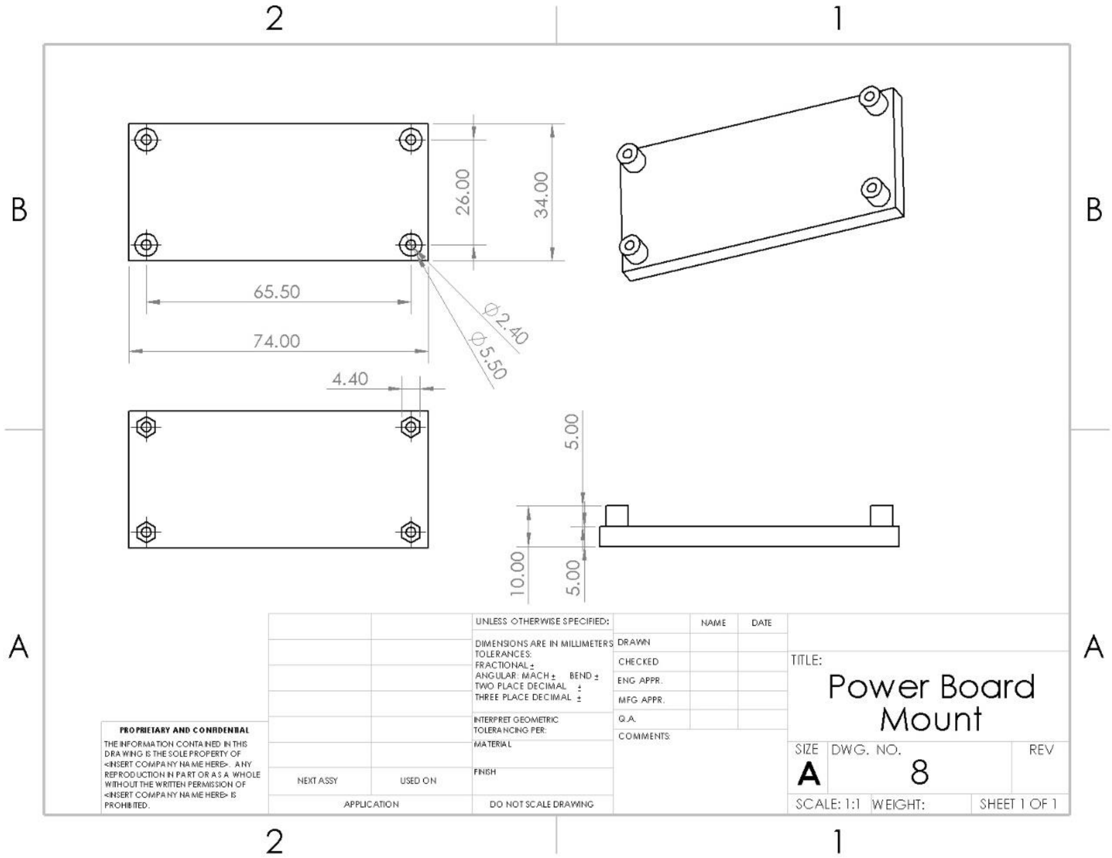


21.00
29.28
12.50
35.84
∅2.80
∅5.00
5.00
1.73
6.45
11.45
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Pi Cam Mount
SIZE
A
DWG. NO.
6
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

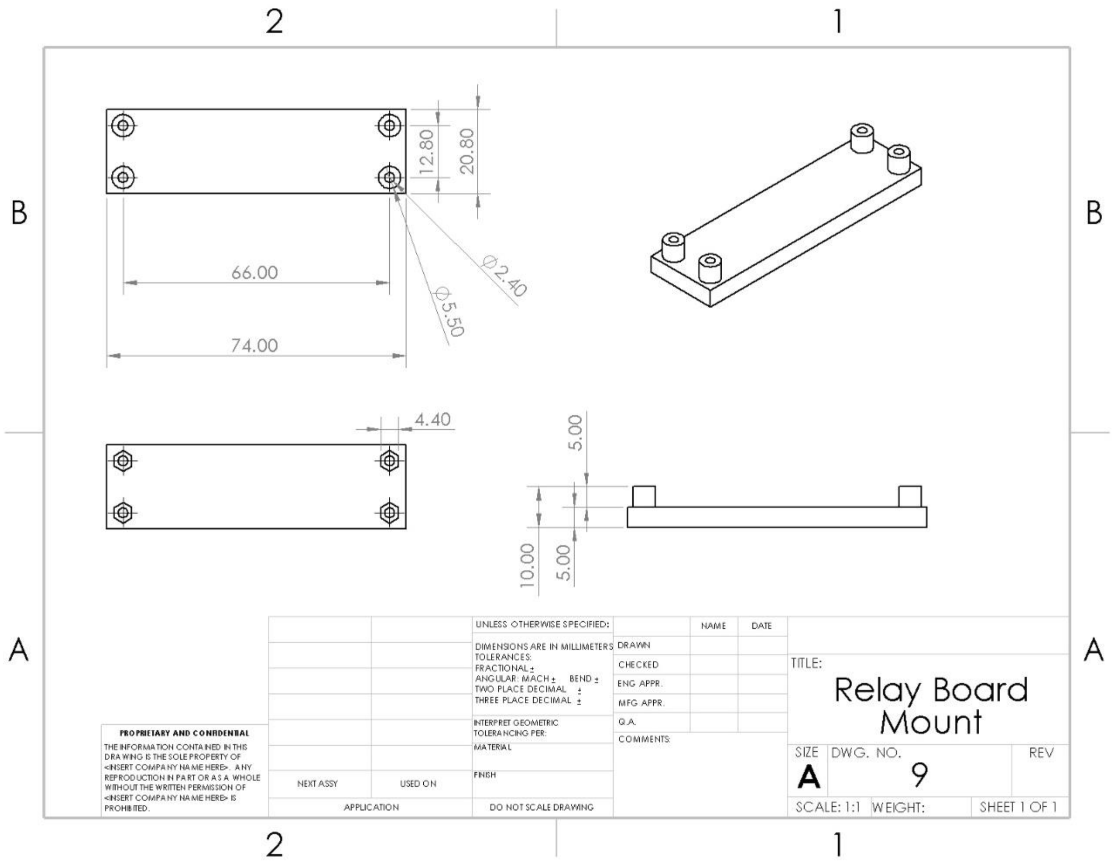
Transceiver Board Mount



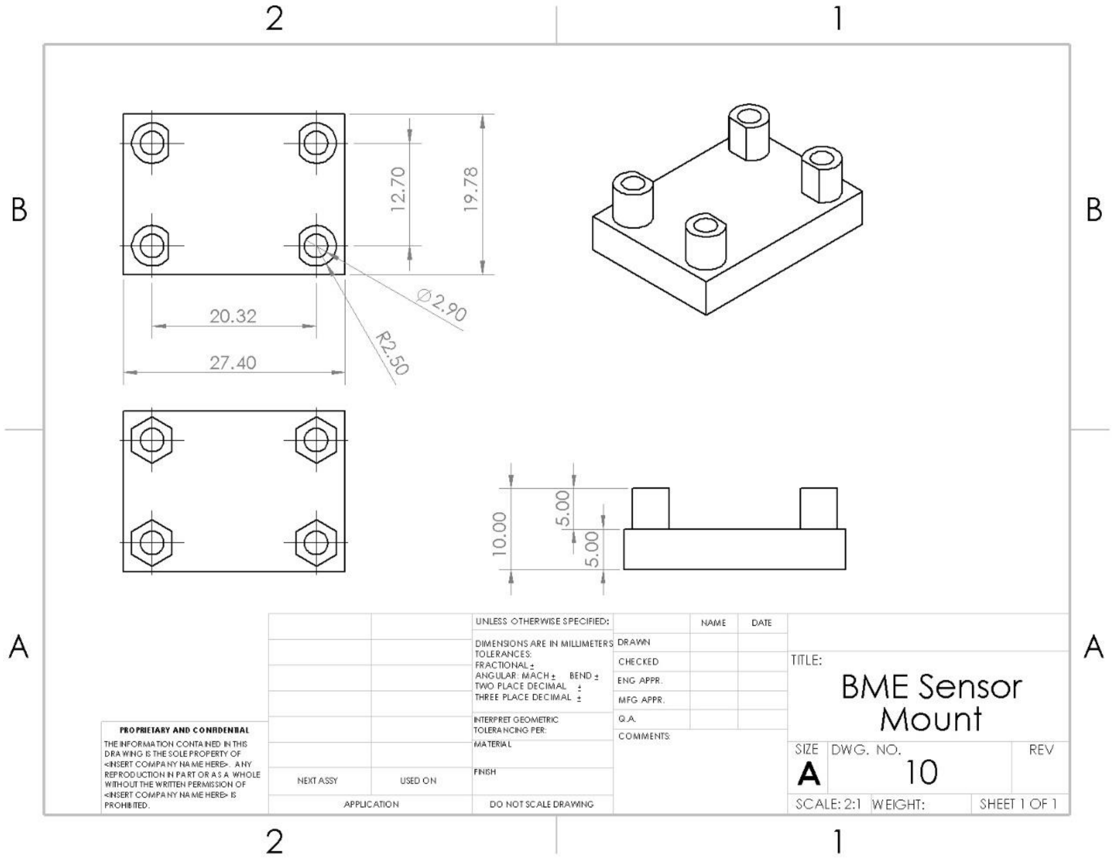
Power Board Mount



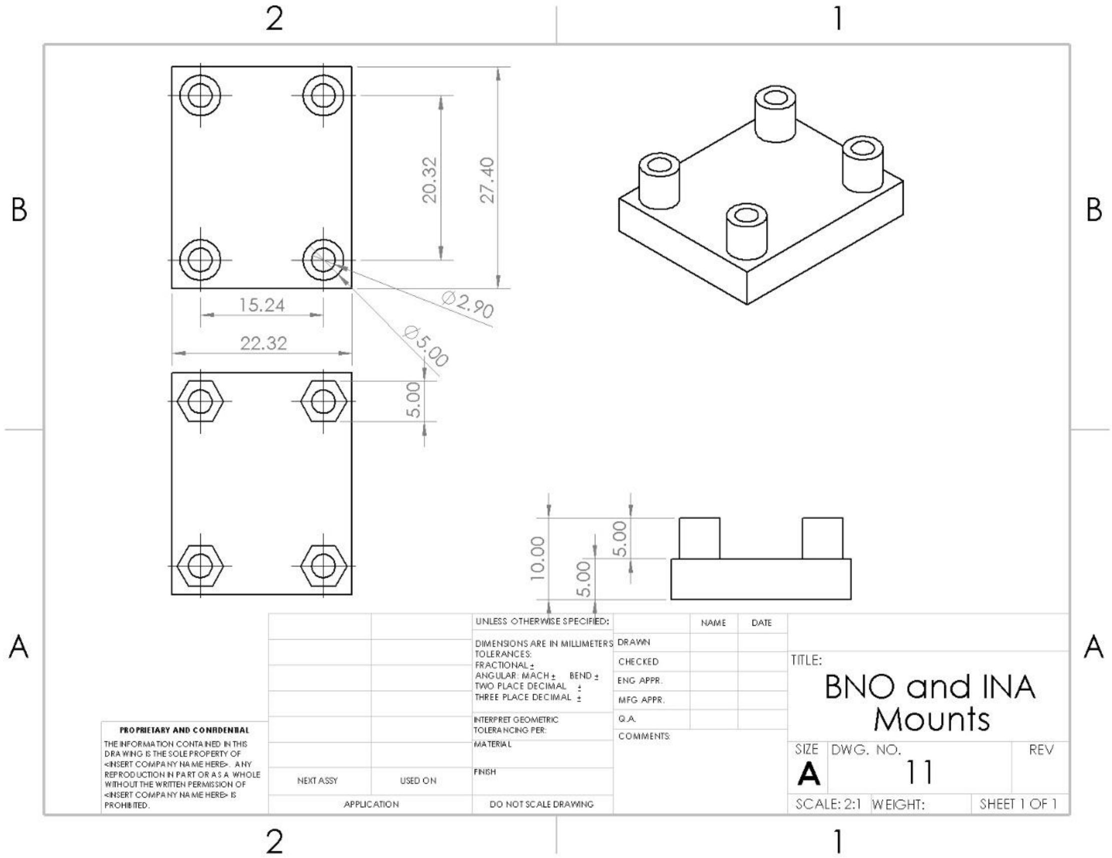
Relay Board Mount



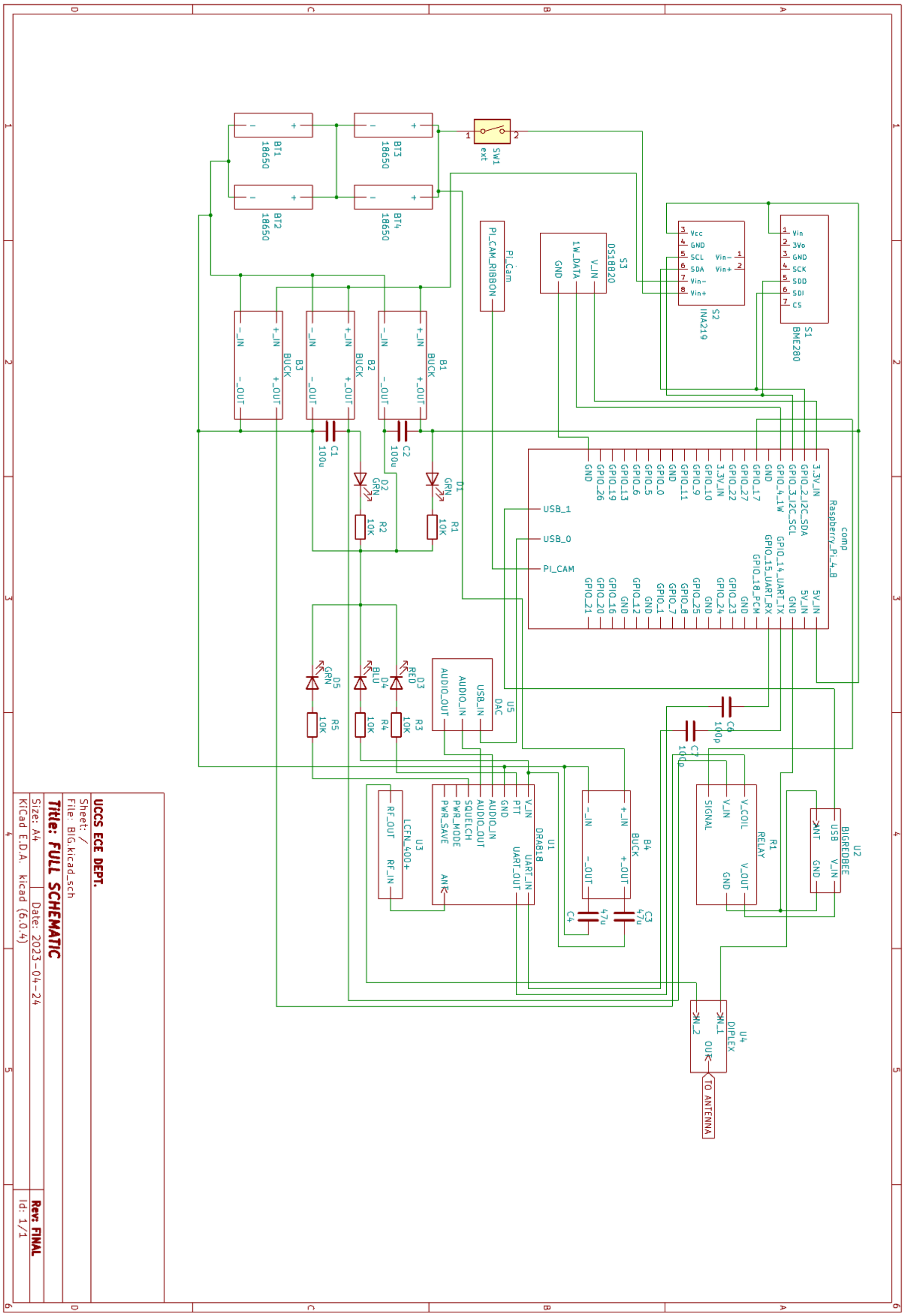
BME Sensor Mount



BNO and INA Sensor Mounts



Appendix B – Complete System Circuit



Appendix C – Requirements and Verification

Requirements:

Communications Requirements				
ID	**Requirement**	**Rationale**	**Expected Value**	**Verification**
CO M-1	Communication systems shall have uplink capability.	To support backup control of communications subsystem and for any changes in mission parameters. Each transmitter shall be capable of being shut down in flight in the event of interference with essential EOSS channels or other users.		Shut off demonstrati on
CO M-2	The telecom system shall be capable of supporting a data volume of 1200bps.	A 1200bps data volume must be met so that the data from sensor package can be obtained. Requirement assumes mission duration of up to 3 hours.	1200bps	Demonstrati on
CO M-3	antennas shall not interfere with sensors.	position of components to decrease interference		Inspection
CO M-4	System transmission power shall remain within limits of power budget allocation.	To support power of system but shall not exceed Effective Isotropic Radiated Power (EIRP) (300mW)		Test E2
CO M-5	The communications subsystem shall be compliant with restrictions set by the FCC.	Specified by the FCC. The following frequencies are off-limits during all launch and recovery day activities: 144.340 MHz, 147.555 MHz and 445.975 MHz.**Allowed:145.600 MHz and 446.050 MHz**		Demonstrati on
Communications Requirements Continued				
ID	**Requirement**	**Rationale**	**Expected Value**	**Verification**
COM -6	The payload shall implement its own unique satellite ID in the telemetry downstream.	Each transmitter shall be operated by a licensed HAM and ID'd per Part 97 of the FCC Rules.		Demonstrati on

COM -7	The EIRP (Effective Isotropic Radiated Power) limits.	Shall be max 300m or no more than 1W (30dBm) FCC while remaining within the limits of the link budget	300mW>1 W	demonstrati on
COM -8	The communications subsystem shall be capable of interfacing with ground station operations and support 1200bps.	transmissions must be capable of interfacing with ground station to provide telemetry for up to three hours. (Estimated duration of flight)	1200bps	demonstrati on
COM -9	Communications Subsystem shall be able to function in simulated environment.	Shall function in environmental specifications provided by DemoSat		Demonstrati on

Sub-System Requirements - Power				
ID	**Requirement**	**Rationale**	**Parent Requirement**	**Verification**
POW -1	Power sub-system shall supply sufficient current to all other systems at a minimum of 5 V DC.	The primary purpose of the power system is to supply sufficient energy to all other onboard systems	Power	Demonstrati on
POW -2	Power sub-system shall provide sufficient voltage regulation from variable power source (Batteries).	Due to the sensitivity of onboard RF equipment to dirty power, the sub-system must provide clean power from a variable source	Power	Demonstrati on
POW -3	Power sub-system shall include overcurrent and overvoltage protection.	The power subsystem must be resilient to potential electrical hazards such as fire and battery RUD	Power	Demonstrati on

Sub-System Requirements – Telemetry/Control				
ID	**Requirement**	**Rationale**	**Parent Requirement**	**Verification**
TEL-1	Data collected from sensors package shall be downlinked every 5 minutes.	Due to the main mission of this payload being centered around communications, having data to communicate is a paramount goal.	Telemetry	Demonstrati on

TEL-2	Telemetry data collected shall be exported to the memory in a readable configuration.	When the data is transferred, the format should maintain a human-readable output so that the information is useful.	Comms	Demonstration
TEL-3	Telemetry data shall be stored locally as back-up in case of failure.	Due to the risks associated during flight, the data stored should be saved so that the mission is not a total loss.	Sensors	Inspection
TEL-4	Telemetry data shall consist of 9-axis position data, current reading, internal temperature, external temperature.	Since this is the data that will be transmitted, it is important to get a picture of what the CubeSat is experiencing during flight both internally and externally.	Sensors	Demonstration
CON-1	The control System shall manage telemetry and comms integration by implementing a data down-link algorithm.	Once the sensors gather and store the data, the control system must facilitate the data push to the comms system	Control	Demonstration

Sub-System Requirements - Mechanical				
ID	**Requirement**	**Rationale**	**Parent Requirement**	**Verification**
ME-1	Total system shall weigh 800 g or less	As listed as a design requirement from the COSGC, each CubeSat must be within this weight range for a nominal flight.	Structure	Inspection
ME-2	Frame shall maintain functional integrity at –40 C	Due to the max altitude that the payload will be exposed to, it must be able to function at this low temperature.	Structure	Test M4
ME-3	Frame shall protect and ensure functional integrity after impact tests	As listed as a flight readiness requirement, the CubeSat must survive the respective impact tests. In case of a failure during flight, this requirement will further protect the payload.	Structure	Test M1, M3
ME-4	Frame shall ensure functional integrity after jerk test	As listed as a flight readiness requirement, the CubeSat must survive the respective jerk tests. In case of a failure during flight, this requirement will further protect the payload.	Structure	Test M2

Sub-System Requirements - Thermal					
ID	**Requirement**	**Rationale**	**Required Values**	**Expected Values**	**Verification**
TH -1	Batteries maintained between operational temperatures.	Maintain System Operation	-20°C to 60°C	-15°C to 50°C	Test
TH -2	Electrical components maintained between operational temperatures.	Maintain System Operation	-30°C to 65°C	-15°C to 50°C	Test

Appendix D– Management

CubeSat

Company Name UCCS

Project Start: Fri, 1/20/2023

Display Week: 7

SIMPLE GANTT CHART by Vertex42.com

https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Feb 27, 2023 | Mar 6, 2023 | Mar 13, 2023 | Mar 20, 2023 | Mar 27, 2023 | Apr

1 2 3 4 5 6 7 8 9 ### 1 2 3 4

Phase 1	**Design and Execute PDR**			
Systems	***Isaac, Alondra, Ed***	***100%***	***1/20/23***	***2/8/23***
	schematics of major subsystems	100%	1/20/23	1/27/23
	Initial schematics of system	100%	1/20/23	2/8/23
	Hardaware spefications flow chart of system	100%	1/20/23	2/8/23
Structural	***Ed, Max***	***100%***	***1/20/23***	***2/8/23***
	design structure	100%	1/20/23	1/27/23
	~~print structure~~	100%	1/20/23	1/27/23
	verify initial structure shape and design	100%	1/20/23	2/10/23
	Mass budget	100%	1/20/23	2/8/23
Thermal	***Max, Ed***	***100%***	***1/20/23***	***2/6/23***
	design the insulation for structure	100%	1/20/23	2/6/23
Power	***Ian, Lauren, Alondra***	***100%***	***1/20/23***	***2/6/23***
	Power budget	100%	1/20/23	2/6/23
	Schematics of connections (board, sensors)	100%	1/20/23	2/8/23
	Integration of sensors and main board	100%	1/20/23	2/6/23
Comms	***Caleb Alondra, Ian , Lauren***	***100%***	***1/20/23***	***2/6/23***
	Purchase antennas	100%	1/20/23	1/23/23
	Link budget	100%	1/20/23	1/27/23
	General connectivity schematic for electrical system	100%	1/20/23	1/27/23
	Characterize antenna	85%	1/20/23	2/6/23
Experiment Payload	***Lauren (all)***	***100%***	***1/20/23***	***2/6/23***
	~~Design experiment placement~~	100%	1/20/23	1/27/23
	~~order components~~	100%	1/20/23	1/27/23
	~~Design sperimental procedure for collection of data~~	100%	1/20/23	1/27/23
	~~Describe application for experiment~~	100%	1/20/23	1/27/23
	~~Program the data fetch sequence (error correcting code)~~			
Administrative	***Max, Ed, Issac***	***100%***	***1/20/23***	***2/6/23***
	Assignments to turn in for school updates	100%	1/20/23	2/6/23
Technical Writing	***all***	***100%***	***1/20/23***	***2/6/23***
	PDR	100%	1/20/23	2/6/23

CubeSat

Company Name UCCS

Project Start: Fri, 1/20/2023

Display Week: 7

SIMPLE GANTT CHART by Vertex42.com

https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Feb 27, 2023 | Mar 6, 2023 | Mar 13, 2023 | Mar 20, 2023 | Mar 27, 2023 | Apr 3, 2023 | Apr 10, 2023 | Apr 17, 2023

Phase 2 Testing and Validation CDR				
Systems	***Isaac, Ed, Alondra***	***100%***	***2/6/23***	***3/6/23***
	add minor subsystems to schematics or flow chart	100%	2/6/23	3/6/23
	Maintain system under mass budget	100%	2/6/23	3/6/23
Structural	***Ed, Max***	***87%***	***2/6/23***	***3/6/23***
	structure to pass temperature test	60%	2/6/23	3/6/23
	Structure to pass drop test	100%	2/6/23	3/6/23
	Integrate with thermal	75%	2/6/23	3/6/23
	Whip testing of structrure with some weight	100%	2/6/23	3/6/23
	Testing with string, washer, and tubing	100%	2/6/23	3/6/23
Thermal	***Max, Ed***	***50%***	***2/6/23***	***3/6/23***
	Assemble structure and thermal test	50%	2/6/23	3/6/23
Power	***Ian, Lauren***	***50%***	***2/6/23***	***3/6/23***
	Integrate with Comms	50%	2/6/23	3/6/23
	environmental testing of integration	50%	2/6/23	3/6/23
Comms	***Alondra, Ian (all)***	***52%***	***2/6/23***	***3/6/23***
	Initial Component table testing of main board antenna Program code	60%	2/6/23	3/6/23
	table test communication system program code	80%	2/6/23	3/6/23
	environmental testing of communication system	0%	2/6/23	3/6/23
	analysis of communication system	60%	2/6/23	3/6/23
	link budget check update	60%	2/6/23	3/6/23
Experiment Payload	***Lauren (all)***	***93%***	***2/6/23***	***3/6/23***
	integrate with power system	100%	2/6/23	3/6/23
	validate	90%	2/6/23	3/6/23
	System integration	90%	2/6/23	3/6/23
Technical Writing	***all***	***100%***	***2/6/23***	***3/6/23***
	CDR	100%		
Operations	***all***			
	Design a operations for ground comms			

CubeSat

Company Name UCCS

Project Start: Fri, 1/20/2023

Display Week: 7

SIMPLE GANTT CHART by Vertex42.com

https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

Feb 27, 2023 | Mar 6, 2023 | Mar 13, 2023 | Mar 20, 2023 | M

Phase 3 Integration an Verification FRR				
Systems	***Isaac, Max, Ed (all)***	***20%***	***3/6/23***	***3/27/23***
	integrate major systems and minor subsystems on flow chart or schematic	20%	3/6/23	3/27/23
	Verify architecture of system (check budgets)	20%	3/6/23	3/27/23
	validate architecture of system (physical testing and measurement)	20%	3/6/23	3/27/23
Structural	***Ed, Max***	***50%***	***3/6/23***	***3/27/23***
	Verify structure with system integration (whip, drop)	50%	3/6/23	3/27/23
	Validate structure with system ingration	50%	3/6/23	3/27/23
Thermal	***Max, Ed***	***35%***	***3/6/23***	***3/27/23***
	Verify thermal material interatcions with componens	20%	3/6/23	3/27/23
	Validate temperature endurance for flight time	50%	3/6/23	3/27/23
Power	***Ian, Lauren***	***25%***	***3/6/23***	***3/27/23***
	Verify Power consumption per flight duration	0%	3/6/23	3/27/23
	Validate power budget	50%	3/6/23	3/27/23
Comms	***Alondra, Ian (all)***	***100%***	***3/6/23***	***3/27/23***
	Verify Communicatinon and operations enveronment	100%	3/6/23	3/27/23
	Validate comm system for flight duration	100%	3/6/23	3/27/23
Experimental Payload	***Lauren (all)***	***100%***	***3/6/23***	***3/27/23***
	Validate data fetch for flight duration	100%	3/6/23	3/27/23
Technical Writing	***all***	***100%***	***3/6/23***	***3/27/23***
	FRR	100%	3/6/23	3/27/23
Operations	***all***	***100%***	***3/6/23***	***3/27/23***
	Validate operation plans for ground comms	100%	3/6/23	3/27/23

Weight Budget

Part name	Description	Weight(g)	Weight(lbs)
Raspberry Pi 4	Controller board	47	0.1036
Pi cam 2	camera	4	0.0088
BME280	temperature and humidity sensor	2.2	0.0049
BNO055	Gyro sensor	2.2	0.0049
INA219	Current sensor	2.2	0.0049
Samsung 25R 18650	Batteries(4)	180	0.3968
DS18	External Temp Sensor	40	0.0882
Foam core	Case material	94	0.2072
Connectors	Connections/switches	50	0.1102
BRB VHF Dipole antenna	tranmission antenna	70	0.1543
PLA Mounts	Mounts	88	0.1940
Wires	Miscellaneous connection wires	100	0.2205
MP2307	Buck converter	6	0.0132
Flight Readyness		90	0.1984
Fastners		75	0.1653
Total Weight		850.6	1.8753

Monetary Budget

Part name	Description	Count	Cost
Raspberry Pi 4	Controller board	1	150
Pi cam 2	Camera	1	32.49
BME280	Temperature and humidity sensor	1	14.95
BNO055	Gyro sensor	1	29.95
DS18B20	Exterior temperature sensor	1	4
INA219	Current sensor	1	9.95
Samsung 25R 18650	Batteries	4	20
MP2307	Buck converter	1	9.95
bq24074	Battery charger	1	14.95
PETG spool 1 kg	Printing material	2	50
Foam core	Case material	1	5
BRB VHF Dipole antenna	Tranmission antenna	1	35
M2 and M2.5 nuts and bolts	Fasteners	1	10
Hot glue	Casing sealant	1	7
Aluminum tape	Exterior sealant	1	10
Wires	Electrical connectors	1	15
Big red bee	Transmitter	1	265
			683.24