

Project: JB3-CBS3

Thermal, Telecommunication and Power Systems for a CubeSat

A Major Qualifying Project

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Abstract

The objective of this project was to design the power, telecommunication, and thermal control subsystems for an earth-orbiting CubeSat. This mission payload is an X-ray detector designed to study solar radiation. Requirements on the spacecraft imposed by the National Aeronautics and Space Administration (NASA) and California Polytechnic State University (Cal Poly) were reviewed and organized to provide a reference for future design teams. The power subsystem defined by previous Worcester Polytechnic Institute (WPI) student projects was re-evaluated and the power budget finalized. In addition, wiring diagrams were created to show how the power subsystem hardware interfaces with other spacecraft systems. The telecommunication subsystem was designed in order to allow communication between the satellite and ground stations. A ground station plan was established, including a cost budget for hardware and identification of an existing network which could support the mission objectives. With this information, a telecommunications link budget was created and expected ground tracks calculated using Systems Tool Kit (STK) software. To better understand the thermal requirements for the mission, calculations of spacecraft-sun vectors as a function of time while in orbit were performed using STK. This data was then used to simulate such effects on the structure using COMSOL. The report concludes with recommendations for thermal-vacuum testing and future work with respect to these three subsystems.

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We certify this final report can be considered a group effort, with multiple partners collaborating on each section.

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Executive Summary

The CubeSat Design Project began in 2010; since then the design process is well underway working toward funding and an eventual launch in the near future. The Mechanical, Power, and Thermal CubeSat Major Qualifying Project (MQP) 2012 [1] worked to create a preliminary hardware selection and created a model in COMSOL Multiphysics (Burlington, Ma.) for internal, external, and “Lab Option” simulations. This year, the project got even closer to reality through hardware finalization and breaking ground in the telecommunication subsystem.

Due to the cost of such a project and other CubeSat missions already in space, there many reference documents specifying requirements for launch and mission operations. A thorough review of documentation and research related to existing CubeSat missions revealed that a CubeSat mission must follow specifications given by the following institutions: California Polytechnic State University (Cal Poly) [2], National Aeronautics Space Association (NASA) [3], and the United States Air Force (USAF) [4]. The necessary requirements were compiled for future design teams’ reference.

Within the power subsystem there was an existing power budget to ensure there will always be enough power supplied to all hardware within the CubeSat. As changes were made to on-board hardware, the budget was updated with the respective required power supply data. As the hardware for all other subsystems became finalized, the requirements for the power supply system became clearer, and therefore helped to finalize the power subsystem hardware. The wiring for power supply was defined in detail and shared with the CubeSat Structural team.

Telecommunications on-board and between the CubeSat and ground station were investigated for the first time in the CubeSat Design process. Ground stations were researched to determine the best hardware and ground station network for a successful CubeSat mission. It was determined that joining the Global Educational Network for Satellite Operations (GENSO) would be an effective way to become part of an established network in a relatively short time. Creating a link and access budget using System Tools Kit (STK) (AGI, Exton, Pa.) was crucial in choosing the ground station hardware. A monetary budget for the on-board and ground station hardware was also created to prepare a Worcester Polytechnic Institute (WPI) Ground Station proposal.

The thermal subsystem maintains the spacecraft temperature within acceptable limits. The group evaluating this subsystem was responsible for conducting thermal analysis for the CubeSat within the space environment and in the vacuum chamber. Spacecraft-sun vectors were calculated using STK and imported into COMSOL for external component analysis to generate more accurate results. Continuing with the Lab Option from last year’s MQP team, a procedure of the vacuum chamber test was written. A model was generated in COMSOL to compare results from the thermal analysis to the vacuum chamber test

1 Introduction

1.1 Project Goals and Objectives

The goal of the CubeSat project is to provide a sufficient definition of the spacecraft and mission to support a proposal for a CubeSat Mission to fly the SphinX-NG X-ray solar flux detector. The focus of this team is on three subsystems of the CubeSat: the power subsystem, the telecommunication subsystem, and the thermal subsystem. The objectives of the project are to confidently show how each subsystem will work in the CubeSat, and provide the necessary analysis and hardware recommendations for the actual systems to be created. For the spacecraft to be eventually approved for launch, the CubeSat must be able to meet all requirements stated by the involved parties. These include standards for testing set forth by National Aeronautics Space Association (NASA) [3], California Polytechnic State University (Cal Poly) [2], and Department of Defense standards [4]. This team was responsible for understanding and creating procedures for these requirements, so that the CubeSat Mission could be approved.

1.2 Power Subsystem Objectives

Power subsystems are used to produce, condition, store, and distribute power to various devices throughout the CubeSat. There were two primary objectives for the power subsystem. The first objective was to build upon last year's work and have an updated power budget, to ensure that the payload and all CubeSat subsystems have the power they need at all times [1]. The second objective was to detail the wiring of all the power subsystem circuit boards and the CubeSat devices (i.e. "power consumers"), to ensure that everything was connected and could receive power, as well as relay information to the controlling CubeSat On-Board Computer (OBC).

1.3 Telecommunication Subsystem Objectives

The CubeSat requires communication between earth and itself. Telecommunication subsystems are used to relay commands and data to and from the CubeSat and ground stations on Earth. To make sure this was possible for the CubeSat, this team was responsible for three primary objectives. The first was to determine, using Systems Tool Kit (STK), the extent of ground coverage the CubeSat would have access to through the use of various ground stations. The second objective was to define a data link budget based upon the extent of ground coverage as well as the CubeSat telecommunication hardware. The third objective was to identify and recommend hardware to be used in the CubeSat Mission.

1.4 Thermal Subsystem Objectives

The thermal control subsystem ensures the CubeSat does not exceed the maximum and minimum operational temperatures of its components. With that in mind, this year's team was responsible for two primary objectives. The first objective was to refine last year's thermal analysis by using STK to determine the angles at which the sun strikes the CubeSat and then use those values in COMSOL to produce a more detailed thermal modeling of the CubeSat as it orbits the Earth [1]. Using this data, an analysis can be performed to determine a recommended thermal control method. The second objective was to test a model of the CubeSat in the Worcester Polytechnic Institute (WPI) vacuum chamber for comparison to the COMSOL analysis in order to verify the findings.

2 Background

2.1 Power Subsystem

2.1.1 Mechanical, Power, and Thermal CubeSat MQP 2012 [1] Final Budget

Power is one of the most important considerations when planning a CubeSat mission. If the power budget was incorrect or the power system shorted out, the entire mission would be compromised. The 2011-2012 Major Qualifying Project (MQP) team [1] created a power budget based on the instruments selected and the information available at the end of the project. Table 1 below shows the final power budget proposed by the 2011-2012 teams.

Component	Part Number	Peak Power (W)	Nominal Power (W)	Quiescent Power (W)	Current (mA)	Voltage (V)
GPS	SGR-05U	.080	0.080	.080	16	5
OBC	Pumpkin	0.300	0.300	0.000	TBD	TBD
Magnetorquers (3)	Zarm Technik AG MTO 2.1 (Optimized)	0.420	0.420	0.420	28	5
Sun Sensor	ComTech AeroAstro	0.050	0.050	0.050	3.5	N/A
Gyro	ADXRS450	0.030	0.030	0.030	6	Variable
Magnetometer	Honeywell HMC5883L	0.001	0.001	0.000	0.25	3.6 (max)
Instrument		8.000	8.000	1.000	TBD	TBD
EPS Board	ClydeSpace	0.1	< 0.1	< 0.1	TBD	TBD
PDM Board	ClydeSpace	0.160	0.160	0.160	TBD	TBD
PPM	ARM922T	0.180	0.180	0.180	TBD	TBD
UHF Transceiver		2.000	2.000	0.000	TBD	TBD
Total		11.321	11.321	2.020		
Total Available		12.520	12.520	12.520		
Margin		1.199	1.199	10.500		

Table 1: Final Power Budget from 2012 AE CubeSat MQP [1].

This was a preliminary power budget that does not include all necessary information to properly estimate available power. Even though the numbers in Table 1 are based on data from the manufacturer, these numbers will be tested by future groups once the hardware is acquired. These tests will verify the hardware to make sure they do not deviate from manufacturer values. For values listed as To Be Determined (TBD), a manufacturers value will be inserted and verified to make certain there will be enough power for the CubeSat. Once the current values have been verified and the budget has been updated, the flight will then be broken down into the different phases of the mission which will each have their own power budgets based on instrument usage.

2.1.2 Power Subsystem Hardware

Power is a key element of CubeSat design and can be the determining factor in lifetime of the CubeSat. The goal of the power subsystem is threefold:

1. To generate and/or store power for the CubeSat
2. To condition and distribute power for the CubeSat
3. To protect the CubeSat in the case of a fault

In the majority of CubeSats that have been launched, the first goal is accomplished with the use of solar arrays in combination with a battery giving the satellite power while in view of the sun or from albedo radiation and retaining power in the battery for peak loads and while in eclipse. The second goal is accomplished through the use of power management and distribution (PMAD) modules. These modules ensure that the power is supplied to users throughout the CubeSat and that the power is properly conditioned. The final goal is accomplished through the use of regulators and safeguards within the PMAD modules that monitor current flows to prevent damage to other components. The PMAD modules should also be able to function if the OBC

were to malfunction or need to be rebooted in order for the CubeSat to continuously have power once it exits the Poly-Picosatellite Orbital Deployer (P-POD). An overview of the power subsystem is shown by the flowchart in Figure 1.

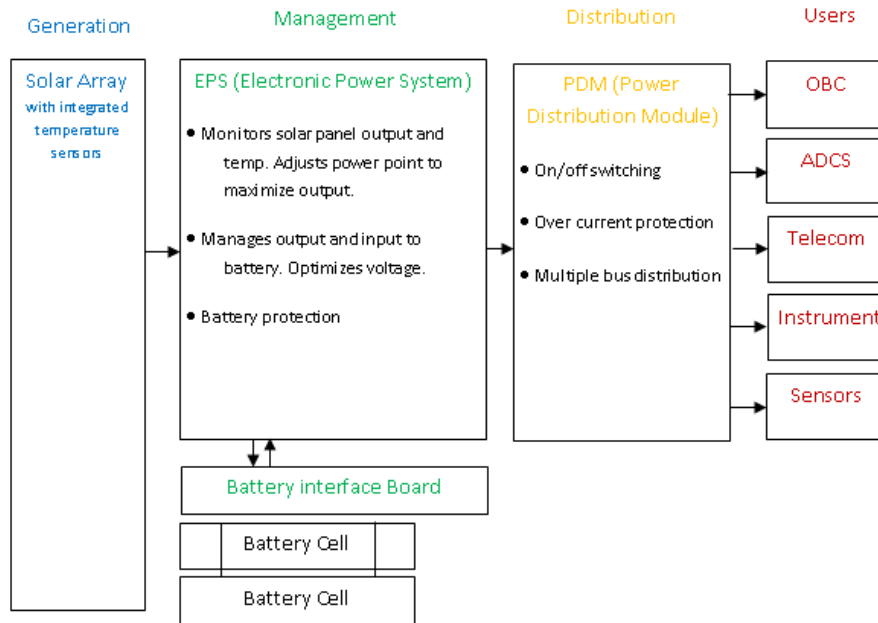


Figure 1: Power Subsystem

Solar Array

Power generation duties on CubeSats are covered by solar arrays due to the abundant solar energy available in orbit; there is over four times the energy available to satellites compared to ground based panels. As such, the panels used on CubeSats are small and light while still providing plenty of power to users. Many solar panels designed for operation in space use gallium arsenide cells because of its higher efficiency compared to silicon, and a lightweight substrate made of fiberglass Printed Circuit Board (PCB), aluminum, carbon fiber or an alternative composite.

The power level generated by the cells is a function of their efficiency, area, cell density, and temperature. While the physical qualities of the panels are only affected by degradation over time, temperature of the panels is far from constant and as a result the panels must be optimized for specific temperatures. Furthermore, as can be seen in Figure 2, solar cells operate more efficiently at lower temperatures and produce a higher peak voltage, so heat should be dissipated from the panels as quickly as possible. Note that there is an optimal point for a given temperature where power is highest. This is the peak power point.

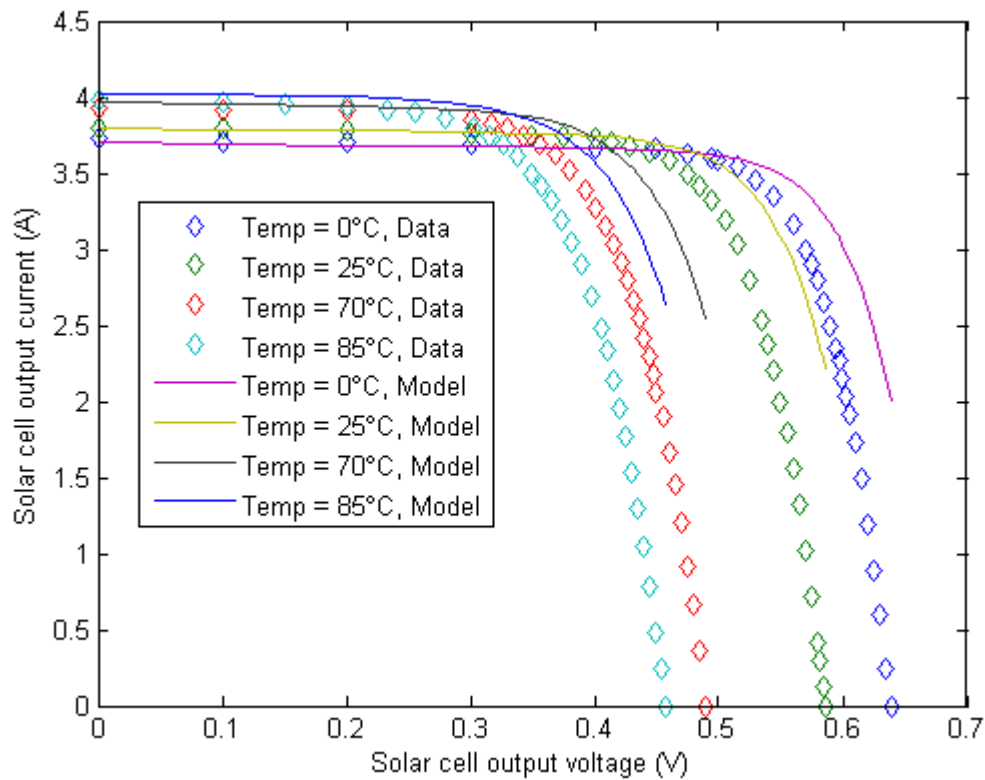


Figure 2: Solar panel output as a function of temperature [5].

The 2011-2012 MQP team chose to use a three panel system for the power generation needs; the system consists of a front mounted Two Unit (2U) panel and two single-deployed 2U panels on the sides as shown in Figure 2 [1].

EPS (Electrical Power System)

The EPS board controls power handling functions and the power subsystem as a whole. It is directly connected to the solar arrays, PDM (Power Distribution Module), battery, and OBC and as such is in charge of monitoring output from the arrays, power to and from the battery and PDM, and supplying information to and taking commands from the OBC. It is also tasked with maintaining the solar panels at the peak operating power point for a given temperature.

The 2011-2012 MQP group identified the Clyde-Space PMAD modules as the ideal boards for CubeSat power needs [1]. The EPS from Clyde-Space has flight heritage in a robust, Three Unit (3U) CubeSat specific package that can handle the planned solar array configuration and has built in power point tracking. It has built in overcurrent and battery under voltage protection and was designed from the start for the CubeSat application. An image of the board is shown in Figure 3.



Figure 3: Clyde-Space 3U EPS [6].

PDM (Power Distribution Module)

The PDM distributes power to users along specific power busses, which are connectors supplying power and data to all the electronics in the CubeSat. It includes the ability to switch different users on and off, along with protection for every circuit. Power is provided by the EPS, whether the satellite is running on battery power alone, a mix of array and battery power, or the arrays alone. The PDM also utilizes overcurrent protection on every circuit to protect users. The Clyde-Space PDM board is shown in Figure 4. It is designed to integrate directly with the EPS and has the same form-factor.



Figure 4: Clyde-Space PDM [7].

Battery

Batteries supplement the energy output from the solar arrays at peak usage while also providing power while in eclipse. Lithium ion or lithium polymer cells are commonly used for their characteristically high energy density compared to alternative cells. Unfortunately, lithium ion or polymer batteries tend to become unstable near their extreme operating temperatures, so it is imperative that the batteries are constantly monitored to avoid loss of the batteries or worse. These batteries can only handle a finite number of charge and discharge cycles before failure, usually in the range of as few as 50 cycles up to thousands of cycles depending on the battery

specification. To maximize battery life it is important to properly budget power so the battery never exceeds the recommended depth of discharge, which is 20% to 30% for most CubeSat batteries. While more battery cells could be added for redundancy and to offset power requirements, it should be noted that batteries incur a high cost in both weight and volume. Despite these limitations, batteries are necessary on most CubeSat missions and play an important role in the power system maintaining power in eclipse and supplementing power at times when need exceeds that produced by the solar panels.

2.1.3 Power Subsystem Related Interface Control Document (ICD) Requirements

The requirements outlined in the document supplied by Cal Poly San Luis Obispo [2] stipulate that no electronics shall be active during launch. This is to prevent any interference, either from electrical or RF sources with the launch vehicle and primary payloads. The CubeSat must also have a Remove Before Flight (RBF) pin. The RBF pin when installed must cut all power to the CubeSat bus, and must be removed after the CubeSat is integrated with the P-POD. If a RBF pin is not present, the satellite must launch with its batteries fully discharged. The CubeSat must also have at least one deployment switch located on the -z face of the CubeSat as shown in Figure 5. The deployment switch must keep the satellite powered off while it is actuated. Once the satellite is deployed, the deployment switch will no longer be actuated and this will start the deployment timer. The deployment timer requirement is a separate requirement from the deployment switch. It ensures that no mechanical structures or appendages are deployed until 30 minutes after the satellite is ejected from the P-POD. It also ensures that no transmissions are generated until 45 minutes after the satellite is ejected from the P-POD. The deployment switch must also be able to reset the deployment timer if the switch is toggled from the actuated state and then actuated again. After the CubeSat is loaded into the P-POD, it can

then be charged through access ports located on the P-POD as shown in Figure 6. However, the total stored energy in the battery after charging must be no more than 100 Watt hours. As the CubeSat has a battery onboard, the CubeSat must also be capable of receiving a command to shut down the transmitter.

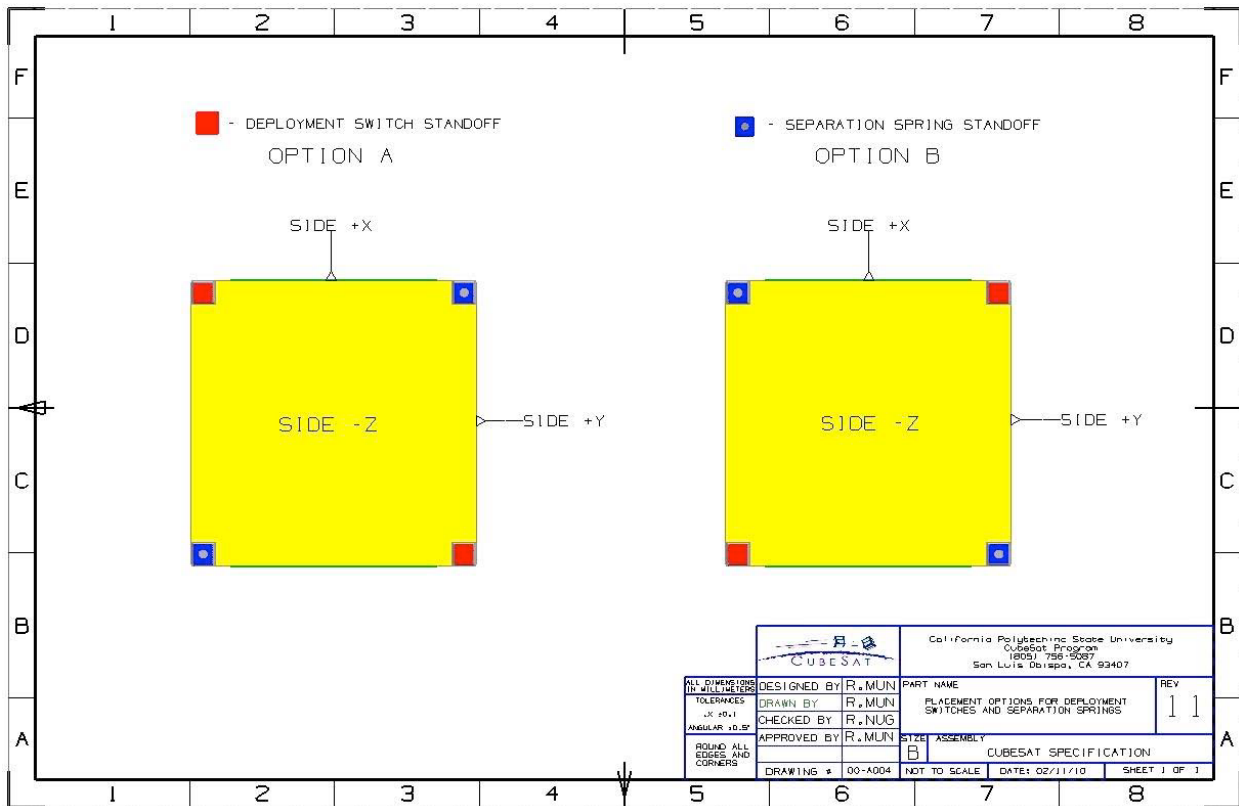


Figure 5: Location of Deployment Switches [2](2011)

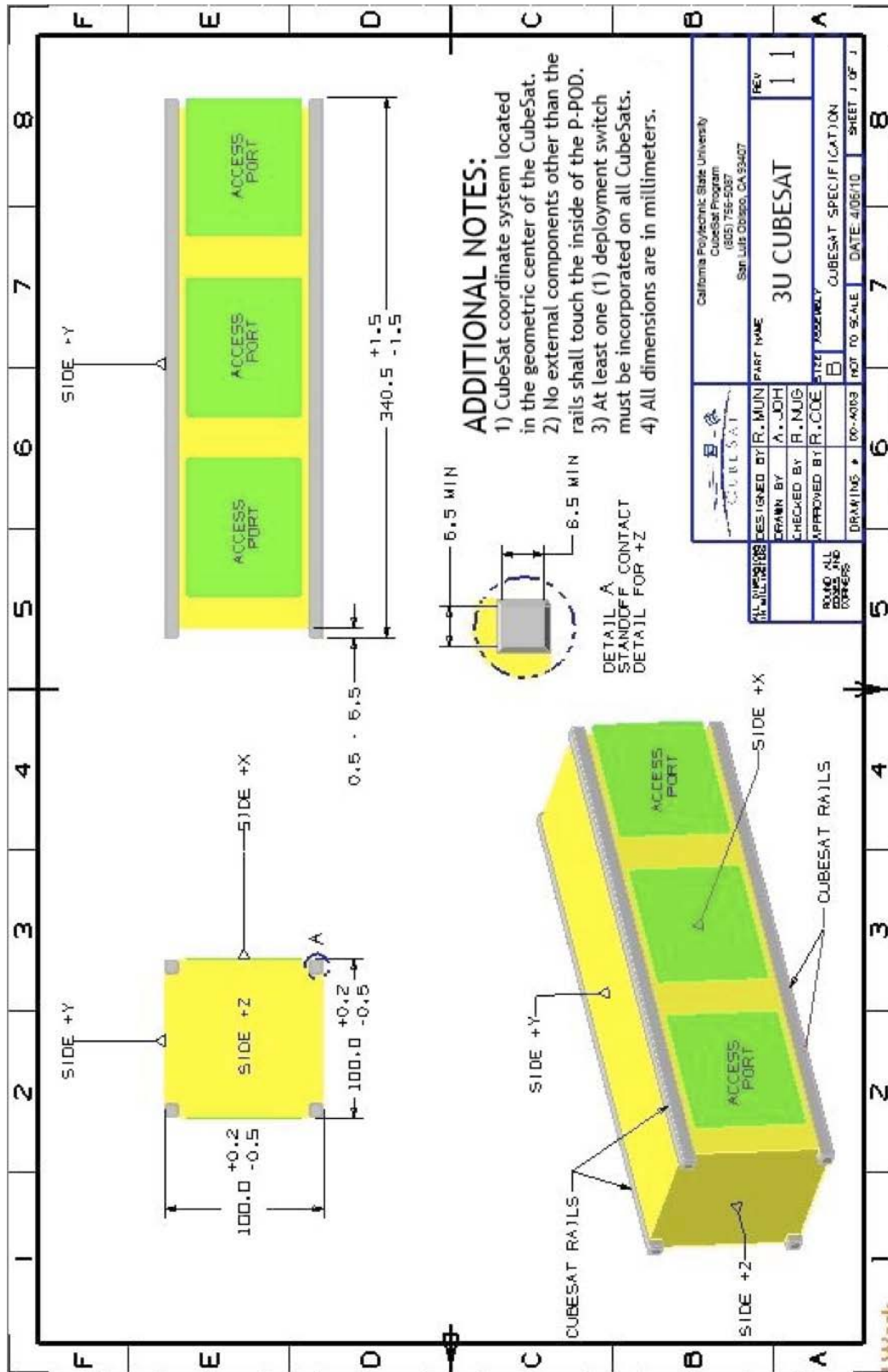


Figure 6: Location of Access Port for 3U CubeSat [2] (2011)

The CubeSat shall also be self-contained, providing its own power, sequencing and wiring [3]. The requirement of the CubeSat being able to provide its own sequencing refers to it being able to carry out its tasks without constant commands from a ground station. The electrical wiring of the satellite, specifically its insulation, shall also be inspected for flammability prior to its launch [3]. If the wire insulation is chemically and physically similar to a material found to be acceptable by NASA-STD-(I)-6001, then the material may be used without testing and justified on an approved Material Usage Agreement (MUA). After the thermal vacuum bakeout test is performed, the electrical functionality of the satellite needs to be re-verified [3].

NASA requires the CubeSat also have an End of Mission (EOM) plan [8]. Prior to the EOM the satellite needs to be passivated for earth orbit or earth reentry. The passivation of the satellite will entail the removal of all forms of stored energy. It must be depleted to a point where it would be insufficient to cause a breakup of the satellite. The electrical systems, specifically the batteries and the charging circuits shall be part of the passivity analysis.

2.2 Telecommunication Subsystem

2.2.1 Telecommunication Subsystem Related ICD Requirements

In recent years, CubeSat launches have become more common. With this increase, the potential problems that may be encountered have become more clear, but also preventable. Requirements for sending a CubeSat into space have been established and continuously updated by a variety of authors. For the 3U CubeSat under study for this project, the required specifications are given by Cal Poly, NASA, and the USAF. A full list of CubeSat applicable mandates can be found in Appendix 1. These documents create a profile for the size and shape of a CubeSat, along with restrictions to prevent any perturbations to the Launch Vehicle (LV) or

other satellites already in orbit. There is an orbital verification process which reviews the mission flight plans in order to prevent collisions and ejection conflicts. Frequency restrictions during the mission are put in place to prevent radio interference between the LV and other satellites. A frequency application must be filled out, approved, and a license issued for a specific frequency to be used for communication between the satellite and ground station. It has become necessary to have requirements that ensure redundancy in place, so that in the event of error or failure there are back-up commands in place. Another command prerequisite is to make sure the CubeSat has the capability for Global Positioning System (GPS) tracking and real-time on board system updates to assure the hardware is working correctly. Requirements are in place to assure that all Commercial Off-the-Shelf (COTS) hardware used is in accordance with all the NASA and Cal Poly standards. There are LV requirements to assure the CubeSat is installed correctly onto the LV. This means that the CubeSat must meet vibration testing limits, and assures that the satellite does not interfere physically or electronically with the mission of the LV. These requirements also demand any testing that will assure the CubeSat's ejection from the LV goes smoothly. These tests include, but are not limited to, testing the CubeSat switch to ensure the power stays off and that the ejection portion of the mission plan will not interfere with the LV's mission or the LV physically.

2.2.2 Hardware

The purpose of the telecommunications system in a CubeSat is to provide a link between the OBC and ground operations. This is necessary for two reasons:

1. To satisfy the mission requirements for retrieving instrument data.
2. To satisfy the mission requirements for telemetry, tracking, and command.

A CubeSat is only as good as the information it provides to the organizations sending it into orbit. Information stored on a CubeSat does no good until it is transmitted to ground stations by some means. This is achieved through radios operating under Ultra High Frequency (UHF), Very High Frequency (VHF), or S-band¹ specifications which communicate with ground networks. The full system is composed of two main elements; the transceiver, which is the radio itself, and an antenna that tunes the radio's signal. Data handling and compression are also a part of the telecommunications system. A representation of the system is shown below in Figure 7.

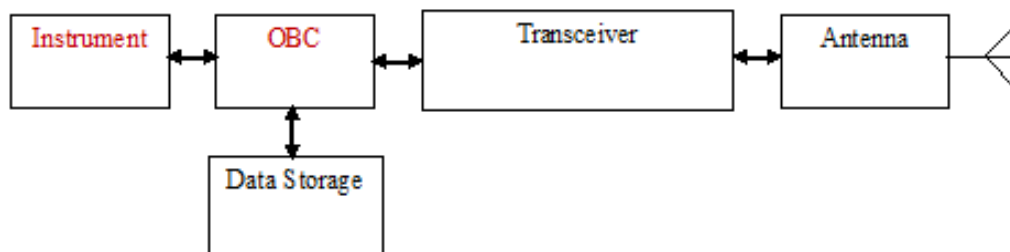


Figure 7: Telecommunications subsystem

The main driving factors in specifying telecommunications components are data rates, reliability of data delivery, and power consumption. Data rates are driven by instrument data requirements and are a function of signal sampling rate and bit rates. The reliability of the system is based on the robustness of the physical components along with correct specification of frequency bands and compression algorithms. Data is transferred by the use of packets, which are strings of data including control and user information. Packets received from the CubeSat should be able to be salvaged if incomplete; otherwise the packet would need to be resent,

¹ Frequency ranges for VHF, UHF, and S bands are as follows: VHF = 30-300MHz, UHF = 300-3000MHz, S-Band = 2-4GHz

costing precious downlink time. Finally, power consumption plays a key role as the radio is a comparatively large power draw, at up to 1.5W.

An important aspect of the telecommunications system is the ability of ground stations to monitor telemetry, track, and command the CubeSat. Various telemetry measurements taken by the OBC verify that the CubeSat is functioning properly and if not can give clues as to why a part is malfunctioning. Tracking provides verification of the CubeSat's position and trajectory by analyzing the time delay in sent and received packets. Finally, command functions allow the ground operations to access different modes of the CubeSat or address immediate problems.

Antenna

CubeSat antennas are optimized for small size and low mass while integrating with available UHF, VHF, or S-band transceivers. Two common antenna designs for CubeSats are patch antennas which affix to a side of the CubeSat and are little more than a thin, flat PCB with an imbedded antenna and deployable tape spring antennas which are affixed to a standard base and spring outwards from recesses in the CubeSat. An example of an ISIS deployable antenna system being considered for the current proposal can be seen below.

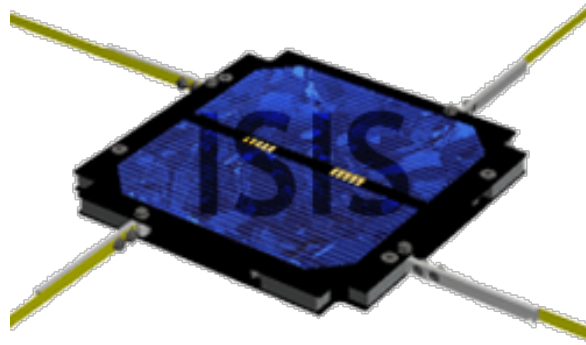


Figure 8: ISIS deployable antenna [9]

The common antenna types seeing use on CubeSats in the aforementioned configurations are monopoles, dipoles, and turnstiles. A monopole takes the form of a single radiating wire with a low gain and nearly spherical radiation profile. This makes it favorable for systems with low complexity and little to no pointing ability. The dipole and turnstile antenna types are comprised of 2 and 4 monopoles, respectively, which boosts antenna gain at the expense of more directional radiation profiles.

Transceiver

A transceiver is a single board housing both a transmitter and receiver circuit. The transceiver converts data from the OBC into a form that can be sent to ground stations via a carrier signal. The most common Transceivers for CubeSats operate in both the UHF and VHF bands. This allows the use of the VHF band for downlink and UHF band for uplink or vice-versa.



Figure 9: ISIS UHF/VHF transceiver [10]

Data Handling and Storage

The CubeSat does not have the luxury of being connected to a ground station during all times the instrument is taking data. For this reason it is necessary to include some variety of data handling and storage to process information from the instrument. A number of compression algorithms may be applied to the data on-board so as to reduce the storage requirement and increase the amount of data transferred to ground stations during the specified fly-over time. The compression and storage of data from the instrument is usually carried out by the OBC with the option of adding additional processing units and flash memory for dedicated high data operations.

2.2.3 Ground stations

An integral part of CubeSat communications are ground stations and ground station networks. A ground station is an on-ground terminal that links to the CubeSat through antennas,

transmitter, receiver, and control equipment to transmit and receive messages, track, or control the satellite [11]. Ground stations are located all around the Earth in a series of networks or within the atmosphere, such as using other satellites to communicate. There are different uses for ground stations: telecommunication with satellites, communication with space stations or space probes, or tracking. The earth stations use radio waves in super high frequency or extremely high frequency bands, with a frequency band of 3 GHz to 30 GHz for Super High Frequency (SHF) and 30 GHz to 300 GHz for Extremely High Frequency (EHF) [12].

When the station successfully transmits these radio waves a telecommunications link is established. A link is the communications channel that connects two or more communicating devices. There are several different types of telecommunication links: uplink, downlink, forward link, and reverse link. An uplink is the transmission between the earth terminal and the satellite. It is the inverse of the downlink, which is the link from the CubeSat to the ground station. A forward link is the link from a fixed location, such as a base station, to a mobile user. A forward link will contain an uplink, base station to satellite, and downlink, satellite to mobile user, if a communications relay satellite is involved. A reverse link is the link from a mobile user to a fixed base station. In the case of a communications relay satellite, the reverse link will have both an uplink, mobile station to satellite, and a downlink, satellite to base station [12]. A crosslink is the link between a satellite and another satellite. These links are part of a larger network within the ground station, a telecommunications network. This network is created through a collection of terminals, links, and nodes that all connect to ensure telecommunication between terminals and ground stations. A unique address is created for each terminal in the network so messages will be sent correctly. Address space is the collection of these unique addresses in each network.

The geometry of the links and the ground station create the telecommunication architecture. There are different types of architectures, each with their own advantages and disadvantages. “Store and forward” is an architecture for relaying communications by satellite. For this, the satellite orbits at a low altitude and receives data that is stored in its memory. The data is transmitted when the satellite is in view of a receiver ground station. The advantages of this architecture are that a low-cost launch vehicle and low cost satellite can be used due to the low altitude and wider antenna beam width which reduces the satellite antenna size and stabilization requirement. The disadvantage is there is a long message access time and transmission delay since they are waiting for the satellite to pass into view [13].

Geostationary orbit is used by communication relay satellite systems and meteorological satellites. The satellite is placed in a near-zero degree inclination orbit at about 36,000 km altitude. The orbit of the satellite is equal to the period of Earth’s rotation which is one of its advantages. The cost of a ground station is less because there is no need for antenna pointing control so it is a stationary network. A stationary network is easier to set up, monitor, control, and there is no need to switch satellites since the satellite is always in view. The disadvantage is the lack of coverage above 70 degree latitude and the high launch cost. There is also a delay time for propagation to and from the orbit which can cause problems [13].

A Molniya orbit is used to cover the northern Polar Regions with the satellites in highly elliptical orbits. The specification for the orbit is an apogee of 40,000 km (which is over the North Pole), a perigee of 500 km, and an inclination angle of 63.4 degree. The period of the orbit is 12 hours and since the orbit is highly elliptical, the satellite spends about 8 hours of each period over the northern hemisphere. A disadvantage of this geometry is that there is a continuous change of antenna positioning and switching links between satellites [13].

Geostationary orbit with crosslink is an architecture used when a geostationary satellite is beyond the line of sight of a ground station and a secondary satellite relays data to the ground station. A relay satellite is better than using two adjacent ground stations because the adjacent ground station is on foreign territory. Since it is on foreign territory there is more cost and the transmission is less secure and less survivable. The disadvantage of the relay satellite is it increases the architecture's complexity, risk, and cost [13].

2.3 Thermal Subsystem

2.3.1 Thermal Control Related ICD Requirements

A thermal vacuum bakeout test must be performed to ensure acceptable levels of component outgassing [2]. Outgassing is the release of volatiles (gas or vapor) that has been dissolved, trapped or absorbed in a material. The thermal vacuum bakeout test entails the CubeSat being placed in a high vacuum level of a minimum of 10^{-4} Torr and exposed to either 70 °C for 3 hours or 60 °C for 6 hours. The satellite must also be able to survive the temperatures of its environment (both during the launch and in space). The launch condition temperatures range from 1.7 °C to 37.8 °C and the thermal environment temperatures during its powered flight range from 7.0°C to 55.1°C [2]. The thermal environment the CubeSat will encounter should be considered for the two extreme cases where the satellite is fully lit by the sun and when the satellite is in an eclipse.

2.3.2 Analyses Required

The CubeSat needs to survive in the harsh space environment, which depending on the position of the satellite can be either extremely hot or cold. The thermal control system needs to keep the temperature within the allowable thermal limits of all components. This is why there is

a series of mandatory analyses and tests before CubeSat can be launched. The GSFC-STD-7000 reference document provides a table of requirements that must be met for different levels of assembly as well as identifying if analysis or testing is necessary [14]. It also outlines the requirements for each test: providing special considerations, demonstrations, and acceptance requirements. The table in Appendix 1 from the GSFC-STD-7000 document presents the vacuum, thermal, and humidity requirements.

According to the table, testing is required for all levels of assembly to meet the Thermal-Vacuum requirements as listed. For Thermal Balance, testing and analysis is required for payload or highest level of assembly, a completely assembled space craft [14]. If analysis verification is provided for subsystems and components, testing is not required at these levels of assembly. The CubeSat will not have any devices that contain fluids, so Temperature-Humidity and Leakage analysis and testing will not be required.

There are two vacuum tests that must be performed before launching the CubeSat: Thermal Vacuum Cycle and Thermal Vacuum Bakeout. According to the table included in the DNEPR² Safety Compliance Requirements reference document, the P-POD must go through both tests whereas the CubeSat must be tested in the Thermal Vacuum Bakeout [14]. For each test, the CubeSat and P-POD must undergo a protoflight and acceptance test. A list of requirements per test is in Figure 10³. The components are tested at safe levels to ensure they work.

² DNEPR is a Russian launch vehicle. It carried 14 CubeSats to be launched into space but failed to launch. [66]

³ Protoflight test levels are the same as qualification levels. They are performed on prototype components at extreme levels, nearly 1.4 times over the operating loads of the components [65].

Acceptance test levels are performed when the CubeSat passes the qualification and protoflight tests [65].

Table 1 – PPOD and CubeSat Environments Test Table

Tests	Qualification by Test	Protoflight Test	Acceptance Test
Thermal Vacuum Cycle (PPOD Only) Ref: MIL-STD 1540 B, GSFC-STD-7000	MPE ² +/- 10° C Minimum Range = -14 -3/+0°C to +71 -0/+3°C Cycles = 8 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr	MPE ² +/- 10° C Minimum Range = -14 -3/+0°C to +71 -0/+3°C Cycles = 4 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr	MPE ² +/- 5° C Minimum Range = -9 -3/+0°C to +66 -0/+3°C Cycles = 2 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr
Thermal Vacuum Bake out (PPOD Only) Ref: MIL-STD 1540 B, GSFC-STD-7000	N/A	Min. Temp 70°C ^{4,7} Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = N/A Vacuum = 1x10 ⁻⁴ Torr	Min. Temp 70°C ^{4,7} Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = N/A Vacuum = 1x10 ⁻⁴ Torr
Thermal Vac Bake out (CubeSat Only) Ref: MIL-STD 1540 B, GSFC-STD-7000	N/A	Min. Temp 70°C ⁵ Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr	Min. Temp 70°C ⁵ Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr
<p>(1) Dynamic Environments random MPE envelopes a P95/50 or mean + 5 dB of flight environments. Sinusoidal levels envelope loads predictions and flight environments. Shock MPE envelopes P95/50 for at least (3) samples, with 4.5 dB uncertainty factor applied where less than (3) samples are used.</p> <p>(2) Thermal MPE = Max predicted via simulation + 11° C for uncertainty.</p> <p>(3) Shock testing is not required when the following conditions are met: 1) The qualification random vibration test spectrum when converted to an equivalent shock response spectrum (3-sigma response for Q=10) exceeds the qualification shock spectrum requirement at all frequencies below 2000 Hz. 2) The maximum expected shock spectrum above 2000 Hz does not exceed (g) values equal to 0.8 times the frequency in Hz at all frequencies above 2000 Hz, corresponding to the velocity of (50 inches/second).</p> <p>(4) Maximum bake out temperature set to same maximum temperature for thermal cycle test for consistency, assuming bake out would be performed during same vacuum exposure.</p> <p>(5) If the CubeSat cannot achieve these temperature levels, the CubeSat shall hold a minimum temperature of 60°C for a minimum of 6 hours.</p> <p>(6) Levels are defined to be at the PPOD to Launch Vehicle mechanical interface.</p> <p>(7) Thermal bake out temperatures are not to exceed qualification temperatures</p>			

Figure 10: P-POD and CubeSat Environment Tests (Thermal) (2011) [3]

Thermal Balance

The purpose of the thermal balance requirement is to verify that the thermal control system is adequate during its orbit. For the analysis, simulations of extreme hot and cold case environments during orbit are required. Creating an analytical model of the CubeSat, its components, and the space environment allows for analysis of the thermal performance of the spacecraft [14]. A model can also predict the thermal performance of the CubeSat in a vacuum

chamber. Although it is not possible to simulate the exact space environment, analysis of the testing environment in the vacuum chamber is practical. The Mechanical, Power, and Thermal 2011-2012 MQP team used COMSOL as a tool to simulate the CubeSat within the space environment [1]. In the thermal simulation, factors such as solar and earth fluxes, conductive and insulated interfaces, ambient temperature, and emissivity of materials should be taken into account.

For the testing aspect of the Thermal Balance requirement, the duration depends on the payload, mission, payload operating modes, and time to reach stabilization. Stabilization occurs when control sensors change less than 0.05° Celsius per hour over a 6 hour period [14]. The CubeSat passes the Thermal Balance test when the difference between the predicted and measured temperatures is within the qualifying range⁴. The test precedes the thermal vacuum test in order to establish temperature goals for the vacuum test. For instance, the analysis gives a range of temperatures of the CubeSat throughout its orbit. From there, the Thermal Maximum Predicted Environment (MPE) can be generated. Thermal MPE is the maximum temperature from simulation plus 11 degrees Celsius added to account for uncertainty [14]. Knowing this, it can be much easier to match a profile for the Thermal Vacuum Bakeout and Cycle tests. These profiles are flexible for components that have more temperature sensitive ranges.

Thermal Vacuum Bakeout

During the Thermal Vacuum Bakeout test, the CubeSat is cleaned and placed in a vacuum chamber at an initial pressure of 10^{-4} Torr. Then temperature is then increased from 25°C to 70°C at a rate of no more than 5° Celsius per minute. It must bake for 3 hours to allow

⁴ The qualifying range is 10 degree increase in maximum and minimum expected flight temperature range. This range is determined from the thermal analysis [14].

proper outgassing of components in the CubeSat. Outgassing releases any gases or contaminants that were once trapped, frozen, or absorbed in the materials. If the CubeSat does not outgas properly, it could affect the performance of its components.

The bakeout profile depends on the results from the Thermal Balance analysis. For instance, the Thermal MPE can help choose a profile that is best for the CubeSat. It is important that thermal bakeout temperatures do not exceed qualification temperatures. From the plot in Figure 11, there are two profiles, each with a different bakeout temperature and duration. If there is a reason that the CubeSat cannot test at 70°C, the temperature may be lowered to 60°C, but it must bake for six hours instead of three.

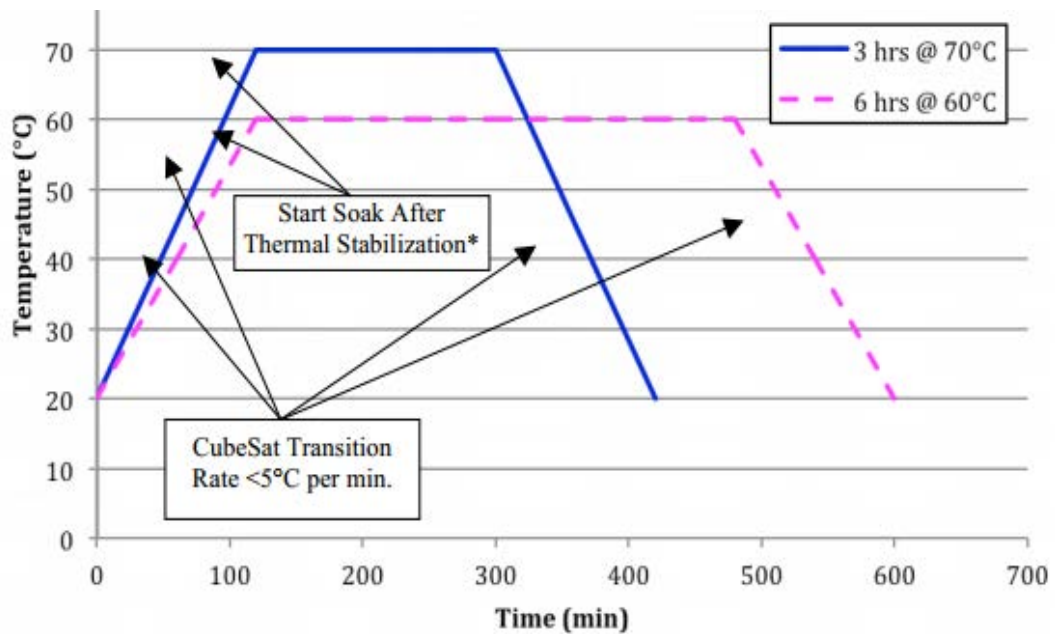


Figure 11: Thermal Vacuum Bakeout Profile [2] (2004)

Thermal Vacuum Cycle

The Thermal Vacuum Cycle test must be performed on fully assembled CubeSats before integrating into the P-POD. The DNEPR Safety Compliance Requirements document outlines

the procedure for the Thermal Vacuum Cycle test. The Thermal Vacuum Cycle procedure is listed in Appendix 1.

Based on analysis prior to testing, the temperature of the bakeout can decrease to 60° Celsius. However, an additional hour is added to the bakeout. When completing both vacuum tests, the profiles must be the same for consistency. So either the 70 or 60 degree Celsius profile must be picked for both tests. In the vacuum chamber, the pressure should remain constant and not exceed 10^{-4} Torr from the original pressure. If this happens, additional thermal baking is required until the vacuum chamber pressure is stabilized. In order for the P-POD to pass the Thermal Vacuum Cycle test, its maximum temperature range must be $MPE \pm 5^{\circ}\text{C}$.

2.3.3 Active/Passive Thermal Control Methods

The thermal control system of a spacecraft regulates the temperature for the entire unit. This system ensures that the temperature of the spacecraft does not exceed the survivability limits of any component at any time. It also ensures that the operational temperature for any component is not exceeded while the component is in use. If the temperature is not controlled, it can lead to component failure, or even the mission.

The thermal environment in space is extremely cold when there is no direct sunlight, radiation, or another source of light. When the spacecraft is exposed to radiation or sunlight the temperatures can climb above the operable or survivable limits. This is dependent on orientation of the CubeSat, or position in the orbit. However, inside the CubeSat there is a thermal control system to regulate the temperature, so that it does not depend purely on its orientation.

There are two categories of thermal control systems: active and passive. Active systems have the capacity to turn on or off to adjust the temperature in a more precise manner, whereas

passive systems are fixed in place and heat is transferred through a natural process rather than a mechanical one. Examples of active systems are heat pumps, louvers, or electric heaters or coolers, which are commonly used in larger spacecraft such as those transporting humans, or a very sensitive payload [15]. Passive systems can be in the form of heat pipes, thermal coatings, blankets, or radiators used in many different spacecraft, especially in smaller, simpler spacecraft, such as a CubeSat or other small satellites [15]. Passive thermal control will be used for this CubeSat.

Based on analysis of the model of the CubeSat performed in COMSOL, the use of thermal coatings and a well-placed radiator will suffice for the majority of the life of the CubeSat. The P-POD requirements state very specific temperature ranges that the CubeSat must survive in. In order to meet these requirements, the most careful analysis and testing will need to be focused on this portion of the mission.

3 Methodology

3.1 Power Subsystem Distribution

The electrical boards associated with the CubeSat can be stacked vertically and interface with each other through an integrated CubeSat bus. The CubeSat bus is a 104 pin connector interface that consists of two side by side 52 pin headers that each has a part number of ESQ-126-39-G-D and is as labeled in Figure 35 [7]. Starting from the top, a possible board stack is layered as follows: the UHF Transceiver, the Attitude Determination and Control (ADC) board, the battery board, the EPS board, the PDM board and the OBC board. The UHF Transceiver board regulates the transmitted and received signals. The ADC board regulates the attitude of the CubeSat. The EPS board converts the power provided by the solar arrays into specific usable voltages and provides power to the battery for charging. The PDM board distributes the power to the various components of the CubeSat and the OBC board regulates the entire board stack and all the devices attached to it.

Electrical power is generated by three solar panels and is routed to the Solar Array (SA) connectors on the EPS board. The SA connectors have a part number of DF13-6P-1.25DSA (50) and are as labeled in Figure 37 [6]. Each of the three SA connectors allows a maximum of two solar panels to be connected to it, enabling a total of six solar panels to be connected to the EPS board [6]. SA connectors one and two are for a maximum of eight Watt solar arrays, and the third SA connector is for a maximum of three Watt solar arrays [6]. As the CubeSat Solar Panels being used each generate more than three Watts, only two of the three SA connectors on the EPS board are suitable for connecting to the solar arrays. The third SA connector will therefore remain unconnected. Each SA connector then connects to its own Battery Charge Regulator (BCR) on the EPS board. The BCR's charge the battery and have two modes of operation. The

Maximum Power Point Tracking (MPPT) mode is enabled when the voltage of the battery falls below a preset voltage. Once it falls below this voltage the BCR's operate at the maximum power of the solar panels to charge the battery. The End of Charge (EoC) mode is enabled when the voltage of the battery reaches the preset value. Once it reaches the preset voltage, it is held constant and a current from the solar panels is used to finish charging the battery. The BCR's are also responsible for supplying power to two Power Conditioning Modules (PCM's). The PCM's then condition the power into separate 3.3 Volt and 5 Volt power outputs with a deviation of +/-1 percent [6]. The output power of the PCM's as well as a direct connection to the battery, are then routed to the PDM board through the CubeSat bus.

The PDM board has 24 switches which can be used to turn different components of the CubeSat on or off. Switches 1-7 have a max voltage of 3.3 Volts, switches 8-14 have a max voltage of 5 Volts, and switches 15-19 have a max voltage of 8.3 Volts as they connect directly to the battery. Switches 20-24 allow for a user specified max voltage, however the user specified voltage must be applied to pins H2:51 and H2:52 of the CubeSat bus. Each switch also has a recommended current trip of 0.25 Amps, 0.5 Amps, 1 Amp or 4 Amps. The current trip is a maximum current that the switch can handle before it trips a circuit breaker. A complete list of each of the switches maximum voltage and current trip are located in Table 9 and Table 10 of Appendix 9. Three of the switches (7, 14 and 19) also differ from the other 21 switches as they can connect three devices to one switch. The power return for all switches must also go to the ground pins H2:29, H2:30, or H2:32 of the CubeSat bus.

The boards in the stack and the OBC receive power through pins 35 and 36 of the second header of the CubeSat bus and as a result are not powered on or off through a switch on the PDM board. Once the pull pin is removed and the deployment switches are no longer actuated the

boards in the stack receive power without interruption [6]. The only components that require switches to power them on or off are the three magnetic torquers, the magnetometer, the GPS, the payload, and the gyroscope.

3.1.1 Telemetry Communication

Each SA connector on the EPS board receives sensor information about the temperature, voltage, and current of each solar panel and sends it through the CubeSat bus. The sensor information for the 3.3 Volt bus, the 5 Volt bus, and the 8.3 Volt battery bus are also sent to the CubeSat bus along with the ground sensor information. In a case where six solar panels are used this would total 32 analog inputs, and if only three solar panels are being used, only 25 of the allotted 32 analog inputs would be used. The 32 analog inputs are located on the Header 1 (H1) header of the CubeSat bus as shown in Table 9 of Appendix 9. The analog inputs begin their numbering with 9 instead of 1 because the PDM board has a different connector for its own separate eight analog inputs. The board interfaces with the 32 analog inputs through one multiplexer and the other 8 analog inputs through another multiplexer. This is done because the 32 analog inputs all range from 0 to 3 Volts, and the other eight analog inputs may not have the same voltage range. The multiplexer is used to forward the selected analog input to the OBC.

Each of the 24 switches can be commanded on or off by the OBC. The status and current through the switch can also be retrieved at any time by the OBC. To control the switches and access any of the analog inputs an Inter Integrated Circuit (I²C) network is used. An I²C network consists of a two line system between the boards; a clock line and a data line. Each board connected to the CubeSat bus also has an I²C node on it which can communicate with the master I²C node on the OBC. The I²C network can also be used to specify an initial switch configuration on power up of the CubeSat.

The PDM Board is also capable of connecting to five serial-based devices. The Serial interfaces are designed to act as bridges or buffers between serial based devices and the I²C network. The components of the CubeSat that would connect to the PDM through a serial interface are the magnetometer, the GPS and the payload.

3.1.2 EPS Switch Configuration

The EPS Board has connection points that connect to the two separation switches and the pull pin. When the pull pin is inserted in the CubeSat or either of the deployment switches is actuated all power to the CubeSat is stopped. A possible connection between the CubeSat bus's second header pins and the deployment switches and the pull pin is shown in Figure 12 below. The dummy load prevents damage to the BCR when the solar arrays are attached and the battery is not connected. This feature is not a requirement and is only intended as a suggested protection while the pull pin is connected.

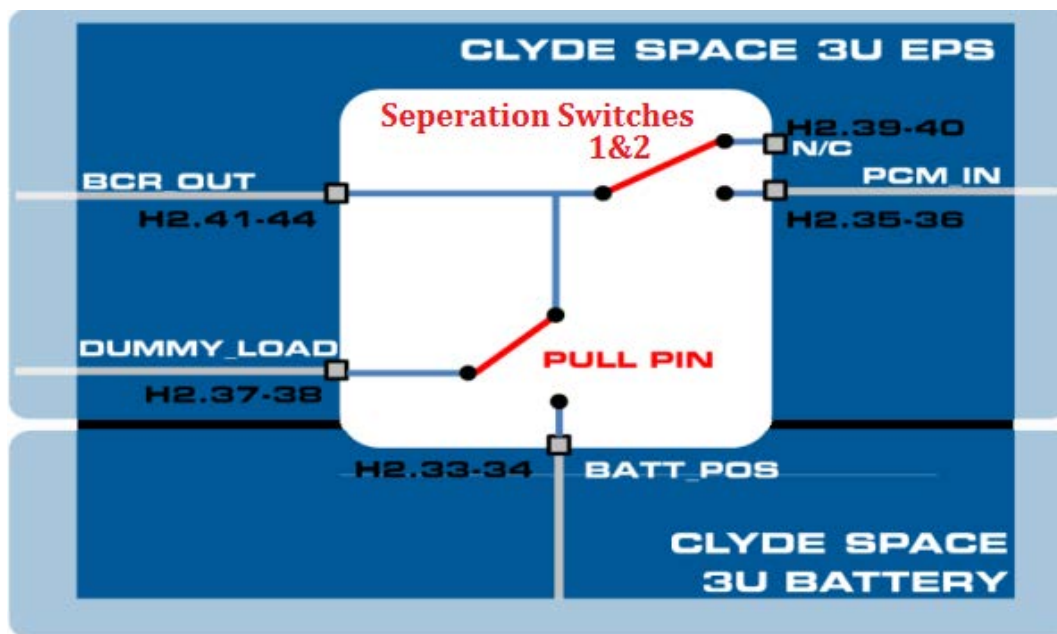


Figure 12: Possible Configuration of Pull Pin and Separation Switches (adapted from [6])

3.2 Telecommunication Subsystem

3.2.1 Implementation of Telecommunication Subsystem Hardware

For the proposed mission, a strong emphasis will be put on transferring data collected by the onboard instrument back to ground stations. This requires a telecommunication system structured around multiple robust, efficient connections with high data transfers. To meet these requirements, hardware designed for CubeSat communication has been selected to maximize transmitter output and data rates. This selection will set the baseline for selecting ground stations to maximize access and in turn the total data that can be transferred.

UHF Primary Downlink and VHF Uplink

The ISIS TRXUV UHF (400-450MHz)/VHF (130-160MHz) Transceiver has been selected for the primary radio for its reliability and full-duplex (simultaneous transmit and receive) capability. It is a well rounded platform offering reasonably high data rates of 9600bits/s in a CubeSat specific package designed to work seamlessly with the other components. It fulfills all the requirements of a CubeSat transceiver, accommodating telemetry downlink, tracking, and command uplink.

Modulation is handled by Binary Phase Shift Keying (BPSK), Frequency Shift Keying (FSK), Audio Frequency Shift Keying (AFSK), or Manchester FSK as specified by the user. These are simple modulation schemes centered around either phase or frequency shifting to carry data; in this case a series of binary bits. While there are more powerful modulation techniques to expand bandwidth or raise efficiency compared to these simple modulations schemes, the simplicity of the proposed system makes implementation straightforward and makes the system more robust and flexible.

The antenna options for cubesats are limited due to space requirements. Generally CubeSats use one of four configurations: monopole, dipole, turnstile, and patch antennas. The antenna system best suited to the mission is the ISIS deployable UHF/VHF antenna system. This allows the use of one of three configurations: four monopole antennas, two dipole antennas, or one turnstile. For this mission, the dipole configuration was chosen because of its ability to run both a UHF transmitter and a VHF receiver from the same unit providing a compact solution. Along with the semi-omnidirectional profile of the dipoles, which will limit the pointing losses regardless of orientation, this antenna offers a comprehensive solution to the antenna choice for the CubeSat.

S-Band Secondary Downlink

To further increase the downlink data rate, a secondary radio operating on the 2.4 GHz S-band is being considered. The Clyde Space STX⁵ is a transmitter designed specifically for this purpose on CubeSats and could significantly enhance the transmission capabilities of the CubeSat. The S-band allows for data rates up to 2 Mbps⁶, however it comes at the price of reliability, power, and cost. There are also fewer ground station options for S-band CubeSats, although the band is widely used on larger commercial satellites.

Modulation is handled by QPSK (Quadrature Phase Shift Keying), which is partly responsible for the high data rate. QPSK uses four phases of modulation, as opposed to two for BPSK, so it can handle twice the data for the same bandwidth and Bit Error Rate(BER). The downside is the complexity of QPSK and the higher power needed.

⁵ STX: S-Band Transmitter from ClydeSpace

⁶ Mbps: Mega Bytes per Second

Antenna options for S-band are primarily limited to patch antennas due to the higher power required for equivalent bandwidth compared to UHF or VHF. Although patch antennas are simpler and easier to implement than deployable dipoles or similar, they are highly directional, producing a beamwidth of approximately 65° with significant losses outside of this range. This proves problematic for this mission proposal since the pointing requirements for the Cubesat are sun dependent and there is no primarily nadir (Earth facing) side to mount the antenna. A possible solution is the use of ground stations near the equator where the $-Z$ side of the satellite would be within the pointing requirements.

3.2.2 Ground Station Network

Ground tracks are the projected path of a satellite's orbit on the surface of the Earth, which traces the movement of an imaginary line between the satellite and the center of the Earth. Also it is considered a set of points that the satellite will pass directly over in the frame of reference of a ground observer [16]. There are a few parameters that can cause variations in the ground tracks, such as orbital period and orbital inclination. A satellite with an orbital period of an integer fraction of a day (24 hours, 12 hours, 8 hours, etc.) will for the most part follow the same path day to day. The ground tracks will be shifted east or west depending on the longitude of the ascending node, which vary over time due to perturbations of the orbit. If the period is slightly larger than an integer fraction of a day the ground track will shift west over time and will shift east if it's slightly shorter. Orbital inclination is the angle formed between the plane of an orbit and the equatorial plane of the Earth. The orbital inclination, i , will range from $-i$ to i for the geographic latitudes covered by the ground track. The larger the inclination then the further north and south the satellite's ground track will pass. An inclination of exactly 90° is said to be in a polar orbit, it passes over the Earth's north and south poles.

To create the CubeSat's ground tracks, STK was used to analyze the orbit and input ground station characteristics. Baseline orbital characteristics for this year's project: a 24-hour period, an inclination of 98.44° , an altitude of 700 km, and relative angle of the ascending node (R.A.A.N) of 142.252° were used to create a satellite in the program. Once the data was entered, ground stations could be added. Initial studies used ten different ground stations from the Global Educational Network for Satellite Operations (GENSO) network listed below in Table 2 [17].

Institution	Location	Country
CalPoly	San Luis Obispo, CA	United States of America
Warsaw University of Technology	Warsaw	Poland
Politecnico di Torino	Torino	Italy
University of Michigan	Ann Arbor, MI	United States of America
University of Texas	Austin, TX	United States of America
University of New Mexico	Albuquerque, NM	United States of America
Delft University of Technology	Delft, South Holland	Netherlands
University of Applied Sciences	Heidelberg	Germany
University of Montpellier	Montpellier	France
University of Vigo	Vigo, Galicia	Spain

Table 2: Preliminary 10 Ground Station Locations

To input each ground station, latitude and longitude of each ground station was found and recorded. This provided a basic ground station model in STK but allowed for further restrictions to be added, such as altitude of the ground station. A ground track and access a report of coverage could then be created using through STK. The access report states how long the satellite is in contact with each ground station and how many times it is in contact.

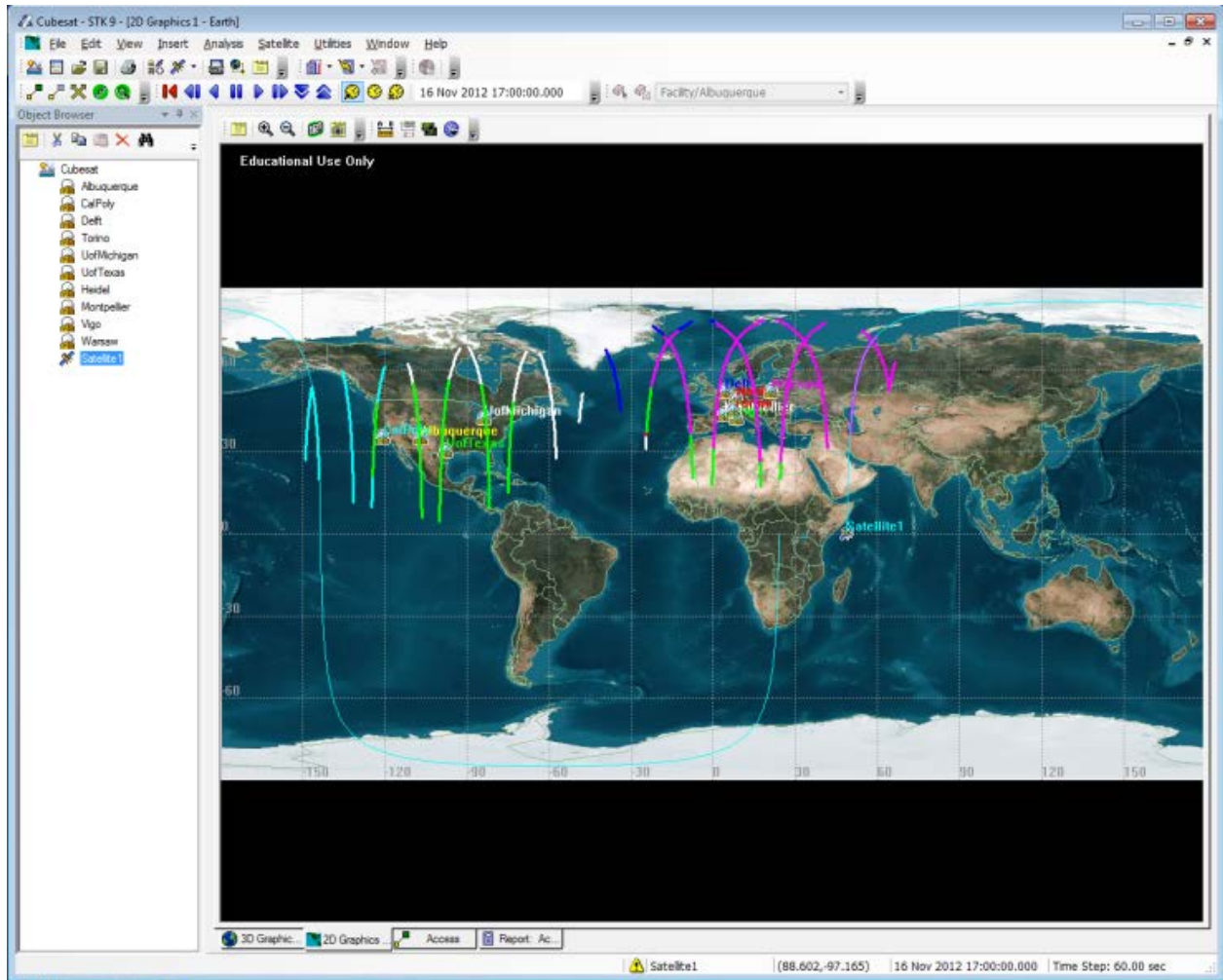


Figure 13: Ground track with ground stations

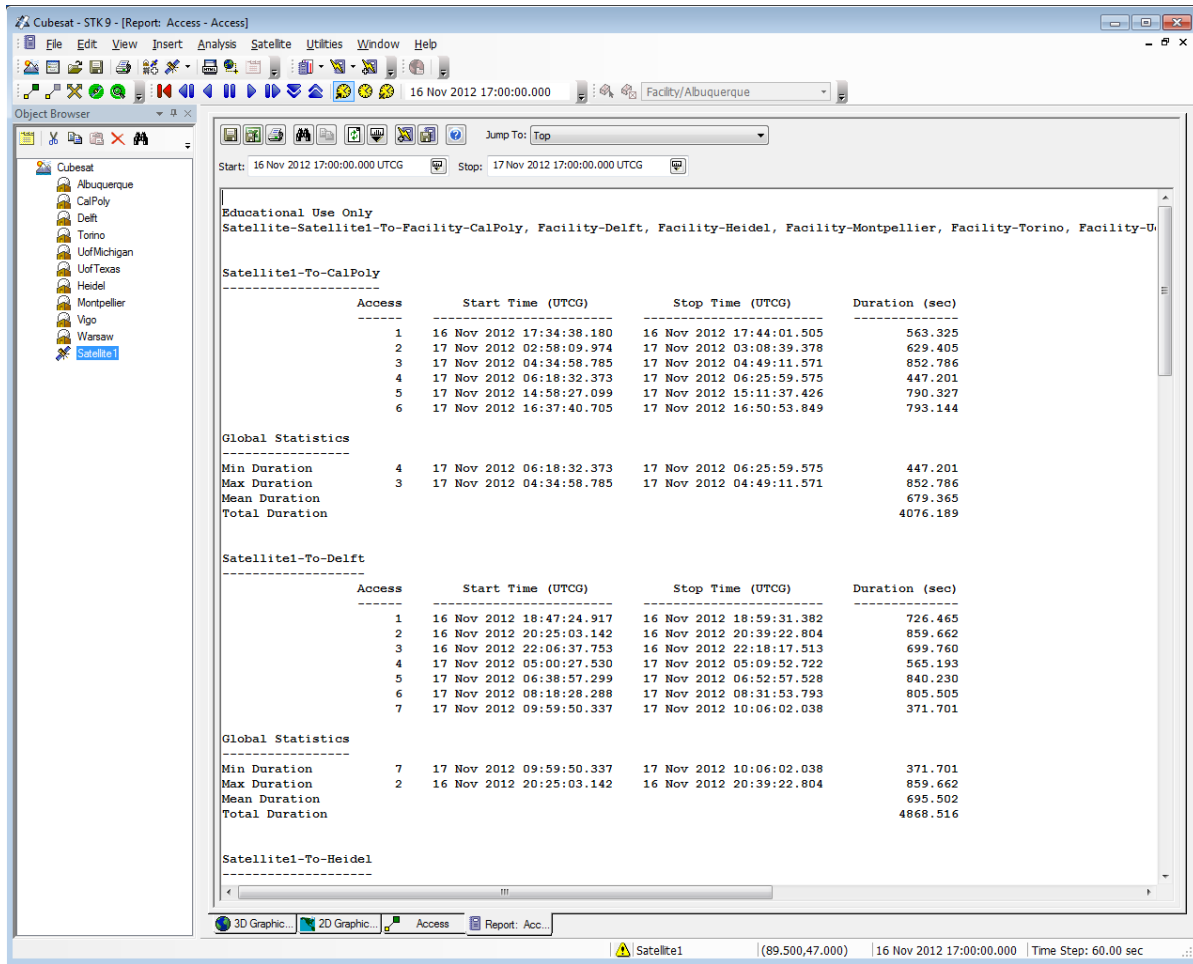


Figure 14: Access Report

Figure 13 is a screen shot of the ground tracks over the ground stations. The thin, light blue line is the ground track that the satellite is on. The thicker, different colored lines are the portion of the ground tracks during times the satellite is in contact with a ground station. The different colors correspond with the different ground stations. Figure 14 is a screen shot of the access report that STK compiles from the information on the satellite orbit and the ground stations. From this information ground stations were streamlined to only focus on how much data could be transmitted. The final choices are listed below in Table 3.

Institution	Location	Country
Nicolaus Copernicus Astronomical Center	Warsaw University of Technology	Warsaw, Poland
Delft Command Ground Station (DCGS)	Delft University of Technology	Delft, Netherlands
FASTRAC	University of Texas at Austin	Austin, Texas
Cal Poly Earth Station – N6CP	California Polytechnic State University	San Luis Obispo, California

Table 3: Final Ground Station Locations

The appropriate antenna information was added to each ground station and a second access report and link report was run. From the link report shown in Figure 15, the amount of data that will be transmitted during the 24 hour period is given.

	Time (s)	Data (Mb)
Total:	10008.3	96.0
Min:	240.2	2.3
Max:	632.8	6.0
Mean:	500.4	4.8

	EIRP (dBW)	Rcvd. Frequency (GHz)	Rcvd. Iso. Power (dBW)	Flux Density (dBW/m ²)	g/T (dB/K)	C/No (dB*Hz)	Bandwidth (kHz)	C/N (dB)	Eb/No (dB)	BER
Min	4.99	0.43549	-145.28	-131.04	4.43	87.79	288	33.20	47.97	1E-30
Max	23.13	0.43551	-118.58	-104.34	4.52	114.54	288	59.95	74.72	1E-30
Avg.	18.23	0.43549	-131.73	-117.49	4.49	101.35	288	46.76	61.53	1E-30

Figure 15: Link Budget

Calpoly			
Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	08:56.7	19:01.9	605.1
2	46:11.5	53:38.8	447.3
3	58:22.4	03:46.3	323.9
4	31:58.9	42:22.7	623.7
		Total:	2000.2
		Min:	323.9
		Max:	623.7
		Mean:	500.0

Delft			
Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	08:46.6	19:19.1	632.4
2	47:38.8	53:36.5	357.7
3	48:26.6	56:10.1	463.5
4	23:22.4	33:55.2	632.8
5	00:05.2	07:25.1	439.8
6	46:06.8	55:05.2	538.3
		Total:	3064.7
		Min:	357.7
		Max:	632.8
		Mean:	510.7

University of Texas			
Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	31:11.0	40:47.4	576.3
2	07:40.9	15:48.1	487.1
3	23:32.0	27:52.1	260.0
4	56:32.9	06:54.9	621.9
		Total:	1945.6
		Min:	260.0
		Max:	621.9
		Mean:	486.4

Warsaw			
Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	09:30.8	18:06.1	515.2
2	13:18.2	17:18.4	240.2
3	46:51.1	57:16.4	625.3
4	23:02.6	32:04.0	541.3
5	10:48.7	18:11.4	442.7
6	44:20.2	54:53.1	632.8
		Total:	2997.7
		Min:	240.2
		Max:	632.8
		Mean:	499.6

Figure 16: Access Report for the Four selected Ground Stations

As the access report in Figure 16 shows, the total data in a 24 hour period is 98 Mb. To increase the possible amount of data transmitted, more research on adding more ground stations to expand the coverage of the satellite will have to be done. Figure 16 also shows the most the satellite will pass over any given ground station is six times every fifteen orbits. Ground stations in the area of Asia or at least further away from other ground stations will need to be researched since there is significant overlap between current ground stations being used.

3.2.3 STK Analysis

A critical step in design of a telecommunications system is modelling of the links through STK an AGI (Analytical Graphics Inc.) software suite designed to model various satellite systems and missions. This project made use of various communications tools within STK.

Scenario

STK allows users to define orbital and mission based parameters to simulate various systems and scenarios. Various orbits can be simulated to understand the direct effects of orbital characteristics on the system. Objects such as satellites, ground stations, targets, and celestial bodies can be added to the model and constrained to the mission specifications. The satellite capabilities can be constrained through specification of transmitters, receivers, and antennas to map the various links. Ground stations are indicated on the earth map with the analysis using the transmitters, receivers, and antennas specified by the user for each of the sites.

Figure 17 below shows the ground tracks of the CubeSat and locations of the four chosen ground stations in Warsaw, Delft, Cal Poly, and University of Texas. The access to these stations is highlighted and color-coded to the specific stations.

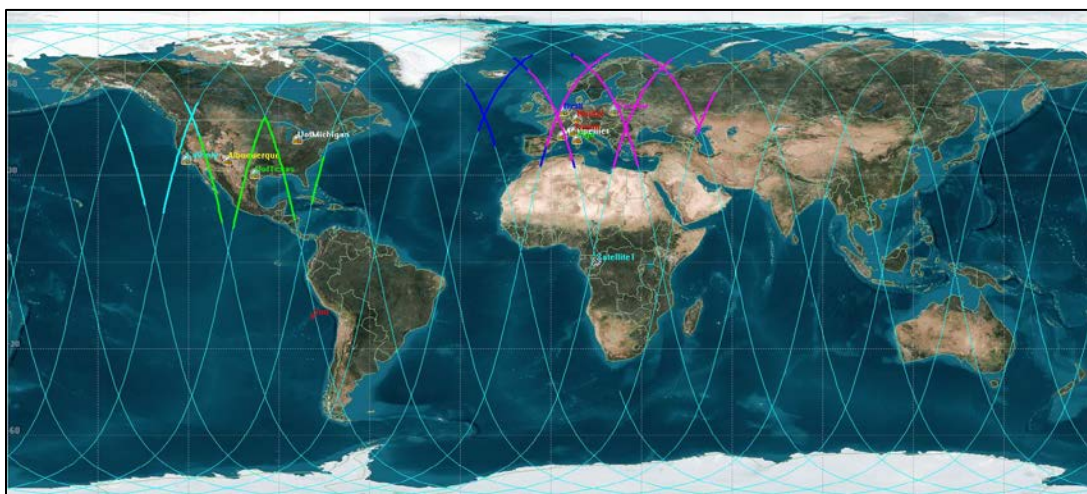


Figure 17: Ground tracks of the CubeSat plotted using STK.

Limits and Constraints

The satellite itself is constrained by the orbital parameters, which are the baseline orbital characteristics for this year's project: a 24-hour period, an inclination of 98.44° , an altitude of 700 km, and R.A.A.N of 142.252° . Optimally, a sun synchronous repeating trace orbit would be used, but this is beyond control.

The satellite is assumed to have a transmitter operating in the UHF band with the following characteristics:

- Frequency : 435.5 MHz
- Power: 0 dBW (1 Watt)
- Data Rate: 9.6 Kb/s
- Modulation: FSK
- Pointing loss: -1 dB

The assumed antenna on the CubeSat is designed for the UHF band with the following characteristics.

- Dipole
- Length: 0.55 m
- Length/Wave Length: 0.799
- Efficiency: 55%
- Refraction Model: ITU-R P.834-4 ⁷
- Range limit: 3000 km.

Each of the ground stations incorporated a medium complexity receiver model with the following constraints:

- Gain 32.8 dB
- Line Loss: 4dB
- Antenna noise from sun, atmosphere, rain computed by STK
- LNA (low noise amplifier) noise figure 1.2 dB
- Refraction Model: ITU-R P.834-4
- Min Elevation angle 5 deg.
- Doppler Shift: +/- 25 kHz

⁷ ITU-R P.834-4: Effects of tropospheric refraction on radiowave propagation. International Telecommunications Union. [67]

Reports

From the aforementioned modeling constraints, STK can calculate the maximum access and link conditions for the model. This data is recorded within STK and can be exported in a number of report formats. The reports providing the needed information to accurately assess the telecommunication system capability.

The Access Reports consist of the duration and occurrence of links between the satellite transmitter and ground station receivers. This is affected by the orbital parameters and the field-of-view of the satellite and ground station, especially the effective range of the transmitter and the minimum elevation of the field-of-view from the ground station. Figure 18 shows the CubeSat within range of the Delft and Warsaw ground stations. STK calculates the coverage for both, although when considering the amount of data received, it should be noted that data will be redundant when two ground stations are connected to the Cubesat simultaneously. However, this does have the benefit of being able to check the stream of data using two or more sources for increased accuracy.

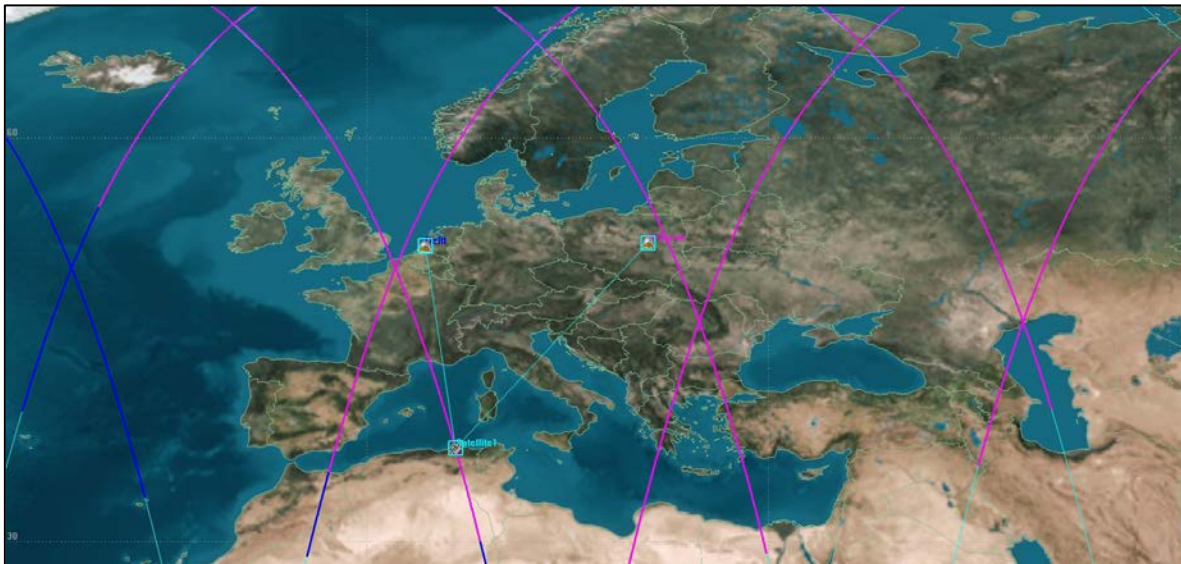


Figure 18: Ground track showing location of satellite connected to two ground stations (Delft and Warsaw).

Figure 15 is the access report data from a 24 hour period. In this time the CubeSat would make approximately 15 orbits around the earth, clearly demonstrating that there is marked room for improvement in coverage.

The link budget supplies vital data of the various link characteristics such as EIRP (Effective Isotropically Radiated Power), RIP (Received Isotropic Power) and BER. The values are calculated by STK and can be analyzed to determine further constraints in the simulation and specify the proper components. The output values can be seen in Figure 16.

3.3 Thermal Subsystem

3.3.1 Thermal Analysis from External Sources

CubeSat Attitude Determination and Control MQP Team 2011-2012 [18] used STK to find spacecraft-sun vectors for multiple orbits. The spacecraft-sun vector is coordinates of the satellite from its location to the sun. These values were converted to beta values where the magnitude of the vectors equal 1. Once the time-dependent beta values were found, the next task was to import them into COMSOL to begin the next step in the thermal analysis. With these values the solar flux can be made time dependent. Since the position of the CubeSat is changing over the course of its orbit, the solar flux will vary with time. The Mechanical, Power, and Thermal CubeSat Team 2011-2012 defined the magnitude of the solar flux during its orbit by using a rectangle function [1]. This function is set with a one variable expression with a lower limit and an upper limit. The team set these limits to 0 to represent no sun and 1 for full exposure to sunlight. The rectangular function was then imputed into an analytic function where it was periodically repeated for the time of two orbits. However, the group did not take into account the position of the satellite with respect to the sun. That is why the beta values are essential for the

thermal analysis. It will produce more accurate results in order to create a better thermal management plan.

To import the spacecraft-sun vectors, an interpolation function was used, as defined under Global Definitions in COMSOL. An interpolation function can fill in a table or be imported as .csv or .txt files. A defined interpolation function contains values of t and $f(t)$. For this model, the t represents the time in orbit and $f(t)$ represents the beta values. A .csv file was imported for each component of beta. Beta will change over time since the position of the satellite is changing throughout its orbit. With the beta values defined, an equation was created for a time dependent solar flux. The solar flux is defined as:

$$q_{sun} = 1367 \frac{W}{m^2} \quad \vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \quad \vec{\beta} = \begin{bmatrix} \beta_x \\ \beta_y \\ \beta_z \end{bmatrix}$$

$$Q = q_{sun}(\vec{n} \cdot \vec{\beta}) \quad \text{Equation 1}$$

The average flux from the sun is q_{sun} and \vec{n} is the unit normal vector of each face of the CubeSat. Q is the total solar flux on the CubeSat. Some preliminary analysis was needed to ensure Equation 1 worked. First, it was tested on an arbitrary Two-Dimensional (2D) surface of dimensions 10cm by 10cm in order to see the effects of solar flux over time on the surfaces. Once the results from the 2D analysis concluded that COMSOL can solve the solar flux equation, a Three-Dimensional (3D) cube of dimensions 10cm by 10cm by 10cm was modeled. As shown in Figure 19, there is a significant difference in temperature from the initial to final time step, 0 to 172800 seconds. With the preliminary analysis complete, the analysis was implemented onto the final version of the CubeSat Model.

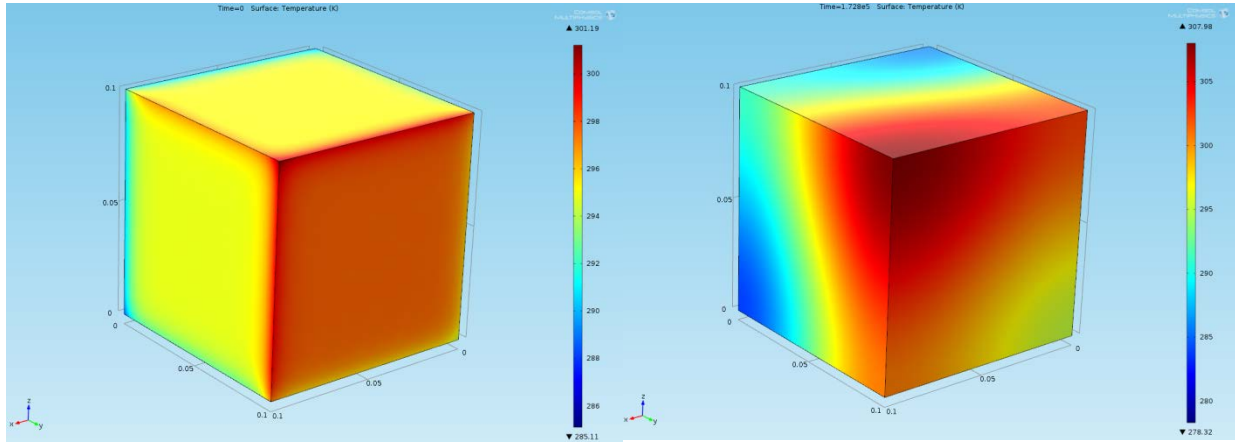


Figure 19: (Left) 3D cube at time $t=0$ sec & (Right) 3D cube at time $t=172800$ sec

3.3.2 STK Analysis

The sun's effect on the CubeSat throughout its orbit was analyzed using a program called Systems Tool Kit. This program has the capability to simulate any orbit for any period of time and export the data needed to understand all aspects of the orbit. The data gathered for this project were the components of the vector between the satellite and the sun, in reference to the spacecraft's coordinate system. The data was taken for a simulated orbit over a 24 hour period and the data was recorded every 5 minutes. The data consisted of the x-component, the y-component, and the z-component of the spacecraft-sun unit vector.

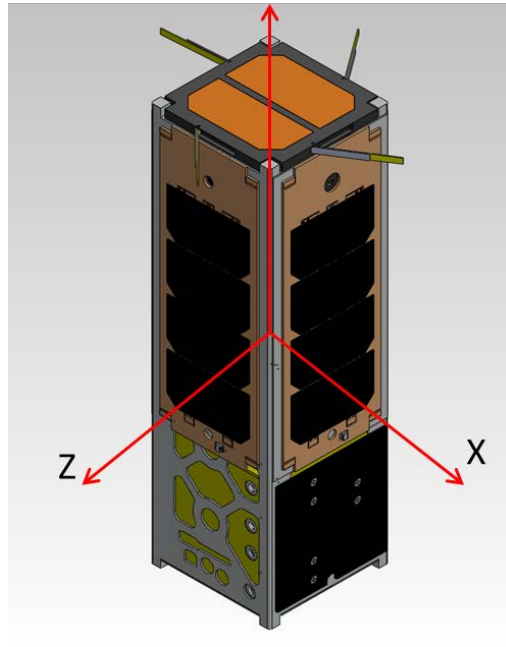


Figure 20: CubeSat Axes [1]

As shown in Figure 20, the x, y and z correspond to the CubeSat coordinate system with its origin located in the center of the CubeSat. The z-axis points in the general direction of the sun (not directly at it, or there would be no x or y components), the y-axis points through the “top” of the CubeSat, and the x-axis points through the “side” of the CubeSat. The data (See Appendix 3) was exported into a .csv file to be used to set boundary conditions in the COMSOL program (see Section 3.3.1).

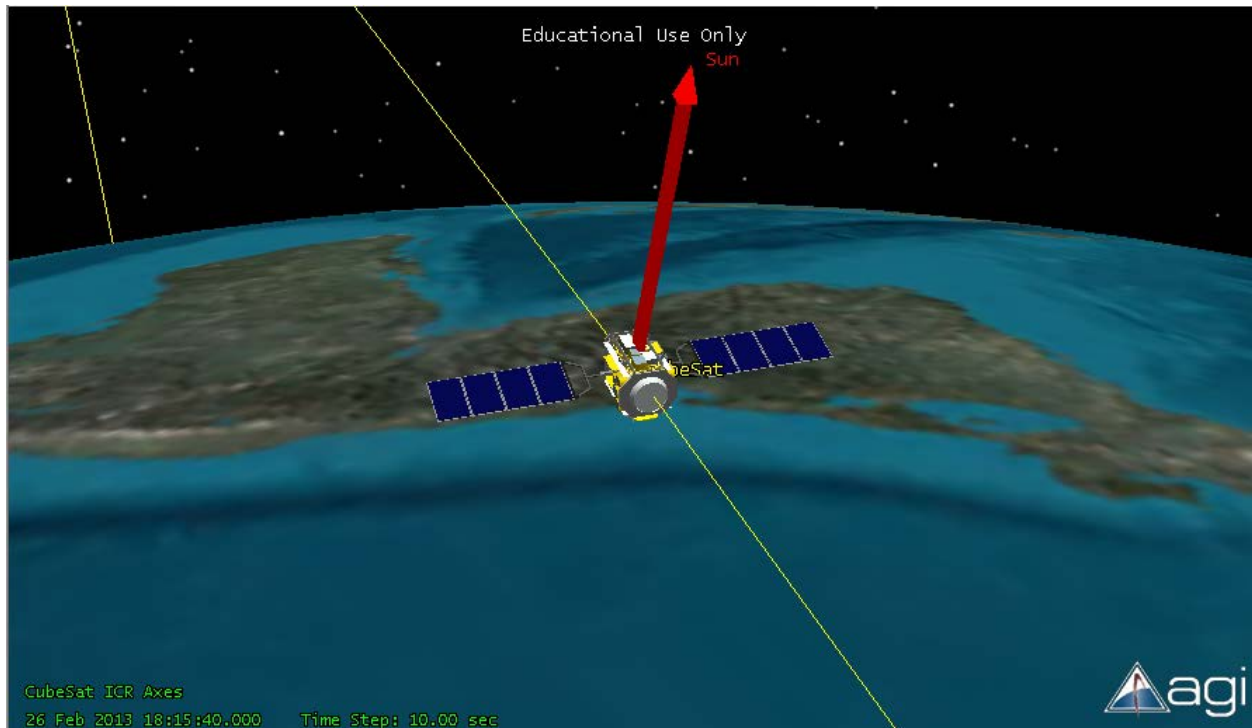


Figure 21: CubeSat-Sun Vector

Figure 21 shows the simulated orbit and the vector from the CubeSat pointing to the sun (which changes its angle over time). It can be seen here that the orbit path goes behind the earth on multiple occasions. However the recorded data does not indicate when the CubeSat is behind the Earth or when it is in direct sunlight. These periods of occultation need to be independently identified by the user because it will affect the fluctuation of the thermal profile.

3.3.3 Vacuum Modeling in COMSOL

One of the thermal P-POD requirements states that a CubeSat must undergo a Thermal Vacuum Bakeout test before it is integrated into the P-POD. The Mechanical, Power, and Thermal CubeSat MQP 2011-2012 team began a lab option to perform a vacuum test using the vacuum chamber located in the basement of Higgins Laboratories on the WPI campus [1]. For analysis and testing, they chose the simple aluminum structure that the Mechanical and

Structural Subgroup built which is shown in Figure 22. They believed that using this structure would be much easier to perform thermal analyses and form meshes during COMSOL analyses. Using what was suggested for future groups, a model was created to be simulated in COMSOL.



Figure 22: Aluminum Skeleton for Lab Option (2012) [1]

Before creating a model for analysis, a layout had to be developed for the Lab Option. In the chamber, the CubeSat skeleton would be suspended from the aluminum stand, created by the Mechanical and Structural Subsystem. The stand and the skeleton would be positioned in front of the cryopump. A halogen lamp will simulate the heat flux from the sun and be positioned on the other side of the cryopump.

In choosing which heat transfer module to use, the best option was “Heat Transfer with Surface-to-Surface Radiation.” Two other options had “Radiation in Participating Media” which implies that there is air or fluid in the system. When the cryopump pumps air out of the chamber,

it reaches temperatures close to absolute zero and pressures below 50 mTorr. Based on this knowledge, the ambient temperature inside the chamber was set to 30 degrees Kelvin.

During testing, five thermocouples measure the temperature at arbitrary points on the aluminum CubeSat skeleton. Since the size and weight of the thermocouples are relatively small in comparison to the other geometries, there is no need to model them in COMSOL. A 1-D plot group was chosen to view the temperature readings from the thermocouples. In this setting, edges or points of the skeleton are selected to view the temperature range for each time interval. These plots allow for comparison of results from the analysis to the lab option test.

3.3.4 Lab Option in Vacuum Chamber

To validate the COMSOL thermal model of the CubeSat structure, an experiment in a vacuum chamber was prepared. All materials were purchased so but there was not enough time to run the experiment.

<u>Material</u>	<u>Manufacturer</u>	<u>Part Number</u>
Halogen Lamp and Bulb	Workforce	778-980
Aluminum Sheet	MSC Industrial Supply Co.	09426057
PCB	Mouser Electronics	590-588
Thermocouples	Omega	5SRTC-GG-(K)-24-(36)
Thermocouple extension wires	McMaster-Carr	3870K32
Connectors for the thermocouples to the chamber feedthroughs	McMaster-Carr	3869K48
Chamber electrical feedthrough	Kurt J. Lesker Co.	EFT0042031

Table 4: Lab Option Materials Purchased

Additional information on each item listed in Table 4 can be found in Appendix 4. The LabView file that will be used to collect and analyze the data was developed by the CubeSat MQP 2011-2012 team that first provided suggestions for a vacuum chamber experiment [1].

The experimental procedure involves three major steps as follows. Prior to actual testing, a detailed procedure will need to be prepared for each of these.

1. Mount lamp and CubeSat model so that they are thermally isolated from the chamber walls using monofilament (fishing) line.
2. Place thermocouples in selected locations to measure the thermal profile of the CubeSat.
3. Run vacuum chamber with lamp on and take data both from the sides exposed to the light and not exposed to the light.

The results of this experiment can be compared to the results of the COMSOL simulation of the same situation.

3.3.5 Thermal Control System

The thermal control system ensures that the operational temperatures of each component are not exceeded. The following table shows the operating temperatures for the equipment on board. The data has been collected from the specifications given by the manufacturers.

Component	Operational Temp (°C)		Reference
OBC	-40	85	[19]
ADC board	No Data		[20]
Course Sun Sensor (3 or 5)	-40	100	[21]
Fine Sun Sensor	-25	50	[9]
Gyro	-40	105	[22]
Magnetic Torquers (3)	No Data		[23]
Magnetometer	-30	85	[24]
GPS	0	50	[25]
SphinX NG Instrument	Self-regulating thermal abilities		-
EPS Board	-40	85	[6]
PDM Board	-40	85	[7]
Battery	-10	50	[26]
Front Solar Panels	-40	80	[27]
Side Solar Panels	-40	80	[28]
UHF Transceiver	-30	70	[10]

Table 5: Operational Temperatures

From Table 5, it is evident that certain components have more limited ranges of operable temperatures and the minimum temperature at which the entire system can function is 0 °C and the maximum is at 50 °C. Since the temperature in space can range from -100 °C to 120 °C [29] this limited range of operational temperatures means that the use of heaters may be necessary. There will also need to be insulation to prevent overheating while in direct sunlight.

4 Results

4.1 Power Subsystem

4.1.1 Power Subsystem Hardware, Monetary and Power Budget

As the details of the project changed, the previously discussed power budget was updated. As hardware became finalized, power consumption values were established. Table 6 lists the different hardware items and their respective average power consumption values at the time this report was completed. The table was created in order to ensure that margins of power will always cover the entire system at any point. Each phase of the orbit will require different amounts of power supply from each piece of hardware. The solar power supply however, will fluctuate over the course of the CubeSat's orbit, as the spacecraft goes into and out of eclipse. During sunlight periods, the solar panels will re-charge the battery for use during the periods of time in eclipse. With Table 6 establishing power by mission phase was simple to budget.

Group	Component	Company	Part Number	Peak Power (W)	Nominal Power (W)	Quiescent Power (W)	Current (mA)	Voltage (V)
OBC	OBC	Tyvak	Intrepid	0.300	0.30	0.20		
ADC	ADC board	Clyde-Space	CS-ADCS-INT-01	0.100	0.10	0.10		
	Course Sun Sensor (5)	ComTech AeroAstro	CubeSat Sun Sensor	0.000	0.00	0.00	<5	3.3/5
	Fine Sun Sensor	SSBV Space and Ground Systems	Fine Sun Sensor	0.140	0.14	0.14	7.5(26)	3.3 / 5(5-50)
	Gyro	Surrey	ADXRS450	0.030	0.03	0.03	6.0	3.15 - 5.25
	Magnetic Torquers (3)	Zarm Technik AG	MTO 5.1 (Optimized)	0.275	0.275	0.14	55.0	5
	Magnetometer	Honeywell	HMC5883L	0.000	0.000	0.00	0.100	2.16-3.6
	GPS	Surrey Satellite Technology US LLC	SGR-05U	0.800	0.80	0.80	16.0	5
Payload	Instrument	Sphinx	NG - XRAY	8.000	8.00	1.00	TBD	TBD
Power	EPS Board	Clyde-Space	CS-3UEPS2-NB	0.100	< 0.1	< 0.1	over current protection	3.3/5 / raw battery
	PDM Board	Clyde-Space	CN-SWT-0035-CS	0.160	0.16	0.16	24 switches each with own current telemetry	3.3/5/12 / battery
	Battery	Clyde-Space	CS-SBAT2-30				1.25 Ah	8.2
	Front Solar Panels	Clyde-Space	SP-L-F2U-0033-CS	5.200	3.35	0		12.26-7.52
	Side Solar Panels	Clyde-Space	SP-L-S2U-0031-CS	15.600	6.70	0.00		12.26-7.53
Telecom	UHF Transceiver	ISIS	Transceiver and Antenna	2.100	0.20	0.00	TBD	6.5-12.5
Total				12.005	9.705	2.370		
Total Available				50.800	40.050	30.000		
Margin				38.795	30.345	27.630		

Table 6: Updated Power Budget

According to established CubeSat requirements, all power must be off for launch. Once launched and ejected from the launch vehicle, the battery must power everything until de-tumbling is complete and the solar panels have been deployed to begin providing power. For this period, the battery will provide up to 2.4 hours of power to supply the entire CubeSat even in the event that all hardware were to be on at the same time [2].

The CubeSat hardware must also be completely enclosed in the skeleton. With all of these requirements, a method of charging the battery must be established. A Universal Serial Bus (USB) cord and an adapter that can be plugged into the PDM board will allow the battery to be charged to a full 30 Watt-Hours in order to begin the de-tumble sequence and to deploy the main power source consisting of the solar panels.

The specifications for the hardware chosen and discussed have been reviewed to insure that the CubeSat can work efficiently. The final hardware choices are shown above in the power budget in Table 6. A cost estimate for the hardware can be seen in Table 7.

Component	Part Number	each	number	cost
EPS Board	CS-3UEPS2-NB	\$ 4,500.00 ¹	1	\$ 4,500.00 [6]
PDM Board	CN-SWT-0035-CS	\$ 7,750.00 ¹	1	\$ 7,750.00 [7]
Battery	CS-SBAT2-30	\$ 3,550.00 ¹	1	\$ 3,550.00 [26]
Front Solar Panels	SP-L-F2U-0033-CS	\$ 4,000.00 ¹	1	\$ 4,000.00 [27]
Side Solar Panels	SP-L-S2U-0031-CS	\$ 4,150.00 ¹	2	\$ 8,300.00 [28]
Total				\$ 28,100.00

Table 7: Power Hardware Costs

All power hardware chosen for the CubeSat is manufactured by the same company, Clyde Space. The choice to use only one company for all parts of this subsystem almost guarantees that the component boards will communicate well between each other.

4.1.2 Wiring Results

The CubeSat bus will connect the transceiver, ADC, battery, EPS and PDM boards together with the possible exception of the OBC as indicated in Figure 34 of Appendix 8. The location and type of the OBC interfaces are as yet unspecified and need to be determined. As a result, ribbon cable will probably be needed to connect the board stack and the OBC. The CubeSat bus has two 52 pin headers which are as labeled in Figure 35 of Appendix 8. The purpose and connections of each of the pins of the CubeSat bus are also listed in Table 9 and Table 10 of Appendix 9. The devices that connect to the board stack can then be divided into three groups. The first group consists of devices that use power and relay information to the OBC. The second group relays information to the ADC board directly and receives power from the PDM board with the exception of the four Coarse Sun Sensors. The third group consists of the magnetic torquers which are actively powered, but do not relay any information to the board stack. The wire connections to the magnetic torquers via the CubeSat bus are listed in Table 11 of Appendix 9.

The devices in the first group consist of the solar arrays and the Sphinx instrument. Each of the three solar arrays has three connecting wires as labeled in Figure 36 of Appendix 8. The solar array wires are connected to the EPS board through the SA connectors labeled in Figure 37 of Appendix 8 and the pin numbering of the SA connectors is as labeled in Figure 38 of Appendix 8. The connections of the solar array wires to the connector pins are listed in Table 11 of Appendix 9. The payload wiring consists of a wire that will provide power through the PDM board, a ground wire and a wiring harness that will relay information to the OBC directly. The connectors for the Sphinx and OBC are unknown at the present time, so the design of the wiring harness to connect them should be a goal of future work. The power and ground wire

connections to the payload instrument are listed in Table 10 of Appendix 9. Although the connectors to the OBC are unknown, the connection types can be found in Appendix 10. The devices in the second group consist of the gyroscope, the magnetometer, the four Coarse Sun Sensors, the CubeSat Sun Sensor, and the GPS. The devices listed should connect directly to the ADC board from Clyde Space. According to one of their representatives the ADC board can be built to suit the interface needs of each of the devices. The wires and wire connection points for the gyroscope, magnetometer, coarse sun sensor, and GPS are labeled in Figure 39, Figure 40, Figure 41 and Figure 42 of Appendix 8. The location of the CubeSat sun sensor's wire connection points are unknown and will have to be identified in future work. However it is known that the CubeSat sun sensor has four analog wires which will provide information to the ADC board, aside from the power and ground wires [30]. The connection of the devices to the ADC board and the CubeSat bus are as indicated in Table 11 of Appendix 9.

4.2 Telecommunication Subsystem

4.2.1 Mission Modeling and Timelines

The STK model allows for precise estimations of both ground station access and link budgets as described in the methodology. The data from these reports was imported into Excel files and organized by simulated mission date range and ground station. The plots in Figures 25-27 were created from this data.

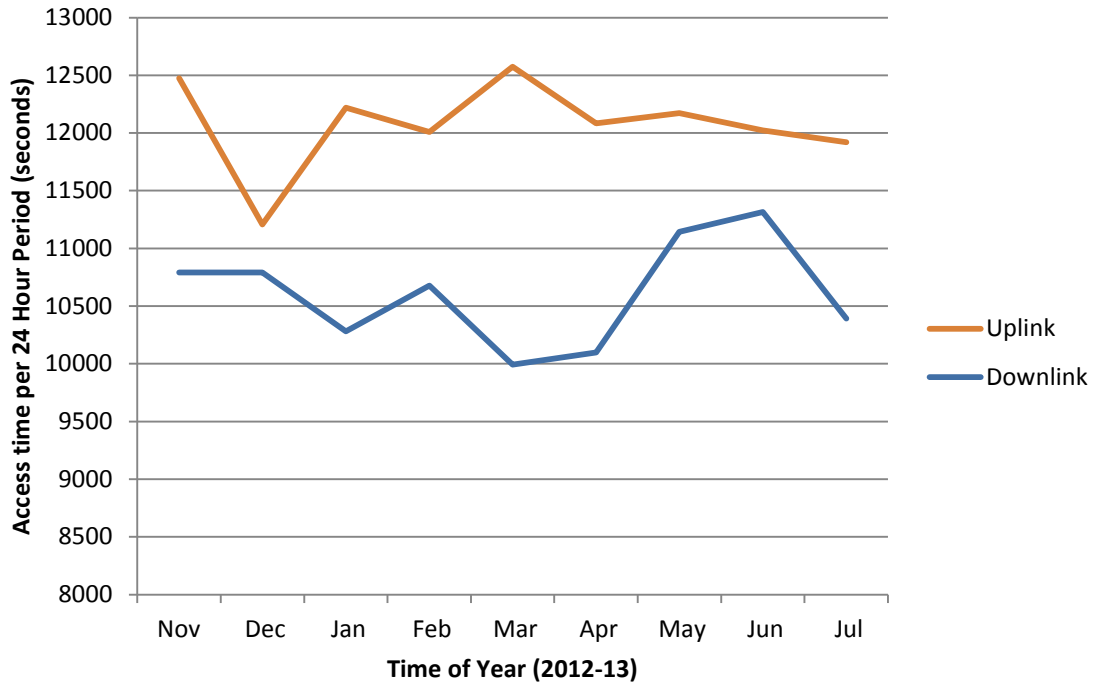


Figure 23: Total expected daily access time as a function of launch date.

Figure 23 shows the access time that can be expected over all 5 selected ground stations for both the uplink and downlink. The data in the figure was generated using data from various simulations, with different launch dates, in STK. The propagation of the CubeSat’s orbit is the main determining factor in access time achieved, while weather and other atmospheric effects contribute to varying path losses. It was expected that the uplink access would be higher than the downlink access (in simulations, about 20% on average for downlink) due mainly to the increased transmission power achievable at the ground stations compared to the CubeSat transmitter. Another factor is the increased distance achievable with VHF compared to UHF at a given power level. Overall, a mean access of 10609.7 seconds for the downlink and a mean access of 12076.1 seconds for the uplink can be expected over a 24 hour period. Figure 24 and Figure 25 show the access discussed above divided among the various ground stations.

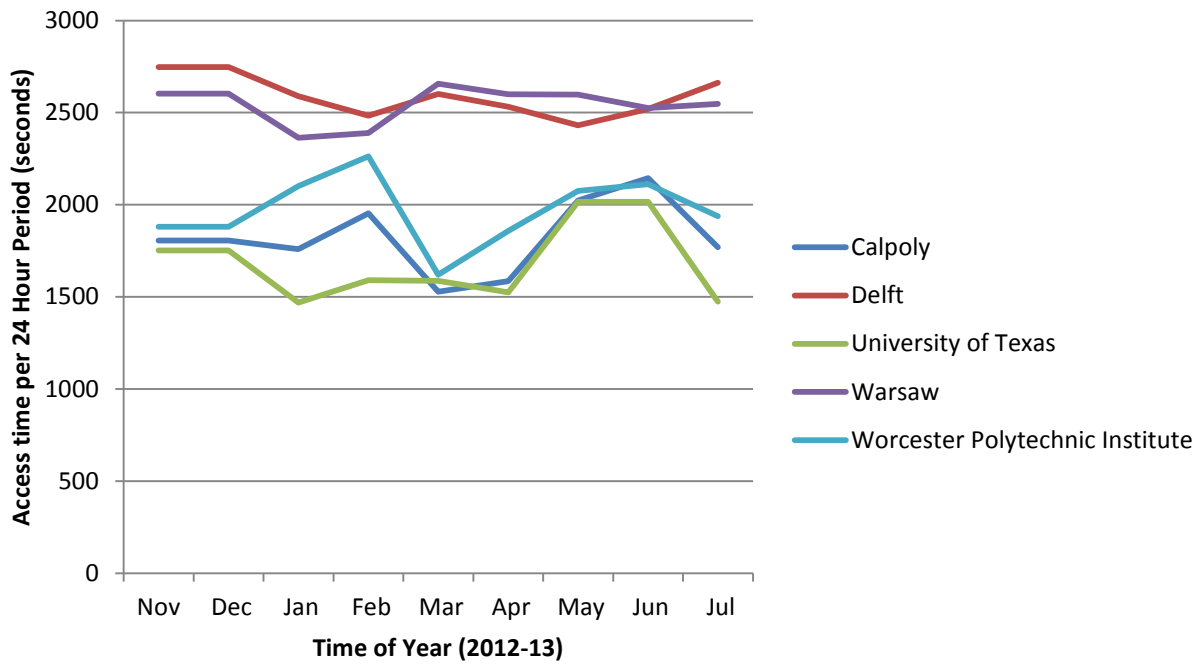


Figure 24: Expected daily downlink access at each ground station as a function of launch date.

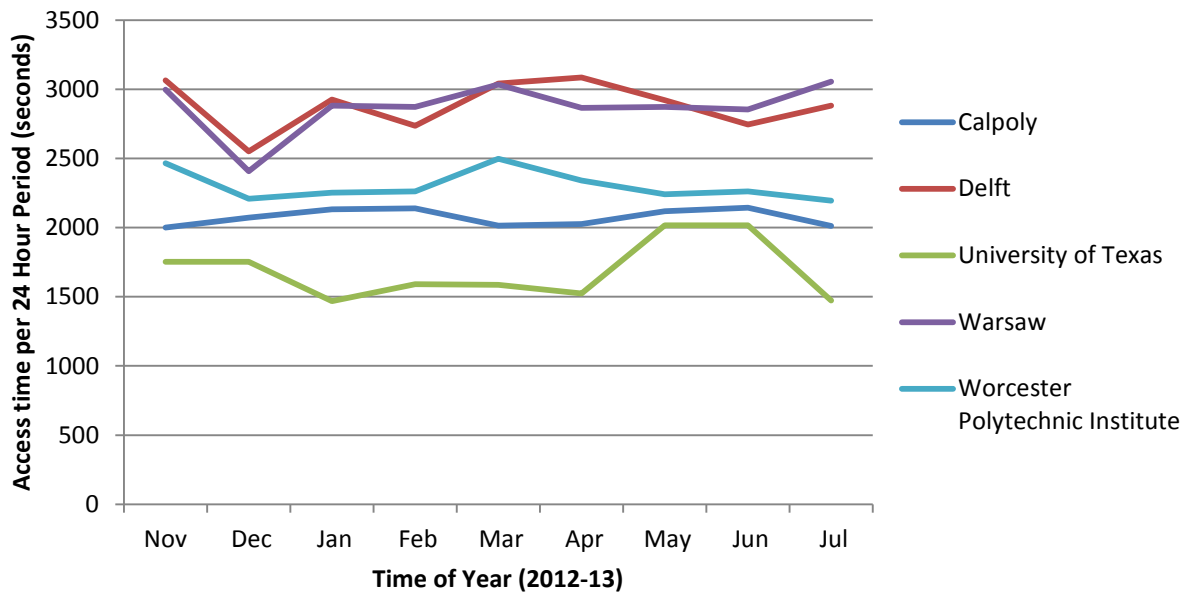


Figure 25: Expected daily uplink access at each ground station as a function of launch date.

From the plots, there is a preference towards use of the European ground stations in order to maximize total access time. This is in part due to the choice of orbit when modeling and may

need to be reassessed when the CubeSat’s actual orbit is known. Although the individual contributions will vary depending on the actual orbit, there should remain a balance between the location and spread of ground stations as one station loses access and another gains access. The scenario modeled is likely a worst case, in which the area of higher coverage over North America is traversed less than the area of lower coverage over mainland Europe. In all cases simulated, a (future) WPI ground station is a good middle ground with around 2000 seconds of downlink access per day and 2300 seconds of uplink coverage.

In Table 8, the average access time was used to calculate a mean data throughput per day. The main link characteristics are summarized and then the packet protocol is specified and used to calculate an actual data rate. The Bit-Error-Rate (BER⁸) is also accounted for with a worst case value of 10E-5 used.

	UHF Downlink		VHF Uplink	
Mean:	10609.7	s/day	12076.1	s/day
Parameter	Value	Units	Value	Units
Frequency	435	MHz	135	MHz
Transmitter Power	1	Watt	1	Watt
Trans. Bit rate	9600	bps	1200	bps
Duty Cycle	1		1	
CubeSat Ant. Gain	5	dB	5	dB
GS Ant. Gain	15.5	dB	14.39	dB
Pointing Losses	1	dB	1	dB
Desired Signal/Noise	15	dBm	15	dBm
Noise Temperature	542	K	542	K
Receiver Sensitivity	N/A		-100	dBm
Packet Protocol	AX.25		AX.25	
Max Packet Size	256	bytes	256	bytes
Packets/second	4.69		0.586	
Overhead	21	bytes	21	bytes
Data per packet	235	bytes	235	bytes
Adjusted Data Rate	1101.6	bytes/s	137.7	bytes/s
	8813	bps	1102	bps
Access time	10609.7	s	12076.1	s

⁸ Bit-error-rate (BER): The number of altered or incorrect bits, caused by interference, distortion, or noise, divided by the total number of bits in an interval of time.

	UHF Downlink		VHF Uplink	
Packets Received	49733.0		7076.6	
Data Received	11687248	bytes	1662822	bytes
	116.87	Mb	16.63	Mb
BER (worst case)	1.00E-05		1.00E-05	
Bit Error	117	bytes	17	
Usable Data	11687131	bytes	1662806	bytes
	116.87	Mb/day	16.63	Mb/day

Table 8: Key parameters in data rate calculation and expected data values.

As expected, the capability of the UHF downlink is an order of magnitude higher than then that of the VHF uplink. This is due solely to the maximum transmitter bit rate as the access time is 20% higher for the VHF link. In total, the ground stations should be able to receive around 116.87 Mb of data and send 16.63 Mb per day. The worst case scenario for bit error is approximately 117 bytes of downloaded data a day requiring either resending of packets or use of methods to fix incorrect bits within packets. It should be noted that the 20% increase in coverage via VHF is useful for tracking and establishing a connection with the CubeSat and gives more time to upload important commands.

4.2.2 Communication Hardware

The only hardware required for this subsystem is the UHF Transceiver. The choice of the ISIS TRXUV UHF/VHF Transceiver was made due to the communication requirements of the OBC and the Sphinx NG, along with the link capabilities. The ISIS UHF Transceiver meets these requirements with a UHF downlink, and a VHF uplink option. The transceiver comes with a multidirectional antenna giving the CubeSat optimal coverage. The cubesatshop.com sells this and other versions of the transceivers; this particular model is rated at \$11336.00 [31].

4.3 Thermal Subsystem

4.3.1 COMSOL Analysis Results

When performing simulations, COMSOL solved for the temperature of the surrounding chamber and the lamp structure. This was undesirable for the model since simulations would take more time to solve for geometries that were not part of the CubeSat. COMSOL Support was contacted to see if they could shed some enlightenment to help solve this issue. In their response, they stated that if the walls of the inner chamber were approximated as far away surfaces, then the CubeSat structure can be modeled without the vacuum chamber. Since the size of the skeleton is comparable to the actual chamber, it had to be included in the analysis. Based on this feedback, simulations were performed to see if adding the chamber to the model would have a significant effect on the final calculated temperature.

For the purposes of the modeling, simple geometry was used. To reduce the simulation time, the lamp and vacuum chamber were modeled as surfaces instead of solid shapes. However, when applying boundary conditions, surfaces (that are not part of a “solid”) cannot be selected for any of the heat transfer choices such as initial values and heat flux. Because of this, the chamber was given a relatively thin thickness. To be consistent, the chamber was defined using dimensions approximating the actual chamber used for testing. The chamber has a 24.625 inch inner radius and a length of 70.5 inches. For simplicity, the CubeSat was modeled as a 10 by 10 by 30 centimeter rectangular prism. Figure 26 shows the final model for the vacuum chamber simulation.

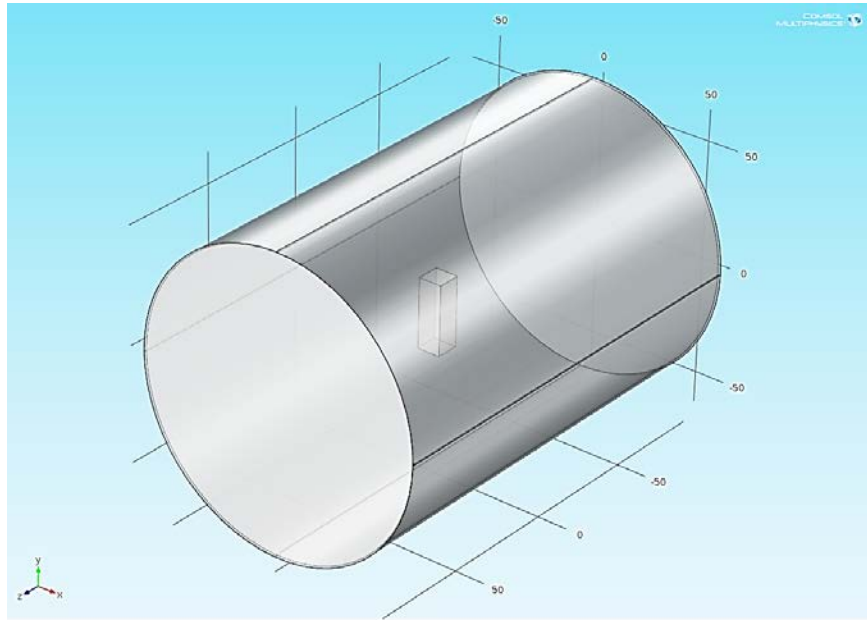


Figure 26: Vacuum Chamber Model

Once the geometry was formulated, the environment in the chamber was created. Using the materials browser, materials can be selected and applied to the skeleton and chamber. The skeleton is made out of 6061 aluminum. The vacuum chamber is made from stainless steel and was modeled as SS 316L. The outer walls of the chamber were set with an initial temperature of 250 degrees Kelvin. Next, using the External Radiation Source module heat flux from the lamp was simulated onto the CubeSat structure. The point coordinate option was selected. The coordinates of the heat source was positioned at (0, 20, 0) centimeters with a power output of 250 Watts. Surface-to-surface radiation was applied to the geometry. The stainless steel vacuum chamber has an emissivity of 0.8 while the aluminum CubeSat has 0.77. In the surface-to-surface setting the radiosity can be calculated. COMSOL calculates the radiosity of the surface using Equation 2.

$$J = (1 - \epsilon)G + \epsilon\sigma T^4$$

Equation 2

G is the unknown incident radiation, T is the initial temperature of the surface, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \frac{J}{m^2sK^4}$), and ϵ is the emissivity of a material. In the Surface-to-Surface Radiation setting, T and ϵ are set as initial values. COMSOL calculates G values from the geometric surfaces in the model.

After completing the simulation, results from the two studies were compared qualitatively using two 1D plot groups. The first group graphed the temperature over the X, Y, and Z coordinates of the CubeSat. Since the CubeSat is fixed at the origin and its dimensions are 10 by 10 by 30 centimeters, the coordinates for the X and Z directions were from -5 to 5 centimeters. The coordinates in the Y direction is -15 to 15 centimeters. In Figure 27: Temperature vs. Coordinate X, Y, Z, the dashed lines represent the study where the vacuum chamber is modeled, and the solid lines are from the study where just the CubeSat was modeled. There is a significant difference in temperature, about a 4 degree increase in temperature range. The second group shows the radiosity over the coordinates of the CubeSat. Because the radiosity increased, the temperature will also increase. Figure 28, Figure 29, and Figure 30 show the radiosity over the X, Y, and Z coordinates of the CubeSat respectively.

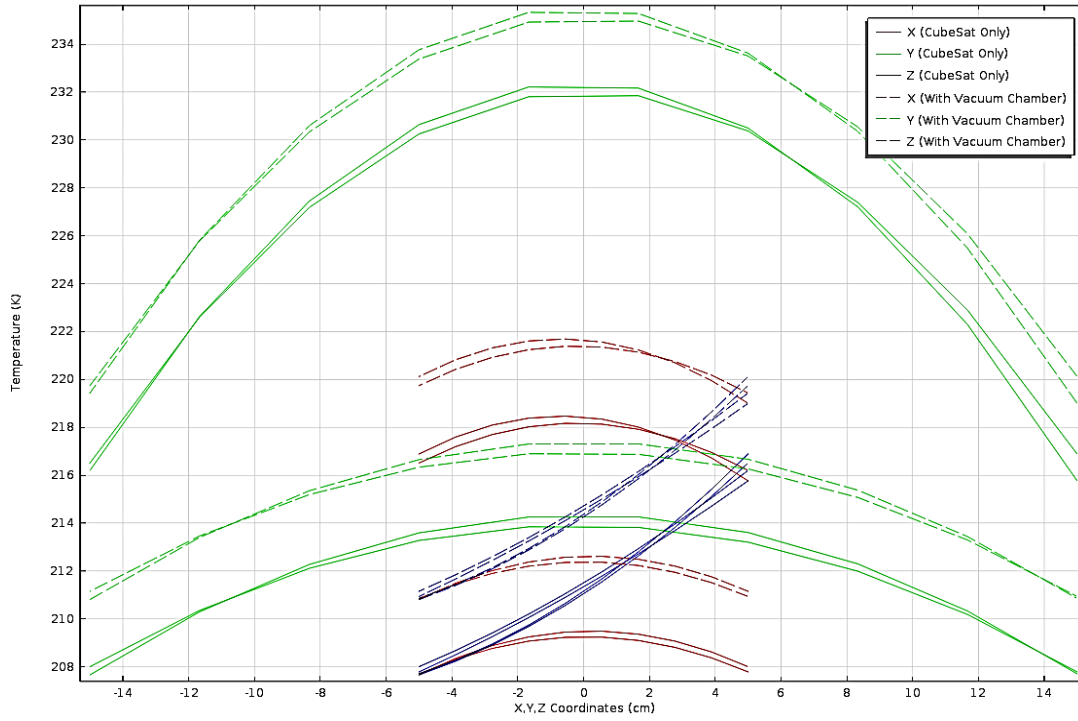


Figure 27: Temperature vs. Coordinate X, Y, Z

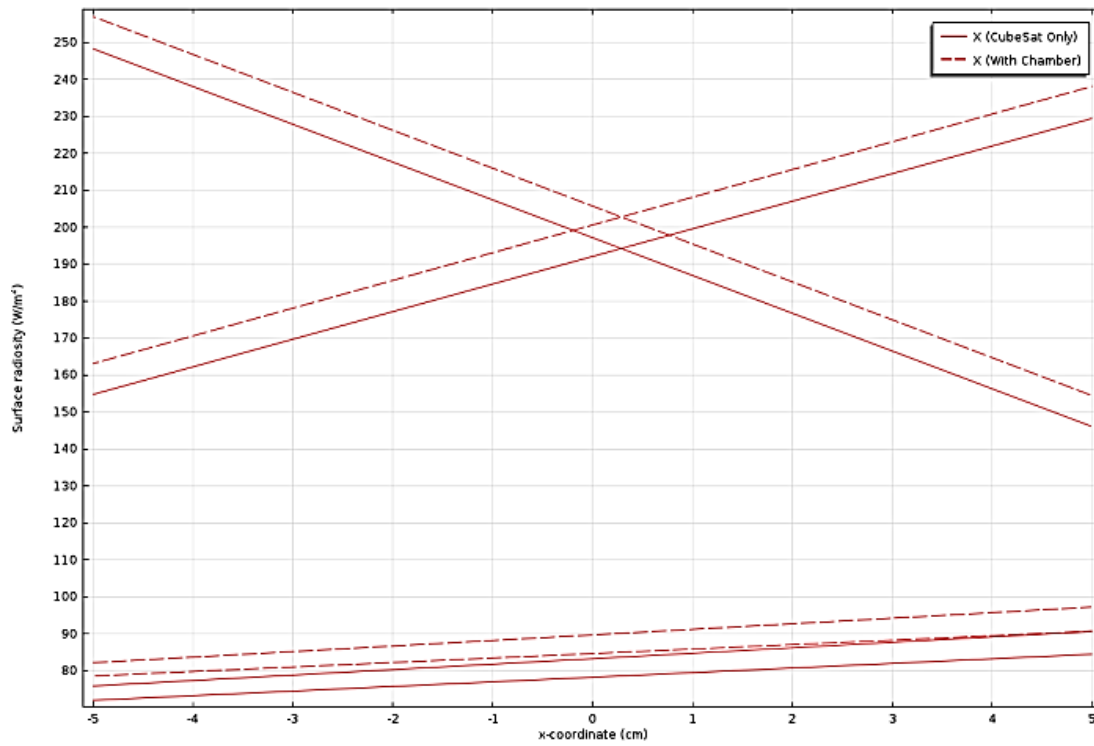


Figure 28: Radiosity vs. Coordinate X

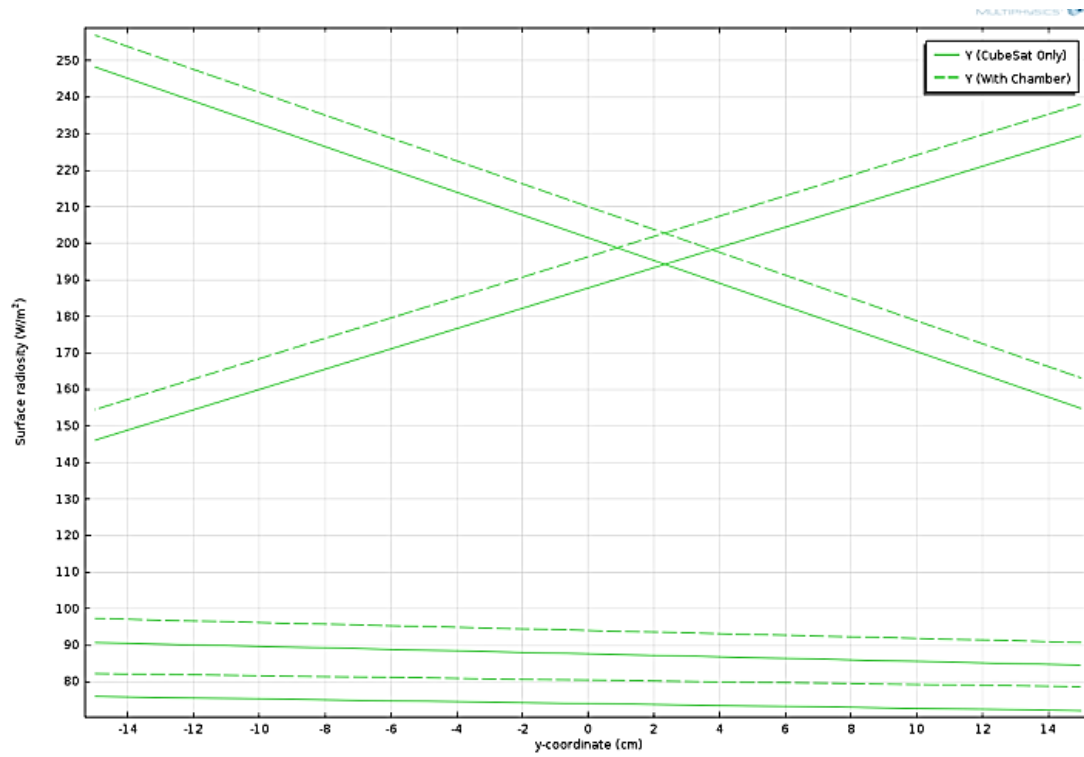


Figure 29: Radiosity vs. Coordinate Y

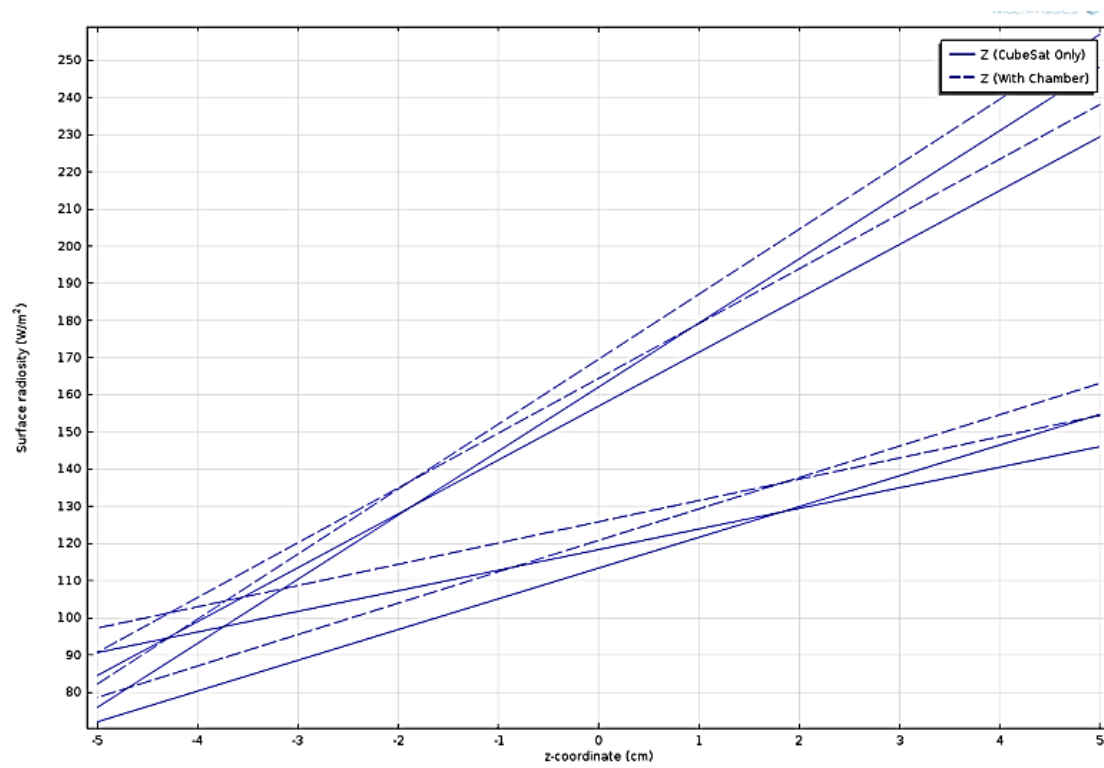


Figure 30: Radiosity vs. Coordinate Z

4.3.2 Thermal Analysis from External Sources

From the preliminary analysis in Section 3.3.1, COMSOL can easily solve time dependent solar flux equation. The next step was to take the solar flux equation and apply it to the model of external components. COMSOL has the ability to import 3-D CAD assemblies to create the geometry. With the help of the current Mechanical Subsystem MQP team, a simplified structure of the CubeSat model in SolidWorks was created. The model contains the aluminum structure from Pumpkin Inc., solar panels and hinges from ClydeSpace, and 1 millimeter thick aluminum panels to protect the CubeSat.

Once the CAD file was imported, the material boundaries were applied to the components. The Pumpkin structure and hinges are made of 7071 aluminum. After looking at the ClydeSpace data sheet, the solar panels are actually made of multi-layered printed circuit board, not solid copper as the Mechanical, Power, and Thermal CubeSat MQP 2011-2012 team assumed [1].

To set up the solar flux equation, three interpolated functions were inserted, one for each beta component. As explained in Section 3.3.1, an interpolated function contains values of t and $f(t)$. Beta values were calculated from STK and then exported into an Excel file. The values were extracted and three “.txt” files were created. In each file there were two columns. The first column contained the time values from 0 to 172,800 seconds with an interval of 30 seconds. In the second column was one component of beta corresponding to each time interval. The three interpolation functions were renamed “Bx”, “By”, and “Bz.” Next, the solar flux and earth flux constants were defined using the Global Parameters section in COMSOL. The constant solar flux is $1367 \frac{W}{m^2}$ and constant earth flux is $245 \frac{W}{m^2}$.

Most of the boundary conditions that Mechanical, Power, and Thermal CubeSat MQP 2011-2012 team created were implemented in the model [1]. The heat flux was the major change. When analyzing the CubeSat in a worst case scenario, multiple walls of the spacecraft are subjected to the solar flux. If the CubeSat was oriented to have its solar panels facing the sun at all times i.e. best case scenario, only the front face of the spacecraft would be subjected to the solar flux. Equation 1 and the earth flux were used to formulate the total heat flux on the CubeSat in orbit, shown in Equation 3.

$$q_{tot} = q_{earth} + q_{sun}[n_x B_x(t) + n_y B_y(t) + n_z B_z(t)] \quad \text{Equation 3}$$

In Equation 3, q_{earth} is the constant earth flux and q_{sun} is the constant sun flux defined in Global Parameters. $B_x(t)$, $B_y(t)$, and $B_z(t)$ are the interpolated functions that are dependent on time. The normal unit vectors n_x , n_y , and n_z are for the X, Y, and Z faces of the CubeSat.

As for the remaining boundary conditions, surface-to-ambient radiation was applied to each material. This setting defines the ambient temperature and surface emissivity.

According to several online references, the emissivity of a typical multilayer printed circuit board was around 0.85. The emissivity of aluminum stayed the same at 0.77. Ambient temperature represents an equivalent, blackbody temperature for the surroundings (the vacuum of space) that the CubeSat is exposed to, or about 30 degrees Kelvin.

Meshing the simplified CubeSat structure was tedious. The main problem with imported CAD files is the errors COMSOL generates when trying to apply the mesh. The option to use a physics controlled mesh was not possible for most of the CubeSat structure. When “physics controlled mesh” is selected, COMSOL automatically applies a mesh to components of the

model. There were many narrow edges that required sizing techniques. Figure 31 shows the final mesh for the CubeSat.

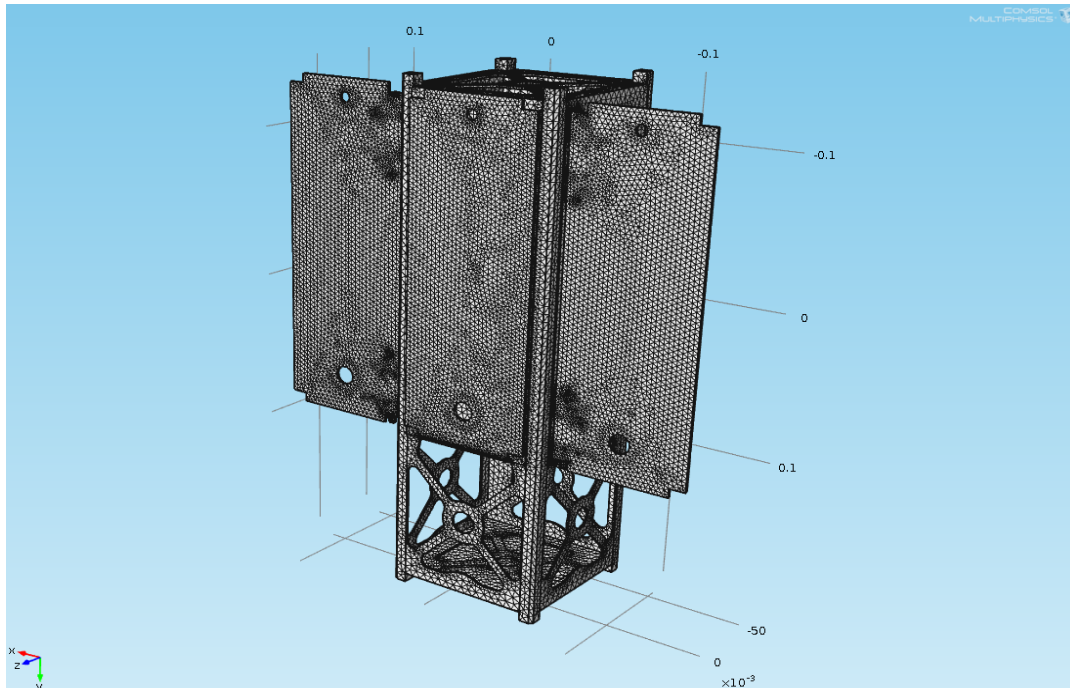


Figure 31: Mesh for External Components

To analyze the temperature range during multiple orbits, the range of time was defined to be from 0 to 10200 seconds with a 510 second interval (8.5 minutes). This interval was chosen to minimize the calculation time without sacrificing the time resolution of the results. Because of its fine mesh, choosing a smaller number for the time interval would result in the simulation taking hours to run. After running the simulation, to see if there was a temperature trend over multiple orbits, a line graph was created. All edges were selected and then plotted over time.

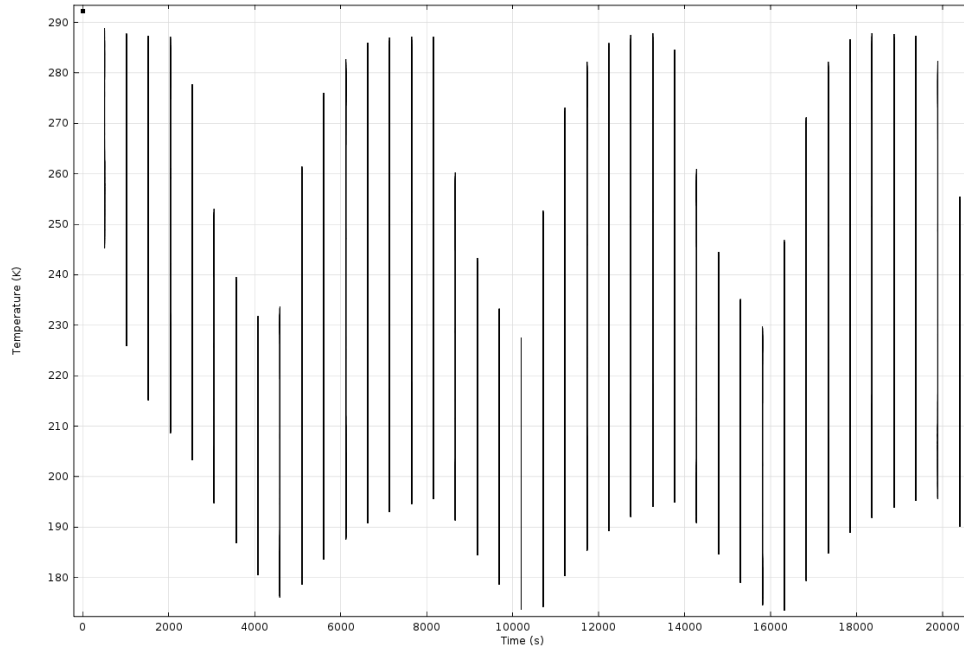


Figure 32: Temperature vs. Time over 3 orbits.

Figure 32 shows the temperature ranges over the time interval. In this plot, the vertical lines represent the range of temperatures between the minimum and the maximum calculated for the entire structure.

5 Conclusions and Recommendations

5.1 Power Subsystem

The next major step in the power subsystem is to establish a power timeline. This timeline is established by the orbit, hardware use, ADC, and instrument use. As the CubeSat goes in and out of eclipse, it will create a timeline for battery recharging and power supply. The users' power phases will then be established. Each phase will inform when and how much power is necessary. Once the phases have been established, the OBC, transceiver, instrument, and ADC timeline within each phase can be created. From these more detailed timelines, an on/off sequence can be acquired. The power supply cycle will then need to be cross referenced with the power user's requirements to create a complete "On/Off" sequence to ensure sufficient power will be received on time.

5.2 Telecommunication Subsystem

5.2.1 Hardware Testing Recommendations

Testing of the telecommunications system should be conducted when the hardware is eventually obtained. The major focus of testing should be on verification of the manufacturer's specifications, comparison to link models, verification of link integrity, and verification of power system compatibility [32]. This can be done through the use of link testing in an Radio Frequency (RF) isolated chamber to limit any external RF interference with the test. The transceiver should be connected to the ground station radio and terminal via a cable with known loss and a variable signal attenuator. The signal attenuator is a device that acts as a RF power dissipater, reducing the signal strength to incur a loss.

The transceiver should be set up to send a constant stream of "dummy" data to the radio. Once a connection is established and verified, the signal attenuator can be used to mimic various losses. The data received can be compared to data transmitted at various loss levels to determine the BER. Once the BER reaches a maximum value of $10e-5$, the loss should be recorded and compared with values from the STK model. This loss counts for the sum of all losses in the system and should be used as a metric to reanalyze the model.



Figure 33: Basic setup showing ISIS transceiver © 2012 isispace.nl (Left), bench-top variable signal attenuator © 2012 jfwindustries.com (Middle) and ICOM radio © 2012 icomamerica.com (Right) [10] [33]

It is important to evaluate the current needed by the transceiver while running these tests to refine and certify power requirements. A digital meter or LabView program could easily be used to monitor current draw by the transceiver when sending and receiving data. Also the power consumed while in a beacon mode⁹ should be measured and included in the quiescent power budget. If the power consumption is higher than expected, it may be necessary to run the transmitter only when no scientific data is being collected.

⁹ Beacon Mode allows tracking of the CubeSat when not actively transmitting or receiving packets.

5.2.2 WPI Ground Station Proposal

Through research into the requirements from Cal Poly and the other requirement documents as well as the ground stations in the GENSO network, a finalized list of hardware was created for both on board the CubeSat and the ground station at WPI. A monetary budget of the hardware, part number, and price for all telecommunication related hardware has been created; maximum and minimum cost analyses tables can be found in Appendix 5. The maximum estimated cost for implementation of a WPI Ground Station is \$11,646. The antenna currently located on top of Atwater Kent has been approved to be relocated to the top of Higgins Laboratories, to be used for the WPI ground station. Facilities will need to be contacted to begin the bidding for a company to relocate the antenna from Atwater Kent to Higgins Laboratory. The room currently reserved for the WPI ground station has been cleared out and is ready for the necessary equipment.

With a ground station at WPI, the unique address of the frequency may be added to the GENSO network. Every ground station has its own frequency, for which an application with the Federal Communications Commission (FCC) needs to be completed. Different current and future CubeSat mission orbits will be reviewed to see if other satellites will be able to use the WPI ground station for their telecommunication architecture. This analysis will likely that the WPI ground station will not only be useful to the WPI CubeSat, but potentially to other satellites in the GENSO network

5.3 Thermal Subsystem

5.3.1 Recommendations Based on Vacuum Thermal Analysis

Due to time constraints, thermal analysis for the Lab Option could not be completed. The experiment that was planned would have used an aluminum model of the structure for testing in

a vacuum chamber. The aluminum frame should be fitted with panels of aluminum sheets and copper-clad PCB to simulate the properties of the body of the actual CubeSat and the solar arrays respectively. A 250 Watt halogen bulb should be used to simulate the sun in the vacuum chamber. To measure the thermal profile of the model five thermocouples should be placed in strategic positions, and the data sent to a LabView file through a Data Acquisition (DAQ) box.

A final simulation model for the Lab Option analysis has been created using COMSOL. One issue with the model was the mesh was too fine. This made the simulation take hours and even days to run. Future teams should look into making the mesh a bit coarser to allow relatively quicker simulation times.

The external components thermal model does not incorporate the rear flux on the solar panels. In the original model the rear flux was controlled by the analytic function. Modeling of internal components is more complex and requires much more time to analyze. Future teams should combine the internal and external components into one model. This will ensure an accurate thermal control management plan.

5.3.2 Lab Option

Future teams working on the thermal analysis of the CubeSat model can run the experiment in the vacuum chamber. The materials have all been procured, and the experiment can now be set up. They should also consider designing and running more complex experiments. Such experiments could include turning the lamp on and off to simulate the change between eclipse and direct sunlight. Experiments could also vary the placement of the thermocouples on the model to see where high or low temperature spots are.

The results of the vacuum chamber testing are expected to indicate that there is a profile across the skeleton of the CubeSat such that it is warmer on the face pointing at the lamp (heat source) and is cooler on the “back side”.

Another factor that should be considered is the influence of the material of the CubeSat on the temperature. The expected observation is that the aluminum surfaces will distribute the temperature to the rest of the CubeSat model more readily than the copper clad PCB.

The model used in these experiments should be composed of materials with similar properties to those of the external components of the CubeSat. The material selection thus far has been working from a very basic assumption that was made for simplicity of data collection and to reduce the number of thermocouples that need to be placed. Future teams could consider adding additional internal structure to the model to simulate internal components as well.

5.3.3 Thermal Control System

Once the thermal profile of the CubeSat over its lifetime is finalized, and the final structure make-up is known, the control system options should be determined. The factors taken into consideration for the thermal control selection should be primarily concerned with mass and volume limitations of the CubeSat, the P-POD requirements, and the maximum and minimum operational and survivable temperature limits. Due to the power restrictions of the CubeSat, passive thermal control methods are the only realistic option. Future groups will need to look into thermal coatings, and ensure that they comply with the P-POD requirements. Research on passive radiators should also be conducted if there is available space to place such control mechanisms.

Works Cited

- [1] J. Bauer, M. Carter, K. Kelley, E. Mello, S. Neu, A. Orphanos, T. Shaffer and A. Withrow, "Mechanical, Power, and Thermal Subsystem Design for a CubeSat Mission," Worcester Polytechnic Institute, Worcester, MA, Project JB3-CBS2 2012.
- [2] Cal Poly SLO, "Launch Services Program: Program Level Poly-Picosatellite Orbital Deployer (PPOD) and CubeSat Requirements Document," National Aeronautics and Space Administration, John F. Kennedy Space Center, Florida, LSP-REQ-317.01 Rev. A 2011.
- [3] National Aeronautics and Space Administration, "Standard Materials and Processes Requirements for Spacecraft," Launch Services Program, Washington DC, NASA STD-6016 2013.
- [4] L. C. P. M. Solie, "Launch Safety Requirements For Air Force Space Command Organizations," Air Force Space Command, AFSPCMAN91-711 2007.
- [5] The Mathworks, Inc., "Mathworks," 2013. [Online]. Available: http://www.mathworks.com/products/demos/shipping/elec/elec_solar_opt_m_02.png. [Accessed 3 March 2013].
- [6] Clyde Space, "User Manual: CubeSat 3U Electronic Power System," 27 June 2011. [Online]. Available: www.clyde-space.com. [Accessed 3 March 2013].
- [7] Clyde Space, "CubeSat Power Distribution: User Manual," 14 March 2011. [Online]. Available: www.clydespace.com. [Accessed 03 March 2013].
- [8] National Aeronautics and Space Administration, "NASA Procedural Requirements for Limiting Orbital Debris (w/ Change 1 - 5/14/09)," NASA, 2009.
- [9] CubeSatShop.com, "CubeSat Sun Sensor," ISIS, 2013. [Online]. Available: http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=104&category_id=7&option=com_virtuemart&Itemid=69. [Accessed 3 March 2013].
- [10] CubeSatShop.com, "Deployable Antenna System for CubeSats," ISIS, 2013. [Online]. Available: http://www.cubesatshop.com/index.php?page=shop.product_details&category_id=6&flypage=flypage.tpl&product_id=66&option=com_virtuemart&Itemid=70. [Accessed 3 March 2013].

- [11] F. S. 1037C, "Earth Station," General Services Administration, 1996.
- [12] I. T. Union, "ITU Radio Regulations – Article 1, Definitions of Radio Services," retrieved 2009-04-23.
- [13] J. Wertz and W. Larson, "Communications Architecture," in *Space Mission Analysis and Design (3rd edition)*, Microcosm Press, 1999, pp. 533-586.
- [14] NASA, "General Environmental Verification Standard (GEVS)," 2005, pp. 2.6-1,2,4.
- [15] C. D. Brown, *Elements of Spacecraft Design*, Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2002.
- [16] R. S. D. Fred J. Dietrich, "Communications Architecture," in *Spacecraft Mission Analysis and Design 3rd ed.*, Microcosm, 1999, pp. 533-586.
- [17] Cubesat, "GENSO," 2013. [Online]. Available: <http://www.cubesat.org/index.php/collaborate/genso>. [Accessed 2012-2013].
- [18] E. Dawson, N. Nassiff and D. Velez, "Attitude Determination And Control System Design For A CubeSat Mission," Worcester Polytechnic Institute, Worcester, 2012.
- [19] Pumpkin (TM), "CubeSat Kit (TM)," September 2009. [Online]. Available: http://cubesatkit.com/docs/datasheet/DS_CSK_MB_710-00484-D.pdf. [Accessed 3 March 2013].
- [20] Clyde Space, "CubeSat ADCS Module," 2013. [Online]. Available: http://www.clyde-space.com/cubesat_shop/adcs/adcs_board/299_cubesat-adcs-module. [Accessed 3 March 2013].
- [21] Comtech AeroAstro, "AeroAstro Space Micro," 28 December 2012. [Online]. Available: http://www.spacemicro.com/Comtech_Areoastro/Data_Sheets/Coarse_Sun_Sensors.pdf. [Accessed 3 March 2013].
- [22] Analog Devices, Inc., "Analog Devices," Analog Devices, Inc., 2013. [Online]. Available: <http://www.analog.com/en/mems-sensors/mems-gyroscopes/adxrs450/products/product.html>. [Accessed 3 March 2013].
- [23] Zarm Technik AG, "Zarm Technik," 2010. [Online]. Available: http://www.zarm-technik.de/downloadfiles/ZARMTechnikAG_CubeSatTorquers_web2010.pdf. [Accessed 3 March 2013].
- [24] Honeywell, "Sparkfun Electronics," [Online]. Available: <http://dlnmh9ip6v2uc.cloudfront.net/datasheets/Sensors/Magneto/HMC5883L-FDS.pdf>.

[Accessed 3 March 2013].

- [25] Surrey Satellite Technology US LLC, "SGR-05U-Space GPS Receiver," 2013. [Online]. Available: <http://www.sst-us.com/shop/satellite-subsystems/gps/sgr-05u---space-gps-receiver>. [Accessed 3 March 2013].
- [26] Clyde Space, "User Manual: Standalone 30Wh Battery," 28 April 2010. [Online]. Available: www.clyde-space.com. [Accessed 20 February 2013].
- [27] Clyde Space, "2U Front Solar Panel," 2013. [Online]. Available: http://www.clyde-space.com/cubesat_shop/solar_panels/2u_solar_panels/87_2u-front-solar-panel. [Accessed 3 March 2013].
- [28] Clyde Space, "2U CubeSat Side Solar Panel," 2013. [Online]. Available: http://www.clyde-space.com/cubesat_shop/solar_panels/2u_solar_panels/79_2u-cubesat-side-solar-panel. [Accessed 3 March 2013].
- [29] I. t. S. Initiative, "CubeSat Structure," University of Illinois, [Online]. Available: <http://cubesat.ece.illinois.edu/Structure.html>. [Accessed 3 March 2013].
- [30] SSBV, "CubeSat Sun Sensor," 13 February 2013. [Online]. Available: <http://www.ssbv.com/ProductDatasheets/page39/page29/index.html>. [Accessed 20 February 2013].
- [31] CubeSatShop.com, "Small Ground Station," ISIS, 2013. [Online]. Available: http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=24&category_id=3&option=com_virtuemart&Itemid=72&vmcchk=1&Itemid=72. [Accessed 2012-2013].
- [32] T. Bleier and et. al., "QuakeSat Lessons Learned: Notes from the Development of a triple CubeSat," Quakefinder LLC, 2004.
- [33] JFW, "JFW Benchtop Rotary Attenuators," JFW, 2013. [Online]. Available: http://www.jfwindustries.com/catalog/Benchtop_Rotary_Attenuators-61-1.html. [Accessed 3 March 2013].
- [34] Cal Poly, "DNEPR Safety Compliance Requirements," August 5, 2004, pp. 2-3,10.
- [35] H. DEPOT, "Workforce250-Watt Halogen Portable Work Light," Homer TLC Inc., 2011. [Online]. Available: http://www.homedepot.com/p/t/202071327?storeId=10051&langId=-1&catalogId=10053&productId=202071327&R=202071327#.UTPLwjD_mSp. [Accessed 2013].

- [36] M. I. S. Co., "Aluminum Sheets," MSC Industrial Direct Co., Inc., 2012. [Online]. Available:
http://www1.mscdirect.com/cgi/NNSRIT2?PMAKA=09426057&PMPXNO=4463866&cm_re=ItemDetail-_-ResultListing-_-SearchResults. [Accessed 2013].
- [37] M. Electronics, "Copper Clad Boards SINGLE SIDED 6X9 COPPER CLAD 1/32in," TTI and Berkshire Hathaway, 2013. [Online]. Available:
<http://www.mouser.com/ProductDetail/MG-Chemicals/588/?qs=sGAEpiMZZMuwe2fyn7eX6%252bVQtT7NeG%252bLat9KTJDReHE%3d>. [Accessed 2013].
- [38] OMEGA, "Ready-Made Insulated Thermocouples with Kapton®, PFA, Glass Braid Insulation and Molded Connectors," Omega Engineering Inc., 2013. [Online]. Available:
http://www.omega.com/ppt/pptsc.asp?ref=5LSC_5SRTC. [Accessed 2013].
- [39] McMaster-Carr, "Thermocouple and RTD Wire & Converters," [Online]. Available:
<http://www.mcmaster.com/#catalog/119/601/=lq0mjw>. [Accessed 2013].
- [40] McMaster-Carr, "Thermocouple and RTD Probes & Connectors," [Online]. Available:
<http://www.mcmaster.com/#catalog/119/600/=lq1zwl>. [Accessed 2013].
- [41] K. J. Lesker, "Power Feedthroughs - Weldable 500 Volts," Kurt J. Lesker Company, 2013. [Online]. Available:
http://www.lesker.com/newweb/feedthroughs/power_feedthroughs.cfm?pgid=500v_weld. [Accessed 2013].
- [42] T. S. Tuli, N. G. Orr and D. R. E. Zee, "Low Cost Ground Station Design for Nanosatellite Missions," University of Toronto Institute For Aerospace Studies, 2006. [Online]. Available: <http://www.utias-sfl.net/docs/canx2-amsat-2006.pdf>. [Accessed 2013].
- [43] CubeSatShop.com, "Small Ground Station," ISIS, 2013. [Online]. Available:
http://www.cubesatshop.com/index.php?page=shop.product_details&flypage=flypage.tpl&product_id=24&category_id=3&option=com_virtuemart&Itemid=72&vmcchk=1&Itemid=72. [Accessed 2013].
- [44] The Department of Aerospace Engineering and Engineering Mechanics, "FASTRAC Mission Plan," The University of Texas at Austin, 2004. [Online]. Available:
http://fastrac.ae.utexas.edu/documentation/FASTRAC_missionplan_FCR.pdf. [Accessed 2013].
- [45] PolySat, "Ground Station," Mantra & Word Press, 2012. [Online]. Available:

- <http://polysat.calpoly.edu/the-lab/ground-station/>. [Accessed 2013].
- [46] H. W. Oelze, "Magnetic Torquers for Micro-Satellites," ZARM Technik AG, Bremen, Germany.
- [47] F. Chip, "USB to RS422 Serial Converter Cable Datasheet FT_000116," Future Technology Devices International Limited (FTDI), Glasgow UK, 2012.
- [48] FTDI, "UM232R USB - Serial UART Development Module Datasheet FT_000051," Future Technology Devices International Ltd, 2002.
- [49] "VHF/UHF All Mode Transceiver IC-910H," ICOM, Japan, 2005.
- [50] Kantronics, "KPC-9612+ Packet Communicator," Kantronics, Inc, 2011. [Online]. Available: <http://www.kantronics.com/products/kpc9612.html>. [Accessed 2013].
- [51] B. Tracey, "KD5TFD Station: SDR-1000, Software Defined Radio," 8 March 2005. [Online]. Available: <http://www.ewjt.com/kd5tfd/station-sdr1000.html>. [Accessed 2013].
- [52] Velleman, "EXTENDED USB INTERFACE BOARD," Velleman, 2013. [Online]. Available: <http://www.velleman.eu/products/view/?country=gb&lang=en&id=364910>. [Accessed 2013].
- [53] eHam.net, "eHam.net Classifieds Detail," eHam.net, LLC, 2011. [Online]. Available: <http://www.eham.net/classifieds/detail/379484>. [Accessed 2013].
- [54] Texas Towers, "Yaesu G-5500," TexasTowers.com, [Online]. Available: <http://www.texastowers.com/g5500.htm>. [Accessed 2013].
- [55] Rakuten, "Linksys EtherFast BEFSR41 Broadband Router - 1 x 10/100Base-TX WAN, 4 x 10/100Base-TX LAN - BEFSR41-LA," Buy.com Inc., 2013. [Online]. Available: <http://www.rakuten.com/prod/linksys-etherfast-befsr41-broadband-router-1-x-10-100base-tx-wan-4-x/10346262.html>. [Accessed 2013].
- [56] Martin RF Supply, "Bird Model 43P ThruLine RF Wattmeter Peak/Avg Kit (New)," [Online]. Available: <http://www.chuckmartin.com/category/Bird-43-Wattmeters-2>. [Accessed 2013].
- [57] "Meters & Test Equipment," Universal Radio Inc., 2012. [Online]. Available: <http://www.universal-radio.com/catalog/meters/1739.html>. [Accessed 2013].
- [58] Ettus Research, "Quick Order," National Instruments , 2013. [Online]. Available:

- https://www.ettus.com/product/quick_order. [Accessed 2013].
- [59] Texas Towers, "Polyphaser IS-50NXC2," TexasTowers.com, [Online]. Available: <http://www.texastowers.com/is50nxc2.htm>. [Accessed 2013].
- [60] DXEngineering, "PolyPhaser Rotator Control Line Protectors IS-RCT," Auto Sales Incorporated, 2013. [Online]. Available: <http://www.dxengineering.com/parts/ppr-is-rct>. [Accessed 2013].
- [61] Analog Devices, "Evaluation Board User Guide: UG-245," 17 March 2011. [Online]. Available: http://www.analog.com/static/imported-files/user_guides/UG-245.pdf. [Accessed 20 February 2013].
- [62] Sparkfun, "Triple Axis Magnetometer Breakout - HMC5883L," 3 March 2013. [Online]. Available: <https://www.sparkfun.com/products/10530>. [Accessed 3 March 2013].
- [63] Surrey Satellite Technology LTD, "Space GPS Receiver: SGR-05U," 9 November 2012. [Online]. Available: <http://www.sstl.co.uk/getattachment/97ae8ccc-024d-4376-a99d-7d3c2266a7f7/SGR-05U-05P>. [Accessed 20 February 2013].
- [64] Tyvak, "Intrepid Pico-Class CubeSat System Board," [Online]. Available: http://www.tyvak.com/products/Pico/IntrepidSystemBoard_2012July.pdf. [Accessed 20 February 2013].
- [65] R. Simmons, "MOLA Analysis Definitions," 20 December 1995. [Online]. Available: <http://analyst.gsfc.nasa.gov/ryan/MOLA/definit.html>. [Accessed 21 February 2013].
- [66] "CubeSat," Wikipedia, 9 April 2013. [Online]. Available: <http://en.wikipedia.org/wiki/CubeSat>. [Accessed April 2013].
- [67] I. R. Assembly, "Recommendation ITU-R P.834-4 Effects of tropospheric refraction on radiowave propagation," International Telecommunication Union, 2003.

Appendices

Appendix 1: Requirements per Reference Documents

The following eight lists are each a governing requirements document provided by institutions that help regulate what can and cannot be flown on a CubeSat. Each has been thoroughly read through and streamlined to determine what is directly related to the Sphinx CubeSat mission.

CubeSat Design Specification Rev. 12 The CubeSat Program, Cal Poly SLO [2]

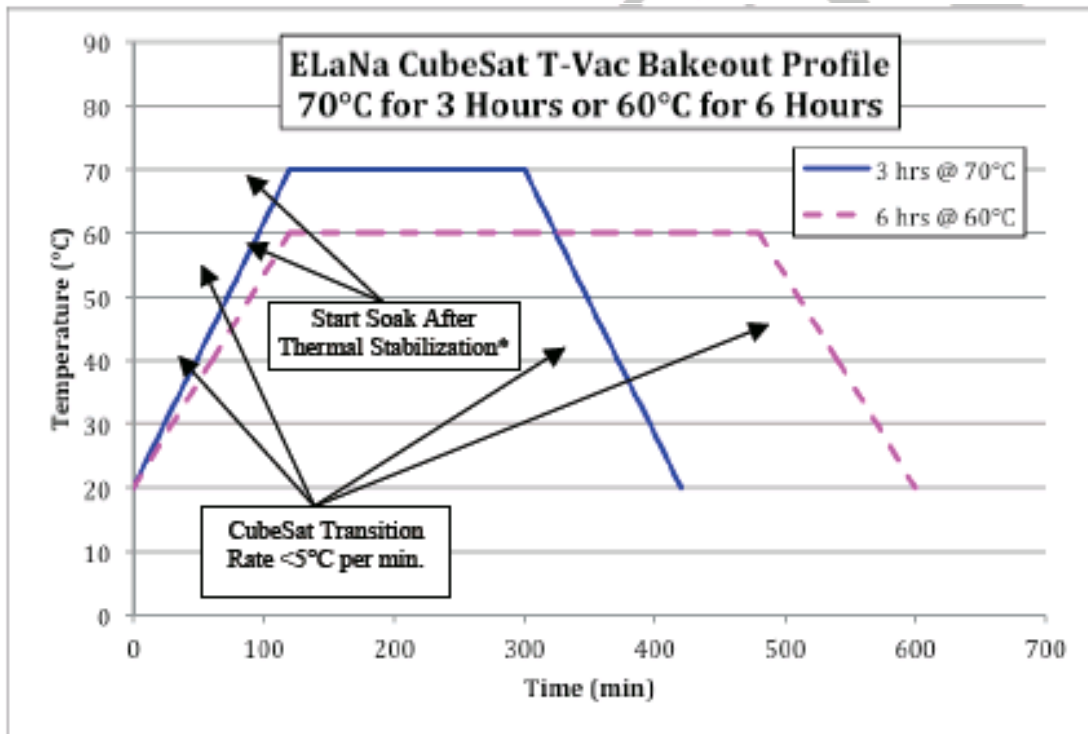
- 2.4.1 FCC requires all CubeSats with batteries must have ability to receive a transmitter shut down command
- 2.4.3 RF transmitters > 1mW must wait 30 min minimum after CubeSat deployment switches are activated from PPOD ejection (2) 6.2.10 says 45 min for communication sequences to begin
- 2.4.4 Need to obtain/provide licenses for use of certain frequencies – 2.4.4.1 proof of frequency coordination from IARU (international amateur radio union) (3) 2. Inputs for frequency licensing
- 2.4.5 Orbital decay must be < 25 years after end of mission life
- 3.4.1 Processing and Ground Operations Thermal Environments
Upon delivery to Cal Poly, the P-POD team will provide a temperature-controlled environment for the CubeSats while in the Cal Poly facilities. Temperatures are typically controlled at 75°F ± 10°F. Humidity will also be monitored. Expected pre-launch environments at the Range are defined as follows:
Temperature 35°F to 100°F (1.7°C to 37.8°C), Relative Humidity 0% to 100%
- 3.4.5 Thermal Environment
The CubeSat thermal environments are obtained from integrated thermal analysis (ITA). The maximum expected temperature range is from 44.7°F to 131.2°F (7.0°C to 55.1°C).
- 3.4.6 Thermal Vacuum Bakeout

CubeSats shall perform a thermal vacuum bakeout at a high vacuum level (minimum 1×10^{-4} Torr).

3.4.6.1 Thermal Vacuum Bakeout Profile

The CubeSat shall test to one of the two bakeout profiles outlined in Table 3 and Figure 3, with a temperature ramp rate of no greater than 5°C per minute.

Profile	Duration	Minimum Temperature
1	6 Hours	60°C
2	3 Hours	70°C



***Each profile is one continuous soak at the temperature and duration specified**

- 6.2.1. CubeSats shall be designed, and verified to the environments defined in Table 1 – PPOD and CubeSat Test Environments Testing Table and per Figure 1 - PPOD and CubeSat Qualification and Acceptance Test Flow Diagram

Table 1 – PPOD and CubeSat Environments Test Table

Tests	Qualification by Test	Protoflight Test	Acceptance Test
Random vibration⁴ (CubeSat and PPOD) Ref Mil-Std 1540C	MPE + 6 dB for (3) minutes, each of (3) axes ¹	MPE + 3 dB for (2) minutes, each of (3) axes ¹	MPE for (1) minute, each of (3) axes ¹
Sinusoidal Vibration⁶ (CubeSat and PPOD) Ref Mil-Std 1540C	MPE + 6 dB. Testing shall be performed for content that is not covered by random vibration testing	1.25 x MPE. Testing shall be performed for content that is not covered by random vibration testing	MPE. Testing shall be performed for content that is not covered by random vibration testing ¹
Shock⁶ (CubeSat and PPOD) Ref Mil-Std 1540C	MPE + 6 dB, 3 times in both directions of 3 axes (FB 1.1.6 Dispo) ^{1,2}	MPE + 3 dB, 1 times in both directions of 3 axes ^{1,2}	N/A
Thermal Vacuum Cycle (PPOD Only) Ref: MIL-STD 1540 B, GSFC-STD-7000	MPE ² +/- 10° C Minimum Range = -14 -3/+0°C to +71 -0/+3°C Cycles = 9 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr	MPE ² +/- 10° C Minimum Range = -14 -3/+0°C to +71 -0/+3°C Cycles = 4 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr	MPE ² +/- 5° C Minimum Range = -9 -3/+0°C to +66 -0/+3°C Cycles = 2 Dwell Time = 1 hour min. @ extreme Temp. after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr
Thermal Vacuum Bake out (PPOD Only) Ref: MIL-STD 1540 B, GSFC-STD-7000	N/A	Min. Temp 70°C ^{3,7} Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = N/A Vacuum = 1x10 ⁻⁴ Torr	Min. Temp 70°C ^{3,7} Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = N/A Vacuum = 1x10 ⁻⁴ Torr
Thermal Vac Bake out (CubeSat Only) Ref: MIL-STD 1540 B, GSFC-STD-7000	N/A	Min. Temp 70°C ³ Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr	Min. Temp 70°C ³ Cycles = 1 Dwell Time = Min. 3 hour after thermal stabilization Transition = < 5° C/minute Vacuum = 1x10 ⁻⁴ Torr
Hardware Configuration	PPOD - Flight identical unit (includes NEA, cable and connector) CubeSat - Flight Identical unit	PPOD - Flight unit (includes flight NEA, cable and connector) CubeSat - Flight unit	PPOD - Flight unit (includes flight NEA, cable and connector) CubeSat - Flight unit
<p>(1) Dynamic Environments random MPE envelopes a P95/50 or mean + 5 dB of flight environments. Sinusoidal levels envelope loads predictions and flight environments. Shock MPE envelopes P95/50 for at least (3) samples, with 4.5 dB uncertainty factor applied where less than (3) samples are used.</p> <p>(2) Thermal MPE = Max predicted via simulation + 11° C for uncertainty.</p> <p>(3) Shock testing is not required when the following conditions are met: 1) The qualification random vibration test spectrum when converted to an equivalent shock response spectrum (3-sigma response for Q=10) exceeds the qualification shock spectrum requirement at all frequencies below 2000 Hz. 2) The maximum expected shock spectrum above 2000 Hz does not exceed (g) values equal to 0.8 times the frequency in Hz at all frequencies above 2000 Hz, corresponding to the velocity of (50 inches/second).</p> <p>(4) Maximum bake out temperature set to same maximum temperature for thermal cycle test for consistency, assuming bake out would be performed during same vacuum exposure.</p> <p>(5) If the CubeSat cannot achieve these temperature levels, the CubeSat shall hold a minimum temperature of 60°C for a minimum of 6 hours.</p> <p>(6) Levels are defined to be at the PPOD to Launch Vehicle mechanical interface.</p> <p>(7) Thermal bake out temperatures are not to exceed qualification temperatures</p>			

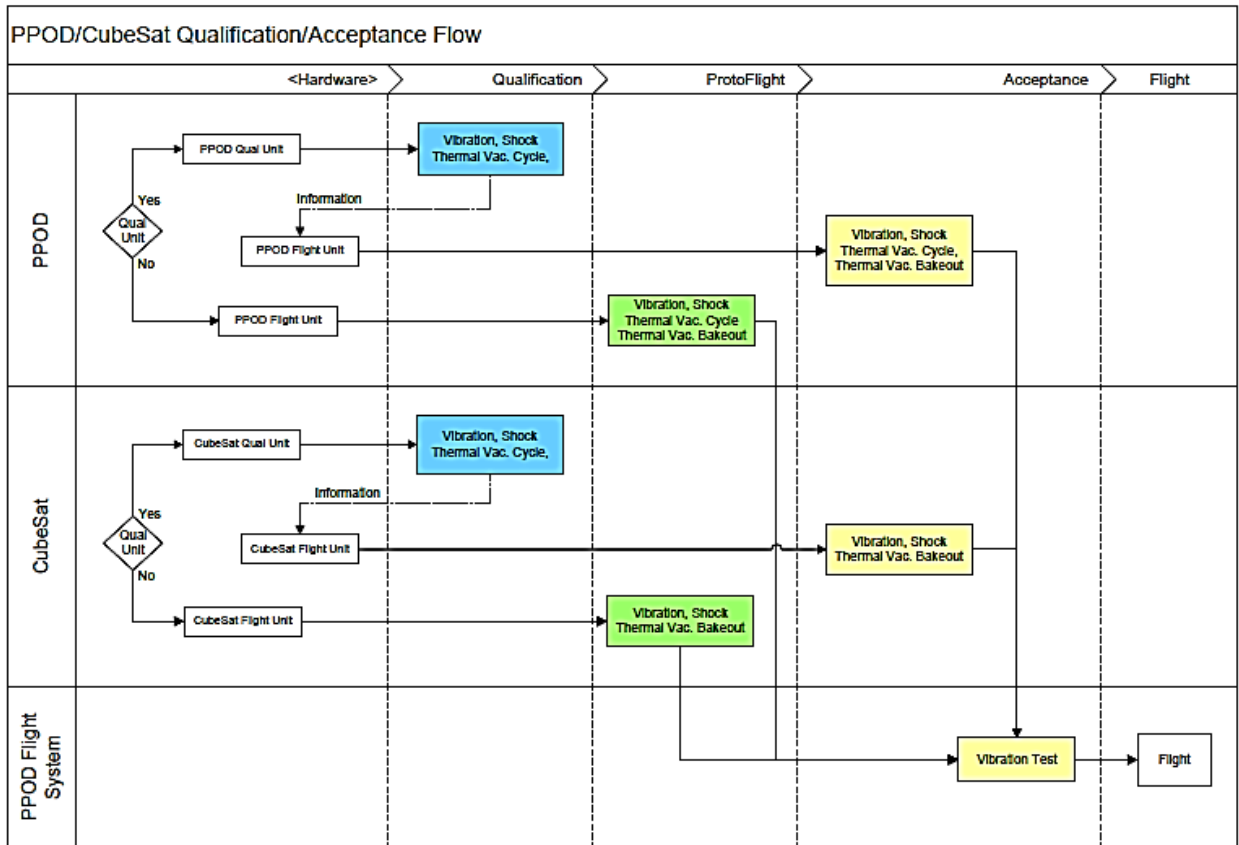


Figure 1 PPOD and CubeSat Qualification Acceptance Flow Diagram

6.3.7 PPOD door release must be designed to accept redundantly initiated signals

6.4.4 LV shall accommodate PPOD door position indicator in the flight telemetry stream.

6.4.5 LV avionics shall provide redundant-separation signals to the PPOD door actuation device.

6.4.9 LV shall command deployment of the PPOD's CubeSats.

6.4.10 LV trajectory design shall not result in LV contact with deployed CubeSats

6.4.11 LV shall not deploy the CubeSats in a trajectory that will contact the Primary Mission or LV

6.3.15 PPOD must have a fixed base frequency > 120 Hz

7. Development of Mission/Ground Operations Plan

- a. Identification of pre-launch activities (functional tests, handling, etc.) and requirements (basic facilities, time needed, etc.)

- b. Description of spacecraft operations plan post LV-separation (particularly transmitter initialization and first contact)

DNEPR Safety Compliance Requirements [34]

2. Thermal Vacuum Compliance

Thermal-vacuum bakeouts are critical in assemblies of space flight hardware to ensure the lowest levels of outgassing. Thermal bakeout of smaller subassemblies and components help reduce overall bake time and decrease the final levels of outgassing. A minimum vacuum level of 5×10^{-4} Torr must be attained to observe the outgassing of components.

Note: NASA certified materials should always be used in space flight hardware, especially epoxies and glue. If in doubt about the materials you are using, please contact the CubeSat Coordinator. **Thermal-vacuum bakeout must be performed on fully integrated flight CubeSats before integration into the P-POD.**

2.1 How to Test

2.1.1 Please read and understand all steps before performing any actions.

2.1.2 Clean the external surface of all hardware with lint free wipes and lab grade isopropyl alcohol before inserting the hardware into the thermal-vacuum chamber.

2.1.3 Place the clean hardware into the thermal-vacuum chamber.

2.1.4 Bring the chamber to a vacuum level of at least 5×10^{-4} Torr. Outgassing will be easily observed at higher vacuum levels.

2.1.5 Record the initial pressure level and temperature in the Bakeout Compliance Checklist attached at the end of this document.

2.1.6 Starting at room temperature, approximately 25°C raise the temperature of the shroud or heating element to 70°C.

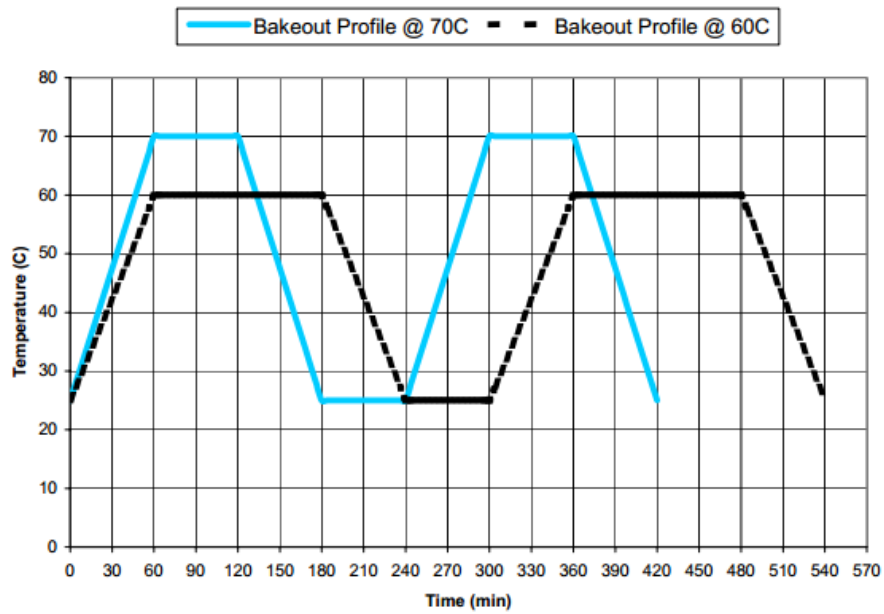
2.1.7 As temperature is increasing, record the pressure level along with the corresponding temperature every 20 minutes.

- 2.1.8 Wait until the exterior surface of the hardware has reached 70°C. Note: There may be an initial increase in pressure, this is to be expected.
- 2.1.9 Let the hardware bake at 70°C for one hour.
- 2.1.10 Record the temperature and pressure every 10 minutes during this first bake, making note of any unusual pressure readings.
- 2.1.11 If you do not wish to bring your flight hardware to 70°C, you may set the upper temperature extreme to 60°C. However, you must let the hardware bake for two hours.
- 2.1.12 Bring the chamber and hardware back to room temperature.
- 2.1.13 As temperature is decreasing, record the pressure and temperature every 20 minutes.
- 2.1.14 Keep the shroud and hardware at room temperature for one hour.
- 2.1.15 Record the pressure and temperature every 20 minutes.
- 2.1.16 Bring the shroud and hardware back up to 70°C for the final bakeout.
- 2.1.17 As the temperature increases, record the pressure and temperature every 20 minutes.
- 2.1.18 Let the hardware bake for one hour at 70°C.
- 2.1.19 Record the pressure and temperature every 10 minutes.
- 2.1.20 If you do not wish to bring your flight hardware to 70°C, you may set the upper temperature extreme to 60°C. However, you must let the hardware bake for two hours.

This will eliminate most of the outgassing that will occur at this temperature extreme. The pressure should remain constant and should not exceed $+ 1 \times 10^{-4}$

Torr from the original pressure at room temperature. If the pressure does increase, longer thermal baking is needed until the pressure stabilizes. The shroud and hardware are now brought back to room temperature.

2.1.21 Thermal bakeout is now complete.



General Environmental Verification Standard (GEVS) [14]

VACUUM, THERMAL, AND HUMIDITY REQUIREMENTS

Requirement	Payload or Highest Practicable Level of Assembly	Subsystem including Instruments	Unit/ Component
Thermal-Vacuum ^{1,7}	T	T	T ²
Thermal Balance ^{1,3,7}	T and A	T,A	T,A
Temperature-Humidity ³ (Manned Spaces)	T/A	T/A	T/A
Temperature-Humidity ⁴ (Descent & Landing)	T/A	T/A	T/A
Temperature-Humidity ⁵ (Transportation & Storage)	A	T/A	T/A
Leakage ⁶	T	T	T

1. Applies to hardware carried in unpressurized spaces and to ELV-launched hardware.
2. Temperature cycling at ambient pressure may be substituted for thermal-vacuum temperature cycling if it can be shown by a comprehensive analysis to be acceptable. This analysis must show that temperature levels and gradients are as severe in air as in a vacuum.
3. Applies to flight hardware located in pressurized area.
4. Applies to hardware that must retain a specified performance after return from orbit and is carried in the unpressurized cargo bay.
5. Consideration should be given to environmental control of the enclosure.
6. Hardware that passes this test at a lower level of assembly need not be retested at a higher level unless there is reason to suspect its integrity.
7. Survival/Safehold testing is performed on that equipment which may experience (non-operating) temperature extremes more severe than when operating. The equipment tested is not expected to operate properly within specifications until the temperatures have returned to qualification temperatures.

T = Test required.

A = Analysis required; tests may be required to substantiate the analysis.

T/A = Test required if analysis indicates possible condensation.

T, A = Test is not required at this level of assembly if analysis verification is established for non-tested elements.

Note: Card level thermal analysis using qualification level boundary conditions is required to insure derated temperature limits, for example, junction temperature limits, are not exceeded.

STANDARD MATERIALS AND PROCESSES REQUIREMENTS FOR SPACECRAFT

National Aeronautics and Space Administration, Washington, DC 20546-0001 [3]

4 .1.1.4 Commercial Off-The-Shelf (COTS) Hardware

- a. A procedure shall be established to ensure that all vendor-designed, off-the-shelf, and vendor-furnished items are covered by the M&P requirements of this document.
- b. The procedure shall include special considerations for off-the-shelf hardware where detailed M&P information may not be available or it may be impractical to impose all the detailed requirements specified in this standard.
- c. The procedure shall include provisions for ensuring that this hardware is satisfactory from an overall M&P standpoint.

NASA Procedural Requirements for Limiting Orbital Debris (w/ Change 1 - 5/14/09) (limiting orbital debris) [8]

- 3.1.2 The NASA Program/Project Manager, with the NASA Center SMA organization, shall track and monitor the noncompliances (to this NPR and NSS 1740.14 or NASA-STD 8719.14, as applicable per paragraph P.2.4) with the design and operations of the spacecraft and orbital launch vehicle stages beginning at PDR and shall have the tracking reviewed by the Center SMA organization prior to CDR and launch (Requirement57313).
- 3.3.1.3 When significant capabilities affecting the spacecraft's planned ability to passivate, maneuver, or reenter at end-of-life change either through graceful degradation, malfunction, or via command, the EOMP shall be updated/annotated by the NASA Program/Project Manager (Requirement 56867).
- 3.3.2.5 The NASA Program/Project Manager shall ensure that all spacecraft and launch vehicles designed to be operated in GEO are designed to be able to maneuver at least 300 km above GEO altitude (closest approach to GEO greater than 300 km above GEO altitude) (Requirement56882).

- 3.4 Conjunction Assessments during Mission Operations (for Earth-Orbiting Spacecraft)
 - 3.4.1 The NASA Program/Project Manager shall have conjunction assessment analyses performed routinely for all maneuverable Earth-orbiting spacecraft with a perigee height of less than 2000 km in altitude or within 200 km of GEO (Requirement56891).
 - 3.4.2 Conjunction assessment analyses shall be performed using the USSTRATCOM high-accuracy catalog as a minimum (Requirement56892).
 - 3.4.3 The NASA Program/Project Manager shall have a collision risk assessment and risk mitigation process in place for all maneuverable Earth-orbiting spacecraft that are performing routine conjunction assessment analyses (Requirement 56893).

LAUNCH SAFETY REQUIREMENTS FOR AIR FORCE SPACE COMMAND ORGANIZATIONS [4]

- 6.1. Flight Safety System Composition. The entire FSS consists of the airborne and ground FTSs, air- borne and ground tracking systems, and airborne and ground telemetry data transmission systems. This publication only addresses the Launch Safety requirements for the ground components of the FSS. Requirements for the airborne components of the FSS are in AFSPCMAN 91-710. The ground element of the FSS consists of the TDTS, the RTS, and the FTS. The RTS includes a RSD system, which displays vehicle flight performance data that the MFCO uses as the basis for a flight termination decision. The TDTS provides for the transport of onboard launch vehicle position and performance data to the RSD and the Range User. The CDS provides the MFCO the capability to terminate the vehicle's flight.
- 6.4. RTS Requirements. An RTS is composed of the hardware, software, and manpower required to transmit, receive, process, and display selected launch vehicle data. This data, when qualified as described below, allows a MFCO to compare actual and nominal flight trajectories, verify performance in conjunction with vehicle telemetry, and identify violations of destruct criteria.

With this information, the MFCO knows when a flight rule has been violated and flight termination actions are required.

- 6.5. TMIG Data as a Metric Tracking Source. TMIG data is a mandatory tracking source for programs using a launch vehicle inertial guidance system when validated by the AFSPC range or certified to the RCC Standard 324. The TMIG data is required at a 10 samples per second update rate from T-0 through the end of Wing Safety responsibility.
- 6.7.1. An RSD system is required as the primary information display system used by the MFCO to evaluate launch vehicle flight.
- 6.7.2. Flight Analysis (a part of the Launch Safety Section of Wing Safety) shall provide RSD requirements, instructions, and data necessary for display generation to range personnel responsible for RSD systems operations.
- 6.7.3. Real-Time Prediction Requirements.
 - 6.7.3.1. PP and IIP solutions shall be provided for display on the RSD at a rate of 10 samples per second or faster.
 - 6.7.3.2. The PP and IIP solutions shall be computed from data supplied by the tracking sources identified in the RSOR and/or its operational supplement as applicable.
 - 6.7.3.3. PP and IIP computations and displays shall be single failure tolerant.
 - 6.7.3.4. Range specific real-time calculated IIP accuracy requirements are provided in AFSPC- MAN 91-710 and the SW supplements to AFSPCMAN 91-711.
 - 6.7.3.5. Velocity vs. time, altitude, fast/slow time relative to nominal, plus count time, dynamic nominal and other data identified in the RSOR shall also be displayed.
- 6.7.4. Wing unique RSD requirements shall be included in the respective wing supplement to AFSPCMAN 91-711.
- 6.7.5. Video Display Requirements.
 - 6.7.5.1. Video monitors with channel switching capability shall be provided to the MFCO and Senior MFCO positions.
 - 6.7.5.2. Specific video coverage requirements peculiar to a mission shall be identified in the RSOR for the vehicle or the Ops Sup for the mission.
- 6.7.6. Telemetry Display Requirements.

- 6.7.6.1. Specific telemetry display requirements shall be documented in the RSOR or Ops Sup for a mission.
- 6.10. Telemetry Systems. Real-time information on in-flight vehicle performance and behavior typically includes but is not limited to, engine chamber pressures, roll rate, attitude, launch vehicle velocity vs. time, automatic gain control values of the command destruct receivers, and occurrence of discrete event. Additional telemetry system requirements are provided in the SW supplements to AFSPCMAN 91-711 and the program specific RSOR.
- 7.1.3. Command Capability. AFSPC ranges shall ensure that range managed instrumentation provides uninterrupted command capability for all systems that use an FTS or thrust termination system. For systems that use command receiver decoders, capture from FTS turn-on through flight control end of mission is required.
- 7.4.1. The Flight Control communication circuit requirements shall be specified in the applicable RSOR, Ops Sup, or operations directive (OD).

Appendix 2: Definition of Key Terms

- 2D: Two-Dimensional
- 2U: Two Unit
- 3D: Three-Dimensional
- 3U: Three Unit
- ADC: Attitude Determination and Control
- AFSK: Audio Frequency Shift Keying
- AGI: Analytical Graphics Inc.
- Bandwidth: The maximum change in frequency for a continuous set of frequencies.
- BCR: Battery Charge Regulator
- BER: Bit Error Rate - The number of altered or incorrect bits, caused by interference, distortion, or noise, divided by the total number of bits in an interval of time.
- BPSK: Binary Phase Shift Keying - Form of phase modulation where the signal phase can be one of 2 possible values.
- C/N: Carrier to noise ratio dependent on bandwidth.
- C/No: Carrier to noise ratio independent of bandwidth.
- CAD: Computer-Aided Design
- Cal Poly: California Polytechnic State University
- CDMA: Code Division Multiple Access- Multiple Access technique which uses a PN code to spread a narrow band signal over a wider band.
- COTS: Commercial Off-The-Shelf
- DAQ: Data Acquisition
- DCGS: Delft Command Ground Station
- DNEPR: Russian launch vehicle. Carried 14 CubeSats but failed to launch.
- Eb/No: Receiver bit energy to noise ratio.
- EHF: Extremely High Frequency
- EIRP: Effective Isotropically Radiated Power- The amount of power that a theoretical isotropic antenna would emit to produce the peak power density observed in the direction of maximum antenna gain. Measured as the transmitter power plus the antenna gain minus line losses.
- EoC: End of Charge

- EOM: End of Mission
- EPS: Electrical Power System
- FCC: Federal Communications Commission
- Flux Density: The transmitter's radiated power over the surface area of a sphere whose radius equals the distance between the transmitter and receiver.
- FSK: Frequency Shift Keying - Modulation technique in which digital information is carried by discrete changes in frequency of a carrier wave.
- g/T: Ratio of gain over temperature.
- GENSO: Global Educational Network for Satellite Operations
- GPS: Global Positioning System
- Ground Tracks- projection of the satellite's orbit onto the surface of the Earth
- H1: Header 1
- I²C: Inter Integrated Circuit- Consists of a data line and a clock line, allowing for a connection of a low speed device to a motherboard or an embedded system.
- ICD: Interface Control Document
- LNA: Low Noise Amplifier- Low gain amplifier optimized to minimize the amount of noise the amplifier adds to the signal.
- LV: Launch Vehicle
- Mbps: Mega Bytes per Second
- MPE: Maximum Predicted Environment
- MPPT: Maximum Power Point Tracking
- MQP: Major Qualifying Project
- MUA: Material Usage Agreement
- NASA: National Aeronautical Space Association
- OBC: On Board Computer
- PCB: Printed Circuit Board
- PCM: Power Conditioning Modules
- PDM: Power Distribution Module
- PMAD: Power Management and Distribution
- P-POD: Poly-Picosatellite Orbital Deployer

- QPSK: Quadrature Phase Shift Keying - Form of Phase Modulation in which the carrier phase can be one of 4 possible phases. Has the same Bit error rate as BPSK but for 1/2 the bandwidth.
- R.A.A.N : Relative Angle of the Ascending Node
- RBF: Remove Before Flight
- RF: Radio Frequency
- RIP: Received Isotropic Power- The power of a signal at the receiving station relative to an isotropic antenna. Computed by taking the EIRP and subtracting the free space loss, atmospheric loss, and pointing loss.
- SA: Solar Array
- S-Band: IEEE standard for radio waves (frequencies that range from 2000 to 4000 MHz)
- SHF: Super High Frequency
- STK: Systems Took Kit
- TBD: To Be Determined
- TVB: Thermal Vacuum Bakeout
- UHF: Ultra High Frequency (frequencies that range from 300 to 3000 MHz)
- USAF: United States Air Force
- USB: Universal Serial Bus
- VHF: Very High Frequency (frequencies that range from 30 to 300 MHz)
- WPI: Worcester Polytechnic Institute, Worcester, Massachusetts

Appendix 3: Normalized Beta Values over 24 Hours at 5 minute Step

The following tables show a sampling of the x, y, and z normalized coordinates for the vector between the spacecraft's center and the sun over time in five minute increments over the span of one day. This vector can be seen in Figure 21. (Electronic file available in the project file archive.)

Time (UTCG)	X	Y	Z
00:00.0	0.184064	-0.9277	-0.3248
05:00.0	0.163786	-0.93148	-0.32483
10:00.0	0.143436	-0.93482	-0.32485
15:00.0	0.123022	-0.93772	-0.32488
20:00.0	0.102553	-0.94017	-0.3249
25:00.0	0.082036	-0.94218	-0.32491
30:00.0	0.06148	-0.94374	-0.32492
35:00.0	0.040893	-0.94486	-0.32492
40:00.0	0.020282	-0.94552	-0.32493
45:00.0	-0.00034	-0.94574	-0.32493
50:00.0	-0.02097	-0.94551	-0.32493
55:00.0	-0.0416	-0.94482	-0.32493
00:00.0	-0.06221	-0.94369	-0.32493
05:00.0	-0.08279	-0.9421	-0.32494
10:00.0	-0.10333	-0.94007	-0.32495
15:00.0	-0.12383	-0.93758	-0.32497
20:00.0	-0.14426	-0.93465	-0.32499
25:00.0	-0.16462	-0.93127	-0.32502
30:00.0	-0.1849	-0.92745	-0.32505
35:00.0	-0.20508	-0.92318	-0.32507
40:00.0	-0.22516	-0.91848	-0.3251
45:00.0	-0.24513	-0.91335	-0.32513
50:00.0	-0.26498	-0.90778	-0.32515
55:00.0	-0.2847	-0.90178	-0.32516
00:00.0	-0.30429	-0.89536	-0.32517
05:00.0	-0.32373	-0.88851	-0.32518
10:00.0	-0.34302	-0.88124	-0.32518
15:00.0	-0.36216	-0.87355	-0.32518
20:00.0	-0.38112	-0.86545	-0.32518
25:00.0	-0.39991	-0.85693	-0.32518
30:00.0	-0.41852	-0.848	-0.32519

Time (UTCG)	X	Y	Z
35:00.0	-0.43692	-0.83866	-0.32519
40:00.0	-0.45512	-0.82892	-0.3252
45:00.0	-0.47311	-0.81878	-0.32522
50:00.0	-0.49086	-0.80825	-0.32524
55:00.0	-0.50838	-0.79734	-0.32526
00:00.0	-0.52565	-0.78605	-0.32529
05:00.0	-0.54267	-0.77439	-0.32532
10:00.0	-0.55942	-0.76236	-0.32535
15:00.0	-0.5759	-0.74998	-0.32537
20:00.0	-0.59211	-0.73724	-0.32539
25:00.0	-0.60804	-0.72415	-0.32541
30:00.0	-0.62367	-0.71072	-0.32543
35:00.0	-0.63901	-0.69696	-0.32544
40:00.0	-0.65405	-0.68286	-0.32544
45:00.0	-0.66879	-0.66844	-0.32544
50:00.0	-0.6832	-0.6537	-0.32544
55:00.0	-0.6973	-0.63864	-0.32544
00:00.0	-0.71107	-0.62327	-0.32544
05:00.0	-0.7245	-0.6076	-0.32545
10:00.0	-0.73759	-0.59164	-0.32546
15:00.0	-0.75032	-0.5754	-0.32547
20:00.0	-0.7627	-0.55888	-0.32549
25:00.0	-0.77471	-0.5421	-0.32551
30:00.0	-0.78635	-0.52506	-0.32553
35:00.0	-0.79761	-0.50777	-0.32556
40:00.0	-0.80848	-0.49025	-0.32559
45:00.0	-0.81897	-0.4725	-0.32562
50:00.0	-0.82907	-0.45453	-0.32564
55:00.0	-0.83878	-0.43634	-0.32566
00:00.0	-0.84808	-0.41795	-0.32568

Appendix 4: Lab Option Hardware List

The following are images and details for the equipment purchased for the vacuum chamber experiment.

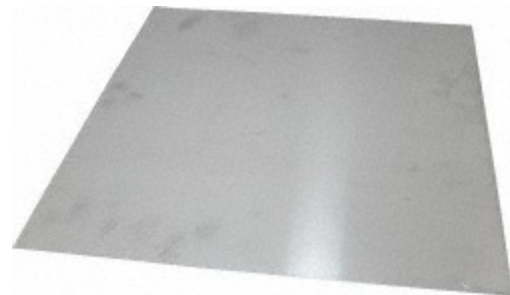
Halogen Lamp & Bulb [35]

Workforce 250-Watt Halogen Portable Work Light
Home Depot
Model # 778-980, Home Depot Store SKU # 778980
\$8.99



Aluminum Sheet [36]

Alloy 3003 Aluminum Sheet
Dimensions:
Thickness: 0.0252 in
Width: 12 in
Length: 12 in
MSC Industrial Supply Co.
MSC #: 09426057
\$4.52



PCB [37]

PCBs / Circuit Boards Single-Sided
Copper Clad
Dimensions:
Thickness: 1/32 in
Width: 6 in
Length: 9 in
Distributor: Mouser Electronics
Mouser Part #: 590-588
\$7.46



Thermocouples [38]

Ready-Made Insulated Thermocouples with Kapton®, PFA, Glass Braid Insulation and Molded Connectors

Thermocouple, type k, insulate (glass braid), exposed junction

AWG Gage: 24

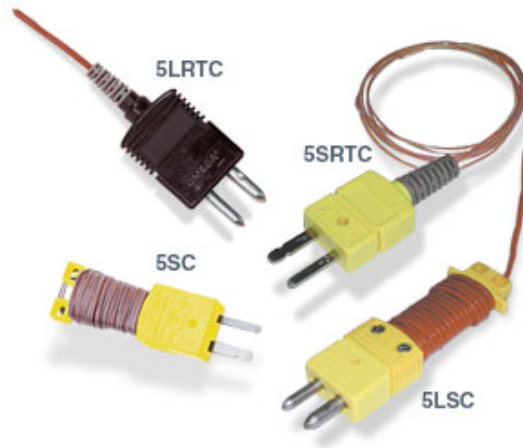
Diameter: 0.020 in

Miniature connector

Omega

Part Number: 5SRTC-GG-(K)-24-(36)

\$50.00



Extension Wires [39]

24 Gage Solid Thermocouple Wire with FEP Insulation and Jacket, K-type

McMaster-Carr

Part Number: 3870K32

\$1.20/ft.



Connectors for the thermocouples to the chamber feedthroughs [40]

Panel-Mount Thermocouple Female Connectors

Panel Cutout: 7/8 in. diameter

McMaster-Carr

Part Number: 3869K48

\$10.82



Chamber electrical feedthrough [41]

Power Feedthroughs - Weldable 500 Volts
Stainless Steel – 4 pins

Kurt J. Lesker Co.

Part Number: EFT0042031

\$81.50



Appendix 5: WPI Ground Station

Below are two cost estimates of all required hardware, excluding the antenna, needed to create a WPI Ground Station. The difference between Upper and Lower is simply pricing. All part numbers are the same between the two, Lower is the used version of the parts. The decision to show two different cost estimates was to establish a range of possible totals for all hardware. Upper values are all new parts from the manufacturer or commercial sources, while Lower is used hardware from various different places. In the event that a cheaper used part is unavailable, the Upper value will be available.

Cost Analysis (Upper)

part	use	cost
ICOM CIV radios IC9100	Radio	\$3,349.95
Yaesu G5500	rotor	\$749.95
Yaesu G5500 sep kit		\$24.00
Rotor Controller GS-232B	controller	\$ 870
ST-1 Rotor Controller		\$ 45
K9612+ (Kantronics)	TNC	\$ 400
MixW	TNC	Free
K8055 (Velleman)	Switch	\$ 58
SP7000 SSB ELECTRONICS	amp	\$ 412
Ground Station Control Computer	comp	\$ 1300
1 Terabyte External Hard drive	comp	\$ 85
Linux Laptops for SDR Control	comp	\$ 1100
Kantronics 3 plus Modem	comp	\$ 200
Wireless Network Router BEFSR41	comp	\$ 11
Uninterruptable Power Supply 1000AVR	power	\$ 150
12 Volt Power supply 1692	power	\$ 345
RF Directional Thruline Watt Meter Mdl. 43	power	\$ 350
USRP-2 SDR	interface	\$ 650
USRP-1 SDR	interface	\$ 700
USRP daughter board WBX	interface	\$ 450
USRP daughter board TVRX	interface	\$ 200
(2) Coax protectors Polyphaser IS-50NX-C2 Lightning suppressors	lightning rod	\$ 63
(2) Cable protectors Polyphaser IS-RCT Lightning suppressors	lightning rod	\$ 133
		\$11,646

Cost Analysis (Lower)

part	use	cost per
ICOM CIV radios IC910h	Radio	\$2,000
Yaesu G5500	rotor	480
Yaesu G5500 sep kit		w/ above
Rotor Controller GS-232B	controller	\$ 630
ST-1 Rotor Controller		\$ 39
K9612+ (Kantronics)	TNC	\$ 400
MixW	TNC	Free
K8055 (Velleman)	Switch	\$ 40
SP7000 SSB ELECTRONICS	amp	\$ 330
Ground Station Control Computer	comp	\$ 800
1 Terabyte External Hard drive	comp	\$ 70
(2) Linux Laptops for SDR Control	comp	\$ 302
Kantronics 3 plus Modem	comp	\$ 30
Wireless Network Router BEFSR41	comp	Free
Uninterruptable Power Supply 1000AVR	power	\$ 100
12 Volt Power supply 1692	power	\$ 345
RF Directional ThruLine Watt Meter Mdl. 43	power	\$ 155
USRP-2 SDR	interface	\$ 850
USRP-1 SDR	interface	\$ 700
USRP daughter board WBX	interface	w/ above bus
USRP daughter board TVRX	interface	\$ 200
(2) Coax protectors Polyphaser IS-50NX-C2 Lightning suppressors	lightning rod	\$ 62
(2) Cable protectors Polyphaser IS-RCT Lightning suppressors	lightning rod	\$ 130
		\$7,663

Appendix 6: Other Ground Station Hardware

The following tables are compilations of the hardware and software being used by each of the ground stations that have been used in calculating the ground tracks and data link budget. The information was used to determine antenna information for the data information. The lists were also used in determining hardware for the proposed WPI Ground Station. By using similar or the same hardware and software, the ground stations will more easily be able to communicate.

Nicolaus Copernicus Astronomical Center, Warsaw University of Technology, Warsaw, Poland [42].

hardware	use
two Yagi- Uda antennas for UHF	Antenna
structure 10 feet	Tower
2.08m parabolic dish (Figure 4) with a right-hand circularly polarized feed is used to receive the S-Band Andersen Manufacturing	Antenna
Two 435MHz 42-element circularly polarized (with polarization switch) Yagi- Uda UHF signal.	Antenna
single Yagi- Uda antenna VHF	Antenna
S-Band signal PSM-4900 by Datum Systems.	Radio
Half-duplex Yaesu FT-897 amateur transceiver UHF link.	Radio
VHF radio Yaesu FT-847	Radio
Rotator AlfaSpid Radio full Azimuth/Elevation design.	Rotator
Custom designed microcontroller uses a simple 8-bit microcontroller (uC), the ATmega32.	Controller
A pair of low-cost H-Bridge motor	Motor
200MHz ARM Single Board Computer (SBC) by Technological Systems	Computer
Linux	operating system
SCC PEB20525 Serial Communications Controller	Controller
Rotator Interface RS-422 interface	Interface
S-Band Modem Interface	Interface
Since the TNC control board	
S-Band modem (DATUM Systems PS2100	Modem
UHF Modem CMX589 synchronous GMSK	Modem
RS-232 serial ports interface with the UHF radio.	Interface
“Plan13” algorithm fed by NORAD TLE’s. A set of scripts have been developed that interface with the SpaceTrack website to automatically retrieve new NORAD TLE’s.	Software
Operator Interface Software created “ <i>Nanosatellite Interface Control Environment (NICE)</i> ”. NICE was	Software
The Terminal Interface Program (TIP) created	Software

Delft Command Ground Station (DCGS), Delft University of Technology, Delft, Netherlands [43]

*The ISIS ground station kit has been designed to be compatible with the Global Educational Network for Satellite Operations (GENSO)

hardware	Use
38k4 FSK TNC	TNC
12-U 19" rack which allows the ground station to fit in almost any location.	Tower
VHF Yagi antenna	Antenna
UHF Yagi antenna	Antenna
VHF Low Noise Amplifier	Amp
UHF Low Noise Amplifier	Amp
21dBic gain S-band parabolic reflector	Antenna
Lightning protection system	lightning
Heavy duty all-weather azimuth – elevation rotator	Rotator
Terminal Node Controllers (TNC's) for 1200-9600bd AX.25 AFSK, FSK and BPSK	TNC
38k4 FSK Terminal Node Controller (TNC) and high speed modification of ground station transceiver option available	TNC
Uninterruptible Power Supply	Power
Industrial rackmount PC with tracking software	Computer Software

FASTRAC, University of Texas at Austin, Austin, Texas [44].




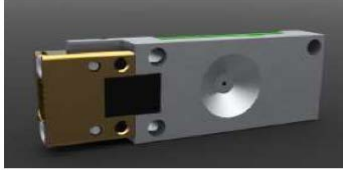
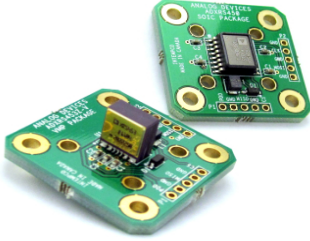


hardware	use
Windows HyperTerminal	software
MacDoppler for Cocoa	software
MixW	TNC
ONEStop	software
two UHF/VHF Yagi	antenna
IC-910H	radio
ICOM PS-125	radio
Astro Dev Helium 100	
Hamtronics r100 VHF FM RECIEVER	radio
MO-96 9600 baud modem kit	modem
Kantronics KPC-9612+	TNC
Hamtronics ta451 modification kit	modem modifier
Hamtronics r451 modification kit	modem modifier
Hamtronics crystals	
tantalum caps	


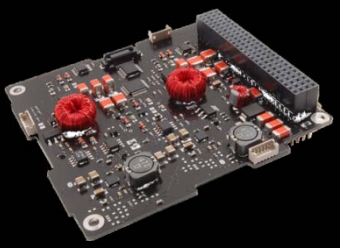
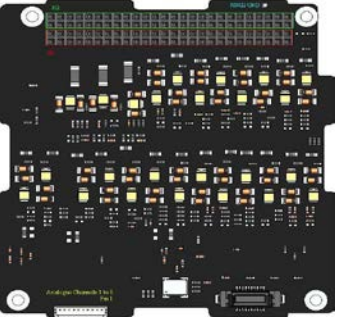


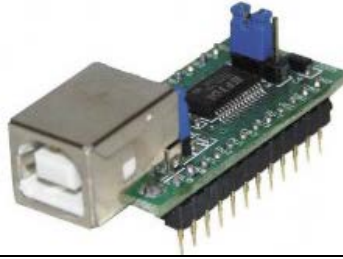
Cal Poly Earth Station – N6CP, California Polytechnic State University, San Luis Obispo, California [45].


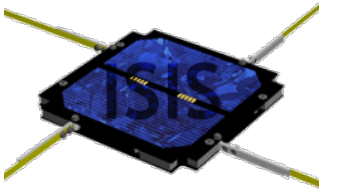


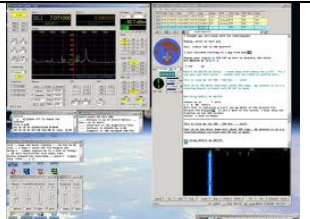
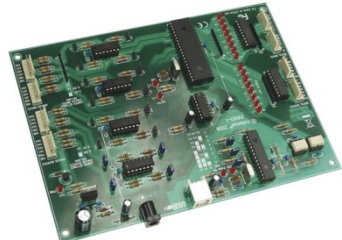

hardware	use
Chipcon CC1000	Software
Yaesu FT-847 radio	Radio
cc1000.c	Software
Microchip PIC18LF6720	Chip
KPC9612+ [23]	Interface
MixW	TNC
RF Microdevices RF2117	Chip
Yaesu 847 radio	<i>Radio</i>
2m and 70cm Yagi	<i>Antenna</i>
HF antenna.	Antenna
Tower Rohn JRM23810 non-penetrating roof mount.	Tower
Yaesu G-5500 rotor system	Rotator
M-squared 436CP42 antenna is used for 70cm	Antenna
SSB Electronics preamplifier	Amp
LMR-400 coax	Cable
50 foot run of 5/8" heliax goes thru	Cable
1200 baud can be just straight speaker audio (after the filters)	Interface
9600 baud data must be taken before the filters (discriminator-tapped).	Interface
CAT interface FT-847	Interface
DB-9 serial port needs null-modem adapter	
standard PC	Computer
WindowsXP	operating system
<u>MixW</u>	TNC
COM port drivers	
MacDopplerPRO (Dog Park Software)	Software
two Mac computers (MacOS X)	Computer
SatPC32	Software
· Predict by John A. Magliacane, KD2BD. This is a small terminal-based prediction program that will work on *nix and DOS platforms. It has a very clean and clear interface, and will run over an SSH connection. It will even run on the built-in terminal in MacOS X.	Software
· Instant Track from AMSAT. This is a DOS-only program. It can run on current machines, but has trouble with the screen. If you have an old DOS computer, drop this on it and practice tracking some satellites. Make sure to read the README documents.	Software
· Space Track - The official Keplerian Elements source. Requires free registration.	locating software
· AMSAT - Keplerian Elements for all the amateur satellites in 2-line format.	locating software
· Celestrak - Another distributor of elements.	locating software

Appendix 7: Complete Hardware Parts List with Images





The table below is a hardware and parts list for the major components required to implement the CubeSat mission. This includes on-board ADC, Power, and Communication parts, and the ground station hardware and software.

Group	Component	Company	Part Number	Image
OBC	OBC	Tyvak	Intrepid	
[20]	ADC board	ClydeSpace	CS-ADCS-INT-01	
[30]	Course Sun Sensor (3 or 5)	ComTech AeroAstro	CubeSat Sun Sensor	
[9]	Fine Sun Sensor	SSBV Space and Ground Systems	Fine Sun Sensor	
[22]	Gyro	Analog Devices	ADXRS450	
ADC				
[46]	Magnetic Torquers (3)	Zarm Technik AG	MTO 5.0 (Optimized)	
[24]	Magnetometer	Honeywell	HMC5883L	

[25]	GPS	Surrey Satellite Technology US LLC	SGR-05U		
Payload	Instrument	Sphinx	NG - XRAY		
Power	[6]	EPS Board	ClydeSpace	CS-3UEPS2-NB	
	[7]	PDM Board	ClydeSpace	CN-SWT-0035-CS	
	[26]	Battery	ClydeSpace	CS-SBAT2-30	
	[47]	Battery Charge Cord	FTDI Chip	FTDI USB-RS422-WE	
	[48]	Battery Charge Cord Adapter	Bravekit	FTDI UM232R	
	[27]	Front Solar Panels	ClydeSpace	SP-L-F2U-0033-CS	
[28]	Side Solar Panels	ClydeSpace	SP-L-S2U-0031-CS		

[10]	UHF Transceiver	ISIS	Transceiver	
	UHF Transceiver	ISIS	Antenna	
[49]	IC910	ICOM	Radio	
	MercuryRotor driver.	YASU	rotor	
[50]	K9612+ the two ports (1200 & 9600)	Kantronics		
[51]	MixW		TNC	
[52]	K8055 (Velleman)	Velleman		
[53]	SP7000 SSB ELECTRONICS			

[54]	Yaesu G-5500 AZ/EL	Yaesu	Controller	
	Ground Station Control Computer		Control Computer	
	1 Terabyte		External Hard Drive	
		Linux	Laptop (SDR Control)	
[55]	BEFSR41		Wireless Network Router	
	Uninterruptable 1000AVR		Power Supply	
	1692		12 Volt Power supply	
	1460 1PS		12 Volt Power supply	
[56, 57]	RF Directional ThruLine Watt Meter Mdl. 43			
[58]	USRP-B100			
[58]	USRP-1 SDR			

[58]	WBX	USRP	daughter board	
[58]	TVRX	USRP	daughter board	
[59]	(2) Coax protectors Polyphaser IS-50NX-C2		Lightning suppressors	
[60]	(2) Cable protectors Polyphaser IS-RCT		Lightning suppressors	

Appendix 8: CubeSat Bus Wiring Diagrams

This appendix provides a labeling of all the connection points between the CubeSat bus and the devices attached to the CubeSat. Below are the figures that show the locations of the headers, the pins of the headers, and the labeling of the wires or connection points of the devices.

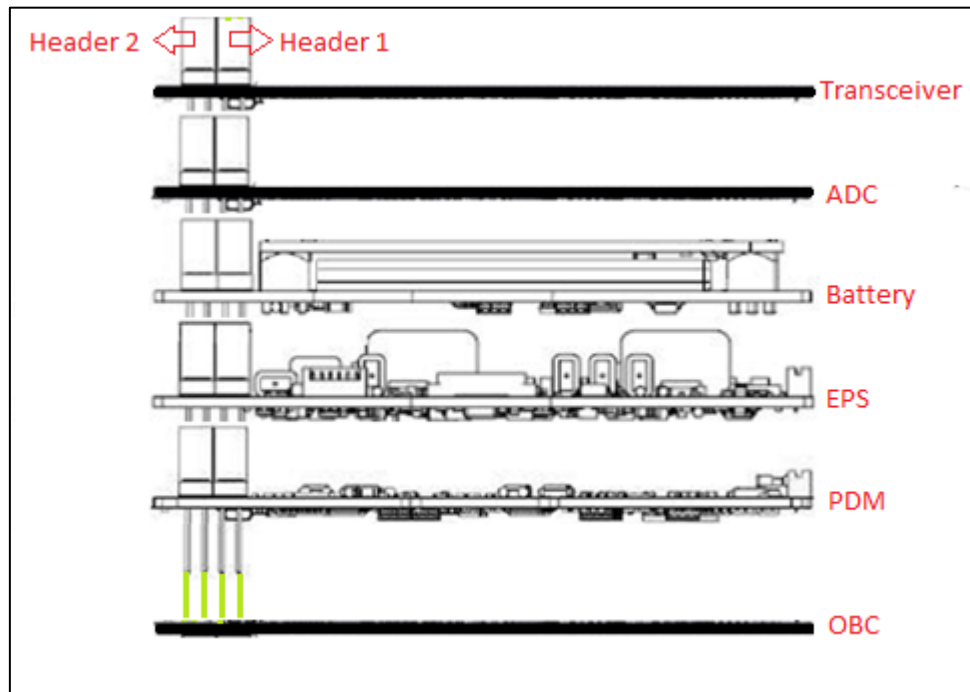


Figure 34: Vertical Board Stack (Side Images of boards adapted from [7], [6] and [26])

H2	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51
H1	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51

Figure 35: CubeSat Bus's Pin and Header Labeling

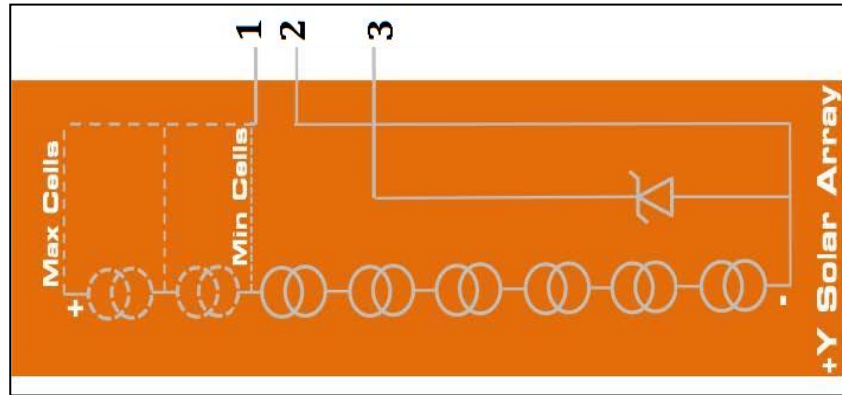


Figure 36: Solar Array Wire Labeling (adapted from [6])

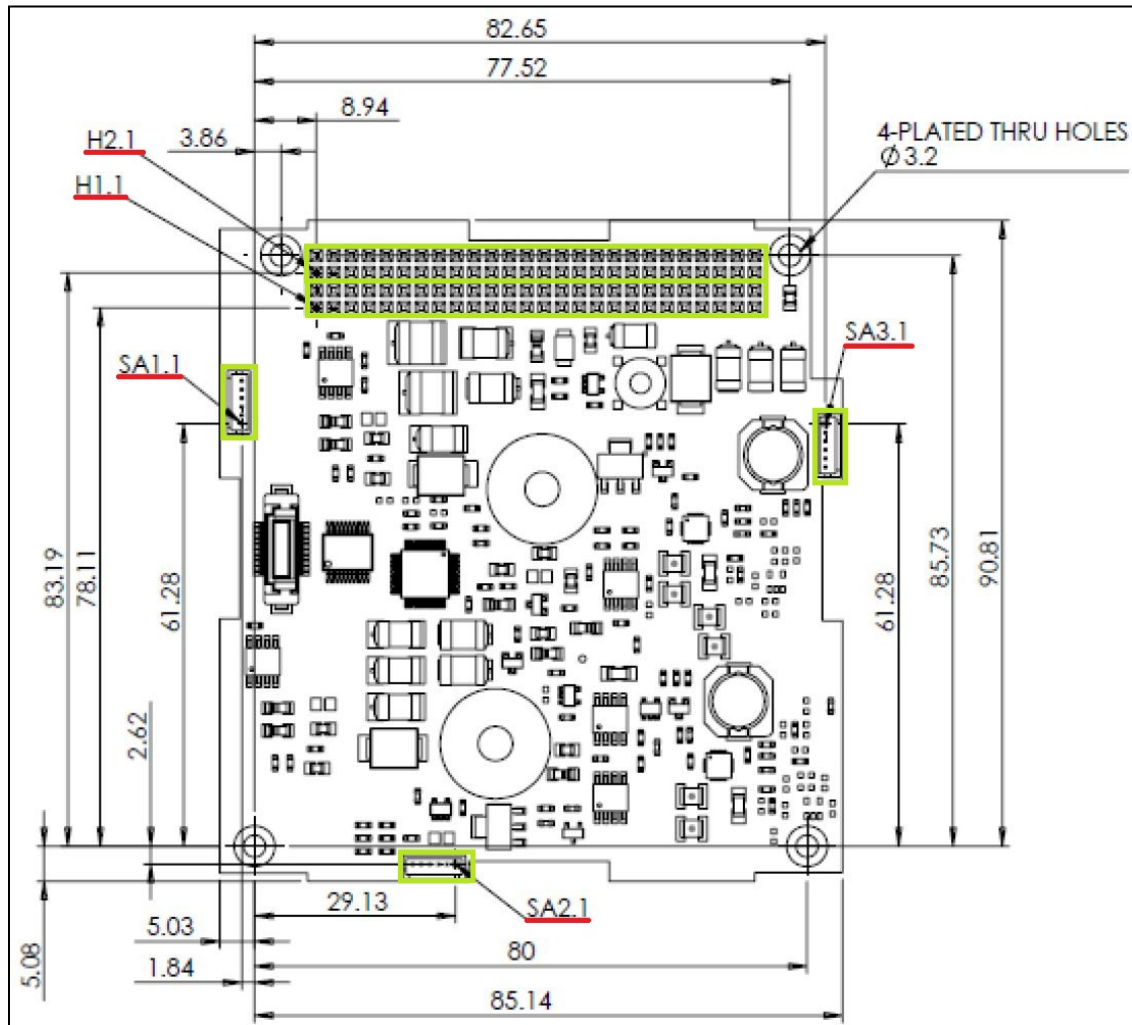


Figure 37: SA Connector Location and Labeling (adapted from [6])

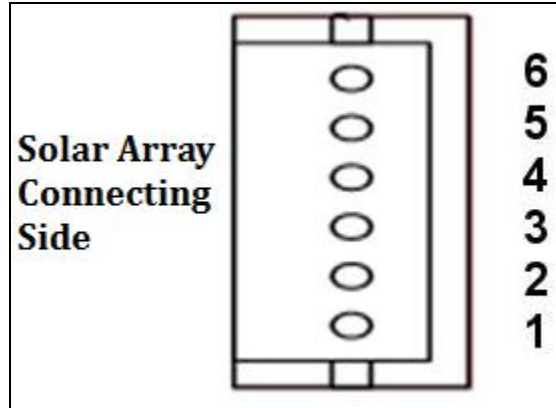


Figure 38: SA Connector Pin Labeling (adapted from [6])

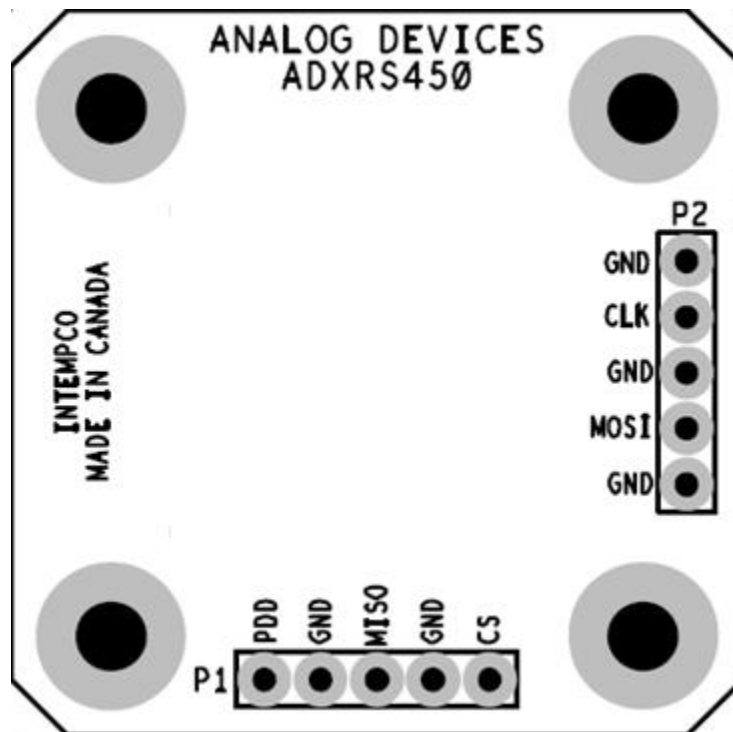


Figure 39: Gyroscope's Mounting Board Wire Connection Labeling (adapted from [61])



Figure 40: Magnetometer's Mounting Board Wire Connection Labeling (adapted from [62])



Figure 41: Coarse Sun Sensor's Wire Labeling (adapted from [21])

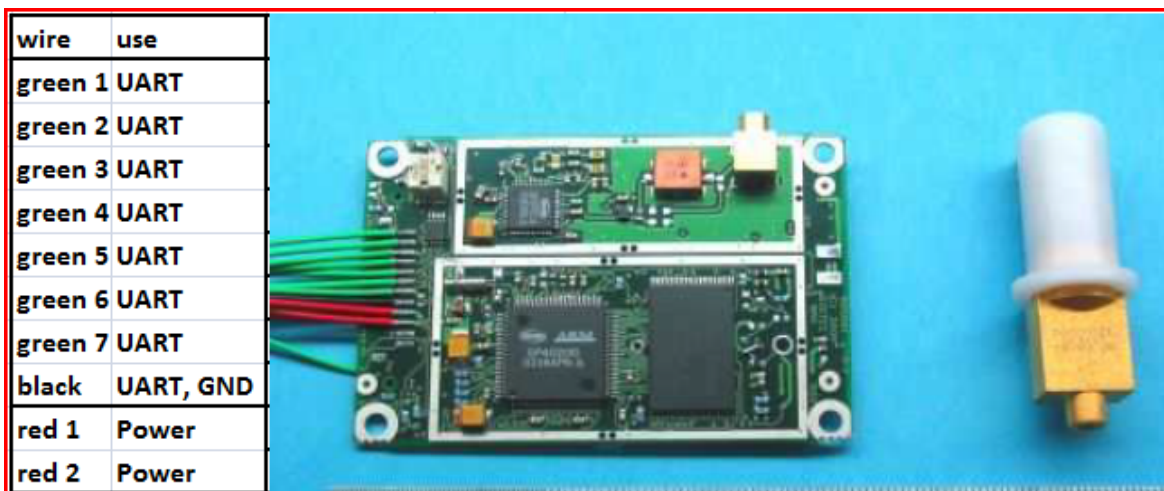


Figure 42: GPS's Wire Labeling (adapted from [63])

Appendix 9: CubeSat Bus Power Board Pin Assignments

This appendix details the connections between the 104 pins of the two headers of the CubeSat bus and devices attached to the CubeSat using the labeling conventions described in Appendix 8. The first two tables describe the purpose of each pin of each header of the CubeSat bus and where they connect to. The third table describes the connections between the devices and either the ADC board or the CubeSat bus.

Table 9: CubeSat Bus, Header 1					
SW=Switch AI=Analog Input -=Not Applicable ()=Originating Board, Device					
Pin	Purpose	Maximum Voltage (V)	Maximum Current (A)	Connection	References
1	SW: 19, (PDM)	8.3	4	-	[7]
3	SW: 19, (PDM)	8.3	4	-	[7]
5	SW: 22, (PDM)	opt+2.5%	4	-	[7]
7	AI: GND, (EPS)	3	-	board stack connection only	[7], [6]
9	AI: GND, (EPS)	3	-	board stack connection only	[7], [6]
11	AI: GND, (EPS)	3	-	board stack connection only	[7], [6]
13	-	-	-	-	[7], [6]
15	-	-	-	-	[7], [6]
17	AI: GND, (EPS)	3	-	board stack connection only	[7], [6]
19	AI: +Y CURRENT, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
21	AI: +Y TEMPERATURE, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
23	AI: Y PAIR VOLTAGE, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]

25	AI: -Y CURRENT, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
27	AI: -Y TEMPERATURE, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
29	AI: X PAIR VOLTAGE, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
31	AI:	-	-	-	[7], [6]
33	AI:	-	-	-	[7], [6]
35	AI:	-	-	-	[7], [6]
37	AI:	-	-	-	[7], [6]
39	AI:	-	-	-	[7], [6]
41	I2C DATA	3	-	board stack connection only	[7], [6]
43	I2C CLOCK	3	-	board stack connection only	[7], [6]
45	AI: GND, (EPS)	3	-	board stack connection only	[7], [6]
47	AI: +X CURRENT, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
49	AI:+X TEMPERATURE, (EPS, Solar Array)	3	-	board stack connection only	[7], [6]
51	AI: GND, (EPS)	3	-	board stack connection only	[7], [6]
2	SW: 19, (PDM)	8.3	4	-	[7]
4	SW: 23, (PDM)	opt+2.5%	0.5	-	[7]
6	SW: 24, (PDM)	opt+2.5%	1	-	[7]
8	AI: Battery Bus Current, (EPS)	3	-	-	[7], [6]
10	AI: GND, (EPS)	3	-	-	[7], [6]
12	AI: GND, (EPS)	3	-	-	[7], [6]
14	AI: GND, (EPS)	3	-	-	[7], [6]
16	AI: GND, (EPS)	3	-	-	[7], [6]
18	AI: GND, (EPS)	3	-	-	[7], [6]
20	AI: GND, (EPS)	3	-	-	[7], [6]
22	AI: 5V BUS	3	-	-	[7], [6]

	CURRENT, (EPS)				
24	AI: 3.3V BUS CURRENT, (EPS)	3	-	-	[7], [6]
26	AI: GND, (EPS)	3	-	-	[7], [6]
28	AI: GND, (EPS)	3	-	-	[7], [6]
30	AI: (EPS)	-	-	-	[7], [6]
32	AI: (EPS)	-	-	-	[7], [6]
34	RS232RX	-	-	-	[7]
36	RS232TX	-	-	-	[7]
38	serial RX1	-	-	-	[7]
40	serial TX1	-	-	-	[7]
42	serial RX2	-	-	-	[7]
44	serial TX2	-	-	-	[7]
46	serial RX3	-	-	-	[7]
48	Serial TX3	-	-	-	[7]
50	Serial RX4	-	-	-	[7]
52	Serial TX4	-	-	-	[7]

Table 10: CubeSat Bus, Header 2					
SW=Switch AI=Analog Input -=Not Applicable ()=Originating Board, Device					
Pin	Purpose	Maximum Voltage (V)	Maximum Current (A)	Connection	References
1	SW: 1, (PDM)	3.33	0.5	Magnetometer	[7], [62]
3	SW: 3, (PDM)	3.33	0.5	-	[7]
5	SW: 5, (PDM)	3.33	1	-	[7]
7	SW: 7, (PDM)	3.33	4	-	[7]
9	SW: 7, (PDM)	3.33	4	-	[7]
11	SW: 9, (PDM)	5.05	0.5	-	[7]

13	SW: 11, (PDM)	5.05	1	Magnetic Torquer 1	[7], [23]
15	SW: 13, (PDM)	5.05	1	Magnetic Torquer 3	[7], [23]
17	SW: 14, (PDM)	5.05	4	-	[7]
19	SW: 15, (PDM)	8.3 (BATT)	0.5	-	[7]
21	SW: 17, (PDM)	8.3 (BATT)	1	Payload	[7]
23	SW: 20, (PDM)	opt + 2.5%	-	-	[7]
25	5V, (EPS)	5V	-	Board Stack Connection Only	[6]
27	3.3V, (EPS)	3.3V	-	Board Stack Connection Only	[6]
29	GND, (EPS)	-	-	Magnetic torque 1-3, CubeSat Sun Sensor	[6], [30], [23]
31	AGND, (EPS)	-	-	Board Stack Connection Only	[6]
33	Batt POS, (EPS)	-	-	DO NOT CONNECT	[6]
35	PCM IN, (EPS)	-	-	Deployment Switch 1 & 2: input to PCM's and PDM (switch on state), Power Flow to Board Stack	[6]
37	Dummy Load, (EPS)	-	-	Pull pin inserted: off state	[6]
39	-	-	-	Unused Connection (Deployment switch 1 & 2: off state)	[6]
41	BCR Out, (EPS)	-	-	BCR out to Deployment Switches	[6]
43	BCR Out, (EPS)	-	-	BCR out to Deployment Switches	[6]
45	BATTERY	-	-	Board Stack Connection Only	[6]
47	RS422 RXA	-	-	-	[7]
49	RS422 RXB	-	-	-	[7]
51	OPTIONAL V	-	-	-	[7]
2	SW: 2, (PDM)	3.33	0.5	-	[7]
4	SW: 4, (PDM)	3.33	1	-	[7]

6	SW: 6, (PDM)	3.33	1	-	[7]
8	SW: 7, (PDM)	3.33	4	-	[7]
10	SW: 8, (PDM)	5.05	0.5	CubeSat Sun Sensor	[7], [30]
12	SW: 10, (PDM)	5.05	0.5	Gyroscope	[7], [61]
14	SW: 12, (PDM)	5.05	1	Magnetic Torquer 2	[7], [23]
16	SW: 14, (PDM)	5.05	4	GPS (red 1)	[7], [63]
18	SW: 14, (PDM)	5.05	4	GPS (red 2)	[7], [63]
20	SW: 16, (PDM)	8.3 (BATT)	0.5	-	[7]
22	SW: 18, (PDM)	8.3 (BATT)	1	-	[7]
24	SW: 21, (PDM)	opt + 2.5%	-	-	[7]
26	5V	-	-	Board Stack Connection Only	[6]
28	3.3V	-	-	Board Stack Connection Only	[6]
30	GND	-	-	Magnetometer; CSS1-4	[7], [62], [21]
32	GND	-	-	Payload; Gyro	[7], [61]
34	Batt POS, (EPS)	-	-	Pull Pin Removed, DO NOT CONNECT	[6]
36	PCM IN, (EPS)	-	-	Deployment Switch 1 & 2: input to PCM's and PDM (switch on state); Power Flow to Board Stack	[6]
38	Dummy Load, (EPS)	-	-	Pull pin: off state	[6]
40	-	-	-	Unused Connection (Deployment switch 1 & 2: off state)	[6]
42	BCR Out, (EPS)	-	-	BCR out to Deployment Switches	[6]
44	BCR Out, (EPS)	-	-	BCR Out To Deployment Switches	[6]
46	BATTERY	-	-	Board Stack Connection Only	[6]
48	RS422 TXA	-	-	-	[7]
50	RS422 TXB	-	-	-	[7]

52	OPTIONAL V	-	-	-	[7]
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Table 11: Device Connection Information					
Device	Pin Number; Wire Number; Wire Color	Use,	Type of Connection	Connection	References
Magnetic Torquer 1	Red	5.05V	-	CubeSat bus, header 2, pin 13	[7], [23]
	Black	Ground	-	CubeSat bus, header 2, pin 29	[7], [23]
Magnetic Torquer 2	Red	5.05V	-	CubeSat bus, header 2, pin 14	[7], [23]
	Black	Ground	-	CubeSat bus, header 2, pin 29	[7], [23]
Magnetic Torquer 3	Red	5.05V	-	CubeSat bus, header 2, pin 15	[7], [23]
	Black	Ground	-	CubeSat bus, header 2, pin 29	[7], [23]
Coarse Sun Sensor 1	Red	Analog Input	AI	ADC board, pin and connector TBD	[21]
	Black	Ground	-	CubeSat bus, header 2, pin 30	[7], [21]
Coarse Sun Sensor 2	Red	Analog Input	AI	ADC board, pin and connector TBD	[21]
	Black	Ground	-	CubeSat bus, header 2, pin 30	[7], [21]
Coarse Sun Sensor 3	Red	Analog Input	AI	ADC board, pin and connector TBD	[21]
	Black	Ground	-	CubeSat bus, header 2, pin 30	[7], [21]
Coarse Sun Sensor 4	Red	Analog Input	AI	ADC board, pin and connector TBD	[21]
	Black	Ground	-	CubeSat bus, header 2, pin 30	[7], [21]
Solar Array 1 (+Y)	1	Power	-	EPS Board, SA1 connector, pin 1	[6]
	2	Ground	-	EPS Board, SA1 connector, pin 2	[6]
	3	Temperature	-	EPS Board, SA1 connector, pin 3	[6]

		Telemetry			
Solar Array 2 (-Y)	1	Power	-	EPS Board, SA1 connector, pin 4	[6]
	2	Ground	-	EPS Board, SA1 connector, pin 5	[6]
	3	Temperature Telemetry	-	EPS Board, SA1 connector, pin 6	[6]
Solar Array 3 (+X)	1	Power	-	EPS Board, SA2 connector, pin 1	[6]
	2	Ground	-	EPS Board, SA2 connector, pin 2	[6]
	3	Temperature Telemetry	-	EPS Board, SA2 connector, pin 3	[6]
Magnetometer	1	GND	-	CubeSat bus, header 2, pin 30	[7], [62]
	2	3.3V	-	CubeSat bus, header 2, pin 1	[7], [62]
	3	I2C DATA	I2C	ADC board, pin and connector TBD	[62]
	4	I2C CLOCK	I2C	ADC board, pin and connector TBD	[62]
Gyroscope	P1, PDD	5.05V	-	CubeSat bus, header 2, pin 12	[7], [61]
	P1, GND	Ground	-	CubeSat bus, header 2, pin 32	[7], [61]
	P1, MISO	Master In Slave Out	SPI	ADC board, pin and connector TBD	[61]
	P1, GND	Ground	-	CubeSat bus, header 2, pin 32	[7], [61]
	P1, CS	Chip Select	SPI	ADC board, pin and connector TBD	[61]
	P2, GND	Ground	-	CubeSat bus, header 2, pin 32	[7], [61]
	P2, CLK	SPI CLOCK	SPI	ADC board, pin and connector TBD	[61]
	P2, GND	Ground	-	CubeSat bus, header 2, pin 32	[7], [61]
	P2, MOSI	Master Out Slave In	SPI	ADC board, pin and connector TBD	[61]
	P2, GND	Ground	-	CubeSat bus, header 2, pin 32	[7], [61]
GPS	Green 1	TBD	UART	ADC board, pin and connector TBD	[63]
	Green 2	TBD	UART	ADC board, pin and	[63]

				connector TBD	
	Green 3	TBD	UART	ADC board, pin and connector TBD	[63]
	Green 4	TBD	UART	ADC board, pin and connector TBD	[63]
	Green 5	TBD	UART	ADC board, pin and connector TBD	[63]
	Green 6	TBD	UART	ADC board, pin and connector TBD	[63]
	Green 7	TBD	UART	ADC board, pin and connector TBD	[63]
	Black	Ground	UART	ADC board, pin and connector TBD	[63]
	Red 1	5.05V	-	CubeSat bus, header 2, pin 16	[7], [63]
	Red 2	5.05V	-	CubeSat bus, header 2, pin 18	[7], [63]
CubeSat Sun Sensor	TBD	Analog Input	AI	ADC board, pin and connector TBD	[30]
	TBD	Analog Input	AI	ADC board, pin and connector TBD	[30]
	TBD	Analog Input	AI	ADC board, pin and connector TBD	[30]
	TBD	Analog Input	AI	ADC board, pin and connector TBD	[30]
	TBD	5.05V	-	CubeSat bus, header 2, pin 10	[7], [30]
	TBD	GND	-	CubeSat bus, header 2, pin 29	[7], [30]

Appendix 10: On Board Computer (OBC) [64]

This appendix shows the interface connections of the OBC. As it is not yet known if the OBC can connect directly to the vertical board stack, this appendix can be used as a starting point for future teams to wire the OBC to the vertical board stack.

Intrepid Pico-Class CubeSat System Board

Interfaces (note: unused peripherals act as additional GPIOs)

- **Daughterboard A Interface**
 - SPI with 1 Select
 - I2C
 - 1 GPIO
 - 1 UART
 - 1 Hardware Interrupt
 - Dedicated, resistor adjustable 1.2 to 5.5V Regulator @8W peak power
 - Low power 3.3V for logic and sensors
 - Unregulated Battery Power
 - Hard Reboot Line
 - Processor Power-On Reset
- **Daughterboard B Interface**
 - SPI with 1 Select
 - I2C
 - 1 GPIO
 - 1 UART
 - 1 Hardware Interrupt
 - USB 2.0 (12Mbps)
 - Dedicated, resistor adjustable 1.2 to 5.5V Regulator @8W peak power
 - Low power 3.3V for logic and sensors
 - Unregulated Battery Power
 - Line to force hard reboot
 - Battery Ground for Custom Battery Packs
 - Processor Power-On Reset
- **Inter-Board Connectors**
 - SPI with 12 Selects
 - 2 I2C (1 Dedicated for Payload)
 - 5 GPIOs
 - 3 UART
 - USB 2.0 (12Mbps)
 - CMOS Image Sensor Interface (16 pins)
 - 5.0V Regulated Power @8W peak power
 - 3.3V Regulated Power @8W peak power
 - Unregulated Battery Power
 - Deployment Indicator
 - Solar Power
 - Processor Power-On Reset

- **Custom Battery Interface**
 - Battery Ground, and Unregulated Power
 - I2C
- **Umbilical A**
 - SPI (All Device)
 - Ethernet
 - RS232 (Terminal Access)
 - Two USB 2.0 (Host)
 - USB 2.0 (Device)
 - Unregulated Battery (Charging)
 - Line to force Hard Reboot
 - Processor Power-On Reset
- **Umbilical B**
 - 2 I2C
 - 3 UART
 - CMOS Image Sensor Interface
 - 6 GPIOs
 - ICE/JTAG Debug Interface
 - Payload Programming (3 Pins)
 - Four Power Good Indicators for Primary Regulated Power