NAD-2001

Design and Analysis for a CubeSat Mission-III

A Major Qualifying Project Report

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WORCESTER POLYTECHNIC INSTITUTE

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in Aerospace Engineering

by

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0. Abstract

This project supports the design of a six-unit Cube Satellite (CubeSat) mission in an extreme Low Earth Orbit (eLEO). The goal is to perform Ionosphere experimentation using the NASA mini Ion Neutral Mass Spectrometer (mINMS). The CubeSat design addresses the mission and NanoRacks Deployer requirements. Mechanical design of the CubeSat is performed using SolidWorks. Vibration and stress analysis for expected launch conditions is performed using ANSYS, and thermal analysis in our desired orbit is performed with COMSOL software. Thermal characteristics are determined using the Systems Tool Kit (STK) software to model the CubeSat's thermal environment throughout its orbit. All important documents and launch requirements are identified.

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1. Introduction

This Major Qualifying Project (MQP) is part of a 16-student group dedicated to the design and mission planning of a 6U CubeSat. Similar recent CubeSat projects have taken place at WPI with a different payload in the 2016-2017 and 2017-2018 academic years.

The primary goal of the MQP-2001 Cube Satellite Project is to create a conceptual design of a 6U CubeSat, carrying a mini Ion Neutral Mass Spectrometer (mINMS) made by the National Aeronautics and Space Administration (NASA) Goddard Institute for the purpose of scientific experimentation and data collection in the Ionosphere. During the course of this project there were two orbits considered for our CubeSat, which from here on out is referred to as **NeAtO** (mI**N**MS **e**LEO **At**mospheric **O**bserver). The first and ultimately chosen option will have NeAtO deployed from the International Space Station (ISS) via a NanoRacks Double Deployer at 400 km with a 51.6-degree inclination. The second orbit considered would have placed NeAtO in a Polar Orbit, deployed from a Quadpacks Duo Pack Deployer at 400 km, on a rideshare mission. With the first option, following launch from the ISS, NeAtO will then enter a 200-440 km orbit after detumbling, maintaining a perigee within extreme Low Earth Orbit (eLEO) for as long as possible with the given propulsion system.

The MQP-2001 CubeSat Project is composed of three MQP sub-teams, each with a different focus. This specific MQP, NAD-2001, referred to as Team Three, is led by Professor Karanjgaokar with team members Christian Anderson, Rory Cuerdon, Brian Kelsey and Nicole Petilli, with a focus on the mechanical design and the structural and thermal analysis. Team One is led by Professor's Taillefer and Gatsonis, with team members Tristan Andreani, Edward Beerbower, Roberto Clavijo, Samuel Joy, Benjamin Snyder and Jeremiah Valero. These members are responsible for the orbital analysis and environmental effects analysis along with the power, propulsion and telecommunications subsystems. Lastly, Team Two, led by Professor Demetriou with team members Robaire Galliath, Oliver Hasson, Andrew Montero, Chris Renfro and David Resmini, focuses on CubeSat attitude determination and control, orbital control, and command and data handling subsystems. Team 2 is also taking lead on the design and development of a test bed.

While the overall goal of the project is to collect data from the ionosphere at a 200km perigee, each team (separate MQP's) has their own primary objectives that work towards the success of the mission. The objectives of this MQP are to perform mechanical design, structural analysis, and orbital analysis for the NeAtO in compliance with NanoRacks deployer requirements. Additionally, thermal cycling effects will be considered for a given loading scenario on the frame of the 6U.

The objectives of Team 1 are to perform propulsive analysis to maximize flight-time in eLEO, create a power profile per orbit and implement the necessary hardware to satisfy these parameters, manage the interfacing payload of the CubeSat, determine important orbital parameters, and determine the daily data uplink and downlink budgets per orbit. Team members will also investigate the hazardous environmental effects of eLEO on the structure and internal components of NeAtO.

The primary objective of Team 2 is to choose the sensors and actuators necessary for attitude determination and control. Team 2 is also responsible for the performance of algorithms used to detumble, determine initial attitude, attitude maintenance throughout the orbit and NeAtO's lifetime utilizing MATLAB, Simulink and Systems Tool Kit (STK). This will require the team to consider sensor noise, refresh rates, and actuator limitations.

1.1 Background and Literature Review

CubeSats are small, cost effective satellites that expand commercial access to space. Defined by the standardized scale, 'U,' a cube with dimensions of 10cm x 10cm x 10cm, ~1.3kg, seen in the figure below, CubeSats are typically 1U, 2U, 3U, 6U, or 12U [25, 29]. Each Unit is comprised of hardware components specifically selected to complete the satellite's mission.

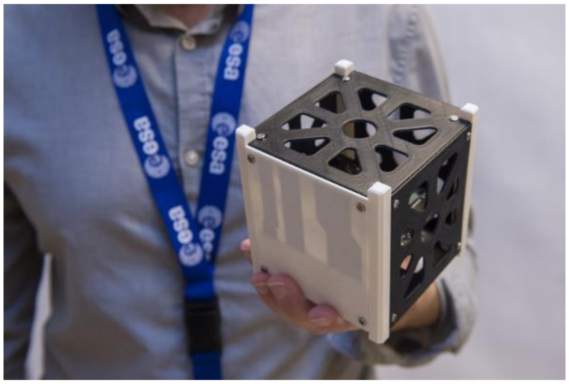


Figure 1: 1U CubeSat Frame [5]

The concept began in 2000 as a method to provide scientific and military laboratories another tool to grow their operations in space. Today, many colleges and high schools have programs that allow students to design and build their own CubeSats, illustrating that the concept lends itself to valuable educational experience [12, 29].

In recent years, the CubeSat has become a unique tool in the scientific community. A cooperative culture has formed around the implementation of CubeSats into everyday space science. NASA's CubeSat Launch Initiative (CSLI) provides opportunities to launch small satellites aboard larger launch vehicles as secondary payloads [5]. The industry consists of companies (Clyde Space, ISIS, etc.) providing interested parties with components necessary to construct the satellite, who then work with integration services (NanoRacks, SpaceFlight Services, etc.) to facilitate the satellite's flight aboard a launch vehicle.

CubeSats are currently in an era of rapid growth in popularity and technological opportunity. It is estimated that the global CubeSat market was valued at $152 million in 2018 and was projected to rise to nearly $375 million in 2019. The coming years expect reduced mission costs, increased opportunity in government, military, and commercial applications, and a greater demand for data from earth observation in LEO. One promising project is SpaceX's Starlink, which aims to provide reliable and affordable broadband internet services around the globe. There are currently about 300 Starlink satellites in orbit, with plans to build the constellation to 12,000 by the completion of the project. At the minimum number of Starlinks necessary for operation, the program could bring its services to all U.S territories in time for the 2021 hurricane season.

1.1.1 Broader Impacts (Social, Educational, Economic)

The continual expansion and development of Cube Satellite opportunities has yielded a variety of positive social, economic and educational effects. Since CubeSats were first theorized and developed by Cal Polytech, many educational institutions have started similar micro satellite programs as a result of their affordable cost, in addition to a flux of new commercial companies [29, 30]. Growth of CubeSat mission numbers are displayed in figure 2 below:

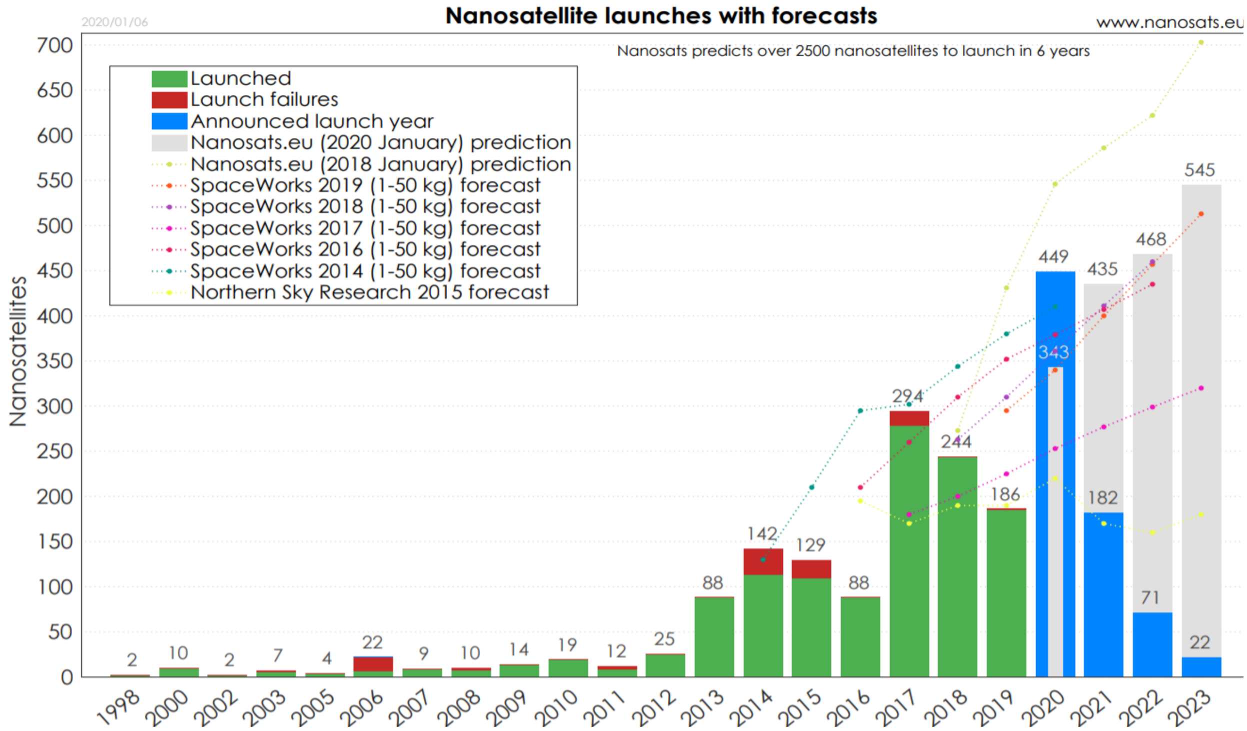


Figure 2: Nanosatellite Launches and Predictions [19]

The CubeSat industry has already left a substantial impact on the space industry, which has seen a surge of space start-ups in the last five years. From 2000 to 2014, space startups received a total of $1.1 Billion in venture capital investments. That number increased exponentially in the following 3 years, with more than 120 investors contributing $3.9 billion to space start-ups in 2017 alone! Many of these start-ups reflect new technologies and abilities related to CubeSat Components, Development, or Launch and Integration. CubeSats have also created a shift from cost plus to fixed cost payments, which are less risky for the government or investors and maintains performance control of contractors [12, 22].

One of the major benefits of CubeSats is their versatility. CubeSats themselves are a significantly cheaper method to test new technologies so that they can undergo better development and flight testing before integration on larger missions. CubeSats cost less because of their low mass and thus low launch cost. Their smaller, modular size also simplifies development and testing, as many subsystem components are available from different off-the-shelf suppliers. Often

CubeSat projects can be flight ready within one or two years. Many Universities and Institutions develop CubeSats with a specific payload in mind, including but not limited to remote sensors or communications modules [6, 12].

In recent years, CubeSats have seen expanded use with the ISS as a result of the Japanese Experiment Module Small Satellite Orbital Deployer and have even flown with missions to the moon and to Mars. The first commercial entity to utilize the ISS as a deployment option was NanoRacks LLC in 2013. With NASA and Japanese Aerospace Exploration Agency (JAXA), NanoRacks developed and launched a deployer directly tied to the Japanese Experiment Module, allowing CubeSats to be checked by astronauts before deployment. This provides a quick and efficient method of launching CubeSats into LEO. Between 2014 and 2017, NanoRacks deployed a total of 176 CubeSats from their deployer on the ISS, with plans to ramp up these numbers in the next few years. One such deployment in action is shown in figure 3 below:

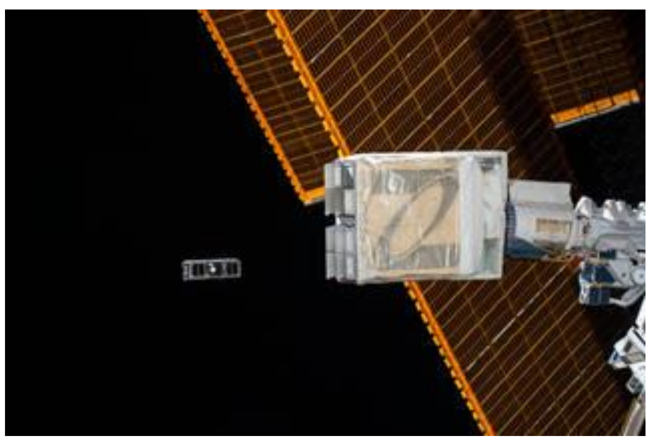


Figure 3: The NanoRacks CubeSat Deployer (NRCSD) 12 on the International Space Station releases ExAlta-1 [12]

The many advantages and developments of CubeSats has attracted more startup companies in recent years. As of 2018, 51% of CubeSats are developed by the private sector, showing CubeSats are no longer just for research conducted by universities or scientific institutes. The larger commercial flux has led to many impressive satellite technologies, including the first commercial optical communication downlink system (Analytical Space, Inc.) and the first CubeSat to employ a new hybrid (dual-purpose) antenna and solar power system [25, 27]. Technological developments can be found in a variety of topics, including solar and space physics, Earth sciences and applications from space, planetary science, astronomy and astrophysics, and biological and physical sciences in space. From 2000 to 2015, the number of publications on CubeSats has risen to 536 publications total outlining the many advances made [27].

Expansion and promotion of CubeSat use has also helped NASA and the European Space Agency (ESA) collaborate with interested schools and students to further promote the benefits of the space industry. CubeSats inspire students from many levels of education to pursue Science, Technology, Engineering and Math (STEM) fields and take part in an innovative and exciting new part of the space sector. These programs teach students about the many components in a CubeSat as well as the many fields of knowledge needed, organizational skills and communication necessary to efficiently design and build a CubeSat [6].

Unfortunately, not all CubeSat effects are positive. More traffic complicates flight paths and adds an element of danger to many missions as the risk of collisions increases. Unlike larger satellites, CubeSats are generally designed without collision avoidance capabilities and without a specified deorbiting plan. Being so small makes them difficult to track, adding to the uncertainty of any region in space containing CubeSats being safe for other spacecraft. Additionally, having such a large number of satellites also increases the risk of debris resulting from potential collisions. The European Space Agency has already experienced a collision due to CubeSat debris. Their Sentinel-1A was struck and had its solar panel destroyed by CubeSat related debris and the debris from that collision put their Sentinel-1B spacecraft at risk. A study using NASA's LEGEND (LEO to-GEO Environment Debris) model, assuming a post mission disposal compliance rate of 90%, shows that continuing the current increase of CubeSats could result in a 75.3% increase of collisions in J1, a 342.2% increase in J2, and an 89.8% increase in J3 (J's refer to varying sections in space). This increase of collisions and debris could make operations in LEO difficult and interrupt human spaceflight, or cause damage to the International Space Station. NASA estimates that of all launches into space, 94% are now space debris, where 64% of that are fragments (volume ~100cm^2) [27].

There is also a risk of nanosats being used to gather intelligence from other satellites, disrupting the operations of larger satellites or by spying on others directly. Their size makes them difficult to detect and prevent these activities. CubeSats being used for communications could then become targets for hackers to cause disruptions. As CubeSats increase in accessibility, more effort and technology will be necessary to keep other satellites and communications secure [2, 27].

1.1.2 Previous Cube Satellite MQP's

There are two MQPs in recent history which focused on CubeSat development. The 2017 MQP CubeSat project designed a 3U CubeSat with the mission of observing space weather. These observations would be done with a Sphinx-NG instrument payload developed by the Space Research Center in Warsaw, Poland. The instrument collects solar and terrestrial X-ray spectroscopy data from its 600km sun-synchronous polar orbit. This project in turn expanded upon the earlier work of the 2012 and 2013 MQPs which utilized the same instrument. Their CubeSat was designed to be deployed into a circular polar orbit of 600km, and achieved a lifespan of 17.8 years, which would allow the SphinX-NG instrument to perform its scientific duties and provide more than sufficient data collection through such a long life time [4].

The 2018 MQP CubeSat project created two designs for two different objectives. The first part of their mission was to evaluate the feasibility and duration of flights in eLEO (approximately 210km altitude). This team determined a 3U configuration could not successfully produce enough power, instead opting for a custom 4U frame to accommodate enough solar panels (NAG-1801, 2018). Despite not reaching its desired 90-day orbit, the team succeeded in obtaining a 24-day lifespan and analyzing the effects of eLEO over that duration (NAG-1801, 2018). The second part of the 2018 mission was to test the possibility of maintaining a 100km arc distance between two CubeSats. Achieving this goal would support being able to use several small satellites in place of one large one, which would make it easier to replace malfunctioning components and reduce the operation cost. There was no real conclusion as to whether this rendezvous operation could be successfully completed [13].

1.1.3 Payload: mINMS

The payload of this mission is the mini Ion Neutral Mass Spectrometer or mINMS for short. It was developed at NASA's Goddard Space Flight Center, with two apertures for detecting ions of densities between $10^3 - 10^8/cm^3$ and Neutrals of densities between $10^4 - 10^9/cm^3$, with very low energies between 0.1eV and 20eV. These apertures must be oriented in the RAM facing direction (the direction of movement), and are capable of making high resolution, in-situ measurements of [H], [He], [O], [N2], [O2] & [H+], [He+], [O+], [N2+], and [O2+]. The instrument occupies nearly 1.5U of volume and has a mass of 560 grams [26]. A picture of the mINMS is shown in figure 4 (human hand for size comparison):

Figure 4: mINMS in hand [26]

Since its creation, the mINMS has been used on a few missions, with more planned in the next few years. This includes the ExoCube 3U CubeSat launched in January 2015 on a rideshare mission and the Dellingr 6U launched in August 2017 from the ISS. The PetitSat is planned to be launched in August 2021 also from the ISS. The ExoCube was designed by Cal Polytech in collaboration with NASA Goddard Institute with the mINMS as its primary payload. It was a 3U CubeSat with a mass of 4kg deployed in Low Earth Orbit (LEO). The mission had issues with transmitting power, however it was able to validate that the mINMS was operating. ExoCube, shown in figure 5, was in operation for 7 months [16].

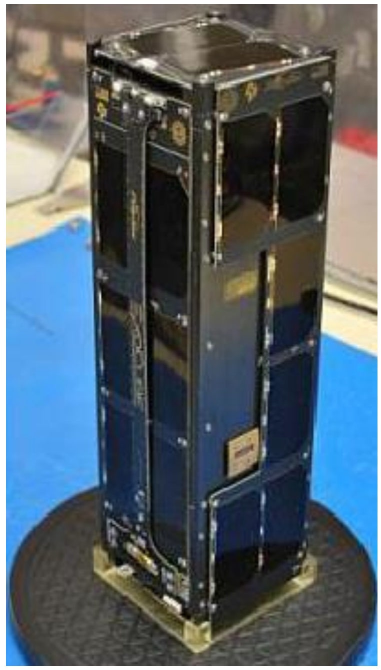


Figure 5: ExoCube [16]

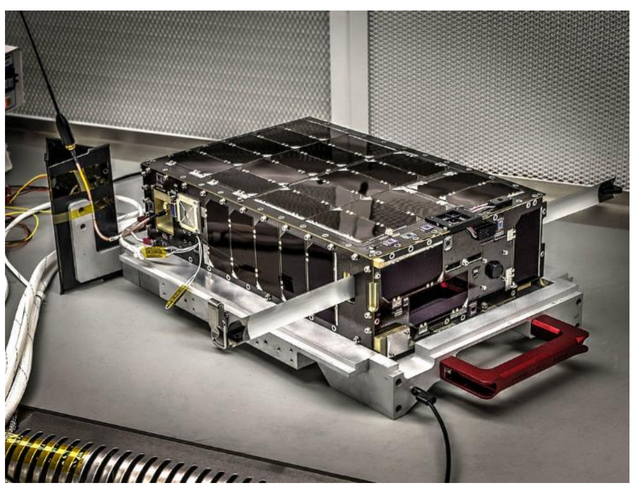


Figure 6: Dellingr [17]

Following the ExoCube mission was the Dellingr 6U mission, shown in figure 6 launched from the ISS NanoRacks Deployer. Despite many issues that arose, the team successfully achieved a resilient mission and provided many lessons and areas of growth for CubeSat missions, eventually inspiring the PetitSat, GTOSat and BurstCube missions.

Dellinger was also able to provide clear detection of ionized hydrogen (H+), helium (He+) and oxygen (O+) in the atmosphere in May of 2018, proving Ion detection capabilities. As of October 2018, the team turned on the neutral mode, which is still the primary focus. These measurements are necessary for studies of the dynamic ionosphere- thermosphere- mesosphere system, or simply put to define the steady state background atmospheric conditions [7, 17].

The final mission with the mINMS payload, the Plasma Enhancements in the Ionosphere-Thermosphere Satellite, or PetitSat, is planned to be launched in 2021 with a very similar design to that of Dellingr. It is the first to utilize a Dellingr-X frame, designed based on lessons learned from the Dellingr mission, which is more reliable, cheaper, and protects electronics. Additionally, deployable solar arrays and a more advanced star tracker were included to avoid previous issues. The goal of the PetitSat mission, run by NASA scientists at the Goddard Space Flight Center, is to determine how perturbations in the density of plasma within the ionosphere, also called “blobs,” distort the transmission of radio raves. These blobs commonly interfere with GPS and radar signals from Earth (which are reflected back into space), and it is theorized that fast-traveling waves coming from the thermosphere may have an effect, as they lead to a phenomenon called Medium Scale Travelling Ionospheric Disturbances. Scientists are trying to determine the relationship between these two phenomena, therefore the mINMS will continue to observe density changes in response to daily and seasonal cycles, while a second instrument measures distribution, motion and velocity of ions [11].

1.2 Overall Project Goals

The CubeSat analysis Systems Engineering Group (SEG), comprised of three separate teams, was tasked with creating a 6U CubeSat to gather atmospheric information in an extreme Low Earth orbit (eLEO). Not many cube satellite missions orbit this low to the earth, so being able to take atmospheric readings from eLEO utilizing the NASA Goddard mINMS payload will provide researchers with valuable information from a scientifically rich area not frequently explored.

The principal goal of the subsystems design project team, Team 1 (GT), is to maximize the lifespan of the CubeSat in LEO. By modifying orbital parameters and maximizing the efficiency of burns, the mission and lifespan of the satellite will be optimized, providing an increased duration of data collection, adding to the value of the mission.

The primary goal of the CubeSat analysis MAD team, Team 2, is to deploy the 6U CubeSat from the International Space Station (ISS) at approximately 440km, then move to have a periapsis of approximately 200 km (eLEO).

The first goal of the NAD project team, Team 3, is to perform mechanical design of the 6U eLEO CubeSat, in accordance with components chosen by Teams 1 and 2, to meet deployer design requirements. The second goal of Team 3 is to conduct thermal and structural analysis on the 6U eLEO CubeSat and ensure all chosen components are suitable for the eLEO mission.

1.3 Overall Project Design Requirements, Constraints and Other Considerations

1.3.1 Deployer and Launch Options

With the exponential growth of CubeSat missions, one can find multiple deployer options for CubeSats based on size and target orbit. The first deployer ever designed was the P-POD (Poly-Picosatellite Orbital Deployer) by Stanford and CalPoly Tech SLO in the early 2000's. The P-POD is a standard deployment system developed around the 10 cm x 10 cm x 10 cm initial CubeSat design, with a length of 34 cm to hold up to three 1U CubeSats. The design minimizes interaction with the primary payload by enclosing CubeSats in a dormant state and uses a spring and pusher plate to guide CubeSats along interior rails and out the deployer door, as seen in figure 7 below. P-POD's have a good flight heritage and have been used extensively for over a decade. An updated design can hold a 6U CubeSat in a 2x3U orientation. P-POD's allow up to 1 kg per Unit and can eject multiple CubeSats at once per deployer [15].

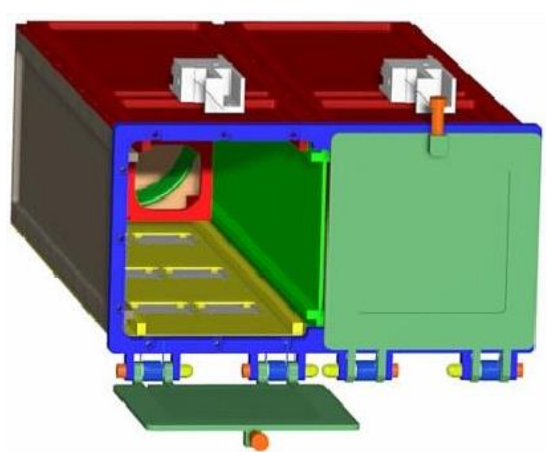


Figure 7: Illustration of P-POD Double Deployer (2x3U), [18]

Since the invention of the P-POD, multiple similar designs have been used to decrease weight or increase the size or mass of payload. This includes Tyvak Launch Systems deployer, which promotes custom manufactured deployment mechanisms with flight tested Commercial Off-The-Shelf (COTS) 3U, 6U, and 12U deployment mechanisms used on rideshare missions, as well as the ISIPOD or ISIS Payload Orbital Dispenser, later upgraded and renamed as Quadpacks. The Quadpacks deployer, developed by Planetary Sciences Corp, provides a variety of opportunities for various CubeSat sizes, ranging from 1U to 16U. The mechanism is very closely related to that used in a P-POD, however the main designs include a 12U dispenser broken into 4 sections of 3U areas (4x3U), or a 16U (4x6U). It offers a very flexible configuration or deployment sequence, with the ability to release many satellites at a time, for example four 3U's, a combination of 3U's, 2U's and 1U's, or 12 to 16 1U's in total. Each section of the Quad Pack can its door independently of the other 3 doors. Figure 8 shows a few 12U Quadpacks deployers.

Figure 8: Quadpacks 12U dispenser for Dnepr launch June 2014 [18]

Quad Packs are also extensively used on SHERPA Kick Stage Vehicles (also known as the "space tug") to move payloads into desired orbits. SHERPA's can be carried on any Evolved Expendable Launch Vehicle (EEVL) including the Atlas V, Delta IV, and Falcon 9 (all certified), and can hold up to 1500 kg of payload, with 40+ Quad Packs [18].

The final and most recommended deployment mechanism is the NRCSD, or the NanoRacks CubeSat Deployer, located on the Japanese Experiment Module (JEM) on the ISS. When CubeSat deployment operations begin, the NRCSDs are unpacked, mounted on the JAXA Multi-Purpose Experiment Platform (MPEP) and placed on the JEM airlock slide table for transfer outside the ISS. A crew member operates the JRMS (JEM-Remote Manipulating System) – to grapple and position for deployment. The CubeSats/nanosatellites are deployed when the JAXA ground controllers command a specific NRCSD. The NRCSD Configuration can be seen in figures 9 and 10:

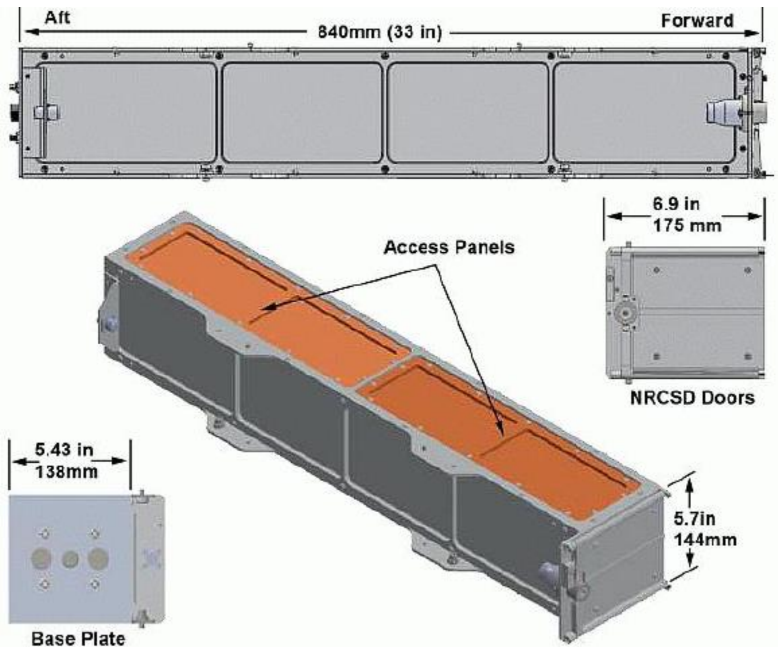


Figure 9: NRCSD Configuration [23]

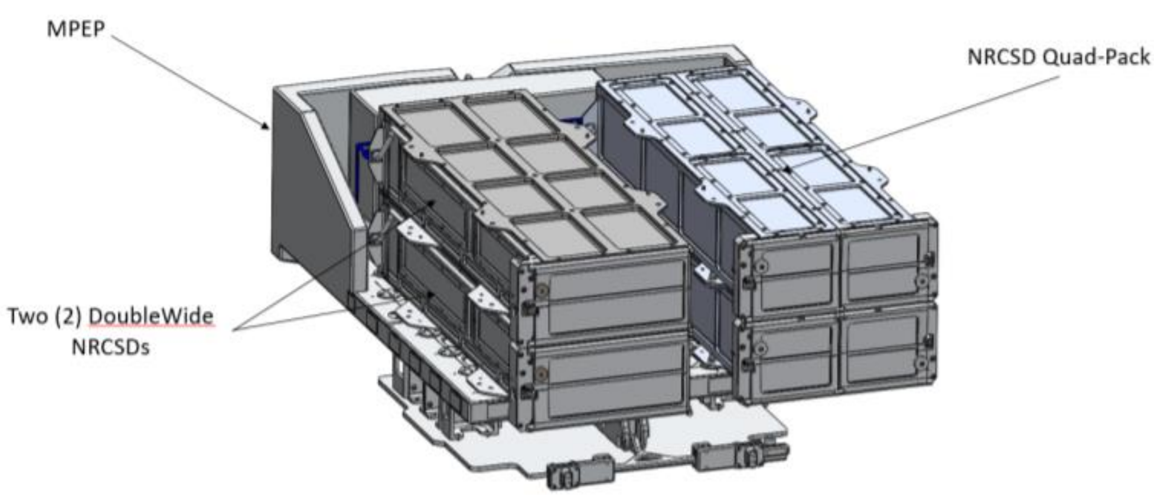


Figure 10: NRCSD Standard and DoubleWide Deployers [23]

Since its first use in July 2014, 200+ payloads have been sent to the ISS and deployed from the NRCSD. The NRCSD is a self-contained system that is still electrically isolated from the ISS to protect the crew. Onboard the ISS, NanoRacks Platforms are installed in EXPRESS Rack inserts to supply power and USB data transfer capability for NanoRacks Modules, allowing CubeSats to conduct experiments on the ISS and be checked by astronauts. The NRCSD can launch CubeSats with a maximum length of 50 cm [18].

As noted above, a 6U CubeSat is a major limiting factor, such that only a few of deployers are designed for such a mission, including the NanoRacks and Quadpacks deployers. Based on these two options, there are certain launch opportunities able to carry a 6U CubeSat.

To be deployed by NanoRacks, CubeSats must first reach the ISS by a Cygnus or Dragon Spacecraft. This of course limits CubeSats to a 51.64 degrees inclination and requires additional compliance with ISS safety regulations. Additionally, using any of the EELV's, a SHERPA Spacecraft carrying our 6U CubeSat in a 16U Quadpack could deploy the satellite at a variety of orbits.

Lastly, in certain cases, Antares and Falcon 9 rockets (not going to the ISS) will have additional space and can carry pico or micro satellites. This is known as a rideshare opportunity. Antares launches are currently limited to P-POD configurations, while the SpaceX rideshare website provides little information on the deployment options or capabilities. Therefore SEG recommends launching on a Falcon 9 carrying CubeSats inside the Dragon Module to the ISS, and deploying from a NanoRacks deployer on the JEM. This would provide many available launch opportunities as Dragon Spacecraft frequently visit the ISS [28].

1.3.2 Launch Decision and NanoRacks Requirements:

The SEG team decided first that the best deployer option would be the NanoRacks deployer. This was the best option as NanoRacks is one of the most flight tested deployers compatible with a 6U CubeSat, has a strong mission success flight record, and allows multiple launch options for NeAtO to ride share to the ISS [23]. NanoRacks also outline many requirements to be deployed from the ISS.

The NanoRacks requirements are broken up into various sections, some requiring further collaboration with the other two SEG teams. The topics are listed and further explained below:

- 10 Rail or 10 Tab Requirements
  - The first ten requirements all relate to the dimensions, placement, and material properties of the rails or tabs along which NeAtO will be deployed from the NRCSD. It is the full SEG's choice to decide between the rail or tab configuration. Both have similar requirements that are the responsibility of the design team, who create a final CAD model of the whole structure including the rails or tabs.
- 2 Major Design Requirements (Mass and COM)
  - Two major design requirements that are affected by all teams' decisions are the total mass and distance from the center of geometry distance to the center of mass along each axis. It is the design team's responsibility to ensure these requirements are met by adding components carefully while considering component specifications provided by the other teams.
- 12 Deployment Requirements (Switches, locations, deployables)
  - The deployment requirements denote the locations and directions for a variety of possible deployment switches, in accordance with the minimum of 3 deployment switches corresponding to independent electrical inhibits on the main power system. The 6U system must also consider deployment velocity and tip off rate.
- 3 RBF/ABF and Electrical Switch Requirements
  - Remove Before Flight and Apply Before Flight features are necessary design considerations when utilizing NanoRacks Deployer to ensure the safety of the ISS and its habitants. The design team in collaboration with the command team must ensure that these features are included and that an access panel is placed on the +Y face for physical accessibility.

- 10 Structural and Environment Requirements (7 Considered)
    - The structural analysis team must ensure that NeAtO can withstand the random vibration environment during launch though a vibration test report, as well as integrated loads of 1200N across all load points in the Z-direction and depressurization/ vacuum conditions.
    - Should NeAtO contain any detachable parts, additional coordination with NanoRacks is required.
- 14 Electronics Requirements (battery, capacitors and wiring)
    - An electric schematic and battery test report ensures that the battery and its charging methods are safe and that all wiring and circuitry is protected. This will require coordination between the design and power team.
- 3 Material Based Requirements (outgassing, hazardous materials)
    - In addition to a materials list for the rails, the design team must provide a bill of materials for the entire CubeSat to ensure all materials are resistant to stress corrosion, comply with NASA guidelines from hazardous materials as well as outgassing regulations. Total Mass Loss (TML) must be less than 1% and Collected Volatile Condensable Material (CVCM) less than 0.1%.
- 3 Orbital Requirements (debris, re-entry)
    - Lastly, the thermal and orbital analysis teams are responsible for creating an Orbital Debris Assessment Requirements (ODAR) report should NeAtO exceed 5 kg, or if it is determined that NeAtO will survive re-entry.

As can be seen above, meeting all chosen NanoRacks requirements will require the coordination of members from each team, in addition to continual updates to our important documents ensuring all notable components are safe and the best choice for this mission [23]. All

NanoRacks requirements are further outlined in Appendix A, with many further discussed in the following Section 1.3.3.

1.3.3 Design Requirements and Constraints

The following section outlines the various requirements and constraints relevant to each subsystem. Often these parameters require the teams to coordinate with one another to ensure all components and aspects of the mission will operate as planned. The requirements and constraints of the design team's subsystems will be discussed first.

The design of the 6U itself has specific Center of Mass and rail requirements according to NanoRacks Double Deployer specifications, which can be found in Appendix A. All components provided by the other teams (excluding solar panels) must fit within the walls of the 6U sized structure, which is in a 30 cm x 20 cm x 10 cm configuration (height, length, width). On top of that, the components must be situated in such a way that the center of mass is as close as possible to the center of geometry to minimize the necessary attitude control computation time/ complexity. Additional Center of Mass requirements are provided by NanoRacks, as seen in the table below:

Table 1: NanoRacks Geometry Requirements [23]

Axis	Closeness to Geometric Center
X-Axis	+/- 5 cm
Y-Axis	+/- 3 cm
Z-Axis	+/- 8 cm

Location requirements are provided by the other teams; examples include the accelerometer, which must be at the Center of Mass, the reaction wheels along each axis intersecting with the COM, and the payload which has its aperture in the RAM facing direction (opposite side of the engines). The design team must also create rails or tabs for proper ejection from the deployer.

Design of the 6U CubeSat must additionally comply with the following constraints. The most important constraint provided is limiting the mass of the 6U NeAtO to a maximum of 12 kg. Additionally, the design team must ensure that no hazardous materials are used according to section 4.4.10.3 of the NanoRacks Deployer requirements, and must ensure Total Mass Loss (TML) is less than 1%, and Collected Volatile Condensable Material (CVCM) less than 0.1% due to outgassing.

The structural analysis team must ensure that the final design of NeAtO is strong enough to withstand all conditions of the mission. NASA requires that all vehicles entering space pass the ground structural tests outlined in the general environmental verification standard (GEVS). For our project we followed the requirements for structural tests from NanoRacks (sec. 1.3.2) because they are more relevant to CubeSats specifically and still comply with the GEVS requirements. NanoRacks requires the vehicle to survive a random vibration test, a structural load test for 1200N in the z-axis direction, an airlock depressurization test, and must ensure no detachable parts come loose.

The thermal analysis team is responsible for ensuring that all selected components discussed above will operate within their allowable temperature ranges throughout the duration of the mission. It must also be ensured that any heat that these components produce within the internal CubeSat structure is negligible in order to maintain allowable internal temperature profiles.

1.3.4 ADC Subsystem Components

The selected magnetorquer is the NCTR-M002, manufactured by New Space. The NCTR-M002 requires less than 200 mW of power, each, to operate and its dimensions are 70 mm by a diameter of 10 mm. The NCTR-M002 can operate within a range of -20 ˚C to 60 ˚C. NeAtO will require three of the NCTR-M002 magnetorquers, one oriented for each axis. There is no specific location the magnetorquers must be located in.

The selected reaction wheel is the RWP050, manufactured by Blue Canyon Technologies. The RWP050 requires less than 1 Watt of power, each, to operate and its dimensions are 58 mm by 58 mm by 25mm. The RWP050's operating temperature was not specified within Blue Canyon's provided spec sheets. Like the magnetorquers, NeAtO will require three reaction wheels, one oriented for each axis, and can be placed wherever they fit within NeAtO.

The selected GPS is the NGPS-03-422, manufactured by New Space. The NGPS-03-422 can operate within a range of -10 ˚C to 50 ˚C while consuming less than 1.0 W of power. The GPS can be placed anywhere in NeAtO and has the dimensions of 96 mm by 91 mm by 18 mm with an antenna that has the dimensions of 54 mm x 54 mm x 14.1 mm.

The ADC decided on a component that combines the accelerometer and magnetometer into one piece of hardware. The combined accelerometer and magnetometer make up the LSM303 that has the dimensions of 17.8 mm by 17.8mm by 0.9mm and consumes 0.002376 W while operating and 0.000000216 W while idle. The LSM303 can operate within a temperature range of -40 ˚C to 85 ˚C. This component must be located at or very close to the center of mass of NeAtO to function effectively.

The selected gyroscope is the EVAL-ADXRS453, manufactured by Analog Devices. The single gyroscope will be aligned in the center of all three primary axes at the center of mass. The EVAL-ADXRS453 consumes 0.0189 W, can operate at a temperature between -40 ˚C and 105 ˚C and its dimensions are 33 mm by 33mm by 3 mm.

The final component of the ADC subsystem are the analog sun sensors. The sun sensor chosen is the Nano-SSOC-A60, manufactured by Space Micro. NeAtO will incorporate five analog sun sensors, located in all four corners with one attached to the front of the payload. To work effectively, the analog sun sensors should be located 90 degrees apart for best coverage.

1.3.5 Power Subsystem Components

The selected solar panels are the Photon 3U body mounted panels, manufactured by Clyde Space. These panels utilize Spectrolab XTJ Prime solar cells with a BOL efficiency of 30.7% and

EOL efficiency of 26.7%. The Photon 3U panels have a standard operating temperature range of -40 ˚C to 80 ˚C, though they are advertised to have available testing for different ranges. NeAtO will require 6 of these body mounted panels.

The chosen battery is the Optimus-40, manufactured by Clyde Space. The Optimus-40 has dimensions of 95.89 mm by 90.17 mm by 27.35 mm and a full discharge voltage of 6.2 V. The battery's operating temperature is -10 ˚C to 50 ˚C. NeAtO will require a single battery.

The selected EPS (motherboard) is the Starbuck Nano-Plus, manufactured by Clyde Space. The EPS has dimensions of 95.89 mm by 90.17 mm by 20.82 mm and has PDMs with 10 latching current limiters. The Starbuck Nano-Plus has an operating temperature of -40 ˚C to 85 ˚C. The EPS can be placed anywhere inside NeAtO.

1.4 Overall Project Management

As previously mentioned, the SEG is divided up into three teams by closely related subsystems and the relevant analysis required for each. Students and Professors are split among these teams based on the amount of responsibility given to each team. The figure below simplifies how the teams are divided and the major roles of each team:

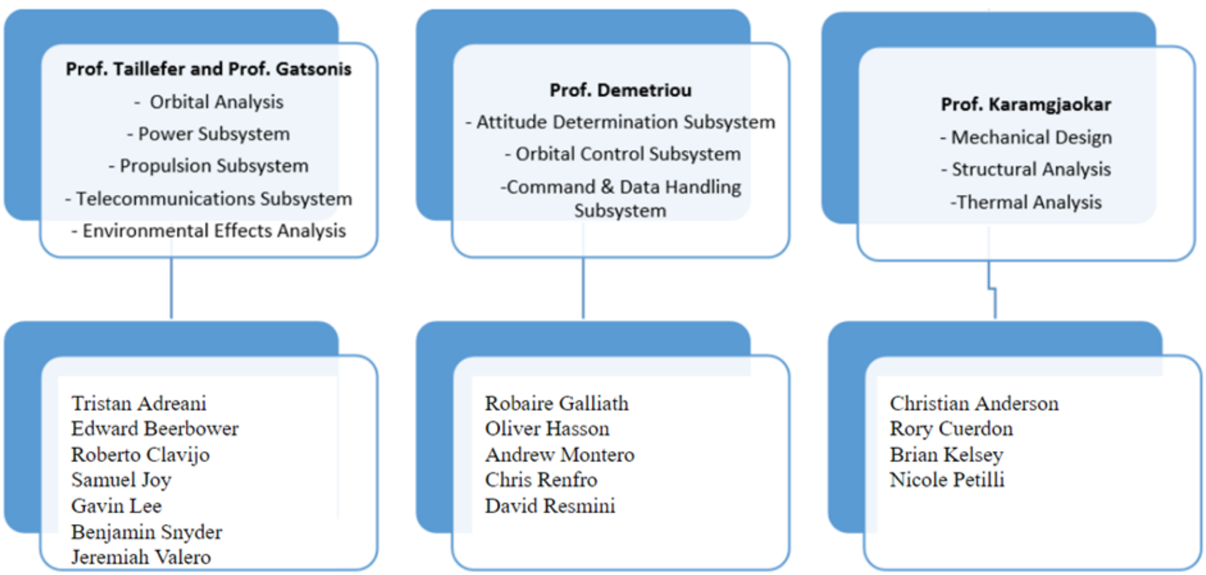


Figure 11: SEG group structure

Sub-Groups communicate via Slack and have a shared google drive for component lists and other necessary information that needs to be shared with the whole team. Sensitive documents deemed able to share with the whole group were stored on a secure OneDrive folder.

Team 3 is comprised of the four aforementioned students: Christian, Rory, Brian and Nicole. Tasks and responsibilities were closely related to the sub-group led by specific members of the team, as seen listed below:

- Design: Brian and Nicole
    - Base Responsibilities:

                - Coordinating with the other SEG teams to choose appropriate and realistic components to meet mission requirements
                    - Obtaining Spec Sheets for each component
                    - Creating CAD models for each component or defeaturing the models provided by respective companies
                - Compiling all components into the 6U Design using CAD (SolidWorks), ensuring the correct location, orientation, and fixture to the frame
        - Deployer:
            - Designing and integrating the rails/ tabs onto the 6U frame
            - Center of Mass and Total Mass requirements
            - Choose, model, and integrate the Deployment Switches
            - Material based requirements
            - Coordinate with Team 1 on Electronics Requirements
- Structural: Rory
    - Base Responsibilities:
        - Modal Analysis of NeAtO; data is then used for random vibration testing
        - Random Vibration Simulations of the frame and full assembly
            - Material Model chosen based on frame material
    - Deployer:
        - All Structural Requirements (previously mentioned): ensuring NeAtO can survive depressurization and vacuum conditions, the random vibrations experienced during launch and later deployment, and integrated loads
- Thermal: Christian

- Base Responsibilities:
    - Utilizing STK to calculate the heat flux values for solar radiation, blackbody radiation, and albedo flux
    - Determining the impact of internal components and eLEO drag on the total heat flux
    - Compiling heat flux values into COMSOL Multiphysics Radiative Heat Transfer module to determine which components are most susceptible to the rapidly changing thermal environment in space
        - Internal and External Temperatures (max and min)
- Deployer:
    - Creating an Orbital Debris Assessment Requirements (ODAR) report to determine atmospheric re-entry survival and concerns. Requires coordination with NASA to obtain specialized software
    - Aiding the design team with electronic requirements coordination

In addition to the above sub-team designated responsibilities, team members presented twice a week, first all together to their advisors on technical advances and weekly progress, then on a rotating schedule for the full SEG meetings. As team leader, Brian focused on managing team tasks and coordinating with the other teams more often than designing CAD models and assemblies. This included taking notes during meetings, tracking tasks based on a yearlong timeline for the three subsections, and coordinating with the other SEG teams to complete the Component List. During this coordination he contributed to research and writing on launch options, deployment options and requirements, and payload specifications. As the design lead, Nicole was responsible for providing design specifications (locations relative to COG) and sharing frames and assemblies for other teams and members simulations.

1.5 Project Objectives, Methods and Standards

To meet the overall mission goal, each team developed their own goals. These goals, stated in Section 1.2, were met by creating objectives for each team (corresponding to a specific goal) and benchmarks on when to complete said objectives (further described in Section 1.6).

The objectives of team 3 were broken into three subsections: design, thermal, and structural. These objectives are listed below:

Design Objectives:

- Create a CAD model of our 6U CubeSat "NeAtO" in SolidWorks
    - Including all essential components requested by other teams in proper locations and orientations
    - Have a detailed synopsis regarding mounting components, and operation of the cart feature
    - Create a de-featured version for structural and thermal analysis ease
- Ensure the structure and materials used in NeAtO meet NanoRacks and environmental standard requirements as listed in Appendix A.
    - Adjust design and components as seen fit based on thermal and structural teams' analysis to ensure the above requirements are met

Structural objectives:

- Make an educated selection of a material model that adequately represents the CubeSat created
- Perform a modal analysis simulation on the structure
- Execute a random vibration analysis simulation using provided material models in ANSYS, or create a User Defined Material (USERMAT)

- Integrate the thermal analysis data to simulate how the material changes based on temperature over time

Thermal objectives:

- Generate heat flux profiles throughout internal and external CubeSat structure in STK
- Simulate thermal loads and distributions on the external CubeSat structure throughout elliptical orbit in COMSOL/ANSYS

In order to achieve these objectives, an iterative design process was used. The first step was to gain the necessary training on all relevant software. The design sub-team focused on utilizing SolidWorks, thermal analysis required ANSYS, COMSOL, and STK software, and structural analysis was also done in ANSYS and COMSOL. Many members trained with more than one software.

Team 1 divided their objectives by subsection: Power, Propulsion, Telecommunications, Environmental Effects, Payload and Orbital. The power subsystem for this project is responsible for supplying the power that is generated, stored, and distributed throughout NeAtO. Many of NeAtO’s components will require continuous power draw for NeAtO to remain functional during its lifespan. To account for this, a power budget was created considering all the power consuming hardware that will be implemented into the design. To ensure proper power delivery, hardware power requirements and their operational priority and duration were taken into consideration. A power budget timeline of hardware was created to help illustrate and analyze the overall power consumption of NeAtO. The timeline showed what hardware should be turned on and off throughout the mission for each orbit.

The propulsion subsystem has two objectives in order to reach NeAtO’s goals. The first objective is to determine the number of thrusters required to keep NeAtO in orbit. It has been decided that the Busek electrospray thruster BET-300P will be the thruster used for the mission.

The second objective of the propulsion subsystem is to determine the burn time to optimize the lifespan of NeAtO in orbit.

The Telecommunications sub-system has three primary objectives. The first is to select hardware that meets requirements posed by other subsystems, such as power usage and structural placement. The second is to identify a viable Ground Station Network (GSN) that will allow NeAtO to transmit data at an acceptable daily rate. The ground station sites should be inside the satellite's coverage, given the orbital inclination, and able to transmit and receive in X-band frequencies. The third is to establish the uplink and downlink budgets, for use by the payload and data handling instruments.

Understanding how NeAtO will behave in the space environment is key to the success of the mission. In our team's desired orbit there is atmospheric drag, solar radiation pressure and free electrons. This makes up the thermosphere and ionosphere. The environment will affect the structure of NeAtO, along with the telecommunications, propulsion, and detumbling and control systems. In order to accurately predict the functional lifetime and success of NeAtO, it must be designed with consideration to every environmental hazard. In addition, the temperature fluctuations must be taken into consideration as the thermosphere can range from 500 °C to 2000 °C. This is due to the ionosphere harboring extremely charged electrons to make a plasma environment. However, the atmospheric density is quite low, thus the ambient temperature would feel cold to the human skin.

The payload subsystem is the driving parameter behind the entire mission. At this current time, the team does not have the exact payload specifications beyond knowing it is approximately 1U, does not require specific pointing parameters, and collects data within the ionosphere. Once the technical parameters such as power draw, mass, and data transmission speed are determined, the team will properly interface the payload with NeAtO and determine many of the design parameters and constraints for the mission.

Team 1 is also responsible for determining the orbital parameters for the mission. Utilizing STK, the team will determine the propellant needed to transfer from initial orbit to the desired elliptical orbit, then maintain that orbit for as long as possible with the provided propulsion system. Other orbital parameters to analyze include the solar flux upon the spacecraft to determine power draw, the drag profile on the spacecraft, and environmental effects of eLEO such as electron flux.

Finally, Team 2 objectives are divided into their three main areas: Attitude Determination and Control (ADC), Command and Data Handling (CDH), and testbed development. For the ADC portion of the project, the first objective is to define the control modes, such as detumbling, based on system-level requirements. The next objective is to quantify the disturbance torques based on the mission profile. Once that is completed, the objective is to select spacecraft control methods (e.g. b-dot) for each control mode (e.g. detumble) based on mission requirements and constraints. Then, the objective is to select and size sensors and actuators in order to determine attitude and control spacecraft for each control method. The next objective is to define attitude determination algorithms and control algorithms based on capabilities, requirements, and constraints.

For the CDH portion of the project, the first objective is to define mission phases (e.g. pre-deployment, deployment, data acquisition) based on system-level requirements and mission profile. The next objective is to quantify data requirements. Once that is completed, the objective is to select data handling and spacecraft command methods for each mission phase (e.g. apogee raising) based on mission requirements and constraints. Then, the objective is to select computer components in order to handle data and command spacecraft. The next objective is to define data handling and transmission algorithms based on capabilities, requirements, and constraints. During the entire project and for all portions, iterating steps as necessary to achieve goals and document steps are objectives as well.

For the test bed portion of the project, the main objective is to construct a 3 DOF lab testbed for the test and validation of ADCS control systems. Once the physical testbed is completed the next objective is to create an electronic control system for the remote control and analysis of the system.

1.6 Project Tasks and Timetable

To complete each objective and ultimately reach the goals of our mission, tasks were broken up into sections based on the three areas of Team 3. These tasks were tracked throughout the year, with a breakdown of when each task should be worked on/ completed. The below Gantt chart outlines Team 3's major tasks and their completion periods (main colors are when they are completed, second colors refer to a grace period if challenges arise):

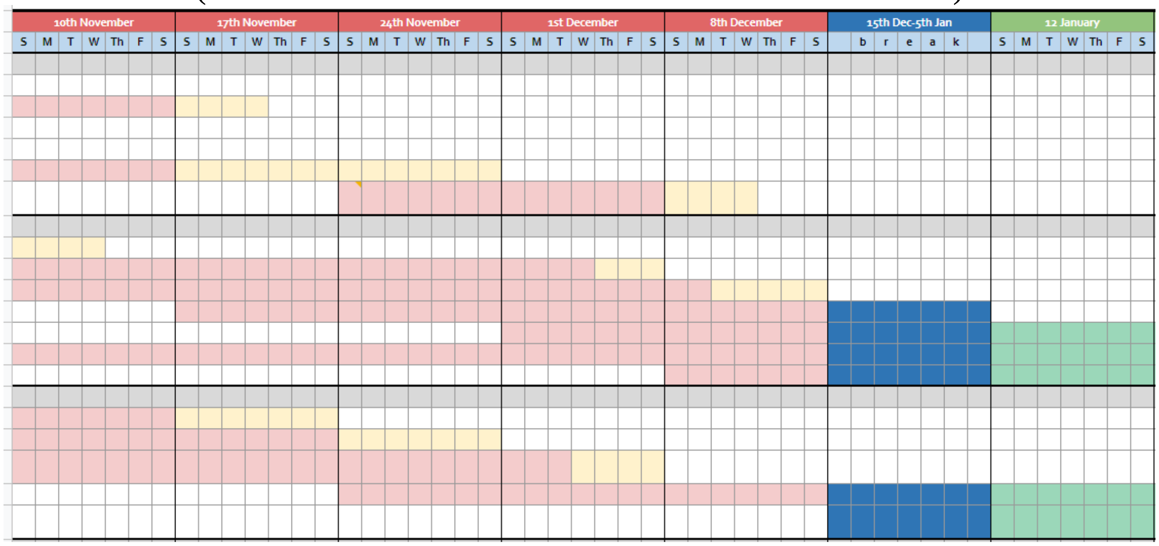
(Start- Top 3 Sections)

PROJECT TITLE	CubeSat NAD 2001	**COMPANY NAME**	WPI Aerospace Department
PROJECT MANAGER	Brian Kelsey	**DATE**	20th February 2020

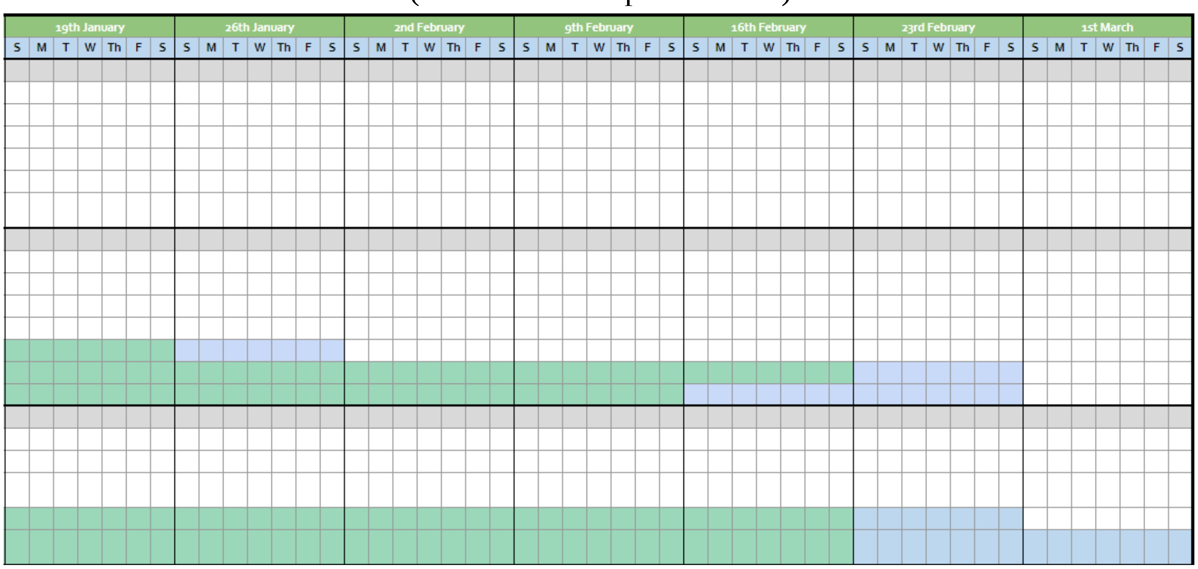
WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE
1	**Familiarization**			
1.1	Learning STK and Certification	Christian	8/22/19	10/20/19
1.2	ANSYS and COMSOL Training	All	8/22/19	11/20/19
1.3	Read through past papers	All	8/22/19	10/10/19
1.4	Initial background research	All	9/25/19	10/20/19
1.5	Compiling CAD files and relevant documents	Nicole and Brian	10/2/2019	11/30/19
1.6	Determining launch vehicles and deployment methods	Brian	9/25/19	11/2/19
2	**Design**	Nicole and Brian		
2.1	Initial 4U Defeatured Model	Nicole	10/31/19	11/13/19
2.2	Featured Frame Models	Brian	11/10/19	12/7/19
2.3	Rail and Deployment Switch Design	Brian	11/10/19	12/14/19
2.4	Reiterated 6U design with final components	Nicole	11/17/19	1/5/20
2.5	Featured 6U Model with Solar Panels	Nicole	12/1/19	2/1/20
2.6	Deployer Requirements Coordination	Brian	10/20/19	2/29/20
2.7	Design Summary	Nicole and Brian	12/8/19	2/29/20
3	**Structural Analysis**	Rory		
3.1	Material Model Background Research	Rory	8/22/19	11/23/19
3.2	Initial ANSYS Simulations	Rory	10/27/19	11/30/19
3.3	Methods and Approach for Vibrational and Structural Analysis	Rory	10/20/19	12/7/19
3.4	Final ANSYS Simulation	Rory	11/24/19	2/29/20
3.5	Compile Results and create risk analysis of components	Rory	12/15/19	3/6/20

Aug 22nd-Oct 19th	20th October							27th October							3rd November						
	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S	S	M	T	W	Th	F	S

(Middle Term and Start of Final Term – Bottom 2 Sections)

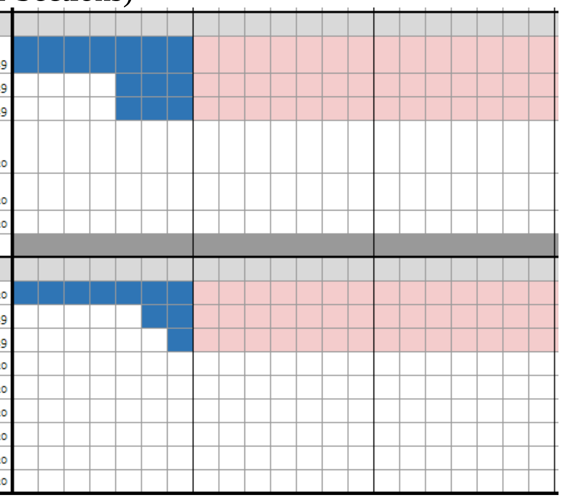


(Final Term - Top 3 Sections)



(Start – Bottom 2 Sections)

4	**Thermal Analysis**	Christian		
4.1	Determine Sources of Heat (background research)	Christian	8/22/19	11/16/19
4.1.1	Thermal Effects of Atmospheric Drag	Christian	10/10/19	11/27/19
4.1.2	Heat Flux of Internal Components	Christian	10/10/19	11/27/19
4.2	Data Collection: STK (Solar Radiation, Blackbody Radiation, Albedo Flux) - Initial Simulation	Christian	11/10/19	1/5/20
4.3	COMSOL Multiphysics Radiative Heat Transfer module - Initial Simulation	Christian	11/24/19	2/24/20
4.6	Final Simulations and Results	Christian	12/15/19	3/6/20
4.7	Orbital Decay Analysis	N/A	N/A	N/A
5	**Paper**	All		
5.1	Introduction	All	8/22/19	1/11/20
5.2	Socioeconomic Implications	Brian	10/12/19	11/16/19
5.3	Requirements and Constraints	All	10/15/19	11/16/19
5.4	Methodology (Technical Sections)	All	11/17/19	2/1/20
5.5	Results (Technical Sections)	All	12/1/19	2/29/20
5.6	Conclusions & Recommendations	Brian	1/19/20	2/29/20
5.7.1	Final revisions & edits	All	2/9/20	2/29/20
5.7.2	Final formatting	Brian	2/16/20	3/6/20
5.7.3	Submit paper for approval	All	3/1/20	3/6/20



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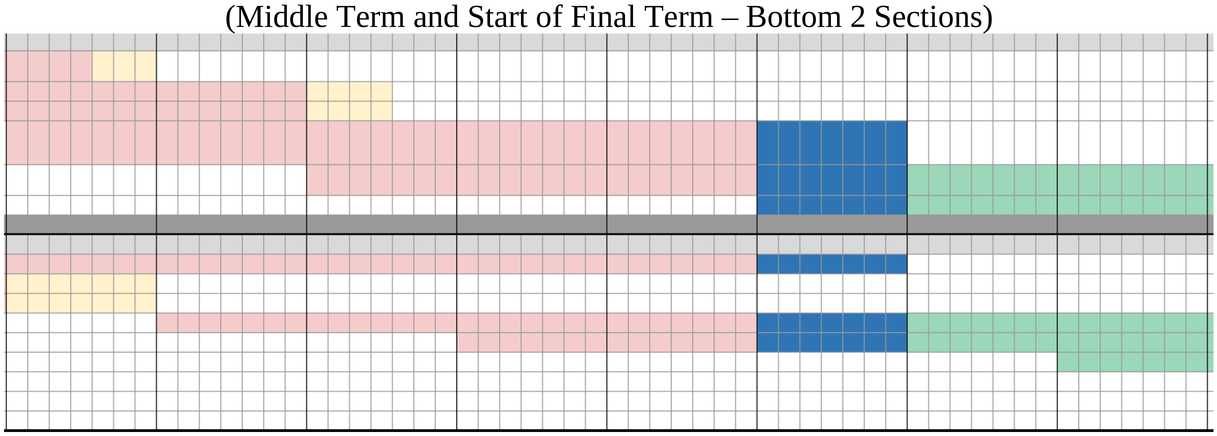

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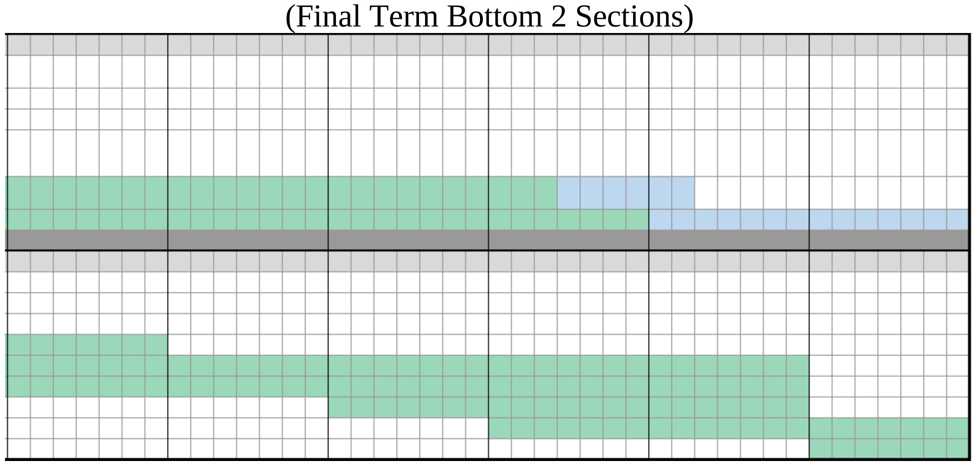


Figure 12: Team 3 Gantt Charts

2. Mechanical Design

This chapter discusses the mechanical design of our 6U eLEO "NeAtO" CubeSat, which involved creating and maintaining the CubeSat in CAD for analysis performed by various sub-teams. This was performed through an iterative process: an initial design was first created when all essential components CAD files and specification sheets were provided by the other teams. Once the initial design was created, it was put through thermal and structural testing. If singular components or the whole design failed the aforementioned analysis, the design was modified and tested again. Throughout the process the design team communicated with other SEG teams to ensure components were in their optimal location of functionality, and to notify teams if/when changes were necessary.

2.1 Design of an eLEO CubeSat

2.1.1 Design Drivers

Many important factors and requirements affected the design process of NeAtO, including the aforementioned NanoRacks deployer requirements and constraints, as well as location specifics of the payload and special components which were provided by Teams 1 and 2. The SEG Team began with a 4U as previous CubeSat teams had calculated the propulsion for our eLEO orbit using a 4U system. Once design started, it was decided that a 4U was not feasible and the design was changed to a 6U. Following the SEG choice to move to a 6U (reasoning explained in Section 2.1.2), the Dellingr CubeSat was used as a baseline design, as it was an overall successful mission of a 6U CubeSat with the mINMS as its primary payload. A cut open view of the Dellingr is shown in figure 13 (we substituted engines for instruments as our mission requires orbit maneuvering to eLEO).

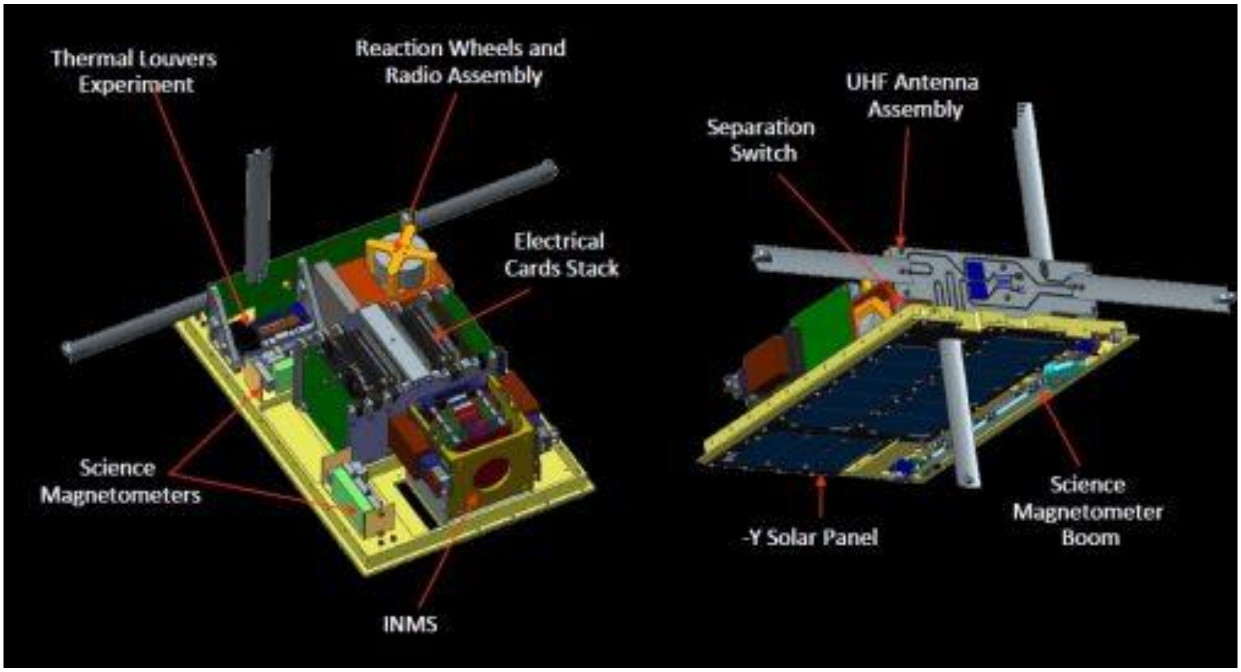


Figure 13: Dellingr Cutout View [17]

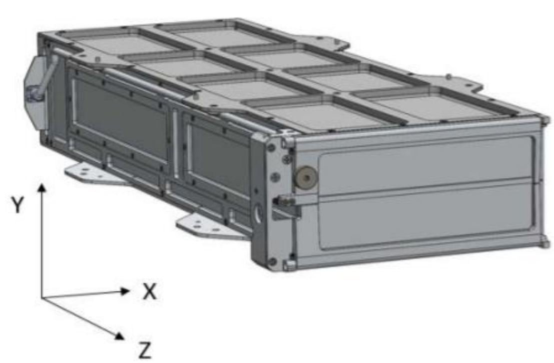


Figure 14: NanoRacks Deployer Coordinate System [23]

The leading design requirement was to ensure the mass and volume constraints provided by NanoRacks as outlined in Chapter 1 were met. This included the maximum mass of 12 kg, and the necessity to fit all components excluding the solar panels within an internal volume of 7,742.6 cm^3. Prior to the mINMS being chosen as our payload, there were concerns regarding exceeding the mass limitation of a 4U CubeSat (8kg) and a lack of inside volume should the payload exceeds 1U of space. These concerns played a role in the switch to a 6U (described in the following section) once the payload was chosen [23].

The second most important design requirement was the Center Of Mass (COM) requirement. As components were added and the final CAD model began to take form, the design team had to ensure that the COM was within a certain distance of the Center of Geometry (COG). To add to its importance, this was not only a NanoRacks requirement, as locating the COM at or close to the COM allows for faster calculations by the ADC team. The COM requirements and respective coordinate system is provided below and in Figure 14 above:

- X-axis: (+/- 5cm)
- Y-axis: (+/- 3cm)
- Z-axis: (+/- 8cm)

The COM requirement was greatly affected by components requiring specific locations within NeAtO. Since the payload aperture must be oriented in the RAM facing direction, the most logical choice was to locate the payload centered at the top of the 6U, with the engines at the rear of the 6U (3U length along the Z axis). Despite a similar volume of these subsystems, the propulsion system mass greatly outweighed that of the payload, which affected where many electronic components were added (to balance out the COM in the Z direction). The ADC team also requested that the three reaction wheels be placed along each of the 3-axis originating from the COM. This posed a challenge to shuffle around non-location specific components while fixing the reaction wheels along each axis.

The design team also aimed to increase efficiency of the external surface, by maximizing surface area for the solar panels, while still allocating space on the frame for the antennae and sun sensors. The analog sun sensors were required to be placed at each corner on the side 3Ux2U panels near the top of NeAtO (close to the Z+ face), with each facing a different direction. Another sun sensor was placed next to the payload aperture on the Z+ face, for a total of 5 sun sensors. The antenna, which can be described as a thin square box with 3 antennae from its sides, was placed inside NeAtO behind the payload. With this in mind, and the top and bottom faces of the 6U off limits (payload, antennae, deployment switches and engines), the 3Ux2U side faces provided the most surface area, with sections of the 3Ux1U side faces also utilized by the sun sensors [23].

As components were chosen by the separate teams, the design team emphasized choosing mainly COTS parts, most of which are flight proven and all of which have gone through extensive testing. This student set requirement ensured that all components met outgassing requirements for non-metallic materials: a Total Mass Loss (TML) of less than 1% and a Collected Volatile Condensable Material (CVCM) of less than 0.1%. To provide ease of access to the internal components, the design team created their own pull out cart. To avoid any issues with outgassing, the same aluminum alloy as the frame was chosen for the cart.

In addition to outgassing requirements, NanoRacks also mandated that the Maximum Effective Vent Ratio (MEVR) should not exceed 5080cm, as outlined in Section 4.4.2 in Appendix A. The MEVR is calculated as follows:

$$MEVR = \left(\frac{Internal\ Volume\ (cm)^3}{Effective\ Vent\ Area\ (cm)^2}\right) \leq 5080\ cm$$

The effective vent area is considered the summation of the unobstructed surface area of any vent hole locations or cross-sectional regions that air could escape NeAtO [23]. We calculated our internal volume to be 7742.6 cm^3(3207 cm^3internal volume with components inside) and our effective vent area to be greater than 10.9 cm^2considering an open region in the RAM facing side and small opening on the side of NeAtO. This yielded an MEVR of 704.5 cm (or less), meeting NanoRacks requirements [23].

Another NanoRacks requirement for the first mission was to include tabs or rails on the outer frame as well as load points, necessary for a controlled deployment from the ISS. The design team determined that the tabs were a better option to help raise our center of mass closer to the center of gravity (Y direction). Figure 15 below shows a 6U payload with tabs being deployed from the NanoRacks double deployer:

Figure 15: NanoRacks Payload Jettison Configuration with Tabs [23]

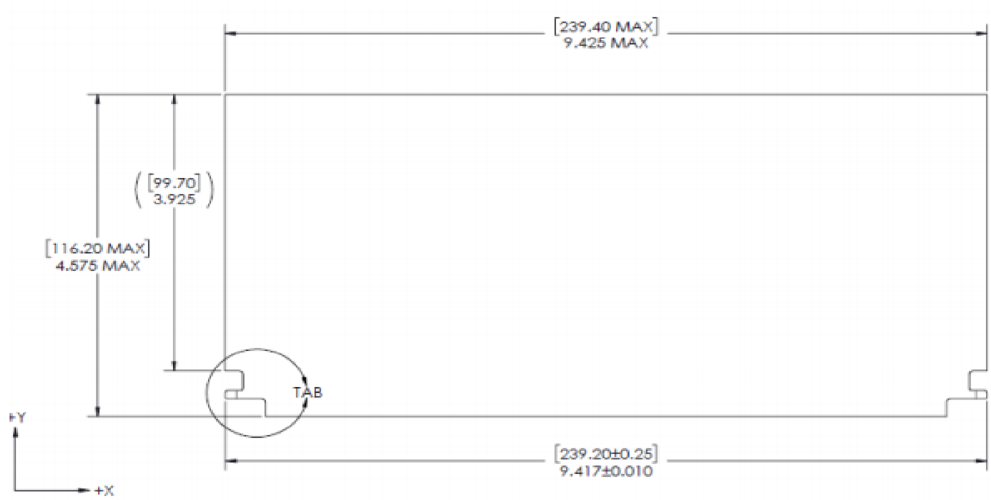


Figure 16: Tab Dimensions with Respect to X and Y axis' [23]

NanoRacks has many specific design requirements for the tabs. Their length in the Z direction must be 366mm, with a divide between the ends of the tabs 239.2 mm plus or minus 0.25 mm in the X direction. The maximum distance in the Y direction of the entire body is 116.2 mm, while the first cutout that forms the tabs must be 99.7 mm as shown in the figure 16 below (coordinate system provided).

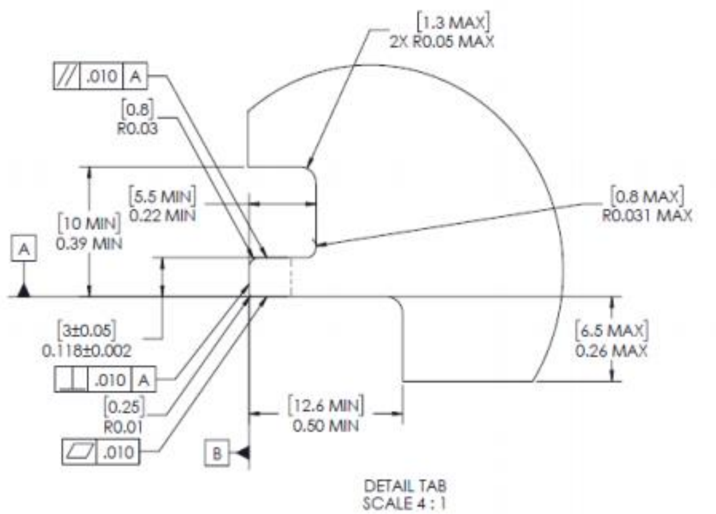


Figure 17: Tab Dimensions: Close-Up [23]

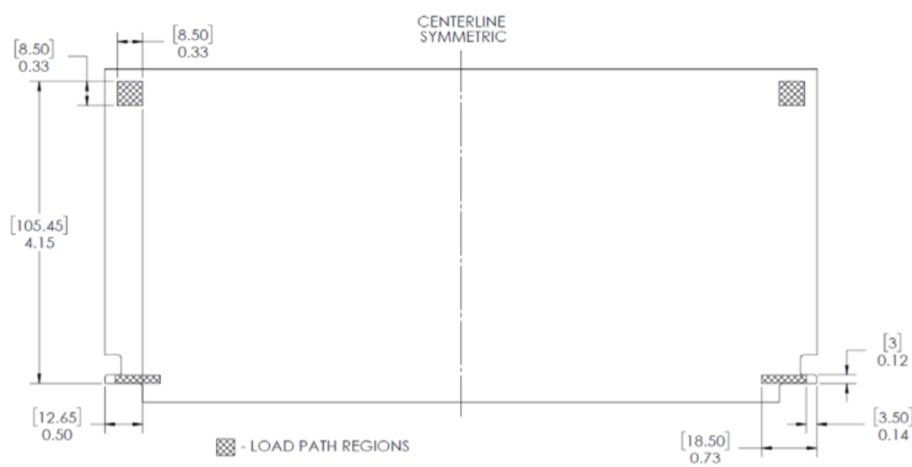


Figure 18: Load Points for Tab Configuration [23]

The exact shape of the tab and measurements of individual cutouts are outlined in figure 17 below. The depth (X) of the top cut must be a minimum of 5.5 mm from the end of the tab, with a height (Y) of 7 mm. The lower cut should have a minimum depth (X) of 12.6 mm from the end of the tab, and a max height of 6.5 mm from the bottom of the frame. The tab remaining should therefore be 3 mm in height.

The load points for the tab configuration are shown in figure 18 below, including two square load points on the opposite side of the tabs, 8.5 mm width, as well as two load points on the tabs, specifically 15 mm of the tab, starting 3.5 mm from the outer edge.

NanoRacks also requires 3 deployment switches that act as electrical inhibitors which can be found on the -Z axis near the engines. In addition to the quantity and location of the deployment switches, NanoRacks required that the total force be less than 18N. Our team chose the Honeywell V15W2 Series Basic Switch for Hazardous locations, for its large range of operating temps between -25 to 85 C. Figures 19 through 21 below display the Deployment Switch as well as our CAD models of it (featured and defeatured).

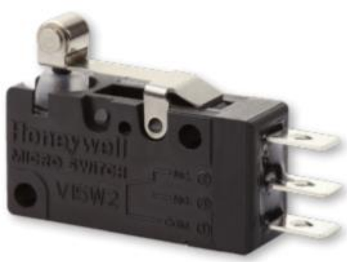


Figure 19: Honeywell V15W2 Series Basic Switch [9]

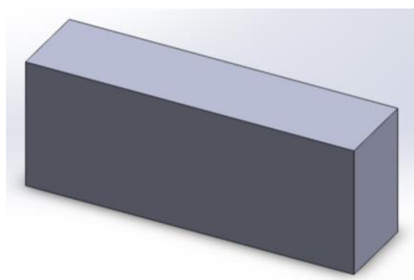


Figure 20: De-Featured CAD Model of the Deployment Switch

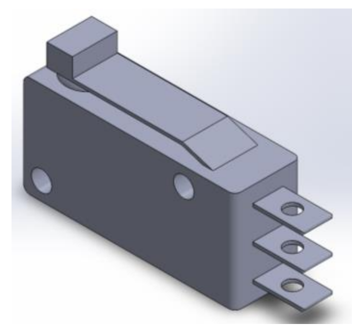


Figure 21: Featured CAD Model for the Deployment Switch

The final design requirement according to NanoRacks requirements was to include an access port on the +/-X face. This is necessary to physically connect to NeAtO for the Remove Before Flight (RBF) feature and/ or apply before flight (ABF) feature. To accommodate this requirement, a "placer" port was positioned next to the sun sensor on the +X face where a solar cell had already been removed (as connections to a real port could vary).

2.1.2 Design Process

The design team started with determining how information regarding necessary component details should be passed between teams. A tracking document called the component list was created and can be found in Appendix B. It includes all the components the other teams chose, as well as detailed information about each component. Information relevant to the design team included the dimensions, weight, CAD files, spec sheets, any location or orientation requirements, and a person of contact for any clarifications on the component. It was shared over google drive so teams could add components and update details as the project progressed. This allowed for quick accessibility and uniform organization of necessary information without having to meet with other teams to discuss component requirements throughout the design process.

The first design was with a 4U frame provided by Clyde Space. Multiple issues arose out of the use of the 4U frame. At the start of the project, the thrusters were placed along the ram facing axis, which was initially assumed to be through the 1U sides. The first problem with the 4U frame occurred when the propulsion team specified they wanted three thrusters, however the 1U rear face only has enough area for two thrusters when tightly packed, as they are slightly less than 5 cm across and the interior base of the frame is 9.74 cm across. After discussion the propulsion team stated that the mission could still be completed with just two thrusters.

However, once the payload was provided, and our team found specific dimensions for it, we realized that the side that needed to be ram facing was 13cm x 9 cm, not 9cm x 10 cm as previously assumed. This meant that a 4U x 1U face of our 4U CubeSat needed to be the ram facing side in order to orient the payload correctly. The controls team stated that due to the increased drag in this orientation, the mission would require 4 thrusters. This brought up a new issue as there was no outlet for the thrusters on the side they needed to be mounted as seen in figure 22. Our team decided we could modify the frame to create proper mounting for them, should a better solution not appear. More problems, however, arose with this new orientation. The increased number of thrusters made it physically impossible to line up the reaction wheels with each axis along the Center of Mass, as the payload was over the center of mass and could not be moved due to interference with the thrusters seen in figure 23. Lastly, with nearly two 4U faces needed for the payload apertures, sun sensors and thruster outlets, the number of solar panels was greatly reduced, such that the mission did not have enough power to operate fully.

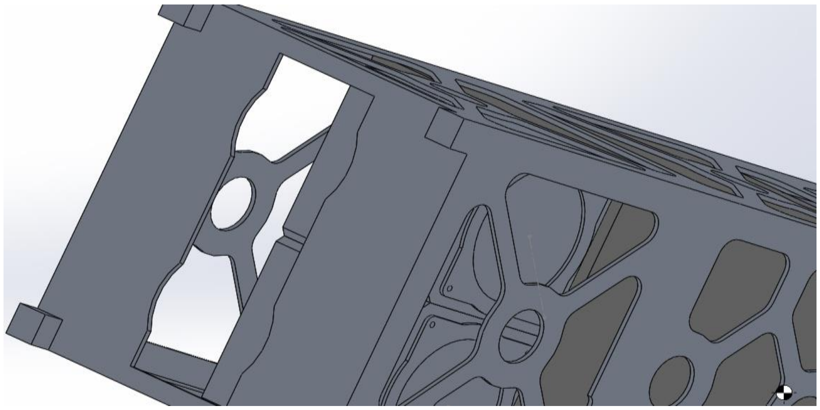


Figure 22: Thruster Mount - only exists -Z Face

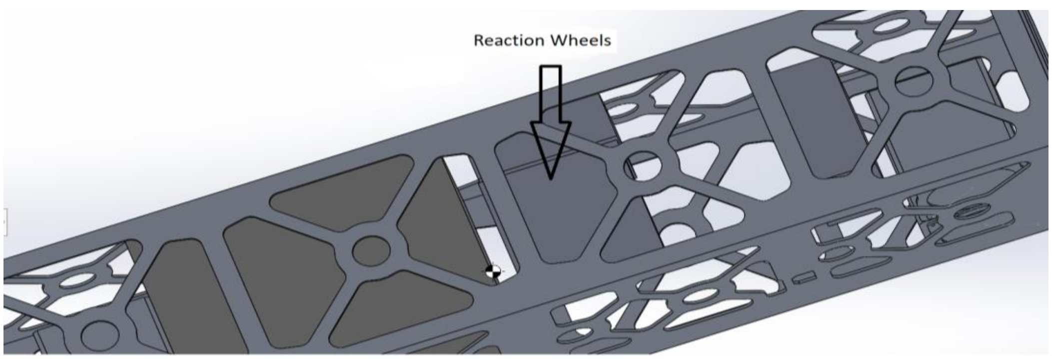


Figure 23: COM Difficulties due to 4U Configuration

Due to the accumulation of these issues the design team proposed a switch to a 6U frame. This would make our ram-facing-side the top Z+ face (2U x 1U) instead of a 4U x 1U face, greatly reducing the amount of drag on the CubeSat. Additionally, the 6U would have more inside volume to allow the reaction wheels and magnetorquers to be lined up along the proper axis'. Lastly, we could increase the number of solar panels to properly power NeAtO since the payload and thrusters would no longer be on the larger faces on the CubeSat. A comparison of the 4U and 6U frames can be seen in Table 2.

Table 2: 4U and 6U Comparison

4U Frame	**6U Frame**
Less Total Mass	More Total Mass
Non-Standard frame (not previously used)	Standard frame, more common size
4U on ram side (more drag)	2U on ram side (less drag)
Requires 4 thrusters	Requires 4 thrusters
No mounting for thrusters on proper side (must	Built in mounting for thrusters on correct side
Can’t line up all location/ orientation sensitive	Can line up components (enough volume)
Insufficient space for a cart to mount components (harder to access for astronauts)	Most components can be mounted to a cart for convenient access
Insufficient number of solar panels	Sufficient number of solar panels
Can fit in NanoRacks deployer	Can utilize multiple deployer options (including NanoRacks)
Must use rails for deployer	Can choose between rails and tabs for deployer

After presenting this table to SEG and discussing the change with our advisors, the change to a 6U frame was made. Our design approach for the 6U frame changed slightly from our previous approach due to inspiration from a previous CubeSat mission called Dellingr, mentioned in the previous section. Our team began with designing a cart that could be pulled out of NeAtO for ease of access and mounting. The cart assembly was created such that the origin would coincide with the geometric center of the whole CubeSat. This made checking the distance of the center of mass to the geometric center significantly easier. Components were added to the cart based on weight and required locations first. A list of components and various specifications is shown in Table 3.

Table 3: Abridged Component List

Component	Selected Part	Quantity	Mass/unit (kg)	Location/orientation
Payload	mINMS	1	.56	Ram-facing apertures exposed (+Z)
Engine	BET300	4	.214-.230	Opposite of payload
Reaction Wheel	RWP050	3	.24	One aligned with each body axis
Magnetorquer	NCTR-M002 Magnetorquer Rod	3	.12	One aligned with each body axis
Sun Sensor	Nano-SSOC-A60	5	.008	Near Payload, each on a different face of NeAtO
GPS	NGPS-03-422	1	.13	NA
Battery	Optimus-40	1	.335	NA
OBC	KYREN M3	1	.0619	NA

Motherboard	Starbuck Nano-Plus	1	.148	NA
Reaction Wheel Controllers	DCE Gen 3	3	.05304	NA
Transceiver	ISIS VHF/UHF	2	0.075	NA
Accelerometer/ Magnetometer	LSM303AGRTR	1	0.00285	At Center of Mass
Gyroscope	ADXRS453	1	.0567	At Center of Mass

The payload and thrusters were added first since they had specified locations. Next the reaction wheels and magnetorquers were added and lined up through the geometric center since the CG was placed as close as possible to the geometric center. Next, the OBC, controllers for the reaction wheels, battery, GPS, and motherboard were added such that the CG was brought closer to the geometric center as all these components are not dependent on location or orientation.

Lastly, the accelerometer and gyroscope were placed at the CG once this location was better defined. Once all the components were placed, the cart was modified to create mounting surfaces for each component. The mount for the cart to the frame was created last and was temporarily added to the cart assembly to verify the CG while waiting for the 6U frame from Clyde Space. Our team was unable to acquire a 6U frame from Clydespace who had designed the previous 4U frame until late in project development. Therefore, we created a 6U frame based on NanoRacks requirements for tabs and load points, in union with external dimensions found on Clyde Spaces' website for their 6U frame. The team utilized a similar material thickness and design from the previous 4U frame for this hybrid design, as seen in figure 24 below.

Once the frame and the antenna were received the complete assembly of NeAtO was created. Initially, the antenna was placed in front of the payload to affect the fewest number of solar cells and allow the antenna space to deploy. This was done because the apertures for the payload were on the outer edges and would not be directly blocked by the antenna. However, when this was brought up in the SEG it was determined that the location of the antenna would still interrupt the flow of particles. To correct this the antenna was moved to be internal. Should a problem come up with deployment during testing, a small pvc pipe could be used to direct the antennae as they unravel out the small holes of NeAtO for this purpose.

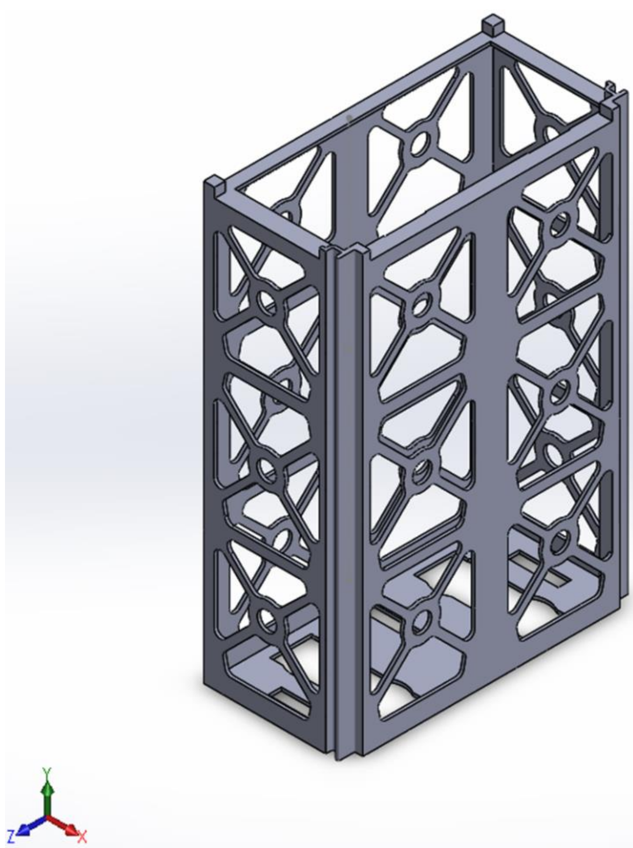


Figure 24: Clyde Space Hybrid Frame

Once this design was completed, the SEG team suggested that our power budget could benefit from a sun synchronous orbit, if deployed from a polar orbit launch. The new orbit would require a different deployer, as the NanoRacks deployer is only on the ISS (wrong inclination, too much delta V to go from ISS inclination to a polar orbit). The new deployer we chose was the Duo Pack, a specific type of Quadpacks Deployer. Unfortunately, the hybrid Clyde Space frame was not compatible, which led to the second design assembly for NeAtO. Since the new orbit was not finalized at the time, we decided to create two CubeSat designs, one with our hybrid Clyde Spaces frame for the NanoRacks deployer, and a second version with the ISIS extended 6U frame designed to work with the Duo Pack deployer. It is important to note that Duo Packs has the same 6U maximum mass as NanoRacks. Since ISIS also creates frames for the Duo Pack deployer, their 6U extended frames dimensions determined our second mission options internal volume constraints. This second frame also had to be replicated in SolidWorks by our team, as the model provided by ISIS came as one part with removable interior shelves already built in that we are not using, and a modified CAD model could not be provided to our team. The replicated CAD model of this frame can be seen in figure 25.

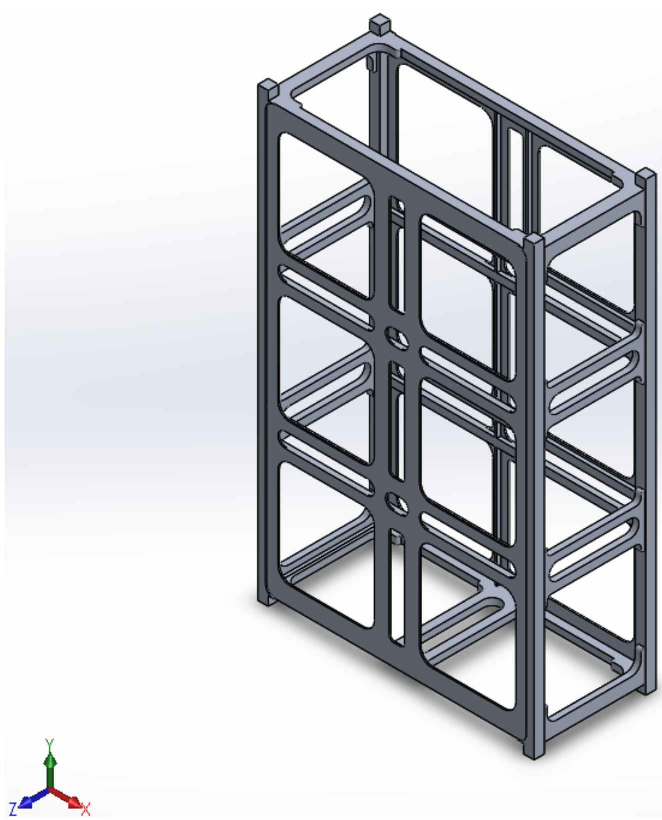


Figure 25: Innovative Solutions in Space (ISIS) Frame

The internal dimensions of the Innovative Solutions in Space frame create a slightly shorter but wider volume than the Clyde Space hybrid, therefore our pull-out cart was modified, with many components moved to a new configuration to fit into the new space. The orbit was then finalized to the original orbit and Version 2 of NeAtO was on longer necessary.

Late in the design process the Clyde Space 6U frame was then received. It was decided to consider this frame because a COTS part would be significantly cheaper than a custom manufactured frame, and thus a third assembly version was created using the Clyde Space frame as seen in figure 26.

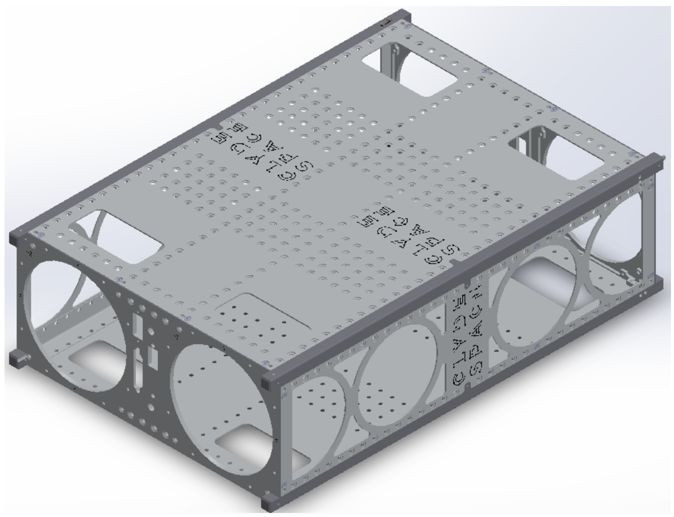


Figure 26: Clyde Space Frame

Since the custom frame was based off the Clyde Space dimensions, the cart from version 1 did not need modifications to fit into the third version. A comparison of these two frames can be seen in table 3. Both frames were presented to the SEG, where Version 1 was selected as cost was not a major concern, version 1 better filled mission requirements, and Version 1 specifications had already been shared/ distributed to other teams for initial calculations. Once this was completed, Version 1 of NeAtO was put through thermal and structural testing. All components were deemed safe for flight and no further design changes were necessary.

Table 4: V1 and V3 Frame Comparison

	V1	V3
Pros	*Open space for free flow of particles to the payload *Built to fit selected components	*COTS part would be cheaper *In built deployment switches
Cons	*Heavier by 200g *Costs more to manufacture	*Needs some modifications to thrust plate to fit smaller thrusters *Has a piece in front that may block the flow of particles to the payload

2.2 Materials, Fasteners, Brackets

The cart started as a thin rectangular plate, dimensioned to fit perfectly along the interior of the 2U section, and stop 60 cm short of the back of NeAtO to leave space for the thrusters and their plumbing. The thickness was set by the amount of space left over from the payload in the Y direction (to provide the maximum strength). Mounting surfaces were extruded off the plate once the locations of the components were known. The plate is mounted to NeAtO's frame using an L shaped bar that extends the length of the cart and has a lip on the back end to prevent the cart from sliding back into the thrusters. The L shaped bar is bolted to the frame such that the unbolted side is the thickness of the cart away from the base of the frame. This keeps the cart constrained between the base of NeAtO, the L bars, and the top of NeAtO. Additionally, the cart will be bolted to the L frame in the front where the cart is inserted into the frame.

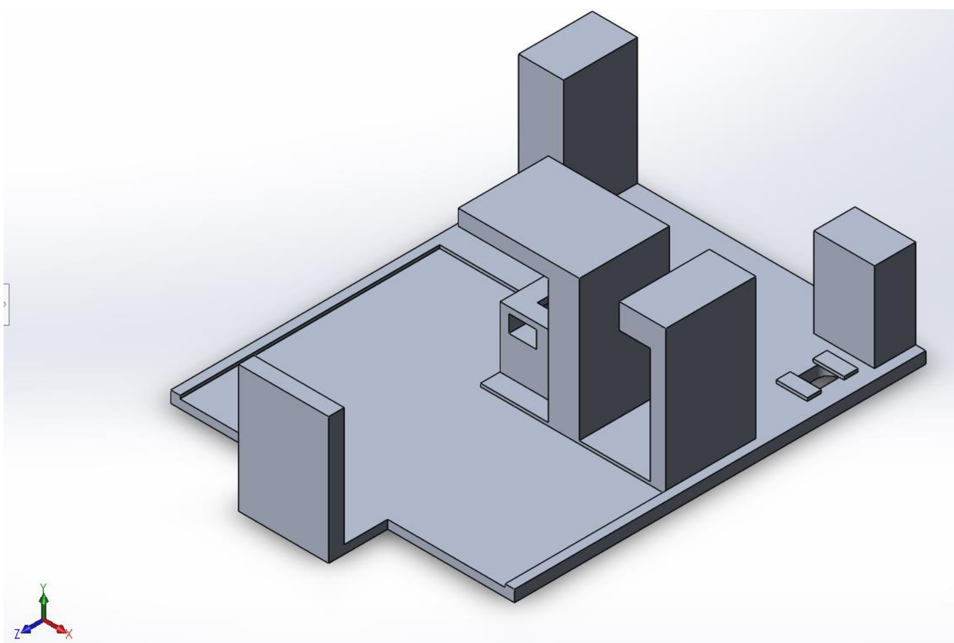


Figure 27: Final Cart V1 and V3 for the Clyde Space Hybrid Frame

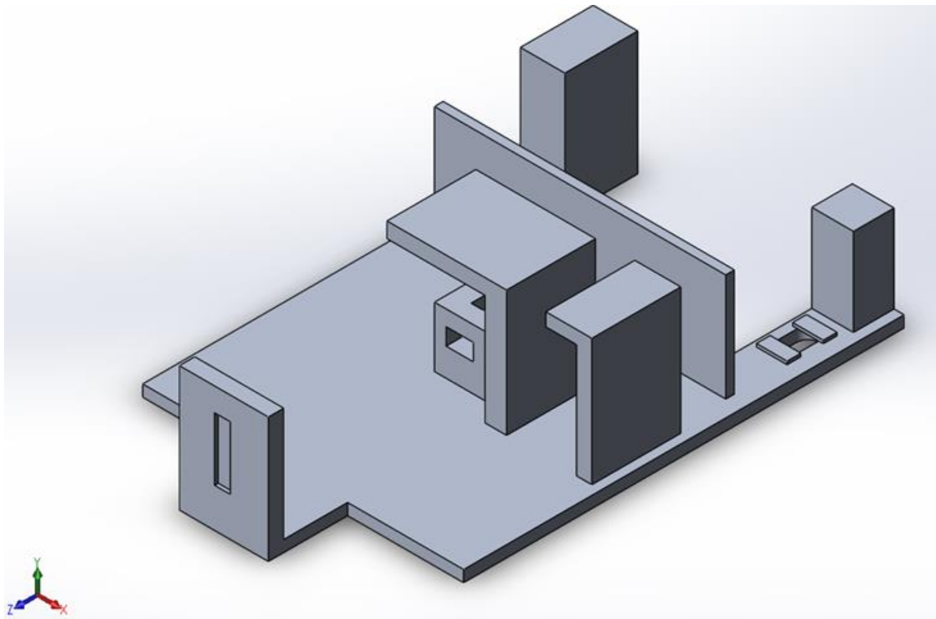


Figure 28: Final Cart V2 for the Innovative Solutions in Space Frame

The material selected for the cart and screws is aluminum alloy AL 7075 -T6. This material was used because it matched the frame and will prevent stresses were the cart and bars interface with the frame since they will be expanded and contracting at the same rate.

2.3 Design Summary

The three assemblies were finalized with the Clyde Space based frame as Version 1, the Innovative Solutions in Space frame as Version 2, and the Clyde Space 6U frame as Version 3. In all three designs the center of mass starts behind the center of geometry and moves in front of it as the propellant is used. Due to space and weight constraints it was impossible to get the gyroscope, accelerometer and magnetometer exactly on the center of mass. The coordinate frame used to describe the location of the center of mass has its origin at the center of geometry of the frame. The Y is perpendicular to the component side of the cart. The Z axis points in the ram direction of NeAtO. Lastly, the X axis can be found with the right-hand rule going from the Y axis to the Z axis. This coordinate frame can be seen in Figures 28 and 29. All the points given are distances in millimeters.

Version 1, shown in figure 29, is made with the custom frame based on the Clyde Space 4U frame design, and has a wet mass of 6539.45 grams and a dry mass of 6475.45 grams. The Wet Mass CG is located at (2.22, -10.95, -0.11) and the dry mass is at (2.24, -11.06, 1.29). The accelerometers and magnetometers are located at (-2.10, -11.52 ,27.75). The gyroscope was placed at (-2.10, -4.41, 27.57). All these values are within the NanoRacks deployer requirements. In this configuration two solar cells needed to be removed to accommodate a sun sensor and the ABF/ABF Port and two needed to be remover to accommodate the antenna for a total of 4 cells removed.

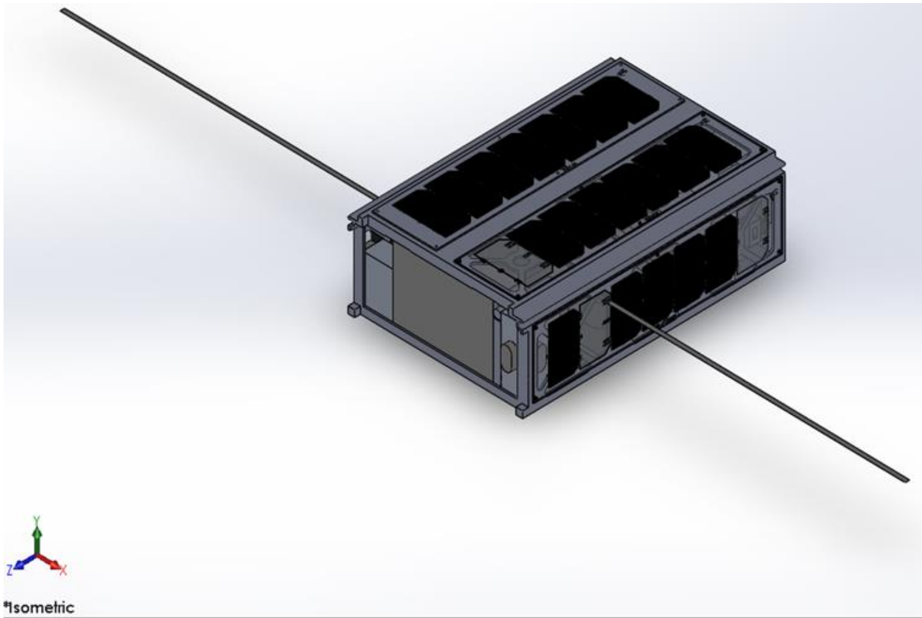


Figure 29: Version 1 of NeAtO

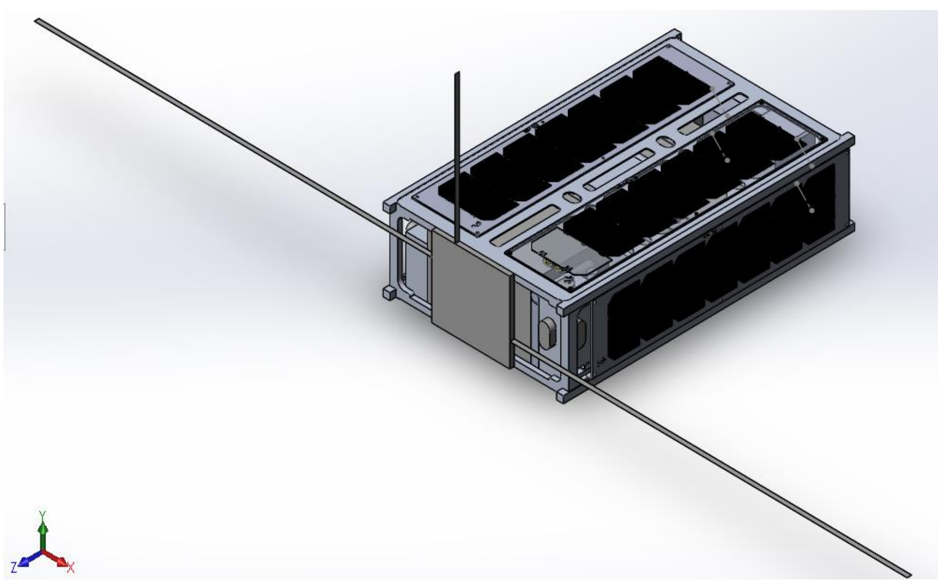


Figure 30: Version 2 of NeAtO

Version 2, shown in figure 30, uses the Innovative Solutions in Space frame, and has a wet mass of 6932.71 grams and a dry mass of 6868.71 grams. The Wet Mass CG is located at (-6.41, -5.08, -11.13) and the dry mass is at (-6.47, -5.13, -9.89). The accelerometers and magnetometers are located at (-0.10, -9.02, 1). The gyroscope was placed at (-0.10, 1.88, 1). All these values are within the Duo Pack deployer requirements. In this configuration one solar cell needed to be removed to accommodate a sun sensor. This configuration was discarded before the concern about blocking flow to the payload was considered, hence the location of the antenna.

Version 3, shown in figure 31, is comprised of the Clyde Space frame and the same cart as Version 1. It has a wet mass of 6344.86 grams and a dry mass of 6280.86 grams. The Wet Mass CG is located at (1.01, -7.65, -1.14) and the dry mass is at (1.02, -7.73, 2.53). The accelerometers and magnetometers are located at (-1.00, -6.67, 27.05). The gyroscope was placed at (-3.1, .4381, 27.05). All these values are within the NanoRacks deployer requirements. In this configuration 3 solar cells were required to be removed to accommodate the sun sensors, and 2 more removed to accommodate the antenna. Payload apertures are on the outer edges of the +Z face and thus are not disrupted by the frame. It is also important to note that the Clyde Space frame was designed to be compatible with NanoRacks and meets all rail requirements with load points on all 4 ends.

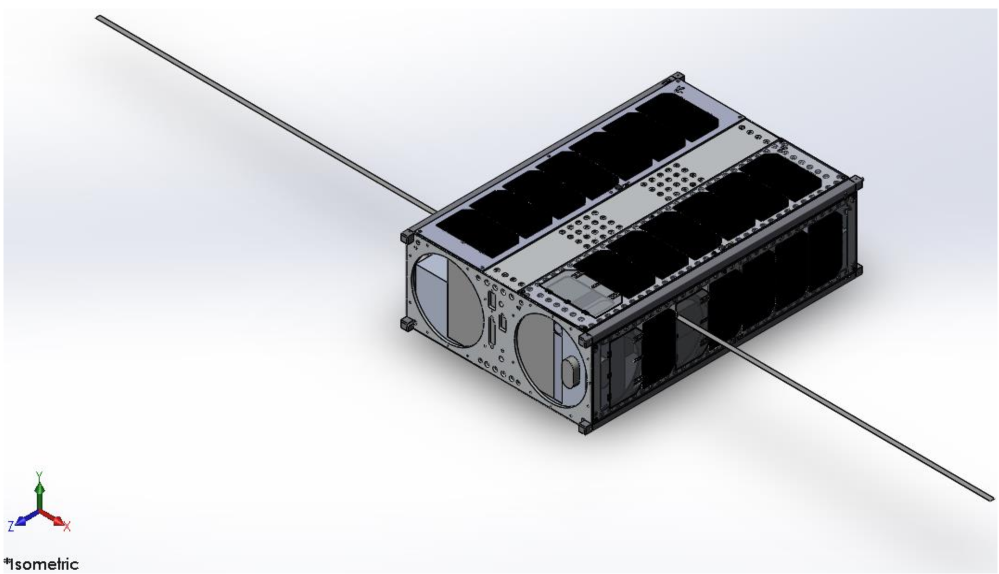


Figure 31: Version 3 of NeAtO

3. Structural

The structural analysis section of the project involves a series of simulations to ensure the overall mechanical structure of NeAtO is safe for flight. The previous CubeSat projects from 2013, 2017, and 2018, conducted structural analysis exclusively on the structural components of the CubeSat. It was expected that the other components chosen from manufacturers would already be flight tested for space and therefore need no further testing. For this project we will make the same assumptions in order to simplify the simulations thus greatly decreasing runtime. The simulations for the structural analysis will primarily be conducted in the engineering simulation software ANSYS.

3.1 Requirements

The general environmental verification standard (GEVS) published by NASA details the required tests for all vehicles entering space. The experimental tests involve structural loads, vibroacoustic, sine vibration, mechanical shock, and pressure profiles. For each class of vehicle, assigned through weight and size of the vehicle, there is a minimum requirement that the vehicle must withstand in order to be cleared for space flight. The general mass properties and proper mechanical functioning are also verified [24].

Previous CubeSat projects primarily referenced the GEVS requirements for the random vibration test frequency profiles shown in figure 32.

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800\ Hz)}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800\ Hz)}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

Figure 32: GEVS Random Vibration Test Profile [24]

For our project, we will be using the structural requirements provided by NanoRacks. NanoRacks considers the GEVS requirements for vehicles in space, but provides a more relevant set of requirements pertaining to CubeSats specifically. Using NanoRacks over the GEVS also allows the overall project to have a consistent set of requirements across all design subsystems. Related NanoRacks requirements pertaining to structural analysis include: 4.3.2 Random Vibration Environment, 4.3.5 Integrated Loads Environment, 4.3.8 Airlock Depressurization, and 4.4.6 Space Debris Compliance will be considered. Further detail on each of these requirements is outlined in Appendix A [23].

3.2 Material Models

The process of selecting the best material to be used in simulating the behavior of the material used for the frame of NeAtO began with background research on the different types of material models. The basic material models of hardening are isotropic hardening and kinematic hardening. In isotropic hardening, the graph of the yield surface in the four directions of stress expand uniformly outwards in all directions, increasing hardening in all directions. In kinematic hardening, the yield surface is translated in one direction, increasing hardening on one axis but not the other. For this application uniaxial loading is the case so kinematic hardening was selected as the type of material model to use [10].

In the case of some materials, they possess a viscoplastic behavior, where time becomes a relevant factor. For this application, high temperatures must be accounted for as well. NeAtO will be exposed to many different vibrations and forces from the environment of space as well as heat from the propulsion system and the sun. NeAtO will also be constantly subjected to large temperature changes as it orbits the earth. For this reason, it is also important to choose a material model that can accurately predict thermal cycling which is a form of ratcheting.

Ratcheting is a behavior in which plastic deformation accumulates due to cyclic mechanical or thermal stress. There are many viscoplastic material models that can address the time factor that ratcheting creates on a material. Based on this research, the best material model for the application of this project is one that includes a viscoplastic model with kinematic hardening, ensuring that the material model is dependent on temperature changes. In order to accurately see the effect of ratcheting on the material, the structural analysis was conducted at two different points of the orbit, the point of highest average temperature and lowest average temperature. Including the temperature that NeAtO is subjected to is an important aspect of the simulation because temperature can greatly change the properties of the material causing a large amount of extra deformation due to the external applied forces.

In order to select the best viscoplastic model to use, further research was done on the subject. The topic of viscoplasticity began in 1960 when Richard von Mises started to develop boundary-layer-flow theory. This theory was eventually turned into the von Mises criterion which most viscoplastic material models stem from. There are many different models that have been developed and updated since the 60's. One model is the Armstrong and Frederick model which was first developed in 1966. The model has been updated numerous times with the current known as the linearization approach for implementing nonisothermal rate-dependent, nonlinear kinematic hardening model [1].

Another useful viscoplastic material model is the Chaboche model. The Chaboche model is similar to the previously described Armstrong and Frederick model. Bari and Hassan studied several kinematic hardening models for ratcheting prediction on steels. They compared available models and showed that the Armstrong and Frederick model cannot predict ratcheting whereas the Chaboche model has reasonable answers for ratcheting in the case of uniaxial loading which is the case in this project. For this reason, the Chaboche model was selected as the material model used in our structural simulations [21].

ANSYS can import any user defined material model; ANSYS provides an example Fortran file which can be modified to include the equations that define any material model. The material properties must also be included in the user defined model including the parameters required specifically for the Chaboche model. After modifying the Fortran file, an Intel Fortran Compiler is used to convert the file into a custom ANSYS compatible file which is then called on from the ANSYS workbench. There are a couple of issues with using the custom material model method in respect to this project. The first is that in order to use the Intel Fortran Compiler, it must be run with admin privileges seeing as it can risk corrupting the system files of the computer that it is being run on. WPI would not allow using this method on their computers. Secondly, this method is slightly outdated and possibly would not work in the current version of ANSYS installed on the computers. For these reasons, it was decided to use the version of the Chaboche model pre-installed on ANSYS.

The material we used for the frame is an aerospace grade aluminum called AL7075-T6. Many material properties are required for running the Chaboche model. The basic material properties for the chosen AL7075-T6 can be seen in table 5. Many Chaboche model parameters are determined for a material through experimentation. The parameters used in this project were obtained from a scientific article that found the parameters for the AL7075-T6. These parameters can be seen in table 6 [21].

Table 5: AL7075-T6 Material Properties

	Density	2.81	g cm^-3
⊟	Isotropic Elasticity		
	Derive from	Young's Mo...	
	Young's Modulus	7.17E+07	Pa
	Poisson's Ratio	0.33	
	Bulk Modulus	7.0294E+07	Pa
	Shear Modulus	2.6955E+07	Pa
⊞	Chaboche Kinematic Hardening	Tabular	
	Tensile Yield Strength	503	MPa
	Tensile Ultimate Strength	572	MPa

Table 6: AL7075-T6 Chaboche Parameters

Temperature (C)	Yield Stress (MPa)	Material Constant C1 (MPa)	Material Constant γ1
20	503	5324	31.06
100	448	6226	73.9
400	30	1768	28.68

3.3 Structural Load

For the integrated load environment, the test can be executed with any loading test equipment. NanoRacks requires that NeAtO can withstand 1200 Newtons in the positive z-axis direction (the direction NeAtO is travelling). For this project, the loading test was conducted in the engineering simulation program ANSYS. First, a defeatured solid model of NeAtO was imported into ANSYS. Then, the material properties of AL 7075-T6 described in section 3.2 was assigned to NeAtO. The temperature distribution over NeAtO was imported into ANSYS from a .csv file provided from the thermal analysis conducted in COMSOL described in section 4. This temperature distribution was then used to generate a mesh over the surface of NeAtO. The temperature distribution is shown in figure 33. Note that the axes in the ANSYS simulations are at a different orientation than in the SolidWorks models. This was accounted for when choosing the direction of loads.

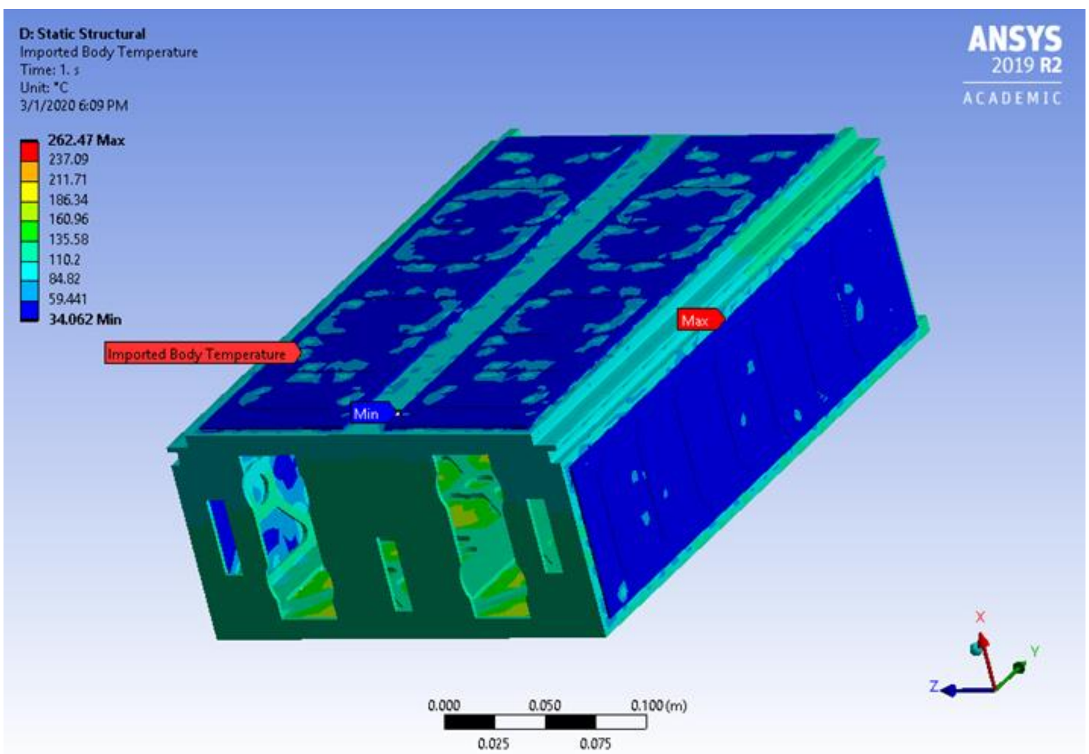


Figure 33: Temperature Distribution

A fixed support was then attached to the top surface of NeAtO to hold it in place during loading. The 1200 Newton force was then applied to the thruster (Y) face. The previous version of this project did not incorporate temperature into the structural analysis, so it is important to see how much temperature affects the result. The results of this simulation are shown in section 3.5.

3.4 Random Vibration

Vibration tests are conducted on a vibration shock table. Vibration shock tables can simulate both soft-stow and hard-mount configurations. ANSYS simulates the soft-stow configuration by running the vibration test with an elastic support attached to the thruster end (-Z face) surface of NeAtO. The hard-mount configuration is simulated by attaching a fixed support to the thruster end surface of NeAtO. For both the soft-stow and hard-mount flight configuration, NeAtO must withstand the random vibration environment provided by NanoRacks.

In order to perform a random vibration simulation, a modal simulation must first be conducted. The modal analysis requires nothing more than basic material properties and mesh. The analysis was conducted for all modes up to the NanoRacks required frequency of 2000 Hz in both soft-stow and hard-mount configurations.

The result of the modal analysis is used in the setup of the random vibration analysis to define the way the structure deforms in each mode. The analysis then requires an excitation through Acceleration Spectral Density (ASD). NanoRacks provides the required excitation data for both the soft-stow and hard-mount tests at various frequencies shown in table 7 [23].

Table 7: Vibration Test Profiles [23]

Soft-Stow Test Profile	
Frequency (Hz)	ASD (g^2/Hz)
20	4.000E-02
25	4.000E-02
31.5	4.000E-02
40	4.000E-02
50	4.000E-02
63	4.490E-02
80	5.062E-02
100	5.660E-02
125	6.200E-02
160	6.200E-02
200	6.200E-02
250	5.558E-02
315	4.102E-02
400	2.998E-02
500	2.236E-02
630	1.651E-02
800	1.206E-02
1000	9.000E-03
1250	6.034E-03
1600	3.878E-03
2000	2.600E-03
grms	**5.76**
Duration (sec)	**60**

Hard-Mount Test Profile	
Frequency (Hz)	ASD (g^2/Hz)
20	5.700E-02
153	5.700E-02
190	9.900E-02
250	9.900E-02
750	5.500E-02
2000	1.800E-02
grms	**9.47**
Duration (sec)	**60**

Unlike the structural load test, temperature has very little effect on random vibration so the temperature distribution from the thermal analysis was omitted from the analysis. The results of this simulation are shown in section 3.5.

3.5 Results

3.5.1 ANSYS and COMSOL Results

A defeatured version of NeAtO was used in ANSYS to produce structural analysis results. Each simulation has a result showing the directional deformation and the equivalent stress distributions. The NanoRacks requirement for both the random vibration and structural load is to ensure that NeAtO can withstand the load environment. Figure 34 shows the equivalent stress on the soft-stow configuration. The maximum stress was 249.8 Pascals occurring in the corners of the open end of NeAtO.

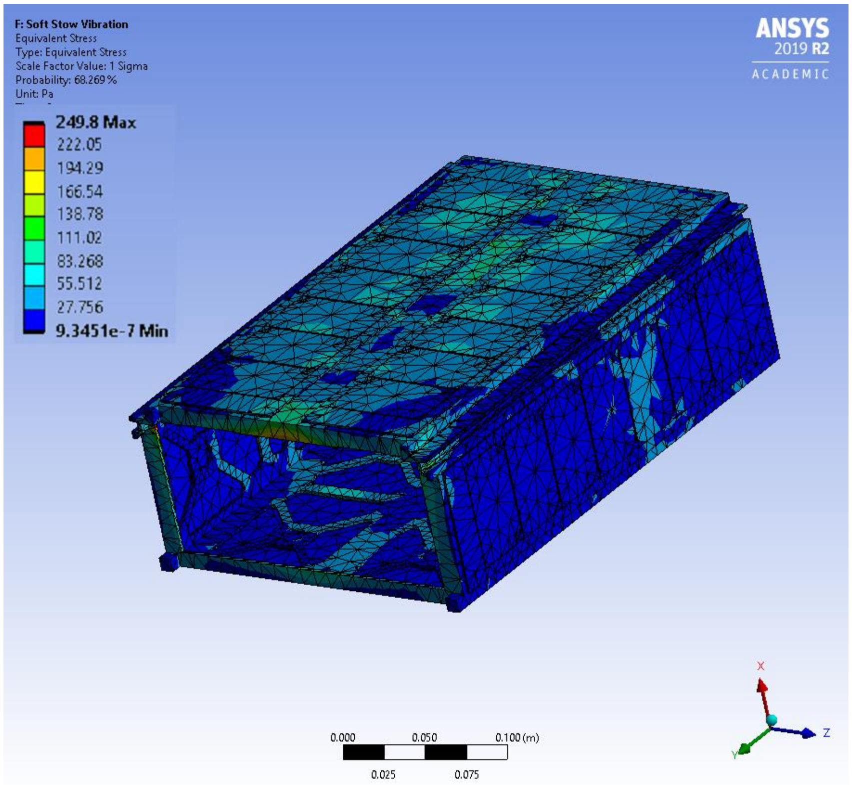


Figure 34: Soft-Stow Equivalent Stress

Figure 35 shows the directional deformation of the soft-stow configuration. The maximum deformation was 1.765e-6 meters occurring on the large face of NeAtO.

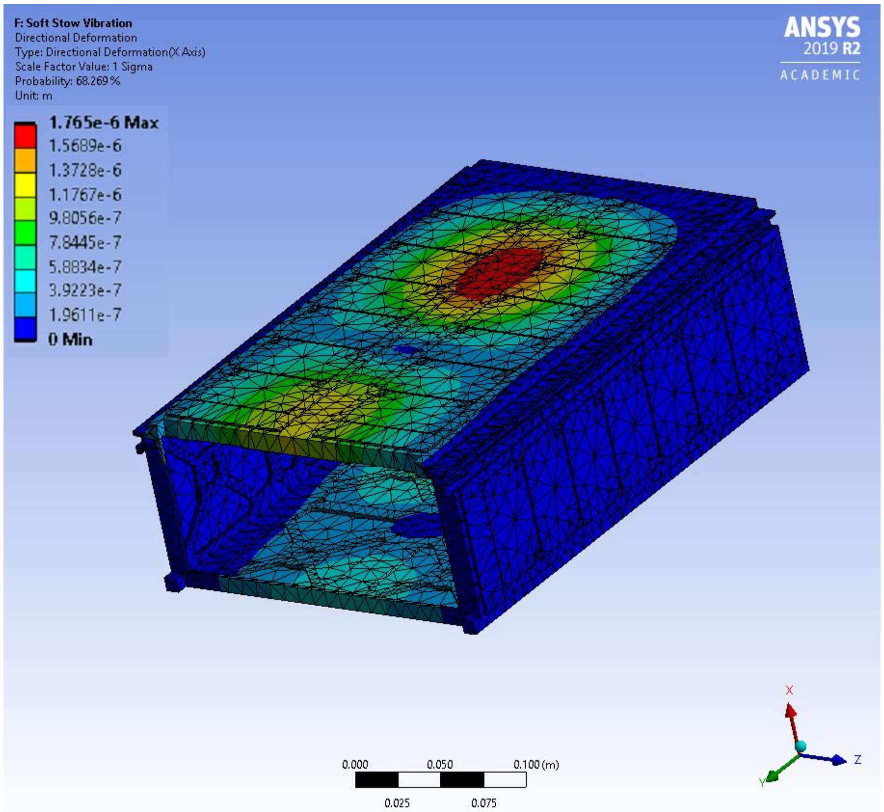


Figure 35: Soft-Stow Deformation

Figure 36 shows the equivalent stress of the hard-mount configuration. The maximum stress was 298.07 Pascals occurring along the inside lip of the open end of NeAtO.

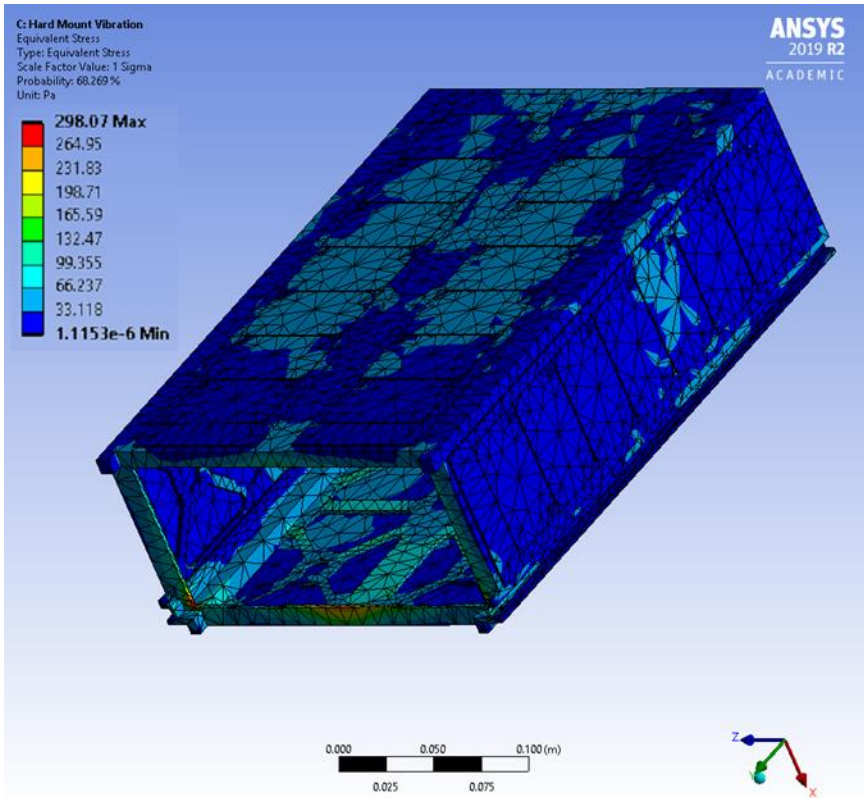


Figure 36: Hard-Mount Equivalent Stress

Figure 37 shows the directional deformation of the soft-stow configuration. The maximum deformation was 2.1046e-6 meters occurring on the large face of NeAtO.

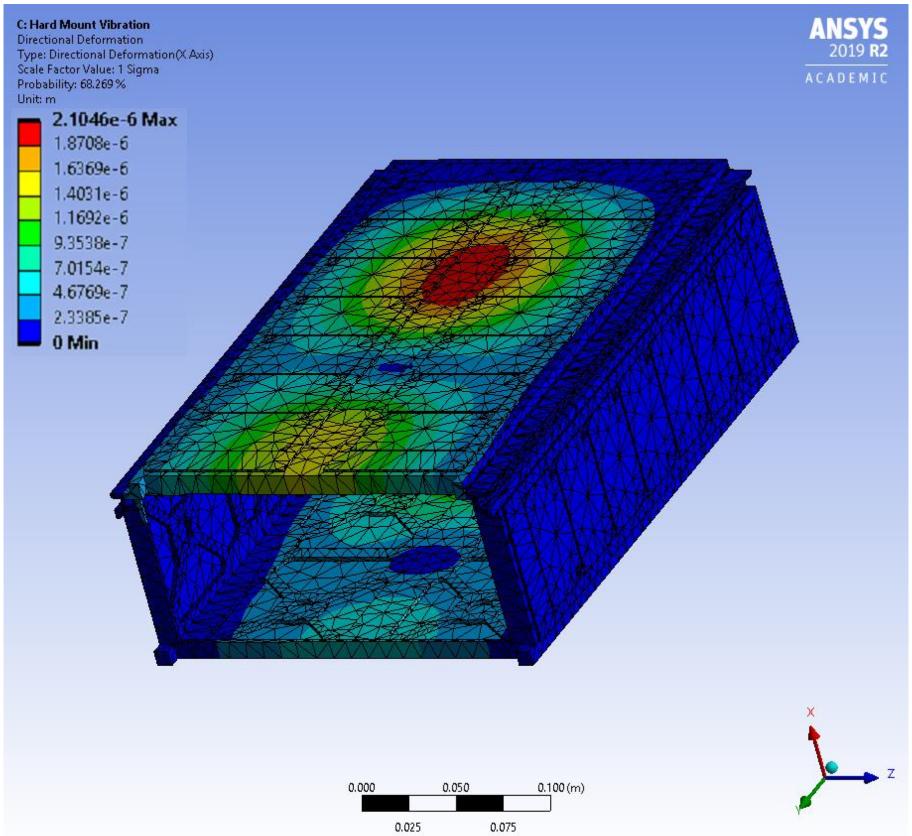


Figure 37: Hard-Mount Deformation

Overall, the level of stress and amount of deformation applied to NeAtO due to the random vibration environment is minimal. Therefore, NeAtO falls well within the NanoRacks requirement of withstanding the random vibration environment for both configurations tested.

The thermal simulation was not able to get an accurate reading for the individual points in the orbit because it was not possible to run a thermal test in one place of the orbit for a long enough time to get an accurate amount of thermal gain. Therefore, the structural analysis was only run on the average temperature distribution over a 24-hour orbital period.

Figure 38 shows the equivalent stress of the structural load environment. The maximum stress was 4.2498e7 Pascals occurring in the middle of the surface at which the load was applied.

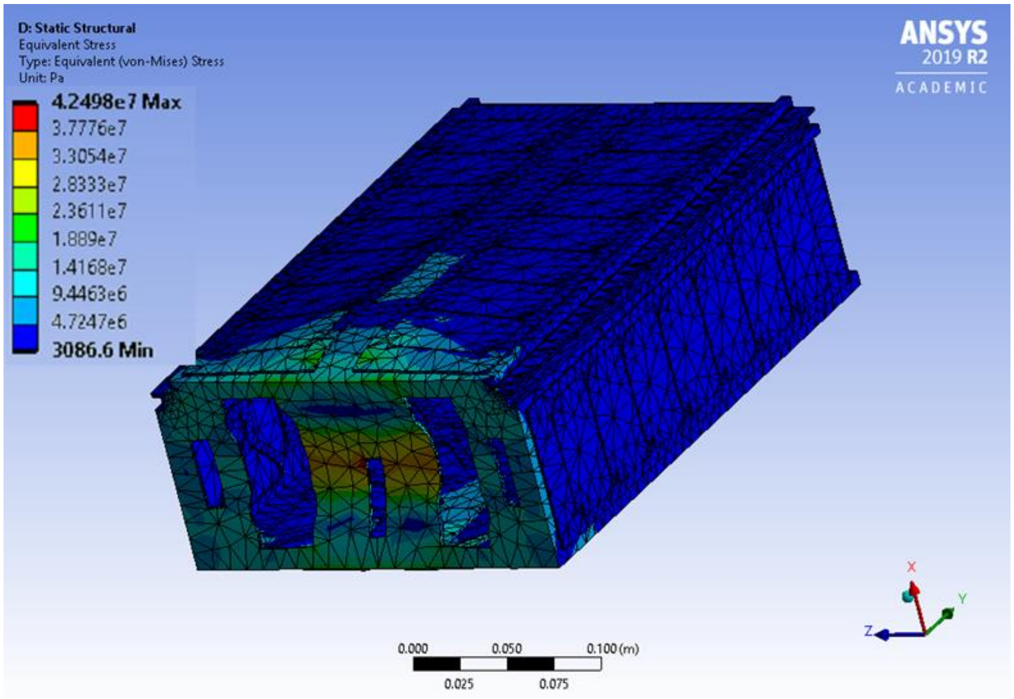


Figure 38: Structural Load Equivalent Stress

Figure 39 shows the directional deformation of the structural load environment. The maximum deformation was about 3.5 centimeters occurs in the middle of the surface at which the load was applied.

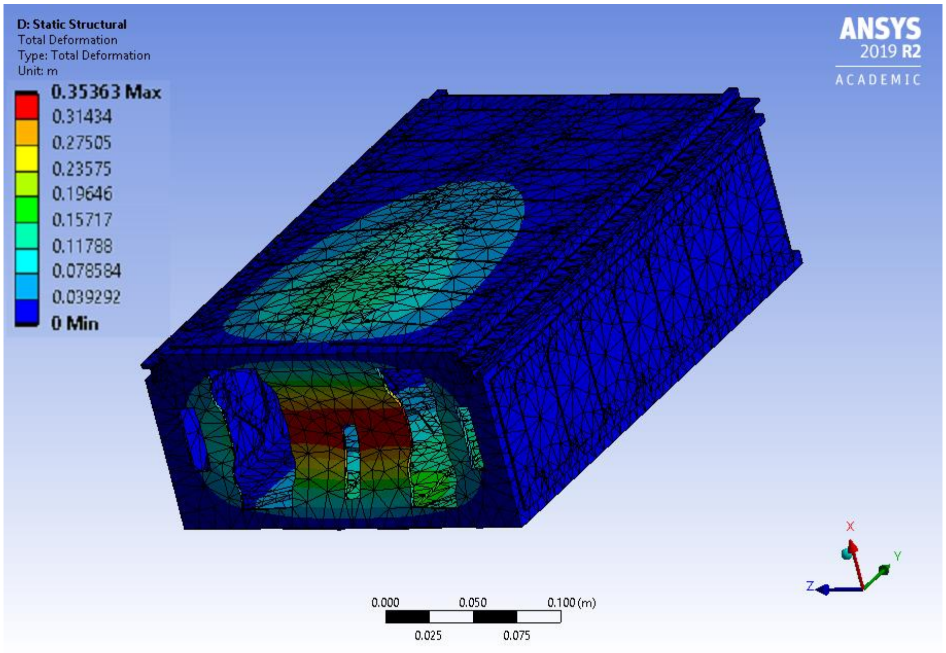


Figure 39: Structural Load Deformation

Overall, the level of stress and amount of deformation applied to NeAtO due to the structural load environment was a substantial amount. NeAtO is tightly packed with components so a deformation of 3.5 centimeters could have a substantial impact on the components inside. However, this simulation does not account for the reactive force from internal components of NeAtO as the simulation is only conducted on the frame. With the engines mounted around the Y face center plate, the deformation would likely be greatly reduced. Although there was a substantial effect due to the load environment, NeAtO was still able to withstand it therefore completing the NanoRacks requirement.

3.5.2 ORDEM Results

The Orbital Debris Engineering Model (ORDEM) software was investigated for the purpose of evaluating structural integrity. ORDEM is a software made by NASA that can model the debris a satellite will encounter as it orbits the earth. There are two methods of inputting data to calculate the fluxes the spacecraft will experience in a specific year. The first is to input the perigee, apogee and inclination of the orbit the spacecraft will be in. The second would be to input a Two-Line Element (TLE), which outlines various spacecraft and orbit data. The components of a TLE can be found in Appendix C. Although a TLE would have given a better description of the orbit, the first method was used due to limiting time remaining on the project. Once the simulation is run, ORDEM can output 4 different types of graph to show what debris the spacecraft will encounter. The first shows the flux of debris per year vs the size of the debris as seen in figure 40.

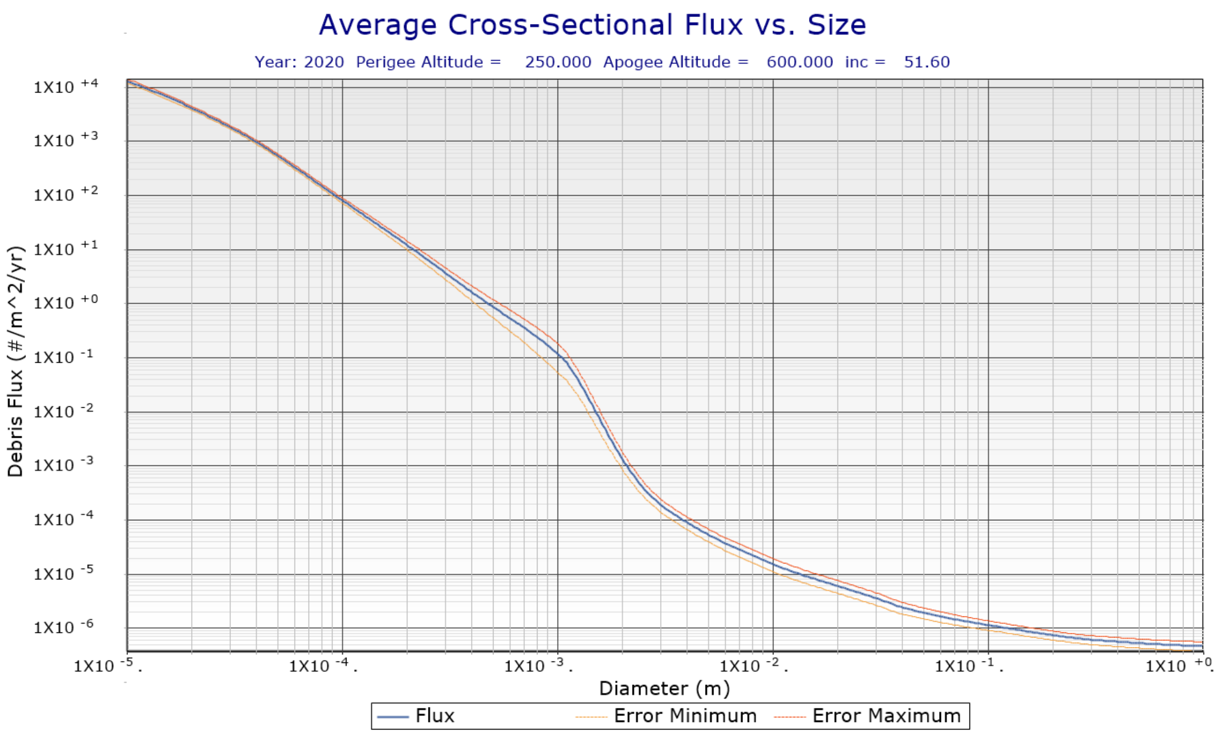


Figure 40: Debris flux vs Diameter

The remaining three graphs must be generated for a certain size of debris. There are options to generate the plot between >= 10 micrometers to >= 1 meter. The next graph is a flux vs local azimuth graph. This shows the flux in a given direction relative to the spacecraft ram direction and can be shown in either a butterfly or a skyline. For the purpose of this project a >=10 micrometer size was used as primarily, only small particles are encountered. Figure 41 below shows that most of the debris impact the CubeSat would experience are at 2 planes ±20 degrees from the ram direction respectively:

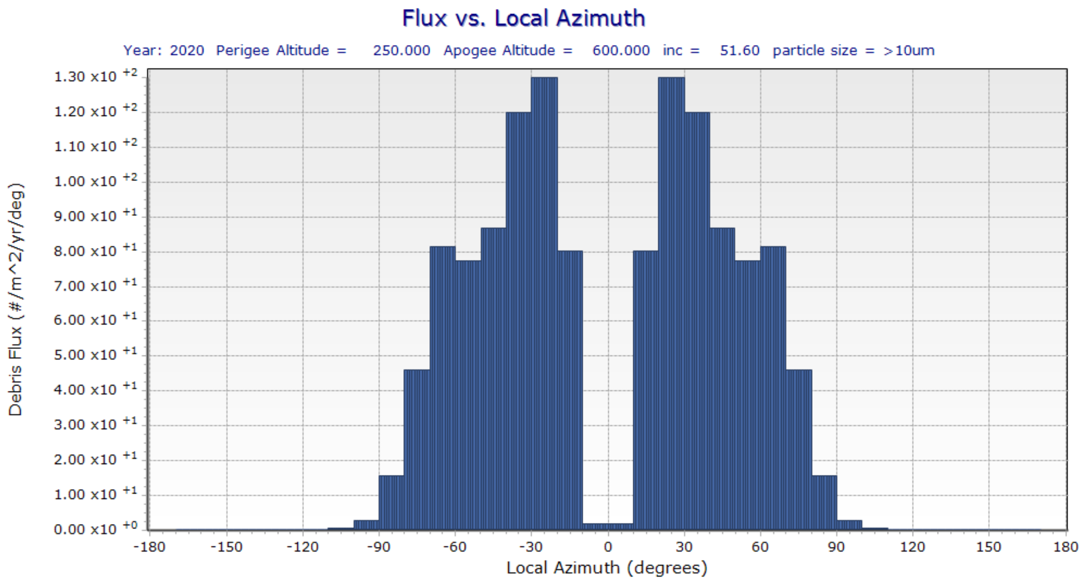


Figure 41a: Direction of flux skyline

The next graph, shown in figure 41, also shows directional flux but includes local inclination as well as azimuth angle. The zero azimuth is still in the ram direction and elevation runs from -90 degrees at the bottom of the spacecraft to 90 degrees at the top. This plot also uses a >=10 micrometer diameter for debris. It also shows that there is a higher flux of particles around 20 degrees off the front plane, however it also displays that as the elevation angle deviates from the front plane, the amount of flux decreases. The last graph that can be generated, shown in figure 42, is the velocity distribution of the debris. For our CubeSat a large portion of the >=10 micrometer debris have a velocity of 13 km/s. This could be used to calculate the energy the debris are impacting the CubeSat with and help determine the amount of damage caused by the debris. Unfortunately, there was not enough time to do any calculations with the data gathered with the ORDEM software due to time limitations.

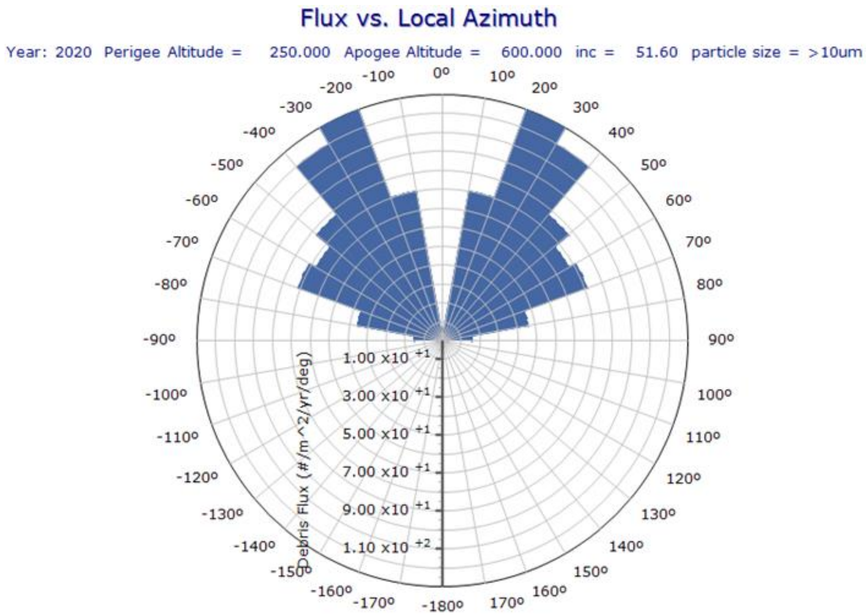


Figure 41b: Direction of flux butterfly

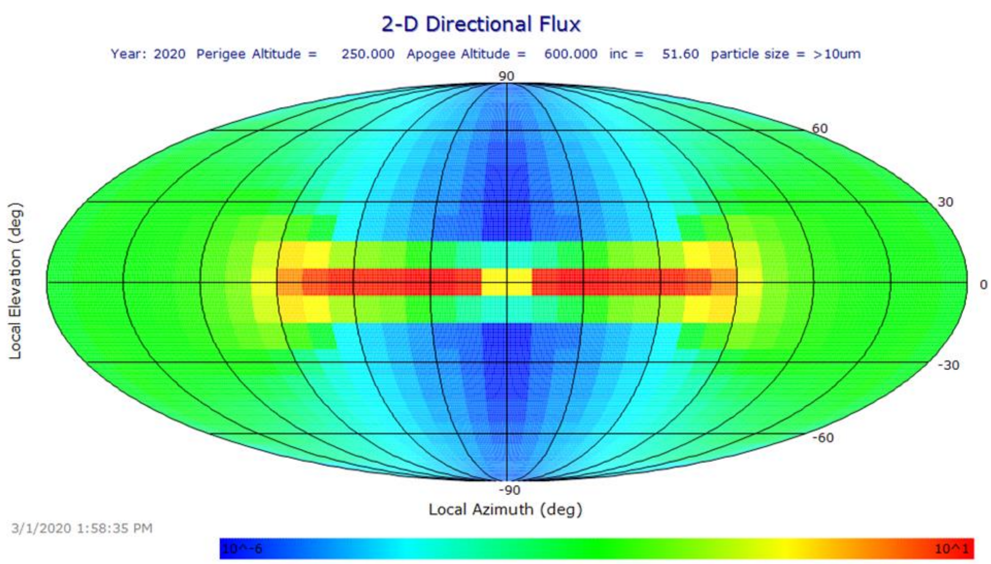


Figure 42: Direction of flux with elevation angle

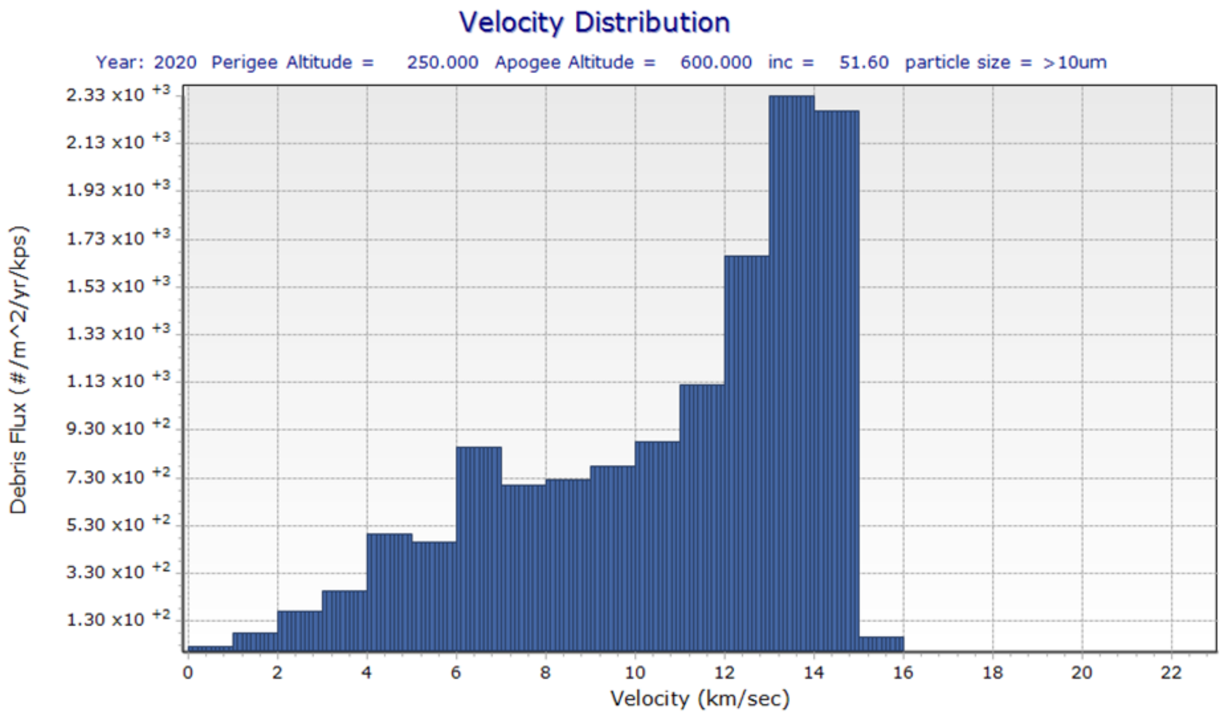


Figure 43: Velocity distribution of debris

Since the process for obtaining the ORDEM software is now known, future groups of students may be able to access it and use the data to calculate the amount of degradation their CubeSats will receive due to various debris on their orbit.

4. Thermal

The thermal environment of space contains a number of challenges that NeAtO will encounter as it progresses through its orbit. The spacecraft will be exposed to large temperature fluctuations, as a result of sun exposure as it moves in and out of eclipse. The three major sources of heat within the environment of space are solar radiation, blackbody radiation, and albedo flux. The thermal loads experienced by NeAtO are governed mainly by solar radiation. Through these sources of radiation, it is important to determine the heat and radiative flux that each face of the CubeSat structure would experience in order to gain an understanding of the overall spacecraft temperature.

Thermal effects are also attributed to the nature of the elliptical orbit. NeAtO will experience a certain level of atmospheric drag, since its entire mission is based in extreme low earth orbit (eLEO). At a perigee altitude of 200 km, where the spacecraft will be at its closest point in its orbit to Earth, the atmospheric drag will make its highest contribution to the overall thermal loading.

Additionally, the combined dissipation of heat from internal components contribute to the thermal stability of NeAtO. It is important to take this into account in order to simulate the overall internal temperature and ensure that all components remain within their specified operating temperatures. Otherwise, there would be a risk of overheating, and possible component malfunctions. Therefore, the operating temperatures for all the components were found and recorded. Ideally, the total efficiency of the component would be used in order to determine heat dissipation of each component, however, most of the component data sheets accessible did not provide efficiency values. Therefore, a very generalized assumption was made that every component had a 90 percent efficiency rating [13]. Using this assumption and the maximum power output for each component, a rough estimate of the total heat dissipation was calculated. This calculation of course, was not completely accurate, but was reasonable enough in order to get an estimation for further thermal simulation. Through collaboration with the power sub-team, the maximum power production was found to be 17 W, but there also would need to be a clearance of

3 W to account for overconsumption of power. Therefore, the total dissipation was calculated to be 14 W.

4.1 Approach

The thermal analysis of NeAtO underwent several phases throughout the duration of the project. The first of these was a base analysis of the 4U CubeSat to learn the basics of the necessary software. Using the initial 250 km to 600 km orbit and material properties from the 4U used in previous MQP projects, the STK and COMSOL simulations were designed and tested to ensure that they functioned. The next iteration was completed for the same orbit, but with updated material properties; namely, a new grade of aluminum (AL 7075-T6) for the satellite frame. When the design decision was made to change from a 4U to a 6U, the 6U model was then imported into the simulations and run for the new geometry and meshing requirements. Finally, when the final orbit was optimized to a 200 km to 440 km elliptical orbit, the simulations were adjusted to the final orbital parameters and ran again for the 6U model.

4.2 Thermal Characteristics from the Orbit

A simulation was first designed using Systems Tool Kit (STK) software to determine the following thermal characteristics: solar intensity and fixed sun vector coordinates. The simulation used the desired elliptical orbit and several other known parameters to determine these values at any defined time step in the orbit. These thermal characteristics were used as input parameters within a COMSOL simulation in order to generate a thermal model that would be dependent on the location and orientation of NeAtO along the orbit relative to the position of the sun. Thus, the thermal model would be able to simulate heat flux through every face.

In order to determine these values, the 250 km perigee and 600 km apogee altitudes of NeAtO's desired elliptical orbit were input into an initial STK simulation to generate the full orbit in the simulation. The inclination angle was set to the desired 51.6 degrees. Next, the full 4U CAD model was imported into STK and set as the satellite model. To set NeAtO to its desired orientation, the attitude type was set to "Nadir alignment with ECI velocity constraint". This allows for the CubeSat to always have its x-axis (1U front plate face) aligned in the direction of the velocity vector along the orbit, while also constraining the z-axis (a single 4U face) to the geocentric nadir direction.

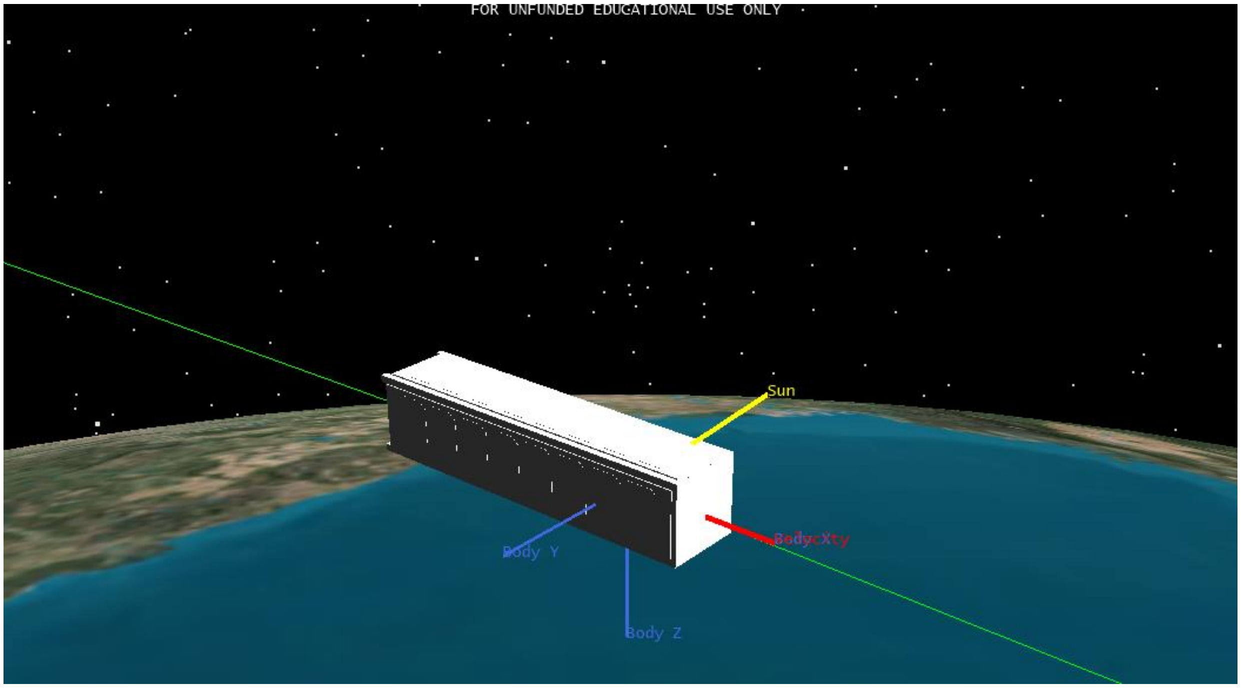


Figure 44: 4U CubeSat STK Simulation in Elliptical Orbit

The thermal characteristics found from the STK simulation were then imported into a MATLAB script (Appendix D) written and used in a previous iteration of the project done by graduate student Harrison Hertlein. The script takes the STK data and converts the files into readable csv files that could then be used in COMSOL [8].

Once the 4U thermal data was collected and converted, this process was repeated for the 6U model. In this second STK simulation, the 6U model was imported in and placed into the orbit, with the same attitude and orientation. The orbit, however, was adjusted due to various orbital design changes made by the orbital analysis team. The perigee altitude of the 6U orbit was set to 200 km, and the apogee altitude was set to 440 km. With the updated orbit, solar intensity and sun vector coordinate data points were found for NeAtO for a period of 24 hours.

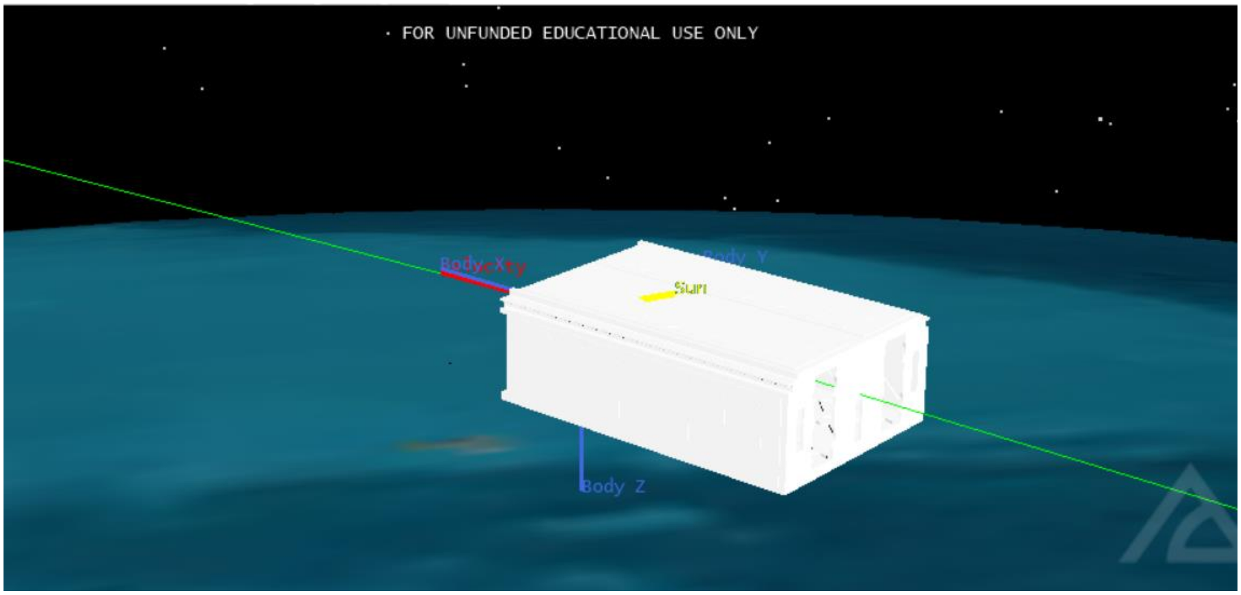


Figure 45: 6U CubeSat STK Simulation in Elliptical Orbit

In order to achieve reasonable computation times and reduce complexity, a de-featured CAD model was utilized in the thermal analysis simulations. Since initial base-simulations were completed with a 4U CubeSat design, several de-featured models were tested. In the de-featured SolidWorks model designed in the previous MQP, the components included were the Aluminum 4U base skeleton structure, the Aluminum front plate and thruster plate, and simplified assemblies for the four solar panels modeled as carbon fiber. For the updated simulations in this project, the model was further de-featured so that the solar panels were only modeled as thin, flat plates with no additional components. This helped reduce a lot of the complexity associated with the meshing of the model in COMSOL.

4.3 Heat Transfer Analysis Using COMSOL

The first step in designing the COMSOL simulation was defining a set of simulation parameters. These parameters were used throughout the simulation to complete the desired heat flux and temperature calculations. A table of these parameters is presented below:

Table 8: Initial COMSOL Parameter Definitions

Parameter	Value	Description
S	1367	Solar Flux [W/m^2]
Tspace	2.7	Temp. of deep space [K]
B	193	Earth IR Flux
A	0.35	Albedo constant
R	5539.775	Period [s]
F	0.9	View Factor
k	1	Constant used in materials

Next, the STK thermal data was imported into COMSOL as interpolation functions so that temperature data points could be computed at the designated time step. In total, seven interpolation functions were defined within the simulation: the solar intensity readings, as well as the computed positive and negative x, y, and z coordinates of the sun vector relative to the position and orientation of NeAtO.

NeAtO's SolidWorks model was then transferred into the COMSOL simulation using the import function in order to define the geometry and generate a mesh for the analysis. Initially, this was done by converting the SolidWorks file into an STL file. However, meshing proved to be a significant issue within the COMSOL interface. After numerous attempted iterations it was determined that this conversion simplified and altered the meshing of the geometry to the point where faces within the model were no longer aligned or connected. This resulted in many meshing errors. Therefore, the SolidWorks file was instead converted to a STEP file, which eliminated all previous meshing errors. The element size of the mesh selected for this analysis was the predefined “Coarser” size.

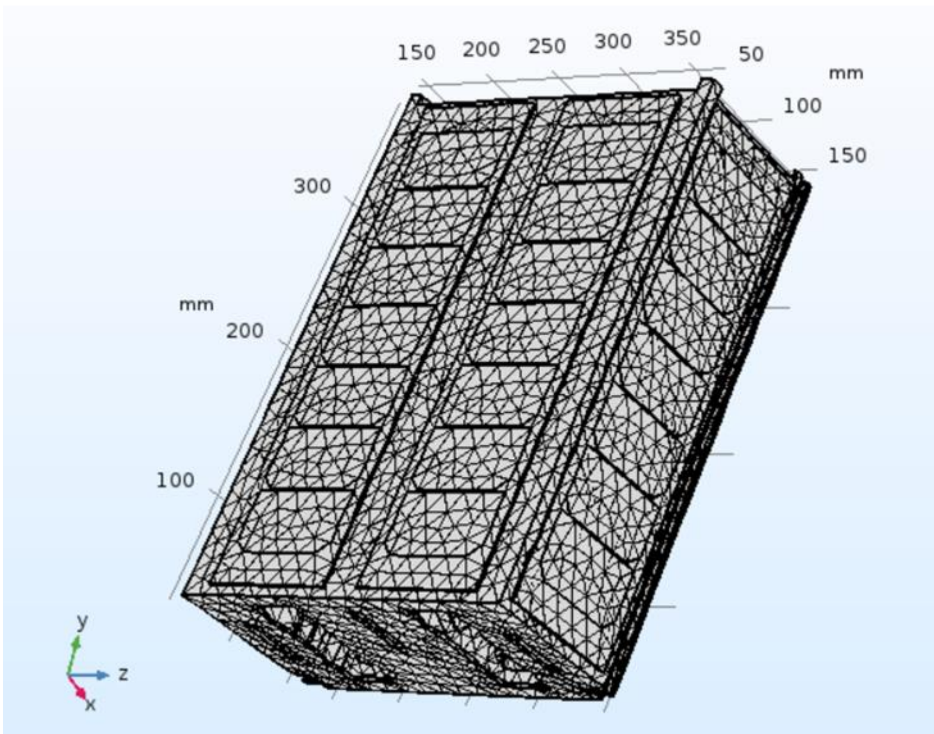


Figure 46a: Final mesh for Heat Transfer Analysis

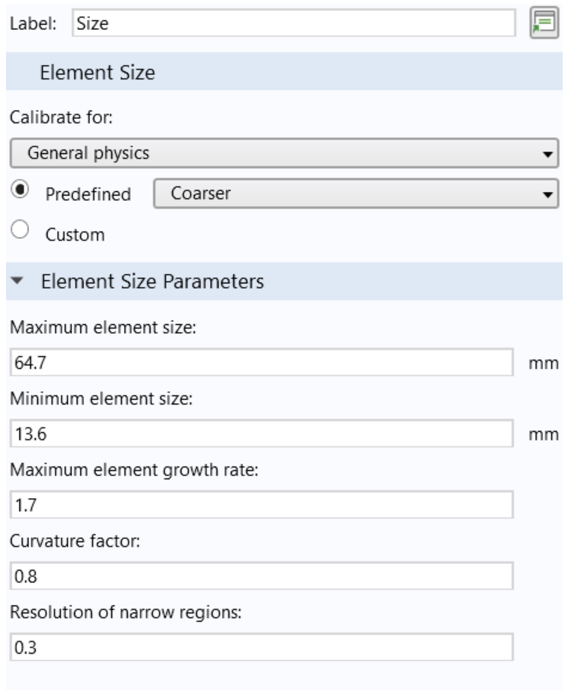
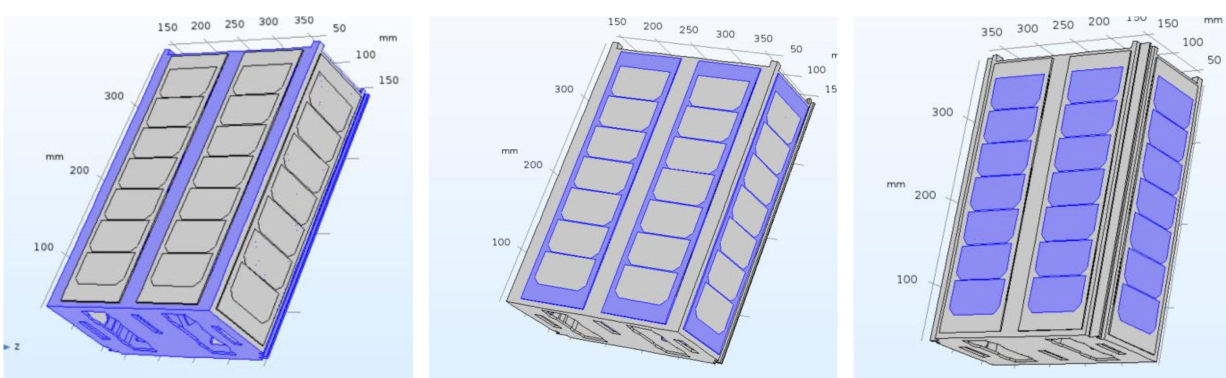


Figure 46b: Final Mesh Element Size Parameters



(a) (b) (c)

Figure 47: Boundary Definitions

Boundary conditions were then created and defined for the satellite geometry. The three boundaries defined were the aluminum boundary which included all faces of the frame, and the solar panel boundaries which included a boundary for the solar panel mount and a boundary for the solar cells. Figure 47 depicts the definitions of the boundaries in the COMSOL interface. The image in (a) shows the faces selected for the entire frame, (b) shows the faces selected for the solar panel mount, and (c) shows the faces selected for the solar cells. The definition of the boundary layers allowed for association of material properties and further identification of faces within the heat transfer module.

Three materials were defined for the model. The frame was modeled as Aluminum 7075-T6. The solar panel assembly included the solar cell mount modeled as carbon fiber/epoxy, and solar cells modeled as silicon. The properties defined for each material were the heat capacity at constant pressure, density, thermal conductivity, and surface emissivity. Table 9 displays all of these values identified.

Table 9: Material Properties of De-featured CubeSat Model

Material	**Heat Capacity at Constant Pressure, C_p [J/(kg*K)]**	**Density, ρ [kg/m^3]**	**Thermal Conductivity, k_{iso} [W/(m*K)]**	**Surface Emissivity, ε**
Aluminum 7075-T6	960	2810	130	0.22
Carbon fiber / epoxy	1130	1700	162.5	0.9
Silicon	678	2320	148	0.83

In order to determine the full temperature profile, the physics module "Heat Transfer with Surface-to-Surface Radiation" was implemented. This module takes into account the radiation flux between surfaces defined in the model, and uses both the solar intensity and sun vector coordinate to determine external heat flux for a set of particular boundaries. This is shown in the following equation,

$$Q_0 = S \cdot SI(t) \cdot SV(t)$$

where Q_0 is the inward heat flux of a selected face, S is the solar flux, SI(t) is the solar intensity as a function of time (imported from STK), and SV(t) is the sun vector fixed component for the selected CubeSat face as a function of time [3]. To fully define the heat flux of NeAtO, six individual heat flux definitions were added to the module- a module for each of the positive and negative x, y, and z faces of the model. For each definition, the sun vector data point was selected for the corresponding satellite face orientation. In addition, all of the selected boundary faces were defined for each of the corresponding orientations. An example of this can be seen below:

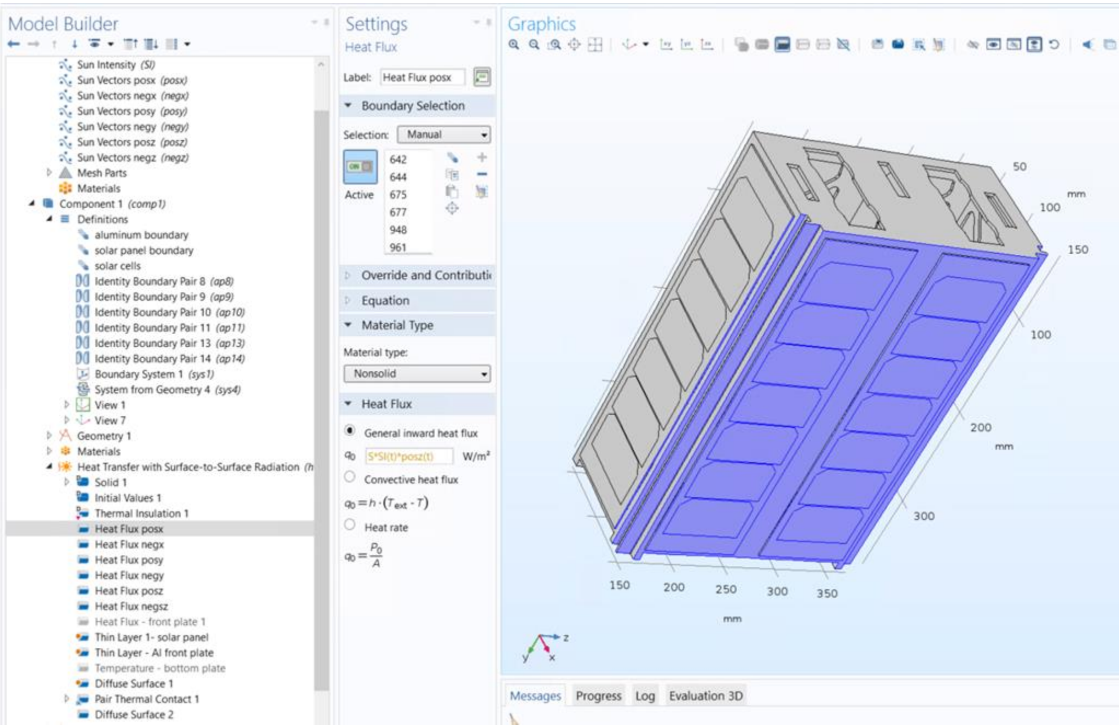


Figure 48: Heat Flux Definition for Positive X-Face

The Heat Transfer with Surface-to-Surface Radiation module also requires the calculation of the irradiation, noted as "G", of the model, which is the total incoming radiative flux that NeAtO will experience. The irradiation at a given point is the sum of several radiative flux contributions. The first is the irradiation transmitted from other boundaries, G_m. This is determined through the following equation, which considers the normal vectors of the particular point, the distance between the point and the point source of the heat flux, and the local radiosity:

$$G_m = \int_{S'}^{S} \left(\frac{(-n' \cdot r)(n \cdot r)}{\pi |r|^4} J' \right) ds$$

The second contribution is the irradiation from external sources, G_{ext} [3]. For the analysis of NeAtO, the external source considered was solar radiation. Therefore, G_{ext} accounts for the external heat flux Q_0, as well as the view factor F:

$$G\_ext = \sum (F \cdot Q_0)$$

The last contribution that makes up G is the ambient irradiation, G_{amb}. Through the following equation, it can be seen that G_{amb} takes into account the view factor F, the ambient temperature, and the radiated power e_b:

$$G_{amb} = F \cdot e_b \cdot T_{amb}$$

where e_b is calculated based on the Stefan-Boltzmann law:

$$e_b(T) = n^2 \cdot \sigma \cdot T^4$$

Furthermore, the heat transfer analysis involved computation of the CubeSat radiosity J, which is the total radiation both reflected and emitted by the model surfaces. Radiosity is calculated within the heat transfer module as follows:

$$J = (\rho \cdot G) + (\varepsilon \cdot e_b(T))$$

where ρ is the material density and ε is the material emissivity. Ultimately, the total inward heat flux at a specific point in the model is calculated as the difference between G and J. The heat transfer module in COMSOL utilizes all these relations based on user-input values in order to solve for temperature T at the specified point [3, 14].

Therefore, to completely define the heat transfer module, the solar panel and RAM-facing side were defined as thin layer surfaces, and the ambient temperature was set to “Tspace”, or the temperature of deep space. Once all parameters of the heat transfer module were defined, a corresponding study of the heat transfer was set for an 86400 second (24-hour) simulation period, with a 3600 second (1-hour) long-time step-in order to maintain reasonable computation times.

4.4 Results

4.4.1 STK Thermal Characteristics

The STK simulation was run for a constant 440 km apogee altitude / 200 km perigee altitude orbit, through which two reports were generated: one containing the solar intensity data and the other containing the sun vector fixed component data. The solar intensity report (Appendix E) included the time step and a corresponding percentage value of the solar intensity, either 0 or 100. The sun vector report included the time step and the corresponding x, y, and z component of the sun vector (Appendix E). Together, the reports were imported into COMSOL for the base final thermal profile.

4.4.2 COMSOL Temperature Profile

With the STK thermal data input into the COMSOL simulation, the heat transfer study was run for the 86400 second simulation period, with a time step of 3600 seconds. The orbit used in this analysis was 200 km/440 km with a true anomaly of 0, which originated at the perigee. The simulation was first run with a defeatured model that included a front plate on the RAM-face. The purpose of the plate was to simplify the surfaces of the payload, cart, and other components exposed to the space environment. The resulting temperature profile is displayed in Figure 49 below:

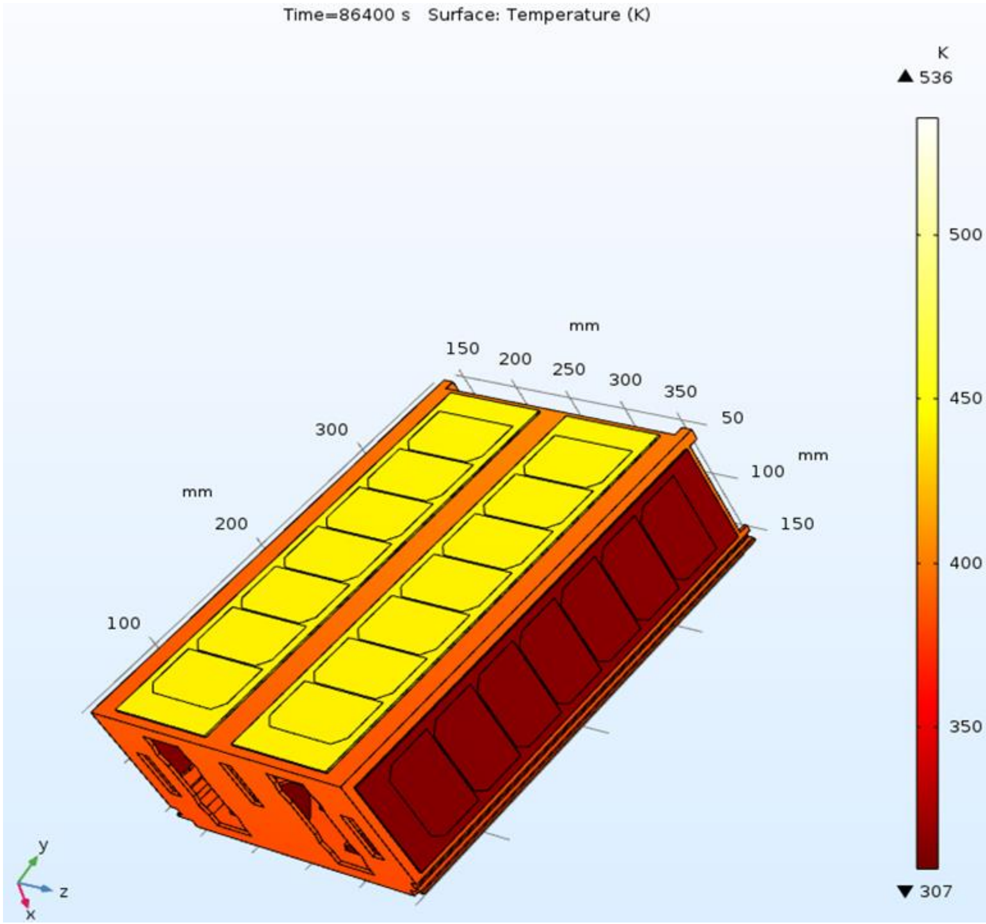


Figure 49a: NeAtO Temperature Profile Modelled with a Front Plate (View 1)

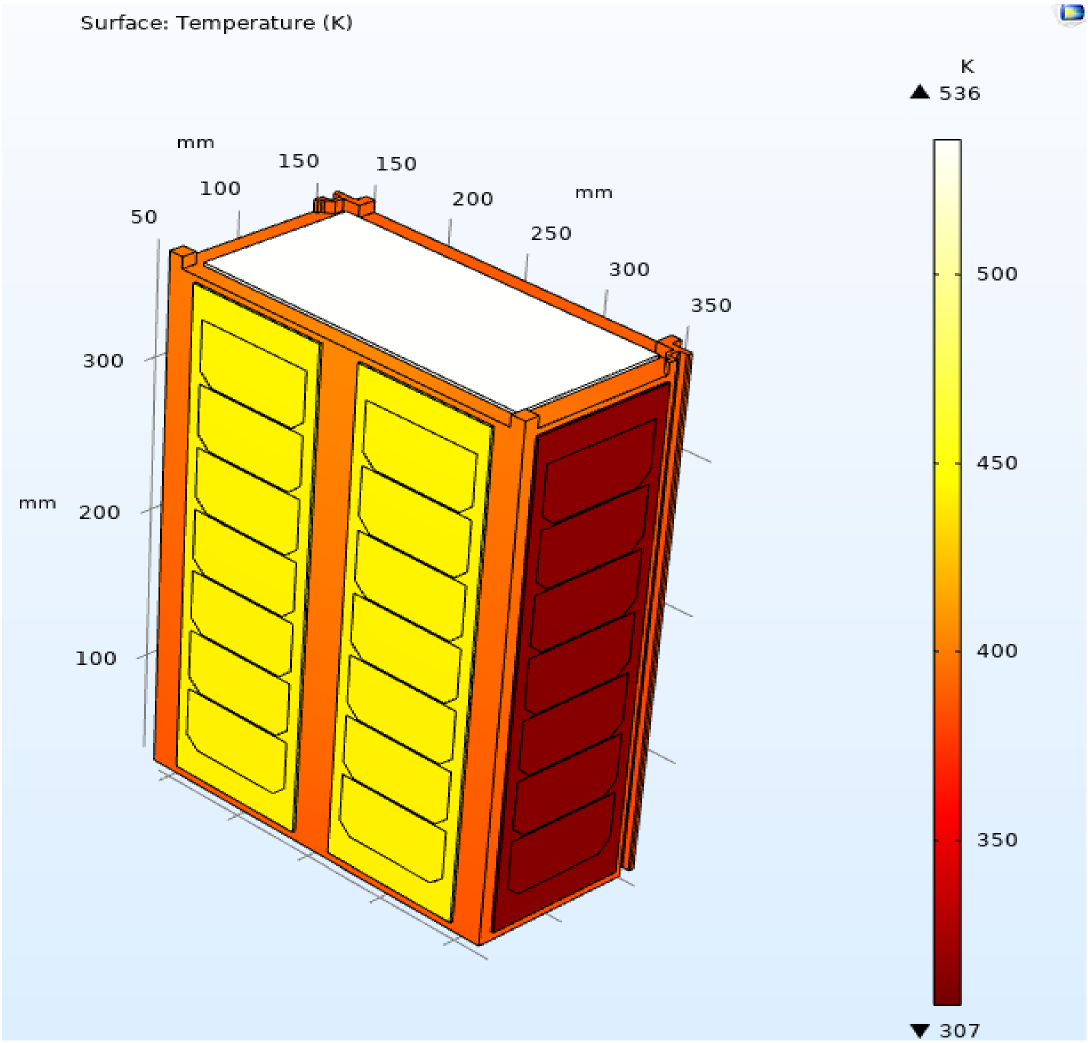


Figure 49b: NeAtO Temperature Profile Modelled with a Front Plate (View 2)

The next iteration of the temperature profile used a defeatured model with no front plate, so that the only components considered were the frame and the simplified solar panel assemblies. Therefore, the RAM-face was modelled as an open side. The new resulting temperature profile of NeAtO at the 86400-second time stamp is displayed in Figure 50 below:

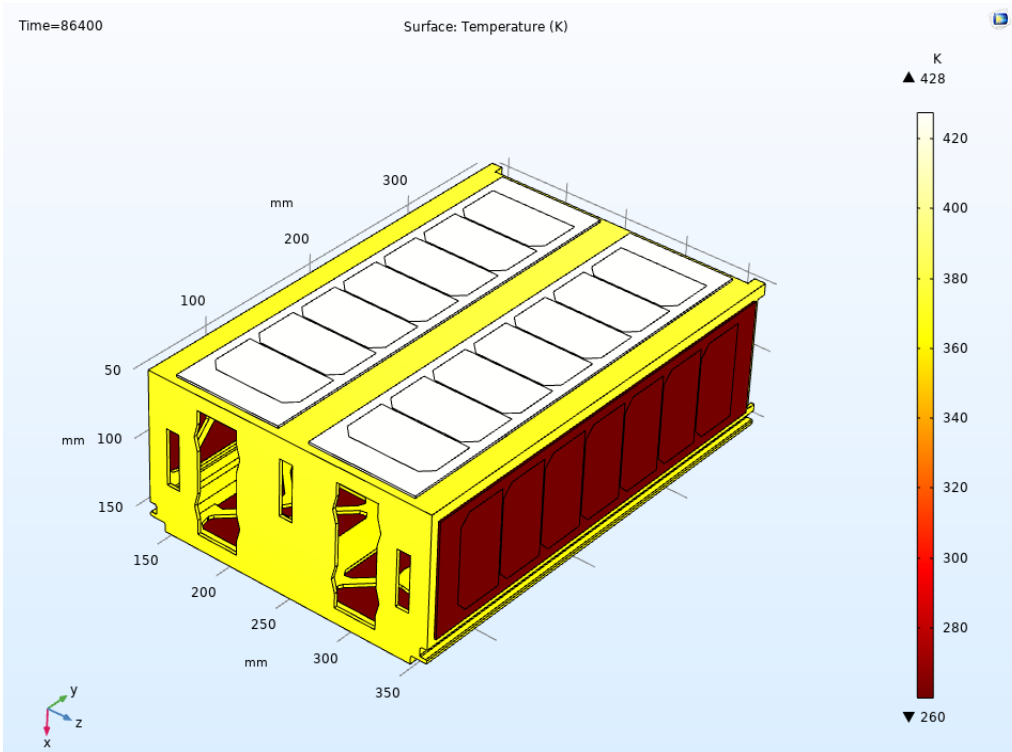


Figure 50a: NeAtO Temperature Profile after 24 Hours in Orbit (View 1)

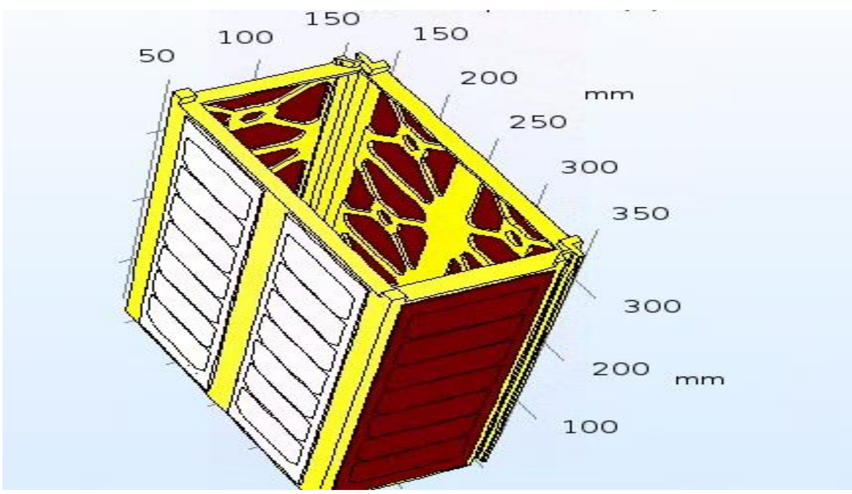


Figure 50b: NeAtO Temperature Profile after 24 Hours in Orbit (View 2)

Based on the figure we can determine that the temperature over the whole CubeSat ranges from a minimum of 260 K to a maximum of 428 K. The maximum temperature occurs on the solar panel assemblies mounted on the negative-x-oriented face as seen above. This is as expected, because NeAtO's nadir-aligned and velocity-constrained attitude caused this particular face to always point in the negative normal direction to Earth, which in turn meant that it would have the most exposure to solar radiation than all other model faces. The other four solar panel assemblies experienced temperatures on the lower end of the temperature range, around 260 to 280 K. The aluminum frame appeared to experience a fairly consistent temperature range of 360 to 400 K all throughout the entire structure.

Through a comparison of the temperature profiles with and without the front plate, it can be seen that taking out the front plate significantly reduced the overall temperature range. Figure 49 shows that the front plate would experience the highest temperature (536 K), as it would experience effects of solar radiation and atmospheric drag. By neglecting the front plate and only considering the frame and solar panels, the overall temperature range was reduced by almost 100 K. The temperature profile displayed in figure 50 was exported as a csv file, which contained x-y-z coordinates of the mesh points, and the corresponding temperature data point, found in Appendix F. This data was then integrated into the structural analysis simulations discussed in section 3.4.

4.4.3 STK Average Temperature Determination

STK simulations were also run to generate plots of average temperature of the CubeSat at different points in the orbit. This was done in order to determine the points in the orbit at which NeAtO would experience its highest and lowest average temperatures, so that corresponding temperature profiles could be generated in COMSOL. To obtain these temperature values, the CubeSat orbit was used in the Space Environment and Effects Tool (SEET) Vehicle Temperature Module within STK. Furthermore, the module took into account several thermal parameters: an Earth albedo value of 0.34, a material emissivity value of 0.22 (Aluminum 7075-T6), a material absorptivity of 0.4, and an internal component dissipation of 14 W.

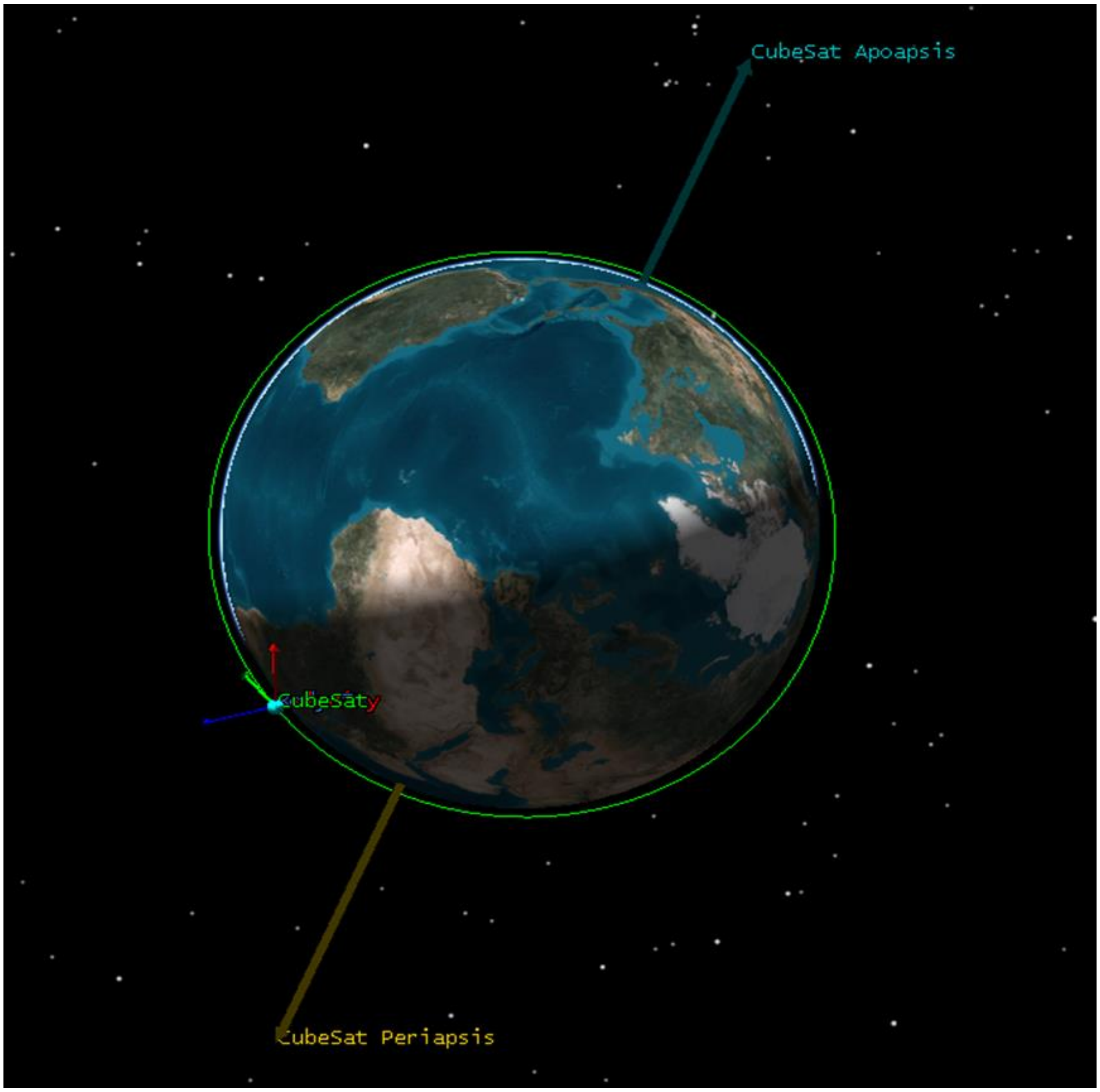


Figure 51a: Lowest Average Temperature in Orbit

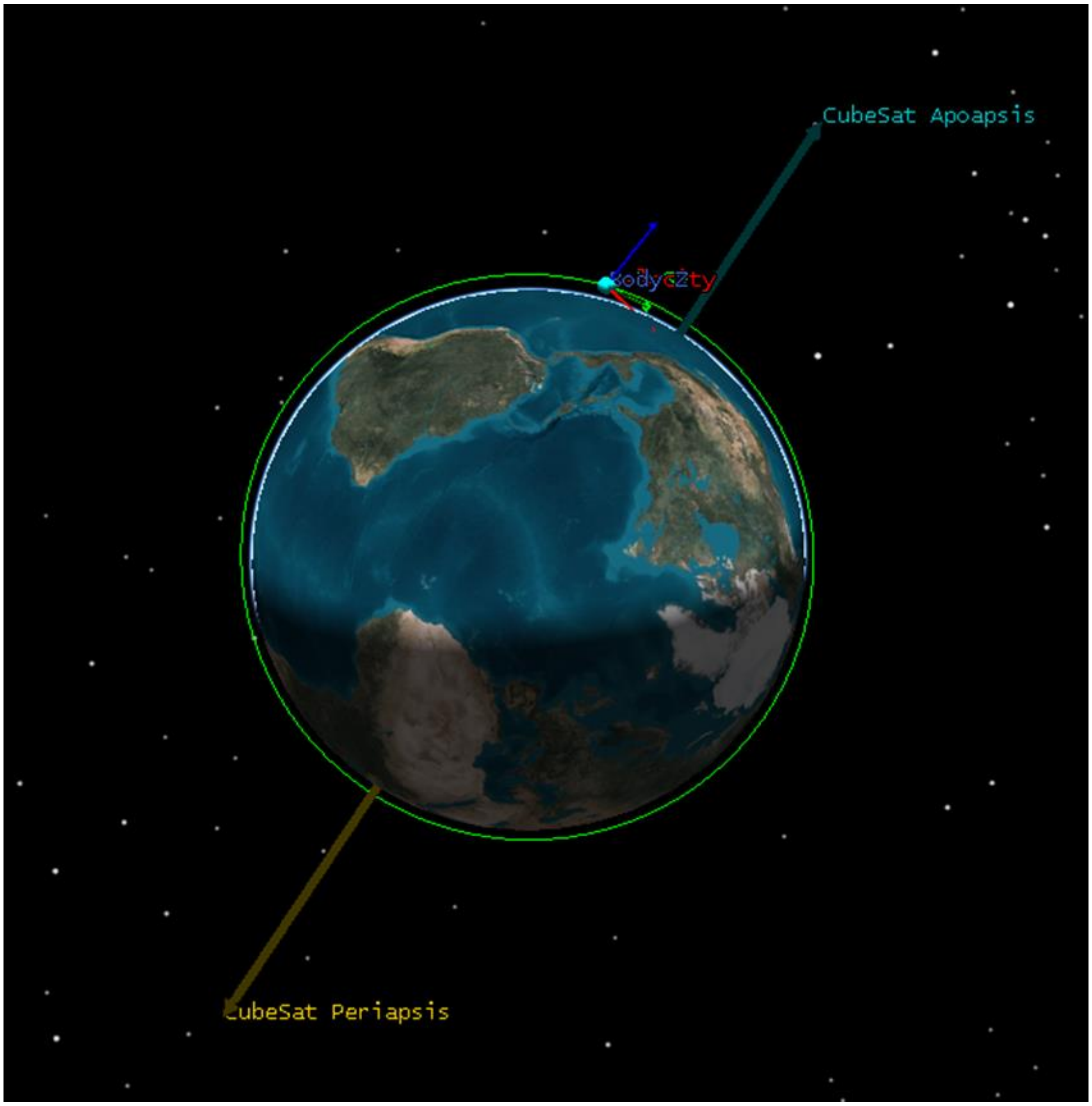


Figure 51b: Highest Average Temperature in Orbit

Figure 51 (a) shows the point in the orbit at which NeAtO experiences the lowest average temperature, whereas (b) shows the point in the orbit at which the average temperature is highest. It is evident that the minimum and maximum average temperatures of the CubeSat are offset from the perigee and apogee, respectively. From the original STK simulation, the orbit is defined to have a true anomaly of 0° directly at the perigee. The point of lowest average temperature was found to be at a true anomaly of 331.612°, and the point of highest average temperature had a true anomaly of 224.231°.

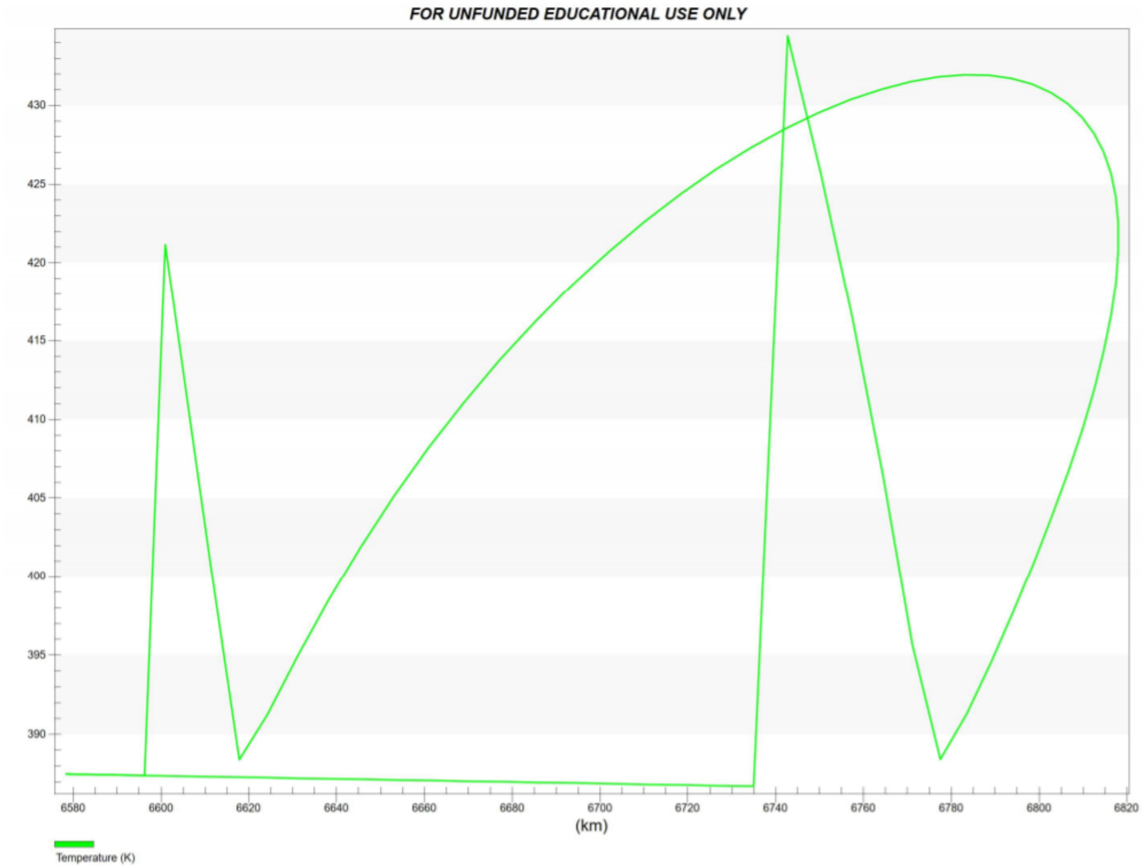


Figure 52a: Average Temperature as a function of Orbital Radius

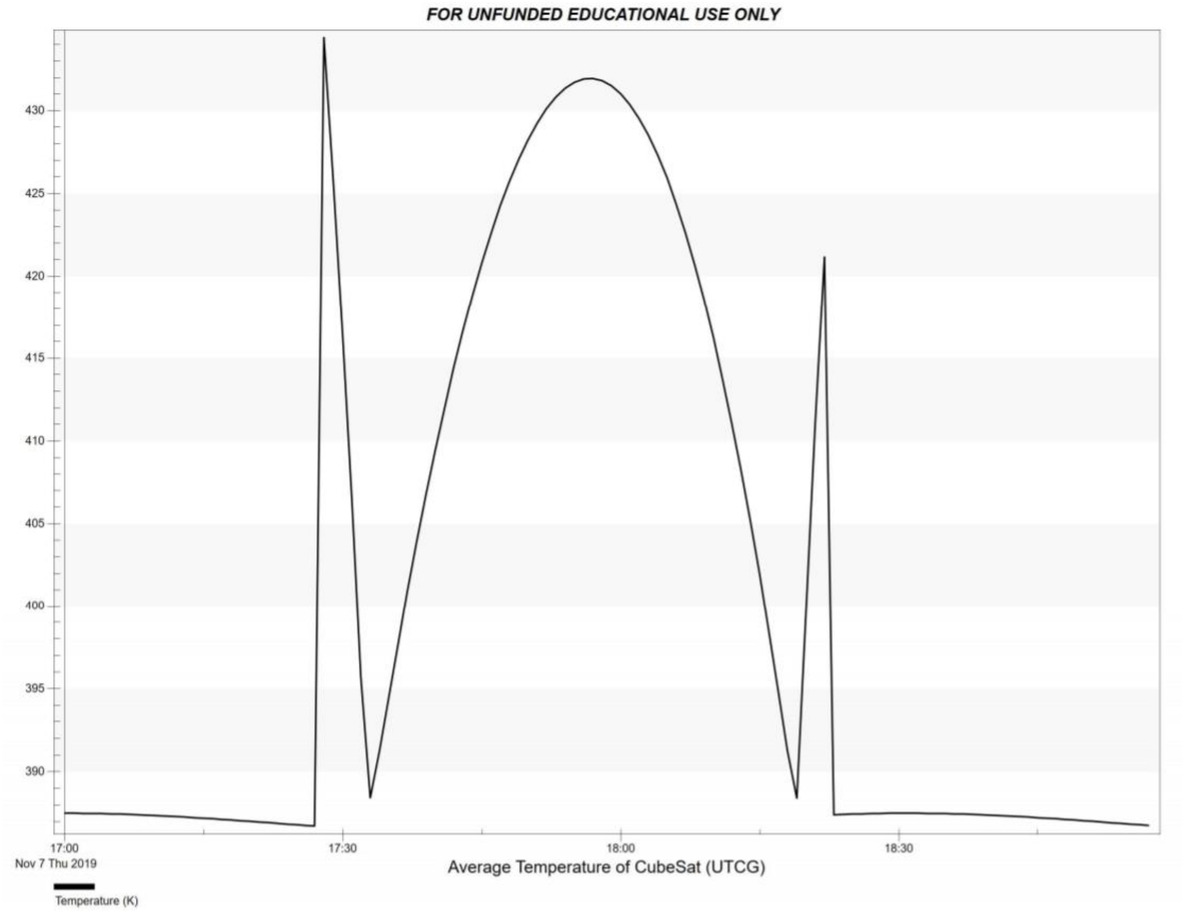


Figure 52b: Average Temperature over One Orbit

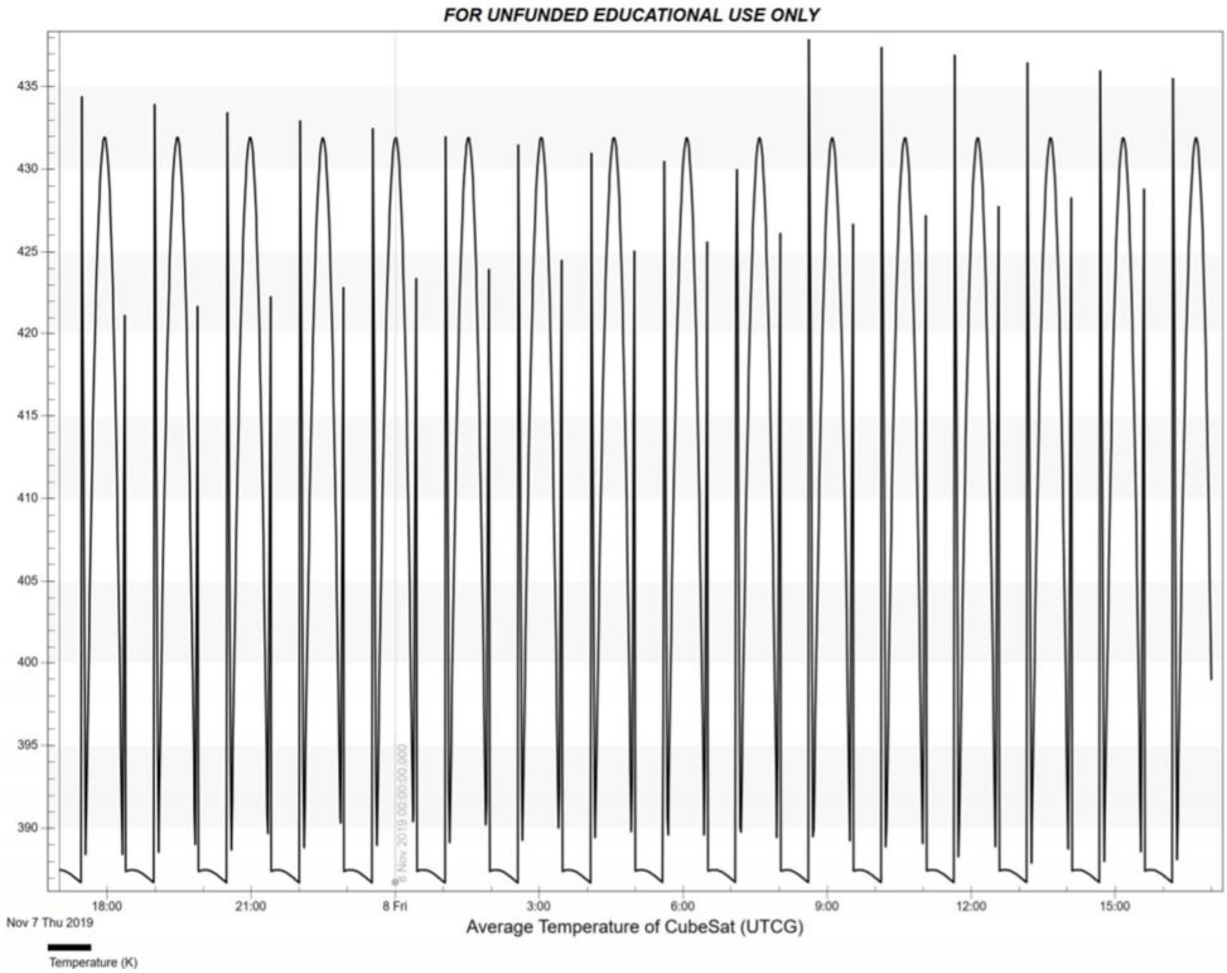


Figure 52c: Average Temperature over Several Orbits

Figure 52 shows the average temperature of the CubeSat as it progresses through the 440km apogee/ 200km perigee orbit. At perigee (6578 km) the average temperature is around 387 K. At apogee (6818 km) the average temperature is around 422 K. The maximum average temperature would be 434 K at the tip of the larger spike (6742 km).

However, these temperature values were concluded to not be entirely accurate due to certain simplifications within the STK interface. First, the SEET Thermal Module only allows the user to model the CubeSat as either a sphere or a flat plate. The flat plate option was selected, for which the plate cross-sectional area was set to 0.06 m^2 to model the 2U x 3U face of NeAtO, where the normal vector was defined as “CubeSat Earth” to ensure that the surface area being considered was the negative z-oriented face of the CubeSat. Since the module simplifies the entire satellite geometry to one surface area, the average temperature determined from the simulation is not representative of the entire CubeSat body. Furthermore, the module only allows the user to enter the emissivity and absorptivity of one material. Aluminum 7075-T6 was the chosen material in this simulation in order to model the frame, but this meant that the carbon fiber and polysilicon material that make up the solar panels could not be represented in the determination of average temperature.

Although there was slight inaccuracy in this temperature determination, the STK results were still able to be used as validation of the COMSOL temperature profile. The average temperatures fell within the allowed temperature range determined in section 4.4.2.

5. Concluding Remarks

5.1 Executive Summaries

5.1.1 Design Executive Summary

NeAtO's design began with determining the method of deployment, for which each deployer has differing requirements and available launch integration options. Initially we continued with a 4U design used in the most recent CubeSat MQP as Clyde Space provided recently designed COTS 4U frame. Once the payload was chosen, our team realized that the payload orientation, requiring a surface area of 20cm x 10cm in the RAM direction, and payload 1.5U size, would have required a 40 cm x 10 cm side of the 4U CubeSat to be the RAM side, creating too much drag to meet mission goals. The 6U was chosen as the successor to the original 4U, with only a 2U x 1U side in the ram direction, and enough volume for two additional thrusters to accommodate the larger size and mass.

A few months into the project, a polar (sun synchronous) orbit was suggested, which would require a new deployer as NanoRacks is only utilized on the ISS. The design team from then on created two mission options to accommodate the two potential orbits until the orbit was finalized. The first Version of NeAtO, designed for the NanoRacks deployer, had a custom-made frame based off the Clyde Space 4U frame and the dimensions of the Clyde Space 6U, as the 6U frame was not provided to late in the project. The second version of NeAtO featured a frame created by Innovative Solutions In Space, and is designed for deployment from a Duo Pack deployer. Both deployers have similar requirements for center of mass, total mass and load points. NanoRacks also has many additional requirements ranging from the necessity of deployment switches, the option to choose between tabs and rails (each with load points), outgassing and materials considered, and an access point for astronauts to check the system on the ISS before deployment.

To increase ease of assembly for NeAtO and further increase accessibility for the astronauts, a cart was designed to slide into each frame. The cart was designed such that the origin of the SolidWorks assembly would coincide with where the center of geometry of NeAtO would be relative to the cart. This made design easier since the distance to the center of mass from the geometric center would be directly measured inside of SolidWorks. The components were placed in order of specified locations and orientations, then based on mass and similar components in the same area. This meant the payload and engines were placed first, followed by the reaction wheels, the magnetorquers, the accelerometers, and finally the gyroscope. Other components were then placed based on size and to meet the CM requirements.

The cart design was iterated until the CM was within requirements and the location and orientation requirements of certain components were satisfied within a reasonable limit. For both carts the center of mass stared closer to the thrusters in the Z direction at the star of the mission and ended closer to the ram facing side at the end of the mission. The center of mass was offset slightly towards one of the reaction wheels in the X direction, and closer to the cart in the Y direction. The tab design was chosen for the NanoRacks frame as it would help bring the center of mass closer to the center of geometry and bring NeAtO further within requirements. This was not possible with the Duo Packs design which requires rails, but the location of the CM was still within requirements. The antenna was the last component received and placed into the assembly. It was initially placed exterior to NeAtO in front of the payload, since it would be protected by the load points and would have ample space to deploy. This was initially assumed to be acceptable because the apertures for the Payload are on the outer edges of the module and were not being directly blocked by the antenna. When this design was presented to the SEG team it was brought up that the antenna would still interrupt the flow of particles to the payload and therefore the antenna was moved to the interior of NeAtO.

At this point the orbit was finalized to the ISS orbit, around the same time the official Clyde Space frame was also acquired. A Version 3 assembly was created with this new COTS frame, as it met all NanoRacks requirements and would be significantly cheaper than a custom manufactured frame. Since the dimensions of the custom frame were based on the NanoRacks frame the cart from version 1 and version 3 could be identical. Both versions were presented to the overall project group and Version 1 was chosen as the official frame. This was because the front and rear end of the Clydespace frame had the potential to obstruct the payload and the mount for the thrusters required significant modification respectively. Additionally, the cost was considered less important since NeAtO will not be manufactured or assembled. Version 1 of the NeAtO was then checked against all NanoRack materials, venting, geometry and deployment requirements to ensure the design was viable and then sent to Thermal and Structural members for testing.

5.1.2 Structural Analysis Executive Summary

The structural analysis involved running simulations for random vibrations and structural loads in the simulation software ANSYS. The structural analysis began with determining the material model that would best describe the behavior of the material. The material model also had to be dependent on temperature because in the environment of space, NeAtO will be exposed directly to the heat from the sun as well as some heat from the propulsion system. The Chaboche material model was selected because it is a viscoplastic model that is dependent on temperature and can accurately account for thermal cycling.

Once the material model was selected the next step was determining all the required material properties for the material used for the frame, AL7075-T6. The basic material properties were easy to find, however the additional parameters required for the Chaboche model are found through experimentation. A study in determining these parameters for AL7075-T6 was outlined in a scientific paper so the parameters were taken from there. An attempt was then made to write a custom material model to be imported into ANSYS in order to have full control of the way the material behaves. However, the method used to create the custom material model requires access to the system files which is not possible due to restrictions on the computers used in the project. Instead, the Chaboche model built into ANSYS was used.

The first simulation conducted was the random vibration simulation. For this analysis, NeAtO would have to withstand the random vibration environment provided by NanoRacks. This involved two different test configurations with test profile data for each configuration. The result was that very little stress and deformation was applied to NeAtO meaning the result fell well within the requirement of withstanding the test environment.

The next simulation was the structural load. For this analysis, NeAtO would have to withstand a 1200 Newton load applied in line with the direction the thrusters would fire. For this simulation, the temperature distribution acquired from the thermal simulation was applied to NeAtO in order to get a more accurate representation of how the frame would behave in the environment of space. The simulation resulted in a large amount of stress and substantial deformation was applied to NeAtO, but the structure was able to withstand the load and therefore complete the NanoRacks requirement.

5.1.3 Thermal Analysis Executive Summary

The thermal analysis of NeAtO involved the development of a set of simulations using STK and COMSOL software. An STK simulation was set up with the optimized 200 km to 440 km orbit with a true anomaly of 0 (originating at perigee). The model of the CubeSat was imported into the orbit, and a set of thermal properties were defined based on NeAtO's frame material properties. The simulation was then run for a 24-hour period, which simulated about 16 total orbits. From STK, the solar intensity and sun vector component data points for the defined simulation were calculated and exported as csv files.

A second simulation was then developed in COMSOL to determine the temperature profile of NeAtO. Two defeatured SolidWorks models were used in the thermal simulation. The first included the CubeSat aluminum frame, the simplified solar panel assemblies, and a front panel on the RAM-face to simulate the exposed faces of the payload, cart, and other exterior components. The second defeatured model only considered the frame and solar panels. The selected model was imported into the COMSOL interface to define the NeAtO geometry. Next, boundary conditions were defined for the frame and solar panels, and a set of material properties was defined for each boundary. The thermal data found from STK was imported into COMSOL as interpolation functions defined for each face in the geometry. The mesh model was then defined from the geometry, which would determine the points in the model at which temperature would be analyzed.

The Heat Transfer with Surface-to-Surface Radiation Module of COMSOL was implemented in order to analyze the irradiation and radiosity at the specified mesh points. Completing the heat transfer module involved the implementation of heat flux definitions at each face of the CubeSat and the designation of a set of initial values and radiative properties.

With all parameters fully defined, the simulation was run for a 24-hour time period with a 1-hour time step in order to maintain a reasonable computation time. Plots of the temperature profile were generated for the two defeatured CubeSat models. The data was then imported into ANSYS to complete temperature-dependent structural analysis.

The STK simulation was revisited to determine the average temperature of the entire CubeSat throughout the progression of its orbit, and the points in the orbit at which the average temperatures reached minimum and maximum.

5.2 Conclusion

For similar future CubeSat projects at WPI, our team has provided a few considerations and recommendations; if possible, request funds for a real COTS frame (possibly the 6U from Innovative Solutions in Space) to allow for possible structural and attitude tests to be completed. This would further involve the test bed, requiring it to be fully functional, and possibly require testing using a thermal cycling vacuum chamber. One possible consideration is that NASA only uses Creo for its mechanical design/ assemblies, and thus students may want to switch from SolidWorks to Creo. Future teams may have the opportunity to better utilize NASA's ORDEM to calculate the flux and direction of debris the CubeSat will encounter. This would allow them to determine the degradation from potential debris strikes on the CubeSat, and thus fill out an ODAR report in its entirety, meeting another NanoRacks requirement (one that our team did not specifically finish).

In addition to these considerations, our team recommends that future teams determine their payload early and avoid using 4U frames as they pose more challenges for launch opportunities due to less deployer integration (and confusing requirements). For structural analysis, we recommend looking more into the user defined material model in ANSYS. ANSYS was recently updated which meant that information on usermats for the current version was limited but possibly by next year there will be more information. For thermal analysis, we recommend focusing more on understanding COMSOL thermal heat flux calculations rather STK, which other groups within the SEG team focused on. Lastly, one area of growth is better defining the mounting of solar panels and bracketing of the cart and other components to the frame.

As the popularity and number of CubeSats missions continues to grow, so too will the number of technical advancements, new discoveries, and lessons learned in space. Cube Satellites provide an amazing opportunity for students and scientists from a variety of fields to learn the basics of launch requirements and mission possibilities, with a much cheaper price tag than previous larger satellites. We look forward to the future of these endeavors in the space industry and the many opportunities that will come from them.

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7. Appendices

Appendix A [23]

A summary of the NanoRacks Double Wide Deployer requirements, based on section number, with relevant descriptions and Person in Charge noted.

PP Number	**Paragraph Title**	**Requirement Text**	**Submittal Data Type**	**Person in Charge**
4.1.1 CubeSat Mechanical Specification - NRDD with Tab Configuration				
4.1.1-1	Tab Specification	The CubeSat shall have two (2) tabs that protrude from the main payload envelope and allow the payload to slide into the rail capture interface of the NRDD as outlined in Figure 4.1.1-1.	Engineering Drawing and Fit-Check	Brian
4.1.1-2	Tab Dimensions and CubeSat Envelope	The CubeSat tabs and envelope shall adhere to the dimensional specification outlined in Figure 4.1.1-2.	Engineering Drawing and Fit-Check	Brian

4.1.1-3	CubeSat Load Points	The maximum outer radius of the tab at the ends of the payload (+/- Z axis) shall be 3.5mm as outlined in Figure 4.1.1-3.	Engineering Drawing	Brian
4.1.1-4	Tab Outer Radius	The CubeSat shall have load points on the +/- Z faces of the payload that are coplanar with the end of the tabs within +/- 0.25mm (0.010”) and envelope the designated load path regions / contact zones outlined in Figure 4.1.1-4.	Engineering Drawing and Measurement	Brian
4.1.1-5	Tab Length	The CubeSat tab length shall be the following for the respective 6U and 12U payload form factors. a. 6U Payload Tab Length: 366mm (+0.0 / -65.0) b. 12U Payload Tab Length: 732mm ((+0.0 / -130.0)	Engineering Drawing and Measurement	Brian
4.1.1-6	Tab Continuity	The CubeSat tabs shall be contiguous. No gaps, holes, fasteners, or any other features may be present along the length of the tabs (Z-axis) in regions	Engineering Drawing	Brian

		that contact the NRDD rails (see Figure 4.1.1-1).		
4.1.1-7	NRDD Mechanical Interface	The CubeSat tabs shall be the only mechanical interface to the NRDD in the lateral axes (X and Y axes; does not account for longitudinal, Z-axis contact points).	Engineering Drawing and Fit-Check	Brian
4.1.1-8	Tab Envelope	The CubeSat tabs shall extend beyond the +/-Z faces of the entire payload, including all external features (with the exception of load points on the +/-Z face of the payload)	Engineering Drawing	Brian
4.1.1-9	Tab Hardness	The CubeSat tabs and all load points shall have a hardness equal to or greater than hard-anodized aluminum (Rockwell C 65-70).	Material Certification	Brian
4.1.1-10	Tab Surface Roughness	The CubeSat tabs and all load points shall have a surface roughness of less than or equal to 1.6 µm	Material Certification	N/A

4.1.2 CubeSat Mechanical Specification - NRDD with Rails Configuration				
4.1.2-1	Rail Specification	The CubeSat shall have four (4) rails that are integral with the main payload envelope and allow the payload to slide on the rail interface of the NRDD as outlined in Figure 4.1.2-1.	Engineering Drawing, Fit Check ROA	N/A
4.1.2-2	Rail Dimensions and CubeSat Envelope	The CubeSat rails and envelope shall adhere to the dimensional specification outlined in Figure 4.1.2-1.	Engineering Drawing, Fit Check ROA	N/A
4.1.2-3	CubeSat Load Points	The edges of the rails shall be rounded to a radius of at least 0.5mm +/- 0.1mm.	Engineering Drawing	N/A
4.1.2-4	Rail Outer Radius	The CubeSat shall have load points on the +/- Z faces of the payload that are coplanar with the end of the rails within +/- 0.25mm	Engineering Drawing and Measurement	N/A

4.1.2-5	Rail Length	The CubeSat rail length shall be the following for the respective 6U and 12U payload form factors. a. 6U Payload rail Length: 366mm (+0.0 / -65.0) b. 12U Payload rail Length: 732mm ((+0.0 / -130.0)	Engineering Drawing and Measurement	N/A
4.1.2-6	Rail Continuity	The CubeSat rails shall be contiguous. No gaps, holes, fasteners, or any other features may be present along the length of the rails (Z-axis) in regions that contact the NRDD rails. The exception to this are the deployment switches if rail mounted switches are used.	Engineering Drawing	N/A
4.1.2-7	NRDD Mechanical Interface	The CubeSat rails shall be the only mechanical interface to the NRDD in the lateral axes (X and Y axes; does not account for longitudinal, Z-axis contact points). The exception to this are separation springs or deployment switches if rail mounted switches are used.	Engineering Drawing, Fit Check	N/A

4.1.2-8	Rail Envelope	The CubeSat rails/load points shall extend beyond the +/-Z faces of the entire payload, including all external features, by no less than 2 mm (with the exception of load points on the +/-Z face of the payload).	Engineering Drawing	N/A
4.1.2-9	Rail Hardness	The CubeSat rail surfaces that contact the NRCSD guide rails shall have a hardness equal to or greater than hard-anodized aluminum (Rockwell C 65-70)	Materials Certification	N/A
4.1.2-10	Rail Surface Roughness	The CubeSat rails and all load points shall have a surface roughness of less than or equal to 1.6 µm.	Materials Certification	N/A
4.1.2-1	Mass Limits	The CubeSat mass shall be less than the maximum allowable mass for each respective payload form factor per Table 4.1.3-1. It is 12 kg for a 6U	Mass Properties Report	Nicole w/Brian

4.1.3-2	Center of Mass	The CubeSat center of mass (CM) shall be located within the following range relative to the geometric center of the payload. a. X-axis: (+/- 5cm) b. Y-axis: (+/- 3cm) c. Z-axis: i. 6U: (+/- 8cm) ii. 12U: (+/- 16cm)	Mass Properties Report	Nicole w/Brian
4.1.4-1	RBF/ABF Access	The CubeSat shall have a remove before flight (RBF) feature or an apply before flight (ABF) feature that is physically accessible via the NRDD access ports on the +/-X face of the dispenser / payload. The access port regions on the payload are defined in Figure 4.1.4-1 and 4.1.4-2.	Engineering Drawing, Fit Check	Brian and Nicole
4.1.5-1	Deployment Switch	The CubeSat shall have a minimum of three (3) deployment switches that correspond to independent electrical inhibits on the main power system (see section on electrical interfaces).	Electrical Schematic, Engineering Drawing	Brian and Nicole
4.1.5-2	Deployment Switch Location	NRDD with Tabs CubeSat deployment switches shall all be	Engineering Drawing	Brian and Nicole

		located on the same face of the payload at the front or the back of the CubeSat (+/-Z face). NRDD with Rails CubeSat deployment switches can be of the pusher variety, located on the +/–Z face on one or more of the rail ends/load regions as defined in Figure 4.1.2-1, or roller/lever switches embedded in a CubeSat rail and riding along the NRCSD guide rails in the +/-X and Y axes.		
4.1.5-3	Deployment Switch Travel	The CubeSat deployment switches in the +/-Z axes shall engage / actuate with sufficient travel beyond that of the plane of the tab and load points in either the +/- Z end of the payload.	Measurement and Fit-Check	Brian and Nicole
4.1.5-4	Deployment Switch Travel (2)	NRDD with Rails CubeSat deployment switches that utilize the NRDD rails in the +/-X and Y axes as the mechanical interface shall have a minimum actuation travel of 1 mm to accommodate for design slop and	Measurement and Fit-Check	N/A

		tolerance extremes of the CubeSats and NRDD rails.		
4.1.5-5	Deployment Switch Reset	The CubeSat deployment switches shall reset the payload to the pre-launch state if cycled at any time within the first 30 minutes of the switches closing (including but not limited to radio frequency transmission and deployable system timers).	Test Report	N/A
4.1.5-6	Deployment Switch Captivation	The CubeSat deployment switches shall be captive.	Engineering Drawing	Brian
4.1.5-7	Deployment Switch Force	For plunger switches used in the +/- Z axis or roller switches used in the +/- X and Y axes, the total force of all the switches shall not exceed 18N.	Switch Spec and Measurement	Brian and Nicole
4.1.5-8	Switch Location	NRDD with Rails CubeSat deployment switches that utilize the NRDD rails in the +/- X and Y axes as	Fit-Check	N/A

		the mechanical interface shall maintain a minimum of 75% (ratio of roller/slider-width to guide-rail width) contact along the entire Z-axis.		
4.1.6-1	Deployable Restraint Mechanisms	CubeSat deployable systems (such as solar arrays, antennas, payload booms, etc.) shall have independent restraint mechanisms that do not rely on the NRDD dispenser.	Design Information	Brian and Nicole
4.1.7-1	Deployment Velocity	The CubeSat shall be capable of withstanding a deployment velocity of 0.5 to 1.5 m/s at ejection from the NRDD.		Rory
4.1.7-2	Tip-Off Rate	The CubeSat shall be capable of withstanding up to 5 deg/sec/axis tipoff rate.		Brian and Nicole w/ Team 2
4.2.1-1	Power Storage Device Location	All electrical power storage devices shall be internal to the CubeSat.	Safety Data Template	Nicole

4.2.1-2	Post-Deployment Timer	CubeSat shall not operate any system (including RF transmitters, deployment mechanisms or otherwise energize the main power system) for a minimum of 30 minutes where hazard potential exists. Satellites shall have a timer (set to a minimum of 30 minutes and require appropriate fault tolerance) before satellite operation or deployment of appendages where hazard potential exists.	Safety Data Template	N/A (Team 2)
4.2.1-3	Electrical Inhibits	The CubeSat electrical system design shall incorporate a minimum of three (3) independent inhibit switches actuated by physical deployment switches as shown in Figure 4.2-1. The satellite inhibit scheme shall include a ground leg inhibit (switch D3 on Figure 4.2-1) that disconnects the batteries along the power line from the negative terminal to ground.	Electrical Schematic	Brian with Team 1
4.2.1-4	Ground Circuit	The CubeSat electrical system design shall not permit the ground charge	Electrical Schematic	Brian with Team 1

		circuit to energize the satellite systems (load), including flight computer (see Figure 4.2-1). This restriction applies to all charging methods.		
4.2.1-5	RBF / ABF Location	The CubeSat shall have a remove before flight (RBF) feature or an apply before flight (ABF) feature that keeps the satellite in an unpowered state throughout the ground handling and integration process into the NRCSD.	Electrical Schematic, Fit Check ROA	Brian with Team 2
4.2.1-6	RBF / ABF Functionality	The RBF /ABF feature shall preclude any power from any source operating any satellite functions except for pre-integration battery charging.	Electrical Schematic	Brian with Team 2
4.2.1-7	Wire Requirement	The CubeSat Electronics Power System (EPS) shall have no more than six (6) inches of wire 26AWG or larger between the power source (i.e. battery pack) and the first electrical inhibit (MOSFET or equivalent).	Safety Data Template	Brian with Team 1

4.2.2	Electrical Systems Interface	There shall be no electrical or data interfaces between the CubeSat and the NRDD. As outlined in Section 4.2.1, the CubeSat shall be completely inhibited while inside the NRDD.		Brian with Team 2
4.3.1-1	Acceleration Loads	Payload safety critical structures shall (and other payload structures should) provide positive margins of safety when exposed to the accelerations documented in Table 4.3.1- at the CG of the item, with all six degrees of freedom acting simultaneously.	Structural Analysis Report	Rory
4.3.2-1	Random Vibration Environment	The CubeSat shall be capable of withstanding the random vibration environment for flight with appropriate safety margin as outlined in Section 4.3.2.1.	Vibration Test Report	Rory
4.3.3	Launch Shock Environment	Integrated end items packed in the soft-stow configuration do not experience significant mechanical shock. As a result, there is no shock		Rory

		test requirement for CubeSats launching inside the NRDD. Any mechanical or electrical components on the spacecraft hat are highly sensitive to shock should still be identified and assessed on a case-by-case basis as defined in the unique payload ICA.		
4.3.4	On-Orbit Acceleration	The CubeSat shall be capable of withstanding the loads inside of the NRDD when exposed to the acceleration environment defined in Table 4.3.4-.		Rory
4.3.5	Integrated Loads Environment	The CubeSat shall be capable of withstanding a force 1200N across all load points equally in the Z direction.	Structural Analysis Report	Rory
4.3.6	Thermal Environment	The CubeSat shall be capable of withstanding the expected thermal environments for all mission phases, which are enveloped by the on-orbit, EVR phase prior to deployment. The expected thermal environments for all		Christian

		phases of the mission leading up to deployment are below in Table 4.3.6-.		
4.3.7	Humidity	The CubeSat shall be capable of withstanding the relative humidity environment for all mission phases leading up to deployment, which is between 25% to 75% relative humidity (RH) for ascent and on-orbit phases of flight.		N/A
4.3.8	Airlock Depressurization	The CubeSat shall be capable of withstanding the pressure extremes and depressurization / pressurization rate of the airlock as defined below. Airlock Pressure: 0 to 104.8 kPa Airlock pressure depressurization/re-pressurization rate: 1.0 kPa/sec	Effective Vent Area	Rory
4.4.1	Containment of Frangible Materials	The CubeSat design shall preclude the release or generation of any foreign object debris (FOD) for all mission phases.	Vibration Test Report	Rory

4.4.2	Venting	The Maximum Effective Vent Ratio (MEVR) of the CubeSat structure and any enclosed containers internal to the CubeSat shall not exceed 5080cm.	Effective Vent Area	N/A
4.4.3	Secondary Locking Feature	The CubeSat shall have an approved secondary locking feature for any and all fasteners or subcomponents external to the CubeSat chassis that would not be held captive by the spacecraft structure should it come loose.	Design Info and Vibration Test Report	N/A
4.4.4	Passivity	The CubeSat shall be passive and self-contained from the time of integration up to the time of deployment.		N/A
4.4.5	Pyrotechnics	The CubeSat shall not contain any pyrotechnics unless the design approach is approved by NanoRacks		N/A
4.4.6-1	CubeSat Sub-Deployables	CubeSats shall not have detachable parts during launch or normal mission operations. Any exceptions will be	Safety Data Template	N/A

		coordinated with NanoRacks and documented in the unique payload ICA.		
4.4.6-2	Space Debris Compliance	CubeSats shall comply with NASA space debris mitigation guidelines as documented in NASA Technical Standard NASASTD-8719.14A.	ODAR	Christian w/ Team 1
4.4.7.3	Battery Testing	All flight cells and battery packs shall be subjected to an approved set of acceptance screening tests to ensure the cells will perform in the required load and environment without leakage or failure. While the specific test procedures vary depending on the type of battery, the majority of Lithium ion or Lithium polymer cells / batteries used in CubeSats can be tested to a standard statement of work issued by NanoRacks (NR-SRD-139). Some generic battery design requirements are outlined below.	Battery Test Report and Electrical Schematic	Brian with Team 1

4.4.7.4	Internal Short Circuit	Protection circuitry and safety features shall be implemented at the cell level to prevent an internal short circuit.	Electrical Schematic	N/A
4.4.7.5	External Short Circuit	Protection circuitry and safety features shall be implemented at the cell level to prevent an external short circuit.	Electrical Schematic	N/A
4.4.7.6	Overvoltage & Undervoltage Protection	Protection circuitry and safety features shall be implemented at the cell level to prevent overvoltage or undervoltage conditions of the cell.	Electrical Schematic, Battery Test Report	N/A
4.4.7.7	Battery Charging	It should be verified that the battery charging equipment (if not the dedicated charger) has at least two levels of control that will prevent it from causing a hazardous condition on the battery being charged.	Electrical Schematic	N/A
4.4.7.8	Battery Energy Density	For battery designs greater than 80 Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion	Electrical Schematic, Battery Test	N/A

		chemistries) require additional assessment by NanoRacks due to potential hazard in the event of single-cell, or cell-to-cell thermal runaway.	Report, Design Info Only if Power System > 80Wh	
4.4.7.9	Lithium Polymer Cells	Lithium Polymer Cells i.e. “pouch cells” shall be restrained at all times to prevent inadvertent swelling during storage, cycling, and low pressure or vacuum environments with pressure restraints on the wide faces of the cells to prevent damage due to pouch expansion. Coordinate with NanoRacks for guidance on specific implementation.	Design Information	Brian
4.4.7.10	Button Cell Batteries	Button cell or coin cell batteries are often used in COTS components to power real-time clocks (RTCs), watch-dog circuits, or secondary systems for navigation, communication, or attitude control. These batteries shall be clearly	Design Information and Test Report	N/A

		identified by part number and UL listed or equivalent.		
4.4.7.11	Capacitors	Capacitors are used throughout today's modern electronics. Capacitors used as energy storage devices are treated and reviewed like batteries. Hazards associated with leaking electrolyte can be avoided by using solid state capacitors. Any wet capacitors that utilize liquid electrolyte must be reported to NASA. The capacitor part number and electrolyte must be identified along with details of how the capacitor is used and any associated schematics	Design Information and Test Report	N/A
4.4.8	Pressure Vessels	--Sealed container more than 100 psia→ check with propulsion-- Coordination with NR (usually prop tanks are pressurized)	Design Information, Analysis, and Test Report	N/A (not building/ launching)

4.4.9	Propulsion System	--additional assessment required → requires coordination with NR--	Design Information, Analysis, and Test Report	N/A (not building/ launching)
4.4.10.1	Stress Corrosion Materials	Stress corrosion resistant materials from Table I of MSFC-SPEC-522 are preferred. Any use of stress corrosion susceptible materials (Table II) shall be pre-coordinated with NanoRacks and documented in the ICA. Any use of Table III materials shall be avoided.	Bill of Materials	Nicole and Brian
4.4.10.2	Hazardous Materials	Satellites shall comply with NASA guidelines for hazardous materials. Beryllium, cadmium, mercury, silver or other materials prohibited by SSP-30233 shall not be used	Bill of Materials	Nicole and Brian
4.4.10.3	Outgassing / External Contamination	Satellites shall comply with NASA guidelines for selecting all nonmetallic materials based on available outgassing data. Satellites shall not utilize any non-metallic	Bill of Materials	Nicole and Brian

		materials with a Total Mass Loss (TML) greater than 1.0 percent or a Collected Volatile Condensable Material (CVCM) value of greater than 0.1 percent.		
4.5.1	Delta V	Calculate delta V and coordinate with NR	Design Information and Analysis	N/A - Team 1 calculates
4.5.2-1	CubeSats Over 5kg	CubeSats over 5kg shall provide an Orbital Debris Assessment Report (ODAR) that verifies compliance with NASA-STD8719.14.	ODAR, DAS Input File	Christian with Team 1
4.5.2-2	Reentry	CubeSats that are designed to survive re-entry or have components that are designed to survive re-entry shall provide an ODAR that verifies compliance with NASA-STD8719.14.	Design Information and Analysis	Christian with Team 1
4.6.1	Regulatory Compliance	The CubeSat developer shall submit evidence of all regulatory compliance for spectrum utilization and remote	Regulatory Licenses	N/A

		sensing platforms prior to handover of the payload. This evidence shall come in the form of the authorization or license grant issued directly from the governing body / agency (which is dependent on the country the CubeSat originates).		

Appendix B: Components List

Name and Type		Responsibility			Links			
Component Type	**Component Name**	**Team**	**Subsystem**	**Person(s) of Contact**	**Spec Sheet Link**	**CAD Link**	**Technology Readiness Level**	**Company**
Transceiver	ISIS VHF/UHF	Team 1	Telecommunications	EJ	Transceiver	STEP File	9	ISIS
Antennae	ISIS hybrid	Team 1	Telecommunications	EJ	Antenna	STEP File	9	ISIS
Payload	mINMS	Team 1	Payload	Sam Joy	Payload	https://drive.google.cc	9	NASA
Solar Panel	Photon-3U	Team 1	Power	Gavin/ Tristan	Solar Panels	SolarPanels.STP	9	Clyde Space
Battery	Optimus-40	Team 1	Power	Gavin/ Tristan	Battery	Battery.STP	9	Clyde Space
OBC (On board Computer)	KYREN M3	Team 1/2	Power/ Command	Gavin/ Tristan	OBC	https://drive.google.cc	9	Clyde Space
Motherboard (EPS)	Starbuck Nano-Plus	Team 1/ 2	Power/ Command	Gavin/ Tristan	Motherboard (EPS)	EPS .STP	9	Clyde Space
Engine/ Fuel Tank	BET300	Team 1/2	Propulsion/ Orbit Control	Jeremiah/ Ben	Engine	Engine CAD	3-4 (in testing)	Busek
Fuel	1-ethyl-3-methylimidazolium tetrafluoroborate	Team 1/2	Propulsion/ Orbit Control	Jeremiah/ Ben	https://drive.google	N/A	N/A	Busek
GPS	NGPS-03-422	Team 2	Navigation	Oli and Andrew	?id=1fh2fSthv8OJ7I	https://drive.google.cc	9	NewSpace Systems
Reaction Wheels	RWP050	Team 2	ADC	Oli and Andrew	Reaction Wheel	https://drive.google.cc	9	Blue Canyon Technologies
Drive Control Electronics (RW Control	DCE Gen 3	Team 2	ADC	Ollie and Andrew	N/A	DCE CAD	9	Blue Canyon Technologies
Gyroscope	ADXRS453	Team 2	ADC	Oli and Andrew	Gyroscope	https://drive.google.cc	9	Analog Devices
Analog Sun Sensor	Nano-SSOC-A60	Team 2	ADC	Oli and Andrew	https://www.cubesa	https://drive.google.cc	9	SolarMEMS
Accelerometer and Magnetometer	LSM303AGRTR	Team 2	ADC	Oli and Andrew	Accel/Magne	https://drive.google.cc	9	STMicroelectronics
Magnetorquer	NCTR-M002 Magnetorquer Rod	Team 2	ADC	Oli and Andrew	Magnetorquer	https://drive.google.cc	9	CubeSatShop
Deployment Switch	Honeywell V15W2 Series Basic Switch	Team 3	Launch/ Design	Brian/ Nicole	https://sensing.hone	https://drive.google.cc	9	HoneyWell
Cart	Cart V1	Team 3	Design	Nicole	N/A	https://drive.google.cc	3	N/A
Structure	Kelsey V8 Frame	Team 3	Design	Brian/ Nicole	N/A	https://drive.google.cc	3	N/A
RBF ABF Port	Port 1	Team 3	Design	Brian/ Nicole	N/A	https://drive.google.cc	2	N/A

Component Type	Material (s)	Quantity	Mass (kg)	Volume (m^3)	Dimensions	Operating Temp. (C)	Peak/Max Power Consumption (W)	Total Nominal Power Consumption (W)
Transceiver		1	0.075	1.30E-04	90x96x15 mm	-20 to +60	4	0.48
Antennae		1	0.08	6.72E-05	98x98x7 mm	-20 to +60	2 (Deploy)	0.04
Payload		1	0.56	0.00117	90x100x130m m	-20 to 50		1.8
Solar Panel	Aluminum Frame	4		4.28E-05	322.5x83x1.6 mm	-40 to +80	N/A	N/A
Battery	Lithium Polymer Battery	1	0.335	2.36E-04	95.89 x 90.17 x 27.35 mm	-10 to +50	N/A	N/A
OBC (On board Computer)		1	0.0619	4.76E-05	95.89 x 90.17 x 5.51 mm	-40 to +80	1	0.4
Motherboard (EPS)		1	0.148	1.80E-04	95.89 x 90.17 x 20.82 mm	-40 to +85		
Engine/ Fuel Tank	Aluminium Body	4	0.92	0.000125 per engine	5 x 5 x 5 cm	Not Provided	6	2.5
Fuel	N/A	4	0.016	0	N/A	N/A		N/A
GPS		1	0.13	3.15E-05	96x91x18mm Antenna: 54x54x14.1m	-10 to +50	1	1.5
Reaction Wheels		3	0.24	8.41E-05	58 x 58 x 25 mm	Not Provided		3
Drive Control Electronics (RW Control	N/A	3	0.05304	0.00005	100 x 100 x 12.7	Not Provided		
Gyroscope		1	0.0567	0.000003267	33x33x3 mm	-40 to +105		0.02
Analog Sun Sensor		5	0.04	2.26E-06	27.4 x 14 x 5.9 mm	-30 to +85		0.05
Accelerometer and Magnetometer		1	0.002852	4.00E-09	2.00 x 2.00 x 1.00 mm	-40 to +85		0.005
Magnetorquer		3	0.12	0.000066	70 mm ⌀ 10mm	-35 to +75		2.4 (if all are on)
Deployment Switch	Silver Alloy, Silicon, PBT Thermoplastic Polyester	3	0.00529	0.00000529	33 x 10.31x15.9	-25 to +85	Negligible	Negligible
Cart	AL 7075-T6	0	2.37672	0.0008458	N/A	N/A	N/A	N/A
Structure	AL 7075-T6	1	0.319347	0.000119159	10 x 20 x 30	N/A	N/A	N/A
RBF ABF Port	N/A	1	0.01062	0.00000378	25 x 12 x 15	N/A	N/A	N/A

Component Type	Quiescent Power Consumption (W)	When is it drawing peak/max power?	When is it drawing nominal power?	Current Draw (uA)	Port (wiring)	How is it connected?	Shape (general)
Transceiver							Rectangular Prism
Antennae							Rectangular Prism with flat base and circular hole through center
Payload		N/A	On from 441 km to 250 km				
Solar Panel	N/A	N/A	N/A		N/A		Long rectangular sheets
Battery	N/A	N/A	N/A		N/A		Multi-layered rectangular box
OBC (On board Computer)							
Motherboard (EPS)							Dual-layered rectangular circuitboard
Engine/ Fuel Tank	0.5	Never	- 55 min of the 90 min orbit for the maneuvers from ISS. -Once in Orbit it uses quiescent power for 40 min of every orbit	approx 500 uA but 3500 volts (ion populsion is based off of low Amps but high voltage we gonna need a transformer probably)		Using PPU	Cube
Fuel							
GPS							Rectangular Prism
Reaction Wheels							Rectangular prism
Drive Control Electronics (RW Control							
Gyroscope							
Analog Sun Sensor				Two 26 AWG leads	0	Three #2 through holes, 120° apart on a .700" diameter pattern	Cylinder with circular flange
Accelerometer and Magnetometer	0.000005 in full power-down				<1500 uA	Surface mount, must be soldered to PCB	Rectangular prism
Magnetorquer							Cylindrical
Deployment Switch	N/A	N/A	N/A	N/A	N/A	-Z Face Screws	Rectangular
Cart	N/A	N/A	N/A	N/A	N/A	Brakets to the brame	Abstract
Structure	N/A	N/A	N/A	N/A	N/A	N/A	Rectangular
RBF ABF Port	N/A	N/A	N/A	N/A	N/A	N/A	Rectangular

Locations (general)	Orientation (will provide more soon)	Close To??	Additional Details
inside			.0096 Mbps up&down
inside			
must be "top" of our s/c	Ram-facing - apertures along +z axis in direction of velocity vector		13.7kbps nominal data transfer rate; apertures have a 10 deg x 10 deg FOV
body mounted, one on each long face			Efficiency: 30.7% BOL, 26.7% EOL
inside			
inside			
First U at the bottom of the cubesat	cathode facing the opposite direction of payload ram direction		The motor itself does not produce heat, environmental effects can be used. However, Power draw to opperate the motor will heat the board that the current will be passing through
			Fuel within Engine
	Aligned w/ body axes		
	COM		
Corners and next to payload			
COM	Aligned with body axes		
	Aligned with axes		
Near Engines (-Z face)	Buttons facing out (to hit the deployer)	Engines	
Slides in	Positvive X direction	N/A	In Final Assembly
Frame	N/A	N/A	Density: 2.680g/cm^3
Positive X	Facing outward	Engines	

Appendix C: Two-Line Elements

Line 1	
Column	**Description**
01	Line Number of Element Data
03-07	Satellite Number
08	Classification (U=Unclassified)
10-11	International Designator (Last two digits of launch year)
12-14	International Designator (Launch number of the year)
15-17	International Designator (Piece of the launch)
19-20	Epoch Year (Last two digits of year)
21-32	Epoch (Day of the year and fractional portion of the day)
34-43	First Time Derivative of the Mean Motion
45-52	Second Time Derivative of Mean Motion (Leading decimal point assumed)
54-61	BSTAR drag term (Leading decimal point assumed)
63	Ephemeris type
65-68	Element number
69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)

Line 2	
Column	**Description**
01	Line Number of Element Data
03-07	Satellite Number
09-16	Inclination [Degrees]
18-25	Right Ascension of the Ascending Node [Degrees]
27-33	Eccentricity (Leading decimal point assumed)
35-42	Argument of Perigee [Degrees]
44-51	Mean Anomaly [Degrees]
53-63	Mean Motion [Revs per day]
64-68	Revolution number at epoch [Revs]
69	Checksum (Modulo 10)

More documentation on Two Line elements can be found at the link below:

https://www.celestrak.com/NORAD/documentation/tle-fmt.php

Appendix D: MATLAB Script for STK-to-COMSOL Thermal Data Import

```
%% Preprocessing

% Load in the .csv's from STK

eLEO4UCubeSatSolarIntensity = csvread('eLEO4UCubeSatSolarIntensity.csv', 2, 1);

eLEO4UCubeSatSunVectorsFixed = csvread('eLEO4UCubeSatSunVectorsFixed.csv', 2, 1);

%% Processing Solar Intensity

% Name of SI table
Name_SI = eLEO4UCubeSatSolarIntensity/100;

SI = Name_SI;

%% Processing Sun Vectors

%Name of SV table
Name_SV = eLEO4UCubeSatSunVectorsFixed;

% Create unit vectors

magnitude = sqrt(Name_SV(:,1).^2+Name_SV(:,2).^2+Name_SV(:,3).^2);

Name_SVxkm = Name_SV(:,1)./magnitude;
Name_SVykm = Name_SV(:,2)./magnitude;
Name_SVzkm = Name_SV(:,3)./magnitude;

% Translate into Body-Fixed Axis in COMSOL Model
xu = Name_SVykm;
yu = -Name_SVxkm;
zu = Name_SVzkm;

```

```
% Labeled as
VarNames = {'TimeEpSec', 'posx', 'negx', 'posy' ,'negy' ,'posz' ,'negz'};
Suv = [xu yu zu];
Fn_u = [1 0 0; -1 0 0; 0 1 0; 0 -1 0; 0 0 1; 0 0 -1];
num = length(Suv);
cos_theta = zeros(1,6);
cos_theta_all = zeros(num,6);
for k = 1:num
    for face = 1:6
       cos_theta(k,face) = dot(Fn_u(face,:), Suv(k,:));
       if cos_theta(k,face) > 0
           cos_theta(k, face) = cos_theta(k,face);
       else
           cos_theta(k,face) = 0;
       end
    end
end

% Table Variables and Table
TimeEpSec = Name_SV(:,1);
posx = cos_theta(:,1);
negx = cos_theta(:,2);
posy = cos_theta(:,3);
negy = cos_theta(:,4);
posz = cos_theta(:,5);
negz = cos_theta(:,6);

cos_theta_xyz = table(TimeEpSec, posx, negx, posy, negy, posz, negz);
%% Save tables as a csv file

SI2 = table(eLEO4UCubeSatSolarIntensity(:,1), SI);
writetable(SI2, 'SI.csv')
writetable(cos_theta_xyz, 'cos_theta_xyz.csv')
```

Appendix E: Sample of Solar Intensity and Sun Vector Data

6U Solar Intensity - Notepad

File Edit Format View Help

```
"Time (UTCG)","Intensity"
7 Nov 2019 17:00:00.000,0.000000
7 Nov 2019 17:01:00.000,0.000000
7 Nov 2019 17:02:00.000,0.000000
7 Nov 2019 17:03:00.000,0.000000
7 Nov 2019 17:04:00.000,0.000000
7 Nov 2019 17:05:00.000,0.000000
7 Nov 2019 17:06:00.000,0.000000
7 Nov 2019 17:07:00.000,0.000000
7 Nov 2019 17:08:00.000,0.000000
7 Nov 2019 17:09:00.000,0.000000
7 Nov 2019 17:10:00.000,0.000000
7 Nov 2019 17:11:00.000,0.000000
7 Nov 2019 17:12:00.000,0.000000
7 Nov 2019 17:13:00.000,0.000000
7 Nov 2019 17:14:00.000,0.000000
7 Nov 2019 17:15:00.000,0.000000
7 Nov 2019 17:16:00.000,0.000000
7 Nov 2019 17:17:00.000,0.000000
7 Nov 2019 17:18:00.000,0.000000
7 Nov 2019 17:19:00.000,0.000000
7 Nov 2019 17:20:00.000,0.000000
7 Nov 2019 17:21:00.000,0.000000
7 Nov 2019 17:22:00.000,0.000000
7 Nov 2019 17:23:00.000,0.000000
7 Nov 2019 17:24:00.000,0.000000
7 Nov 2019 17:25:00.000,0.000000
7 Nov 2019 17:26:00.000,0.000000
7 Nov 2019 17:27:00.000,0.000000
7 Nov 2019 17:28:00.000,100.000000
7 Nov 2019 17:29:00.000,100.000000
7 Nov 2019 17:30:00.000,100.000000
7 Nov 2019 17:31:00.000,100.000000
7 Nov 2019 17:32:00.000,100.000000
7 Nov 2019 17:33:00.000,100.000000
7 Nov 2019 17:34:00.000,100.000000
7 Nov 2019 17:35:00.000,100.000000
7 Nov 2019 17:36:00.000,100.000000
7 Nov 2019 17:37:00.000,100.000000
7 Nov 2019 17:38:00.000,100.000000
7 Nov 2019 17:39:00.000,100.000000
7 Nov 2019 17:40:00.000,100.000000
```

6U Sun Vector Fixed - Notepad

File Edit Format View Help

```
"Time (UTCG)","x (km)","y (km)","z (km)"
7 Nov 2019 17:00:00.000,26935254.865551,-139701810.488899,-41681421.582287
7 Nov 2019 17:01:00.000,26325685.673225,-139817971.030420,-41682290.353279
7 Nov 2019 17:02:00.000,25715631.791375,-139931442.967459,-41683157.196627
7 Nov 2019 17:03:00.000,25105103.820967,-140042223.801371,-41684020.264769
7 Nov 2019 17:04:00.000,24494112.301753,-140150311.219014,-41684877.732111
7 Nov 2019 17:05:00.000,23882667.717591,-140255703.093130,-41685727.805595
7 Nov 2019 17:06:00.000,23270780.502141,-140358397.481839,-41686568.734996
7 Nov 2019 17:07:00.000,22658461.044927,-140458392.627243,-41687398.822837
7 Nov 2019 17:08:00.000,22045719.697704,-140555686.953164,-41688216.433866
7 Nov 2019 17:09:00.000,21432566.781046,-140650279.062074,-41689020.004001
7 Nov 2019 17:10:00.000,20819012.591111,-140742167.731239,-41689808.048684
7 Nov 2019 17:11:00.000,20205067.406504,-140831351.908147,-41690579.170601
7 Nov 2019 17:12:00.000,19590741.495244,-140917830.705263,-41691332.066695
7 Nov 2019 17:13:00.000,18976045.121676,-141001603.394188,-41692065.534461
7 Nov 2019 17:14:00.000,18360988.553352,-141082669.399291,-41692778.477474
7 Nov 2019 17:15:00.000,17745582.067792,-141161028.290880,-41693469.910148
7 Nov 2019 17:16:00.000,17129835.959112,-141236679.777979,-41694138.961707
7 Nov 2019 17:17:00.000,16513760.544431,-141309623.700800,-41694784.879377
7 Nov 2019 17:18:00.000,15897366.170049,-141379860.022969,-41695407.030797
7 Nov 2019 17:19:00.000,15280663.217374,-141447388.823583,-41696004.905677
7 Nov 2019 17:20:00.000,14663662.108534,-141512210.289158,-41696578.116718
7 Nov 2019 17:21:00.000,14046373.311689,-141574324.705542,-41697126.399826
7 Nov 2019 17:22:00.000,13428807.345987,-141633732.449837,-41697649.613652
7 Nov 2019 17:23:00.000,12810974.786215,-141690433.982401,-41698147.738498
7 Nov 2019 17:24:00.000,12192886.267046,-141744429.838968,-41698620.874629
7 Nov 2019 17:25:00.000,11574552.486982,-141795720.622929,-41699069.240025
7 Nov 2019 17:26:00.000,10955984.211890,-141844306.997815,-41699493.167638
7 Nov 2019 17:27:00.000,10337192.278230,-141890189.680023,-41699893.102167
7 Nov 2019 17:28:00.000,9718187.595911,-141933369.431785,-41700269.596430
7 Nov 2019 17:29:00.000,9098981.150818,-141973847.054438,-41700623.307341
7 Nov 2019 17:30:00.000,8479584.006991,-142011623.381981,-41700954.991568
7 Nov 2019 17:31:00.000,7860007.308544,-142046699.274946,-41701265.500874
7 Nov 2019 17:32:00.000,7240262.281221,-142079075.614588,-41701555.777221
7 Nov 2019 17:33:00.000,6620360.233705,-142108753.297397,-41701826.847629
7 Nov 2019 17:34:00.000,6000312.558618,-142135733.229933,-41702079.818856
7 Nov 2019 17:35:00.000,5380130.733312,-142160016.323982,-41702315.871907
7 Nov 2019 17:36:00.000,4759826.320351,-142181603.492031,-41702536.256410
7 Nov 2019 17:37:00.000,4139410.967821,-142200495.643042,-41702742.284877
7 Nov 2019 17:38:00.000,3518896.409357,-142216693.678540,-41702935.326870
7 Nov 2019 17:39:00.000,2898294.464011,-142230198.488982,-41703116.803098
7 Nov 2019 17:40:00.000,2277617.035885,-142241010.950411,-41703288.179443
```

Appendix F: Sample of Temperature Profile Data

6U no front plate temp data - Notepad

File Edit Format View Help

```
% Model,Christian- thermal simulation - 4.1 (no front plate).mph
% Version,COMSOL 5.3.1.348
% Date,"Feb 23 2020, 09:37"
% Dimension,3
% Nodes,9316
% Expressions,1
% Description,Surface
% X,Y,Z,Color
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