CECIL, 1U Amateur Radio CubeSat

A Technical Report submitted to the Department of Mechanical and Aerospace Engineering

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

The primary objective of this mission is to build and operate a satellite system that is able to reliably communicate with the UVA ground station and facilitate communication between amateur ground stations around the world. This will be accomplished at a low cost and with low risk of failure. To allow for data sharing and collaboration, the satellite will be designed to function within the bounds of an amateur radio license. This project will provide experience in both spacecraft design and project management to the students of the University of Virginia. The development of this CubeSat is crucial in promoting interest in space-exploration and real world technical skills in Virginia's next generation of engineers. Meeting the mission objectives, detailed below, will ensure accomplishment of these goals. This post-PDR all-encompassing design document will first go over the technology investigation required for the project, and then describe in detail the mission architecture, including mission requirements and constraints. This document also provides an in-depth look at each of the spacecraft subsystems and outlines the planned future activities, along with a specific timeline and budget to complete this project.

Technology Investigation and Implementation

The mission objectives for the 1U Amateur Radio CubeSat project are primarily educational in nature: UVA students will gain firsthand experience designing, building, and operating a satellite as part of a team. The satellite design will incorporate an experimental radio transceiver that will receive command for the satellite and transmit images taken by the onboard camera. The mission, if successful, will be considered a "technology demonstration" that will help demonstrate the legitimacy of space mission engineering here at UVA. The project team will design the CubeSat so that the mission objectives can be completed with a low risk of failure in order to ensure a high probability of successful communication with the satellite. The primary and secondary mission objectives are enumerated below:

Primary Objectives:

- High-probability of reliable communication on amateur radio frequencies
- Achievable with a budget similar to or less than previous similar projects
- Develop UVA engineering students' hands-on skills designing, building, and operating satellites
- Able to be used by the UVA ground station and others with amateur radios

Secondary Objectives:

- Promote space-exploration interest and the development of real world technical skills in Virginia's next generation of engineers

The design team decided on the Mission Architecture and Requirements below in order to successfully meet these objectives.

Mission Architecture

In this section, CECIL's mission architecture is outlined in Table 1 below and a detailed explanation of each element follows after.

Table 1: Mission Architecture

Element	Description
Subject	Visible light Earth imagery and Amateur radio community communications
Payload	Radio transceiver, transponder, low resolution camera
Spacecraft bus	Two-axis passive stabilization, passive solar array
Launch system	Antares or Falcon 9
Orbits	LEO, i = 51 deg, e = 0.0006
Ground segment	UVA ground station
Communications architecture	Direct to station, single-ground station control
Missions operations	Part-time operation ground station, partial spacecraft autonomy
Mission concept	Low-resolution Earth imagery, transponder on amateur radio frequencies, communications from LEO

Mission Concept

This mission will carry a radio provided by AMSAT and a camera, with the primary goal of establishing communications between a satellite in Low Earth Orbit (LEO) and the UVA ground station. The AMSAT transceiver will also serve as a repeater operating on amateur frequencies, simplifying long-distance communication among the global amateur radio community. Additionally, the satellite will have the ability to take pictures that will be transmitted to the UVA ground station and distributed through social media.

Subject

There are two subjects of this mission, the radio transmissions on amateur frequencies and the images from the camera. The radio transceiver will establish communication with the UVA ground station and act as a repeater for the amateur radio community. The camera will capture images that can be received by UVA's ground station and then distributed online.

Payload

The payload for this CubeSat will include a radio transceiver and a camera. The camera will be used to take photographs of the Earth on command by UVA's ground station. The radio transceiver will be responsible for the satellite command and control as well as transmitting the images taken by the camera. The radio transceiver will also be capable of repeating incoming messages from amateur ground stations. The radio transceiver and camera are discussed at length in the spacecraft subsystems section.

Spacecraft Bus

The structure used in this mission is the EnduroSat 1U CubeSat Structure. This structure has flight heritage with NanoRacks, the system we are using to launch our satellite, making the EnduroSat structure ideal for our satellite. The method to determine attitude and control will be neodymium magnets with hysteresis rods. These will ensure that our spacecraft will point at the Earth, while taking up very little space within the satellite. The Kryton M3 on-board computer will be used to run the satellite, while the Starbuck PICO EPS and battery will be used to distribute and store power for the satellite. EnduroSat 1U solar panels will be used on the Y, Z, and negative X faces of the satellite. These solar panels will be able to generate more than enough power for the satellite, as discussed later in the power budget. This ensures that the EPS will have plenty of power to keep the satellite running when out of the sun's light. We will require both Ultra High (UHF) and Very High Frequencies (VHF) in order to communicate effectively using the AMSAT Linear Transponder Module. The ISIS Antenna Array operates at both of these frequency ranges and allows for a solar panel to be installed on top of it, making it an appropriate choice for this satellite.

Ground System

The UVA ground station will be used as the primary method of communication with the satellite while in orbit. Initially, UVA's ground station will be the only ground station capable of commanding the satellite, downloading telemetry data, and downloading images taken by the satellite. UVA's ground station uses two circularly polarized yagi antennas from M2 Antenna Systems, a FG2MCP14 antenna (12.34dB gain) and a FG436CP30 antenna (15.5dB gain), to establish and maintain communications. After all mission objectives have been accomplished, and UVA has performed all desired tests, AMSAT will be given commanding privileges of the CubeSat at UVA's discretion.

Amateur radio ground stations around the world will be given access to the satellite's repeater capabilities, once nominal operation has commenced.

Command, Control, and Communications Architecture

According to current FCC regulations (Part 97), command and control signals are the only encrypted transmissions allowed on the amateur band. The radio transceiver will be used to send commands to the spacecraft as well as to transmit telemetry data and images. The majority of the control of the spacecraft will go only through the ground station at UVA. Should the need arise, however, it would be relatively simple to transfer control to another ground station. AMSAT will likely be given some command privileges once the spacecraft enters nominal operation.

The radio transceiver will also be open for any amateur radio station to use as a repeater. Signals of this kind will be received at 144 MHz and retransmitted at 432 MHz, dramatically increasing the effective range of most amateurs.

Selected Orbit

The orbit of the satellite is out of the control of the operators and will depend on where and how it is launched. The CubeSat will be deployed from the International Space Station (ISS), and thus will initially have a very similar orbit. The orbital shape is slightly eccentric, practically circular, with an average altitude of approximately 400 km. These orbital elements are subject to change over the lifetime of the CubeSat, because atmospheric drag will decrease its altitude. A rough estimation of the ground tracks of the orbit can be found in Figure 1.

Figure 1: Predicted Orbit of the CECIL CubeSat

Launch System

The mission is intended to launch through NASA's CubeSat Launch Initiative (CSLI). This program provides an opportunity for educational and research CubeSats to be sent to the ISS as secondary payloads on a launch vehicle, typically Antares or Falcon 9, and deployed by a NanoRacks CubeSat Deployer (NRCSD).

Mission Requirements and Verification

This section describes all of the mission's system level and operational requirements, as well as the functional requirements and constraints. Outlined in the tables below are detailed descriptions of each requirement, a label number, a rationale as to why that requirement exists, and the verification method that will be implemented. Table 2 includes the functional system level requirements and Table 3 lists the operational system level requirements.

Table 2: Functional System Level Requirements

ID	Requirement	Specification	Rationale	Verification Method (Testing, Analysis, Inspection)
SYS-FUNC-01	Flight Heritage	All subsystem components must have previous flight heritage	To ensure high likelihood of mission success	Inspection

SYS-FUNC-02	Coverage	CubeSat must be able to be contacted at least twice weekly by the UVA ground station	To have up-to-date status on satellite’s health and data	Analysis
SYS-FUNC-03	Amateur Radio Frequency	The satellite must transmit through an amateur radio frequency	To be able to communicate with amateur ground station other than UVA	Inspection

Table 3: Operational System Level Requirements

ID	System	Requirement	Specification	Rationale	Verification Method (Testing, Analysis, Inspection)
OPER-001	PROJ	Probability of primary mission success (%)	>95	To provide a reasonable chance that the spacecraft is able to be of use	Analysis
OPER-002	PROJ	Total cost ($)	<65000	To stay within a price range that we are likely to be able to get funding for	Cost Tracking
OPER-003	PROJ	Be built and tested in part by UVA students	Primarily assembled and tested by UVA students	To provide hands-on experience and skills to UVA students	Inspection
OPER-004	PROJ	Mission Timescale	The mission will be completed by the second quarter of 2022 calendar year	To ensure timescale adherence and reduce potential budget increases	Inspection
OPER-005	AV	Satellite Tracking Software	Position of the satellite must be predicted using a software tool with 90% accuracy	In order to adequately predicted and schedule communication windows	Analysis

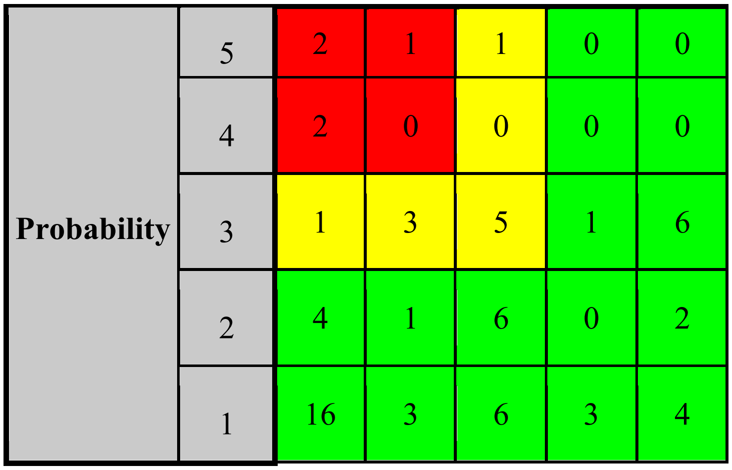
Functional Requirements and Constraints

For a complete list detailing all functional requirements and constraints, please refer to the Requirements Definition document in Appendix A.

Risk Management

Currently, seventy-three potential risks have been identified and quantified in two categories: probability and severity. Each category has a ranking from 1 to 5 where 1 is the lowest denomination (very low probability of occurring, very low severity if problem arises), and 5 is the highest denomination (very high \probability of occurring, very high severity if problem arises). The probability and severity denominations for each risk were then multiplied to yield an "overall severity" denomination for each risk. Figure 2 shows the number of identified risks that fall under each category of ranking. For the complete list of all identified risks, please refer to the risk register document on Appendix B.

Severity				
5	4	3	2	1



Probability	5	2	1	1	0	0
	4	2	0	0	0	0
	3	1	3	5	1	6
	2	4	1	6	0	2
	1	16	3	6	3	4

Figure 2: Number of Identified Risks

The management team decided that only risks amounting to an overall severity of twenty or higher (4 or 5 probability of occurrence and 4 or 5 severity if occur) required closer look and a mitigation strategy. Four total risks amounting to such overall severity were identified. Table 4 below, describes what each of these risks are, which team is responsible for the risk, and how it will impact the mission objectives.

Table 4: Identified High Severity & High Probability Risks

Subteam	ID	Condition	Departure	Consequence
Communications	RISK-006	The UVA ground station will be used to control the CubeSat and command pictures from orbit	The ground station is unable to communicate with the CubeSat	Delayed mission timeline at minimum with the possibility of failure to meet primary objectives 1,2, and 4 if communication can not be established
Power and Thermal	RISK-013	The CubeSat electronics will turn on after release from the P-Pod deployer	The electronics don't turn on after deployment	Failure to meet primary objectives 1,2, and 4 if communication can not be established
Software and Avionics	RISK-036	The CubeSat flight computer will boot after release from the P-Pod deployer	The flight computer does not boot in a flight ready configuration	Failure to meet primary objectives 1,2, and 4 if communication can not be established
Program Management	RISK-026	One aim for this project is to minimize expenses and this may be difficult to maintain	The project may exceed the amount of funding available to the team	The project completion may be put on hold until additional funding is found. The CSLI may de-manifest our CubeSat if timeline is not met

Program Management	RISK-028	The CECIL project will be transferred to next year's students involved in this capstone	Institutional knowledge may be lost during the transfer to a new group	The new team may have to re-complete work done by the previous year’s students

Mitigation Strategy

As discussed in the previous section, only four risks (RISK-006, -013, -026, -028, -036) were considered severe enough to warrant a specific mitigation strategy. Table 5 provides the current mitigation strategy in order to minimize either the probability of each risk or their impact to the mission objectives.

Table 5: High Overall Severity Risk Mitigation Strategy

ID	Subteam	Risk	Mitigation strategy
RISK-006	Communications	Ground station communication issues	Ground based testing with flat sat and additional experience gained through 3U CubeSat
RISK-013	Power and Thermal	Electronics failure at release	Ground based deployment testing
RISK-036	Software and Avionics	Flight computer failure at release	Ground based deployment testing
RISK-026	Program Management	Total project cost overrun	Seek funding from multiple sources
RISK-028	Program Management	Loss of institutional knowledge	Thorough documentation of major project design features including: ● Mission architecture and concept of operations ● Requirements, constraint, and risk registers

Next, the CubeSat’s subsystems- Structure, Power, Communications, Attitude Determination and Control, and Software and Avionics- and their components are described in detail. The Mission Status section will detail, by subsystem, the work that has been completed in each one thus far, and what work will be done next.

Spacecraft Subsystems

Structure Subsystem

Spacecraft Structure

The EnduroSat 1U Structure was selected to serve as the frame for the satellite. This structure was selected because it meets NASA's CSLI and NRCSD requirements. In addition, the structure is easily integrated with the EnduroSat 1U Solar Panels, which were selected by the Power, Thermal, and Environment team to serve as the primary power source for the satellite. Further, the EnduroSat structure has a more open design than 1U structures offered by other vendors. The space between the rails on the X and Y faces is not occupied by load-bearing ribs or spars. This space allows for easy integration of the Raspberry Pi camera on the positive X face of the EnduroSat structure.

The satellite components selected for other subsystems mainly consist of commercial off-the-shelf components. These components will be secured to the EnduroSat 1U structure using one of three methods: threaded bolts, threaded spacers, or a NASA compliant low-outgassing epoxy. The following table summarizes how each component will be fixed to the structure.

Table 6: Integration of Subsystem Components with EnduroSat 1U Structure

Component	Manufacturer	Mode of Fixture	Fixture Specifications
Pi Zero W	Raspberry Pi Foundation	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN
Raspberry Pi Aluminum Case	Custom	Threaded spacers	Custom threaded spacers
Raspberry Pi Aluminum Case Lid	Custom	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN
1U Solar Panel X/Y (x3)	EnduroSat	Threaded bolts	Torx - DIN965/ISO 7046-1 - M3 - Length: 6mm
1U Solar Panel Z (x2)	EnduroSat	Threaded bolts	Torx - DIN965/ISO 7046-1 - M3 - Length: 6mm
Aluminum Panel (x1)	Custom	Threaded bolts	Torx - DIN965/ISO 7046-1 - M3 - Length: 6mm
Deployable Antenna System	ISIS	Threaded bolts	Torx - DIN965/ISO 7046-1 - M3 - Length: 6mm
Starbuck PICO EPS and Battery	AAC Clyde Space	Threaded spacers	Custom threaded spacers
Camera Board v2 - 8 Megapixels	Raspberry Pi Foundation	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN
Camera Board Aluminum Case	Custom	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN
Camera Board Case Lid	Custom	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN
Linear Transponder Module	AMSAT	Threaded spacers	Custom threaded spacers
Kryten-M3	AAC Clyde Space	Threaded spacers	Custom threaded spacers

Hysteresis Rods	--	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN
Permanent Magnet	--	NASA Low Outgassing Compliant Epoxy	20-3652 EPOXY RESIN

The solar panels and aluminum panel will be secured to the structure using the threaded bolts that EnduroSat provides with the components. The aluminum panel will cover the positive X face of the satellite. It contains a portal for the Raspberry Pi camera, and has connector sockets for the remove before flight (RBF) pin and the satellite communication interface. The latter provides a mechanism for charging the battery and EPS without accessing the satellite's interior. This panel is essentially a modified EnduroSat 1U Solar Panel X/Y, and may be custom-ordered from EnduroSat. The ISIS deployable antenna system and the lid to the aluminum Raspberry Pi case will also be secured with threaded bolts. ISIS will provide the bolts used to secure the antenna to the positive Z face of the satellite structure. The bolts used to secure the lid to the aluminum Raspberry Pi case must be purchased separately.

The interior stack components are the AMSAT linear transponder, AAC Clyde Space Kryten M3 onboard flight computer, AAC Clyde Space Starbuck PICO battery and EPS, and the Raspberry Pi Zero W aluminum case. These interior stack components will be secured to the 1U structure using threaded spacers. These threaded spacers must be individually-machined in order to accommodate the AMSAT transceiver. The transceiver was designed for custom AMSAT CubeSat structures that do not have standard 1U dimensions. Thus, a set of threaded brackets was modeled to realign the transceiver spacers with the rod and spacer hole pattern on the EnduroSat structure. These custom brackets are shown below in Figure 3 and highlighted in blue.

AMSAT Linear Transponder Module Stack With Custom Threaded Brackets

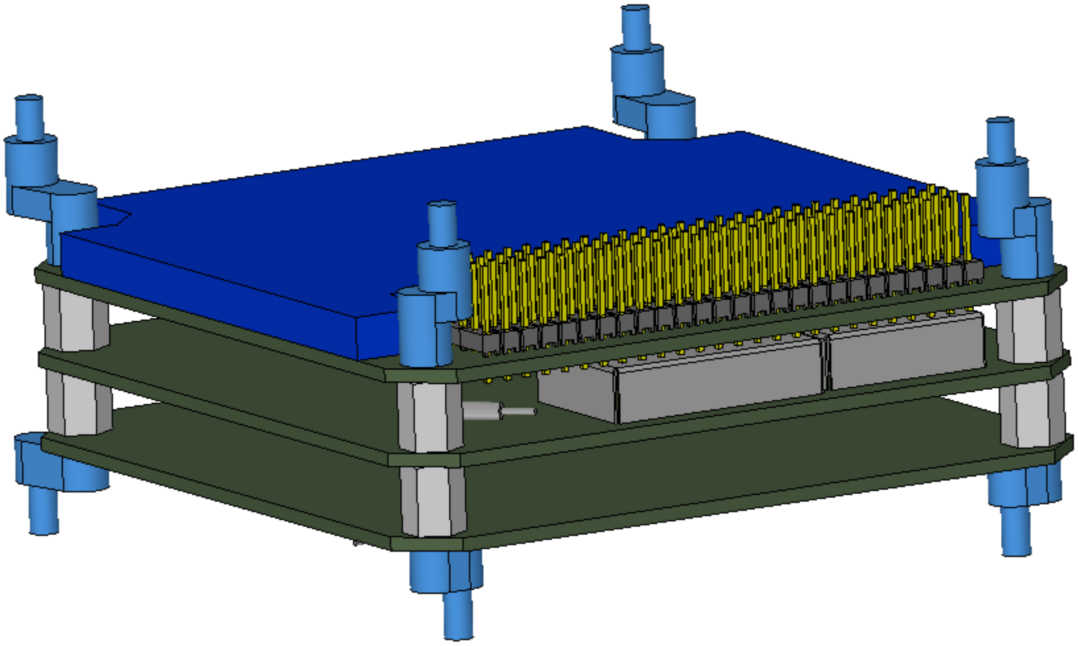
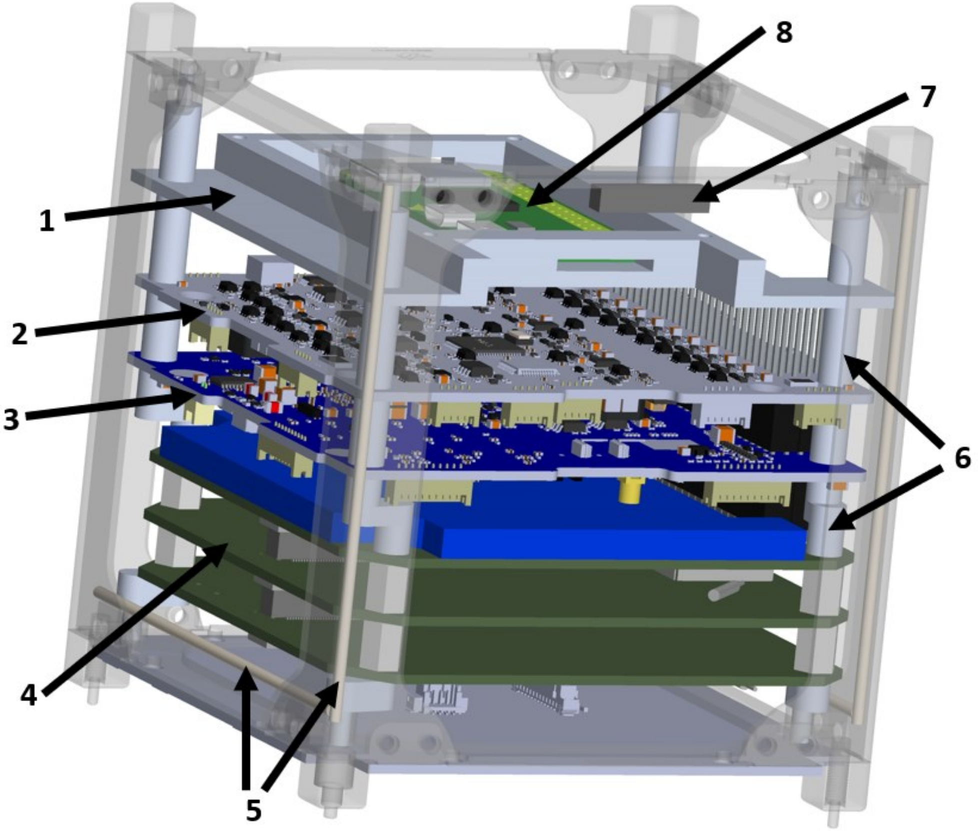


Figure 3: Custom threaded brackets, highlighted in blue, align the AMSAT transceiver with EnduroSat 1U Structure hole patterns for both mechanical and electrical integration

Standard threaded spacers may be used to secure the remaining interior stack components to the 1U structure. However, the length of these spacers will need to be adjusted in order to apply a gentle compressive force on the stack and ensure that it remains stationary. The interior stack and threaded spacers are shown in Figure 4 below. It is important to note that these custom spacers not only allow for mechanical integration between the interior stack and 1U structure, but also ensure alignment of the PC/104 buses on the transceiver, onboard flight computer, and EPS. Thus, the custom spacers allow for mechanical and electrical integration. Figure 5 below shows how these spacers allow for proper alignment of the PC/104 buses.

Interior Components



Number	Component
1	Raspberry Pi Zero W Custom Aluminum Casing
2	AAC Clyde Space Starbuck PICO EPS and Battery

3	AAC Clyde Space Kryten-M3
4	AMSAT Linear Transponder Module
5	Hysteresis Rods
6	Custom Threaded Spacers
7	Permanent Magnet
8	Raspberry Pi Zero W

Figure 4: Interior of CECIL with labels indicating the components within the main stack. The ADACS components (permanent magnet and hysteresis rods) are also indicated.

PC/104 Bus Alignment

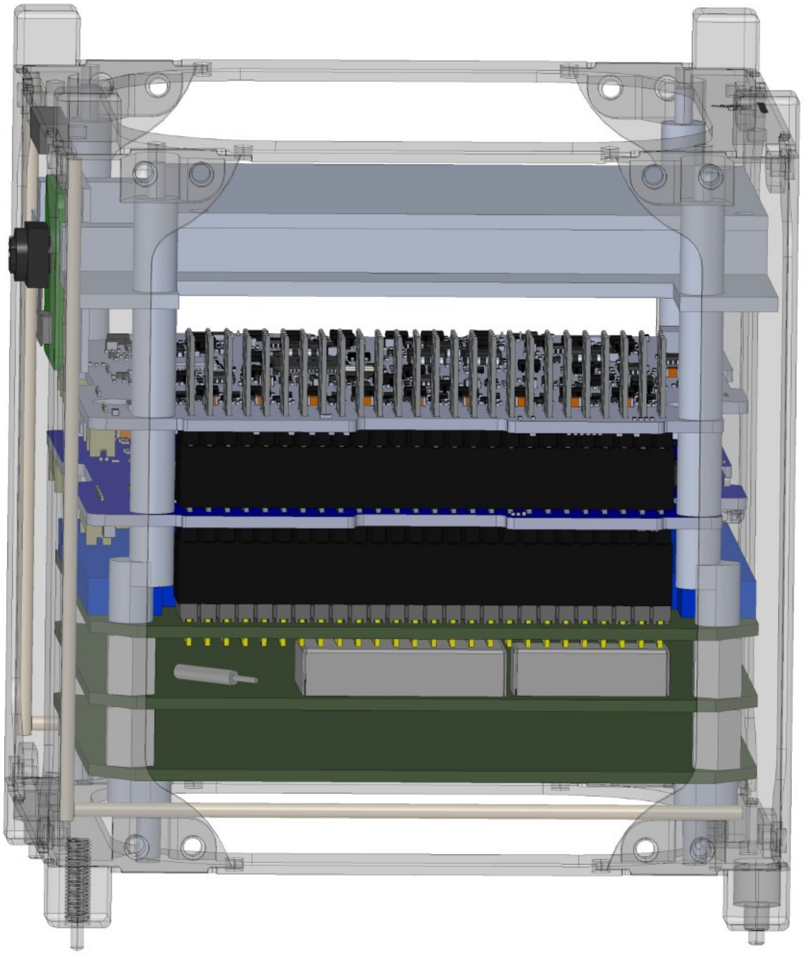
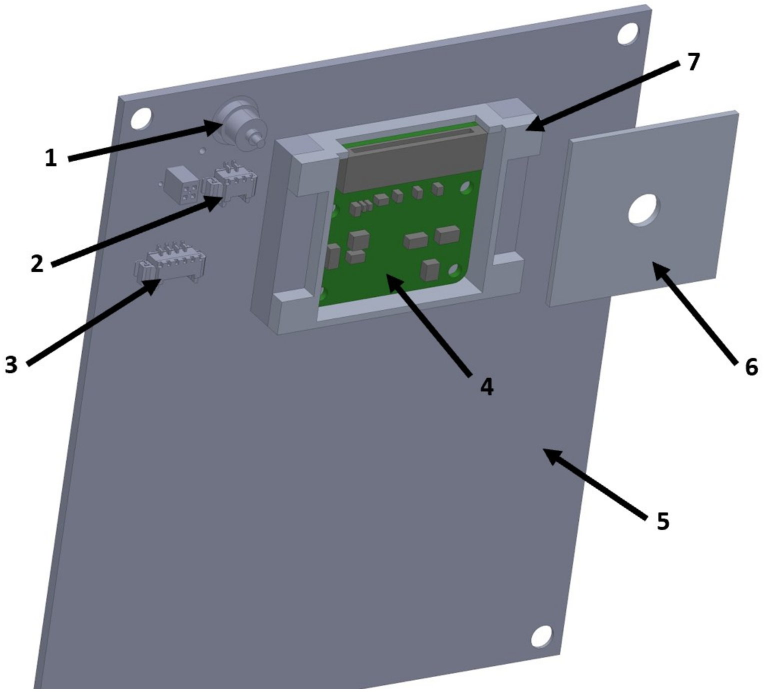


Figure 5: Custom threaded brackets at the top and bottom of the AMSAT transceiver allow for alignment of the PC/104 buses on the transceiver, onboard flight computer, and EPS.

The Raspberry Pi Zero W, Raspberry Pi camera, aluminum camera case, permanent magnet, and hysteresis rods will be secured within the satellite bus using a NASA compliant low-outgassing epoxy. The Raspberry Pi Zero W will be epoxied to the interior of the aluminum case. This case will be secured within the structure using threaded spacers as discussed above. The Raspberry Pi camera will be secured within an aluminum case with a low-outgassing epoxy. This case will in turn be epoxied to the inside of the aluminum panel. This configuration is shown in Figure 6 below. The Raspberry Pi Zero W and Raspberry Pi camera must be placed within aluminum cases in order to ensure that they are not damaged by radiation.

Interior of +X Face Aluminum Panel



Number	Component
1	RBF Pin Connector Socket
2	RBF Pin Interface
3	Satellite Communication Interface
4	Raspberry Pi Camera v2
5	Custom Aluminum Plate Cover
6	Raspberry Pi Camera Custom Aluminum Case Lid
7	Raspberry Pi Camera Custom Aluminum Case

Figure 6: Interior of +X face aluminum panel with labels for each component.

The permanent magnet will be epoxied below the top support of the structure on the +X/+Z face. Four hysteresis rods will be epoxied to the following edges within the CubeSat: +X/+Y edge, +X/-Y edge, +Y/-Z edge, and -Y/-Z edge. The permanent magnet and hysteresis rod placement can be seen in the “Interior Components” figure (Figure 4) above.

Flight Loads and Safety Factor

Another role of the structures subsystem team is to ensure the safety of the spacecraft and mission following launch. As a result, acceleration loads, random vibration loads, launch shock, launch accelerations, and an integrated loads environment were all taken into account in relation to the overall structure and integration of this 1U CubeSat. Figures for the expected loads for this mission were provided by NanoRacks in their 1U CubeSat documentation, a link to which can be found in the references section. To further ensure the safety of the spacecraft during launch, a minimum structural and integration safety factor of 1.5 was decided for this CubeSat. Table 7 outlines the expected loads provided by NanoRacks as well as the adjusted loads to meet this minimum safety factor

Table 7: Expected and Safety Factor Adjusted Loads

Requirement	Given Criteria	Criteria Based on Factor of Safety of 1.5
Acceleration loads (g)	Nx: +-7, Ny: +-4, Nz: +-4	Nx: +-10.5, Ny: +-6, Nz: +-6
Random Vibration loads	See Random Vibration Table	See Random Vibration Table
Launch Shock	“Soft Stow Storage does not experience significant mechanical shock”	N/A
Launch Accelerations (m/sec^2)*	On-Orbit acceleration: 2	N/A, described below
	Air-Lock Carryout: 1.5	
	Emergency Stop: .69	
Integrated Loads Environment**	1200 N across all rail ends in the Z axis	1800N

* “These loads are enveloped by the launch, ground handling, and quasi-static analysis loads. No

verification data shall be required." Because of this, we will not have to design above the given criteria.

** "This number is conservative and will be refined based on qualification testing and further analyses by NanoRacks."

Spacecraft Power Subsystem

Battery/EPS

The ClydeSpace Starbuck Nano-Pico EPS module with integrated 20Wh battery will transmit power to the camera control board, flight computer, and AMSAT radio, as shown below in Figure 7, the Data and Power Flowchart. The following considerations, drawn from the power subsystem functional requirements, drove the selection of this EPS module (over the EnduroSat EPS): weight, dimensions, and electrical integration with the necessary components, particularly the selected Clyde Space Kryten M3 flight computer. A weight of 189.525 g or less (including the integrated battery), minimized dimensions (due to tight space constraints in the CubeSat, see Figure 4 above), and full electrical integration with the flight computer are required of the EPS. The integrated 20-Wh battery has enough capacity to hold the power required for the CubeSat to function through the entire duration of an eclipse, which is a crucial requirement but was not a major driver of the decision to use the Clyde Space EPS. The EPS and battery are 246 g, which represents an accepted noncompliance with functional requirements. The reason the noncompliance is accepted is that the decision to exclude an (unnecessary) GPS from the CubeSat design left ample allowed mass remaining in the design. Its dimensions are 9.589 x 9.017 x 2.74 cm, making it the smaller of the two EPS modules considered. To power the components, voltage outputs of 3.3, 5, 7, and 7.5 V are required of the EPS, and the ClydeSpace Starbuck Nano-Pico EPS module has 3.3, 5, and 12-V outputs. Step-down voltage regulators will be used for integration with components requiring 7 and 7.5-V inputs. Finally, the vendor selected ensures full electrical integration with the flight computer of the same vendor.

Solar Panels

Five solar panels will generate the power for the CubeSat's power-drawing components (camera and camera control board, AMSAT radio, the integrated battery heaters in the EPS, flight computer, and antenna) and charge the battery. The solar panels will be placed on the Y, Z, and negative X faces of the satellite. The following considerations, drawn from the power subsystem functional requirements, drove the selection of the EnduroSat 1U solar panels (over the Clyde Space 1U solar panels): integration (electrical and mechanical), cost, and performance. Full electrical and mechanical compatibility, a total cost (for all five panels) of $13,830 or less, and power generation sufficient to support all mission functions are required of the solar array. Support of mission functions includes powering the payload and other components, and generating enough excess power to charge the battery so the CubeSat can operate during eclipse periods. Size requirements, i.e. weight of less than 50 g per panel and area to fit on a 10 x 10 cm CubeSat face, were also important requirements for the solar panels, but they were not as significant in driving the selection. The EnduroSat solar panels boast full (mechanical) compatibility with the selected EnduroSat 1U CubeSat structure, adaptable (electrical) compatibility with the selected ClydeSpace Starbuck Nano-Pico EPS module with integrated 20

Wh battery, a total cost of $8150 (for all five panels), and a maximum power in LEO of 2.4 W (for two panels). Preliminary analysis indicates that the EnduroSat panels will meet the applicable power subsystem functional requirements.

The EnduroSat solar panel power cable, included with the panels, has a default connector that will not integrate electrically with the selected Clyde Space EPS module without adaptation. The EPS has five-contact Hirose DF13-5P-1.25DSA(50) solar array input connectors, while the solar panel power cable has four-contact Molex 51021-04001 default (output) connectors. However, EnduroSat offers customized power cables and connectors upon request. Customized EnduroSat cables with connectors that will integrate with the Clyde Space EPS connectors are the chosen adaptation to ensure compatibility between the components, even though they are from different vendors. A previous UVA CubeSat mission selected the same adaptation for their satellite design, with integration success despite some coordination and customer service setbacks in acquiring the modified cables. An alternate design option for a single-vendor CubeSat structure, flight computer, EPS, and solar panel configuration is detailed in Appendix D.

Data and Power Flowchart

The solar panels and battery will be the sources of power for the spacecraft. The power will move through the EPS to the rest of the components. This relationship is seen below in Figure 7.

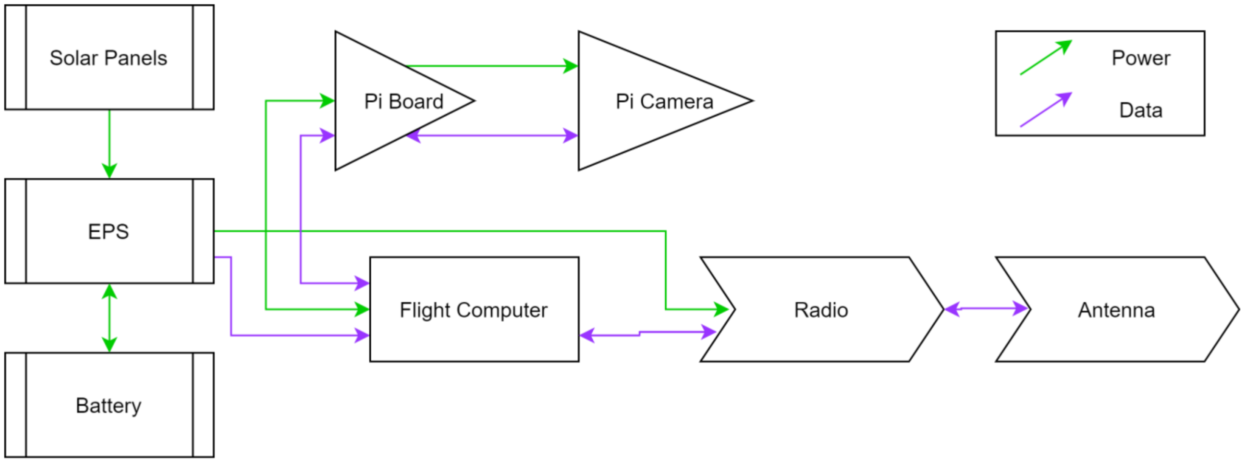


Figure 7: Data and Power Flowchart

Communications Subsystem

Radio Transceiver

The transmission and reception of radio signals will be handled by the AMSAT Linear Transponder Module (LTM). The LTM receives messages on the VHF band at 144 MHz and transmits on the UHF band at 432 MHz at a signal strength of 450 mW. Encrypted command and control signals will be sent from the UVA ground station or other permitted station and decoded using the software library provided by AMSAT. The spacecraft will transmit unencrypted telemetry, health signals, and Slow-Scan TeleVision (SSTV) pictures at regular intervals. Lastly, the transceiver will passively serve as a repeater, receiving signals on VHF and rebroadcasting them on UHF. This is a relatively easy way for amateurs to dramatically increase their effective communication range. The onboard processing of all signals is discussed in depth in the Software and Avionics section.

Antenna

The antenna that will be used is the ISIS Space Crossed UHF and VHF Dipoles (CDUV). The power pattern, shown in Figure 8, was deemed acceptable for our link budget and it integrates well with the LTM and the EnduroSat chassis. The UHF and VHF dipoles are both flexible, deployable, and measure 17 cm and 53 cm in length, respectively.

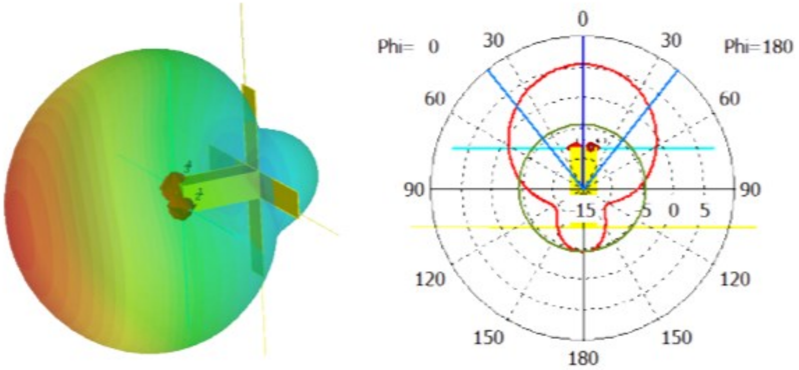


Figure 8: ISIS CDUV Antenna Power Pattern

Attitude Determination and Control Subsystem

Attitude Control

The method of controlling the attitude of the spacecraft will be through the usage of passive magnetic stabilization, which does not allow for active control of the orientation but does ensure that a consistent orientation can be established. This system consists of magnets placed at one edge of the satellite and hysteresis rods on the opposite side. These magnets will allow the satellite to always be aligned with the Earth's magnetic field, and will most likely be placed on the edge of the satellite that has the camera. Hysteresis rods will be placed in the CubeSat to add damping and avoid oscillation due to the push and pull of the Earth's magnetic field. In addition to the Passive Magnetic Stabilization system, the solar panels on the CubeSat will also include sun sensors, which will allow the operators of the satellite to determine the attitude of the satellite based on the rays of sunlight hitting it. The passive magnetic stabilization system will only provide stability on two axes, so the CubeSat will most likely rotate slowly along its Z-axis.

There are a few ways that students can figure out when the camera is pointed at the Earth. First, they can use the sun sensors to determine the orientation of the satellite with respect to the Earth. The other way to determine when to take pictures is to determine the rotation rate of the satellite, and then send a signal to take images at certain time intervals. The rotation of the CubeSat will likely be very slow, so there would definitely be a long window of time in which photographs can be taken.

Software and Avionics

Flight Computer

The Clyde Space Kryten M3 was the flight computer chosen for the satellite, with specifications listed in Table 8. Key considerations were power usage, processor speed, memory, storage, radiation toleration, and integration. The flight computer will handle all health and operational data, while leaving image capture and processing to the Raspberry Pi camera system. Maximum power usage was an important factor because the flight computer needs to stay within the allotted power budget. Processor speed, memory, and storage necessary for the operation of satellite as a whole to be fast and highly responsive. Radiation tolerance allows the satellite to be resistant to single-event effects in the logic and data storage.

Table 8: Criteria used in Choosing a Flight Computer

Criteria	Value
Price ($)	7280
Mass (g)	62
Maximum Power Usage (W)	1.00
Flight Heritage (Yes/No)	Yes
Radiation Tolerance (krad)	20
Footprint (mm^2)	8646
Depth (mm)	6
Customer Support (Qualitative)	Good
Supported Data Transmission (Types)	6
Processor Speed (MHz)	50
Memory (MB)	8
Maximum Storage (GB)	1028
Temperature Sensors	0
Accelerometers	0
Gyros	1
Magnetometers	1
Software Integration (Qualitative)	3

Hardware Integration (Qualitative)	3

Software

The flight computer will run Real Time Operating System (RTOS) using the licensed free version of the software. A modular, component-based framework will be programmed using GenerationOne SDK. This is a C-based program including pre-tested components. The Raspberry Pi camera system may be run in FreeRTOS to be cohesive with the flight computer, or another appropriate operating system. A scheme of how data will be handled by the two systems is shown in Figure 9.

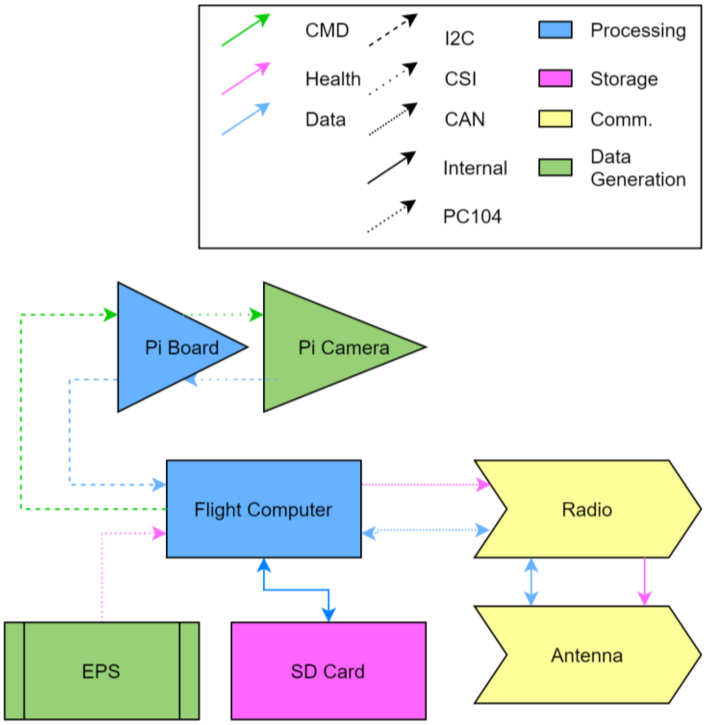


Figure 9: Data Flow Between CubeSat Components.

Camera

The camera that was chosen for this mission is the Raspberry Pi Camera Module v2 connected to a Raspberry Pi Zero. This combination was chosen for a number of reasons including the high resolution of the camera (relative to other cameras of a similar size that were considered), the low cost of the components, the fact that it allows camera operations to be handled largely separately from the primary flight computer, and the fact that, because it is widely used in applications outside of just spacecraft, there is significantly more information and support available for it than any of the other cameras assessed for use.

There are some additional considerations in using the Pi camera, since it is not originally designed for use on a satellite, primarily the questions of whether it will in fact work in space in the first place and how well it will handle long term exposure. On the first front, this combination has been flown before and has been proven to work on the Surrey Satellite Technology Ltd DoT-1 spacecraft in July of 2019 (SSTL, 2019). As to long term operability, although no information was available for the radiation tolerance of the Raspberry Pi Zero and the Pi camera specifically (nor was it available for many of the other cameras), a NASA study indicated that the Raspberry Pi Model B remained consistently operational to a total induced dosage of 40 krad, 20 krad over the rating of the only camera that had such information available as well as most of the CubeSat-rated flight computers (Violette, D. P., 2014). Because there is still some concern, and because the Raspberry Pi is not protected against single event errors, additional aluminum shielding will be placed around both the computer board and the camera module.

The resolution of the Pi camera combined with a 25-mm lens and the altitude of the orbit give it a Ground Sampling Distance (GSD) of approximately 15 m/pixel. At this resolution, terrain should be readily recognizable, but it stays well below the resolution of most commercial satellites (which vary from around 1.2 to 22 m/pixel), so there should be no issue with getting a license from NOAA (NOAA, 2020). Table 9 includes a full list of the criteria that were used in deciding to use the Pi camera.

Table 9: Criteria used in Choosing a Camera

Criteria	Value
Ground Resolution (from 400 km) (m/pixel)	15
Price ($)	80
Mass (g)	81
Maximum Power Usage (W)	1.679
Supported Data Transmission (Types)	4
Flight Heritage (Yes/No)	Yes
Footprint (mm^2)	1296
Depth (mm)	38
Customer Support (Qualitative)	Excellent
Impact on Other Objectives in Case of Failure (Qualitative)	None

Mission Status

Structures and Integration

The foundation of the CubeSat has been solidified. The structure as well as the solar panels and their layout has been designed and accepted. The power and thermal systems, including the battery and EPS have been selected and integrated into the structure. The antenna for communication between the satellite and ground station has been integrated into the design with the solar panels and the structure. The Raspberry Pi camera being used has been fitted into a custom designed housing and side panel in order to integrate the camera and other electrical sockets into the side of the satellite. The onboard computer system has been integrated into the structure of the CubeSat as well. The permanent magnets and hysteresis rods have been selected and integrated into the structure with the help of the ADACS and Orbits team. The linear transponder provided to us by the Amateur Radio Society required the design of custom brackets in order to integrate this device into the structure. The custom brackets are made from an aluminum 6061 alloy, and are designed to keep the transponder centered in the structure while ensuring it is rigidly connected at the four corners of the device. The brackets also provide for electrical integration by ensuring alignment of the PC/104 buses on the AMSAT transponder, onboard flight computer, and EPS.

The design requirements put forth by NanoRacks and NASA have been reviewed in order to determine what needs to be done to meet these requirements. Most of the requirements listed involve tests that the CubeSat structure, provided by EnduroSat, has already been tested for through previous missions and product flight heritage. These tests will still be performed before the launch of the satellite. However, the structure and its components all have flight heritage, and were likely put through these same tests in previous missions. Other components and items in the design requirements have met compliance through the literature provided by the manufacturers, which lets us know the dimensions and properties of the components that have been selected.

The mass budget for the spacecraft has also been finalized and approved by the rest of the team. The satellite uses 73.7% of the maximum mass of 1.33 kg allowed by NanoRacks. This leaves 26.3% of free mass open to be allocated in the future in case other subsystem components need to be modified or replaced. The finalized mass budget is shown below in Table 10. The AMSAT Linear Transponder Module is the largest device in the spacecraft, weighing 130 g, and takes up the most volumetric space of any component. While the mass of the satellite is below 75% of the maximum allowed weight, little free space remains within the satellite interior. Both the AMSAT transponder and AAC Clyde Space battery and EPS exceed their budgeted masses of 189.5 g and 106 g, respectively. However, a GPS was ultimately not incorporated into the final structure of the satellite, and 26.3% of the allowed maximum mass remains available. Thus, it was determined that the extra mass in the transponder and EPS could be tolerated. The final model for the spacecraft shown above in Figure 4 displays the placement of the devices and modules in the spacecraft.

Table 10: Mass Budget

Subsystem	Component	Mass (g)	Assigned Mass Percentage
Instruments	Raspberry Pi Camera	3.4	0.56%
	Raspberry Pi Zero	4	
Structure and Mechanisms	EnduroSat 1U CubeSat Structure	98	7.37%
	Threaded Spacers	20.5	1.54%
	Custom Raspberry Pi Board Case	83.54	6.28%
	Custom Raspberry Pi Camera Case	5.57	0.42%
	Custom Aluminum Panel	14.35	1.08%

Power	EnduroSat 1U Solar Panel Z (x2)	48	7.22%
	EnduroSat 1U Solar Panel X/Y (x3)	44	9.92%
	ISIS Deployable Antenna System	85	6.39%
	AAC Clyde Space Starbuck PICO EPS and Battery	246	18.50%
Telemetry, Tracking and Command	AMSAT Linear Transponder Module	130	9.77%
On-Board Processing	AAC Clyde Space Kryten-M3	61.9	4.65%
ADACS	Hysteresis Rods	25	1.88%
	Permanent Magnet	2.4	0.18%
Total		856.3	73.70%
Remaining		473.7	26.30%

NanoRacks documentation provides necessary physical and structural parameters that the spacecraft has to pass in order to be deemed space worthy (NanoRacks, 2018). As of this time, the safety factor for the tests have been decided as 1.5. This safety factor has been chosen due to all of the parts and devices chosen for the satellite having flight heritage through the NanoRacks CubeSat process. Because of this flight heritage, almost all of the devices being used have gone through the same tests that are described in the NanoRacks documentation, requiring little work to be done to reinforce the devices and parts to make them ready for the pre-launch tests (NanoRacks, 2018).

Power, Thermal, and Environment

The battery/EPS and solar panel component selections have been finalized, with Clyde Space and EnduroSat as the vendors, respectively. For each component, the operational temperature range has been considered and compared to the expected thermal environment. This showed that insulation and the battery heater included in the Clyde Space battery/EPS component will be necessary to keep the spacecraft's components within their operational range.

The final power budget is shown below in Table 11. Since all the components are settled upon, this power budget is not expected to significantly change.

Table 11: Power Budget

Subsystem	Component	Current (mA)	Voltage (V)	Power (W)	% Power
Payload	Camera	120	3.3	0.396	5.4%
	Radio	650	7	4.55	62.059%
Power	Battery	(included in the EPS)			
	EPS	-	-	0.4	5.456%

Instruments	Microcontroller	0.5	5	0.0025	0.034%
	Antenna	250	5	1.25	17.049%
ADACS	Permanent Magnets	0	0	0	0%
Margin	10%			0.733	10%
Total:				7.331	100%

In order to have a complete understanding of the thermal interaction between the CubeSat and the environment, the heat dissipation in the spacecraft will be modeled. Additionally, the flow chart, Figure 7, showing the power flow through the spacecraft, will be expanded to include power sources, distribution, and wire gauges.

Communications

The transceiver and antenna selection are finalized and they have been fully integrated into the design assembly. A full link budget has been calculated but may need to be revised as more specific detail about the orbit or ground station comes to light. Implementing repeater functionality, especially with AMSAT support, will likely be a simple exercise. At this time the UVA ground station is undergoing upgrades and repairs, but those are expected to be complete long before component validation is required.

ADACS and Orbits

The attitude control system and the predicted orbit of the satellite have been chosen. Due to the coronavirus pandemic, companies that manufacture the magnets needed for the attitude control system could not be contacted. These companies will need to be contacted, and parts must be ordered prior to the manufacturing of the CubeSat. As the process comes closer to the critical design stage, more simulations of the orbit and attitude control must be done. These tests include a rotation rate simulation, an oscillation simulation, and more specific orbit simulations. Once the exact date of launch from the ISS is known, it is suggested that these tests and analyses are done using STK software.

Software and Avionics

The primary flight computer and camera system have been chosen, and should be ordered from their manufacturers. These components were chosen using extensive trade studies, including both technical and qualitative details about the device and the manufacturer. Once these components arrive, the software should be programmed for the operating system. This will require training on the specific programming language to be used, and communication with the manufacturers. Wiring and connections must also be ordered. The planned future activity for the project in general is described below.

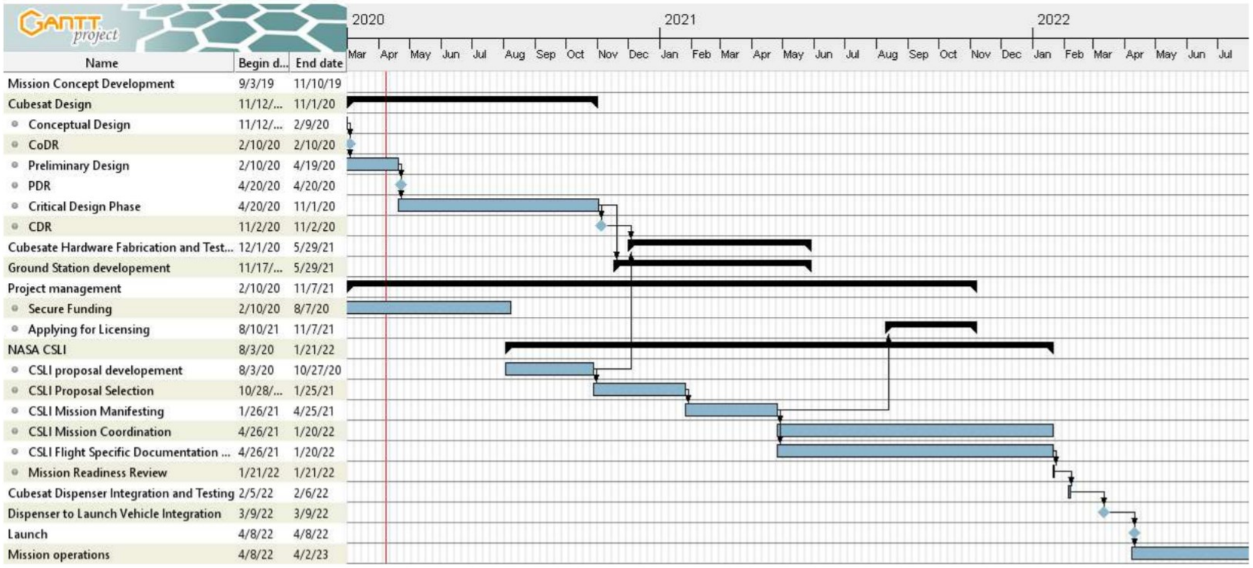
Planned Future Activity

Technical Plans

The CECIL project is expected to have an overall timeline of three years, starting in mid-2019. This consists of five main phases including Mission concept development, Design, construction and testing, Mission selection and integration, and Mission operations. The Mission Design phase is near complete and culminated in the creation of the mission concepts, requirements, and architecture. The design team worked to meet these requirements and has finished preliminary design.

The project is now entering the Critical Design portion which will determine the finalized CubeSat and ground station designs. After the Critical Design Review, the fabrication and testing phase will begin. This will involve the creation of one flight vehicle and a flat-sat used for ground testing and troubleshooting. The flight model will undergo testing to be compliant with NanoRacks and CSLI documentation. During the Critical Design phase, the team will apply for acceptance to the CSLI program. If the project is selected, the launch date is expected to be in early 2022. After launch, it is expected that the CubeSat will remain in orbit for approximately one year.

Schedule and Mission Timeline



Name	Begin d...	End date
Mission Concept Development	9/3/19	11/10/19
Cubesat Design	11/12/...	11/1/20
Conceptual Design	11/12/...	2/9/20
CoDR	2/10/20	2/10/20
Preliminary Design	2/10/20	4/19/20
PDR	4/20/20	4/20/20
Critical Design Phase	4/20/20	11/1/20
CDR	11/2/20	11/2/20
Cubesate Hardware Fabrication and Test...	12/1/20	5/29/21
Ground Station developement	11/17/...	5/29/21
Project management	2/10/20	11/7/21
Secure Funding	2/10/20	8/7/20
Applying for Licensing	8/10/21	11/7/21
NASA CSLI	8/3/20	1/21/22
CSLI proposal developement	8/3/20	10/27/20
CSLI Proposal Selection	10/28/...	1/25/21
CSLI Mission Manifesting	1/26/21	4/25/21
CSLI Mission Coordination	4/26/21	1/20/22
CSLI Flight Specific Documentation ...	4/26/21	1/20/22
Mission Readiness Review	1/21/22	1/21/22
Cubesat Dispenser Integration and Testing	2/5/22	2/6/22
Dispenser to Launch Vehicle Integration	3/9/22	3/9/22
Launch	4/8/22	4/8/22
Mission operations	4/8/22	4/2/23

Figure 10: Schedule and Mission Timeline

Cost Estimation

One of the primary objectives of this project is limiting the cost to equal to or less than that of the Libertas. The cost estimation for this project, shown below in Table 12, accounts for the creation of one flight unit and a second flatsat, which will be used for testing and troubleshooting on the ground.

Table 12: Cost Estimation

Component Type	Name	Manufacturer	Cost per Unit	Qty.	Total Price
EPS and Battery	Starbuck PICO	Clyde Space	$7,100.00	2	$14,200
Command and control	Kryten-M3	Clyde Space	TBD	2	(~$5,000)
1U structure	Structure 1U	EnduroSat	$1,358.00	1	$1,358

Z-face solar panel	1U Solar Panel Z	EnduroSat	$1,630.00	2	$3,260
X/Y-face solar panels	1U Solar Panel X/Y	EnduroSat	$1,630.00	2	$3,260
X/Y-face solar panels w/ RBF Pin	1U Solar Panel X/Y	EnduroSat	$1,738.00	1	$1,738
UHF/VHF antenna	Deployable Antenna System	ISIS	$1,500.00	2	$3,000
Camera	Raspberry Pi zero	Raspberry Pi Foundation	$40.00	2	$80
Camera	Raspberry Pi camera	Raspberry Pi Foundation	$40.00	2	$80
UHF/VHF transceiver	Linear Transponder Module	AMSAT	$0.00	2	$0
Passive attitude control	Permanent Magnets		TBD	1	(~$30)
Passive attitude control	Hysteresis rods				TBD
Total					$32,006

Team Personnel and Responsibilities

The team working on the CECIL Amateur Satellite is composed of fourth-year Aerospace and Mechanical Engineering students from the School of Engineering and Applied Sciences at the University of Virginia. Each student is part of either the management team or functional team, which is further divided into subsystems: Communications, Software and Avionics, Power, Thermal, and Environment, Attitude Determination and Control System (ADACS) and Orbits, and Structures and Integration. Table 13, below, details the different teams, student members, and the team's responsibilities. In addition to the student members, the CECIL team has two advisors: one faculty advisor and one university contractor who is a member of the amateur radio community. Recently, the CECIL team has also teamed up with AMSAT who have agreed to provide operation and licensing support. Faculty and supporting staff, and their responsibilities, can be found in Table 14 below.

The management team focuses primarily on budgeting, scheduling, determining system requirements and verifications, risk management and mitigation, as well as legal procedures such as licensing and ensuring compliance with service providers (see Appendix C: Required Compliance and Regulatory Documentation, for details). Additionally, the management team focuses on producing clear and concise schedules and task lists for the functional team members to follow, in order to avoid confusion and optimize allotted time. On the other hand, the functional subteams focus on developing models and trade studies to identify which components and/or solutions best fit the mission objectives, while ensuring compliance with the system requirements. Functional subteams, specifically the Structures and Integration team, often work in conjunction with each other to ensure that the best component for a specific subsystem also integrates well with the system as a whole.

Table 13: Teams, Members, and Roles

Functional Team	Members	Role
Program Management	Jack Shea Martin Keuchkerian	Manage project's budget & funding, timeline & schedule, radio frequency license acquisitions, purchasing and risk & mitigation.
Communications	Gabe Norris	Develop the on- and off-board radios to be used. Develop the communications architecture to be used.
Software and Avionics	Joshua Choe Andrew Oxford Monica Wuhrer	Develop the on-board flight control system hardware and software. Ensure all digital systems on the spacecraft integrate with each other. Develop the camera payload.
Power, Thermal, and Environment	Eva Femia Ari Goldman Isabella Todaro	Develop the power generation, storage, and distribution systems for the spacecraft. Ensure the spacecraft is able to function in the environmental extremes of LEO.
Attitude Determination and Control System (ADACS), and Orbits	Sean Bergmann Henry Blalock	Develop the systems that the spacecraft will use to determine and control where it is facing. Determine the spacecraft's orbit and assess influences on it.
Structures and Integration	David Broome Nathaniel Craft Zach Wilson	Develop the mechanical structure of the spacecraft. Integrate the hardware on the spacecraft into its structure.

Table 14: Faculty and Staff Supporting the Mission

Name	Title	Role
Chris Goyne	Associate Professor of Mechanical and Aerospace Engineering Department	Instructor for University of Virginia spacecraft design course and mentor to University of Virginia student teams.
Mike McPherson	Amateur Radio Community member	Provide an overview of and insight into the ham community and what they want from a satellite.

AMSAT Personnel	AMSAT Members	Provide integration and licensing support.

Conclusion

CECIL (CubeSat Enabling Communication in LEO) has been designed over the past eight months, through the Preliminary Design phase, to reliably communicate with the UVA ground station and with amateur ground stations around the world using an AMSAT Linear Transponder Module. The mission has a low risk of failure, will cost about $32,000, and will function within the bounds of an amateur radio license. The current student team members, supported by Professor Goyne, Mr. Mike McPherson, and other AMSAT members, have gained valuable experience in spacecraft design and project management. Component selections have been finalized, through the use of trade studies, for all five spacecraft subsystems: Structure, Power, Communications, Attitude Determination and Control, and Software and Avionics. Next year's student team will continue these efforts by completing the Critical Design phase and beginning construction. The CubeSat is expected to launch in 2022.

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Appendices

Appendix A: Complete Functional Requirements and Constraints

ID	System	Requirement	Specification	Rationale	Verification Method (Testing, Analysis, Inspection)
FUNC-001	ADAC	Pointing Rate: communications	The attitude of the CubeSat must be such that it can always communicate with ground stations below the path of orbit	To ensure reliable and consistent communications	Analysis
FUNC-002	ADAC	Pointing Rate: camera	The attitude of the CubeSat must allow for the camera to remain pointed at Earth	In order to take pictures on Earth whenever called upon	Analysis
FUNC-026	ADAC	Onboard attitude control maximum weight	The onboard attitude control shall weigh less than 61 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-015	AV	Electronics Software	Software must coordinate on-board systems and payloads	In order for the UVA ground station to adequately operate satellite's subsystems	Testing
FUNC-020	AV	Flight computer should have flight heritage	Specific model of flight computer must have flown at least once for at least 1 year successfully	To ensure the computer is known to be reliable in space	Inspection
FUNC-021	AV	The primary flight computer shall operate the on-board camera	Control of the on-board camera shall be commanded entirely through the flight computer, with no external communication	To limit access to the camera for only specific purposes and to allow more sophisticated control and data handling/processing	Inspection

FUNC-022	AV	The primary flight computer shall operate all radios on the spacecraft	Radio modes, message processing, and transmission shall all be coordinated by the on-board computer	To ensure reliable access to the spacecraft for maintenance and allow for easier updates if needed	Inspection
FUNC-023	AV	GPS maximum weight	The GPS shall weigh less than 57 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-024	AV	Onboard camera maximum weight	The onboard camera shall weigh less than 37 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-030	AV	Onboard microcontroller maximum weight	The onboard microcontroller should weigh less than 66 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-031	AV	The altitude determination and control components maximum weights	The altitude determination and control components shall weigh less than 93 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-060	AV	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.	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing

FUNC-080	AV	Recovery from loss of communications	The spacecraft will cycle power after two consecutive weeks of no communications from ground stations	To allow for recovery if spacecraft radio or computer reaches a state were communications can not be established from a ground station	Testing
FUNC-016	COMM	Response time	< 1 min	To avoid false-negatives	Testing
FUNC-017	COMM	Simultaneous communications	The CubeSat must be able to communicate to more than one ground station at a time	To allow more than one ground station to communicate with a satellite during a fly over	Testing
FUNC-018	COMM	Antenna hardware	Consistent with amateur radio on spacecraft	In order to achieve mission objectives	Testing
FUNC-019	COMM	Antenna Gain	15 db	To overcome minimum atmospheric, ionospheric, and pointing losses to increase communication reliability	Analysis and Testing
FUNC-028	COMM	Onboard antenna maximum weight	The onboard antenna should weigh less than 93 grams grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-029	COMM	The communication radios used shall weigh less than 106 grams	The communication radios used shall weigh less than 106 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection

FUNC-033	COMM	Beaconing	Satellite must be capable of beaconing upon being deployed	To increase probability of communication with ground station and to allow for more accurate tracking	Testing
FUNC-081	COMM	Recovery from computer freeze	Allow for radio system to bypass motherboard and reset spacecraft	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-003	POWER	Solar panels	The solar panel area which is exposed to the sun must be capable of providing adequate power	Supply enough power to allow the satellite to operate, and hold power while traveling behind Earth	Analysis and Testing
FUNC-010	POWER	Solar Panels power generation	Must generate enough power to support all mission functions	To ensure payload (amateur radio) and other mission functions have access to enough power	Analysis and Testing
FUNC-011	POWER	Solar Panels excess power generation	Must generate enough excess power to charge the battery	To ensure payload (amateur radio) and other mission functions have access to enough power during eclipse	Analysis and Testing
FUNC-012	POWER	Batteries capacity	Must be able to hold enough power for the CubeSat to function through the entire duration of an eclipse	To maintain continuous operation of the amateur radio and other mission functions during the entirety of the CubeSat's orbit	Analysis
FUNC-013	POWER	Battery life	The effective capacity of the battery must not fall below the critical value for the lifespan of the mission	To ensure the CubeSat is fully operational (all mission functions and the amateur	Analysis

				radio working properly) until natural deorbit	
FUNC-014	POWER	Satisfactory Voltage and Amperage	Voltage and amperage must be in safe operating range for all components	To ensure proper function of all components	Testing
FUNC-027	POWER	Solar panels without an attached antenna maximum weight	Solar panels without an attached antenna shall weigh less than 50 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-032	POWER	Battery and EPS maximum weight	The battery and EPS shall weigh less than 190 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-059	POWER	Power Storage Device Location	All electrical power storage devices shall be internal to the CubeSat.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-061	POWER	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 on NanoRacks Interface Definition Document. 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.	To comply with NanoRacks CubeSat deployer requirement	Inspection

FUNC-062	POWER	Ground Circuit	The CubeSat electrical system design shall not permit the ground charge circuit to energize the satellite systems (load), including flight computer (see Figure 4.2-1 on NanoRacks Interface Definition Document). This restriction applies to all charging methods.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-065	POWER	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).	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-071	POWER	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).	To comply with NanoRacks CubeSat deployer requirement	Testing
FUNC-072	POWER	Internal Short Circuit	Protection circuitry and safety features shall be implemented at the cell level to prevent an internal short circuit.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-073	POWER	External Short Circuit	Protection circuitry and safety features shall be implemented at the cell level to prevent an external short circuit.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-074	POWER	Overvoltage & Undervoltage Protection	Protection circuitry and safety features shall be implemented at the cell level to prevent	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing

			overvoltage or undervoltage conditions of the cell.		
FUNC-075	POWER	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.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-076	POWER	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 chemistries) require additional assessment by NanoRacks due to potential hazard in the event of single-cell, or cell-to-cell thermal runaway	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-077	POWER	Pouch Cell Expansion	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.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-078	POWER	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 identified by part number and UL listed or equivalent.	To comply with NanoRacks CubeSat deployer requirement	Inspection

FUNC-079	POWER	Capacitors	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.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-004	STRC	Frame material shock resistance	Frame must be able to withstand physical shock encountered during launch and operations	To ensure structural integrity during launch	Testing
FUNC-006	STRC	Frame material vibration resistance	Must be able to withstand vibrations encountered during launch and operations	To ensure the satellite survives the launch phase of the mission	Testing
FUNC-007	STRC	Component integration	Frame must contain anchoring and fixtures to accommodate all interior components	To ensure all interior components are secure and integrated into the satellite structure so as to achieve proper function	Inspection
FUNC-025	STRC	Cubesat structure maximum weight	The Cubesat structure shall weight less than 100 grams	To ensure the CubeSat weighs less than the constrained maximum weight for launch	Inspection
FUNC-034	STRC	Rail Positioning	The CubeSat shall have four (4) rails along the Z axis, one per corner of the payload envelope, which allow the payload to slide along the rail interface of the NRCSD. Refer	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing

			to NanoRacks Interface Definition Document		
FUNC-035	STRC	Rail and Envelope Dimensions	The CubeSat rails and envelope shall adhere to the dimensional specification outlined in the NanoRacks Interface Definition Document for specific dimensions	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-036	STRC	Rail Width	Each CubeSat rail shall have a minimum width (X and Y faces) of 6mm.	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-037	STRC	Rail Edge Radius	The edges of the CubeSat rails shall have a radius of 0.5mm +/- 0.1mm.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-038	STRC	CubeSat Load Points	The CubeSat +Z rail ends shall be completely bare and have a minimum surface area of 6mm x 6mm.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-039	STRC	Rail Design Tolerance	The CubeSat rail ends (+/-Z) shall be coplanar with the other rail ends within +/- 0.1mm.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-040	STRC	Frame Material Static Load resistance	Must be able to withstand static loads encountered during launch and operations	To ensure the satellite survives the launch phase of the mission	Testing
FUNC-041	STRC	Minimum Structural and Integration Safety Factor	The Cubesat structure and integration components must have a safety factor of at least	To ensure CubeSat survives launch phase	Inspection and Analysis
FUNC-042	STRC	Rail length	The CubeSat rail length (Z axis) shall be the 113.50mm	To comply with NanoRacks CubeSat deployer requirement	Inspection

FUNC-043	STRC	Rail Continuity	The CubeSat rails shall be continuous. No gaps, holes, fasteners, or any other features may be present along the length of the rails (Z-axis) in regions that contact the NRCSD rails.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-044	STRC	Rail Envelope	The minimum extension of the +/-Z CubeSat rails from the +/-Z CubeSat faces shall be 2mm	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-045	STRC	Mechanical Interface	The CubeSat rails shall be the only mechanical interface to the NRCSD in all axes (X, Y and Z axes).	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-046	STRC	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).	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-047	STRC	Rail Surface Roughness	The CubeSat rails and all load points shall have a surface roughness of less than or equal to 1.6 µm.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-048	STRC	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: (+/- 2cm) b. Y-axis: (+/- 2cm) c. Z-axis: i. 1U: (+/- 2cm) ii. 2U (+/- 4cm) iii. 3U (+/- 6cm) iv. 4U (+/- 8cm) v. 5U (+/- 10cm) vi. 6U (+/- 12cm)	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-049	STRC	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 NRCSD access panels (not in the Z-axis)	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing

FUNC-050	STRC	Deployment Switch Requirement	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).	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-051	STRC	Plunger Switch Location	Deployment switches of the pusher/plunger variety shall be located on the rail end faces of the CubeSat's -Z face	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-052	STRC	Roller Switch Location	Deployment switches of the roller/lever variety shall be embedded in the CubeSat rails (+/- X or Y faces).	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-053	STRC	Switch Contact Surface Area	Roller/slider switches shall maintain a minimum of 75% surface area contact with the NRCSD rails (ratio of switch contact to NRCSD guide rail width) along the entire Z axis	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-054	STRC	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 after the switches close (including but not limited to radio frequency transmission and deployable system timers).	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-055	STRC	Switch Captivation	The CubeSat deployment switches shall be captive.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-056	STRC	Switch Force	The force exerted by the deployment switches shall not exceed 3N.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-057	STRC	Total Switch Force	The total force of all CubeSat deployment switches shall not exceed 9N.	To comply with NanoRacks CubeSat deployer requirement	Inspection

FUNC-058	STRC	Deployable Systems Restrain Mechanism	CubeSat deployable systems (such as solar arrays, antennas, payload booms, etc.) shall have independent restraint mechanisms that do not rely on the NRCSD dispenser.	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-063	STRC	RBF / ABF Requirement	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.	To comply with NanoRacks CubeSat deployer requirement	Inspection and Testing
FUNC-064	STRC	RBF / ABF Functionality	The RBF /ABF feature shall preclude any power from any source operating any satellite functions except for preintegration battery charging.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-066	STRC	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 on NanoRacks Interface Definition Document	To comply with NanoRacks CubeSat deployer requirement	Analysis and Testing
FUNC-067	STRC	Integrated Loads Environment	The CubeSat shall be capable of withstanding a force 1200N across all load points equally in the Z direction.	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-068	STRC	Airlock Depressurization	The CubeSat shall be capable of withstanding the pressure extremes and depressurization / pressurization rate of the airlock as defined in Section 4.3.8 on NanoRacks Interface Definition Document	To comply with NanoRacks CubeSat deployer requirement	Inspection
FUNC-069	STRC	CubeSat SubDeployables	CubeSats shall not have detachable parts during launch or normal mission operations. Any exceptions will be coordinated with NanoRacks and documented in the unique payload ICA.	To comply with NanoRacks CubeSat deployer requirement	Inspection

FUNC-070	STRC	Space Debris Compliance	CubeSats shall comply with NASA space debris mitigation guidelines as documented in NASA Technical Standard NASASTD-8719.14A	To comply with NanoRacks CubeSat deployer requirements and NASA technical standards	Analysis
FUNC-005	THRM	Frame material temperature resistance	Frame must be able to resist damage or warping due to temperature fluctuations during launch and operations	To ensure structural integrity during exposed/not exposed to sunlight	Testing
FUNC-008	THRM	Temperature	Able to continually function within an external temperature range between -170˚C and 123˚C	To ensure satellite is able to properly function in its expected environment	Analysis and Testing
FUNC-009	THRM	Heating/cooling	Must keep interior components within safe operating temperature range	To ensure satellite is able to properly function in its expected environment	Analysis and Testing

ID	System	Constraints	Specification	Rationale	Verification Method (Testing, Analysis, Inspection)
CNST-001	STRC	NASA Deployer integration	Must fit within PPOD deployer, with standardized rails	Abide by NASA's CubeSat Program Document	Analysis and Testing
CNST-002	COMM	Radio frequency	Must communicate using amateur radio frequencies	To increase the number of options for ground stations when communicating with the spacecraft and to reduce licensing complexities	Analysis
CNST-003	STRC	Mass (kg)	< 1.33	To comply with NASA's CubeSat Design Specification Guidelines	Inspection
CNST-004	STRC	Materials: out-gassing	Total Mass Loss (TML) ≤ 1.05	Comply with the CubeSat program requirements	Inspection
CNST-005	STRC	Materials: out-gassing	Collected Volatile Condensable Material	Comply with the CubeSat program requirements	Inspection

			≤ 0.1%		
CNST-006	STRC	Materials: flammability	Use only non-flammable materials	Comply with the CubeSat program requirements	Inspection
CNST-007	STRC	Materials: toxicity	Use only nontoxic materials	Comply with the CubeSat program requirements	Inspection
CNST-008	STRC	Materials: CubeSat structure	Must use Aluminium 7075, 6061, 5005, and/or 5052 (can receive waiver)	Comply with the CubeSat program requirements	Inspection
CNST-009	STRC	Dimensions (cm)	10 x 10 x 10	To comply with NASA's CubeSat Design Specification Program Guidelines	Inspection
CNST-010	STRC	Materials	Materials used in the design must be pre-approved by NASA	Comply with the CubeSat program requirements	Analysis
CNST-011	STRC	Magnetic field limitations	Static envelope of <0.5 Gauss above Earth's magnetic field	comply with launch vehicle limitations and allow for CubeSat separation after deployment	Testing
CNST-012	STRC	Ascent venting	Ascent venting per ventable volume/area <2000 inches		Analysis
CNST-013	PAYLOAD	Satellite operations	The satellite must remain powered off while in deployer	Must adhere to NASA CSLI	Testing
CNST-014	AV	SpaceCap	Must use the International Telecommunications Union's (ITU) software SpaceCap to notify the FCC and the ITU of communications with the satellite	Necessary for broadcasting radio in space	Inspection
CNST-015	STRC	Structure's Materials	Must use Aluminium 7075, 6061, 5005, and/or 5052 (can receive waiver)	Comply with the CubeSat program requirements	Inspection
CNST-016	STRC	Standoff Rails Materials	Must be hard anodized aluminium	Prevent cold welding with deployer	Inspection

CNST-017	AV	Photograph restrictions	The satellite can not take pictures of Israel with better resolution than currently available commercial grade satellites	To ensure the mission concept and architecture is approved by NOAA	Inspection
CNST-018	STRC	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 coordinated with NanoRacks and documented in the ICA. Any use of Table III materials shall be avoided.	To comply with NanoRacks CubeSat deployer requirement	Inspection
CNST-019	PROJ	Regulatory Compliance	The CubeSat developer shall submit evidence of all regulatory compliance for spectrum utilization and remote sensing platforms to NanoRacks 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).	To comply with NanoRacks CubeSat deployer requirement	Inspection

Appendix B: Complete Risk Register

ID	Risk	Risk Owner	Probability	Severity	Overall Severity
RISK-001	Attitude control system does not provide sufficient torque	Attitude determination and control	1	2	2
RISK-002	Camera can't see the Earth at any point in orbit	Attitude determination and control	1	3	3
RISK-003	Oscillations are not damped by the attitude control system	Attitude determination and control	2	3	6
RISK-004	Permanent magnets installed incorrectly	Attitude determination and control	2	1	2
RISK-006	UVA ground station is unable to communicate with the satellite	Communications	4	5	20
RISK-007	Satellite fails to beacon upon startup	Communications	3	2	6
RISK-008	Satellite radio does not switch to transmit mode	Communications	3	4	12
RISK-009	Satellite radio does not switch to receiver mode	Communications	3	4	12
RISK-010	Satellite radio communicates on non-amateur radio frequencies	Communications	1	4	4
RISK-011	Satellite radio does not communicate on the expected frequencies	Communications	1	4	4
RISK-012	Satellite radio does not transmit with sufficient power to communicate with ground stations	Communications, Power and Thermal	2	5	10
RISK-013	Electronics fail to power up upon deployment	Power and thermal	5	5	25
RISK-014	1 solar panel stops producing power	Power and thermal	3	1	3
RISK-015	2 solar panels stop producing power	Power and thermal	2	3	6
RISK-016	3 solar panels stop producing power	Power and thermal	1	5	5

RISK-017	4 solar panels stop producing power	Power and thermal	1	5	5
RISK-018	Electrical components fail after leaving operational temperature range	Power and thermal	3	3	9
RISK-019	Solar panels produce insufficient power upon deployment	Power and thermal	1	5	5
RISK-020	Improper voltages are supplied to satellite components	Power and thermal	1	5	5
RISK-021	Selected components are electronically incompatible with one another	Power and thermal	1	5	5
RISK-022	Battery does not store sufficient power for time spent in eclipse upon deployment	Power and thermal	2	4	8
RISK-023	Solar panel power production degrades quicker than expected	Power and thermal	1	3	3
RISK-024	Battery capacity degrades more quickly than expected	Power and thermal	2	3	6
RISK-025	Power draw of components is higher than expected	Power and thermal	2	3	6
RISK-026	Total cost overrun	Program management	4	5	20
RISK-027	Schedule overrun	Program management	5	3	15
RISK-028	Loss of institutional knowledge	Program management	5	4	20
RISK-029	AMSAT does not agree to supply the radio	Program management	3	3	9
RISK-030	AMSAT is not readily available for communication	Program management	3	3	9
RISK-031	Failure to get funding	Program management	1	5	5
RISK-032	Failure of launch vehicle to reach orbit	Program management	1	5	5
RISK-033	Project not approved for launch funding from the NASA CubeSat launch initiative	Program management	3	5	15
RISK-034	Selected parts or components unavailable	Program management	3	1	3

RISK-035	Launch cancellation	Program management	3	1	3
RISK-036	computer components fail to boot upon deployment	Software and avionics	5	5	25
RISK-037	Flight computer and others systems use different communication protocols	Software and avionics	2	3	6
RISK-038	Storage is corrupted	Software and avionics	3	3	9
RISK-039	Camera is exposed to direct sunlight	Software and avionics	3	1	3
RISK-040	Connectors come loose/are damaged during launch	Software and avionics	3	4	12
RISK-041	Camera does not take pictures	Software and avionics	3	3	9
RISK-042	flight computer runs out of memory for normal operation	Software and avionics	1	5	5
RISK-043	Processor is damaged during launch	Software and avionics	1	5	5
RISK-044	Memory is damaged	Software and avionics	1	5	5
RISK-045	Selected components software is incompatible with one another	Software and avionics	2	3	6
RISK-046	Insufficient memory to process images	Software and avionics	1	2	2
RISK-047	Processor overloaded	Software and avionics	1	2	2
RISK-048	Storage is damaged	Software and avionics	1	3	3
RISK-049	Camera lens is damaged	Software and avionics	1	3	3
RISK-050	Camera ground resolution is too high to get a licenses from NOAA	Software and avionics	1	2	2
RISK-051	Flight computer crashes while in orbit	Software and avionics	1	1	1
RISK-052	Runs out of storage	Software and avionics	1	1	1

RISK-053	Flight computer connectors are incompatible with other systems (e.g. ADACs, radio, etc.)	Software and avionics	2	1	2
RISK-054	Components becoming disconnected during launch	Structures and integration	2	5	10
RISK-055	Structural failure due to launch vibrations	Structures and integration	2	5	10
RISK-056	Structural failure due to launch accelerations	Structures and integration	2	5	10
RISK-057	Improper installation of components in satellite	Structures and integration	2	3	6
RISK-058	Failure to deploy antenna	Structures and integration	1	5	5
RISK-059	Material failure due to thermal stress	Structures and integration	1	3	3
RISK-060	Non-compliance to NASA standards	Structures and integration	1	3	3
RISK-061	Components becoming disconnected during deployment	Structures and integration	1	5	5
RISK-062	Space debris impacts	Structures and integration	1	5	5
RISK-063	Destruction of antenna	Structures and integration	1	5	5
RISK-064	Destruction of internal electronics	Structures and integration	1	5	5
RISK-065	Selected components are structurally incompatible with one another	Structures and integration	3	1	3
RISK-066	Failure of component board attachment system	Structures and integration	1	3	3
RISK-067	Components damaged during integration	Structures and integration	3	1	3
RISK-068	Destruction of 1 solar panel	Structures and integration	1	1	1
RISK-069	Destruction of 2 solar panels	Structures and integration	1	1	1
RISK-070	Destruction of 3 solar panels	Structures and integration	1	4	4
RISK-071	Destruction of 4 solar panel	Structures and integration	1	5	5

RISK-072	Schedule overrun due to COVID-19 outbreak	Project management	5	5	25

Appendix C: Required Compliance and Regulatory Documentation

Item #	Requiring Entity	Deliverable	Description
1	Nano Racks	Safety Data Template	Summary of Satellite Design: requires filling in NanoRacks template with basic satellite design information appropriate for processing the satellite through the Safety Review Process.
2	Nano Racks	Bill of Materials	To be utilized for external outgassing contamination assessment and formation of Materials Identification Usage List (MIUL).
3	Nano Racks	Battery Test Report	Test report shows compliance with work instructions provided by NanoRacks.
4	Nano Racks	Vibration Test Report	Integrated test report outlining test set-up, as-run accelerometer response plots, and post-vibration functional and inspection results
5	Nano Racks	Investigation Summary Form	Template provided by NanoRacks documenting the science objectives of the payload for use on a public NASA webpage.
6	Nano Racks	Final Satellite As-Measured Mass Properties	Mass and CM (Mass Measured, CM Calculated)
7	Nano Racks	Power System Functional Test Report for EPS inhibits verification	Safety inhibits part of the spacecraft EPS system.
8	Nano Racks	Structural Analysis	NR to provide specific guidance on what is required depending on the hazard classification of the payload.
9	Nano Racks	Inspection Reports for fracture critical parts (if any fracture critical parts)	N/A
10	Nano Racks	Inspection Reports for stress corrosion parts (if any stress corrosion sensitive parts)	N/A
11	FCC	Appendix 4	A draft "Appendix 4" notification for submission to the International Telecommunications Union (ITU) Radio

			Regulations. The draft notification should be prepared using the ITU software “SpaceCap”
12	FCC	International Amateur Radio Union Letter	A letter from the International Amateur Radio Union (IARU) indicating completion of coordination
13	NASA/FCC/NOAA	Orbital Debris Assessment Report (ODAR), or similar, showing compliance inputs	Document that assures all interested parties that your CubeSat won’t pose an unacceptable hazard to other orbiting spacecraft, will deorbit in a reasonable amount of time, and that no unacceptably large piece of your CubeSat is going to survive reentry when it deorbits and burns up in the atmosphere. Refer to CubeSat 101 Appendix C for template
14	NASA	Transmitter surveys	The transmitter survey is a series of questions about the CubeSat’s communication system. Refer to CubeSat 101 Appendix C for template
15	NASA	Materials list	Document identifying every material used on the CubeSat along with its mass (or expected mass), its location on the CubeSat, and its outgassing properties including Total Mass Loss (TML) and Collected Volatile Condensable Materials (CVCM). Refer to CubeSat 101 Appendix C for template
16	NASA	Mass Properties Report	The mass properties report identifies the CubeSat’s total mass, center of gravity (CG), moments of inertia (MOIs), and products of inertia (POI) relative to each axis.
17	NASA	Battery report	Used to verify that proper battery circuit protection is in place. Refer to CubeSat 101 Section 6.5 for details
18	NASA	Dimensional verifications	To ensure the CubeSat will fit into its flight dispenser. Refer to CubeSat 101 Appendix C for template
19	NASA	Electrical report	An electrical report will be used to verify a number of requirements listed in the CubeSat-to-dispenser ICD

20	NASA	Venting analysis	To show mission integrator that the CubeSat has adequate venting to prevent the explosive decompression of any container in the CubeSat as it makes the quick transition from standard atmosphere to vacuum
21	NASA	Testing procedures/reports	A report will need to be submitted for each test used to verify CubeSat-to-dispenser ICD requirements (Day in the Life Testing, Dynamic Environment Testing, Thermal Vacuum Bakeout Testing)
22	NASA	Compliance letter	a statement from the CubeSat developer guaranteeing that the CubeSat is compliant with the entire CubeSat-to-dispenser ICD, and that no prohibited components are aboard, and it is signed by the principal investigator
23	NASA	Safety package inputs (e.g., Missile System Prelaunch Safety Package—or MSPSP, flight safety panel)	The CubeSat developer typically is responsible for creating the MSPSP, but the mission integrator will create a template, with instructions, for the CubeSat teams to complete.
24	NOAA	Application	Application including all basic information about the mission plan and CubeSat specifications

Appendix D: Alternate (Single-Vendor) Design Option

The final satellite design presented in this report uses an EnduroSat CubeSat structure and solar panels, with an AAC Clyde Space EPS and on-board flight computer. However, a Clyde Space structure and solar panels could feasibly be adopted in place of the selected EnduroSat components if necessary. The Clyde Space structure has flight heritage and meets all NASA CubeSat Launch Initiative and Nanoracks CubeSat Deployer requirements. Further, it has a standard 1U structure rail/spacer hole pattern, which would allow for easy mechanical integration with the interior stack in its current form. The initial choice for EnduroSat solar panels is based on the result of the trade study prioritizing the following elements: weight, dimension, cost, and structural integration. Based on flight heritage (Libertas), there is a compatible electrical integration method between the Endurosat Solar Panels and Clyde Space EPS. In the event that structure choice is changed from EnduroSat to Clyde Space, a re-evaluation of solar panel trade study is advised with further consideration of the Clyde Space solar panels. The Clyde Space solar panels would easily integrate electrically with the (already-selected) Clyde Space EPS, which is chosen for seamless integration with the chosen onboard flight computer of the same vendor. This change of the CubeSat structure and solar panels vendor from EnduroSat to Clyde Space would result in a single-vendor structure, flight computer, EPS, and solar panel configuration.