A SPACE-BASED SOLUTION TO IMPROVE ROADWAY SAFETY AND EFFICIENCY IN VIRGINIA: REAL-TIME WINTER WEATHER DATA FOR NAVIGATION

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By

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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

This University of Virginia spacecraft design capstone class developed a conceptual solution to address one aspect of Virginia's transportation problems using remote sensing and data fusion methods. In August 2020, key stakeholders from MITRE, University of Virginia, Virginia Tech, Old Dominion University, George Mason University, Virginia Transportation Research Council, Virginia Space Grant Consortium, Federal Highway Administration, and National Academy of Sciences met as part of the MITRE University Innovation Exchange (UIX)-Space Initiative Transportation Efficiency Workshop. Their discussion and deliberation identified three key areas to improve transportation efficiency and safety in Virginia: (1) Real time weather data to improve roadway safety, (2) Remote-sensing-enhanced non-destructive evaluation of roadway infrastructure, and (3) Management and tracking of truck parking (Kordella, 2020, Slide 5). During the Fall semester, University of Virginia students in the spacecraft design course were divided into three sub-teams corresponding to these three problems. Each problem was refined and the practicality of possible solutions were examined. For the Spring Semester, the entire class channeled efforts as one team to focus on the first problem, using real time weather data to improve Virginia's roadway safety. This problem was seen as particularly suited to solutions that could be achieved as part of an undergraduate spacecraft design class. During the project brief, MITRE provided a preliminary problem statement, described below. Since that time, the class conducted a science and technology literature review and refined the problem statement further, as discussed in detail on page 2.

Between rain, snow, sleet, and hail, Virginians have unforgettable experiences driving in adverse weather. Similarly, most Virginians know the frustrations of a rush hour traffic jam in Northern Virginia, Richmond, or Hampton Roads. The mechanical and aerospace engineering students in the Spacecraft Design capstone course have developed a remote sensing system concept to provide real time weather data delivery. The goal of this proposal, based on the first objective, is to help alleviate weather-related traffic congestion, and improve roadway efficiency and safety in Virginia.

This paper contains a summary of the problem initially assigned to the students, a review of the current science and technologies to solve the problem at hand, proposed primary and secondary mission objectives, system level requirements, and mission constraints, as well as a baseline mission architecture and concept. Additionally, the six functional domains of the spacecraft design are described and it is explained how they meet the mission objectives. Both hardware and software choices for the spacecraft are proposed. Finally, the paper concludes with recommendations for the future development of the solution as part of MITRE's UIX-Space initiative, along with preliminary risk assessments and mitigation strategies. Table I in Appendix A provides a complete list of all acronyms used in this paper, along with their definitions.

PROBLEM STATEMENT

Picture a driver waking up, looking out the window, checking the weather, and pulling out of the driveway for the day. This morning ritual feels familiar. However, checking the weather before driving may not always provide as much information as drivers may think. The weather could differ between the start and end locations. A storm could blow in from elsewhere mid-drive. A fallen tree or flooding could block a roadway. If the driver is travelling toward a storm, it may not have shown up on a weather app before departure. At this point, the driver cannot easily look for an alternate route in real time, and they may be stuck in weather-induced traffic congestion, once again. These are merely a few examples of adverse weather contributing to road congestion. In many instances, the current method used by drivers to check weather information leads to inaccurate conclusions. By including a combination of real time weather, predicted weather, and traffic data in the information sent to drivers via smart phones and navigation devices, roadway users could have a more accurate representation of the drive ahead.

While the benefit of simultaneous weather and navigational data collection is apparent, current on-road systems do not integrate the delivery of both streams to users. This shortcoming makes roads more hazardous as drivers are not appropriately warned of adverse weather conditions. Nearly all highway capacity approximations assume clear weather. For example, of all the publicly available datasets looked at by Yang, Lillian, and Pun-Cheng (2016), only two, ChangeDetection and Karlsruhe Institute include non-perfect weather conditions (p. 150). Clear weather is an invalid assumption to make when performing traffic data analytics, considering the majority of states in the United States encounter inclement weather conditions for a significant portion of the year (Agarwal, 2005, p. 1). Furthermore, adverse weather conditions contribute to many vehicle crashes each year. For example, Ashley, Strader, Dziubla, and Harberlie (2015) reported that in Fancy Gap, Virginia, excessive driver speed in dense fog caused 17 distinct crashes on March 31, 2013 (p. 756). In 2018, the economic cost of traffic crashes in Virginia amounted to $6.4 billion (TRIP, 2020, p. 2).

Although roadway users may rely on weather forecasts, the Virginia Department of Transportation (VDOT) uses road condition measurements, which could differ significantly from meteorological data reported to drivers via news stations and apps. For example, the roadway could be a couple degrees colder than the atmosphere, which may result in ice. These discrepancies lead to misinformation which contributes to accidents (Fontaine, 2020). Despite the wide availability of weather data via various sources, delivery to individual drivers is extremely fragmented. While many aviation and marine satellite navigation devices already have such capabilities, very few roadway traffic algorithms include weather data. Therefore, navigation sources such as Waze, Google Maps, and Virginia 511 offer different and sometimes conflicting information. Further, although VDOT consistently shares information with the local media, the public does not follow this information unless the report is catastrophic or sensational. Due to these shortcomings, drivers, autonomous vehicles, in-vehicle satellite navigation services, and vehicle to vehicle communication will also benefit from more accurate weather-related traffic data.

SCIENCE AND TECHNICAL INVESTIGATION

While many factors contribute to traffic and vehicle crashes, an unsurprisingly significant number of crashes relate to inclement weather. Graduate research by Yue Liu (2013) studied fourteen-years of National Highway Traffic Safety Administration (NHTSA) data and found that 24% of vehicle crashes were weather related in the state of Maryland, which has a similar climate and geography to Virginia (p. 4). Additionally, 75% of weather-related crashes occurred on wet pavement and 15% occurred during snow (Liu, p. 4). Therefore, rain and snow are the biggest contributors to weather related accidents in this region.

Although a human decision is at the core of every traffic incident or accident, there is a lack of understanding of current weather impacts on road safety for the average commuter.

Researchers relied on phone surveys to determine how drivers use weather data to drive safely. In response to two winter storms in Utah, drivers looked at an average of two-to-three weather sources before commuting (Barjenbruch et al., 2016, p. 481). Most of those sources came from local weather stations and personal connections rather than government websites like that of the National Oceanic and Atmospheric Administration (NOAA). When asked about the available weather data, almost all drivers felt satisfied with its quality. Despite feeling well-informed, the majority of drivers answered that the actual storm was more severe than expected. Additionally, only a small portion of the drivers adjusted their behaviors (Barjenbruch et. al., p. 481). Consequently, any effective solution will need to account for human sentiment.

While human factors are highly important, we cannot neglect the rise of autonomous vehicles. Weather hazards may pose a particular problem for autonomous vehicles, since this adds more variables to an already huge number that control systems in these vehicles must consider when operating on the road. Furthermore, the growing presence of electric vehicles on Virginia's road systems will accelerate the fraction of autonomously driven vehicles. Currently, 2% of passenger vehicles in Virginia are electric, yet this metric is expected to balloon to 46% by 2040 (TRIP, 2020, p. 2). Both electric and autonomous vehicles would benefit from a combined stream of weather and traffic data to optimize their routes and increase passenger safety.

Currently, Virginia's weather information is a synthesis of data from space and ground sources that the entire country shares. VDOT deploys ground sensors from the commercial company Vaisala, as well as dispatching people to observe conditions in-person. In space, the most prominently used satellites are from NOAA's Geostationary Operational Environmental Satellite (GOES) system. The GOES-R series of satellites report weather conditions on the Earth's surface and at different layers of the Earth's atmosphere. These satellites carry an imager that measures incoming infrared radiation from the Sun, and a sounder that observes atmospheric profiles and cloud coverages. The current generation, GOES-16 offers greater imagery and resolution with increased frequency, providing weather updates every 30 seconds (National Weather Service [NWS], n.d.). GOES-16 contains two Earth-pointing sensors, the advanced baseline imager (ABI) and the geostationary lightning mapper (GLM) (National Aeronautics and Space Administration [NASA], n.d.). The GLM is capable of detecting the location, frequency, and extent of lightning discharges, allowing it to identify intensifying thunderstorms and tropical cyclones. The ABI contains a 16-band imager capable of viewing multiple wavelengths in the visible, near-infrared, and infrared spectrum. These bands allow GOES-16 to detect various elements on the surface or in the atmosphere, including cloud formation, snow, ice, rain accumulation, surface temperature, winds, fire, and many other weather-related indicators. According to the National Weather Service, GOES-16 provides three times more spectral information, four times the spatial resolution, and more than five times faster temporal coverage than the previous system (NWS, n.d.).

Even though GOES detects many forms of weather, ground-based forms of data collection are still necessary to produce robust information. Several instruments, such as Doppler radar, ground stations, and weather buoys, supplement satellites by collecting data that is hard to obtain from space, such as precipitation intensity. To improve accuracy, human observations are submitted to NOAA as an additional verification method (NOAA, n.d.). Even still, some weather measurements are collected entirely by hand. For example, snow depth is typically measured by a human at ground-based weather stations (Rasmussen et al., 2012, p. 815). This leads to limited coverage since weather stations are located far apart from one another and manual measurements are infrequently updated.

Similarly, private products such as Google Maps, Apple Maps, and Waze crowdsource information from drivers and relay the data to other app users. Since these applications have standards to ensure their product is consistent, weather data from individual states is often undelivered due to a lack of nationwide availability. When these navigation tools do not include real-time weather updates, local Emergency Management Services (EMS) encounter issues with responding to calls due to inadequate re-routing. Additionally, current weather services are not timely enough, so EMS rely on user reports to address a weather emergency such as flooding.

Overall, NOAA's weather data collection is constantly improving, with increasingly accurate and frequent data, allowing for extremely reliable short-term forecasts and improved long-term forecasts. Despite the incredible capabilities of the GOES satellites, integration of this data into preexisting, popular route planning apps is minimal, even though adverse weather conditions are a significant cause of vehicle crashes every year (Federal Highway Administration, 2020). This is because GOES-16 has a spatial resolution of about 2 kilometers, which is too coarse to distinguish features on the road (GOES-R, n.d.). If, however, similar measurements are obtained at much higher resolution, real time weather data obtained in space could be incorporated into navigational apps for drivers in a useful way. This would improve the economy, health, and environment for Virginians.

MISSION OBJECTIVES AND SOLUTION APPROACH

After conducting a literature review, the team used the space mission engineering process to determine the mission objectives and solution approach. The knowledge gleaned from our research helped us determine the mission objectives, listed below. After discussing the mission objectives, we will share the conceptual approach selected. The mission objectives are:

Primary Mission Objectives:

1. To detect and identify snow-covered, ice-covered, or dry roadways using remote sensing.
2. To effectively distribute measured data to roadway users, first responders, and roadway managers in order to improve roadway efficiency and safety.

Secondary Mission Objectives:

1. Reduce long term costs of roadway monitoring for roadway managers
2. Measure the effect of climate trends on roadways and help predict required maintenance.
3. Measure how effective the system is on driver behavior and safety.

To satisfy the first primary mission objective, we will start with a proof-of-concept focused on the Capital Beltway in Northern Virginia. From there exists the opportunity to scale up to the continental United States. Many efforts to track the effects of weather on roadways require a human-the-loop that our approach hopes to remove, resulting in long term cost savings. Additionally, tracking climate trends again benefits the roadway manager by helping them efficiently allocate their resources and workforce.

The data we collect will not help reduce weather-related traffic congestion without informing the public on road conditions. To meet the second primary objective, partnering with the aforementioned widely used navigation apps will ease the process and allow the capstone team to focus on executing a spacecraft that creates usable data streams. A secondary objective related to data delivery is to measure how effective the system is on driver behavior and safety. Upon launch, conducting surveys and reviewing user reports will provide helpful feedback about the technology's impact on weather-related accidents.

The proposed solution, based on the mission's primary and secondary objectives, is a constellation of 24 6U CubeSats; called collectively the Commuter Live-Yield Traffic Observation Network (CLAYTON). We propose two phases. First, as a technology demonstration during phase I, we will prototype and launch one satellite. Later, during phase II, a follow-on joint UVA and commercial team will build and deploy the 24 satellites. There will be two ground stations; one at the University of Virginia and another at Virginia Tech, for redundancy purposes. There will be a ground calibration site to verify that the spacecraft instruments are functioning properly. With successful data collection and dissemination to the pertinent stakeholders, such as roadway users, VDOT and EMS, further data collection areas can be included through the buildout of more ground stations and launches of additional satellites at a later time. This will allow for coverage of an entire coast, and eventually the whole continental US.

SYSTEM LEVEL REQUIREMENTS AND CONSTRAINTS

The system level functional requirements, operational requirements, and constraints are tabulated in Appendix A in Tables II, III, and IV, respectively. These tables also include specifications and verification methods. The most important parameters are described here.

The functional requirements for this mission dictate that the spacecraft must be able to detect, and distinguish between snow, ice, and dry roadways. In addition, measurements from our remote sensing platform must be of higher resolution than existing NOAA satellites. More specifically, the resolution must be fine enough to be able to distinguish the road from its surroundings. The standard width of a U.S. highway lane is 12 feet (Federal Highway Administration, n.d., "Interstate design standards"). Therefore, assuming the roads under observation consist of one- and two-lane width designations, we require a minimum resolution of 12 feet and a maximum resolution of 24 feet to capture the desired snow and ice accumulations. In order to meet the real time data delivery nature of the project, we require a data update with a frequency of less than one hour.

For successful completion of the operational requirements of this mission, the spacecraft must enable data delivery to government services, such as VDOT or EMS, to promote prompt and decisive action on segments of highway that are unsafe. Additionally, there must be data delivery channels for roadway users, such as third-party apps, to effectively deliver the latest road safety information to a wide audience. The data delivery, and resulting spacecraft, must host a minimum downtime of less than 5 minutes at a time. This ensures frequent availability during its designated service life of 5 years.

The two important system level constraints pertaining to this solution are size and cost. The spacecraft form factor must be within optimal size and mass to carry out the mission's primary and secondary objectives. Secondly, the cost at completion must be at or below the predefined budget of $50M by the course advisor.

BASELINE ARCHITECTURE AND MISSION CONCEPT

This spacecraft summary will outline the mission subject, identify the components of the spacecraft payload, and summarize the mission concept before describing each of the spacecraft subsystems in detail.

The subject of CLAYTON's mission is snow and ice accumulation on roadways in Virginia. In order to demonstrate proof of concept, the acquisition target will be limited to the intersection of Interstate 95 and Interstate 495 near Springfield, Virginia. The payload includes a hyperspectral camera which operates in the 450nm-900nm range. Also onboard the spacecraft are an arrangement of ClydeSpace Photon solar panels, and a CubeADCS 3-axis attitude determination and control system. We anticipate that the CubeSats will be launched into Low Earth Orbit (LEO) onboard a SpaceX Falcon 9, or onboard a Northrop Grumman Antares rocket for delivery to the International Space Station (ISS). Once at the ISS, the CubeSats will jettison and detumble into their operational orbits. Current calculations show 24 satellites at an altitude of 400km and an inclination of 51.6° will ensure a coverage frequency of 1 hour over the target area. While in orbit, CLAYTON will communicate in the S-band frequency range with a ground station located at UVA and a backup ground station located at Virginia Tech. It is also anticipated that UVA will serve as the satellite operator, provided the size of the constellation is limited to a tenable size. The intended lifetime of CLAYTON is five years, with the intention of generating enough accurate data to demonstrate proof of concept. Consideration was also given to a geostationary orbit satellite, however through several trade studies conducted, such a solution would prove costlier while providing less resolution.

Now, each subsystem will be described to explain how each subsystem design meets the system level requirements. The subsystems are addressed in the following order: Instruments, Communications, Software & Avionics, Power, Thermal, & Environment, Attitude Determination & Control Systems, Structures & Integration.

INSTRUMENTS

The objective of the instruments subsystem is to detect snow and ice on roadways in Virginia. The most important requirements for the image sensor relate to its spatial resolution, spectral range, exposure time, and size. The functional requirements and constraints are listed in Appendix B, Tables II and III respectively. Several CubeSat imagers met some of these requirements, but only the Simera Sense HyperScape100 meets all of the necessary requirements.

INSTRUMENT AND PAYLOAD REQUIREMENTS

The requirements for an imager to perform snow/ice detection on roads were determined through research pertaining to the NOAA GOES satellites. The research revealed that the spectral bands in Table I in Appendix B could be used to detect snow and ice on road surfaces (Liu, 2019; Romanov, 2016; Rost, 2012).

It was also found that snow and ice could be detected using passive or active microwave sensors. The spatial resolution and detection capabilities of microwave-based imagery, however, are too limited to determine snow cover in areas as small as the width of a road. Given that microwaves are the only feasible observation method at night, snow cover observation is limited to only daylight hours in the current design. The research showed that the primary method used by current satellites to detect snow and ice cover is the Normalized Difference Snow Index

(NDSI) (Romanov, 2016):

$$NDSI = (R_{vis} - R_{sir}) / (R_{vis} + R_{sir}) \qquad \text{eq. 1}$$

With R_{vis} being the 0.6 µm band used for snow detection in the visible spectrum, and R_{sir} being 1.6 µm band used for distinguishing snow from cloud cover (Romanov, 2016). This was the instrument team's original method of determining snow cover until it was determined that the imagers suitable for CubeSat applications which satisfy spatial resolution requirements would not be able to make observations in spectral bands with wavelengths as high as the 1.6µm band. After discussing the predicament with Peter Romanov from NOAA, it was determined that observations done using spectral bands near or within the visible spectrum would be the best option for snow/ice detection given the circumstances. Using reflected polarization as a method of snow and ice detection was suggested by the MITRE team. Research shows this technique to be a possible approach of detection of snow and ice on roadways and other surfaces. It may even be a superior approach over measuring light reflectiveness at different wavelengths given it's better sensitivity of distinguishing between particular environmental conditions, including ice, snow, and water. This is a relatively new approach (Piccardi & Colace, 2019), however, and more research and testing is needed to determine its feasibility with the particular conditions of a low earth orbit CubeSat, particularly its high altitude.

SPATIAL RESOLUTION

Spatial resolution is the measurement of the smallest area that can be detected by satellite imagery. For example, an image with a spatial resolution of 25 m depicts square areas on the ground of 25 x 25 m with a single pixel. Spatial resolution is affected by many factors such as the lens and filters used as well as the altitude of the orbiting satellite. The spatial resolution required to observe snow/ice cover on roads needs to be less than or equivalent to the width of standard road lanes, which is 3.7 m.

SIZE AND MASS CONSTRAINTS

The payload must have a physical size of 3U (30 x 10 x 10 cm) or less for easy integration with the planned 6U CubeSat. According to CubeSat standards, the mass of a 3U component must be 4 kg or less (Bellardo, 2020). These constraints were among the primary factors for determining the best options for a CubeSat imager.

EXPOSURE TIME

The required exposure time ($t_{exposure}$) is based on spatial resolution (d_{ground}) and velocity (v_{orbit}), as shown in the equation below.

$$t_{exposure} = \frac{d_{ground}}{v_{orbit}} \qquad \text{eq.2}$$

The team calculated an orbital velocity of 7,669 m/s at 400 km altitude, and this value was used along with the spatial resolution of the camera to find the maximum exposure time to prevent motion blur and produce a clear image. After the HyperScape100 was selected, the team calculated a minimum exposure time of 1/2000th of a second or faster based on its 3.8 m resolution.

POTENTIAL INSTRUMENTS

Research was conducted to find CubeSat-class imagers and a list of 12 possible options was compiled. Imagers that met the size/mass constraints included the Chameleon, Gecko, Mantis, and HyperScape100. The Chameleon can be configured as either a multispectral or hyperspectral imager, with a form factor of 3U and a mass of 1.3 kg (Dragonfly Aerospace, n.d.-a). It has an advertised spatial resolution of 9.6 m at 500 km altitude, but further research showed that its actual resolution was either 20 or 40 m depending on the spectral configuration.

The Gecko and Mantis imagers offer similar capabilities despite being slightly smaller. Both have a form factor of 2U and a mass of less than 1 kg (Dragonfly Aerospace, n.d.-b, n.d.-c). However, their spatial resolutions of 39 and 32 m, respectively, fail to meet the requirement established for the design. Another option, the Monitor Imager, was considered for its 2 m spatial resolution at 500 km (SCS Space, n.d.). The team later discovered that this imager is only compatible with CubeSats that are 12U or larger, thus ruling it out. All 7 remaining imagers were disqualified based on either insufficient spatial resolution or incompatible dimensions.

The HyperScape100 meets both the spatial resolution requirement and the size/mass constraint, with a resolution of 4.75 m at 500 km, a form factor of 2U, and a mass of 1.2 kg (Dreijer, 2021). The specified resolution translates to 3.8 m at the expected orbital altitude of 400 km, which is sufficient to resolve snow or ice cover on highways. It has a panchromatic band in addition to over 1000 available hyperspectral bands, uses 5.5 to 5.8 W of power during imaging mode, uses 2.35 to 2.48 W during readout mode, and requires a voltage of 5 V. The imager features 128 GB of built-in storage. Image data output options include LVDS, SpaceWire, and USART, and control interface options are I^2C, SPI, SpaceWire, RS-422, RS-485, or CAN 2.0B. The HyperScape100 is shown in Figure 1 below.

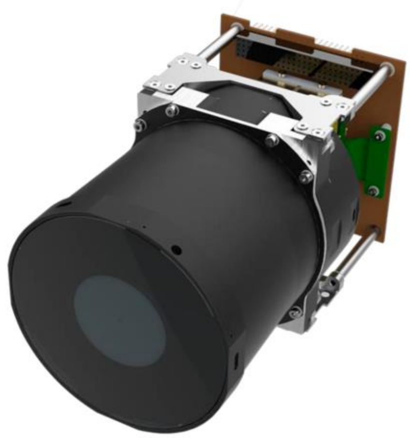


Figure 1. The Simera Sense HyperScape100 imager. (SatCatalog, 2020).

IMAGE ACQUISITION & PROCESSING

In order to distinguish between cloud/forest cover and snow/ice cover, the images will need to be processed using an automated computer process. For a fully-automated processing method, a reflectance threshold would still be used to determine snow cover but distinguishing cloud/forest cover would be automated as well. Forest cover can be distinguished easily at spectral bands around 0.4 - 0.5 microns. Clouds have a reflectance relatively close to that of snow throughout the entire spectrum available to the HyperScape100 as shown in Figure 2, but the difference may be large enough to distinguish the two with only the imager onboard CLAYTON. If it is not, however, CLAYTON data can be cross referenced with data from the NOAA GOES-16 Satellite which can effectively determine cloud cover with a spatial resolution of 1 km. This is a poor spatial resolution in comparison with HyperScape100's 3.8 m spatial resolution, but if GOES-16 determines that a certain area has cloud cover then CLAYTON's data processing will assume the presence of clouds within the same geographic space. Once cloud cover is distinguished from ground observation, the final step is to match the images with a road mapping system or by using ground stations to calibrate the image processor. This will determine the locations of roads within a given image. As a result, such a system would allow observers to determine if there is high reflectance on road surfaces, indicating snow and ice cover, instead of the usual low reflectance due to asphalt or other road materials.

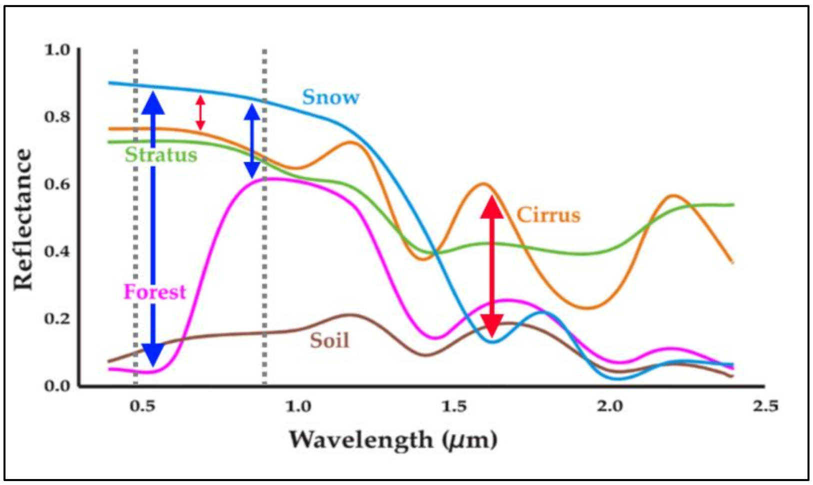


Figure 2. Spectral Reflectance of Objects. Vertical dotted lines represent the boundaries of HyperScape100 spectral range. Arrows show reflectance differences used to distinguish observations. (Romanov, 2016).

COMMUNICATIONS

Determining the communications subsystem concept involved selecting the satellite's antennae and transceivers, outlining the flow of information from satellite to ground station to end users, and specifying subsystem functional and operational requirements.

UHF, S-BAND, and X BAND FREQUENCIES

This section is a summary of the state-of-the-art for different band frequencies in communications, information can also be found in Table VII of Appendix B. This information led the team to decide to use S-band and UHF frequencies for CLAYTON. Conventional CubeSats have communicated in the Ultra High Frequency (UHF) and S-band frequency ranges. S-band is from 2 to 4 Gigahertz (GHz), X band is from 8 to 12 GHz, and UHF is from 300 Megahertz (MHz) to 3 GHz (Dunbar, 2020). As the frequency increases, the potential transmission rate in the CubeSat increases due to the larger bandwidth. While UHF and S-band communication systems are currently more developed than that of X band's, strides have been made in improving X band availability. Regarding affordability, however, X band remains a more expensive option compared to the other two frequency ranges. Both S and X band systems must be pointed at the ground while the UHF has more flexible orientations. This depends on the antenna type. Common UHF band antennas are dipole or turnstile, while common S or X bands are patch antennas. Primary interference was another consideration. Wireless networks dominate the S-band and smaller devices like cell phones or radios dominate the UHF band. While fewer commercial or personal devices occupy the X band, Earth's atmosphere becomes an interference source (Dunbar, 2020).

Using the information above, it was determined that the satellite would need a UHF transmitter and antenna as this can send data in all directions and is effective at sending information about the state of the satellite. It was also determined that either an S-band or X band will be required to send the weather information. The decision between S-band and X band will be determined based on how large of a transmission rate is required.

FUNCTIONAL, OPERATIONAL REQUIREMENTS AND CONSTRAINTS

To ensure timely communication of data between the satellite and the ground station, the functional requirements state that the satellite should transmit at a rate of 15 Mbps to the ground station. This 15 Mbps transfer rate was determined assuming there would be 30 images with a size of 25 MB for each image and a transfer window of about 10 minutes. Weather data is to be transmitted using S-band for the best transmission rate compatibility, while UHF will be used to communicate satellite operational data and as a backup for sending weather data in case S-band fails. The UVA ground station already has a compatible UHF antenna which is why the team chose to use one on the satellite. Requirements will be verified using inspection and testing of equipment.

For operational requirements, during initial testing the data stream will go through the UVA ground station, with Virginia Tech serving as the backup location. Some modifications will have to be made to the UVA ground station to include the S-band antenna. When the project is at its full scale in Phase II, the data stream will go through a commercial ground station. Requirements will be verified using inspection, analysis, and testing of equipment. The spacecraft conceptual design focused on satellite to ground communications, therefore future work will be required on transferring data from the ground station to emergency personnel and roadway navigation companies.

The only major constraint was the amount of space in the CubeSat that the communications equipment could take up. The team decided that all of the required equipment had to fit into less than 2U of the 6U spacecraft in order to leave room for other necessary components. This will be verified using inspection with other structures and integration teams. A table with all of the requirements and constraints can be found in Tables IV, V, and VI in Appendix B.

CHOOSING THE GROUND STATION

For the initial testing, the main ground station will be located at UVA; however, this requires installation of an S-band antenna. This would allow quicker transmission of captured images, satisfying the 5-minute delay requirement. The Virginia Tech ground station will be the backup station. If the project is scaled up to cover all of Virginia or the entire US, then a commercial ground station network will be required.

With a long enough transmission window, about 10 minutes, the data can be downloaded at a lower speed than it was acquired. It is also possible that some of the data can be processed and removed from that bundle before it is sent to the ground. Therefore, a longer transmission window allows for a smaller transmission rate than the data capture rate (McPherson, 2021). The team assumes all data reduction will be done on the ground.

CHOOSING THE ANTENNA AND TRANSCEIVER

For antenna selection on the satellite, there is a tradeoff between the beam width precision and the data transmission frequencies. Antennas using higher frequencies should use a dish with small beam width in the 3–4-degree range. A smaller beam width range requires greater pointing precision. The positioner bought for the UVA ground station is capable of about one degree accuracy; therefore, it is compatible with an S-band dish (McPherson, 2021). An antenna with a higher gain is desirable, as high gain directly correlates with increased signal strength.

The antennas the team compared were the ISISpace UHF antenna, the Helios-brand UHF deployable antenna, the UHF Endurosat antenna, and the Endurosat S-band antenna. The ISISpace antenna was not selected because it can only be deployed once and the manufacturer did not specify the frequency (ISISpace, n.d.). Despite compatibility with 6U CubeSats, the Helios-brand was also not selected because of its large price (Helical Communication Technologies, n.d.). The Endurosat UHF and S-band antenna are the most compatible with the design and each other due to coming from the same manufacturer, having the largest transmission rate, and having positive gains; however, the UHF antenna would have to be custom ordered as a dipole in order to not interfere with the GPS antenna (Endurosat, n.d., -a; Endurosat, n.d., -c).

The S-band and UHF transmitter and transceiver chosen were products of the company Endurosat. As part of the risk mitigation process, the team decided to implement both S-band and UHF transmitters (Endurosat, n.d., -b). The UHF can be a backup for the S-band because it requires less precision for data transmission alignment (Endurosat, n.d., -b). With higher transmission rates being valued, the Endurosat S-band transmitter having 20 Mbps achieved the requirement of 15 Mbps for the instruments used on the spacecraft.

SOFTWARE AND AVIONICS

Design of the software and avionics subsystem included selecting the on-board computer to manage the satellite’s sub-system communication and operation, and to select accompanying software and control interfaces to facilitate these tasks.

FUNCTIONAL, OPERATIONAL REQUIREMENTS AND CONSTRAINTS

The first of the functional requirements seen in Appendix B, Table XII, that was pertinent to the software and avionics subsystem is that it must be able to operate and handle thermal stress within the temperature range of -25°C to +80°C. Exposure to and loss of sunlight during orbit can cause temperature cycling in extreme ranges and the computer must be able to operate continuously to prevent mission failure. The second functional requirement is that it is able to withstand the anticipated levels of radiation in orbit. Space radiation and ion strikes can cause computers to process data incorrectly and even permanently fail if satisfactory resistances are not installed. The third functional requirement for the onboard computer is that it consumes less than 350 mW on average. The final and most important requirement is the on-board computer memory, which will handle the interface of the various subsystems and instruments. Thankfully, the instruments selected throughout this experiment do all pre-processing and compression internally, which greatly reduces the necessary memory on board the onboard computer. A requirement of 500 KB was selected as a conservative estimate of the processing power required for the I2C control interface and other system upkeep tasks.

The first operational requirement for the satellite software and avionics is that all of the data streams are integrated and compatible. This requirement makes it so that data is able to flow and be interpreted all the way from the imager to integrated data platforms. Another planned avenue of delivery, besides customers of Waze, is to successfully transmit the weather data to first responders. Besides software compatibility, the on-board computer must have large enough data storage capacity to contain, store, and transmit the sensor images to the antenna. The onboard communication must be able to transfer the data quickly from different subsystems for efficient operation. This onboard transmission is accomplished using an I^2C bus.

The first constraint for the onboard computer is that it must be 10 cm x 10 cm x 4 cm in order to fit into the cube satellite proposed for this design. The onboard computer must also be 400 grams or less, and have a lifespan of at least 5 years, the planned mission duration. Additionally, the cost per unit of each on board computer and accompanying software must not exceed $10,000.

MEMORY PROTECTION AND REDUNDANCY

Memory protection and redundancy are resilience measures that ensure onboard electrical systems operate as intended. It will primarily utilize built in forward error correction (FEC) and error correction code (ECC) (Kovo, 2020). FEC is designed to save bandwidth, eliminate handshaking between the source and destination, and protect small errors in data transmission between onboard systems. ECC is used to protect memory which builds up over time due to radiation and charged particles in space. Scrubbing is the process through which these buildups are checked and cleaned, and its frequency affects the reliability of on-board memory. Example ECC methods include cyclic block codes or Hamming codes (Fuchs et al., 2015).

DATA FLOW

The data roadmap, as shown by Figure 3 below, depicts the process of converting raw image data into information for end users. After the HyperScape100 imager captures the raw data, it undergoes lossless data compression using CCSDS algorithms with an approximate compression ratio of 3:1. This speeds up the processes of redundancy and data transmission to the ground stations. The data is stored on the HyperScape 100 Imager's internal 128 GB Flash memory until the image capturing window is over, at which point it will be taken through the Endurosat OBC I computer that applies a Federal Communications Commission (FCC) redundancy to the data. The Endurosat OBC I was selected as the on-board computer over the alternative choice, the Satbus 3C2, for a variety of reasons. Namely, it was about $6,000 cheaper per unit than competing off-the-shelf models, it has a lower average power consumption, and had sufficient processing power to operate the control interface. The now compressed and redundant data will be sent from the on-board computer to the Endurosat UHF Transceiver, which will convert it to radio frequency and transmit it down to the University of Virginia and Virginia Tech communications ground stations. With more computational power and no memory limits on the ground station computers, 'HRPT Reader' software processes high resolution picture transmission (HRPT) data. This software will assist in discerning key details from the satellite details, such as snow and ice on the road. Additionally, we will develop algorithms that map the location of image reference points to coordinates so that the weather conditions can be identified on each roadway, and reported accordingly. The weather insight gained using this system is finally disseminated to existing traffic and navigation datasets and applications in order to efficiently reach the roadway managers and end users.

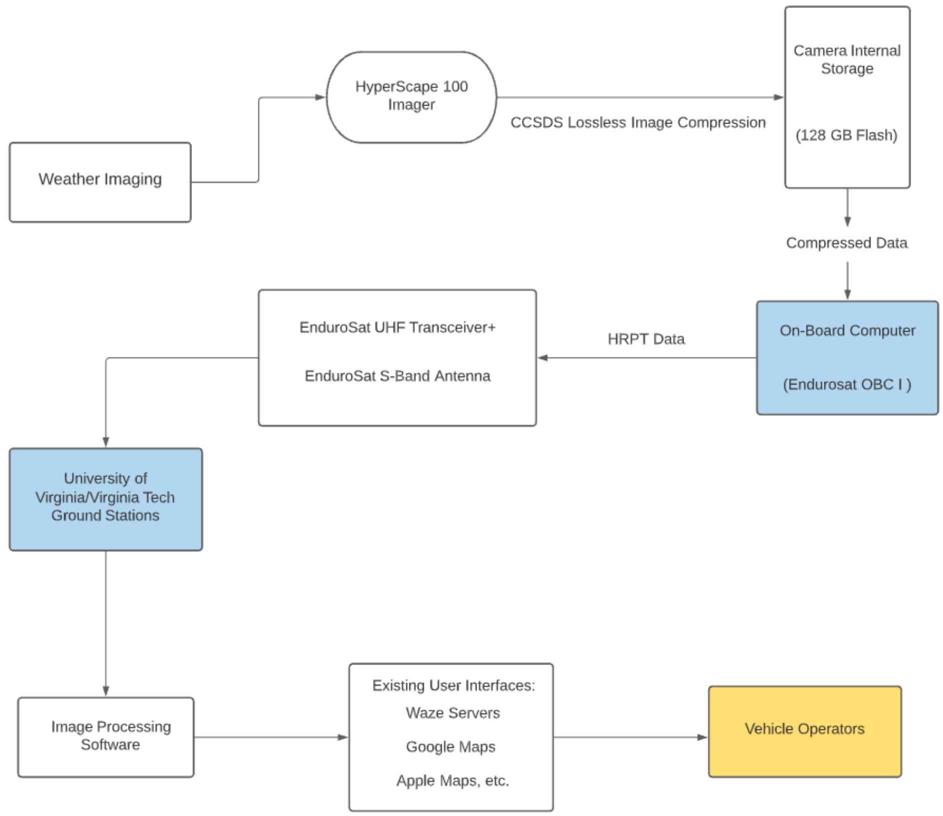


Figure 3. Satellite Weather Data Flowchart. This figure demonstrates the flow of data from the sensor to the end user with each box representing a major step in the process.

POWER, THERMAL, AND ENVIRONMENT

The Power, Thermal, and Environment (PTE) subsystem design involved selecting an appropriate power source for the satellite that will provide enough power to operate all instruments when necessary, for the duration of the mission. The PTE team is also responsible for adding protective elements to the satellite where necessary to ensure thermal stability as well as environmental safety from events like radiation and micrometeoroid collisions.

FUNCTIONAL AND OPERATIONAL REQUIREMENTS

Power, Thermal, and Environment functional requirements include ensuring thermal stability within the bus between the range of -25°C to +80°C, protecting the instruments from radiation in the orbital environment, generating enough power for all instruments during standby and peak operation, storing enough power in the battery for the instruments to operate during eclipses, and ensuring the electronic integrity of the electronic components through the management of voltage and current distributed throughout the system. The majority of these requirements will be verified through testing and analysis or inspection, with the lifespan of systems being verified through simulation and in-orbit inspections. An operational requirement that PTE has is to ensure that the power and environmental protection technologies can last for the entire duration of the mission, or a minimum of five years. The system must operate under effects from UV radiation, and atomic oxygen, and must withstand thermal fluctuations both from the environment and from internal heat dissipation (Appendix B, Table IV).

POWER FLOW CHART

The power flow chart provides a visualization of the power distribution throughout the bus. The power is generated via stationary solar panels and is stored in the battery. The electrical power supply distributes the power based on the voltage each component needs. The onboard computer, multi-GNSS receiver Celeste, Hyperscape100 camera, and CubeADCS require 5V connections. The CubeADCS also requires a 3.3V and a raw voltage connection. The Endurosat transceiver and transmitter also requires 5V connections, as well as the antennas UHF Antenna III and S band ISM shown in Figure 4 below.

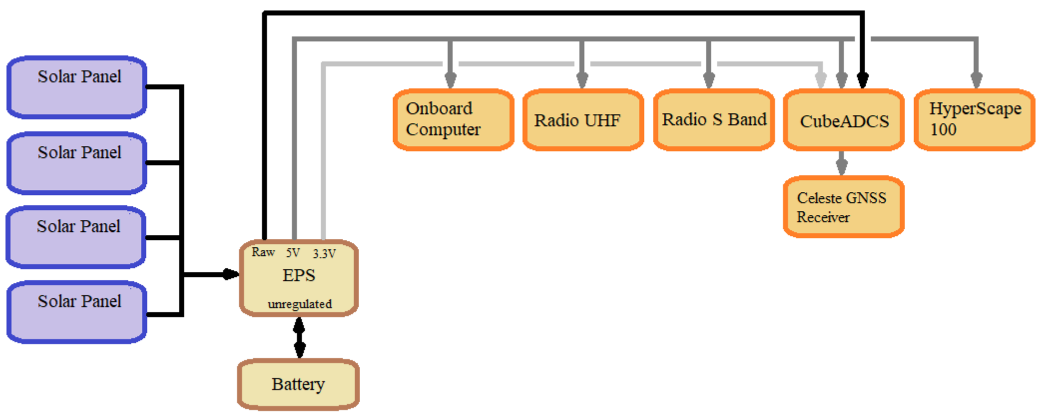


Figure 4. Power flow chart for CLAYTON. This figure depicts the generation, processing, and distribution of power for each component.

PRELIMINARY POWER BUDGET

Three solar panel models were initially considered for the CubeSat, with the options being the ISISpace CubeSat Panels, the Clyde Space Photon Panels, and the Endurosat Solar Panels. The panels were placed into a selection matrix to directly compare key factors and the weighted average scores were then used to objectively determine the most appropriate solar panel. The key factors consisted of cost, weight, power generation, operating temperature, and lifetime operation. With this, the Clyde Space Photon Panels scored highest and were thus selected. The team pre-determined that all exterior faces excluding the top and bottom (i.e. all 3Ux2U and 3Ux1U sides) would be mounted with stationary solar panels, resulting in a total panel area of 18U, with 9U being used as the maximum generation capacity based on the geometry. An in-depth power budget was then created, considering the generation capacity, panel efficiency, supply efficiency, sunlight period, eclipse time, and orbit period to calculate rough values for available power and energy (Table I). Then, the available power was then compared with the energy requirements of onboard subsystems to guarantee that it was sufficient to power the entire system.

To find the required battery size to support spacecraft functions, the peak and eclipse energy usage were estimated. For peak, a conservative estimate was made by using the peak power values, or the standby power where a peak was not given, and an estimated 20 minutes of maximum usage. It was assumed that this peak usage would only occur during the sunlight period, such that power is still being generated during peak consumption. Thus, the power generated was subtracted from the peak power consumption in the calculation. Lithium batteries should be cycled in mid-state-of-charge to preserve longevity, so it was decided to conservatively cap battery drainage at 40% (Battery University, 2020). Thus, the calculated energy value was considered to be 40% of the minimum necessary battery size to support peak usage. A similar process was used to calculate the battery size needed for the eclipse period by using standby power values. The sum of the peak and eclipse values was 19.6 Wh. Thus, among the options offered by Clydespace, it was decided to use the Starbuck-Nano Plus electrical power subsystem (EPS) frame built for 3-12U CubeSats in conjunction with the smallest option for the Optimus battery, 30 Wh. This gives a margin of about 10 Wh, giving ample room for any changes to the power budget in the future.

Table I
Preliminary Power Budget for CLAYTON

	Peak Power (W)	Standby Power (W)	Peak Time (h)	Peak Percentage	Standby Percentage	Power Required (W)
Instruments	5.60	2.40	0.01	1%	99%	2.42
Comm	16.7	1.00	0.17	11%	89%	2.74
ADACS	5.00	1.10	0.05	3%	97%	1.23
GPS	0.100	0.10	24.0	0%	100%	0.10
EPS	0.150	0.15	24.0	0%	100%	0.15
OBC	0.330	0.33	24.0	0%	100%	0.33
Total:	**27.9**	**5.08**				**6.97**

Solar Flux, SF (W/cm^2):	0.135		Power Available, PA (W) = SF*PSE*PE*GA*NoG	
Power Supply Eff., PSE:	0.900		**PA =**	**23.4**
Panel Efficiency, PE:	0.293		Orbit Average Power, OAP (W) = PA*SPct	
Grid Area, GA (cm^2):	73.0		**OAP =**	**14.1**
Number of Grids, NoG:	9.00		Power Budget, PB (W) = OAP-PR	
Sunlight Percentage, SPct:	0.600		**PB =**	**7.09**
Power Required, PR (W):	6.97		Energy Available, EA (Wh) = PA*SPd	

Sunlight Period, SPd (h):	0.900		**EA =**	**21.1**
Eclipse Period, EP (h):	0.645		Energy Required, ER (Wh) = PR*OP	
Orbit Period, OP (h):	1.55		**ER =**	**10.8**

ATTITUDE DETERMINATION AND CONTROL

The attitude determination and control system (ADACS) and orbits subsystem is primarily focused on enabling each individual spacecraft to maintain proper orientation and location in space as the mission is carried out. These systems are crucial for ensuring the acquisition target will be within the field of view of the onboard instrumentation, supporting communication with ground stations, and meeting the observation frequency and lifetime requirements of CLAYTON.

FUNCTIONAL AND OPERATIONAL REQUIREMENTS

Functional requirements for the ADACS subsystem and satellite orbits can be found in Appendix B Table IX include: a pointing accuracy of ±1.86°, a location accuracy of ±10m, a pointing determination of ±0.465°, maintaining an altitude of 400 km and an inclination of 51.6°, and ensuring the orbits support a coverage frequency of greater than one pass per hour. The only operational requirement that pertains to this subsystem is that the orbital lifetime must be at least five years in order to satisfy the mission lifetime requirement. Constraints include minimizing mass, cost, power draw, and size in order to remain within the limits of their corresponding budgets. ADACS requirements will be verified via testing and data analysis, and orbital requirements will be verified via simulation in the AGI STK orbital analysis software. The ADACS functional requirements were largely guided by the spatial resolution requirement of roughly 7.3 m. The specified pointing accuracy guarantees that the target will be within the field of view and the specified pointing determination tolerance guarantees that the target will be within the middle two quadrants of the image produced.

ADACS UNIT TRADE STUDY

Incorporating a commercial off-the-shelf ADACS unit into each satellite offers simplicity and cost-effectiveness during implementation of CLAYTON. A total of eight commercial off-the-shelf ADACS units were initially assessed in terms of their satisfaction of functional and operational requirements and their contribution to the cost, mass, filled volume, and power draw of each spacecraft. From there, we selected two units, and performed a trade study to identify the unit better suited to support CLAYTON’s mission. The results of this trade study are below in Table II.

Table II
ADACS Unit Trade Study

Requirement		Components Evaluated	
		CubeADCS 3-axis	CubeADCS Y-Momentum
Pointing Accuracy	±1.86°	~0.001°	> ~0.001°
Attitude Determination	±0.465°	TBD	TBD
Size	< 6U (10cm x 10cm C-S)	90x96x59mm = 0.5 U	90x96x58mm = 0.5 U
Mass		0.506kg	0.351kg
Cost		$32k	$22k

While both units evaluated in this trade study were within the requirements, the CubeADCS 3-axis unit had increased accuracy and comparable size, mass, and cost compared to the Cube ADCS Y-Momentum unit.

GPS UNIT TRADE STUDY

Similar to the ADACS unit selection, a commercial GPS unit was chosen for CLAYTON. Eight units were examined with a focus on the size, power consumption, mass, and cost, as these were the major constraints for the mission. After comparing the units, two GPS devices fit the mission requirements the best. To choose a final unit for the CLAYTON mission, the team conducted a trade study on the two remaining GPS units. The results of the trade study can be seen in Table III.

Table III
GPS Unit Trade Study

Requirement		Components Evaluated	
		Celeste GNSS Receiver	WARPSPACE GPS Receiver
Location Determination	±10m	2.5m	2.5m
Size	< 6U (10cm x 10cm C-S)	67mm x 42mm x 7mm	24.1mm x 20.2mm x 7.5mm
Power		100mW	150mW
Mass		25g	3g
Cost		$2.5k	$2.5k

The Celeste and WARPSPACE receivers were similar in their low cost, precise location determinations, and low power draw, so the differences stem from the size and mass. With comparable performance, a smaller and lighter GPS unit is the better choice. A smaller unit provides more available space for other instruments, and less mass leads to a lower overall launch cost. For these reasons, the WARPSPACE receiver was selected for the CLAYTON mission.

ORBITAL PARAMETERS

Initial evaluation and modeling of CLAYTON's orbital parameters indicate that an inclination of 51.6°, paired with the altitude of 400 km, is appropriate. Here the satellites will be deployed from the ISS, and this will allow for sufficient resolution and ground coverage to satisfy the objectives of the mission. Moving forward, the constellation size and parameters will be refined using more complex and robust analytical packages within the AGI STK software that were not available for use during the analysis performed in this study. Figure 5 shows a snapshot of the STK simulation run with these orbital parameters. The different colored lines indicate the ground traces of the satellites within the constellation. Attached to the satellites are the imagers that will look at the point of interest. The area on the ground that the imagers can see are represented by the cones that come from the satellite. These cones were given a cone half angle of 45 degrees. This was an estimation based on the ability of the satellite to orient itself to point the instrument towards the point of interest.

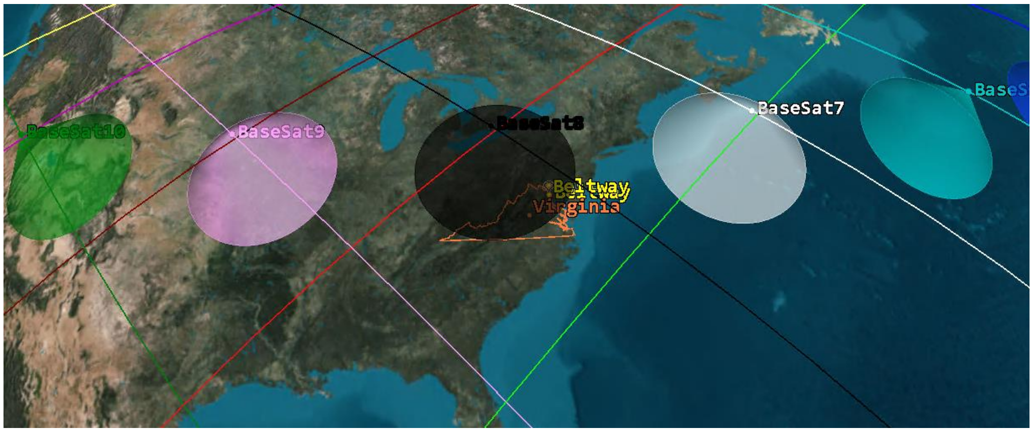


Figure 5. Constellation ground trace of CLAYTON's satellites with estimated imager range. The colored lines represent the multiple paths of the satellites. Each satellite is equipped with an imager, and the range the imager can view is pictured with the colored cone.

ORBITAL SIMULATIONS RESULTS

With 24 satellites at an inclination of 51.6°, altitude of 400 km and separated by 15° of right ascension the coverage of the target region every hour can be seen in the histogram below in Figure 6.

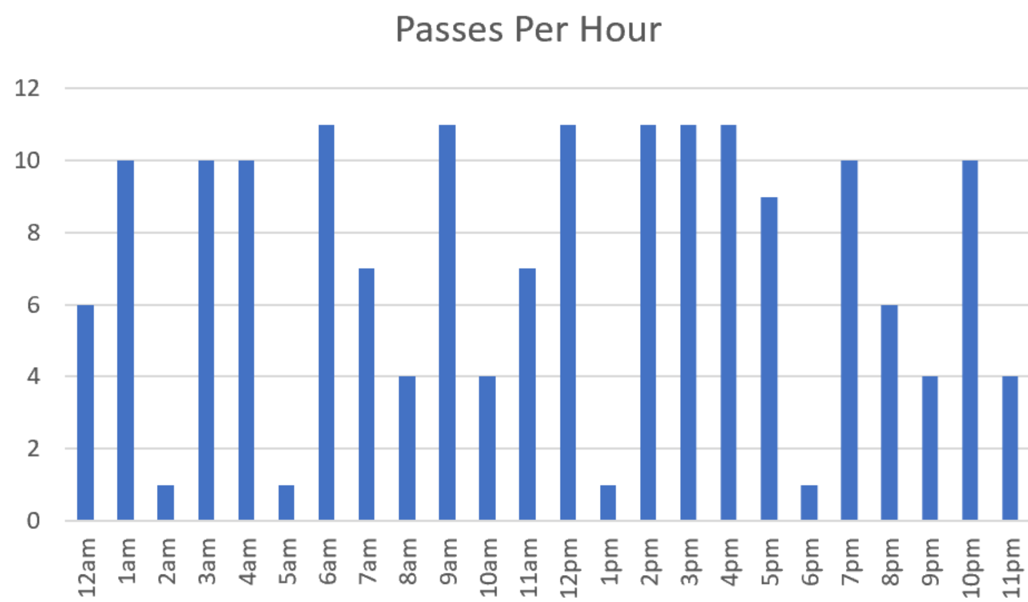


Figure 6. Number of passes over target area made by CLAYTON every hour throughout one day.

From Figure 6, it can be determined that the current constellation design typically provides multiple passes of the target area per hour, but in some cases, there is only one observation per hour. The inclusion of all 24 satellites in the final constellation design is therefore necessary, as the functional requirement is a coverage frequency of greater than or equal to once per hour. With the University's recent acquisition of a student license for the STK

Analyzer and Optimizer software tools, future orbital simulation studies can utilize the robust capabilities included within these add-ons to optimize the constellation's parameters. Optimizing the constellation to maximize coverage frequency while minimizing the number of satellites required would allow for the best satisfaction of functional requirements whilst also reducing overall project costs.

STRUCTURES AND INTEGRATION

The objective of structures and integration is to make sure all parts can operate as a system, and integrate together inside the structure of the CubeSat. Under the California Polytechnic State University CubeSat design specifications, a 6U satellite package must weigh less than 12kg and have dimensions of 100mm x 226.3mm x 366mm (Cal Poly San Luis Obispo, 2018). SolidWorks was used to ensure that the components making up the spacecraft would meet the mass requirements and fit within the designated dimensions. A breakdown of the team's relevant functional and operational requirements as part of the design process can be found in Table X in Appendix B. Constraints on the spacecraft design are listed in Table XI in Appendix B.

SYSTEM ASSEMBLY

The system assembly will be configured in a 6U Cube Satellite Bus designed by AAC ClydeSpace. This structure has a mass of 0.674 kg, meets NASA's general environmental verification standards, and is compatible with ClydeSpace Photon Solar Panels, other ClydeSpace products, and all rail-deployers. As shown in Figure 7, the structure will be able to fit the following components: UHF Antenna, GPS Antenna, UHF Radio, Battery, Computer, EPS, Imager, ADCS, GPS, S-Band Radio, and S-Band Antenna. Each of the components will be held in place using four threaded rods on each side of the spacecraft.

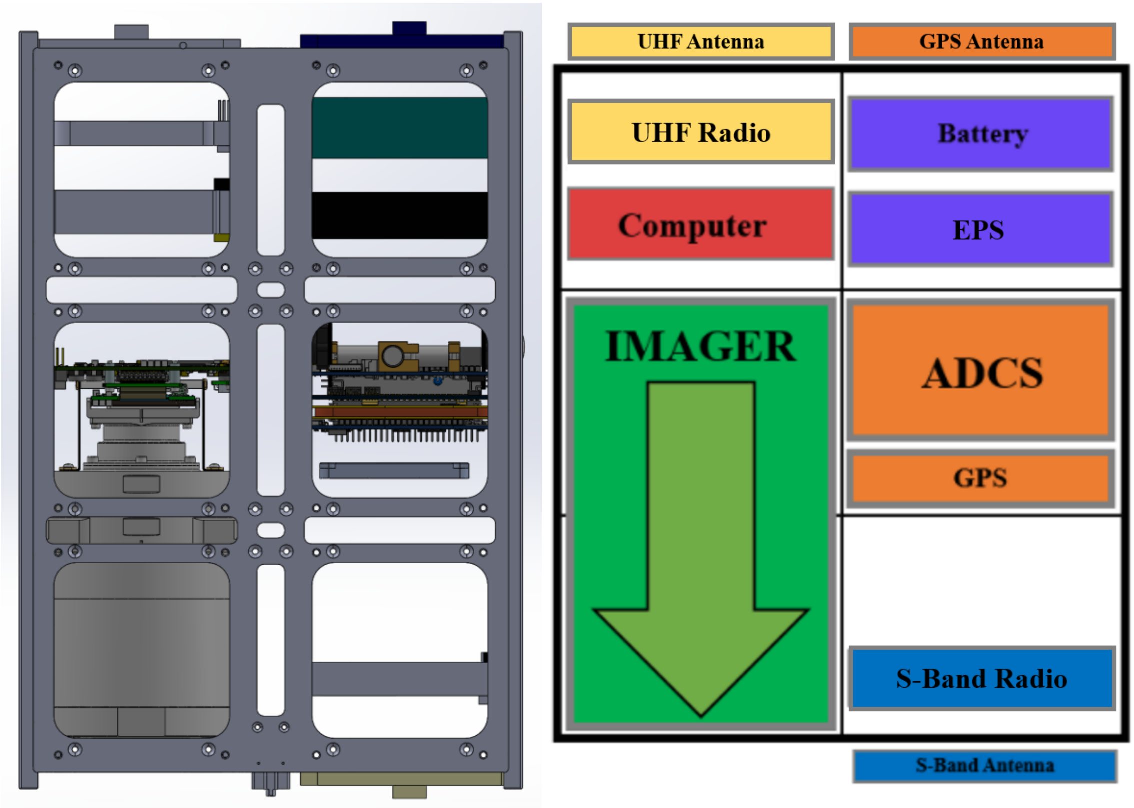


Figure 7. Diagram of each major component in the CubeSat and where it is located (right), CAD Model including all parts except solar panels (left)

LOCATION OF COMPONENTS

The imager was placed at the bottom of the CubeSat as it needs to be facing the Earth in order to take the hyperspectral images. The UHF and S-Band Antennas were placed at opposite sides of the structure to avoid interference between the two signals. The S-Band antenna is located on the bottom of the CubeSat so it will always face the Earth. The UHF and S-band radios were put next to their respective antennas to minimize lead length. The ADCS unit is in one of the central units as it is most effective when located near the center of mass of the structure. It uses information from the nearby GPS unit as well. The battery and EPS units need to be located next to each other, so those objects as well as the computer were placed with the center of mass in mind. The solar panels are located on the outside of the spacecraft, specifically the 1U x 3U and 2U x 3U sides as shown by Figure 1 in Appendix B. With this current system assembly, the center of mass has been approximated in SolidWorks to be within 10mm in the X-direction, 5mm in the Y-direction, and 0.5mm in the Z-direction relative to the geometric center. This is well within the center of mass constraints listed in Table XI in Appendix B.

MASS BUDGET

Tables IV and V below depict the preliminary mass budget for the CubeSat including all the components and parts that are referenced in the initial build plan. Table III shows the system is well within the 12kg allowable mass constraint listed in Table XI in Appendix B.

TABLE IV
Preliminary Mass Budget

	Component	Quantity	Mass (kg)
Structures and Integration	ClydeSpace 6U Zaphod Structure	1	0.67
Power, Thermal, and Environment	6 x AAC Photon Side Solar	6	0.81
	Optimus 40 Wh Battery	1	0.34
	Nano Plus PCDU	1	0.15
ADACS	CubeADCS 3-axis	1	0.53
	Celeste GNSS Receiver	1	0.03
Instruments	HyperScape 100 Imager	1	1.2
Communications	S-Band Transmitter	1	0.18
	UHF Transceiver II	1	0.09
	S-Band Antenna	1	0.064
	UHF Antenna III	1	0.085
Software and Avionics	Onboard Computer	1	0.13
	Total Mass		**4.28**
	Mass Margin		**7.72**
	Mass Constraint		**12**

TABLE V
Percent of Total Mass per Subsystem (without margin)

Subsystem	% Total Mass
Structures and Integration	15.7
Power, Thermal, and Environment	30.4
ADACS	13.1
Instruments	28.0
Communications	9.79
Software and Avionics	3.04

PROPOSED PROTOTYPING

We have identified two methods to prototype the CubeSat before beginning an official manufacturing process: 3D printing and the creation of a FlatSat. Thus far, we have developed a CAD assembly to ensure that all parts can be comfortably integrated within the CubeSat bus. However, it may also be beneficial to 3D print the various components of the satellite, in polymer, using estimated dimensions to ensure there are no dimensional interferences within the spacecraft. This would help save time and money in case some components are found to be too large to fit within the volume available. Furthermore, a FlatSat is a functional prototype of the CubeSat that is laid out flat on a table to facilitate testing and debugging (Ziegler, 2007). This prototype does not necessarily need to include any structural components, but can simply be used to test and debug software without risking any hardware components. The FlatSat can also be used to visualize and test all electrical and wiring components to limit the amount of electrical interface issues that may arise during the actual flight unit integration.

FINANCIAL BUDGET AND FUNDING SOURCES

The constellation is externally constrained to a maximum cost of fifty million USD. The budget was divided into two phases. Phase I is for the technology demonstration in which one spacecraft would monitor an intersection as proof of concept. In phase II, the full constellation would be launched for higher temporal coverage. In phase I, the budget includes one satellite, a backup satellite, as well as a satellite for ground and balloon testing. Additionally, Phase I features a one-time expense, estimated, to be $100,000 USD to add a S-band antenna to the UVA ground station. The budget approach for phase II involves estimating the cost of launch and testing and assuming the constellation would feature twenty-four satellites with one for redundancy and another for ground testing for a total of twenty-six satellites in the constellation. For phase II, the cost of launch was estimated by comparing different launch providers. Using

Spaceflight's rideshare launch services, the cost of launch between different commercial U.S. launch providers were compared. These providers include but are not limited to SpaceX, Virgin Orbit, and Rocket Lab (Spaceflight, n.d.). A majority of the launch providers that could satisfy the parameters of launching the constellation estimated a cost around nine million USD. As a result, ten million USD was allocated for launch. The cost of testing is based on historical pricing provided from receipts from past projects. It is assumed that all twenty-nine satellites would receive a functionality test, thermal test, vibration test, post vibration functionality test, vacuum test, and post vacuum functionality test.

The allocation of funds for each subsystem began with each subsystem submitting a list of predicted purchases along with a justification for each item. During the design phase of the project, only forty percent of the budget is projected to be used. A breakdown of the budget can be found in Table I in Appendix C. However, it is expected that expenses may increase in an unforeseen fashion as the project matures.

Potential funding sources have been identified. VDOT allocates part of its budget for transportation projects in Hampton Roads and Northern Virginia alone. The Virginia Space Grant Consortium (VSGC) features the Small Satellite Virginia Initiative in which funding for launch opportunities and funding for payloads are available every year. NASA has a CubeSat Launch Initiative (NCSLI) that has the potential to provide a discounted or free launch for the project, for phase I. Finally, government grants are open to applications on grants.gov and nsf.gov - transportation related project funding has been identified on such sites. In the following semesters, the project should submit proposals to these entities. The project personnel will contact VDOT, VSGC, and NCSLI for phase I funding. Federal grants from DOT or NOAA will be sought for phase II funding.

RISK ASSESSMENT AND MITIGATION STRATEGIES

Risk analysis for the spacecraft design can be approached with various techniques from understanding failure sources and cascading through event and fault tree analysis to defining requirements and rules with the Systems-Theoretic Accident Model and Processes (STAMP) methodology. Other methods seeking to understand the most effective allocation of improvement resources include multicriteria decision analysis, scenario planning, and resilience-based policy. These risk assessment and management tools can be applied on both a macroscopic level, where economic resources, stakeholders, and end users are all put into consideration, and a microscopic level, where the component and subsystem operations are focused upon. Both will be tackled in this section, though comprehensive formal studies will require further investigation.

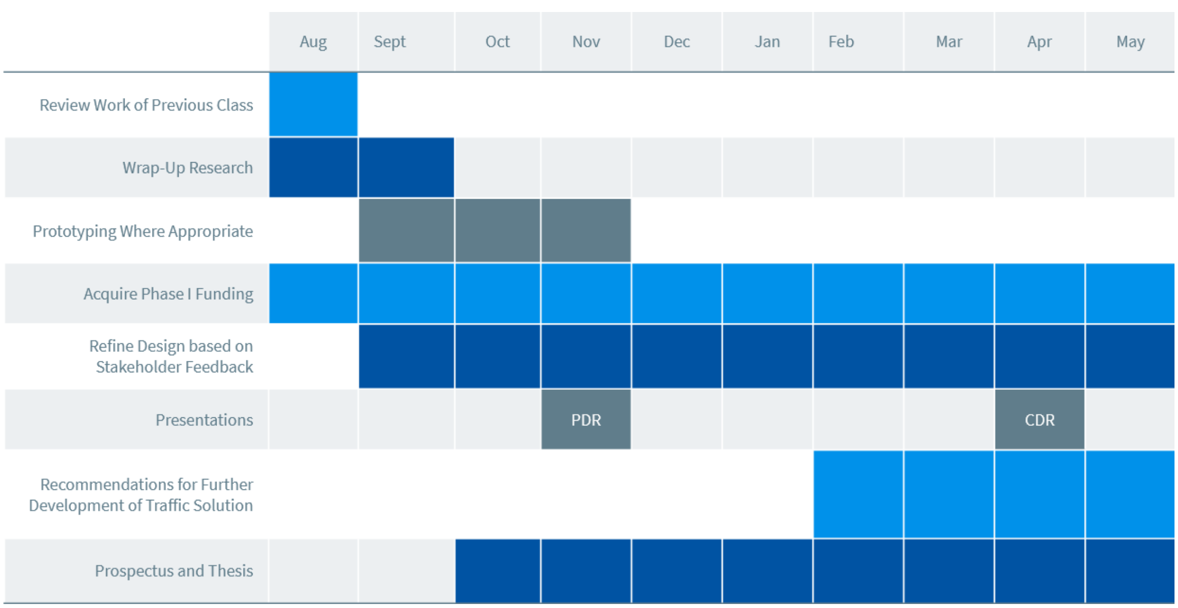
On a higher system level, the end goal of the spacecraft is to satisfy stakeholder requirements and serve roadway users. Varying stakeholder needs often act as a roadblock for addressing improvement resource allocation (the process of deciding where to prioritize system improvements over the base model during iterative design), thus multiple stakeholder priorities must be considered simultaneously through techniques such as hierarchical holographic modeling (HHM). Understanding how spacecraft failures can cascade to the end user through communication systems and application integration can utilize fault tree analysis, where "and" and "or" gates are used in conjunction to model this risk system. Lastly, manufacturing and component acquisition pre-deployment must also be considered, as larger systemic issues with IC part shortages due to COVID-19 or managing timelines to manufacture custom parts contribute to risk management of the design and implementation process. Other macroscopic risk sources exist as the spacecraft design is a complex system with thousands of subsystems and millions of dollars involved. Further research is required to resolve any given risk source as each deserves their own review.

A case study involving the satellite bus itself will be presented here to investigate microscopic system level risks (Appendix C, Figures 1, 2, 3). According to “Survey on the implementation and reliability of CubeSat electrical bus interfaces,” historical data shows that for technology demonstration CubeSats, the known root cause allocation for not achieving full mission success is primarily ADACS, with communications and electrical power subsystems coming second (Bouwmeester et al., 2016). The survey also reveals that I^2C buses are most susceptible to bus lockup, where internal communication clocks go out of sync and data transfer is locked. The most common mitigation technique is to implement a watchdog circuit in which the electronic timer will detect a malfunction and order a reset for both sender and receiver clocks. Other failure modes include packet loss and performance degradation, in which other tolerance implementations exist to combat. This example demonstrates the viability of historical data-driven techniques to decide which systems require additional resilience measures and what subsystems to focus future risk mitigation efforts upon.

RECOMMENDATIONS FOR FUTURE DEVELOPMENT OF SOLUTION

The reader is referred to Table VI for a Gantt chart of the proposed schedule for the Fall 2021/Spring 2022 spacecraft design class. We recommend proceeding with a Preliminary Design Review (PDR) in November 2021 and a Critical Design Review (CDR) in April of 2022. To achieve this goal, the next cohort of spacecraft design students must continue the work where the current class left off. First, to complete the conceptual design stage, the succeeding class should pursue the future work tasks as outlined by this year’s Conceptual Design Review (CoDR).

TABLE VI
Proposed Schedule for the Incoming Capstone Class



An accurate assessment of the spacecraft's capability requires the development of a data link budget to assess the throughput capabilities of CLAYTON and its ground stations. The future communications team should begin mapping out the amount of data space in various locations, as well as the up/down link amount available for all transfer connections. Furthermore, the communications and instrument teams need to collaborate to secure a radio license with the FCC; the class of license required will dictate certain payload component choices. Following this, the ADACS team should extract capability information from all the other sub-teams and perform an assessment on the feasibility of increasing the coverage area with the same 24 satellites. This can be done through the analysis of certain constellation structures, or an increase in the number of ground stations in our project's network. Similarly, all teams should work on contacting vendors for their selected instruments and work to acquire them for prototyping, and later, assembly and testing.

The remaining recommendations largely belong to the future program management team, with help from the other six functional teams. The incoming chief financial officer should apply for various grants to secure funding. This process includes the selection of a launch method, since the price of launching varies greatly between options. We strongly recommend reaching out to Dr. Brian Flanagan of MITRE for his professional opinion of the different launch services under consideration. Although the end of CLAYTON's mission seems far away, it is on the horizon; as such, another task is to evaluate different end-of-mission options, including but not limited to de-orbit and burn-up. Those decisions do not rest on the incoming class, but they should share their informed recommendations with the class after next.

The final thoughts we would like to share with the Class of 2022 pertain to the anticipated work environment. Due to widespread distribution of the COVID-19 vaccination, the University of Virginia plans to reopen in a pre-pandemic state for Fall 2021. Please take advantage of opportunities for hands-on engagement, such as prototyping in labs and meeting with SMEs. Also, despite the luxury of face-to-face meeting within and between functional teams, we hope to offer preventative suggestions to ensure effective teamwork. Keeping proper documentation in a standardized form will help keep everyone accountable. Developing common goals and assigning ownership over tasks that advance team objectives will improve both morale and productivity. We cannot overstate the importance of strong, frequent functional team communication. If the future teams address potential obstacles early and often, we see no reason they cannot meet their capstone requirements and advance the development of CLAYTON.

CONCLUSION

The 2020/2021 spacecraft design capstone team completed a space mission engineering process and conceptual design proposing a space-based solution to weather-induced traffic congestion in Virginia, as identified during the UIX-MITRE Space Initiative Transportation Efficiency Workshop (Kordella, 2020, slide 5). Our research shows that remote sensing within certain spectral bands at a sufficient resolution can improve detection of dangerous roadway conditions associated with snow and ice. A prerequisite for this data stream is the ability to separate conditions on the road from its surroundings. When the proper data delivery channels are developed, through external partnerships such as with VDOT and/or Waze, then roadway users, roadway managers, and first responders can make informed driving decisions that improve safety and efficiency. The potential to mitigate traffic congestion's detrimental effects on the economy, environment, and health warrants continued exploration of the spacecraft design into the preliminary and critical design.

In the initial phases, this constellation will observe the intersection of Interstate 95 and Interstate 495 in Springfield, Virginia as a proof of concept. If practical, with minimal improvements, this project can grow to a national scale. Throughout this year, feasibility assessments indicate that this project should be continued. The incoming class must continue to refine the design, and take advantage of in-person resources for prototyping and stakeholder feedback. As such, we recommend that the incoming spacecraft design capstone team proceed with a PDR in the Fall Semester and CDR in the Spring Semester.

REFERENCES

Agarwal, M. (2005). Impact of weather on urban freeway traffic flow characteristics and facility capacity. *Transportation Research Board.* Retrieved from https://www.researchgate.net/publication/228720996_Impact_of_Weather_on_Urban_Freeway_Traffic_Low_Characteristics_and_Facility_Capacity

Ashley, W., Strader, S., Dziubla, D., & Haberlie, A. (2015). Driving Blind: Weather-Related Vision Hazards and Fatal Motor Vehicle Crashes. *Bulletin of the American Meteorological Society*, *96*(5), 755-778. http://www.jstor.org/stable/26219609

Barjenbruch, K., Werner, C., Graham, R., Oppermann, C., Blackwelder, G., Williams, J., . . . Connolly, J. (2016). Drivers' awareness of and response to two significant winter storms impacting a metropolitan area in the intermountain west: implications for improving traffic flow in inclement weather. *Weather, Climate, and Society*, *8*(4), 475-491. Retrieved from https://www.jstor.org/stable/26388868

Battery University. (2020 September 17). *How to prolong lithium-based batteries.* Retrieved from https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries

Bellardo, J., & Nugent, R. (2020). (tech.). *CubeSat Design Specification.* San Luis Obispo, CA: Cal Poly.

Bouwmeester, J., Langer, M., & Gill, E. (2016). Survey on the implementation and reliability of CubeSat electrical bus interfaces. *CEAS Space Journal.* doi:10.1007/s12567-016-0138-0

Cal Poly San Luis Obispo. (2018). 6U CubeSat Design Specification Revision 1.0. Retrieved from https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/5b75dfcd70a6adbee5908fd9/1534451664215/6U_CDS_2018-06-07_rev_1.0.pdf

Dragonfly Aerospace. (n.d.-a). Chameleon Imager Data Sheet. Stellenbosch, South Africa; Dragonfly Aerospace.

Dragonfly Aerospace. (n.d.-b). Gecko Imager Datasheet. Stellenbosch, South Africa; Dragonfly Aerospace.

Dragonfly Aerospace. (n.d.-c). Mantis Imager Datasheet. Stellenbosch, South Africa; Dragonfly Aerospace.

Dreijer, G. (2021, February 16). HyperScape100 Datasheet. Somerset West, South Africa; Simera Sense.

Dunbar, B. (2020). *Communications.* From State of the Art of Small Spacecraft Technology. NASA. https://www.nasa.gov/smallsat-institute/sst-soa-2020/communications

EnduroSat. (n.d., -a) *S-Band Patch Antenna CubeSat Module.* https://www.endurosat.com/cubesat-store/cubesat-antennas/s-band-patch-antenna/.

EnduroSat. (n.d., -b) *S-Band Transmitter*. https://www.endurosat.com/cubesat-store/cubesat-communication-modules/s-band-transmitter/

Endurosat. (n.d., -c). *UHF CubeSat Antenna Module*. https://www.endurosat.com/cubesat-store/cubesat-antennas/uhf-antenna/.

EnduroSat. (n.d., -d) *UHF Transceiver II CubeSat Communication*. https://www.endurosat.com/cubesat-store/cubesat-communication-modules/uhf-transceiver-ii/.

Federal Highway Administration. (2020, February 20). Road Weather Management Program. In How do weather events impact roads? *FHWA road weather management.* Retrieved from https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm

Federal Highway Administration. (n.d.). Interstate system. In *Interstate design standards*. Retrieved from https://www.fhwa.dot.gov/programadmin/interstate.cfm

Fontaine, M. (2020, October 28). A conversation with Michael Fontaine, associate director for safety, operations, and traffic engineering at VDOT [Personal Communication].

Fuchs, C., Langer, M., & Trinitis, C. (2015). *Enabling Dependable Data Storage for Miniaturized Satellites.* Retrieved 2021.

GOES-R. (n.d.). Instruments: Advanced baseline imager. Retrieved from https://www.goes r.gov/spacesegment/abi.html

HCT (n.d.). Helical Communication Technologies. Helios Deployable Antenna. https://www.helicomtech.com/helios-deployable-antenna

ISISpace (n.d.). Antenna System for 6U/12U Cubesats. https://www.isispace.nl/product/antenna-system-for-6u-12u-cubesats/

ISISPACE. (2021). 6-Unit CubeSat Structure. Retrieved from https://www.isispace.nl/product/6-unit-cubesat-structure/

Kordella, S. (2020, September). *The MITRE –Virginia university innovation exchange* [Presentation slides]. Retrieved from https://collab.its.virginia.edu/access/content/group/3bc17aa0-335d-47d3-9219-6613342327bc/Project/Kordella%20Intro%20UIX%20Space%20Workshop%20Final_4_.pdf

Kovo, Y. (Ed.). (2020, March 30). 8.0 command and data handling. Retrieved April 21, 2021, from https://www.nasa.gov/smallsat-institute/sst-soa-2020/command-and-data-handling

Liu, Y. (2013). Weather impact on road accident severity in Maryland (Published graduate thesis). University of Maryland, College Park, MD. Retrieved from https://drum.lib.umd.edu/bitstream/handle/1903/14263/Liu_umd_0117N_14019.pdf?sequence=1&isAllowed=y

Liu, Y., & Key, J. R. (2019, February 8). Ice Surface Temperature, Ice Concentration, and Ice Cover. Washington, D.C.; National Oceanic and Atmospheric Administration.

McPherson, M. (2021, April). A conversation with Mike McPherson of KQ9P and W4UVA [Personal Communication].

National Aeronautics and Space Administration. (n.d.). Geostationary Operational Environmental Satellites: R Series. In *GOES-R Series Instruments Overview*. Retrieved from https://www.goes-r.gov/spacesegment/instruments.html

National Oceanic and Atmospheric Administration (n.d.). *Weather observations*. Retrieved from https://www.noaa.gov/education/resource-collections/weather-atmosphere/weather observations

National Weather Service (n.d.). *Satellites*. Retrieved from https://www.weather.gov/about/satellites

Piccardi, A., & Colace, L. (2019, March 19). Optical Detection of Dangerous Road Conditions. Basel, Switzerland; Multidisciplinary Digital Publishing Institute. https://www.mdpi.com/1424-8220/19/6/1360/pdf

Rasmussen, R., Baker, B., Kochendorfer, J., Meyers, T., Landolt, S., Fischer, A. P., . . . Gutmann, E. (2012). How well are we measuring snow: The NOAA/FAA/NCAR winter precipitation test bed. *Bulletin of the American Meteorological Society*, *93*(6), 811–829. https://doi.org/10.1175/bams-d-11-00052.1

Romanov, P. (2016, March). Global 4km multisensor automated snow/ice map (GMASI). Washington, D.C.; National Oceanic and Atmospheric Administration.

Rost, A., Painter, T., & Eicher, K. (2012, January 24). Snow Cover. Washington, D.C.; National Oceanic and Atmospheric Administration.

SatCatalog. (2020). HyperScape100 Imager. Retrieved from https://satcatalog.com/component/hyperscape100/

SCS Space. (n.d.). Monitor Imager. Somerset West, South Africa; SCS and Space Advisory Company.

Spaceflight. (n.d.) *Launch Services*. Spaceflight. http://spaceflight.com/services/launch-services/

SpaceX. (2009). Falcon 9 Launch Vehicle Payload User's Guide Rev 1. Retrieved from https://spacex.com.pl/files/2017-10/f9guide.pdf?2ff2ffe278

TRIP. (2020, February). *Virginia transportation by the numbers: meeting the state's need for safe, smooth, and efficient mobility*. Retrieved from https://tripnet.org/wp content/uploads/2020/02/TRIP_Virginia_BTN_Report_February_2020.pdf

Yang, Z., Lilian, S. C., & Pun-Cheng. (2016). Vehicle detection in intelligent transportation systems and its applications under varying environments: A review. *Image and vision computing. 69*, 143-154. doi: https://doi.org/10.1016/j.imavis.2017.09.008

Ziegler, L.A. (2007). Configuration, manufacture, assembly, and integration of a university microsatellite. Retrieved from https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=5578&context=masters_theses

APPENDIX A

TABLE I
Acronyms sorted alphabetically

Acronym	Full Title
ABI	Advanced Baseline Imager
ADACS	Attitude Determination And Control System
CARS	Charlottesville-Albemarle Rescue Squad
CLAYTON	Commuter Live Aggregated Yield Traffic Observation Network
CoDR	Conceptual Design Review
CDR	Critical Design Review
DOT	Department of Transportation
EPS	Electrical Power Subsystem
EMS	Emergency Services
ECC	Error Correction Code
FCC	Federal Communications Commission
FEC	Forward Error Correction
GLM	Geostationary Lightning Mapper
GOES	Geostationary Operational Environmental Satellite
HHM	Hierarchical Holographic Modeling
ISS	International Space Station
LEO	Low Earth Orbit
NCSLI	NASA CubeSat Launch Initiative
NASA	National Aeronautics and Space Administration
NHTSA	National Highway Traffic Safety Administration
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation

NWS	National Weather Service
NDSI	Normalized Difference Snow Index
PTE	Power, Thermal, and Environment
PDR	Preliminary Design Review
SME	Subject Matter Expert
STAMP	Systems Theoretic Accident Model and Process
UHF	Ultra-High Frequency
UIX	University Innovation Exchange
VDOT	Virginia Department of Transportation
VSGC	Virginia Space Grant Consortium

TABLE II
List of System Level Functional Requirements

Requirement ID	Requirement	Specification	Verification
F1	Spectral Bands	Visible Spectrum: 0.4 - 0.7 µm	Testing
F2	Exposure Time	1/2000 s based on spatial resolution of 3.8 m	Calculations
F3	Adverse Weather Road Cover	Detect presence of snow and ice	Ground truthing
F4	Spatial Resolution	3.7 - 7.3 m (12 - 24 ft)	Spectrometer Calibration
F5	Update Frequency	< 1 Hour	Orbital And Spectrometer Analysis
F6	Coverage	Northern Virginia beltway corridor with scalability to continental USA as an option	Orbital Analysis
F7	Environment	Low Earth Orbit	Orbital Analysis and

			Ground Testing
F8	Power	Within max available supply	Ground Testing

TABLE III
List of System Level Operational Requirements

Requirement ID	Requirement	Specification	Verification
O1	All pertinent data streams are integrated and centralized	Weather data overlaid with live traffic data on Waze or another platform	Visual inspection of final product
O2	Data delivery for roadway managers and first responders	Provide data compatible with distribution in existing apps	Proof of information received by government (VDOT/EMS) and/or private services (Waze)
O3	Data delivery for roadway users	Safe engagement with this data via smartphones and/or in-vehicle navigation	Observation of app activity, user reports, user testing
O4	Minimal downtime and Frequent availability	< 5 minutes	Testing Manufacturing Claim
O5	Maintain operational status for length of designated lifespan	5 years	Continued collection and dissemination of data

TABLE IV
List of System Level Constraints

Requirement ID	Requirement	Specification	Verification
C1	Form Factor (Size)	6U CubeSat	Measurements
C2	Budget	Under $50M by project completion	Documentation within functional teams and CFO

APPENDIX B

TABLE I
Summary of Wavelengths Useful for Snow/Ice Detection

Wavelength (µm)	Feature Detected	Frequency Band
0.45 - 0.49	Snow	VIS
0.59 - 0.69	Snow & Ice	VIS
0.8455 - 0.8845	Snow & Ice	NIR
1.58 - 1.64	Snow & Ice	SWIR
2.225 - 2.275	Snow	SWIR
10.80 - 11.20	Ice	LWIR
12.00 - 12.30	Ice	LWIR

(Liu, 2019; Romanov, 2016; Rost, 2012)

TABLE II
List of Instruments Functional Requirements

Requirement ID	Requirement	Specification	Verification
F1.INS.1	Spectral Bands	Visible Spectrum: 0.4 - 0.7 µm	Testing
F2.INS.1	Image Spatial Resolution	3.7 to 7.3 m at 400 km	Testing and Analysis
F3.INS.1	Imaging Frequency	High frequency (1 hour or less) data field during critical traffic times	Orbital Analysis
F4.INS.1	Coverage	At least Virginia	Orbital Analysis
F4.INS.2	Swath	20 - 40 km	Calculation

F5.INS.1	Environmental	Operational: -10°C to +50°C, Survival: -25°C to +65°C, LEO	Testing
F6.INS.1	Radiation	Less than 15 krad LEO	Testing

TABLE III
List of Instruments Constraints

Requirement ID	Requirement	Specification	Verification
C1.INS.1	Dimensions	3U form factor (30 x 10 x 10 cm)	Physical Measurements
C1.INS.2	Mass	4 kg	Testing

TABLE IV
List of Communication Functional Requirements

Requirement ID	Requirement	Specification	Verification
F3.COM.1	Transferring Data	Needs to transmit data at 15 Mbps to ground station	Inspection and Testing
F3.COM.2	Satellite Instruction	Using UHF to give satellite operations for other systems	Inspection
F5.COM.1	Relay information	Send data from satellite to ground station using S-band	Inspection

TABLE V
List of Communication Operational Requirements

Requirement ID	Requirement	Specification	Verification
O1.COM.1	Satellite to Ground Distribution	Data is sent to the UVA ground station	Inspection
O2.COM.1	Ground to Ground Distribution	Data is transferred from ground stations to emergency personnel and private services	Inspection
O4.COM.1	Downtime	Delivery of data has a downtime of < 5 minutes	Analysis and Tests

TABLE VI
List of Communication Constraints

Requirement ID	Requirement	Specification	Verification
C1.COM.1	Size	Data transmission of components are <2U, fit in 6U CubeSat	Inspection

TABLE VII
Comparison of UHF, S band, and X band frequency ranges

Bands	Frequency	Pointing Sensitivity	Primary Interference Sources	Antenna Type
UHF	0.3 - 3 GHz	Not sensitive	Commercial/personal devices	Dipole or turnstile antenna
S Band	2 - 4 GHz	Pointed at ground	Wireless networks	Patch antenna
X Band	8 - 12 GHz	Pointed at ground	Atmosphere	Patch antenna

TABLE VIII
List of Power, Thermal, and Environmental Functional and Operational Requirements

Requirement ID	Requirement	Specification	Verification Method
F5.PTE.1	Thermal Stability	-25°C to +80°C; Can handle stress from thermal cycling	Testing and analysis
F5.PTE.2	Radiation Protection	Shielding techniques must keep radiation at a viable level for operation	Analysis
F6.PTE.1	Power Supply	Generate enough power for instruments to operate when needed	Testing and analysis
F6.PTE.2	Power Storage	Ensure enough power is stored to run CubeSat through eclipses	Testing and analysis
F6.PTE.3	Electronic Integrity	Ensure voltage and amperage is distributed within operating ranges of electric components	Testing and Inspection
O5.PTE.1	Lifespan of Systems	Power system and environmental protection technologies must last minimum of 5 years	Simulation and In-Orbit Inspections

TABLE IX
List of ADACS and Orbits Functional and Operational Requirements

Requirement ID	Requirement	Specification	Verification Method
F5.ADACS.1	Pointing Accuracy	±1.86°	Analysis and Testing

F5.ADACS.2	Location Determination	±10m	GPS Data Analysis
F5.ADACS.3	Pointing Determination	±0.465°	Analysis and Testing
C1.ADACS.2	Size (cross-section)	Fits inside a 6U CubeSat (10cm x 10cm C-S)	Measurement
F3.ADACS.1	Altitude	Initial altitude of 400km	STK Analysis
F4.ADACS.1	Coverage Frequency	> 1 observation /hr.	STK Analysis
F5.ADACS.4	Orbital Parameters	Maintain LEO, <= 24 satellites, inclination = 51.6°	STK Analysis
O5.ADACS.1	Orbital Lifetime	Select orbit attainable ≥ 5 years	STK Analysis

TABLE X
List of Structures and Integration Functional and Operational Requirements

Requirement ID	Requirement	Specification	Verification
F5.SI.1	Launch Integrity	Withstand launch forces: -2 to 6 G axial / -2 to 2 G lateral*	FEA/Simulation
F5.SI.2	Protection	CubeSat can survive small impacts from micrometeoroids/debris with minimal damage	Testing
F5.PTE.1	Thermal Range	-25°C to +80°C; Can handle stress from thermal cycling**	Testing and analysis
O5.SI.1	Lifetime	Maintain Structural Integrity for 5 years	Simulation

*(SpaceX, 2009)
**(ISISPACE, 2021)

TABLE XI
List of Structures and Integration Constraints

Requirement ID	Requirement	Specification	Verification
C1.SI.1	Volume	22.63x10x36.6 cm*	Measurement
C1.SI.2	Mass	12 kg*	Measurement
C1.SI.3	Center of Gravity	X: ±4.5 cm, Y: ±2 cm, Z: ±7 cm*	Measurement/CAD
C1.SI.4	Compatibility	Seamless integration with 6U CubeSat deployer	CAD
C1.SI.5	Ease of Assembly	Design to facilitate assembly and maintenance of spacecraft components	CAD

*(Cal Poly San Luis Obispo, 2018)

TABLE XII
List of Software and Avionics Constraints

Requirement ID	Requirement	Specification	Verification
C1.SA.1	Dimensions	10 cm x 10 cm x 4 cm	Measurement
C1.SA.2	Mass	400 g	Measurement

C1.SA.3	Lifespan	5 years	Prior mission lifespans
C2.SA.1	Cost	< $10,000	NA

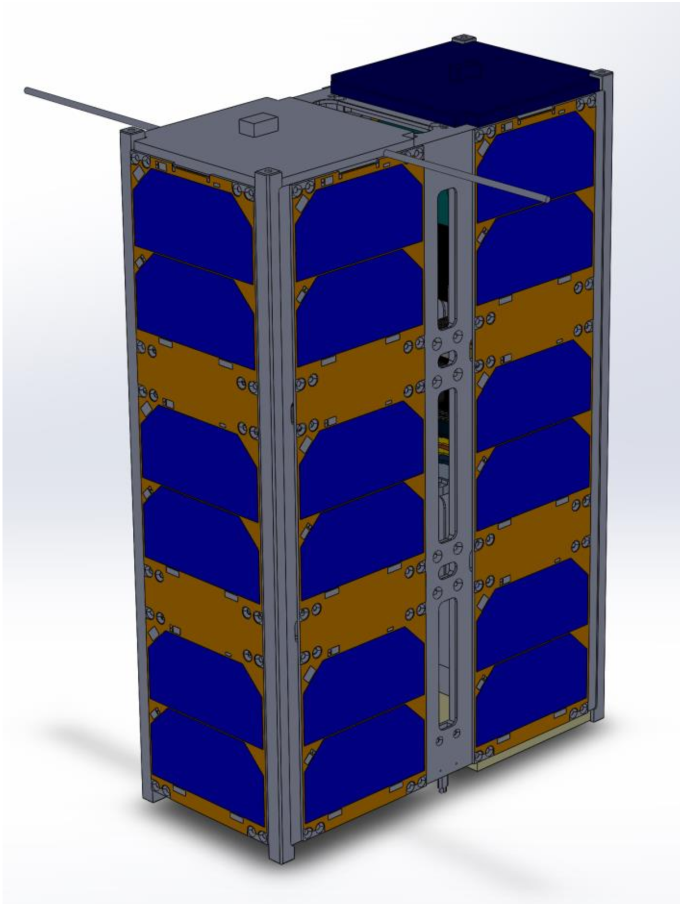


Figure 1. Diagram of Final Assembly with Fixed Solar Panels

TABLE XIII
List of Software and Avionics Functional Requirements

Requirement ID	Requirement	Specification	Verification Method
F5.PTE.1	Thermal Stability	-25°C to +80°C; Can handle stress from thermal cycling	Testing and analysis
F6.SA.1	Radiation Protection	Shielding techniques must keep radiation at a viable level for operation	Analysis
F6.SA.2	Power Consumption	< 1000 mW	Testing and analysis
F7.SA.3	Memory	500 KB	Manufacturer Specifications

APPENDIX C

TABLE I
Projected Budget Breakdown in USD

	Phase I	**Phase II**
n Spacecraft (Including backups)	3	26
Launch	0	10,000,000
COMS	68,700	595,400
SA	10,500	91,000
PTE	90,000	780,000
ADACS	109,500	949,000
SI	24,000	208,000
INST	600,000	5,200,000
Testing	18,900	163,800

One-Time Expense	100,000	0
Cost Per Satellite	307,200	691,816
Total	1,021,600	17,987,200

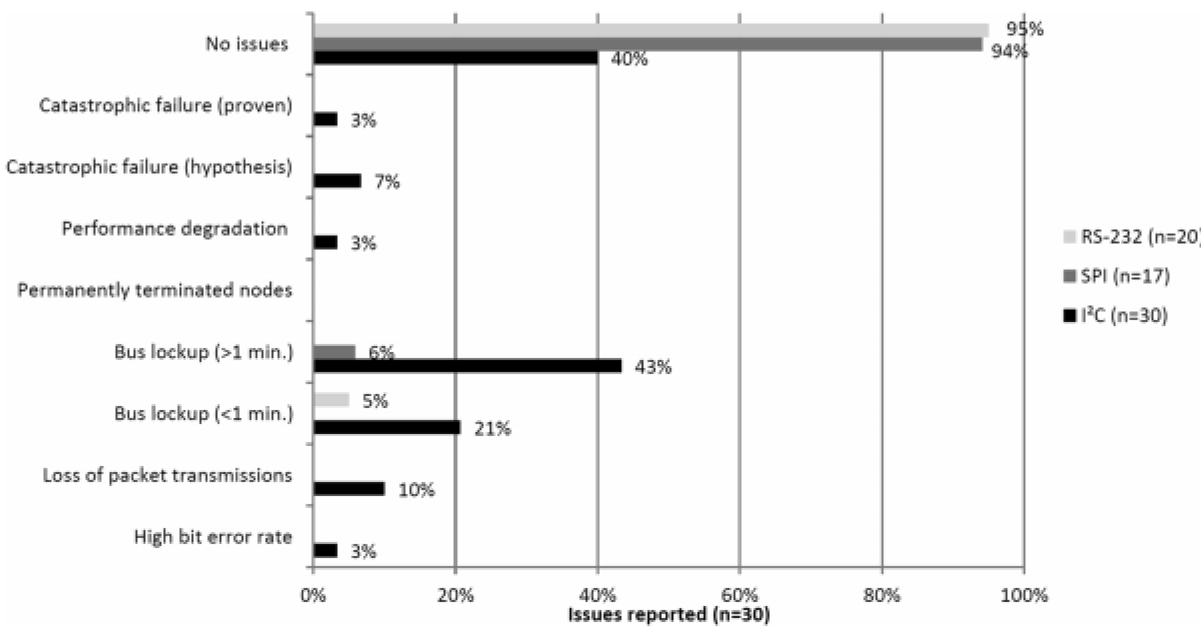


Figure 1. In-orbit issues reported for three bus standards based on "Survey on the implementation and reliability of CubeSat electrical bus interfaces" (Bouwmeester et al., 2016)

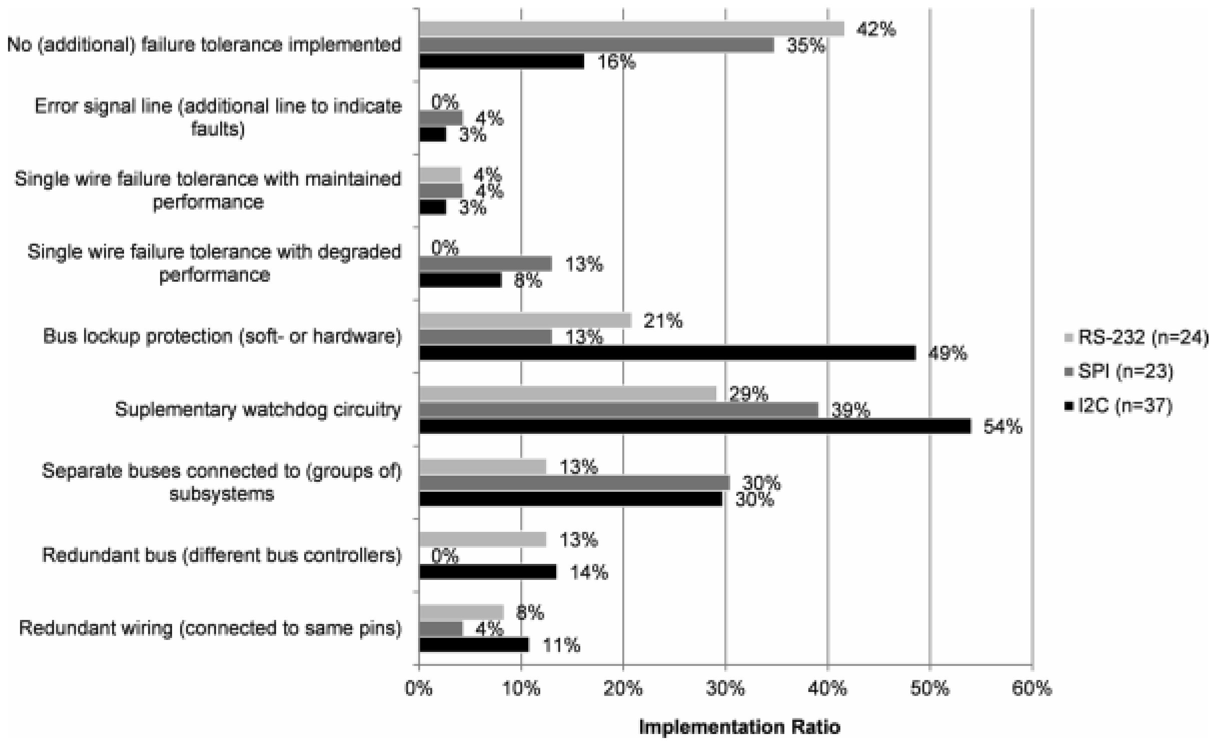


Figure 2. Implementation of failure tolerance features in CubeSats for different data buses based on "Survey on the implementation and reliability of CubeSat electrical bus interfaces" (Bouwmeester et al., 2016)

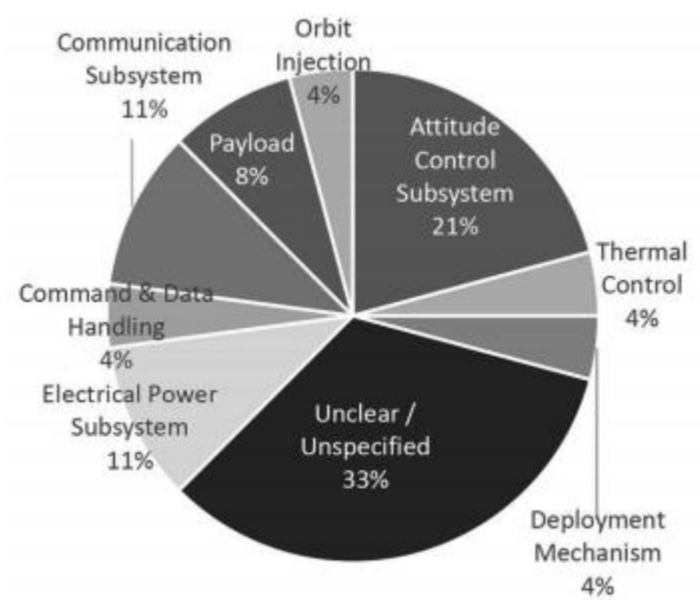


Figure 3. Root cause allocation for not achieving full success for technology demonstration CubeSats. based on "Survey on the implementation and reliability of CubeSat electrical bus interfaces" (Bouwmeester et al., 2016)