Development of a 1U CubeSat as Part of a 3x1U Constellation

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ABSTRACT

In the fall of 2016, the NASA Science Mission Directorate, working with the Virginia Space Grant Consortium, initiated the development of three 1U CubeSats by undergraduate students at universities representing the Commonwealth of Virginia. The University of Virginia, Old Dominion University, Virginia Tech, and Hampton University, were chosen to construct CubeSats for flight in May of 2018.

The mission has three primary goals: to educate students by providing hands-on experience, to measure orbital decay on a constellation of low earth orbit (LEO) satellites, and to evaluate and demonstrate a system for the communication of relative and absolute spacecraft position.

In this paper, we will describe the details of the mission itself, the science behind the mission, and the structure of the mission that was established to accomplish its goals. We will also provide a review of the hardware used by the mission, the software that exists so far, information about the thermal modelling of the CubeSats, the radio system, and environmental considerations.

We hope that this paper will serve as a summary of the mission for those who are not familiar with it, as well as an internal document for describing what we have achieved by this stage of development.

INTRODUCTION

The low cost and increasing utility of CubeSats present the opportunity to conduct student-based missions which can address many of society's technical and scientific needs. CubeSats promote the further understanding of Earth and space science, as well as the development of new space technology, which enhances space exploration capabilities. While providing hands-on flight experience, this project simultaneously allows students to work effectively in groups and collaborate to meet the scientific and technological goals of the mission.

This project was originally proposed and subsequently accepted as a NASA undergraduate student instrumentation project (USIP) through the NASA Science Mission Directorate. As a result, this mission is funded and supported by NASA. This funding covers the construction of 3 1U satellites, beginning in September of 2016 for launch in May of 2018.

The project is conducted through collaboration of science and engineering students at Old Dominion University (ODU), Virginia Tech (VT), University of Virginia (UVA), and Hampton University (HU) under the umbrella of the Virginia Space Grant Consortium (VSGC). This combination of personnel from multiple institutions will provide a knowledge base and student experience that goes beyond what can be offered by any one academic institution. As multiple universities from across the Commonwealth of Virginia are involved in the mission, this mission has been named the Virginia CubeSat Constellation.

PROJECT DETAILS

Overall Goals

The specific objectives of the Virginia CubeSat Constellation mission are to:

1. Provide a hands-on, student-led flight project experience for undergraduate students by designing, developing, integrating, testing and flying an orbital constellation of three 1U CubeSats.

2. Obtain measurements of the orbital decay of a constellation of satellites to develop a database of atmospheric drag and the variability of atmospheric properties.

3. Evaluate and demonstrate a system to determine and communicate relative and absolute spacecraft position across an orbiting constellation.

Science and Technological Background

There is a rapidly-increasing number of CubeSats populating low Earth orbits that have a limited ability to make orbit adjustments or even to stabilize their orientation. Because of this, detailed knowledge of the aerodynamic behavior of basic CubeSat geometries is a necessity.

Currently, solar weather does not reliably correlate with atmospheric response in the thermosphere. This limitation severely impacts the ability to predict LEO satellite aerodynamic behavior. That lack of fidelity limits an ability to forecast the local, orbital, and time-of-day-dependent density and atmospheric chemistry needed to reliably predict orbital descent. Furthermore, the actual aerodynamic behavior of simple spacecraft varies with local atmospheric conditions to an extent that requires additional documentation. By measuring acceleration histories of a constellation of CubeSats with different drag and ballistic coefficients, it is possible to provide additional, statistically-characterized data. This data will help improve the understanding of the aerodynamic behavior of spacecraft during their final, near-Earth orbital decay flight phases.

Three near-polar orbiting magnetic explorer satellites launched by the European Space Agency (ESA) in November 2013 utilize this approach.[1] Instrumentation that will be incorporated in this CubeSat constellation cannot achieve the measurement precision attributed to the Swarm Earth Explorer spacecraft. However, the data reduction algorithms developed by Doornbos et al in support of ESA's 2013 mission can be used to extract useful neutral density and cross-wind data by employing six-axis CubeSat accelerometer measurements.[2] We believe that the Swarm Earth Explorer Mission validates our approach towards the goals of the Virginia CubeSat Constellation. Additionally, more in situ data is required to correlate thermospheric density response to distinct types of solar activity to improve the ability to model that coupling. Therefore, the new data of our mission will enable us to predict satellite orbital decay rates more accurately.

In contrast to the Swarm Earth Explorer mission, two of the CubeSats in this constellation have the same external geometries, while the third CubeSat has been designed to deploy a drag brake to achieve a vastly different ballistic coefficient. Each CubeSat incorporates instrumentation to measure its three components of acceleration, its orientation with respect to the Earth's magnetic field, and pitch, roll and yaw rates.

The developed drag database will be used to examine orbit propagation models that are available in the Systems Tool Kit (STK) software by Analytical Graphics, Inc (AGI). The most recent available atmospheric models include three Mass-Spectrometer-Incoherent-Scatter (MSIS) models which are empirical databases derived from a variety of rocket and satellite measurements, with the most recent being the NRLMSISE-00 developed in 2000. In describing the importance of including new data, the authors of this model report, "The only way in which empirical models can maintain currency with the recent state of the atmosphere is by continually adding recent data to the database and then modifying the parameter set."[3] This desire for information provides the background for the second goal of our mission.

The third goal is a technological endeavor. It encompasses the desire to develop and test a system that can estimate and communicate relative spacecraft position among different satellites in an orbiting constellation or formation. This is because scientific data obtained from single satellite missions invariably suffer from an issue known as "spatial-temporal ambiguity." This problem arises because a satellite traveling through the LEO space environment is moving much faster than the thermal speeds of the gas particles in the medium. Consequently, the measurements made aboard a spacecraft are like a series of photographic snapshots from different locations – each snapshot captures a dataset that represents the geophysical conditions at a particular location and particular time. Consider a specific example wherein an electric field sensor measures a large electric field over a spatial distance of a few hundred meters, such as the field observed at the edge of an auroral arc. In looking at one auroral zone, crossing such fields may be obvious, yet similar data are not observed at every crossing of the auroral zone. Given this scenario, it is impossible to unambiguously determine whether the large field observed is a steady-state spatial phenomenon that happened to be sampled because the satellite was in the right place, or a transient temporal event that the satellite happened to capture because it was in the right place at the right time. By having three independent platforms for measurement that can communicate their relative position to each other, we hope to provide an example on how to resolve this problem.

Mission Team Structure

Each University designing a CubeSat (Old Dominion University, the University of Virginia, and Virginia Tech) have teams of around 25-30 full-time undergraduate students dedicated to the project.

The University of Virginia used the project as their senior design class, limiting enrollment to seniors in their Department of Mechanical Engineering.

Both Old Dominion University and Virginia Tech established the project as an Undergraduate Research Course, allowing for multi-disciplinary teams consisting of students from all levels of college education. Half of Virginia Tech's team are volunteers.

Hampton University, responsible for post-mission data analysis, has a small team of 2-3 fully-enrolled undergraduates.

Each university has a faculty member that serves as their respective principal investigator for the project, providing general guidance and leadership for their team. Each university also has their own undergraduate student team leader. Staten Longo from the University of Virginia served as the representative for the mission in both external and internal affairs. Because the project is an Undergraduate Student Instrumentation Project (USIP) through NASA, individuals at NASA Wallops Flight Facility and the Virginia Space Grant Consortium (VSGC) serve as additional mentors for the project. Most of the funding comes from NASA and the VSGC. The universities meet bi-weekly throughout the course of the mission, with major meetings and deadlines scheduled around design reviews.

University Team Structure

At Virginia Tech, the overall mission team was broken into four sub-teams: Attitude Dynamics and Control Systems (ADCS); Command and Data Handling (C&DH); Power, Thermal and Environmental (PTE); and Structures.

A sub-team leader leads each sub-team, and the sub-teams consist of around five members. Each sub-team is composed of students with relevant skills, involving students from the Departments of Aerospace Engineering, Computer Science, Electrical Engineering, and Mechanical Engineering respectively. Every sub-team has a specific focus. The ADCS sub-team developed the attitude control systems of the CubeSat. The C&DH sub-team developed the flight software and the radio communication aspects of the satellite. The PTE sub-team developed the flight hardware and electrical layout of the CubeSat, while working with the Structures team on thermal diagrams, environment consideration, and the material structure and form of the CubeSat.

Mission Timeline

The mission formally began with the Project Initiation Conference, held in September 2016. A deadline of March 2018 was set as the date for the completion of the project and delivery of flight hardware for shipping for flight, giving the total project a timeline of just around a year and half for completion.

Mission reviews marked major milestones. The first milestone was a preliminary design review in November 2016. The next milestone was the critical design review in March 2017. The next planned review is the Mission Readiness Review, planned for October 2017.

CONCEPT OF OPERATIONS (CONOPS)

Introduction

To achieve both the established goals of the mission while operating safely and effectively, mission members developed a mission-wide and CubeSat-specific CONOPS. The individual CubeSats intend to share the same CONOPS, with slight differences due to the presence of a drag brake on one CubeSat in the constellation.

Mission CONOPS

Currently, the most likely form of space deployment for the constellation will be from the NanoRacks CubeSat deployer attached to the International Space Station. The CubeSats will be powered off before deployment, and a remove before flight (RBF) pin will be removed from each CubeSat. The CubeSats will then start a timer, and wait 30 minutes before powering on their respective systems. The three individual 1U CubeSats will be stacked on top of each other in one 3U CubeSat deployer, and deployed in succession, forming a string-of-pearls formation in space.

Following deployment and the expiration of the timer, the CubeSats will power on, and during the initial stage of the mission, operate normally following the individual CubeSat CONOPS modes. This initial stage will continue for 2-4 weeks, depending on the projected lifetime while in flight, and is where a majority of the science and technological information will be recorded. Individual CubeSats will also operate as repeaters for amateur radio enthusiasts during Saturdays and Sundays in this stage. After this initial stage, a university-operated ground station will command the CubeSat with the attached drag brake deploy its braking system, and it will subsequently begin to speed up and descend in orbit. It will also begin transmission of data to the Iridium Network, as there will be too much data generated for transmission during the shortened pass times overhead the various ground stations. During this second stage of the mission, the two CubeSats that do not have braking systems will continue to operate normally, except for ceasing cross-link communication with the third, braking CubeSat once it drifts out of range. This stage of the mission will continue until the CubeSat's orbits decay to the point that they are no longer operable. At this stage, the mission will end. A diagram representing this shown in Figure 1.

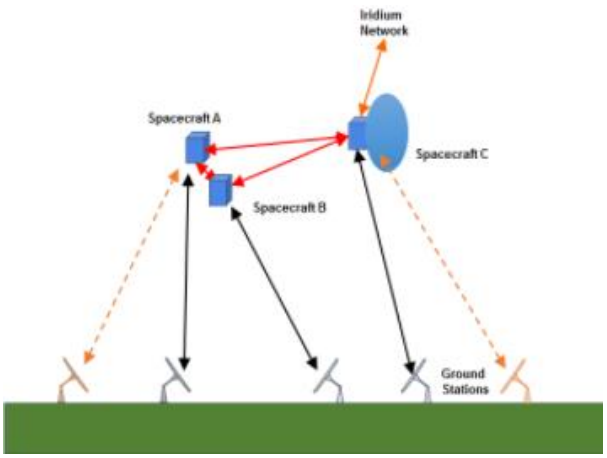

Figure 1: Mission CONOPS Diagram

Individual CONOPS

In the initial stage of the mission, all three CubeSats will have the same individual methods of operation. This involves three modes: Emergency, Science, and Amateur Use.

Emergency Mode

The emergency mode is a blanket state for the CubeSat to enter when any individual part is not operating nominally. All CubeSats in the constellation will default into this mode following power on, and the CubeSat can autonomously enter this mode at any point of operation. Some examples of faults that will cause the CubeSat to enter this mode include the following: low battery voltage, high component temperature readings, and excessive angular rotation. This mode consumes a minimal amount of power, operating the absolute minimum number of components required to maintain communication with the ground. The CubeSats will also operate a low power beacon, repeating a simple sequence of battery voltage, temperature, and other critical flight information. The CubeSats can only leave this state when commanded from the ground. The modes the CubeSats can be commanded into are Science Mode and Amateur Mode.

Science Mode

The science mode is the primary mode of operation for the CubeSats and it is the mode in which they will spend a majority of the mission. All sensors will operate normally, collecting GPS and gyroscopic data to meet the second goal of the mission. At timed intervals when the CubeSats are not overhead of ground stations, they will transmit data packets to each other over a small, low-powered, inter-satellite radio. The CubeSats will transmit messages using a master-minion designation, where a token in memory marks one CubeSat as the master. The master CubeSat is responsible for transmitting and the two other CubeSats will be responsible for receiving. Using the pulse-per-second signal from the GPS, the minion CubeSats start a timer when the master transmits a packet. When the minion decodes that packet, it fires an interrupt to stop the timer. This timer value is the time it took for a radio message to travel in between the satellites, which can easily be resolved to a distance by dividing by the speed of light. This serves to satisfy the third goal of the mission, allowing each CubeSat to know its relative distance and drift from the other CubeSats in the constellation over successive orbits.

The master token can be granted to or taken from a CubeSat whenever it is over ground stations operated by HU, ODU, UVA, or VT.

The CubeSats will also be listening for data requests during this mode. These data requests will come from ground stations. The request will be a unique identifier that indicates legitimacy as well as another identifier specifying what kind of data is desired. The specific packet structure for data handling is still under development.

Amateur Use

In this mode, each individual CubeSat will operate as a repeater for Ultra High Frequency (UHF) radio signals. Each CubeSat will have a slightly different center frequency, and messages transmitted at their respective frequencies in the right format will be re-transmitted at the same frequency. This will allow messages transmitted to the constellation from the ground to achieve a much greater range than the ground transmitter could achieve normally by avoiding interference caused by trees, mountains, and the Earth's curvature. If the CubeSats have enough power, they are open for use every weekend, allowing the community to participate in the mission. With this mode, we intend to provide a service for the amateur community, which is an important part of being licensed as an Orbiting Satellite Carrying Amateur Radio (OSCAR) and to show the good intention of not wanting to crowd the amateur radio band the transmission of science information that is only useful to the members of the constellation.

Following the mission entering the second stage, the only major change in states will be the lack of a third CubeSat for both ranging and amateur radio use. The time that each CubeSat is occupied with operating in each individual state will be adjusted, allowing the mission to maintain the same overall division of time by state.

Lifetime Estimation

Estimating the lifetime of the CubeSats in the constellation required significant effort. This lifetime depends on many parameters and can be greatly affected by even the most minute changes, so it is critical to provide an accurate lifetime estimation.

This estimation used STK's High Precision Orbit Propagator (HPOP) Tool. The tool takes various physical aspects of the satellite into account, such as Cd, Cr, drag area, mass, and the area exposed to the sun. By combining our current knowledge of our CubeSat's characteristics and research on past missions, it was found that a Cd of 2.2 and the default STK Cr value of 1.0 is accurate for our constellation. The drag area was calculated using one face of a 1U CubeSat, assuming our active attitude and control system will allow our satellite to maintain a single ram-pointing face. The total sun area used was three faces under direct sunlight during sun exposure. The mass of the satellite used in the calculations was 1.2kg, with a maximum weight of 1.33kg set by the launch requirements of the NanoRacks deployer. Assuming deployment in early 2018 and using the ISS's two-line ephemeris data as a starting point, our projected lifetime estimate is around 204 days.

For the CubeSat that is responsible for deploying a drag brake, the lifetime estimation was like the other satellites until the moment that the drag brake was deployed, in which the remaining lifetime of the satellite would be no more than a few weeks.

It is worth noting that this lifetime estimate carries a great degree of uncertainty. A major part of the mission is to record accelerometer and GPS data in the LEO region in hopes to improve the models we are using for future missions. In any case, even the worst-case estimation of lifetime (87 days) is enough time to conduct the science operations required to meet mission goals.

MISSION DEVELOPMENT

In this section, details about the architecture of one example CubeSat in the constellation will be discussed. The CubeSat developed by Virginia Tech will be used.

Hardware Description

The CubeSat will use a custom structure that was designed to combine the many benefits of Commercial Off the Shelf (COTS) structures while being cheaper to internally manufacture. The structure itself will still have anodized aluminum rails with top and bottom faces that comply with the deployment requirements set by NanoRacks. It will also include space for an RBF pin and secondary locking features that are required. The non-metallic elements of the structure will be coated in S13G high emissivity protective paint.

The electrical components will be arranged on separate Printed Circuit Boards (PCBs), following the design guidelines established in the PC/104 Specification, version 2.6. All electrical connections will go through the headers outlined in the specification, leaving the only wiring as SMA and MCX connections between the radio components of the satellite.

All internal components will be mounted upon five total PCBs, except the antenna. The antenna, a 1U Endurosat UHF/UHF model will occupy the bottom space of our CubeSat. The bottommost PCB has been termed the "Radio Board" as it will contain all the radio communication hardware. This hardware includes a Lithium Li-1 Radio for satellite-to-ground data downlinking, a HopeRF RFM69HCW Transceiver for satellite-to-satellite crosslinking, and a Texas Instruments MSP430F5438A microcontroller. The two radios will both transmit using the same antenna (Endurosat) using a hybrid combiner.

Moving upwards, the middle space of the payload will be occupied by a ClydeSpace 1U Power Bundle, including an Electric Power System (EPS) and 20WHr battery.

Above that, the next board is the "Housekeeping" board containing an MSP430FR5994 and Invensense MPU-9250.

The topmost board contains the GPS, a piNav-L1. A piPatch-L1 will also sit on top of this board, underneath the top solar panel.

There will be ClydeSpace 1U Solar panels on all faces of the CubeSat beside the bottom (-Z) face, which will be occupied by the antenna. These solar panels include sun-sensors and magnetorquers. There will also be Analog Devices Inc. AD590KF temperature sensors spaced throughout the CubeSat. Figure 2 shows the external appearance of the CubeSat. Note the anodized aluminum rails, the visible side solar panels, and the Endurosat UHF/UHF antenna, made visible by displaying the -Z face at the top of this figure.

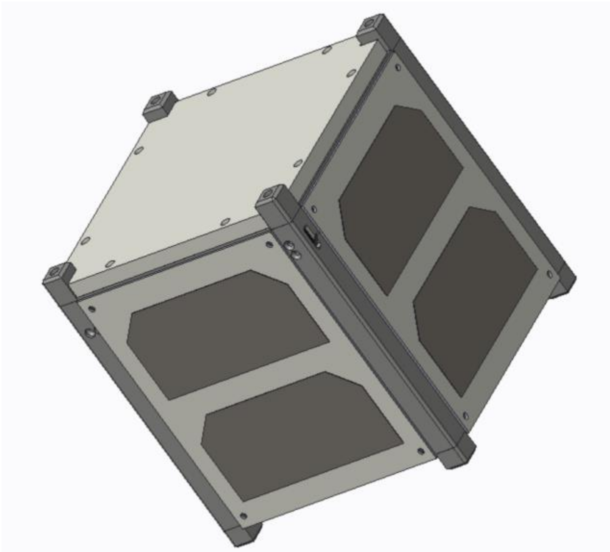

Figure 2: CubeSat External Appearance

Thermal Models

Thermal modeling of the CubeSat was performed in Icepak and STK. The general approach was to use STK to determine maximum and minimum heat flux throughout the orbit of the CubeSat. Worse case scenarios at both temperature extremes were examined. For the LEO hot case, heat flux from the Sun is high (1422 W/m^2) and power usage is at maximum (55 kW/m^3). A thermal model was created after considering Albedo (800 W/m^2), Earth Infrared energy (257 W/m^2), environmental boundary conditions, and various absorptivity and emissivity values of the station's surface. This external hot case is shown in Figure 3. The maximum temperature reached by the ram face is approximately 160 °C, and the temperature distribution is shown by the colored divisions.

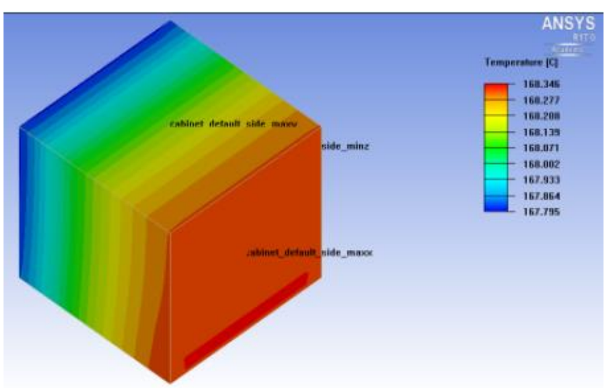

Figure 3: Hot Case for CubeSat Thermal Analysis

The constellation is in eclipse for the LEO cold case, and as such, solar flux and albedo are absent while power usage is at a minimum. A thermal model was created after considering Earth Infrared energy under this scenario (218 W/m^2), environmental boundary conditions, and various absorptivity and emissivity values of the station surface. This scenario is shown in Figure 4.

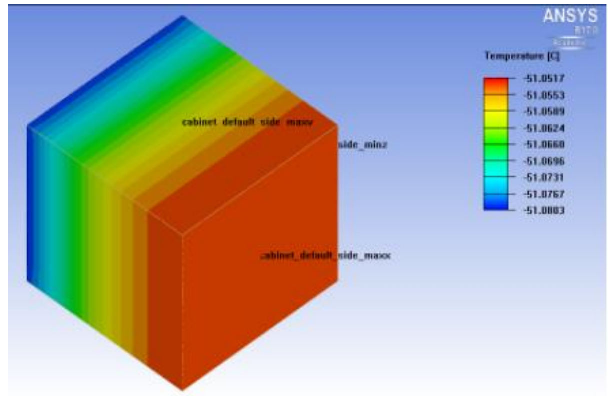

Figure 4: Cold Case for CubeSat Thermal Analysis

The minimum external temperature of the CubeSat based on this analysis is approximately -51 °C. While the model shows a colored temperature distribution, looking closely there is little actual change in the temperature based on location for the cold case, resulting in an almost uniform temperature distribution of -51 °C.

Software Development

To get an overall picture of the software running on the CubeSat, flow diagrams were developed. The first software flow considered was the operating system. The Operating System Control Loop is a function which selects the next task to be conducted by the satellite from the schedule. While executing the task, the operating system monitors the task, to check whether it is executed properly. If the task is not executed properly, and the emergency flag is off, the operating system will record a runtime error and attempt to continue the schedule. If the emergency flag is on and a task is not executed properly, the operating system modifies the schedule and starts again at the beginning with the first scheduled task. This process is shown in Figure 5.

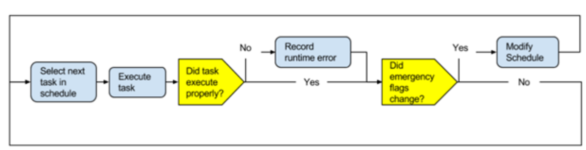

Figure 5: Operating System Control Loop

Unfortunately, the detailed software flow diagram was too complicated to include in this paper.

The software design elements have been reviewed and categorized into primary software functions and secondary software functions. Primary software functions include data downlink to a ground station using the Lithium radio, data transmission to other constellation CubeSats using the RFM radio, command reception from ground stations, data reception from constellation CubeSats, data gathering and processing, telemetry gathering and processing, and error and fault detection. Secondary software functions include: amateur radio transmission, and continuous low power beacon transmission.

Each microcontroller has been assigned an individual job: the microcontroller (MSPMSP430FR5994) located on the Housekeeping PCB has been designated for Housekeeping, and the microcontroller (MSP430F5438A) located on the Radio Board has been designated for Data Handling. The Data Handling microcontroller must ensure that data taken from the various sensors is being stored in the on-board computer, and it is directly interfaced with every component but the MPU-9250. It also acts as a communication medium between ground stations and the in-flight subsystems. It is responsible for transmit data the CubeSat has generated. For the Housekeeping microcontroller, it should provide minimal storage resources and reduce the amount of fragmented data, to ease the load on the satellite's memory banks, as the CubeSat has a limited storage capacity. Additionally, the housekeeping controller should run diagnostics on the various subsystems to gain information on their statuses, and manage the tasks relating to current state of the systems. These tasks ensure the systems on board are not being overloaded with data flow and that the satellite is in an appropriate state to ensure its own survival.

To provide a framework for modular development, we are using FreeRTOS, a real-time operating system with space flight heritage. This increases the ease with which the different sub-teams are able to work in parallel on the same codebase.

Radio

A link budget was also developed based on the capability of the Virginia Tech ground station and the expected performance of the CubeSat's radio and hardware. Assuming a UHF (70cm) uplink and downlink frequency, along with a 9600 baud GMSK modulation scheme, the system has a positive link margin through a majority of the time it is within range of the VT ground station. A link budget has also been made for a hypothetical amateur radio user's hardware. Using a less efficient modulation scheme (G3RUH FSK), amateur radio enthusiasts should still be able to close the link with the satellite and receive packets from the constellation when the slant angle between their stations and the CubeSats is greater than 15 degrees. Unfortunately, these same users would need to purchase a hardware radio able to transmit in 9600 baud GMSK to interact with the constellation.

In terms of getting licensed to legally transmit in space, the mission has selected Jason Harris, a graduate student at Old Dominion University, to lead the licensing effort with the Federal Communications Commission and the International Amateur Radio Union.

Environmental Considerations

The environment in space presents several unusual difficulties that would not occur within the Earth's atmosphere. Among them, the risk of outgassing is especially important. Outgassing is the release of gasses stored inside a material, dissolved or otherwise, which occurs readily in a vacuum. Many materials, including metals, can outgas. However, some materials outgas far more than others. The threat of outgassing comes from the now-free gas condensing upon sensitive surfaces. Condensation on solar panels and camera lenses causes clouding, lowering their effectiveness. Condensation on other circuitry and scientific equipment can also produce many problems. Condensation can also coat radiators, lowering their capability to give off heat.

The biggest sources of outgassing in a CubeSat would be any adhesives and similar substances, as well as the paint we will use to protect the structure from free radicals and atmospheric erosion. The best way to prevent outgassing is through the careful selection of materials. The materials selected for use in the CubeSat have all been chosen with outgassing in mind, by avoiding the use of adhesives, consulting outgassing databases online, and assessing the flight history of the materials we plan on using.

FUTURE WORK

There is still a vast amount of work that needs to be completed before flight. The mission is currently in the latter half of hardware acquisition, expecting to receive all hardware by the end of June 2017. Individual hardware testing has already been conducted on the MSP430 series microcontrollers, RFM69HCW radio, and piNav-L1 GPS and piPatch-L1 Antenna. This hardware testing includes electrical input and output measurements, RF output measurements, and environmental testing. This testing will need to be conducted for the remaining hardware components listed in the hardware section when they are received. Once individual testing is complete, the mission will commence construction of the various sub-systems, which is currently planned for July. Sub-system integration is planned to be completed by the end of August, and the Constellation hopes to have working prototypes completed by September. Having these prototypes established will also provide fit testing, and they will be subjected to vibration and thermo-vacuum testing. The remaining time from August 2017 to February 2018 is reserved for prototype refinement, which will ultimately result in the delivery of the final flight version of the CubeSats before launch in May 2018.

CONCLUSION

In this section, we hope to provide a summary of our paper, as well as advice for reducing the chance of failure for future missions based the problems we have encountered.

To begin, we believe that the mission structure we developed is working well for our mission, and could be used as a base structure for other missions that are established similarly to our own. Appointing separate sub-teams at each university allow for work to be completed in parallel, and it has allowed us to meet deadlines in the past that would have been unreachable with one large team. A clear lead for the mission is also useful for making decisions. We also would like to advocate for university missions employing undergraduates to extensively document their design and development process, as not only does better documentation benefit the university itself as it graduates the students it employs, but more documentation for university CubeSat missions makes it easier to research and conduct missions overall. In a space with such high rates of failure, any benefit, even small, should not be taken lightly.

While this paper only describes the details of one of the CubeSats in the Virginia CubeSat Constellation, the design of the other two CubeSats are similar. The hardware selected was primarily commercial-off-the shelf, leaving only the physical integration of these components and the development of the software to operate these components up to students. We believe that this is the best course of action in order to mitigate risk for university CubeSat missions. Designing more systems internally can only lead to more points of failure, and given the short timeline and great turnover associated with student missions, any additional points of failure greatly hinder the chance of mission success.

Finally, while a vast amount of work still needs to be completed, a great amount of work has been conducted so far. One of the greatest concerns associated with this mission has been the assigned timeline. Undergraduate students are not full-time employees. They have various commitments and distractions outside of school, and it is common for missions involving university CubeSats to have some combination of funding or time issues. Our request for universities or organizations considering engaging in a CubeSat mission involving undergraduates is to grant their mission additional time, as all aspects of a mission, from design to construction, move slower when they involve students.

If you have any questions about our mission, please contact Anthony DeFilippis who can be reached by the email listed on the first page.

Acknowledgments

This mission is supported financially by the NASA Science Mission Directorate, the Virginia Space Grant Consortium, and involves the work of the University of Virginia, Old Dominion University, Hampton University, and Virginia Tech.

We would also like to thank all the unnamed students who have contributed to this mission so far and plan to contribute to it in the future. There are far too many to be named here, but their work and names have not been forgotten.

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