The Virginia CubeSat Constellation Mission

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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

Because Low Earth Orbits (LEOs) do not fully escape the Earth's atmosphere, drag must be considered when modeling the trajectories of spacecraft in LEO. However, air density values can vary greatly in the upper portions of the Earth's atmosphere. Due to this variation, computer models have been employed to predict the amount of drag a satellite will experience once in orbit and how the drag that the spacecraft experiences may alter its trajectory over long periods of time. However, the Skylab reentry incident of 1979 demonstrated that these models incorporated a relatively large amount of error (Dreher, Little, & Wittenstein, 1980). While updated computer models generate more accurate orbital predictions, they still contain statistically significant levels of error.

The Virginia CubeSat Constellation seeks to solve this problem. This constellation is the result of a collaborative project between the Virginia Space Grant Consortium and four of its member Universities: the University of Virginia (UVA), Virginia Polytechnic Institute and State University (VT), Old Dominion University (ODU), and Hampton University (HU). UVA, VT, and ODU have each built CubeSats that will acquire position and velocity data over the lifetime of the mission. From this data, the teams at each school aim to gain a better understanding of the problem at hand and collaborate to produce a more accurate model of the atmospheric density in Low Earth Orbit.

Science Investigation

The motivation behind this mission is to improve the accuracy of atmospheric density models. Current atmospheric models contain significant uncertainties that can result in less-than-ideal predictions for deorbiting satellites. This is due to the fact that atmospheric density at altitudes between 90 and 600 km vary greatly with the solar time of day and can change by an order of magnitude as a result of solar activity. Understanding how solar activity affects the density in the upper atmosphere will improve the accuracy of these models, thus allowing us to better predict orbital lifetimes of satellites and orbital debris. Therefore, the aerodynamic forces acting on these CubeSats will be measured in order to determine the temporal and spatial density variations in the thermosphere.

Mission Architecture

There are two primary mission objectives of the Virginia CubeSat Constellation. Firstly, this mission seeks to obtain orbital decay measurements on a constellation of satellites with the goal of developing a database of (a) atmospheric drag and (b) of the variability of atmospheric properties. Secondly, this mission aims to provide a hands-on, student-led flight project experience for undergraduate students through the development, integration, testing, and launch of a constellation of satellites in LEO. To fulfill these objectives, a three-pronged mission architecture was developed and implemented. From this mission architecture, the CubeSat constellation consists of three 1U CubeSats, with one incorporating a drag brake, and the other two possessing identical outer configurations but with significant differences in mass. The

CubeSat constellation was launched from the International Space Station (ISS) on July 3, 2019 from the NanoRacks CubeSat Deployer. The communications architecture utilizes three separate experimental licenses for each satellite, and each university has their own ground station to communicate with the constellation.

Concept of Operations (CONOPS)

The original Concept of Operations is as follows. The three 1U CubeSats are deployed simultaneously from the NanoRacks CubeSat Deployer on the International Space Station. Once deployed, the satellites turn on between 30 and 45 minutes after the initial release of the separation switches. Once operational, each team establishes communications with the ground stations and requests system health packets from each of the satellites. Once regular communications are established, overhead passes of the satellites are able to be conducted in order to regularly obtain science and health data. Approximately one month after deployment, Old Dominion University's *Aeternitas* CubeSat then deploys a drag brake resulting in altered orbital parameters with respect to the other two satellites in the constellation. The Two Line Elements (TLE's), supplied by CSpOC (Combined Space Operations Center), have allowed for the tracking of the individual satellites that enable each team to establish communications.

Regarding the method of data collection, the three satellites are designed to collect data on position and acceleration (to determine the acceleration due to drag), and relay this information to the three separate ground stations at UVA, VT, and ODU that are operating on their individual experimental licenses. Following data collection, data is sent to Hampton University where it will form the basis of an atmospheric density model using a program made by students and faculty. Pass schedules will also be conducted for each school using the Systems Tool Kit (STK) software by propagating orbital trajectories. These projected values using STK's built in atmospheric model will be compared to propagations conducted using the newly developed atmospheric density model to determine if the new drag model is able to propagate orbits more accurately, for longer durations of time.

In November 2019, these CONOPS changed regarding the operation of the individual ground stations. As a result of the inoperability of two of the three ground stations immediately after deployment, it was decided that the team would pursue further licensing through the FCC to cross-link the three ground stations, allowing each ground station to communicate on the others' frequencies. In addition to the VCC ground stations, the team pursued licensing to allow the Wallops Flight Facility 18m dish to communicate on the team's three designated frequencies to establish contact with the satellites. As a result of this change, the role of the ground stations has evolved to that of a network where each University can utilize each other's ground stations in the event of an emergency.

Instrument

The scientific payload that allows for data collection mainly consists of the GPS and accelerometer units. The *Libertas* CubeSat employs the Skyfox PiNav-Li GPS unit and Skyfox

PiPatch antenna to locate the spacecraft's position. The accelerometer is used to record the directional acceleration of the satellite to be used for drag calculations.

Spacecraft Bus

The spacecraft bus that *Libertas* uses to house its internal components is a 1U skeletonized anodized aluminum chassis, a modified solid baseplate, and a large aperture cover plate, all of which were purchased from Pumpkin Space Systems. Aside from these three major parts, the satellite also utilizes a number of stainless steel screws, nuts, washers, solar panel clips, threaded rods, and aluminum spacers to maintain its structure. These components, once combined, are represented more clearly by Figure 3 on page 9 of this report. This figure also clearly identifies the internal components that comprise the spacecraft payload. As the figure shows, the bus also contains an Electronic Power System (EPS) from ClydeSpace, 4 Solar Panels from ClydeSpace, 1 Solar Panel from EnduroSat, a Lithium-II radio from AstroDev, and a Motherboard from Pumpkin Space Systems.

Purchasing, Building and Testing

All the major components of the *Libertas* satellite were commercially bought off the shelf, and the satellite was primarily constructed at UVA. Testing primarily consisted of bench-top testing of the individual satellites, bench-top testing of the constellation as a whole, and environmental testing. The student team coordinated with NASA to conduct environmental testing at NASA Johnson Space Center, and the testing adhered to the CubeSat environments test requirements of the NASA Launch Service Program, Program Level Dispenser and the CubeSat Requirements Document.

History of the Mission

Important Event	Date
CoDR	October 2, 2016
PDR	November 18, 2016
CDR	March 24, 2017

Integration	February 26, 2019
Original Experimental Licensing Established	March 5, 2019
Launched From Wallops Island	April 17, 2019
Deployed from the ISS	July 3, 2019
Secured STA's from the FCC	October 24, 2019
Made Contact with Libertas	November 23, 2019
NTIA Authorization for Wallops	December 20, 2019 - January 20, 2020
Renewed STA's from FCC	March 31, 2020
Projected Deorbit Date	December 24, 2021

Mission Status

Immediately following deployment, two of the VCC's ground stations experienced persistent technical difficulties, so it was decided to pursue Special Temporary Authority (STA) through the FCC to allow each of the ground stations to communicate with any of the three CubeSats in orbit and provide backup communications capability for the overall mission. While these licenses were being reviewed, a communication structure with secure network connectivity over the Internet and interfaces with each of the three ground stations, including Wallops Flight Facility's U-25 dish that is used to communicate with NASA's SHIELDS-1 CubeSat mission, was developed in order to make this cross-communication possible. These three STA's were granted by the FCC on October 24, 2019.

One month later, the Virginia Ground Station Network (VGSN) was fully operational and tested. On November 23, 2019 using the Virginia Tech Ground Station (VTGS), UVA was able to make definitive contact with *Libertas*. The team was able to collect health data from the *Libertas* spacecraft over numerous passes but was unable to collect science data due to a suspected issue with the GPS aboard the spacecraft. During this time, ODU and VT continued to transmit to their respective spacecraft through the VTGS but did not make contact with either of their satellites.

The team was able to utilize Wallops Flight Facility's U-25 dish once authorization was granted from the National Telecommunications and Information Administration (NTIA) and passes were coordinated with NASA Johnson Space Center to avoid critical operation days of the ISS. Authorization was finally cleared December 20, 2019 and numerous passes were conducted between then and the NTIA authorization end date of January 20. Unfortunately, no contact was made with the CubeSats using the Wallops U-25 Dish and no further passes have been conducted following the end of the NTIA authorization. Due to a combination of signal processing errors, and inherent issues with the Lithium-2 radio onboard the UVA satellite, an erroneous command sent by Wallops appears to have reset the radio settings on the satellite, effectively shutting down operations with it. The UVA team is working with AstroDev, the creator of the Lithium-II, in order to develop methods to reboot the radio.

Libertas Status

As mentioned before, the team established contact with *Libertas* on November 23, 2019 at 1:13 AM. Although no GPS data was collected and transmitted down to the ground, the spacecraft communicated health and housekeeping data, which the VCC team at UVA has used to determine the attitude and rotation period of the spacecraft. Collaboration with NASA Wallops Flight Facility (WFF) was sought after by the VCC team as a back-up effort to communicate with the other two satellites, which had not established contact at that point. In order to test the validity of the setup at Wallops, messages from WFF were to be sent to *Libertas* and the messages received back from the spacecraft would confirm the functionality between WFF and the VCC satellites. Unfortunately, the first time that WFF attempted contact with *Libertas*, the spacecraft did not respond and then failed to respond to regular communication the following day.

It took a few months and many tests with the team's flatsat to determine that the Lithium-II radio has an inherent flaw where the bit sequences that WFF used to precede the actual packets that were sent initiated a fugue state within the spacecraft. These bit sequences corrupt the memory within the Lithium-II far enough that they overwrote the memory settings and switched the frequency to 416.513 MHz instead of the usual 401.04 MHz that *Libertas* normally operates on. At this point, the spacecraft is still able to receive on 401.04 MHz, but it transmits on 416.513 MHz. When the team attempted regular communication with the spacecraft a day after not establishing communication through WFF, the spacecraft received the message and attempted to send a reply. With the memory being partially corrupted, the signal sent from *Libertas* further corrupted the memory to the point where it cannot be communicated with on any frequency. Testing has shown that the only way for the radio to return to normal is to reset the radio through a power cycle of the entire bus. If the radio were to be reset, it would return to its 'Factory settings', which sets the transmit and receive frequency to 437.425 MHz. If a message is sent to *Libertas* on this frequency, the spacecraft would reply on its original frequency of 401.04 MHz and return the spacecraft to normal operation.

Currently, *Libertas* has the option to receive a command in order to reset the radio, however since it is in a state where it cannot receive on any frequency that we know of, the reset signal cannot be decoded and run by the spacecraft. This has led the team to the conclusion that a power cycle of the bus is the only option to repair the radio and continue operations. The testing notes and data from these tests were taken to AstroDev, where they confirmed that this is an issue that they are aware of and see with the CubeSats that are built at the University of Michigan. This issue with the radio design is not documented in user documentation UVA has received in the past. AstroDev's solution is to install a "Watchdog timer" where if the satellite does not hear from the ground station within a certain amount of time, it fully power cycles and resets the radio, thereby fixing it if it was broken. The team is currently working with AstroDev to develop a signal that may be able to corrupt the memory of the radio so far that it initiates corruption protocols and induces a full reset. This signal could potentially allow the team to resume normal operations if it is successful. In the meantime while that is being tested and developed, a full power cycle remains the team's only option.

Update on Ground Station

Following the repair of the USRP N210 radio that occurred when the team sent it back to National Instruments, the Ground Station has not been able to get back up and running to full capacity. The repaired USRP N210 has been reinstalled into the rack that holds the ground station equipment and the rack was then grounded, however a GNU Radio software update has halted immediate operation of the station. This update relies on the newest version of Python in order to run, so all of the code that was created using older versions of Python are now not supported and must be transcribed into the newest version. This operation is currently underway. In the meantime, Mike McPherson has installed an omnidirectional antenna onto the roof of the Mechanical Engineering Building, which has the capability to receive signals from any direction without having to point at objects in order to receive them. The downside to this type of antenna is that it cannot decode weaker signals. Once the directional antenna is re-tuned to its original frequency and running again, the two antennas in combination will allow any signal from the satellite to be captured. As a result of the COVID-19 pandemic, all physical operation within the Mechanical Engineering Building has ceased, however the transcribing of the code and further documentation of the ground station is still being completed.

Attitude Determination

Integral to determining *Libertas's* attitude was to first identify the sides of the spacecraft. As depicted in Figure 1 below, each side is defined by a letter (either A or B) and a number (1, 2, or 4)[1]. The number refers to a pair of sides, while the letter refers to one of the two members of that pair. This naming convention allowed for a clear understanding of the data received from the CubeSat.

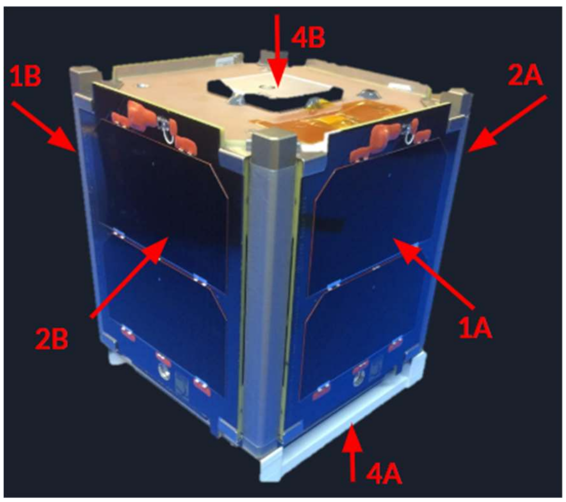

Figure 1: Diagram of *Libertas* detailing the naming convention of each side

A key piece of such data was the solar irradiance measurement. Solar irradiance is defined as the amount of power per unit area produced by the radiation of solar energy from the sun. On *Libertas*, this measurement was particularly useful in determining the orientation of the spacecraft relative to the sun. The sun and temperature sensors are used to collect solar panel temperatures and solar irradiances respectively. The temperature sensors were located on the left

[1] The use of the "1, 2, 4" naming convention, rather than a traditional "1, 2, 3" naming convention is determined by the code designed by Clyde Space. No justification for this convention was provided by the company in the user manual.

and the solar irradiance sensors were located on the right tabs at the top of each solar panel on the spacecraft as shown in Figure 2 below.

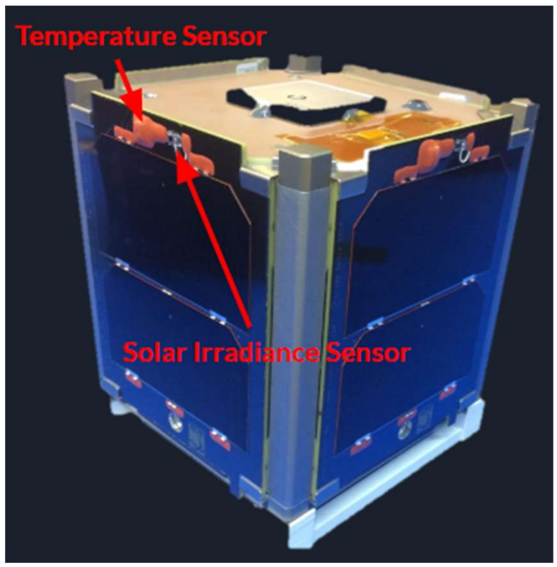

Figure 2: Locations of the Temperature and Solar Irradiance Sensors on each solar panel

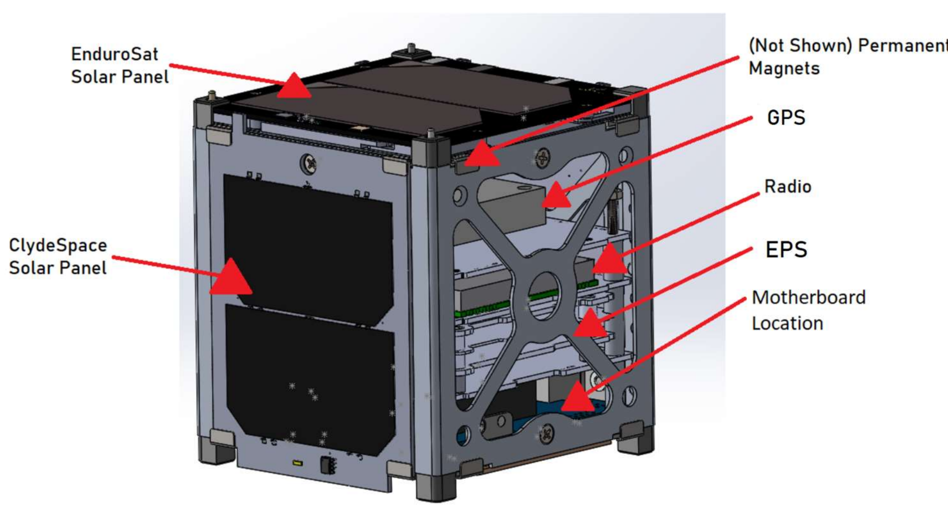

Figure 3: Diagram of the various components of the *Libertas* spacecraft

Solar irradiance data was used to determine the attitude of *Libertas*. Solar irradiance plots for each day-pass consistently demonstrated that sides 1A, 1B, 2A, and 2B had significant fluctuations in solar irradiance from 3.14 W/m^2 to about 1400 W/m^2, while sides 4A and 4B had relatively constant values of about 8 W/m^2 and 28 W/m^2 respectively. It could be inferred from this information that the rotation axis was through sides 4A and 4B. Additionally, the direction of rotation about the 4A/4B axis was determined by the order in which solar irradiance maximums would appear on the plots. Each day-pass plot illustrated that the order went from 2A to 1A to 2B to 1B and so on, such that the rotation would appear to be counterclockwise when viewed from the 4B face. Figure 4 below illustrates the attitude and orientation of *Libertas* using STK software, solar irradiance data, and two-line elements where the yellow arrow represents the sun vector.

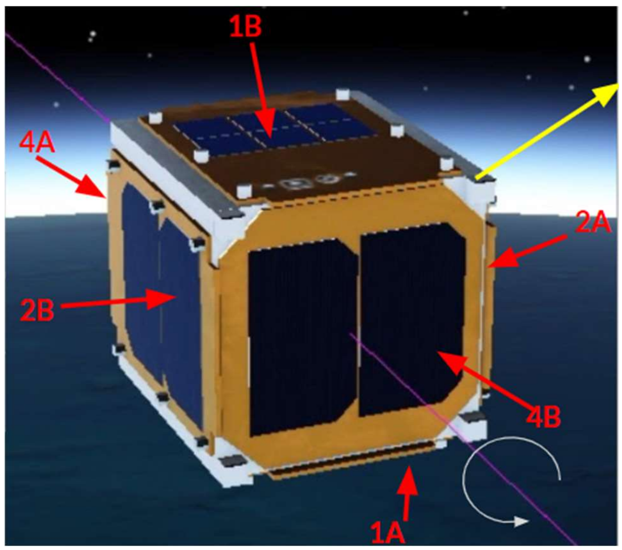

Figure 4: Depiction of orientation of *Libertas* on December 19th, 2019 at 4:00:16 PM UTC

General Trends Day Passes

	11/23/19	11/25/19	11/26/19	12/19/19	12/20/19	12/29/19
Pass Type	Night	Day	Night	Day	Day	Day
Pass Time (UTC)	5:13 AM - 5:19 AM, 6:11 AM- 6:25 AM	10:43 PM - 10:44 PM,	3:36 AM - 3:41 AM 5:12 AM - 5:15 AM	6:02 PM - 6:05 PM	6:51 PM - 6:52 PM	4:00 PM - 4:04 PM

Table 1: Summary of the data received with the dates and times contacted and whether it was a day or night pass. All times in UTC

Before we initiate the discussion on any observed trends, it is necessary to note an important detail on the gathered data. After examining the data, a pattern was revealed that all data points taken within one to two seconds of one another always had the same exact value with the same number of significant digits. This effect could be chained such that quick successive requests of health data would cause the obtained data to all have the same value as those from the first of the successive requests. In our acquired data, this effect was observed to occur up to a max time span of three seconds. It is unclear whether or not this time span can be even longer, since we do not have any successive data requests of more than three times. Upon further investigation, these groupings of data points also possessed the same value for the GPSTIME while the timestamp for the data differed. It seems that the GPSTIME is linked to how *Libertas* chronologically tracks the data. This issue may be attributed to the possibility that the motherboard processes are too slow to keep up with rapid requests of flight health data within a short timeframe. Thus, it may be important to test how short the time interval between health data requests can be before incurring this issue. However, this poses no significant impact on the data analysis discussed below as these groups of data points were generally interpreted and utilized as single data points.

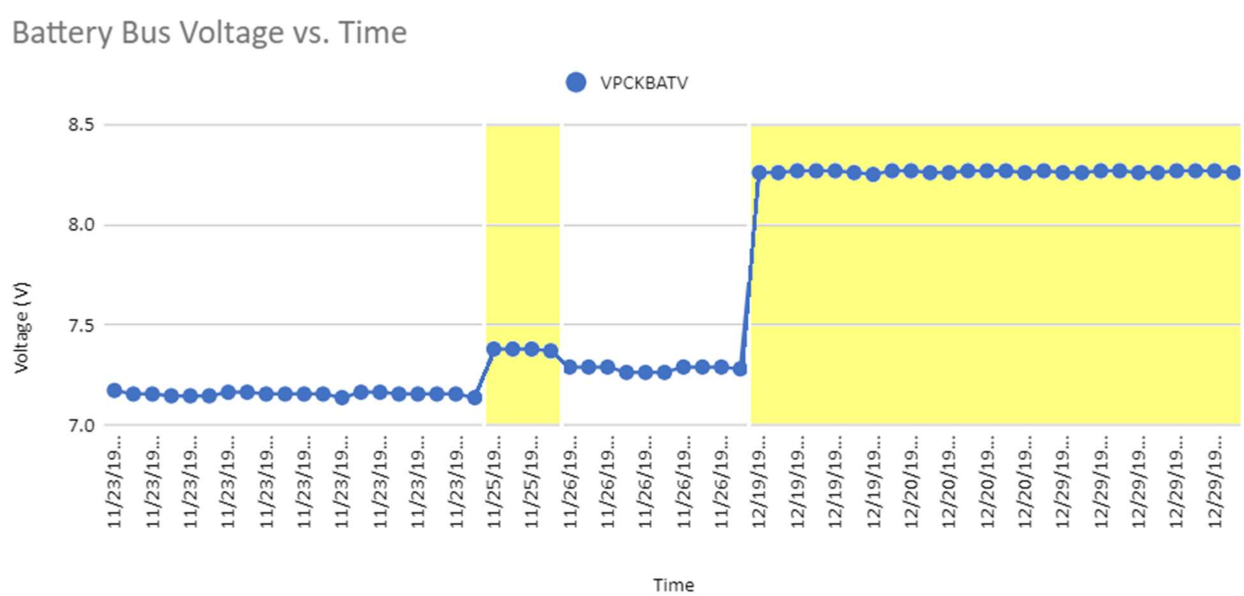

Figure 5: A Voltage vs Time plot of *Libertas*' battery bus over all passes. Highlighted are the passes that occurred during the day, and non-highlighted passes represent those that occured at night. This distinction is important in analyzing the jumps in voltages that this graph displays.

The above figure displays the battery voltage of the spacecraft bus over multiple day and night passes. It is important to note that these day and night passes contain different amounts of data points. This is because each data point was generated by an individual request from the UVA ground station, and the number of these requests from day to day was determined arbitrarily. The nodes within the highlighted area seen in Figure 5 above indicate the measured voltage of the battery bus during day-passes over the UVA ground station. These highlighted sections signify that the battery bus voltage during the four day-passes is generally higher than those of the two night-passes. It is clear that the majority of the day-pass data shows a voltage of around 8.25V, while the night-pass data rests below 7.5V. However, there is not enough information to conclude whether or not the gap between the battery voltage during a day-pass versus a night-pass should be that large. The data gathered within a few days of one another in November shows that the battery voltage during the day-pass sits at around 7.40V, while the voltage during the night-passes lies within a small margin of 0.25V. This voltage difference may be the result of the CubeSat's power consumption without any solar energy to charge the battery during the night. Following this trend, it may be the case that the battery voltage of a night-pass in late December is also just within a 0.25V margin of the corresponding day-pass.

Because the November data was recorded at a different time than in December, it could be the case that the data gathered on November 25th is an outlier, that the time of day during the day-pass dramatically affects the battery voltage, or something independent of whether or not the CubeSat is in the sun caused the voltage to spike between late November and late December. It may be possible to rule out the time of day as a factor. Since the determined rotation period of *Libertas* and it's peak and minimum solar irradiance remains consistent throughout the day-passes at different time-of-days, barring the calculated rotational period for December 29th, this should mean that the amount of power the CubeSat generates, and thus the battery bus voltage should also be consistent at different times of days. In the end, it is difficult to conclude anything more from the battery voltage data without more information.

Data recorded from the temperature sensors over each day-pass showed a significant fluctuation in temperature that was dependent on whether a side was sun-facing or not. Generally, the side that is not facing the will drop to a low of around 11 Celsius. When it is directly facing the sun, the temperature will rise to around 27 Celsius. However, the temperature range measured on December 19th was about 6 degrees higher than the three other days with a low of 16.2 Celsius and a high of 31.6 Celsius. It is difficult to pinpoint why this is the case, but the time of day can, again, be disregarded as a factor. The temperatures recorded by *Libertas* on the following day, December 20th, were taken 50 minutes, relative to time of day, after those taken on the 19th. Furthermore, the data sets from both days were measured in the middle of the afternoon in Eastern Time, such that the amount of energy received from the sun wouldn't be significantly influenced by time-related events, such as the sun setting. Thus, we could reasonably infer that the time of day did not play an important role in whatever caused the temperature to be higher than average on December 19th.

Rotation periods for *Libertas* were calculated using a few different methods of analyzing solar irradiance plots. Rotation periods on December 19th were measured by finding the time between the peak solar irradiance of opposing sides of the satellite. The time that it took between when side 1A was sun-facing to when side 1B was sun-facing was approximately 100 seconds. From this, we inferred that one full rotational period would be around 200 seconds considering one half turn took 100 seconds. The same method was used to determine the rotation period of the *Libertas* CubeSat on December 29th. However, a slightly altered method was utilized to find the rotation period of the satellite on December 20th, since the time frame in which data was collected only showed one peak for each pair of opposing sides.

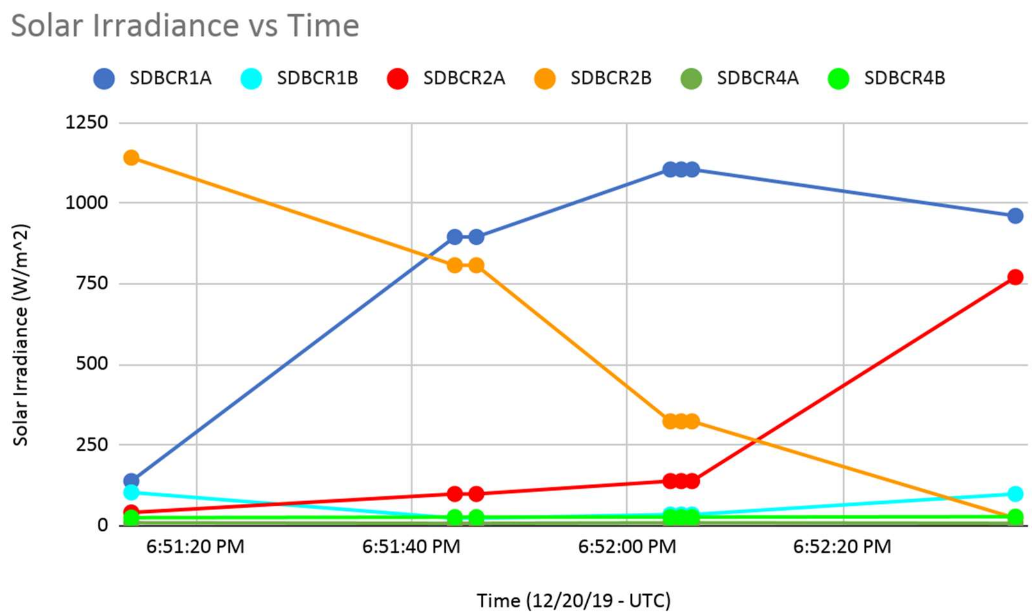

Figure 6: Solar Irradiance vs Time of all sides on December 20th

We noted, as seen in Figure 6 above, that while the solar irradiance side of 1A had a defined curve from trough to a little more after the peak, the opposing solar array side 1B measured no significant solar irradiance. For this to occur, sides 1A and 1B must be adjacent to the sun-facing side such that as side 1A rotates into the view of the sun, side 1B stays in the dark. A visual of this is included in the Appendix as Figure 1. Thus, measuring from when the solar irradiance starts to increase on side 1A till it reaches a maximum gives a quarter of the full rotation period which can be quadrupled to obtain the full rotation period.

Solar Array Pairs	11/25/19	12/19/19	12/20/19	12/29/19
1A / 1B	n/a	~200 sec	~200 sec	~52 sec
2A / 2B	n/a	~218 sec	~200 sec	~50 sec
4A / 4B	n/a	n/a	n/a	n/a

Table 2: Determined Rotation Periods of *Libertas* for each day pass and for each pair of sides

Table 2 details the calculated rotation periods of the *Libertas* CubeSat during each of the four day-passes. No rotation periods could be determined from the night-passes since temperature data and solar irradiance data showed no semblance of any rotation due to a lack of energy received from the sun. A rotation period also could not be determined for the day-pass on November 25th, since the time frame over which data was collected was too short to perceive any peaks to use for period determination. For the days that could have a rotation period determined, *Libertas* exhibited a period of approximately 200 seconds on December 19th and December 20th, but that value drastically dropped to around 50 seconds by December 29th. One possible explanation for this phenomenon is that the time interval between data points taken on the 19th and 20th of December might have been too long to detect faster rotation periods stemming from the same multiple. It could be the case that the true rotation period was 50 seconds all along, however; there are some pieces of evidence that may discount this possibility. This evidence is discussed below.

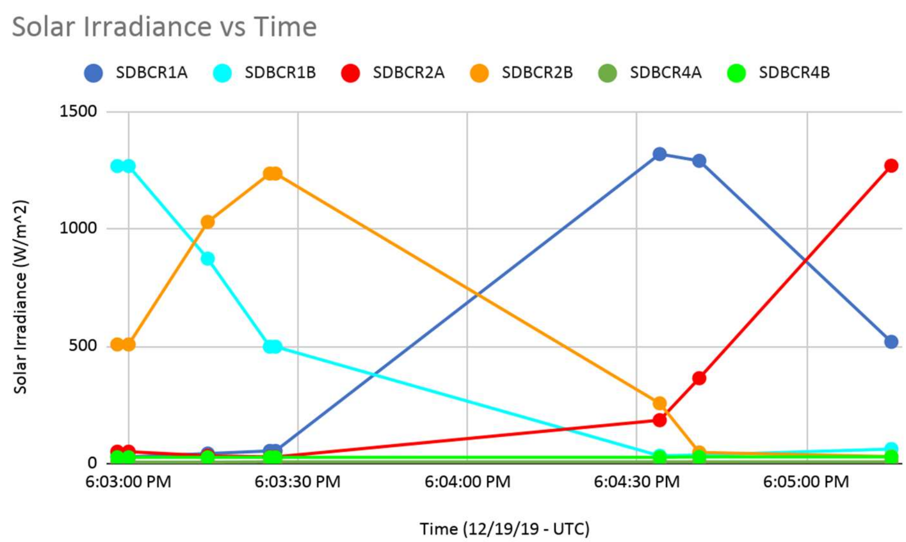

Figure 7: A Solar Irradiance vs Time plot of six solar irradiance sensors onboard *Libertas* on December 19, 2019

Figure 7 above is a solar irradiance plot of the various sides of *Libertas* on December 19, 2019. The variables SDBCR refer to the sun detector and its particular connector such as 1A or 1B. The points of interest on the plot above are the two adjacent sides 1B (light blue) and 2B (orange) from 6:03:00 PM to 6:03:30 PM where we have five data points taken within thirty seconds. If we follow the assumption that the true rotation period is fifty seconds, we would expect to see a much more rapid decline in solar irradiance for those first five data points of 1B. With a fifty second period, it should take about twenty-five seconds to go from trough to peak or peak to trough; however, with side 1B, we see that it takes almost thirty seconds to drop from almost peak solar irradiance to a third of the peak value, which is much slower than we expect. We also cannot make the case that there was too much time between data points since a difference of about fifteen seconds between the data points is small enough to view the changes in solar irradiance for a fifty second period, unless the true rotation period is even faster.

The same argument can be made for side 2B in that same time frame of 6:03:00 PM to 6:03:30 PM. Side 2B starts about forty percent of what we believe to be its peak solar irradiance value (based upon its consistency with peak solar irradiance values with the other sides) and climbs to the perceived peak solar irradiance over the next thirty seconds. If the true rotation period was around fifty seconds, then the data point in the middle of the time frame should be close to the peak solar irradiance and the next data point at around 6:03:30 PM should show the solar irradiance dropping. Thus, it is unlikely for the rotation period on both December 19th and 20th to be fifty seconds. However, it is still within the realm of possibility for the true rotation to be a multiple of what was determined and fast enough that the data points can't illustrate that fact. It could also be the fact that something caused the rotation period of *Libertas* to change between the nine days data was received, or that the rotation axis of the CubeSat is precessing as it rotates, leading to the observation of two different rotation periods. More data and more time for analysis is required to explain the discrepancy in the determined rotational periods.

General Trends Night Passes

As expected, the temperature sensors on all faces recorded very similar and fairly constant temperatures over the span of each night pass. Figure 8 below depicts temperature data for sides 1A, 1B, 2A, and 2B between 12 and 1am EST on November 23, 2019. Temperatures during night passes were consistently measured in the range of -10 to -30 degrees Celsius.

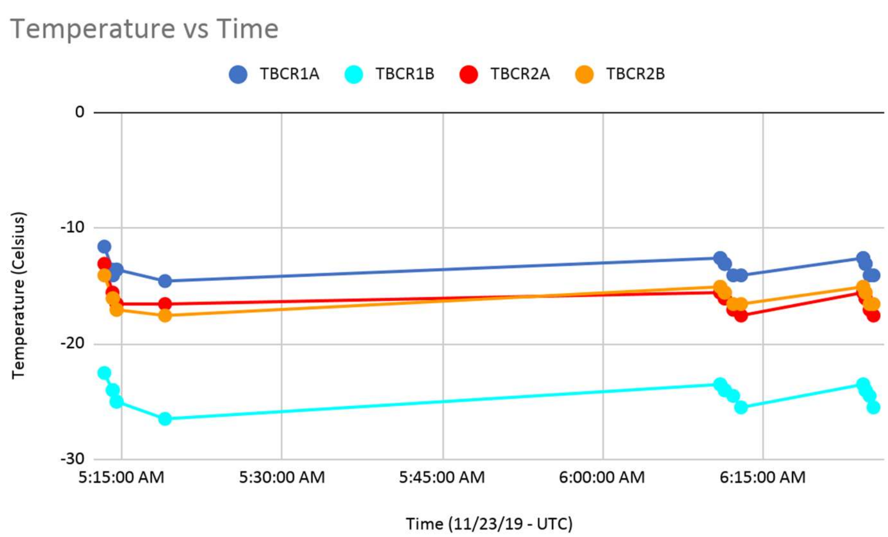

Figure 8: A Time vs Temperature plot of four temperature sensors onboard *Libertas* during the night of November 23, 2019.

The above graph and statistics omit the data points collected from side 4A, which are believed to be the result of a faulty temperature sensor. TBCR4A consistently read a temperature of 229.11 Celsius, which is an unreasonable temperature for night passes.

During this time period, the solar irradiance of all faces also remained constant at 3.19 W/m^2, further disproving the temperature readings of sensor TBCR4A.

Deorbit status

Deorbit status is defined as the time at which a spacecraft's perigee falls below 65 km and starts rapidly decreasing in altitude. When the deorbit status was calculated from deployment on July 3, 2019, STK's Lifetime Function gave a deorbit date of January 30, 2022. This gave the CubeSat a total lifetime of 2.6 years. The atmospheric model used in this deorbit prediction was the Jacchia 1970 Lifetime model as this model predicted the earliest date of deorbit and serves as a conservative estimate for the lifetime of the spacecraft. Table 3 below provides the STK input variables and Figure 9 below is a graphic of this deorbit prediction.

Satellite Characteristics	Value
Coefficient of Drag	2.2
Coefficient of Reflectivity	1.0
Drag Area	$0.01m^2$
Area Exposed to Sun	$0.06m^2$
Mass	1.154 kg
Atmospheric Model	Jacchia 1970 Lifetime
Solar Flux Data	CSSI Solar Geophysical Data provided by STK

Table 3: STK input variables and settings

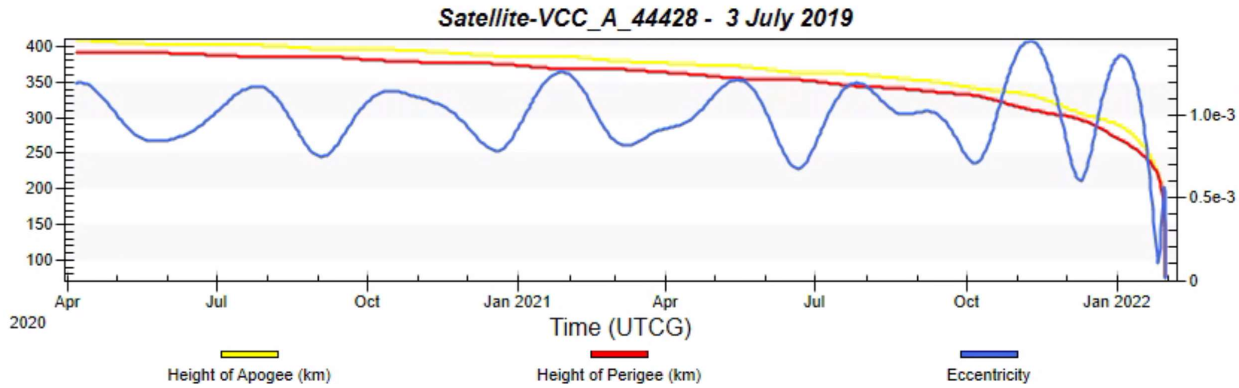

Figure 9: Deorbit status calculated on July 3, 2019

From the graph, one can see that the red line, representing the height of perigee for the *Libertas* satellite, falls exponentially towards the end of January 2022. However, the deorbit status was recalculated using the same inputs as the original prediction, except it used the most recent TLE on April 1, 2020, instead of July 3, 2019 at deployment, and it provided a new deorbit date of December 24, 2021, five weeks sooner than initially anticipated. This means *Libertas* has a lifetime of 1.7 years remaining, or a total lifetime of 2.45 years compared to the original prediction of 2.6 years. Because the Sun will be reaching a solar minimum in 2020, solar radiation pressure is most likely not the cause of this faster deorbit time. It can most likely be attributed to inaccuracies within the different atmospheric models or an incorrectly assumed coefficient of drag. There are many different atmospheric drag models available that can be used to determine orbital drag assessments, however each model is built differently and puts larger emphases on different variables, which leads to the high variability between models. This large variability and proneness to inaccuracy is why it is one of the motivators for the science goals of the VCC mission. Similarly, the default coefficient of drag for the STK model is constant for the operation of the STK Lifetime Function, which leads to inaccuracies if the coefficient of drag in reality does change. The deorbit prediction from April 1 is shown in Figure 10 below.

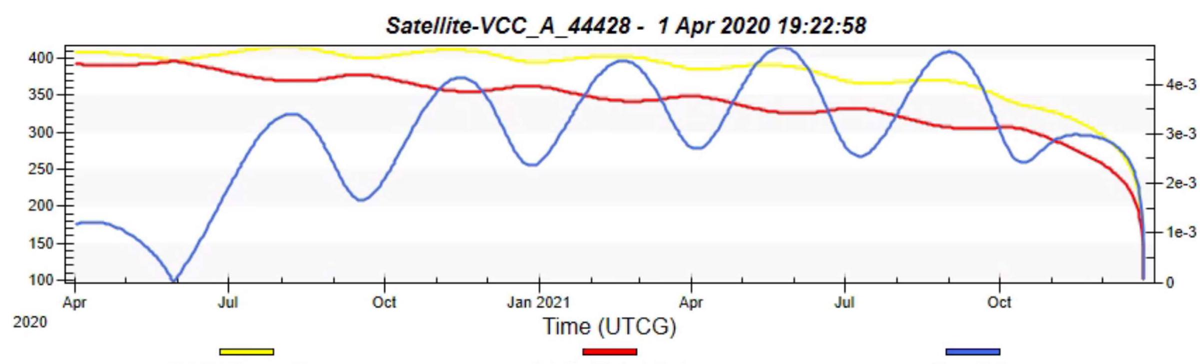

Figure 10: Deorbit prediction calculated on April 1, 2020.

This new graph shows the red line representing perigee falling exponentially in December of 2021.

Lessons Learned

Each University and its teams had their own struggles, which in turn yielded unique insights into the different aspects of the mission as a whole. The management team had a number of learning experiences throughout the project. One particular difficulty of management that is unique to the undergraduate level is the high level of turnover that occurs during a multi-year mission such as this one. In order to tackle this recurring issue, it is important to thoroughly document every step of the process for each sub-team, with writing and pictures, so that new members can be briefed and learn about the intricacies of the project well in advance of the scheduled turnover date. Documenting details about the systems, previous decisions, and solutions to issues that arose help to save time and energy later down the road when similar problems may occur. One major issue that arose as a result of this student turnover is the changing of team priorities from year to year. Clearly it is most important to get the satellite finished on time in order to deliver for launch, but some of the other critical mission objectives can get pushed to the backburner at times.

Ground-station development, Server and Data management development, Data Analysis Software development, and even Radio Licensure are some of these other critical mission objectives that later became sources of these lessons learned as priorities changed from year-to-year. These other aspects of development might not seem as important as developing the CubeSat itself, but as the team found out, if even one these are not completed by the time the CubeSat is launched, or in some cases when it is deployed, then the team potentially cannot fulfill the mission that the CubeSat was designed to do in the first place. For example, a correction on the radio license for this mission was delayed by the 2018-2019 United States Federal Government shutdown, which complicated matters and showed how important it is to get these types of mission objectives started as early as possible. Luckily for the team, the group did manage to finish everything before the deployment of the spacecraft, however it did come down to the last minute in some cases. In hindsight, better planning and preparation would have gone a long way to prevent something like this from happening in the first place.

Another pertinent aspect of management on a mission of this magnitude, in this case a mission between three Universities, is establishing regular communication between schools, management, teams, and sub-teams so that updates are frequent and productive towards finding solutions to the problems at hand. Weekly teleconferences were utilized in the last two years of the project. Another invaluable resource that was discovered was establishing a point of contact with each company that a component was purchased from. Most companies were incredibly helpful when asked questions and even went as far as assisting the team in determining how their components could best serve the mission objectives. Merely asking for assistance from each company helped to solve issues and address problems before they could even arise. The ability to ask questions and know when to ask for help is understated and not readily sought after in a lot of aspects of society today. This skill is necessary in life and was extremely important for this mission because although failing teaches what not to do, asking for help teaches how to do things right.

Some of the more specific instances of lessons learned came from the planning aspect of management. Seeking out funding from multiple sources is fundamental in obtaining enough money for the project throughout the entire process. NASA and VSGC provided significant funding for the project with VSGC helping with a number of additional costs beyond those originally budgeted. Ground-station and travel costs are all incurred by the CubeSat developer and, luckily for the University teams, each respective University was supportive of the mission and partially shouldered some of the costs. Finding multiple avenues for funding also allows for some leeway regarding budgeting. For instance, since CubeSat components can have significant costs, budgeting for replacement parts or for an engineering model is necessary to minimize programmatic and technical risk in the project. Something inevitably will break and when it does it is important to have a spare part on hand or money in the bank to purchase the new part. For example, after the constellation was deployed, the ground-station at the University of Virginia experienced technical difficulties in receiving signals after the low-noise amplifiers stopped working despite being thoroughly tested the week before. Luckily, the ground-station at Virginia Tech contained multiple working antennas and were able to listen for transmissions from all three spacecraft during that time. Similarly, after contact was made with *Libertas*, issues inherent with the Lithium-II radio prevented the satellite from further communicating with the ground after Wallops Flight Facility was used to attempt contact. This design flaw was detected through testing months after the final loss of signal with the spacecraft and was then reported to the manufacturer, AstroDev. Although not documented at all, the manufacturer seemed aware of the problem and recommended that a “Watchdog timer” be put into place in future CubeSats, which resets the spacecraft after a certain number of days that the satellite does not have contact with the ground station. Knowing this beforehand would have solved the issue that shut down *Libertas* in the first place. Although failure of equipment cannot be directly predicted, planning for unforeseen circumstances such as these can help to mitigate losses in productivity if they ever do occur. Lastly on top of the deadlines set by NASA and the deployer, it is a good practice to establish realistic goals and deadlines, and most importantly stick to them. This, along with defining the mission goals and objectives from the start of the project make it easier to stay on track.

Everything considered, most of the team-specific lessons that were learned over the course of this mission can be summarized by being overly prepared, overly organized with parts and documentation, and testing at each step along the way. Despite each University having its own unique set of obstacles and hold-ups, in the end the purpose of this mission was to provide undergraduate students with an industry-level engineering problem and an invaluable learning experience. The Virginia CubeSat Constellation thanks NASA and VSGC for all they have done for the team as well as the opportunity to learn by doing, making everyone on the project better engineers, better teammates, and better people.

Conclusion

Despite not obtaining actual GPS data from *Libertas* during its operation, the health data that was received was analyzed in order to estimate a rotation period, the rotation direction, and determine the general attitude of the spacecraft. Although the team lost contact with *Libertas* as a result of a previously unknown design flaw with the radio, the data that was received indicated that the spacecraft was functioning as expected. This serves as a testament to the hard work completed by all of the previous years of the mission who came up with the ideas and met the deadlines necessary to produce the CubeSat. Since one of the main objectives of this mission was to provide a hands-on, student-led flight project experience for undergraduate students, the team can conclude that this mission has been successful. In order to achieve the first mission objective of obtaining measurements of the orbital decay to develop a database of atmospheric drag and the variability of atmospheric properties, the team would need to receive GPS data from *Libertas,* and ideally the other spacecraft, and analyze the actual orbital decay compared to computer predictions. Over the course of more than four years, the Virginia CubeSat Constellation mission has provided invaluable experiences to many students who have taken their experience on the VCC mission into the workforce with them. Continuing into the future, the VCC team hopes that the lessons learned accumulated over the years past will be put to use within future CubeSat missions that UVA conducts.

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Dreher, P.E. Little, R.P. Wittenstein, G. (1980). Skylab orbital lifetime prediction and decay analysis. NASA Technical Reports, Washington D.C.

Segal, C., Sandy, M., Goyne, C. (2020). NASA USIP Virginia CubeSat Constellation PI's Summary of Research

Segal, C., Greer, C., Pollard, M., Hsiang, C., Brink, J., (2019). 1U CubeSat Proposal

Appendix

Figure 11: Top View of *Libertas* illustrating the attitude determined to calculate rotational period

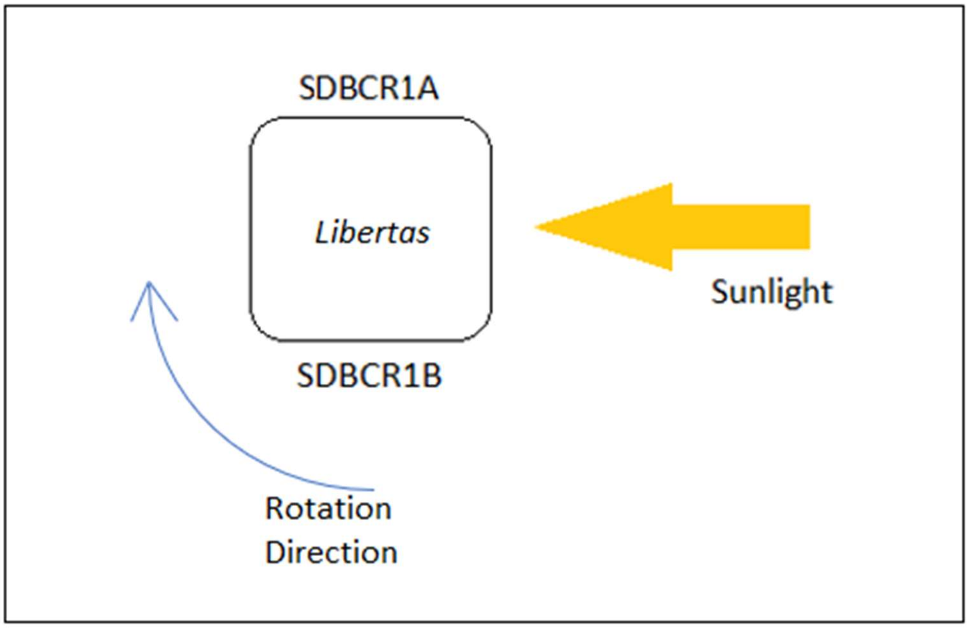

Figure 12: Solar Irradiance vs. Time (12/19/19 Pass)

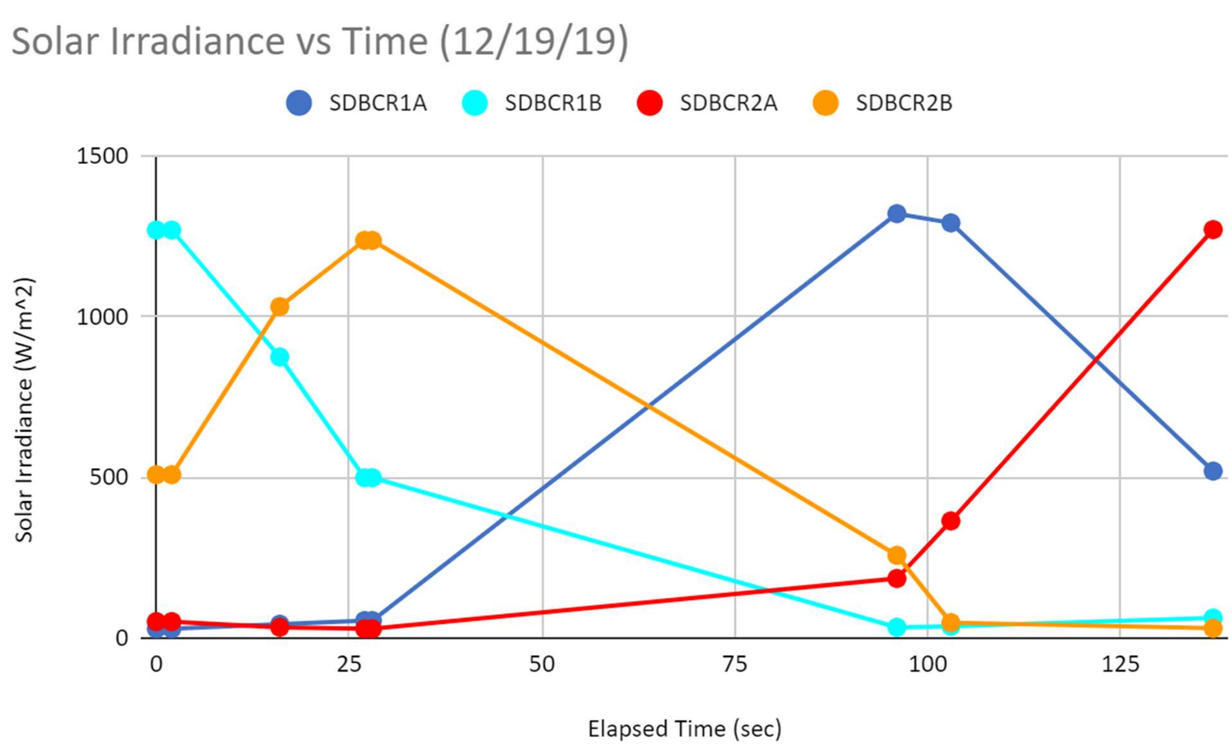

Figure 13: Solar Irradiance vs. Time - Pair 3

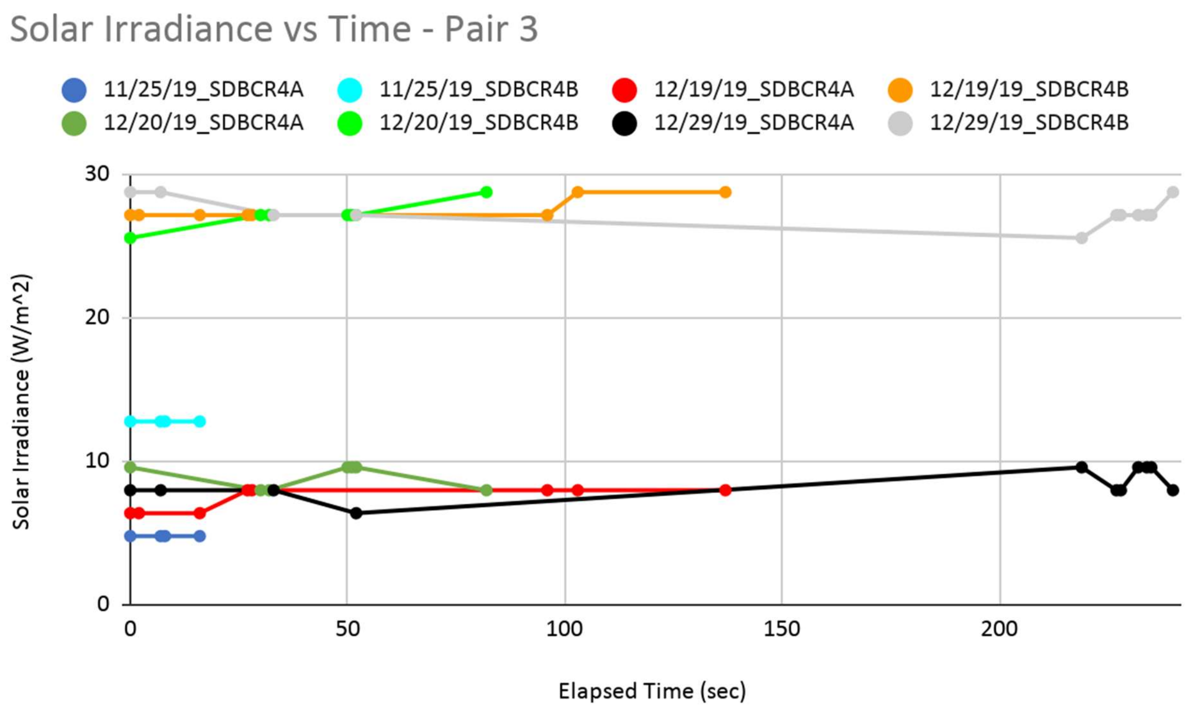

Figure 14: Solar Irradiance vs. Time - Pair 1

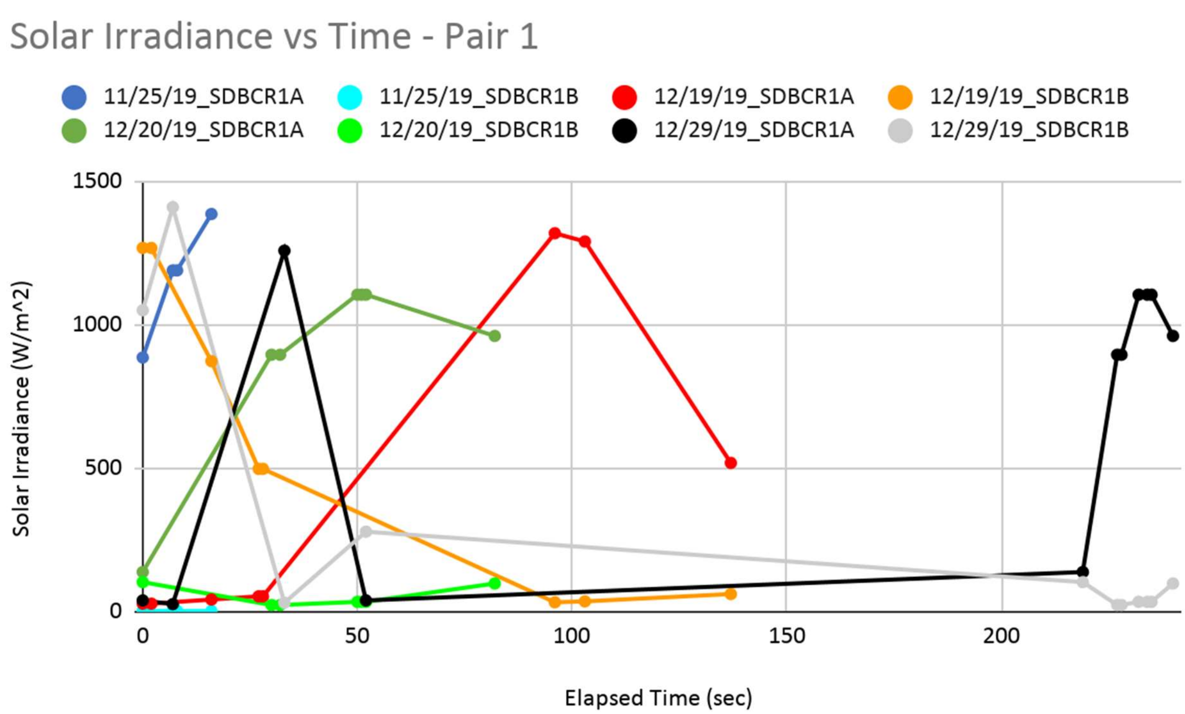

Figure 15: Solar Irradiance vs. Time - Pair 2

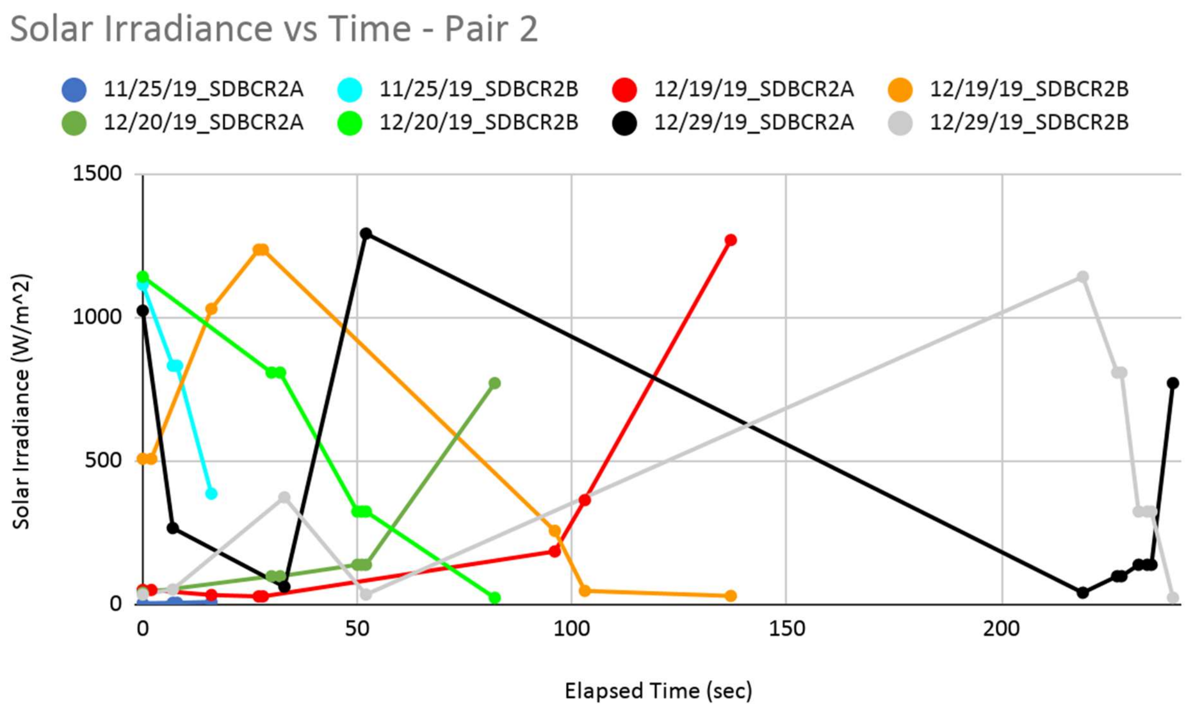

Figure 16: Solar Irradiance vs. Time (11/23/19 Night Pass)

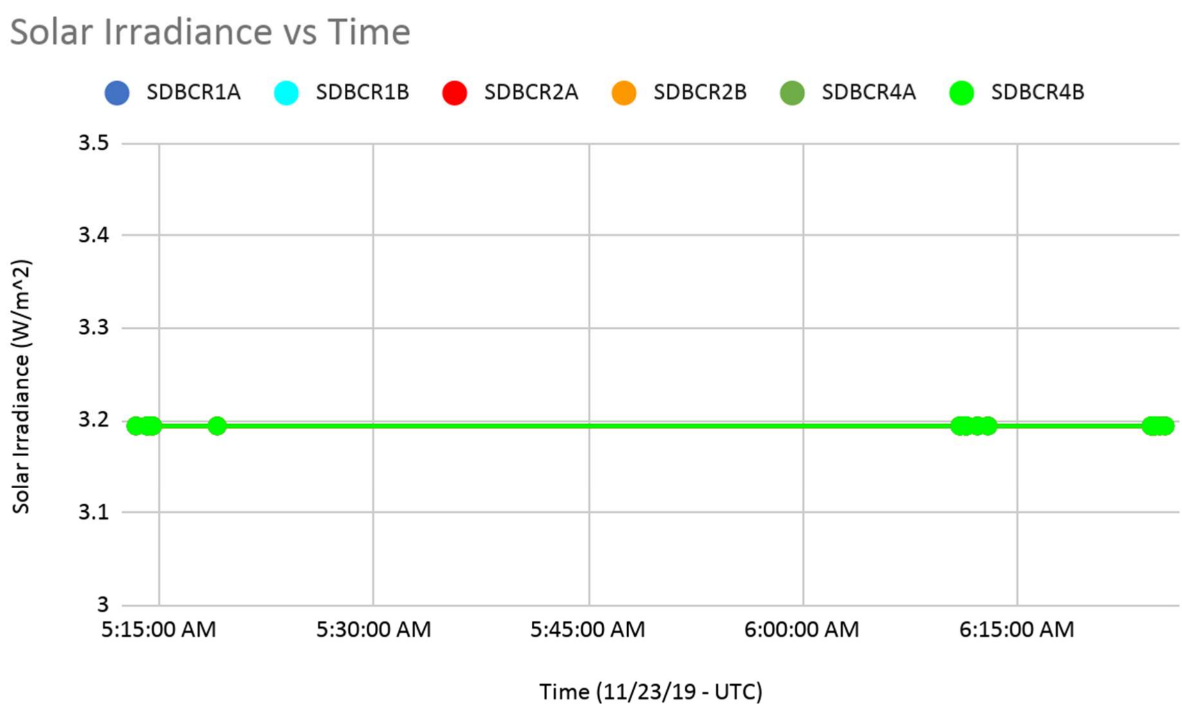

Figure 17: Temperature vs. Time (11/23/19 Night Pass)

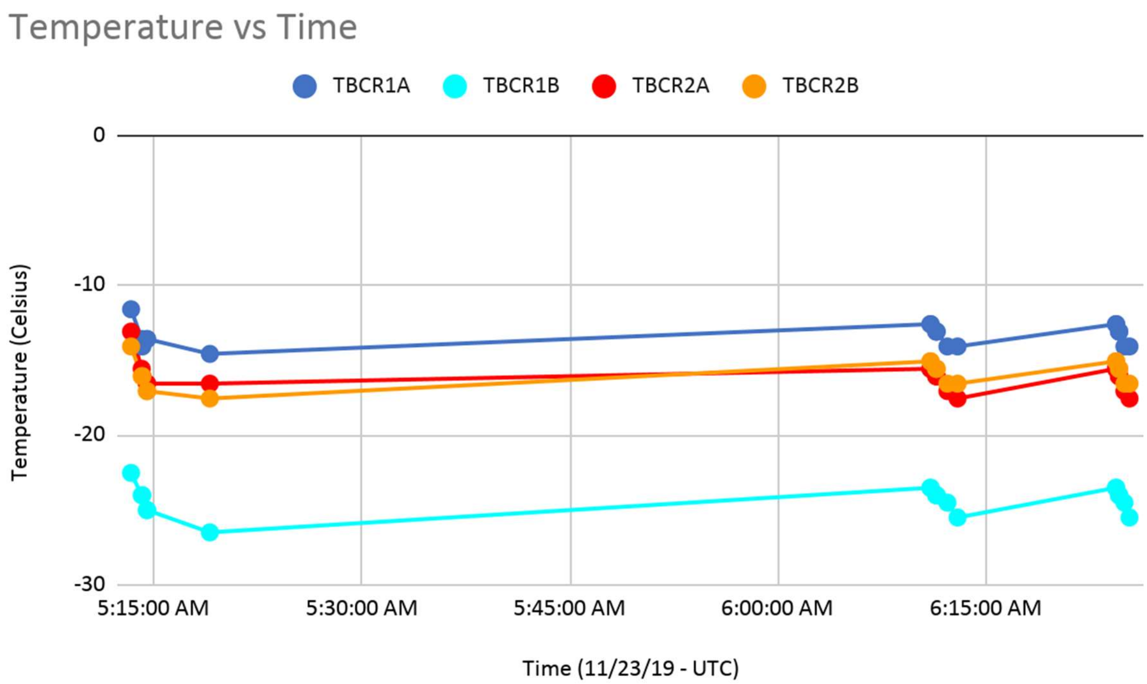

Table 4: First ½ of the important acronyms found within the health data

	Definition of Variable	Sample Data	Units
TIMEUTC	Time & Date, File Name	20191219T180258Z	Time in UTC
BROWNOUT_RESETS	N/A	0	N/A
AUTO_SOFTWARE_RESETS	N/A	0	N/A
MANUAL_RESETS	N/A	0	N/A
COMMS_WATCHDOG_RESETS	N/A	0	N/A
IIDIODE_OUT	Battery Charge Regulator Output Current	0.029326	Amps
VIDIODE_OUT	Battery Charge Regulator Output Voltage	8.29169	Voltage
I3V3_DRW	3V3 Current Draw of EPS	0.021241	Amps
I5V_DRW	5V Current Draw of EPS	0.023896	Amps

Table 5: Second half of the important acronyms found within the health data

	Definition of Variable	Data	Units
IPCM12V	Output current of 12V bus	0.02898	Amps
VPCM12V	Output voltage of 12V bus	12.0466	Voltage
TBRD	Motherboard temperature	27.7767	°C
VBCR1	Voltage feeding Battery Charge Regulator 1	4.61657	Voltage
IBCR1A	Current, Battery ChargeRegulator 1, Connector for the Solar Irradiance sensor on side 1A	0.001955	Amps
TBCR1A	Array temp., Connector for the Solar Irradiance sensor on side 1A	18.1781	°C
SDBCR1A	Sun Detector, Connector for the Solar Irradiance sensor on side 1A	28.7505	W/m^2
ANTENNA_STATUS	Is Antenna Deployed	1	N/A