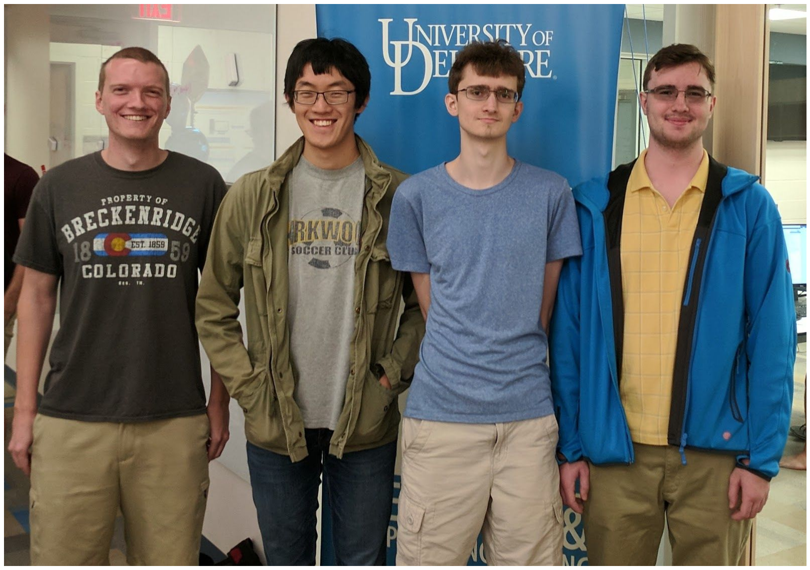
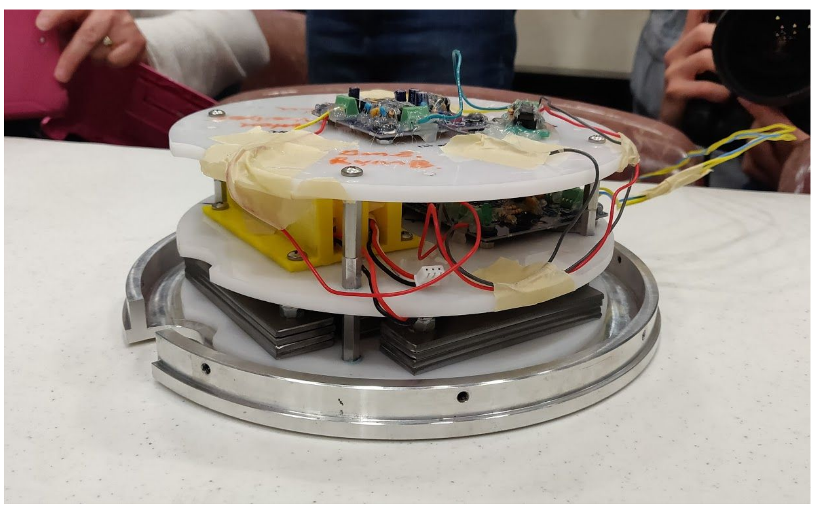
RockSat-C 2018 Final Report

Electrical and Mechanical Testing of Suspended Silicon Diodes

This payload will test the electrical and mechanical characteristics of a set of suspended silicon diodes that are intended to be used for future spaceflight applications.





Ryan Beneck, Aric Lu, Benjamin Steenkamer, Anton Vasilyev

Chase Cotton

University of Delaware

07/27/2018

1.0 Mission Statement

This payload will test the electrical and mechanical characteristics of a set of suspended silicon diodes that are intended to be used for future spaceflight applications. Electrical operating characteristics will be acquired by sampling diode IV curves throughout the flight. Mechanical forces on the payload will be measured with an accelerometer and gyroscope. We expect to be able to acquire the IV curves of the device and detect any damage done to the device during the flight. In the end, we hope to identify points of weakness in the device and methods of reinforcing them to ensure the diodes' suitability for space flight applications.

2.0 Mission Requirements and Description

As space becomes increasingly important for commercial and scientific applications, there is a need for better devices for optical communication between satellites and between terrestrial ground stations. Devices that utilize novel materials and designs have been developed recently to enable the next generation of space-based applications. As these devices move closer and closer to reality, there is also a need to ensure that these devices can survive the rigors of spaceflight. Our mission is to test the durability of silicon-graphene diodes to investigate their suitability for future spaceflight applications.

One particular feature of our device is its design. The diode itself is suspended in air, and is only anchored to the substrate by supports branching off the side of the device. Therefore, it is an open question as to whether or not the diode will survive the spaceflight. To this end, we will test the devices throughout the flight to investigate their mechanical and electrical operating characteristics under the launch.

A second application of these diodes for space is for radiation detection. As these diodes are exposed to radiation, they will react and change in a very specific manner, which can be seen as shifts in the IV curves. This occurs because ionizing radiation introduces defect states into the diode, which reduces its efficiency and provides a path for current to be converted into heat or light by the diode. By flying these diodes on the RockSat-C mission, we hope to see this effect as it is exposed to elevated amounts of ionizing radiation in the upper atmosphere and lower reaches of space.

To investigate these devices properly, we must measure and record mechanical and electrical data from the diodes throughout the flight. The mechanical data we chose to measure were the forces on and the orientation of the diodes throughout the flight. This data will allow us to potentially see the limits of device survivability in the future. To characterize the electrical performance of these devices, we will measure the IV curves of the devices throughout the flight. This will serve as a measure of device integrity as well as a way to measure the effect of exposure to ionizing radiation. We did not include a ionizing radiation detector in our payload as our focus is primarily on the survivability of these devices.

As we are primarily concerned with the survivability of the devices, our device needed to turn on before the launch to capture any events that happened at the ignition of the rocket.

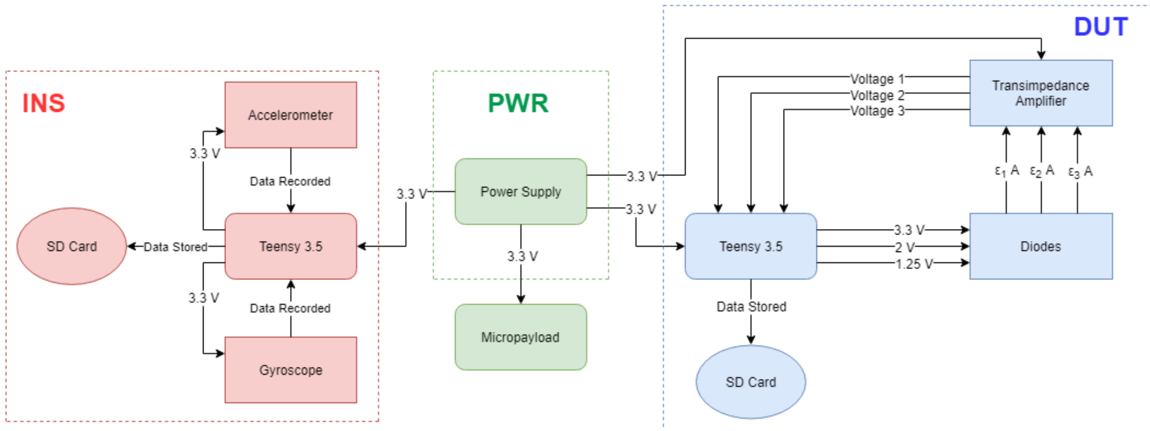
One major requirement that needed to be worked around was the lack of a stable, latching power supply. Having one would enable us to include a real time clock on our payload and record time along with our data to enable a more accurate reconstruction of the flight. In order to work around this obstacle, our device needed to be able to record and preserve data throughout the entire flight, even through loss of power.

In addition, the payload should be able to reconstruct the flight path from the gyroscope and accelerometer data. This will give us a sense of where the major shocks to the payload occur and potentially provide insight into ways to mitigate them.

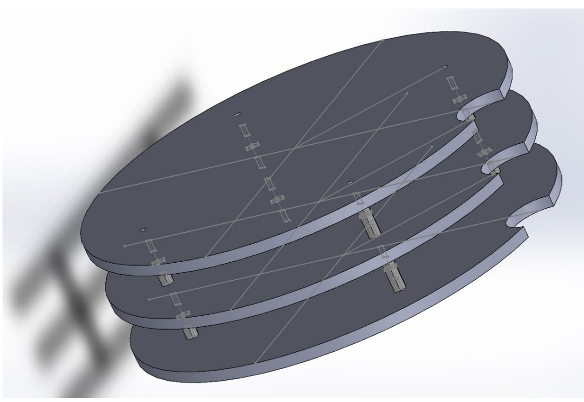
Finally, the payload was intended to support several micropayloads from other students at the University of Delaware. This was eventually dropped due to a lack of interest by the outside groups.

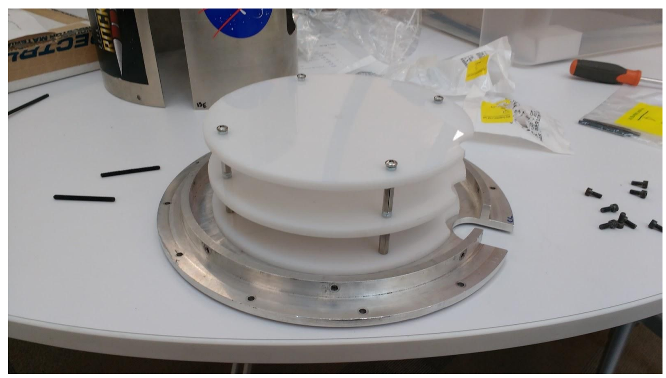
3.0 Payload Design

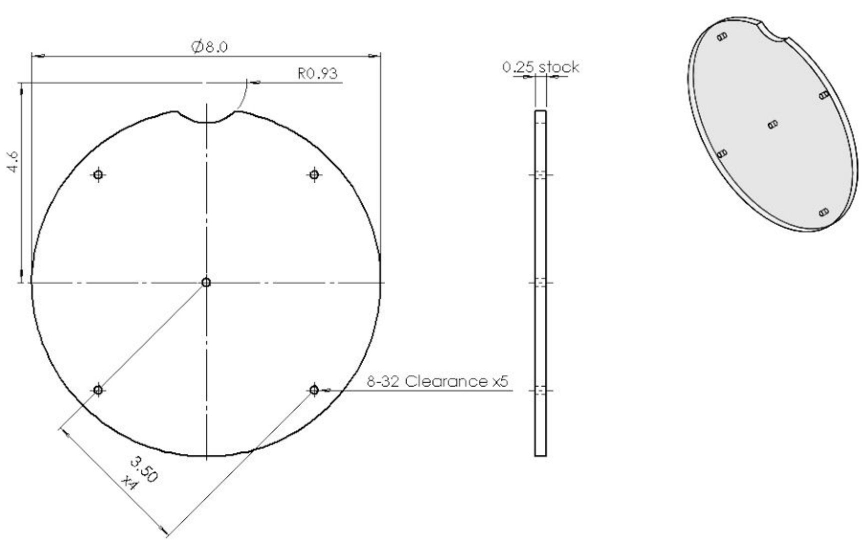
This payload has three main components, the device under test (DUT), inertial navigation system (INS), and power supply. The DUT is contained on its own PCB, and the power supply and INS share a PCB. The DUT will measure microamp currents from the suspended silicon diode. The INS will record linear acceleration in three axes and rotational acceleration in three axes. Both the INS and DUT will share a Teensy 3.5 in order to process data, and store the information on a microSD card for future analysis. The two PCBs will be connected together using jumper wires. Another planned part of the payload includes a “micropayload,” a small modular experiment that only requires a power source from our main system. A block diagram of our payload is shown below.



We have built a three-level mechanical housing to secure our electrical components within the canister. A 3D Solidworks model, and a picture of mechanical housing mounted on the canister plate are shown below.



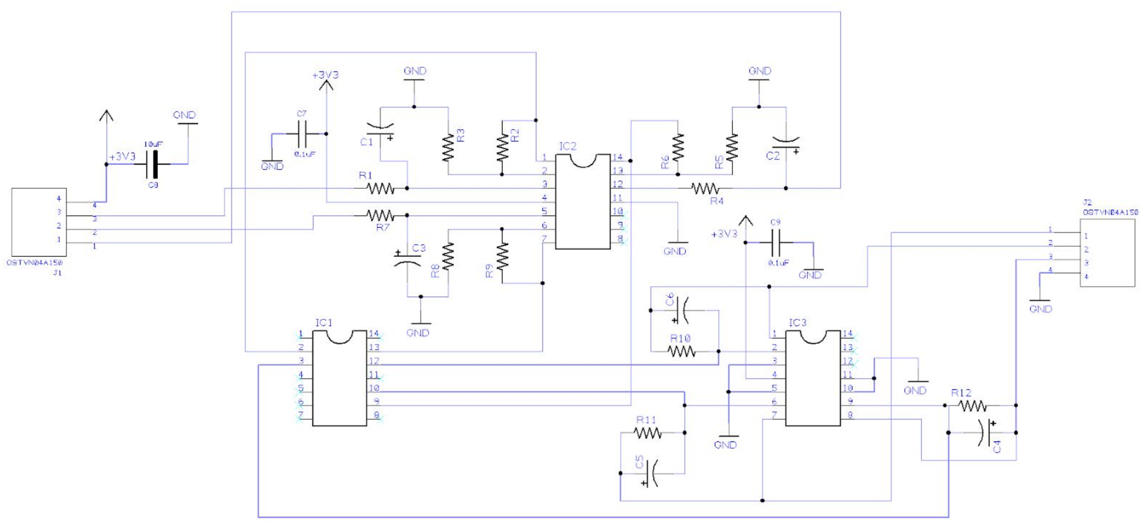




Each polycarbonate plate is identical in design. The dimensions are shown in the CAD drawing below. Every unit is in inches.

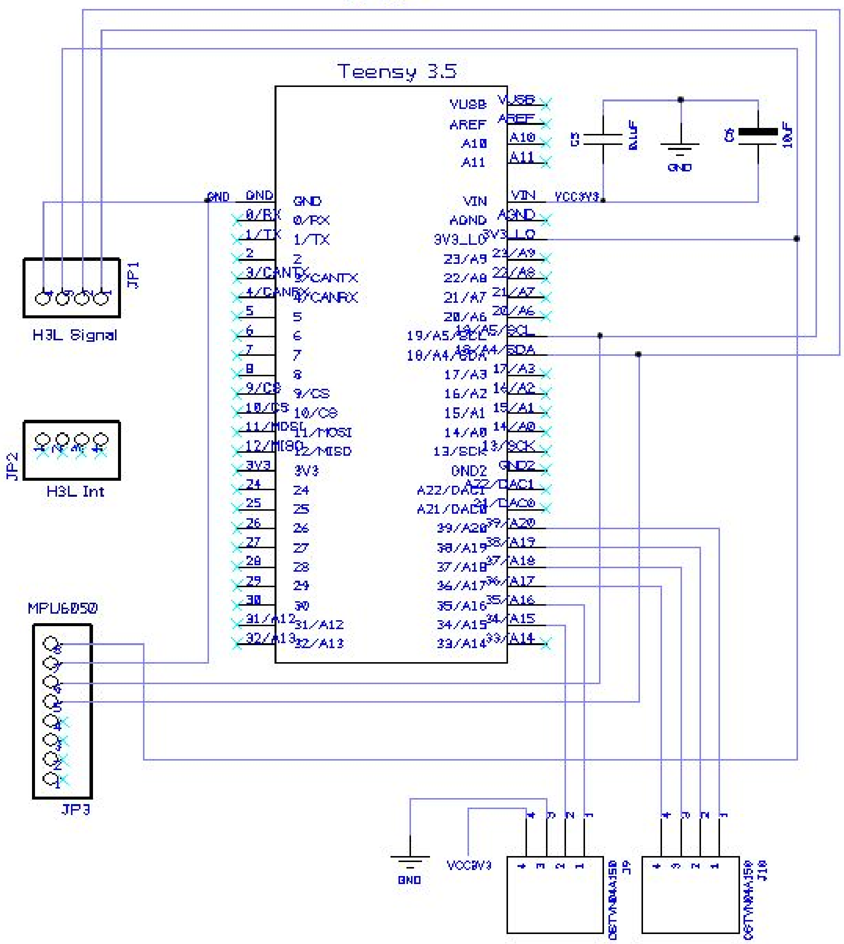
To support each plate we used 1 inch stainless steel standoffs and 3/32 inch tall hex nuts to support the extra height of the Power Supply/INS PCB. This means that the bottom layer has a height of 1 inch, and the middle layer has a height of 1.281 inches (one standoff plus 3 hex nuts). The resulting overall height of our mechanical housing plus the electrical components is approximately 3.5 inches. We had one inch of clearance between the top of our mechanical structure and the beginning of the West Virginia team's half of the canister.

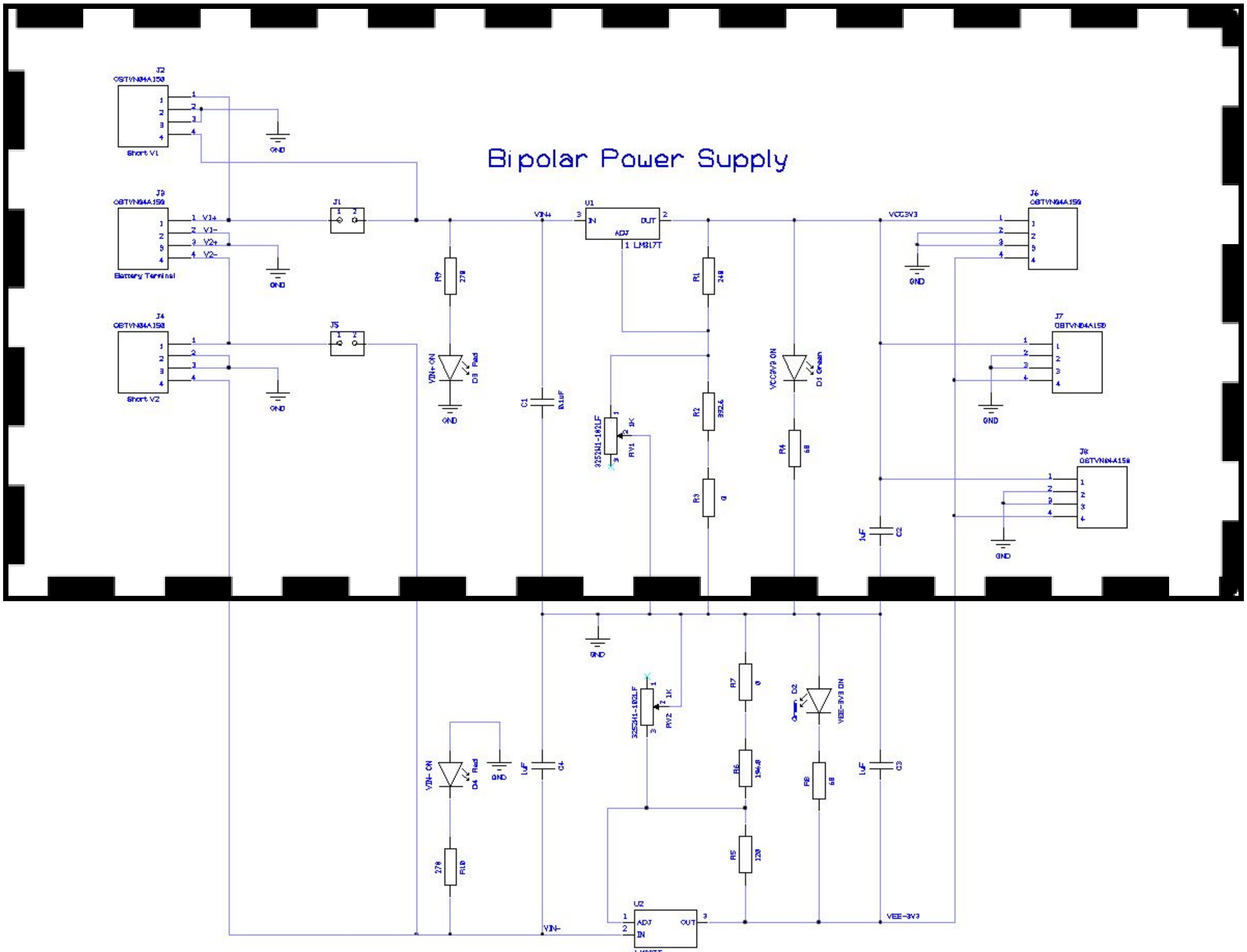
The ballast is housed on the bottom layer, the power supply/INS PCB and battery housing is on the middle layer, and the DUT PCB is on the top layer. A picture of the overall system is shown on the front page of this report.



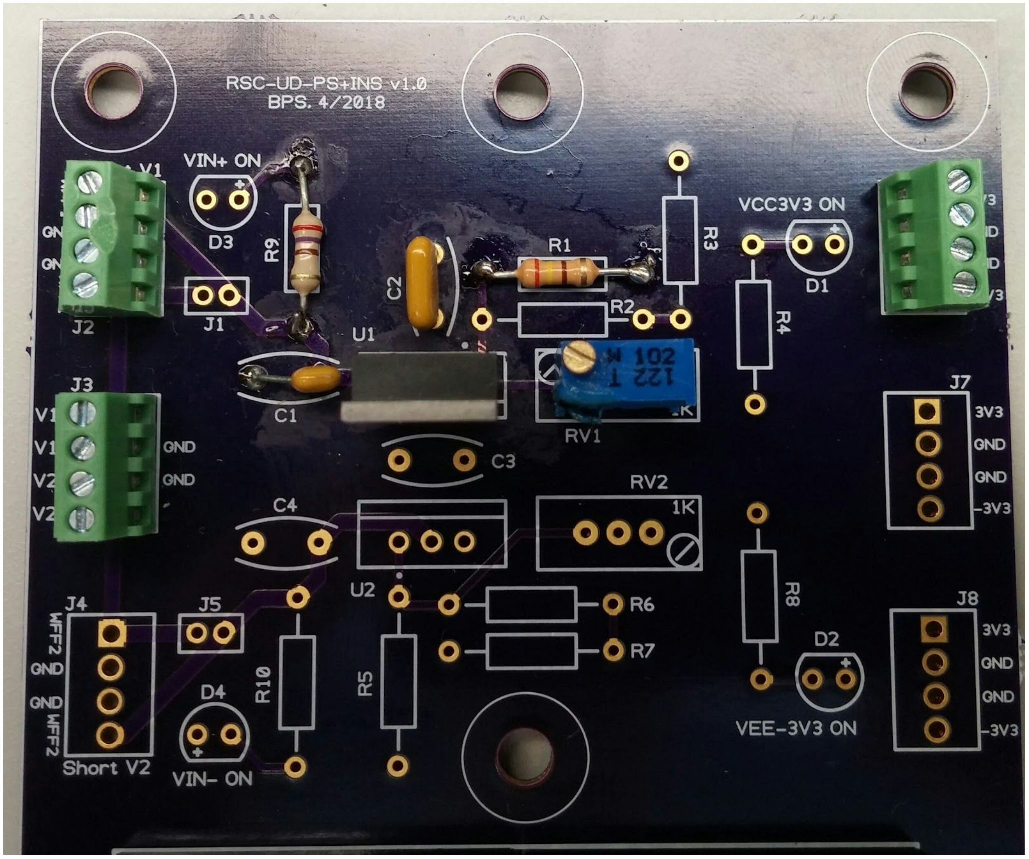
Shown above is the schematic for our DUT testing circuit. Below, on the next page, is the Teensy and INS schematic.

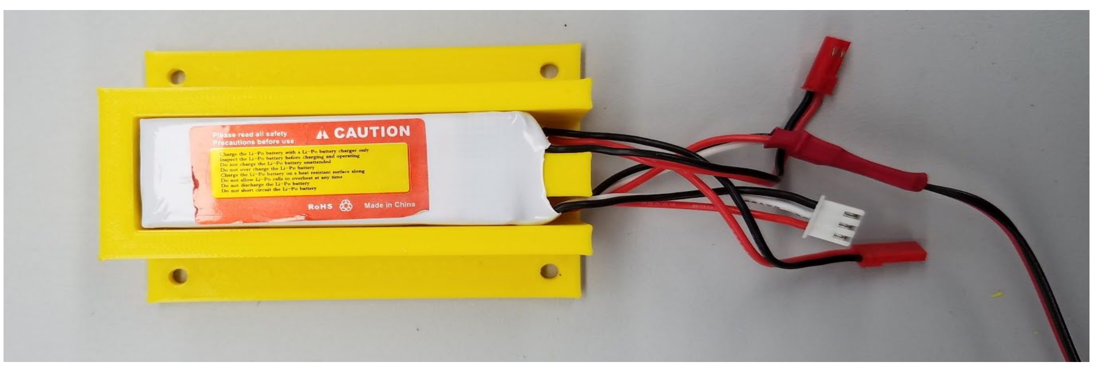
INS


Teensy 3.5
H3L Signal
JP1
JP2
H3L Int
MPU6050
JP3
GND
VCC3V3
J9
J10



The above figure is a picture of our power supply schematic. The black box indicates the +3.3 V power rail, while everything outside is for the -3.3 V power rail. Initially, we planned to use -3.3 V to bias the DUT, but we decided that this was unnecessary. As a result, we choose to only solder the components for the +3.3 V power rail. The soldered board is shown below.

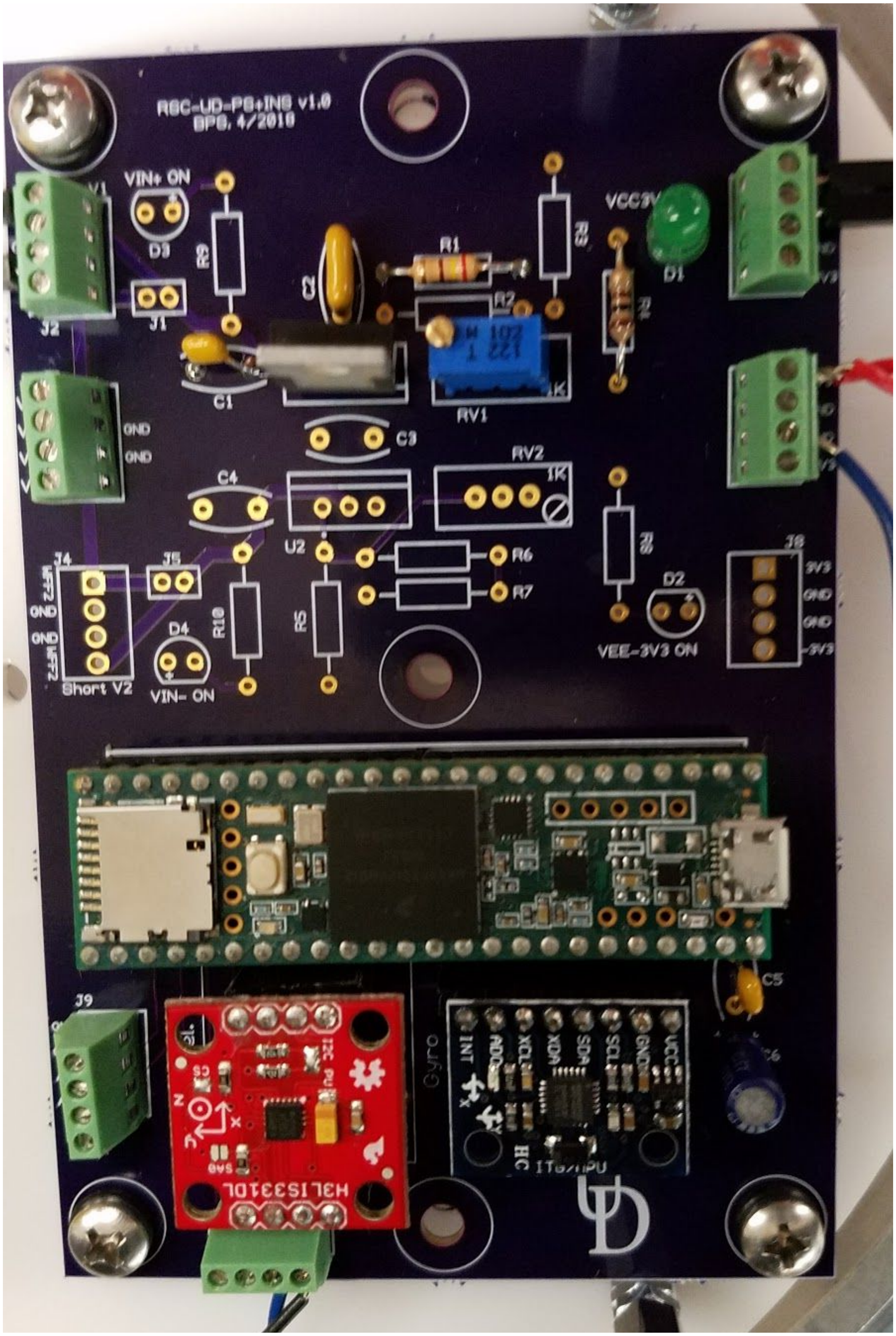


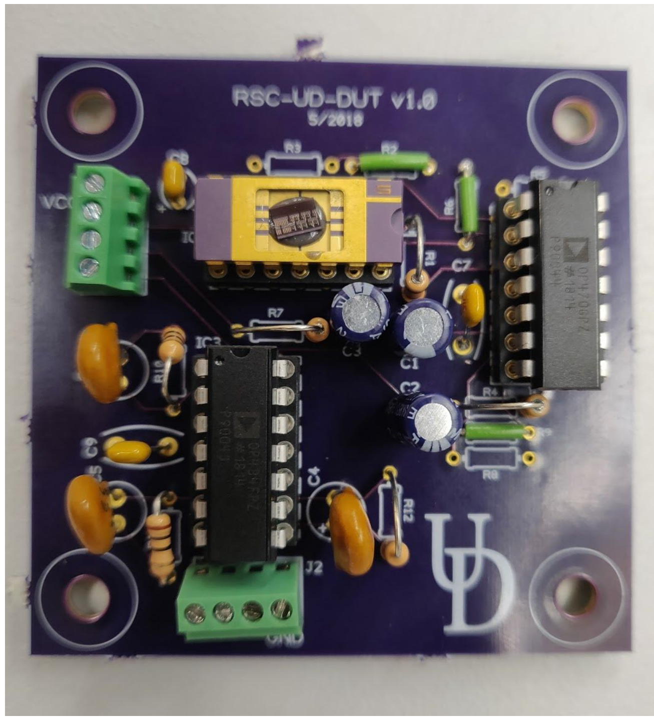


Above is a picture of our battery power source and the 3D-printed casing that was made to secure the batteries to the mechanical housing. The screw holes are 8-32 standard thread size. The housing dimensions are 3.6" by 2.5" by 1.1".

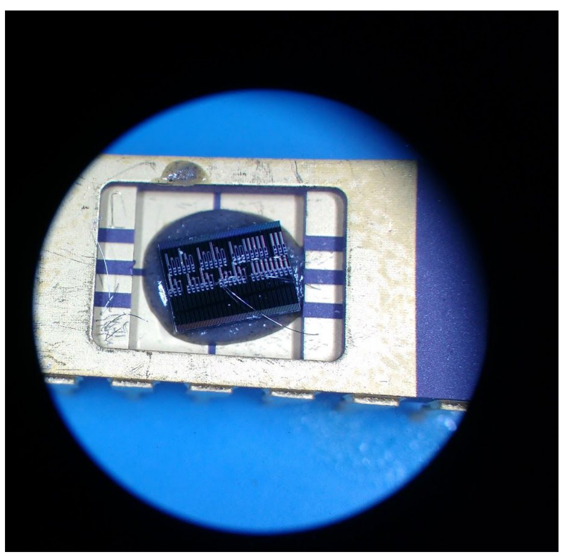
For print settings, a 50% infill and a 0.2 mm layer height was used. For a lid, we used masking tape. This will involve less hassle than having an additional 3D-printed lid screwed onto the battery housing. In addition, male to male jumper wires were used to connect the battery `connectors to the screw terminals on the power supply PCB.

Below is the assembled and soldered Power Supply/INS PCB.





Above is a picture of the completed DUT PCB. The diodes were wirebonded with the assistance of UD Nanofabrication Facility. The diodes were bonded using a wedge bonder and 23 µm thick gold wire. This proved to be a difficult task due to the small size of the wire and the bond pads, which were 50 µm square. A picture of the wirebonds under a 16x microscope is shown below.



The bonds can be seen in the lower right hand corner. We were only able to successfully bond one device; failed attempts to bond the devices can be seen in the lower left hand corner of the device.

Diode forward bias voltages are generated using an RC rectifying circuit to convert the PWM output to the diode. This voltage is then applied to the diodes. Output current from the diodes are then fed into a transimpedance amplifier which converts the current to a voltage the Teensy can sample. There is an additional amplifier (not pictured) that will be added to the device in order to amplify changes in the current to more measurable levels.

Special consideration was given to the choice of amplifier used in our device. Early tests with readily available amplifiers proved to introduce too much noise into the measured voltage in the end. Therefore, we switched to using junction gate-field-effect transistor (JFET) input operational amplifiers for our measurement circuit.

Our payload's software samples the forces on the device from the INS and the diode output current. The Teensy communicates with the INS (accelerometer and gyroscope) using the I^2C protocol. Use of this protocol was determined by our choice of hardware.

Currently, our mechanical housing and electrical components combined weighs 2.200 lbs., with the canister weighing 8 lbs and 15.5 oz. West Virginia's payload currently weighs 3.976 lbs. We plan to add 30 pieces of ⅛" x 4" x 1" steel ballasts (each weighing 0.142 lbs.) to our payload to help bring the overall canister to 20 lbs., while the West Virginia team will add the corresponding amount of weight to finally get our canister to the required weight. We plan to add ballasts in 6 stacks of 4 and 2 stacks of 3 on the bottom plate. In the case that the center of gravity of the overall canister is too low, we will drill extra holes on the top housing to allow us to move some ballast onto the top plate.

Our launch fee was generously contributed by the Delaware Space Grant Consortium, for which we are deeply grateful.

For parts and construction, our budget was nominally $200. However, our budget eventually went over this amount as many of the parts we needed are not sold in the small quantities that we required. As such, the parts for the mechanical constructions ran close to $300 in total. Device packaging materials cost $250 due to their specialized nature and the fact that we needed to make a minimum order. Financial support was provided by Dr. Chase Cotton and Dr. Tingyi Gu for this project.

4.0 Student Involvement

Our project was developed and tested by four students: Jingcheng (Aric) Lu, Ryan Beneck, Benjamin Steenkamer, and Anton Vasilyev.

Jingcheng (Aric) Lu is an Electrical Engineer and was the overall team leader. He was in charge of communicating with the West Virginia team and the RockSat-C Program, and designing the DUT board.

Ryan Beneck is an Electrical Engineer and was the designer of the INS board.

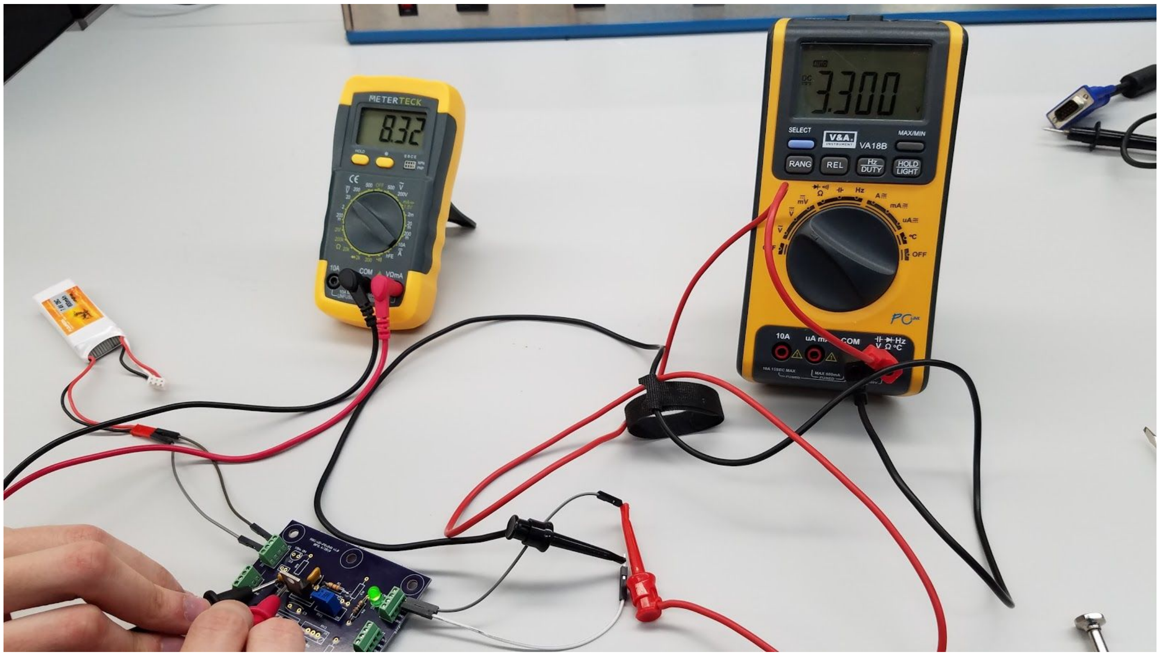
Benjamin Steenkamer is a Computer Engineer and was the designer of the power board. He also helped with finalizing the designs of the INS and DUT boards.

Anton Vasilyev is an Electrical Engineer and was the designer of the Mechanical Housing.

Work on presentations, design updates, and testing was shared among each of the group members.

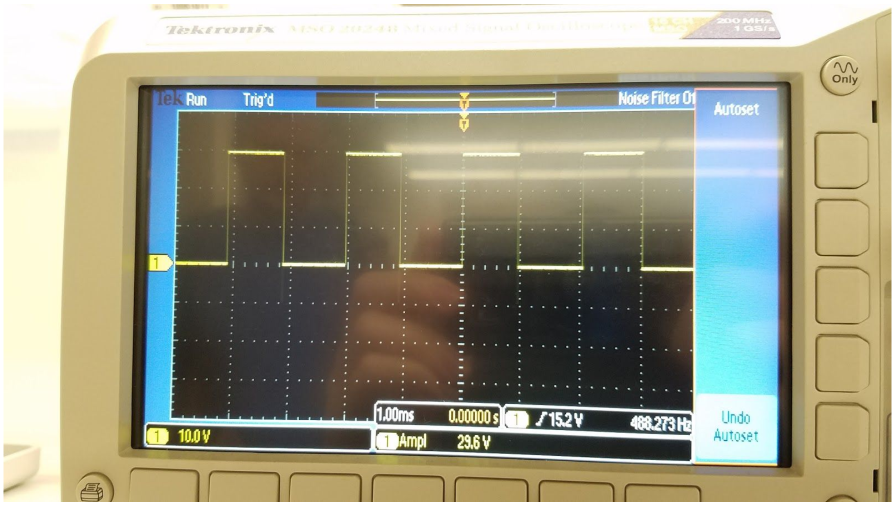
5.0 Testing Results

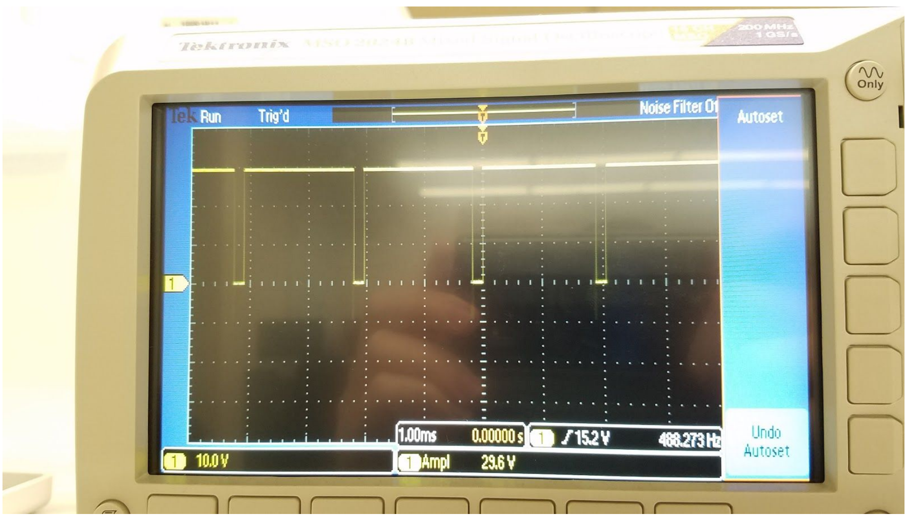
A. Integrated Subsystem Testing Results

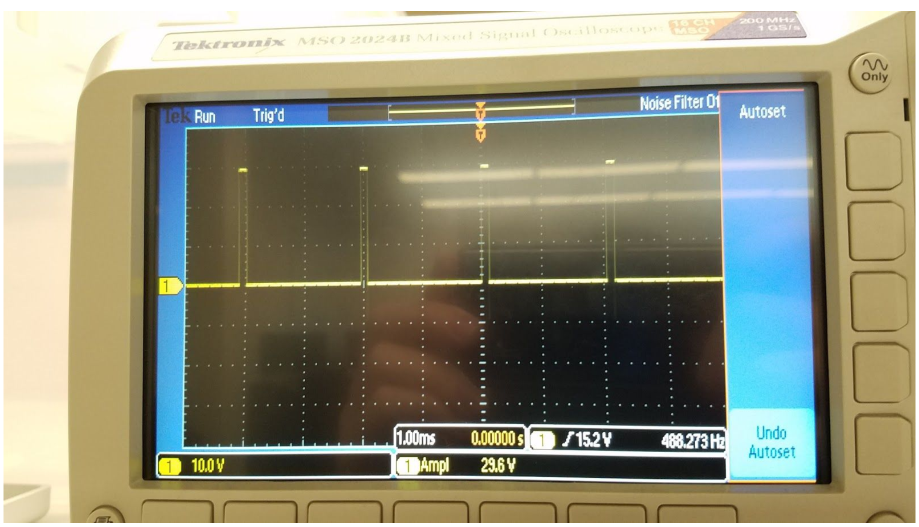


Above is a picture of Ben testing the voltage and capacitance properties of the soldered power supply. We were able to confirm that we correctly soldered the components onto this board.

We next confirmed that the Teensy could be run off the power supply and battery. After this was verified, we wanted to see if the Teensy would be able to ramp through 0 to +3.3 V when running off the supply. The Teensy does this voltage ramp to produce the input voltages for the DUT IV curves. We were able to confirm that it is able to ramp to just about 3.3 V, but our instrumentation was not accurate enough to guarantee that this is the case. Below is a series of images from an oscilloscope which shows our device ramping up to ~3.3 V and then starting over at 0 V once the goal voltage is reached. The Teensy uses PWM waves to achieve this voltage curve.

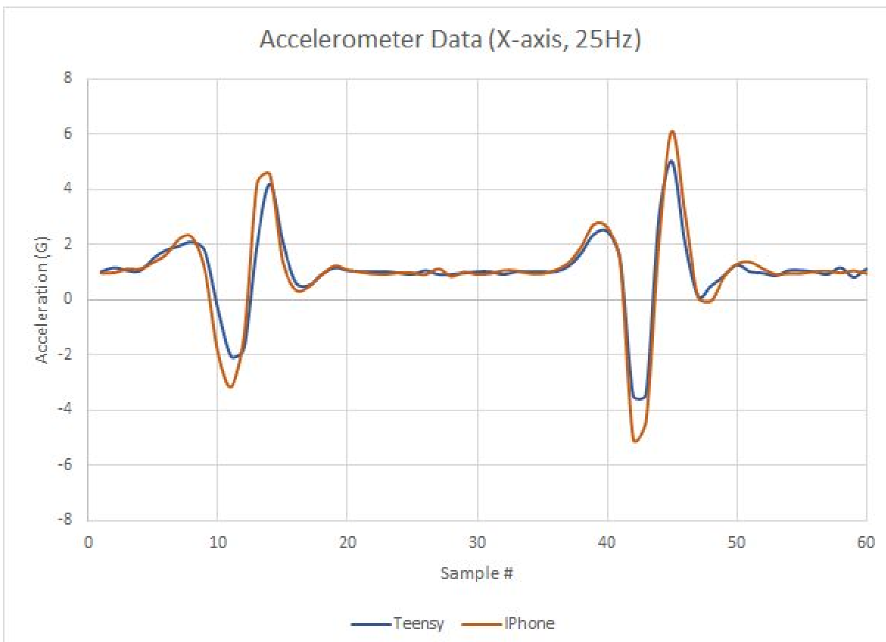

Tektronix MSO 2024B Mixed Signal Oscilloscope
Run
Trig'd
Noise Filter Of
Autoset
Undo Autoset
1.00ms
0.00000 s
15.2 V
488.273 Hz
10.0 V
Ampl
29.6 V


Run
Trig'd
Noise Filter Of
Autoset
Undo Autoset
1.00ms
0.00000 s
15.2 V
488.273 Hz
10.0 V
Ampl
29.6 V


Tektronix MSO 2024B Mixed Signal Oscilloscope
Run
Trig'd
Noise Filter Of
Autoset
Undo Autoset
1.00ms
0.00000 s
15.2 V
488.273 Hz
10.0 V
Ampl
29.6 V

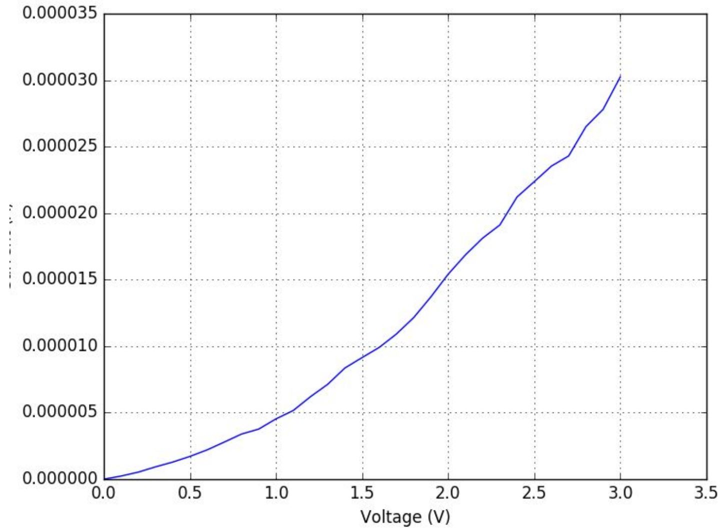
After testing the power supply and INS subsystem, we physically moved the system to see the corresponding acceleration and gyroscope data appear live on a computer. We can sample the sensors at a maximum of 100 Hz accurately, but due to processing time, we will not be able to record to the microcontroller at exactly that frequency. However, this will not negatively impact our experiment and was expected. Data is recorded to a microSD card and stored as a text file. We do not anticipate that we will run out of space on the card during the flight because we are recording at a low enough frequency and text files require little space.

We also tested the accelerometer accuracy by measuring it against a known, calibrated accelerometer. The accelerometer we tested against was the built-in accelerometer on an iPhone. The results of this test are shown below.



As shown in the graph above, there is strong correlation between the two accelerometers. The accelerometer we are using for the payload (shown in blue) shows small defects in at larger accelerations. We think this is due to a mismatch in the sample times and rates during the test. Additional testing with the accelerometer has shown that it is capable of measuring much larger forces on the order of +/- 25G, so we are not concerned about the accuracy of the accelerometer.

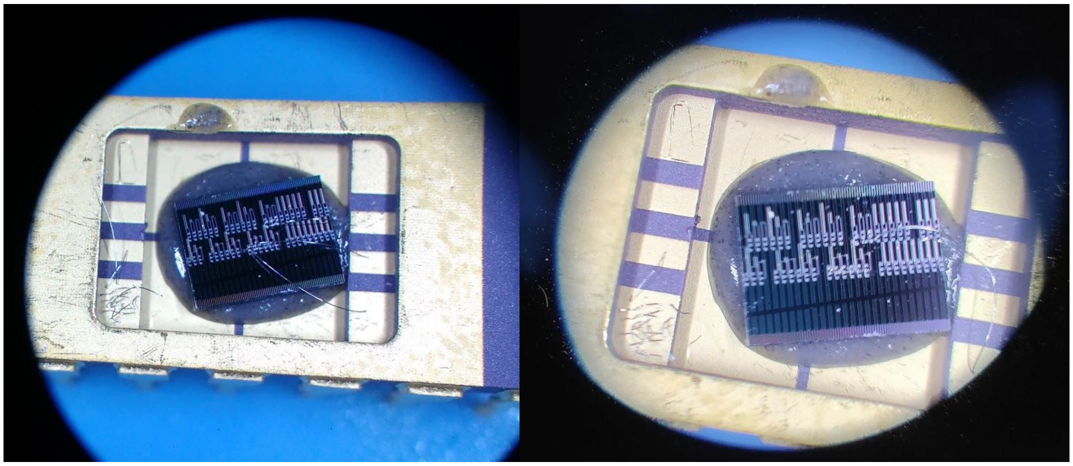
The forward bias IV curves of the device were characterized using a Keithley multimeter to provide a bias voltage and sample the forward current. A typical diode IV curve from our testing is shown below.



Units on the vertical axis are in Amps. As shown, these diodes have a forward bias current on the order of microamps. However, there is an issue with the data: the photosensitive nature of the device means that exposure to light will change the diode IV curves. Unfortunately, we were not able to control diode light exposure during the test due to the limitations of the test environment. However, light exposure moves diode IV curves down. Further tests have shown that the curve shown above represents a fairly ideal curve with minimal effect from stray light. It is unknown how the diodes will specifically behave in the launch environment.

B. Full Mission Simulation Results

During preliminary full mission testing on May 25, 2018, the DUT suffered damage to its wirebonds. The break occurred before forces were measured, so it is unknown what caused them to break, but a quick discussion has yielded lessons for the future. A picture of the damage is shown below to the right, along with a copy of intact wirebonds from above shown below to the left.



As shown above, the wirebonds broke at the gold pad of the device. This is indicative of poor adhesion between the wire and the pad. We speculate several reasons for this. First, the bond pad could have had a layer of oxidation or other contaminant which lowered the adhesion between the bond and pad. Before bonding, we had cleaned the surface of the pads using isopropyl alcohol to attempt to prevent this. Further study is needed to understand proper care of packages and devices.

Additionally, the small size of the bond may have factored into the breakage. Typical bond sizes for 23 μm wires are on the order of 40 μm square. Smaller bonds sizes inherently have lower adhesion.

This circumstance is not fatal to our project. It is still unclear if the diodes themselves will survive launch conditions. A visual inspection of the diodes has given us confidence that the devices themselves are still functional, which will be confirmed before the launch date with additional testing.

On June 3, 2018, the INS and DUT software were combined on the Teensy, and it now outputs 9 values total: sample number, three axes of linear acceleration, three axes of rotational acceleration, diode input voltage, and diode output current. The DUT circuit was tested with this software and it performed as expected. However, this test was performed before the gyroscope was connected.

Sample data is shown below.

```
520;-0.78;0.24;-1.27;0.00;0.00;0.00;145;8;
521;-0.68;0.15;-0.64;0.00;0.00;0.00;108;9;
522;-0.59;0.10;-0.49;0.00;0.00;0.00;85;10;
523;-0.59;0.15;-0.49;0.00;0.00;0.00;84;11;
524;-0.59;0.29;-0.15;0.00;0.00;0.00;96;12;
525;-0.68;0.15;-0.24;0.00;0.00;0.00;113;13;
526;-0.98;0.15;-0.10;0.00;0.00;0.00;112;14;
```

The data format is contains 9 different measurements in each line. The first value is the sample number. The next three are accelerometer measurements, and the next set of three (shown above as 0.00's) are the gyroscope measurements. The gyroscope was taken out to easily differentiate its data values and the accelerometer data. The last two data points are the output voltage and input voltage for the diode. The input value can be converted to a PWM duty cycle by the formula $duty\ cycle = input\ value/255$. The diode current can be recalculated from the stored value by $I = ((data * 3.3/1024) - 1.65)/200)$.

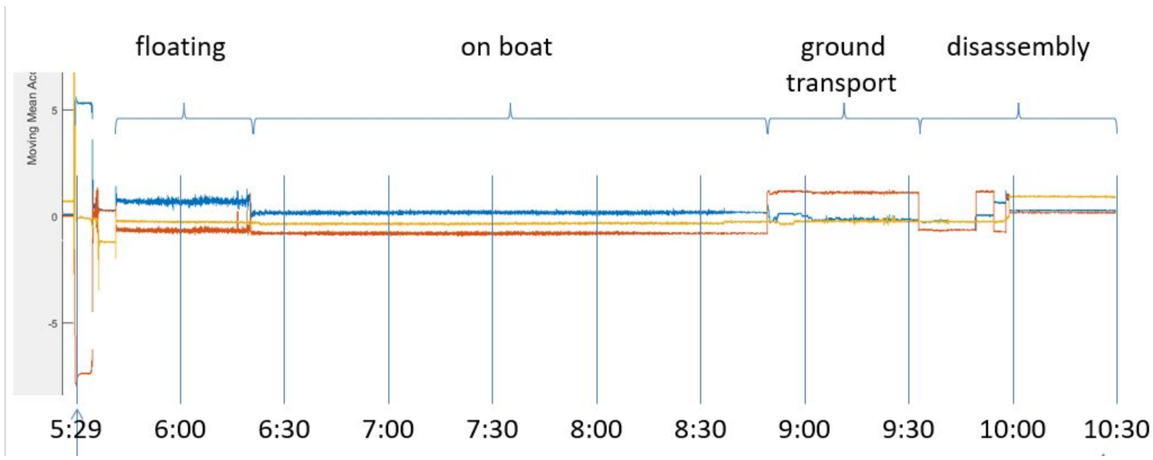
We had electrical issues with our PCBs and had difficulty assembling the full system to test it together. The primary issue was that our boards for the Power Supply and INS kept getting shorted as we soldered components to them. On June 4, 2018, we were finally able to solder most components necessary to begin a full mission test. At that time, only a few minor additions were needed for our payload to be flight ready. The lack of these additions, such as staking wires and connections, would not influence the outcome of a system performance test.

On June 4, 2018, we performed a full mission simulation running both the DUT and INS boards together. The first few simulations were run for 10 to 15 seconds each to check that our devices were working and that everything followed the requirements laid out in the RockSat-C User's Guide. We measured the total current draw from the batteries to be 80 mA, which is higher than previously estimated. This is because we had soldered in an indicator LED to help us debug the circuit and provide a visual aid for us to work with. The total current draw is low enough that it is not necessary to remove the LED before flight. We estimate that the batteries will last 10 hours given the current draw of the circuit.

Additionally, on the same day, we performed a longer test of approximately 2 hours to acquire more sample data, verify performance characteristics, and test the longevity of the battery.

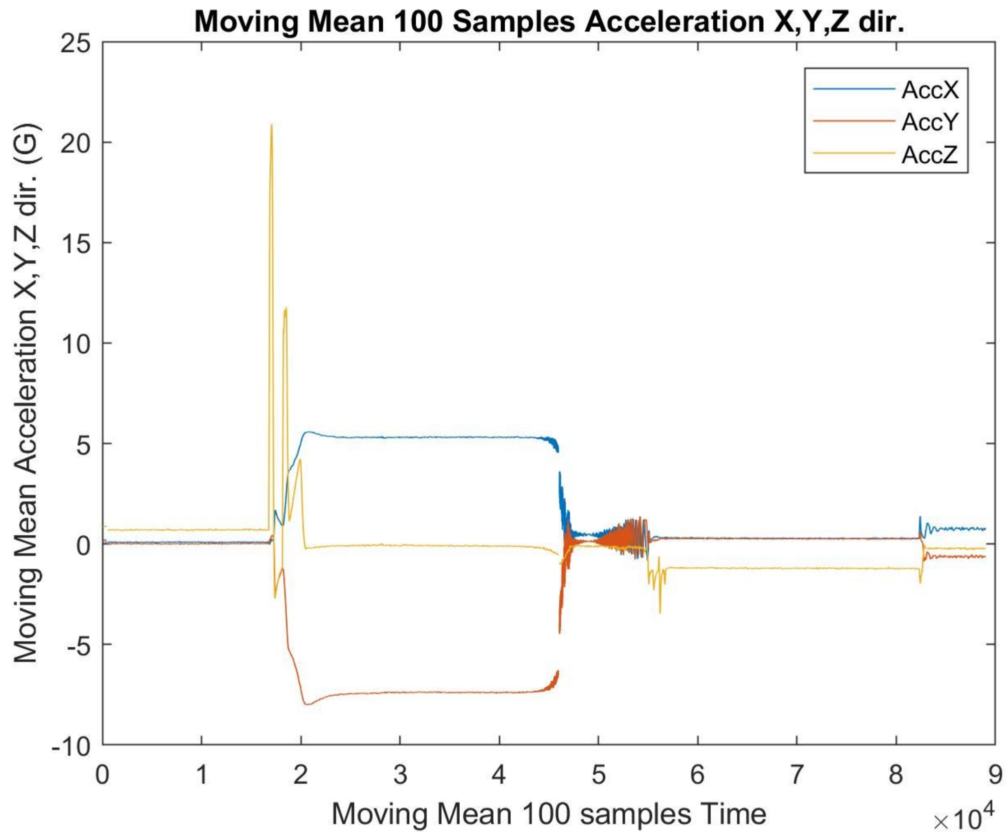
6.0 Mission Results

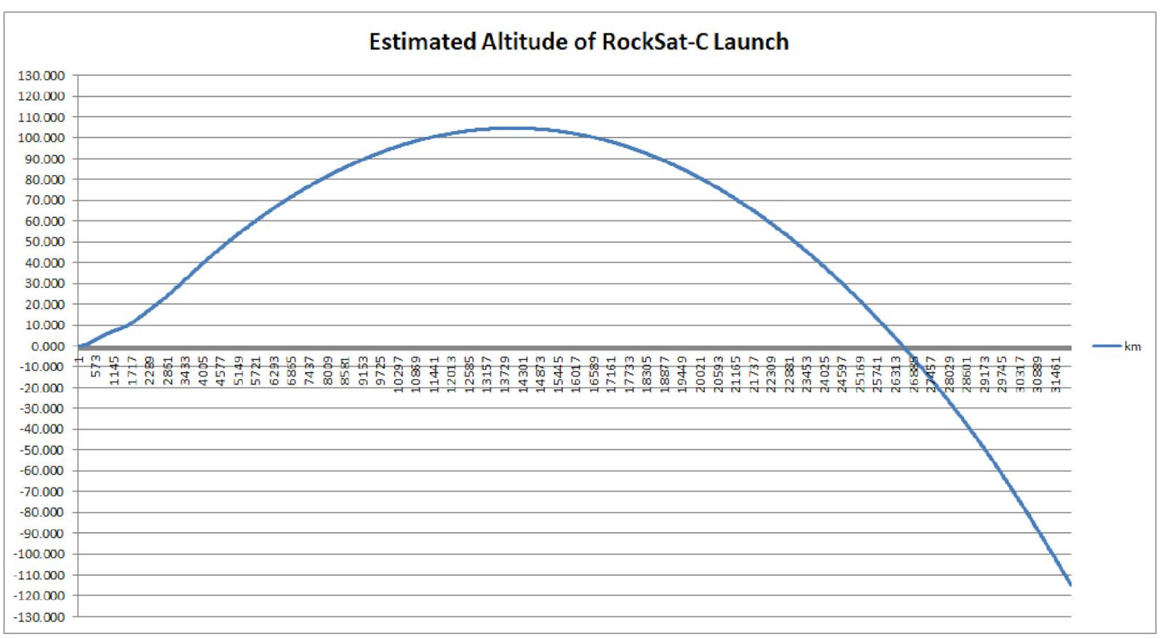
Our payload worked mostly as intended and we were able to obtain a large amount of data. We had nearly 2 million data points, each of which contained three acceleration values, three gyroscope values, and two diode voltage values. Since the payload was on for over four hours, most of our data is from after splashdown when the rocket was stationary in the ocean, on the boat, and being disassembled. We mapped each section in the graph below. Each color represents a different acceleration axis: yellow is Z-axis, blue is X-axis, and orange is Y-axis.



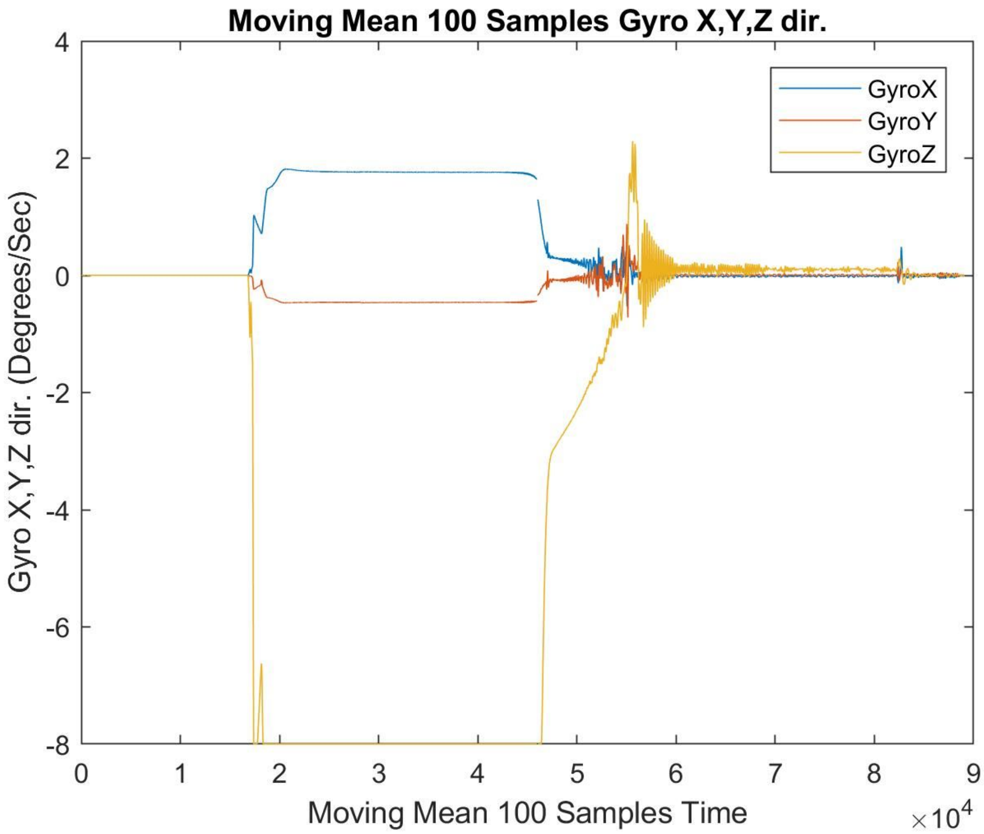
During the next step of analysis, we cut out the section that did not include the launch and plotted our acceleration and rotation in MatLab. In addition, we employed a moving average for each one hundred samples in order to make the data more readable. The acceleration results are shown below on the next page.

There are two sharp spikes in Z-axis acceleration after a few minutes. This represents the initial first and second stages of launch. Based on the accelerations the device experienced, we were able to estimate that the rocket reached an apogee of 104.7 km. The estimated altitude with respect to time in seconds is shown below. According to NASA the actual apogee was about 121 km; a graph of the actual altitude vs distance can be found in appendix D. Just from this result, we can conclude that our acceleration measurements where reasonably accurate. However, we do not have the trajectory of the actual launch to determine if our predicted trajectory is a good estimation. A potential reason why our data does not match up with NASA's is because we do not know the exact time intervals during data entries. This causes our calculated velocity, and hence position, to be slightly off. In a future experiment, we will need to research ways to keep track of time with each recorded entry to guarantee accurate location calculations.


Moving Mean 100 Samples Acceleration X,Y,Z dir.
AccX
AccY
AccZ
Moving Mean Acceleration X,Y,Z dir. (G)
Moving Mean 100 samples Time
×10^4


Estimated Altitude of RockSat-C Launch
km

The gyroscope data is shown below.



Our gyroscope could not handle the forces in the Z-axis as it maxed out for a significant portion of time. This means that the rocket was spinning rapidly while in flight, which is what should happen. But despite this setback, the combination of a large and small reverse spin in the X and Y axis respectively indicate that the rocket was rotating in a way that ensures it maintained a parabolic trajectory. In addition, it is still possible to calculate the Z-axis rotation from the X and Y axis data. From this we can generally say that the X and Y axis gyroscope were successful in measuring the rotations of the rocket.

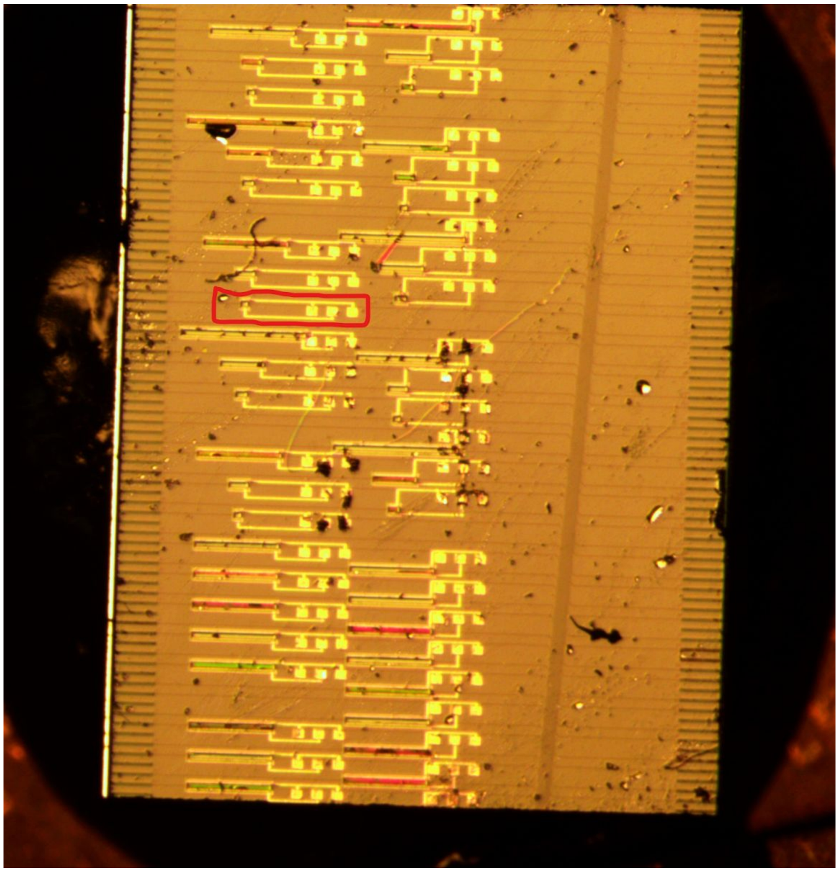
There was a period several minutes after launch that the payload turned off and then back on again. We do not know how long it was turned off for. However, this should not negatively affect the results because it occurred so late in the flight. We know this because in the INS data there 4 sections. The first two are 1000 and 500 samples respectively. Those are tests that are not relevant. The next section is 45500 samples (~7.5 minutes) and the one after that is 1588500 samples (~4.4 hours). It may have turned off a bit during flight. The 7.5 minute section contains a large spike in Z-Axis acceleration, so that appears to be the initial launch. From this data we are able to conclude that the device was at rest for 2.6 minutes before launch and it turned off within 4.9 minutes into launch. From this we are able to conclude that it turned off just during the big spike in the X and Y axis, around 4.5 * 10^4 samples in. Given that this large change occured right after the device is experiencing zero gravity in the Z-axis, we believe that this large acceleration is due to the device experiencing reentry into Earth's atmosphere. It is possible that the device turned on and off due to the large forces that it underwent during reentry. In addition, it possibly turned on and off due to the rocket's power supply restarting during this period. We reason this is possible because our design could not include a latch to keep our device on separately from the rocket. To prove this, we would need to get confirmation from the RockSat-C program to see if the rocket did turn on and off during launch or reentry. But, as of now, we are uncertain what was the actual reason behind the power failure.

Following landing, it then turned on again after an indeterminate time. But that portion of the data was not a main focus of our experiment.

Since we are not able to conclusively say how long the device was turned off for, this causes our altitude measurement to be off by an unknown margin. In addition, we do not have any specific recommendations on how this can be avoided in the future. If this was due to the rocket power supply turning off and on, then this could be rectified if we moved our project to RockSat-X to be able to latch the power supply switch. This would allow our device to run independently of the rocket's power regulators.

One other problem we encountered was that the data recording frequency was most likely lower than the 100 Hz. Due to the Teensy 3.5 processing so much data, it slowed down. We found that the time the payload spent turned on, assuming 100 Hz, is shorter than the actual time it was on in NASA's timeline. This should not have too much of a negative impact on the accuracy of the data, but it is still an issue that should be brought up.

Our analysis shows that at least some of the DUT diodes survived the launch. Below is a image of the device after the launch.

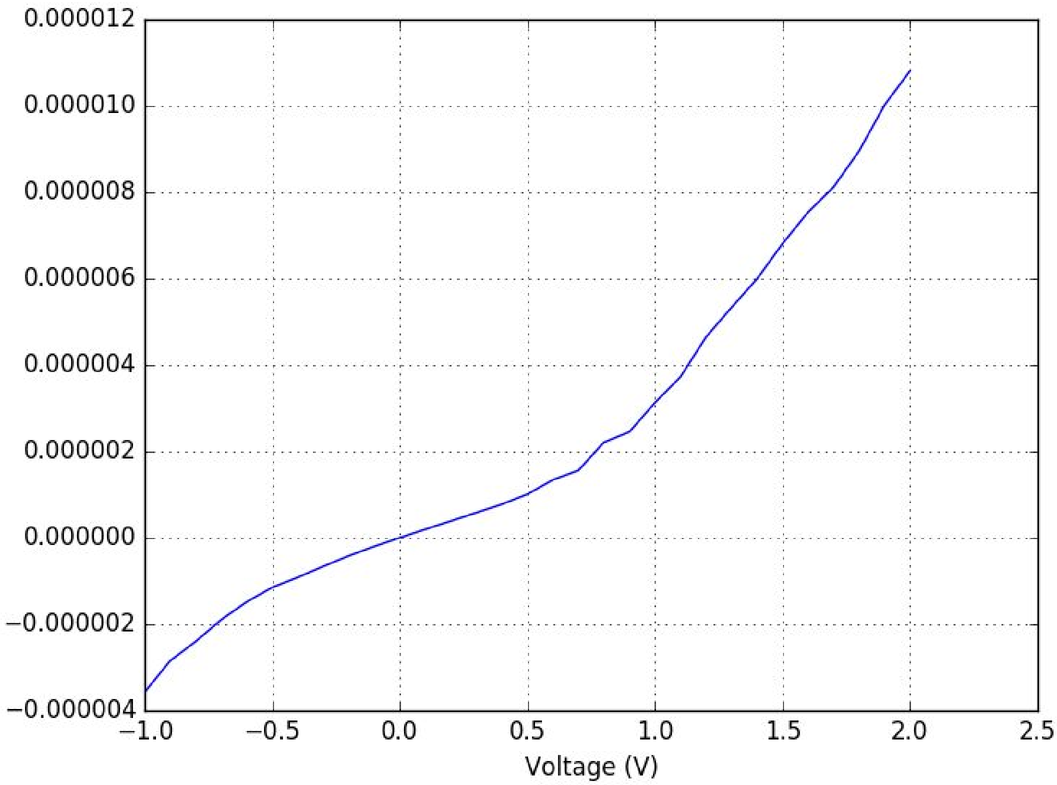


The device appears to be in bad shape. We can see the damage done to the device from the dust and the wirebonds ripping off during pre-testing. The diode boxed in red was tested to verify that a diode works, as many of the devices we had tested earlier are no longer testable. The black spots on the device are areas where the device has either been gouged out or ripped off by impacts or fabrication issues.

An interesting point about the device is that the wire bonds held to the package throughout the flight. This suggests that the wire bonds are in theory capable of surviving the launch. We have not been able to investigate the cause of the initial failure, however these results suggest that these devices can be successfully wirebonded in the future. Better operating and handling procedures would need to be in place to mitigate damaging these devices.

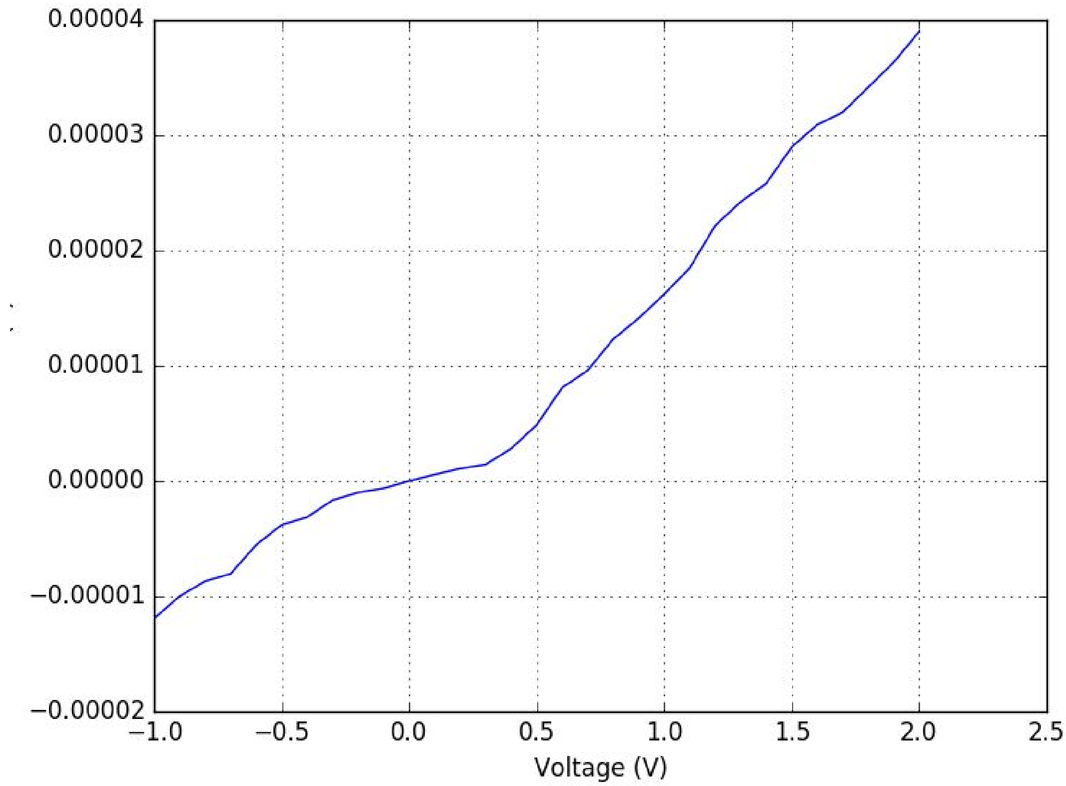
Furthermore, several devices are shown to have taken on a green or red color within the suspended silicon matrix. It is speculated that these diodes are broken, as attempts to measure the IV curves of these devices failed to yield any measurable data. We believe the red and green colors are a result of the suspended silicon matrix breaking and falling into the air gap at an angle such that red and green light is reflected.

A plot of the IV curves of the tested device is shown below.



The diode shows typical behavior that was seen in the other devices that were tested before the launch. This device operates at a slightly higher current than many of the other tested devices, but the data are in line with our expectations for a diode.

Due to the fact that this device was not tested before the launch, we cannot draw conclusions for ionizing radiation exposure. Furthermore, subsequent tests of the devices yield differing IV curves, despite attempts to control light exposure of the diode. Below is data taken immediately after the data shown above.



The second measurement of the diode shows much higher currents for given voltages than the first measurement, shown previously. The reason for this is still unknown. We speculate that our testing setup is imposing a charge onto the device, which is held between tests and influences subsequent tests. However, this does not change the fact that several devices survived the launch.

7.0 Conclusions

After comparing our INS data to the expected path of the rocket, we have found our measurements to be mostly accurate. We were able to successfully sample throughout almost the entire launch. Some problems we encountered were that there was a short period where the payload turned off and then back on again, the data was being recorded at a lower rate than the proposed 100 Hz, and the gyroscope could not effectively measure the Z-axis rotation. Other than these issues, the INS system worked well. Our data lines up favorably with how we expected the rocket to perform in flight.

Our analysis of the diodes performance showed that at least some of the devices survived the flight. However, the device took heavy damage during the pre-flight assembly, testing, and flight itself, limiting the scope of our conclusions for these devices. However, we can confidently say that these devices can be designed in a manner that is likely to survive flight.

8.0 Potential Follow-on Work

Currently, work is being done to develop these devices to use them in a mission to the International Space Station (ISS) and further investigate the applications of these devices. This work is currently being done by Dr. Tingyi Gu and her research group at the University of Delaware. We hope that our devices and work will be useful in this endeavor. In particular, one method to avoid many of the problems we faced would be to add a removable lid to the device to protect it from external damage.

Additionally, our results still leave several open questions about the performance of these devices and the effect of the launch on them. Further work on these devices is necessary to fully understand the data we see, specifically the reasons for the variability in the diode IV curves. We hope to assist in this process in the near future.

Finally, we have demonstrated a path and outline for future RockSat missions from the University of Delaware. We are currently working towards building support and the organization for a sustainable UD RockSat team, for either RockSat-C or -X.

9.0 Benefits to Scientific Community

The diodes used in this experiment have applications in radiation detection technology and may be used on the ISS in the near future. We now have a better understanding of the mechanical forces that the diodes are able to endure as well as the IV curves that should be expected. We can also confirm that the diodes are capable of mechanically surviving a launch.

Additionally, we hope that our work can be used as a resource for future experiments requiring wire bonding. Wire Bonding to pads 50 µm square in size is rarely done due to the difficulty of the task and ease of designing larger pads with lower failure rates. However, it is possible to design such devices provided that great care is taken to ensure its success.

Lastly, we have designed an overall experiment which can be used as a template for future University of Delaware teams to begin designing their own RockSat-C experiments.

10.0 Lessons Learned

One main issue we had was a lack of diverse skill sets on the team. All of us were either electrical or computer engineers, so we had trouble with the mechanical aspects of the project.

We made the mistake of poorly positioning our ballast as well as not securing our screws before the initial vibration and spin testing. After those tests, our payload mostly disconnected from the canister and was dangling by one screw. We were able to fix the problem by moving all the ballast closer to the canister, using longer threaded screws, and applying screw sealant to every connection. In addition, it would have helped if we had been using power tools instead of manual ones. Fortunately, after performing these fixes, our payload held together during and well after the launch.

While our payload worked mostly as intended, there were many inefficient aspects of the design that we would improve upon if we did this project again. Our power board was designed with a negative power supply, but we did not need to use it. Also, it was inconvenient to have to connect the two PCBs with jumper wires. It would have been better to design a payload that only used two mounting plates and one PCB with no wasted components.

Additionally, integrating the design of electrical components and mechanical housings would have enabled us to greatly simplify and clean up the design of our payload. One issue we had was the use of many loose wires attached to screw terminals in our payload. Properly designing or integrating a connector into our system to run data and power between boards would have simplified assembly and made debugging the system easier.

Finally, establishing clear operating procedures for assembly and testing would have clarified many of the issues we faced. Too much time was spent discussing the correct method to assemble the device or how much clearance each part has. Defining all of the mechanical, electrical, and testing responsibilities beyond what is outlined and required by RockSat-C would have strongly aided our team as we moved closer to the launch date.

11.0 Appendices

Appendix A: Integration Procedure

1. Remove SD card, delete any files on the card, and put the SD card back on the Teensy.
2. Charge the batteries. (Needs to be done well in advance)
3. Place package of suspended silicon diode onto PCB
4. Confirm that all screws and standoffs are secure on the payload. Apply hot glue to all screws, terminals, vertical standing PCB components, and wire connections.
5. Confirm the all electrical connections are secure and that the device runs correctly.
6. Integrate our payload together with West Virginia's payload into the canister. Check to see if center of gravity is met. If not change position of the weights until the center of gravity is centered.

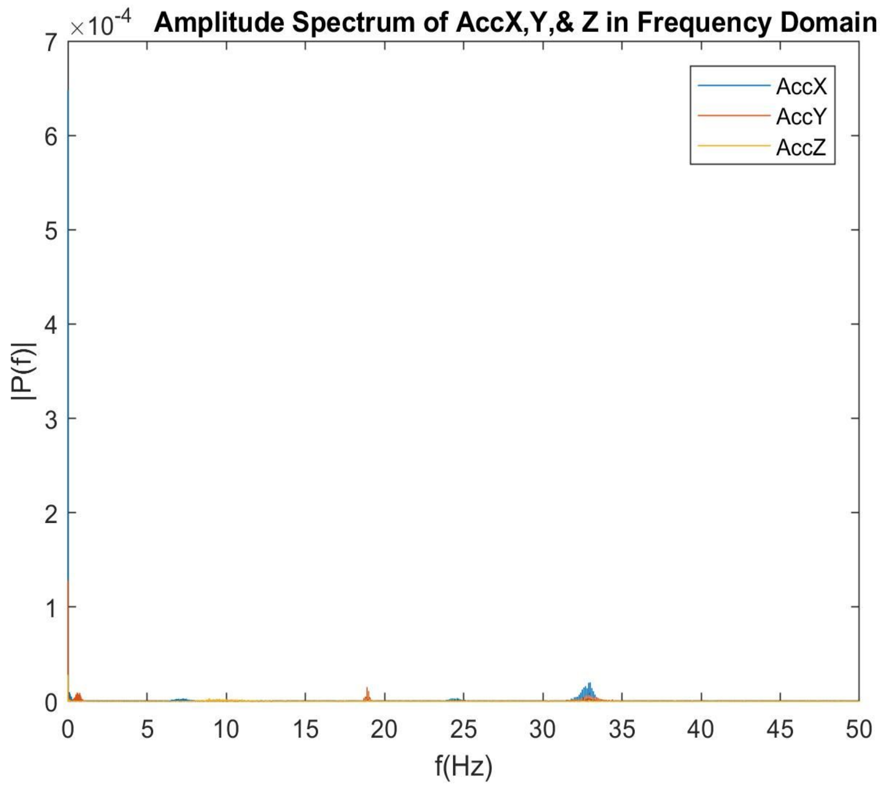
Appendix B: Tools/Parts for Integration

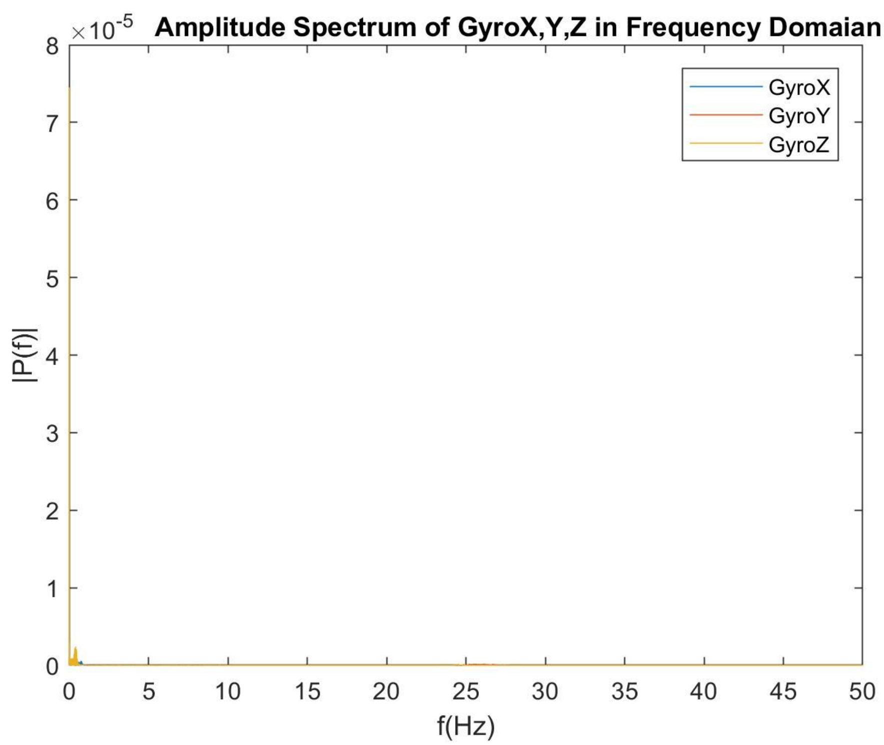
- Tools
    - Allen wrench (9/64 inch)

    - 1/4 inch wrench
    - Small flathead screwdriver (for screw terminals)
    - Wire strippers
    - LiPo battery charger
    - Soldering iron
    - Desoldering equipment (wick and plunger)
    - Hot glue gun and glue sticks
    - Multimeter and prods
- Parts
    - Spare, 24 AWG solid wire
    - Male-male connectors
    - Female-female connectors
    - Duct/masking tape
    - Extra screws, standoffs, nuts, lock nuts, washers, etc.
- Other
    - USB to mini-USB connector for Teensy
    - MicroSD card
    - SD card adapter or microSD reader

Appendix C: Fourier Transform Analysis of 3-axis Acceleration and Gyroscope Data

In addition to the data analysis we did for our primary research goals, we also took the Fourier Transform of the data to see if the rocket vibrated at any frequencies during flight. The graphs of the Fourier Transform of the 3-axis acceleration and gyroscope data is shown below on the next page.



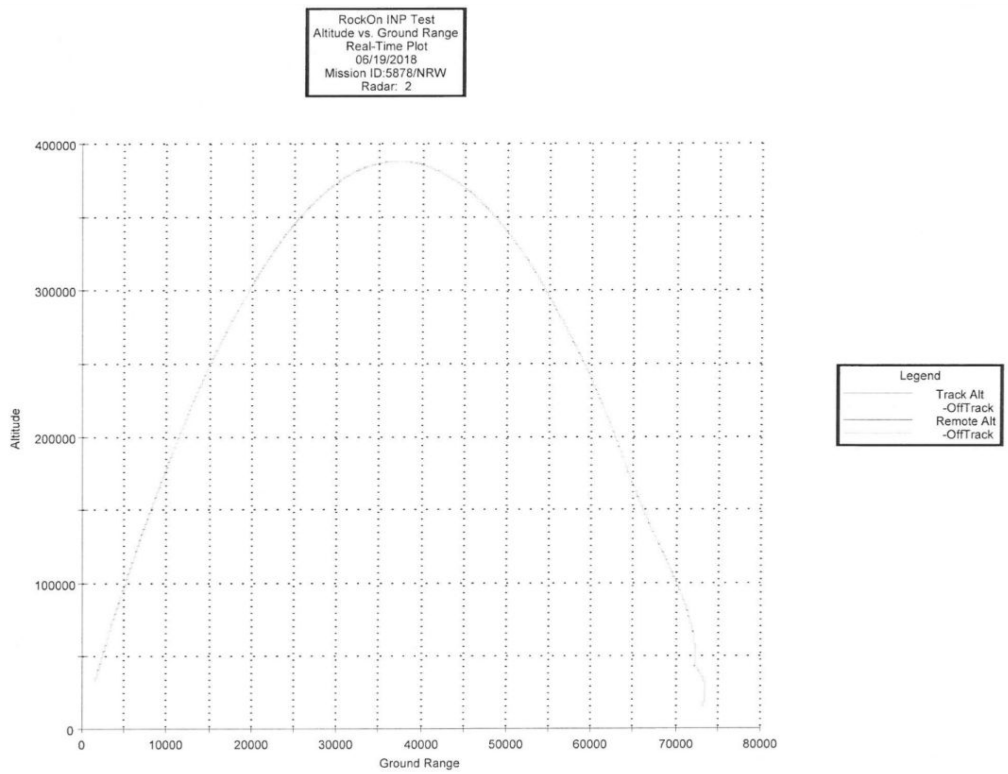


According to these graphs, the rocket did not significantly oscillate at any frequency. The largest oscillations that did occur are close to 0 Hz which is shown in the graph below.

Based on this data we would conclude that future teams would not have to worry about designing around particular resonant frequencies.

Appendix D: Altitude vs Distance traveled of RockSat-C Rocket

Below is the actual trajectory of the rocket, as recorded by NASA. All measurements are in feet.



12.0 Acknowledgements

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We would also like to thank the West Virginia team for their assistance and for sharing a canister with us.

Finally, Ben recorded many details about our project on our project website, located at https://sites.google.com/a/udel.edu/rocksat-c-2018/. This includes a detailed description of our work while at Wallops Island.