“Our mission is to perform an assortment of experiments to teach our class about navigation-based solutions for spacecraft design.”

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1.0 Mission Statement

Gold Team

“The goal of our mission is to use on-board videography to gauge the accuracy of coastal matching by comparing calculated position from collected images to the measured GPS position.” - Gold Team

Blue Team

“Blue Team aims to measure magnetic field data and atmospheric radiation levels to determine their complicity to accepted models, use Software Defined Radio (SDR) to record L-band Radio frequencies to determine the feasibility of an SDR as a positioning system, and implement an Inertial Navigation System to determine the attitude of the rocket.” - Blue Team
2.0 Mission Requirements and Description

**GPS Design Requirements**

- The mission of the GPS is to acquire and log data from satellites. For the GPS to acquire data, it must be able to capture signals. The challenges for capturing signal include a COCOM limit, signal splitting and the antenna port. A COCOM limit is what prevents the GPS from capturing signals at very high altitudes and velocity. To get past this issue we had to have the GPS delimited from the manufacturer. This required some legal assistance from the WVU law department but wasn’t too difficult. There are several criteria we had to follow for the delimited receiver; i.e. storing in a secure container. Splitting the signal was also a challenge we had to tackle because we only have space for one antenna in the multipurpose port and the SDR also must use an antenna. To surpass this, we used a GPS signal splitter. For the actual antenna placement, we used a 3D printed mount for inside the port and an acrylic cover. The acrylic cover is optimal because otherwise it might be difficult for the GPS signal to travel through the standard metal cover. To create the cover, we used the given CAD model to laser cut an acrylic piece that fit the port perfectly. The data collected is stored on an external SD card.

**Coastal matching Design Requirements**

- The goal of Coastal matching is to capture images during flight that can be compared to a library of images for navigational purposes. In order to have a successful mission, the camera must be able to withstand the g-force and keep a good field of view throughout the flight. The camera also must have a high enough frame rate to capture discernable video while the rocket spins. The final challenge of the camera is to have the system turn on with rocket power.

**MAGRAD Design Requirements**

- The Geiger Counter and the Magnetometer’s mission is to collect data throughout the entire flight that can be mapped against a standard model (i.e. WMM). The magnetometer can also provide information for the GPS and SDR experiments. For the MAGRAD to be successful, both sensors must turn on through a microprocessor and then collect data throughout the entire flight.
Inertial Measurement Unit Design Requirements

- The IMU’s mission is to collect inertial data on the rocket throughout the entire flight. The data will include the rocket’s acceleration in 3 different axes as well as the angular velocities about each axis. With this data we should be able to plot the course of the rocket over time. For the IMU to work, it’s necessary the sensor turns on with rocket power and store the data on an external device. The IMU will have to mount to a custom PCB and operate via a microprocessor. The power for the IMU will come from a separate power distribution board. With the high g-forces on the rocket, it is imperative the IMU has a high enough tolerance to measure the high acceleration and angular velocity.

Software Defined Radio (SDR) Design Requirements

- The mission of the SDR is similar to the GPS. The SDR, however, is going to pick up the raw L-band radio signals and use them to locate the rockets position in post-processing. The design challenge for the SDR is that the signals for the SDR need to come from the same antenna as the GPS. This is because there is only one port for the antenna. To do this we used a signal splitter. The splitter requires power that will come from a power distribution board. The SDR we are using is a HackRF. Once the HackRF receives signal, an Intel NUC will capture the binary data from the HackRF. The NUC will also power the HackRF.

3.0 Payload Design

GPS/SDR Apparatus

The GPS apparatus was a big design challenge. The receiver is connected to a GPS splitter, connected to the patch antenna in the multipurpose port. The splitter splits the GPS signal to the Novatel Receiver as well as the SDR. The SDR is mounted underneath the splitter. The splitter required the same power that is output by the headers on the PCB and can be powered from it.

The SDR ended up requiring a minicomputer with enough power and RAM to be able to write the data in a constant stream. This resulted in us acquiring an Intel NUC. The NUC was connected to the HackRF front end via USB which then had a connection to the signal splitter.

For the antenna we used a small patch antenna. We mounted it on a 3D printed stand and used acrylic for the cover of the multipurpose port. Acrylic allows for the signal to pass through.
Camera Apparatus

For our coastal matching experiment, we chose to use a GoPro Hero session 5. Through a lot of trade studies and experimentation, this camera proved to be the optimal choice. It was compact, had a field of view that fit the port, and could capture at the quality and frame rate we needed.

One of the biggest challenges of the Coastal Matching experiment was turning on the GoPro with T-3 switch before launch. We used the Netburner to provide a short digital signal to a non-latching relay. This 3.3 V signal flips the relay and causes a short inside the camera’s record button. This is similar as if you just pressed the record button on a GoPro.

Mounting the GoPro was another big challenge. Lining the GoPro up with the optical port and making sure it can be mounted to a plate was incredibly difficult. Ultimately, we came up with the idea to use a motorcycle helmet mount. The mount has 3 degrees of freedom, uses screws and is small enough to not get in the way of our other experiments. It’s also very important that this mount can withstand the vibration and acceleration of the rocket. This mount is known to withstand +100 mph winds. The screws are also important because each degree of freedom can be secured permanently when it’s time for launch, but we can still adjust the camera as needed. We 3D printed a base mount that could be secured to the canister as well. In the end, the mount withstood the violence of the entire flight.
Magnetometer and Geiger Counter Apparatus

For the magnetometer and Geiger counter we used a Redboard microcontroller that could operate both experiments at the same time. The stack from top down was assembled as a datalogger, Geiger counter, and Redboard. The Redboard received power from the power distribution 5v header. This then supplied each experiment with the necessary voltage through. The data for each experiment was stored onto the datalogger. The magnetometer stood by itself on separate standoffs near the rest of the setup to isolate for calibration purposes, close enough to connect with the Redboard.

Inertial Navigation System Apparatus

For the IMU used was an ADIS 16485AMLZ. For the inertial navigation system to operate properly, it needed to be located as close to the center of the canister as possible. There was just enough room to fit it between the power distribution board and the MAGRAD stack on the center plate. The IMU was supplied power through the power distribution board. the Netburner gave the signal to the IMU to begin reporting data to the data logger.
**Mass and Monetary Budget**

Our final canister weight and center of gravity were both within the required parameters set by NASA Wallops. We were able to be at exactly 20,000 lb, with the aid of some lead ballast. We didn’t require a whole lot of ballast going into weigh in though. Our Intel NUC’s battery was quite large and was a bit of a concern throughout the build of the canister. However, the battery was not too cumbersome, and we didn’t have to worry about cutting down any of the mass.

Monetarily, our engineering department at WVU sponsored us with enough funding to buy our canister and pay for all the experiments and travel. However, we would have maxed out our budget if it weren’t for the fact that we already had a Novatel receiver on hand. However, we would have maxed out our budget if it weren’t for the fact that we already had a Novatel receiver on hand. Not having to buy the GPS saved a lot of money. That was funding we could put towards multiple cameras for experimentation and trade studies as well as giving us the ability to optimize our canister and do as many experiments as possible.

**4.0 Payload Subsystem Integration and Testing Reports and Full Mission Simulation Test Report**

**Novatel GPS receiver and SDR**

Both experiments underwent similar testing to determine their readiness. Each was independently tested outside to ensure that they could accurately collect a position, however they were not tested within the canister. After further tweaking and investigation each was tested with a Labsat3 Signal Simulator to ensure that they could gather position for the entirety of the flight. The Novatel had to be delimited prior to testing so that it could record data at high altitudes and high velocity. The LabSat3 testing proved it had been successfully delimited. Then the two experiments were tested in conjunction with one another and the signal splitter outside. Once all the tests were successful multiple times, we began full integration into the canister.

![Figure 7 – Novatel and Hack RF connected to the splitter and LabSat](image)
Magnetometer and Geiger Counter

The magnetometer and Geiger counter’s main focus was canister integration. There were a lot of parts to make these sensors work. The power distribution board had to send power to the Redboard which then had to send power and control both sensors and the datalogger. Ultimately, it wasn’t until we built the canister that we could fully test our sensors. Once everything was in place though, both sensors turned on and collected data. Prior to canister integration, the only testing that had to be done was with the Redboard, making sure the code was able to correctly control both sensors and log data.

Inertial Measurement Unit and Inertial Navigation System

The testing of the IMU consisted of rotation and translation tests to see if the IMU’s results matched the physical results that were perceived. We confirmed that the IMU was working through a manufacturer provided development board throughout testing. We ran into an issue where the IMU wouldn’t provide correct results using the Netburner’s software. About two weeks before launch, the IMU completely failed and had to be hastily replaced with an IMU that did not have as high of a dynamic range as the original IMU in terms of g’s and rotation rate. The new IMU did work in testing but with mixed results. There would be portions of data that would appear correct, yet it would cut out at times and give false data.

Coastal Matching

There were multiple stages of testing for coastal matching; spin testing, field of view testing, and software testing. The camera was able to capture video at a high spin rate, and we were able to use narrow the field of view without having light saturation and our code was operational. This system didn’t require any integration with the other systems, all of its testing was done individually.
5.0 Testing Results

**Novatel GPS Receiver**

The picture below is a plot from the LabSat3. This plot is the path of the rocket up to 15km. At 15km we were able to prove that the GPS receiver was delimited and ready for flight.

![LabSat GPS simulation](image1.png)

*Figure 8 – LabSat GPS simulation*

This image is a plot of the Novatel collecting data around campus. (Note: it was not collected inside a building. Google Earth is not up to date.)

![Novatel Receiver collecting data](image2.png)

*Figure 9 – Novatel Receiver collecting data*
**SDR**

Below is a plot of the SDR collecting data around campus, we were able to collect data when integrated with the Intel NUC successfully.

![SDR Data Collection](image)

*Figure 10 – SDR Data Collection*

**Magnetometer and Geiger Counter**

For the Magnetometer and Geiger Counter we were able to run the sensors in the lab and collect data. Testing for these sensors was straight forward.

![Geiger counter data collection](image)

*Figure 11- Geiger counter data collection*
Inertial Navigation System and Inertial Measurement Unit

For IMU testing, the main thing we tested was the connection to the Redboard. Once connected the IMU could be tested by displacement and rotation. The graph below showcases how the ADIS 16467 performed when sitting still on a table, then being jostled a bit. When the counter reached about 250 the IMU began to move and it began to read nonsense. After about 25 counts it began reading the correct acceleration until count 350 at which point it began maxing out in the negative and positive x direction, which was incorrect. We attempted to correct the noise, but through the extensive testing the ADIS 16467 failed. We downgraded our IMU to another IMU we had in our lab because the failure came the week before the launch.

![Graph showing IMU performance](image.png)

*Figure 12 – ADIS 16467 Test*
Coastal Matching:

Coastal Matching had 3 parts to testing: the spin, field of view, and software.

Spin Test
We used a drill, a socket welded to a plate, and the GoPro case to spin test the camera at approximately 5Hz. We were able to capture images of the horizon and run them through our software.

![Figure 13 – GoPro mounted on drill](image)

![Figure 14 – Before and After image of horizon ran through a Canny filter](image)
Field of View Testing
We made a to-scale cut out of the optical port and measured how close or how far away the camera could be before light saturation became an issue.

Figure 15 – Cut out to test Field of View

Figure 16 – Image ranging used in Camera Testing
Software Testing
We ran Google Earth images through our software to see if we could apply the necessary filters then match the coastline between different images.

![Diagram showing the process of resizing, applying grayscale, detecting features, applying Canny edge detection, and feature comparison between images.](image)

*Figure 17 – Canny edge detection and feature detection*

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**Example Output:**
- Displays GoPro Image
- Displays Plot of Matching Features between two images
- Displays Matching Database Image

*Figure 18 – Feature Comparison between images*
6.0 Mission Results

**Novatel GPS receiver and SDR:**

Unfortunately, neither of the experiments that attempted to gather GPS data were able to return any usable data. The data from the Novatel returned all zeros within the binary data. This signifies that the Novatel failed to track any GPS satellites while in orbit. The data from the Software Defined Radio failed to return a signal source data file. This could be due to any number of issues and at this time we are unsure as to what caused this since the program was set up to constantly write this file.

We think that the system may have failed due to several factors. Our first theory is that the rocket was spinning at such a high rate that at each instance when the GPS could obtain a solution. Since the multipurpose port and antenna were pointed to one direction on the rocket, the signals from the other side of the rocket may not have been able to pass through the shell of the rocket. It could be argued that the GPS could have obtained a solution on the launch pad since they were active for approximately 3 minutes before launch. Although this is true it does not guarantee that a position fix could have been obtained on the launch pad. The time to first fix (TTFF) can vary greatly from 20 minutes on a clear day with perfect conditions to several seconds on a not so optimal day. It is related to several factors that can affect this time. Our second theory is that the connections for the signal splitter were not secured on the power distribution board and it did not receive enough power. We are unsure that this may have been the problem because when the lid was removed from the can, the person removing it was unaware of how short the cables were. The lid may have been removed in such a way that the cables were torn, or that the cables were loose to begin with an easily came out. Also, during the flight, in the video it can be observed that a cable is loose and flopping around the canister. This could have been the splitter cable, or it could have been any other red cable.

Either of these failures could have been the one to cause the system to behave incorrectly. We feel that the rate of the rocket spin was more than likely the true reason for the failure, although this is based off a gut feeling on how secure all the cables were for the experiments.

**Inertial Measurement Unit and Inertial Navigation System:**

The IMU provided data the entire flight, however, the data received was unrecognizable and unusable. The Z axis sensors were flooded with noise due to the high acceleration of the rocket and the Y and X axis had some data that looked recognizable. At this time, we did not pursue using a filter on the data. Due to the high acceleration and rotation rate of the rocket each axis became saturated with noise. This resulted in the data being unusable. We expected this going into the launch due to an unexpected IMU failure on the original system that was rated for this launch. The IMU we included for the launch was not rated to the same accelerations and rotation rates and this led to the failure of the system.
Figure 19 – Angular Velocity about the X-axis

Figure 20 – Angular Velocity about the Y-axis
Figure 21 – Linear Acceleration in the Z-axis

Figure 22 – Angular Velocity about the Z-axis
Magnetometer and Geiger Counter:

Both the magnetometer and Geiger counter successfully returned data from the launch. Geiger Counters data is unusable for the time period that contained the Rocket booster activation, but analysis of times after that may prove useful if bias can be removed. The magnetometer data may not be able to be completely analyzed since the z-axis rotation of the rocket could not be recorded by the IMU, but at least the z-axis data is usable. The Geiger counter data can be used to determine altitude when the radiation recorded is compared with natural background radiation at different altitudes given proper measurements. The WMM data was processed using the radar data from Wallops. Below are the plots of the altitude of the rocket over the course of the flight in kilometers and miles. Note that these plots start from launch, not T-3 minutes from launch.
Below are the plots of the Geiger Counter and Magnetometer data over the course of the flight and subsequent time after landing until power was cut.

Figure 25 – Geiger Counter data (Top) magnetometer data (bottom)
Below is the intensity of the magnetic field for both the raw uncalibrated data and estimated WMM data. There appears to be some discrepancy between these two plots. Note that time starts at T-3 minutes from launch.
Below is the plot of ionizing radiation vs. time plotted on top of the rocket altitude vs. time plot. Both are adjusted so that the time of launch corresponds to the time in the sensor data. Time starts at T-3 minutes from launch.

*Figure 27 – Geiger Counter Micro Sieverts per hour data (uSv/hr) plotted in sync with the rocket’s altitude (km) from radar data vs. time (sec)*
Here, the Magnetic field in the x, y, and z directions is plotted over the course of the flight. While the x and y axis data have a lot of noise due to the rotation of the rocket, the z axis data has much less noise and is fairly close to the real predicted WMM data. This suggests that the spin of the rocket affected the data in these directions more than the z axis, which makes sense since the rocket chiefly spun about the z axis. The fact that the z-axis magnetometer readings are negative for some of the plot and positive for others suggests that the magnetometer was initially upside down and turned right side up for after landing. Without z-axis attitude rotations from the IMU, the exact field readings cannot be found, though estimation techniques may prove useful. Note that the time in these plots starts at T-3 minutes from launch.

Figure 28 – Magnetic Field Readings vs. time
Coastal Matching

From the flight, the camera was able to automatically start and record video for the entire duration. However, due to the weather on the day of the launch, we were only able to obtain 3 images of the coastline. After these 3 images, the rocket broke through the cloud layer and the coast was no longer visible. Unfortunately, these 3 images were unable to match with the reference library because their altitude was too low.

We tried to create a new library and match these images to very similar ones from Google Earth. The images were unable to match with the new library too. It could be due to several factors. The distortion from the optical port combined with the slight haziness of the ocean is likely the culprit.

We were able to capture video the entire flight. The GoPro and its mount held up very well through the flight. We put up two videos of the flight on YouTube for others to watch. The links can be found in the appendix of this document.

Figure 29 – 3 images of the coast captured from the GoPro
7.0 Conclusion

From our entire canister, only 3 experiments out of 6 returned readily available data, the IMU is still being processed though. We believe some of the IMU data is usable, with more analysis we could potentially get more data from the X and Y axes if we reassemble the binary data. The systems that each failed had unique and isolated reasons as to why they failed, none were related to system wide errors. Ultimately, all the sensors and receivers worked, we just had minute failures with each instrument that caused us to have unusable data.

Things we could have improved on primarily focus on documentation and communication. Something that could be improved, for instance, is the use of quick reference documentation for the PCBs. It would have eliminated the need to refer to the lengthy documentation just to find pin and header information. A second thing that could have been improved was the turnover documentation for certain experiments. For instance, when it came time for the launch, the Magnetometer and Geiger counter experiments were lacking in documentation to assist in integration. The lack of documentation meant the group was basing how to do major things such as analysis of data based off intuition. This is relevant for most experiments. While instrument leads may have known some analysis techniques, communicating these techniques through thorough documentation should have occurred, because without enough documentation to explain these analysis processes, the analysis became difficult and time consuming for those involved. Further analysis may be able to be performed on this data given more time.

For the experiments that failed, we feel there are several ways to remedy the failures. For the IMU, unfortunately this was a pure hardware error from an IMU we had to hastily use for the experiment. If we had had more time to find a replacement IMU and to continue debugging the IMU code, we could have potentially gotten usable data from the launch. Instead, we were forced to use an IMU that would saturate at high rotational rates and high accelerations and left to hope for the best result. For the GPS, our best guess to how to fix the issue of not being able to see enough satellites at a given instant could be resolved with additional hardware. We could include a second antenna on the opposite side of the rocket that would capture the other half of the sky necessary for the constellation. This hopefully would provide the coverage needed to solve for a position during flight.

In the end, our payload design was good. We had a strong design that withstood the violence of the flight. All our experiments were able to turn on and our user compliance was up to par. The minute errors that led to us getting no data are very fixable. There were a lot of lessons learned from this project but we’re proud of our mission, especially considering this was the first time that WVU attempted to take on so many projects in a single canister.
8.0 Potential Follow-on Work

To follow on for this project with the GPS experiments and the INS we need to have gotten usable data. It is possible that we can find a filter for the X and Y axes that will return some usable data. We had planned to develop a Kalman filter using these experiments to get as accurate of a trajectory as possible. Also, we had planned on comparing the GPS solutions of the two receivers and attempt to delimit the SDR, but again neither of these returned usable data. We could continue to further debug the failure in the GPS experiments to try and officially determine what happened.

We could follow up with the magnetometer and Geiger counter data through calibration of magnetometer data. The coastal matching experiment did return usable video and images. However, there weren’t enough images to run through our software that could show coastal matching as a feasible means of navigation for the rocket. Cloud coverage only allowed us to get three images of the coast. But the GoPro and the mount were very successful. We are still putting together documentation to post that future classes and schools can use.

9.0 Benefits to the Scientific Community

The benefits to the scientific community are showing how budget measurement devices can be used to obtain location and attitude. Learning how the earth’s magnetic field and atmospheric ionizing radiation levels change with altitude could benefit guidance and navigation research. Coastal matching may not be usable all the time, but when GPS is unavailable it is a method that could be used to determine position. For example, it could be utilized on planets that have few satellites in orbit but have been mapped by those satellites.

10.0 Lessons Learned

1) Systems testing began late for certain systems and there was time wasted towards the beginning of the year that could have been spent towards system testing.

2) Projects need to have better turnover from previous semesters. When the spring semester started, we found ourselves trying to figure out what past people had done. A lot of times we had to start an experiment or research from scratch.

3) More thorough research on how to properly run experiments before committing to a project/product. Mostly to assist with trade studies.

4) Better documentation, such as quick references, would have made ease of working with unfamiliar experiments more fluid. This would have also streamlined integration for the canister.
11.0 Appendix

Entire Flight Video:
https://www.youtube.com/watch?v=FR1h_oXYdAg&t=166s

Highlight Video:
https://www.youtube.com/watch?v=6XBSrpg2Q4g&t=27s