NDRT Telemetry High Level Design

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1 Introduction

The Notre Dame Rocketry Team (NDRT) has communicated a desire to report data from their rocket during its flight, such that the status of the rocket can be observed and understood in real time. This requires the design and implementation of a sensor system as well as a radio link between the rocket and a ground station. Using concepts from engineering domains such as RF, communications, and embedded systems, a reasonable and robust solution can be developed to address NDRT's goals.

2 Problem Statement and Proposed Solution

The Notre Dame Rocketry Team seeks to implement a telemetry system in its rocket, and it is required that it record and transmit, at a minimum, GPS data once it has landed. This goal of this project is to record GPS, altitude, and acceleration during and after flight.

Along with recording GPS data, altitude will be recorded using an altimeter, and acceleration will be recorded using an accelerometer. A transceiver and antenna will transmit the data to a relay station on the ground far away, and the relay station will transmit the information to the ground station closer to the launch site, where a computer will display live data.

The primary consideration in this project will be the radio link and the conditions in which it must operate. In terms of range, the rocket reaches its apogee at approximately 4,444ft and must communicate information to a ground station a few hundred feet from the launch site. It will also reach a maximum speed of 590ft/s during its flight, with a maximum acceleration of 222ft/s^2. Additionally, the rocket will change orientation throughout its launch, descent, and landing. This means that the transmitter aboard the rocket must be able to transmit data consistently regardless of orientation and up to the maximum range.

There are additional constraints on the size and location of the system, as it must fit into the nose cone of the rocket. The nose cone is 3-D printed and is therefore RF transparent, so all components, including the antenna, can be located inside. All sensors that report useful data must also be located in the top portion of the rocket since the rocket breaks apart during descent.

NASA requires GPS data to be logged during the launch, but the NDRT also wants to measure altitude, measure acceleration, and be able to observe these values on the ground in real time. This requires transmitting, receiving, and processing packets of data, as well as developing a user interface for the ground station.

The proposed solution for the telemetry hardware involves a dipole antenna placed in the rocket to communicate with a ground station. The proposed frequency of operation is 433MHz to achieve better range and prevent interference with the rocket payload transceivers. A dipole antenna has a relatively favorable radiation pattern for ascent, descent, and after landing, and its symmetry is useful given the large variation in rocket orientation. The ADF7030 RF transceivers will be used for communication from the rocket to a relay station, as they are fully integrated and provide the desired frequency range.

At the rocket's apogee, the angle between the rocket and the ground station, located about 300ft from the launch site, would be very steep. Using a dipole antenna at this angle would result in extremely low received power due to the dipole's radiation pattern. To address this issue, a relay station located further away from the launch will be integrated, such that it will be at a more favorable angle in the dipole's radiation pattern. This relay station will serve as an intermediary between the rocket and the ground station by receiving data transmitted from the rocket and forwarding it to the ground station. The ground station will consist of another ADF7030 receiver connected to a laptop. Software on the laptop will pull data from the link, process it, and display relevant data in a GUI.

3 System Requirements

The primary requirement of the telemetry system is that it must transmit GPS data from the rocket to a ground station for the entire duration of the flight. However, per request by NDRT, the system must reliably transmit acceleration and altitude data throughout the flight as well. The rocket will have a target altitude of 4444ft, but could reach as high as 4,900ft and will be at least 2,500ft downrange from the relay station. As a result, the system must be able to transmit and receive at this maximum range to achieve reliable data transfer. While power amplifiers can be utilized to maximize the range of the transmission, the maximum power is limited to 250mW per transmitter aboard the rocket.

The sensor data must be collected and reported such that it is useful to NDRT. This requires that sensors be sampled at sufficiently high respective frequencies to achieve reasonable data resolutions. Data must also be reported in near-real time throughout the launch via a user interface such that observers from NDRT can evaluate the rocket performance during its flight. For post-flight analysis, data must also be stored locally so that it can be reviewed and compared in the future.

The competition will take place in a farm field, meaning that there is no guarantee of a reliable connection to a cell tower for internet access. Therefore, the telemetry system must operate independently from access to a cellular network and the internet. Additionally, the telemetry system must successfully operate in an environment of potential electromagnetic interference both from the NDRT rocket payload and from other teams' transmitters.

The weight of the telemetry system must not exceed 3 pounds, and it must fit entirely within the nose cone of the rocket. The nose cone is approximately 2ft long, and it has a diameter of 8 inches at the base. The antenna will also be located inside the nose cone, positioned in the center to achieve a favorable radiation pattern. The sensor system will be positioned below the antenna, where the radiation pattern is weakest.

The total flight time will be on the order of two minutes, so the selected battery must power the system throughout that time with additional time budgeted to continue transmitting after landing. Preliminary calculations show that a 2500mAh battery would power the system in its current design for 10 hours.

4 System Block Diagram

4.1 Overall System

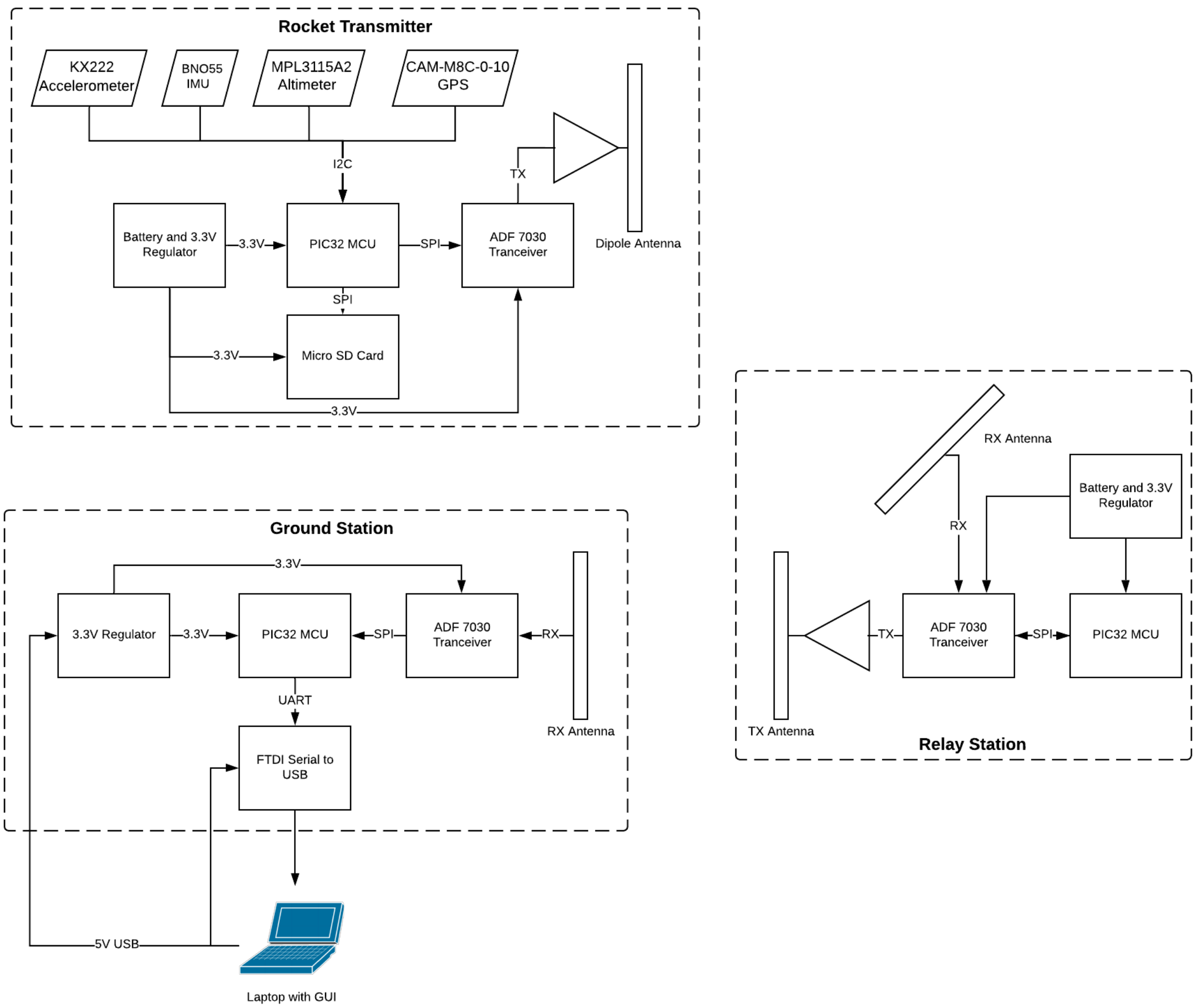

Figure 1: System Block Diagram

This system can be broken into five main subsystems that outline the transition of data: The vehicle sensor management system, the vehicle transceiver, the relay station transceiver, the ground station transceiver, and the ground station user interface. The vehicle sensor management system is responsible for collecting data from the telemetry sensors on-board the rocket, packaging the data into a payload, and providing this payload to the vehicle transceiver. The vehicle transceiver then transmits this data to the relay station transceiver, which in turn forwards the data to the ground station transceiver. The ground station user interface pulls this data from the transceiver and reports it to observers in a highly intuitive manner. These subsystems are explained in further detail in the following section.

4.2 Subsystem and Interface Requirements

4.2.1 Vehicle Sensor Management System

The sensors aboard the rocket, specifically the GPS, accelerometer, and altimeter, must all be able to provide useful data and operate in the system conditions mentioned in Section 3 above. Based on their respective data, each sensor has a minimum frequency at which it must be sampled to give an appropriate resolution. For example, the GPS sensor must be sampled at a minimum of 10Hz, as this frequency is a standard for GPS readings and provides a minimum resolution of 59ft. The accelerometer readings must be more finely grained, as NDRT needs to be able to clearly observe parachute events such as the main parachute and drone deployment. Their current accelerometer samples at 400Hz and does not provide the desirable resolution, so the minimum sampling frequency for the telemetry accelerometer is 800Hz, doubling the original rate. The altimeter must also have relatively high resolution, such that the minimum sampling frequency is 100Hz. This provides a resolution of approximately 6ft which is sufficient for accurate altitude measurements. NDRT has also expressed an interest in being able to track the orientation of the rocket throughout its flight. In order to provide reasonable data, the orientation sensor must be sampled at a minimum of 100Hz which gives a resolution of approximately 6ft.

The sensor system also imposes requirements such as the use of a microcontroller to manage and interface with each sensor. More specifically, the microcontroller is responsible for sampling each sensor at the appropriate sampling frequency and packaging the resulting data into a payload for the transceiver. This means that the microcontroller must have an appropriate number of I/O ports to support all necessary peripherals. Additionally, each payload should be stored locally in order to compare the transmitted and received data after testing, which requires an SD card to be put on-board the rocket.

4.2.2 Vehicle Transceiver

The vehicle transceiver must be capable of transmitting between 200mW to 250mW (23dBm to 24dBm) of radiated power to ensure the maximum transmission strength from the vehicle while remaining within NASA transmission power requirements. It must also be able to maintain a connection to the relay station throughout the entire duration of the vehicle's flight, as well as for a limited time after the vehicle has landed. This requires that the transmitter antenna is able to radiate approximately equal output power towards the relay station regardless of the roll orientation of the vehicle. In addition, because the transmitter is located in the nose cone of the vehicle, after the main parachute is deployed the nose cone will be pointing towards the ground as the rocket descends. For this reason, the transmitter antenna must be able to maintain approximately equal radiation power when oriented upwards and downwards at the maximum transmission angle of 63˚.

Given the sampling requirements of the sensors listed above, we can derive a minimum data rate requirement for the vehicle transceiver. Please reference Section 5.1 for a listing of the sensors used. The calculated data rates for each sensor, as well as the minimum required data rate can be seen in Table 1 below.

Table 1: Calculated Data Rates For Each Sensor

Device Type	Device	# Measurements	# bits	Frequency (Hz)	Data rate (bits/s)
Altimeter	MPL3115A2	1	24	160	3840
GPS	CAM-M8C-0-10	3	32	10	960
Accelerometer	KX222-1054	3	16	800	38400
Accelerometer	BNO055	N/A	243	100	24300
				Total:	67500

Therefore, the vehicle transceiver must be capable of transmitting at a minimum data rate of 67.5kbps. As specified in Section 3, the vehicle's maximum altitude is 4,900ft. Assuming that the relay station is placed approximately 2,500ft from the launch site, the line-of-site distance from vehicle transceiver to relay receiver is 5,500ft. The vehicle transceiver must be capable of reliably transmitting packets over this distance at the transmission angle of 63˚. Finally, the vehicle transceiver must not interfere with other transmitters in the payload of the vehicle, and attempt to avoid interfering with the transmitters of other rocketry teams.

4.2.3 Vehicle Subsystem Power and Weight

The vehicle subsystem consists of the vehicle sensor management system and the vehicle transceiver, which are collectively located in the nose cone of the rocket. As specified in Section 3, there are both power requirements and weight requirements that are imposed on this subsystem. For example, since the total flight time is on the order of two minutes, the battery used to power the telemetry system must, at a minimum, last for this time plus a small margin for continuing transmission after landing. Additionally, the total weight of the subsystem must not exceed 3 pounds.

4.2.4 Relay Station Transceiver

The relay station transceiver must maintain reception of the signal from the rocket throughout the duration of the flight. Because of the limitations of the radiation pattern of the antenna in the rocket, the relay station must be placed at a distance which optimizes its reception at all rocket positions and angles, and its antenna radiation pattern must be acceptable for the path of the rocket.

The relay station must also constantly transmit the data it receives toward the ground station. This means that an antenna must maintain the appropriate directivity in order to be received at the ground station. Finally, to maintain a constant transmission rate within the entire telemetry system, the relay station must be capable of receiving and transmitting at a data rate of 67.5kbps.

4.2.5 Ground Station Transceiver

The ground station receiver must constantly receive the transmission from the relay station, which will be a distance of approximately 2,500ft, throughout the entire duration of the flight and after landing. This means the antenna must maintain proper directivity to remain sensitive to the incoming signal from the relay station. In addition, to maintain a constant transmission rate within the entire telemetry system, the ground station must be capable of receiving at a data rate of 67.5kbps. Finally, the ground station must be capable of communicating with the ground station user interface via a USB connection, over which it will also receive 5V for power.

4.2.6 Ground Station User Interface

The user interface is responsible for reporting the relevant data collected from the rocket sensors to the observers on the ground. This data must be presented in a highly readable way and be updated in near-real time such that the members of NDRT can analyze the rocket performance during its launch and descent. The user interface will operate on a PC laptop which pulls data from the ground station transceiver via USB. The PC will also store this received data locally so that it can be compared to the transmitted data from the rocket after testing.

4.3 Future Enhancement Requirements

One enhancement that would be desirable to add in the future would be a live video feed transmitted wirelessly during launch. Our team investigated this possibility in the beginning, but we decided that the bandwidth required to accomplish that would pose a significant challenge for the rocket team's inaugural telemetry system. However, once the basic telemetry system has been designed, this would be a very useful enhancement for the NDRT. Additionally, the NDRT has a future goal of transmitting to the rocket to manually control the systems on it. Both of these prospects could be explored by future telemetry teams.

5 High Level Design Decisions

5.1 Vehicle Sensor Management System

As discussed in Section 4.2.1 above, all of the sensors aboard the rocket, namely the GPS sensor, accelerometer, and altimeter, must be sampled at high enough frequencies and be able to operate in the system conditions such that useful data can be stored and transmitted. With these considerations in mind, the sensors listed below in Table 1 were selected as they meet the subsystem requirements mentioned in section 4.2.

Table 2. Vehicle sensors with corresponding specifications

Sensor	Product Name	Sampling Freq. (max)	Operating Altitude (max)	Interface

GPS	CAM-M8C-0-10	10 Hz	50,000ft	I2C
IMU	BNO055	100 Hz	N/A	I2C
Accelerometer	KX222-1054	25.6 kHz	N/A	I2C
Altimeter	MPL3115A2	160 Hz	11,775ft	I2C

Two accelerometers, the BNO055 and KX222-1054, will be integrated into the telemetry system to serve different functions. The BNO055 has a fusion mode that performs sensor fusion calculations on measurements from the accelerometer, gyroscope, and magnetometer to obtain an absolute orientation measurement. While in fusion mode, the BNO055 clips at an acceleration of 129 ft/s^2 and is therefore not a reliable accelerometer. To compensate for this, the BNO055 will serve exclusively as an orientation sensor, whereas the KX222-1054, capable of operating at accelerations up to 1029 ft/s^2, will serve as the accelerometer of the telemetry system.

The KX222-1054 is also useful because of its high maximum sampling rate. While it is possible to derive acceleration from GPS measurements, the low sampling rate of the CAM-M8C-0-10 does not provide the desired resolution for acceleration data. Conversely, with a maximum sampling rate of 25.6kHz, the KX222-1054 can comfortably achieve the minimum sampling requirement of 800Hz.

Managing this system of sensors requires the use of a microcontroller that can accommodate four I2C interfaces to read from each device. The PIC32 MCU family from Microchip is suitable for this requirement given the number of I/O ports that are available to support the necessary interfaces. Since this family of microcontrollers requires a 3.3V input, a voltage regulator, such as the LD1117, will also be required to downconvert the 3.7V - 4.2V voltage range from the battery. Additionally, the sensor readings will likely be performed using timer interrupts due to the sampling frequency requirements. In order to ensure a sufficient timing accuracy, an external oscillator will also be used by the microcontroller.

To store each payload locally, the microcontroller must write data to an SD card. The SanDisk Ultra microSDXC is a suitable option due to its memory capacity of 128GB and ease of removal for analysis.

5.2 Vehicle Transceiver

The transceiver module that we have chosen to use is the ADF7030 from Analog Devices, which is capable of operating between 426MHz and 470MHz. Because of the relatively low data rate requirement of our system, we chose to operate in the 433MHz band to decrease path losses and increase our effective range. In addition, none of the other transmitters located in the payload of the vehicle operate in the 433MHz band, ensuring that the vehicle transceiver will not interfere. As mentioned in Section 4.2.2, the vehicle transceiver must be capable of transmitting between 200-250mW of radiated power. The ADF7030 is capable of outputting -20dBm to 17dBm (0.01mW to 50mW) of power from its transmit ports. For this reason, we will place an external 20dB power amplifier on the output of the ADF7030 and use the tunable output power of the transceiver to adjust the exact radiated power of the antenna to be in the proper range of 23dBm to 24dBm.

The ADF7030 is capable of operating with either a 2FSK or 4FSK modulation scheme. Because we do not require extremely high data rates, we have decided to use 2FSK to maximize possible range. When transmitting with the 2FSK modulation scheme, the maximum data rate of the ADF7030 is 150kbps, which meets the requirement of 67.5kbps listed in Section 4.2.2.

Assuming that the relay station is placed approximately 2,500ft from the launch site, the line-of-site distance from vehicle transceiver to relay receiver is 5,500ft. Through future planned testing, we will verify that the vehicle transceiver is capable of transmitting the required distance at the specified transmission angle of 63˚. However, since we are planning on transmitting near NASA's maximum allowed transmission power of 250mW and have made other design decisions specified above to maximize the effective range, we expect that this system will be able to meet the transmission range requirement specified in Section 4.2.2.

In order to guarantee that the transceiver is able to maintain a connection to the relay station throughout the entire duration of the vehicle's flight, we have chosen to use a half-wave dipole antenna, the ANT-433-MHW-SMA-S, designed for use in the 433MHz band. The radiation pattern of this antenna is symmetrical about the XZ plane, as shown in Figure 2 below, which allows the antenna to have an approximately equal gain of 0dB regardless of the roll orientation of the vehicle.

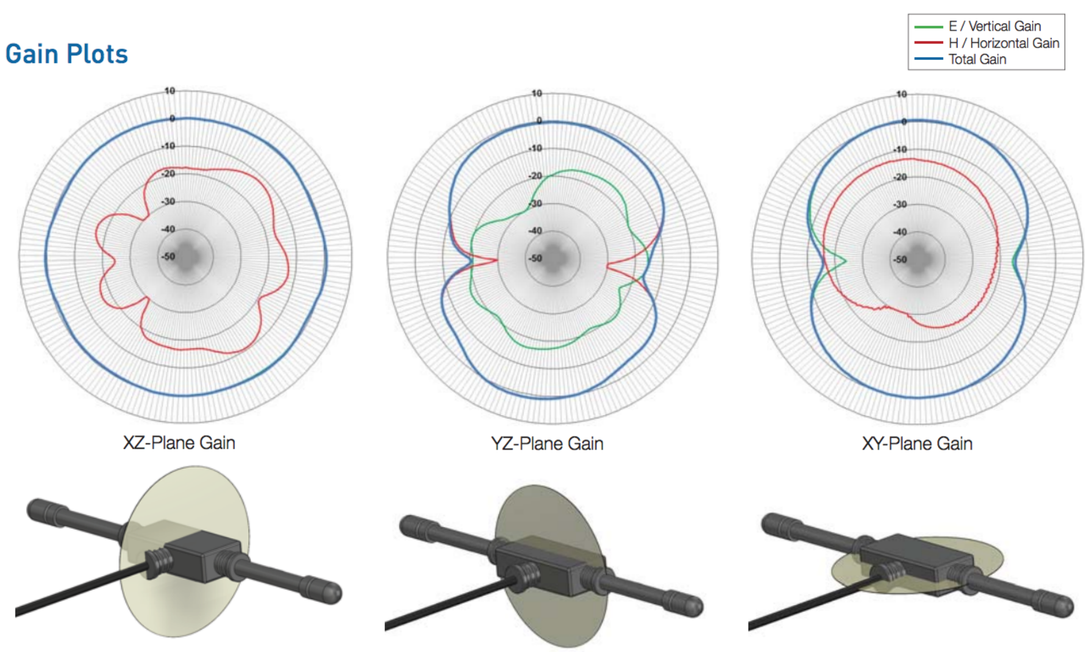

Figure 2: Gain Plots for the ANT-433-MHW-SMA-S Antenna

In addition, the radiation pattern for this antenna is approximately equivalent regardless of whether the antenna is pointing upwards or downwards. For this reason, when mounted in the nose cone, the transmitter antenna will be able to maintain an approximately equal gain of -5dB when oriented upwards and downwards at the maximum transmission angle of 63˚.

5.3 Vehicle Subsystem Power and Weight

Given the generally low weight of our components, including that the battery is 43 grams, we are not concerned about reaching the weight limit of 3 pounds. To estimate the running time of the vehicle subsystem from our selected Adafruit Lithium Ion 3.7V 2500mAh battery, we performed the calculation below in Table 3. This was estimated using the current draw for each device on the vehicle subsystem board, assuming that the ADF7030 is in the transmit state for the entirety of operation to produce a conservative estimate.

Table 3. Estimated Power Budget

Device/State	**ADF7030**	**GPS**	**Accel (KX222)**	**IMU (BNO55)**	**Altimeter**	**PIC**	**Total Current**
Current Draw (mA)	65	71	0.145	12.3	2	100	250.445

Using the above current draw and the specified capacity of the chosen battery, we can estimate that our system will last approximately 10 hours, which far exceeds the required operating time.

5.4 Relay Station Transceiver

In order to achieve an ideal radiation pattern with proper directivity, we propose the use of a cross-polarized patch antenna at the relay station. The radiation pattern of this antenna would capture the position of the rocket throughout its flight. For the transmission to the ground station, this could be achieved either with a second antenna or with one antenna and a switch between transmit and receive.

An ADF7030 transceiver will be used to both receive data from the rocket and transmit that data to the ground station. A PIC32 microcontroller will control this radio chip via an SPI interface by sending timed radio commands. Therefore, as mentioned in Section 5.1, a similar battery, LD1117 voltage regulator, and external crystal will be integrated into this subsystem as well.

5.5 Ground Station Transceiver

In order to maintain directivity towards the relay station, we plan to use a cross-polarized patch antenna at the ground station. A patch antenna would have ideal directivity, and the cross-polarization would allow for better communication between the antennas regardless of their orientation. Additionally, we plan to use the ADF7030-1 transceiver at the ground station to maintain consistency with the relay station and rocket transceivers. This will allow us to maintain a consistent data rate of 67.5kbps, as specified in section 4.2.5.

In addition, to receive the data from the ADF7030, we will include the same microcontroller from the PIC32 family specified in Section 5.1, along with a similar external oscillator to ensure accurate timing. This microcontroller will be capable of communicating with the transceiver chip via an SPI interface, and will be able to process the data stored in each of the packets. In addition, an FTDI FT230XS-R USB to serial UART converter chip will be used to allow the PIC32 microcontroller to send the received data to the ground station user interface over USB.

Because the PIC32 microcontroller, ADF7030, and FTDI FT230XS-R require 3.3V power, an LD1117 linear regulator will be used to convert the 5V input from the USB connection supplied by the laptop down to the required 3.3V.

5.6 Ground Station User Interface

Since the ground station UI must report data from four different sensors in near-real time, this data must be presented clearly and intuitively. This means that instead of reporting purely numerical values, figures and plots should also be utilized. For example, the GPS readings will likely be plotted on a map to provide a visual interpretation of where the rocket is located. Measurements from the orientation sensor, accelerometer, and altimeter will likely be plotted continuously to demonstrate the trajectory and altitude of the rocket respectively throughout the flight. Following the conclusion of the test, these figures and plots can be saved locally for future analysis and reporting as well.

6 Open Questions

Our next step will be to order antennas and test their range. We have had discussions about the type of antenna to use in the rocket (monopole vs. dipole) and whether to purchase or make it ourselves. We will likely purchase one for simplicity, and we have currently selected a half-wave dipole antenna because it has a more favorable radiation pattern than a monopole antenna. The maximum range at which the antennas will function well is uncertain, and so is their performance behind the rocket’s material. We will test the antennas with the transceivers placed on the ground and far away from each other. This is does not perfectly mimic the transmission during flight since transmission along the ground has a higher path loss than transmission through only the atmosphere. We will also test the antenna when positioned behind the appropriate material. Additionally, we must select antennas for the relay station and ground station, and we are considering trying a cross-polarized patch antennas for better directivity. We must order and test these as well. There is a concern that the patch antenna’s radiation pattern would not always be sufficient at the relay station, especially after the rocket lands, so we must test that and potentially consider other types of antennas, such as a half-wave dipole.

One other concern we have is the BNO055 accelerometer. It has a gyroscope, and in its fusion mode, it does the calculations to provide the rocket’s orientation directly rather than only raw data, so it would provide us with useful information about the rocket’s orientation if it works. However, in the device’s fusion mode, the accelerometer measurement clips at 4G acceleration. As a result, it is likely to clip at launch, and we will perform tests to determine whether this will cause the orientation calculation to report incorrect data. Additionally, we found that it is prone to RF interference from other signals, so that is another reason it may fail. As a result, we plan to use it in the rocket as a test of its performance in early test launches, though we will use a more reliable accelerometer (the KX222-1054) to be sure we obtain reliable acceleration data. We will also test the clipping and electromagnetic interference on the BNO055 separately before launch.

Lastly, we must test our ability to read from the sensors that we order. Once we obtain the sensors, we will make sure we can extract, package, and send data at the desired frequencies.

7 Major Component Costs

7.1 Components

- CAM-M8C-0-10 GPS
  - Qty. 1: $25
  - Datasheet
- KX222-1054 Accelerometer
  - Qty. 1: $9.41
  - Datasheet
- BNO055 Accelerometer
  - Qty. 1: $11.16
  - Datasheet
- MPL3115A2 Altimeter
  - Qty. 1: $5.80
  - Datasheet
- Adafruit Lithium Ion Polymer Battery - 3.7V 2500mAh
  - Qty. 2: $14.95 each
- PIC32 Microcontroller
  - Qty. 3: ~$4 each
- ADF7030-1 RF Transceiver
  - Qty. 3: $5.10 each
  - Datasheet
- HMC452ST89 Power Amplifier
  - Qty. 2: $11.71 each
  - Datasheet
- ANT-433-MHW-SMA-S Antenna
  - Qty. 1: $15.04
  - Datasheet
- SanDisk 128GB MicroSD Card - SDSQUAR-128G-GN6MA
  - Qty. 1: $18.97
- FTDI FT230XS-R USB to UART
  - Qty. 1: $2.04
  - Datasheet

Working Component Cost Total: $168.04

7.2 Specialized Equipment

The products used to test our transceivers were purchased by our mentor, Professor Chisum. They belong to him and will be returned to him.

- ADF7030-1 EZ-KIT Evaluation and Development Kit
  - Qty. 1: $599.00
- ADZS-UCM3029EZLITE Motherboard
  - Qty. 1: $216.41

8 Conclusion

This high-level design provides an overview of the telemetry system we are designing for the Notre Dame Rocketry Team. So far, we have used the ADF7030-1 EZ-KIT to program the transceivers and demonstrate wireless connectivity in our subsystem demo. We are now ready to order specific parts and begin further testing and assembly. Our next steps are to order an antenna and test its range, test the BNO accelerometer for clipping, and check that we can operate the sensors at the desired frequency. The final step will be to integrate our design with the rest of the rocket systems for a successful test launch.

9 References

NDRT PDR 2019-2020

2020 NASA Student Launch Handbook