THE NOTRE DAME ROCKETRY TEAM TELEMETRY FINAL PRESENTATION

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Introduction

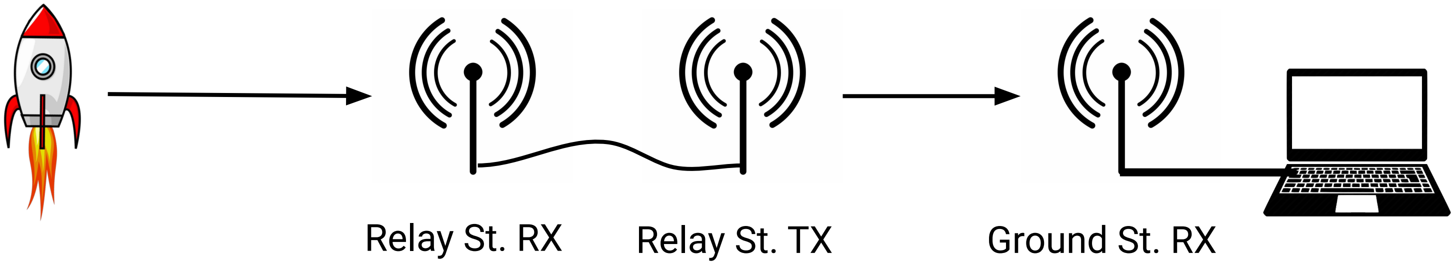
- The Notre Dame Rocketry Team (NDRT) competes in NASA's Student Launch competition annually
  - NASA requires GPS data logging and wireless transmission during the mission to support vehicle recovery
  - NDRT also expressed a desire to measure altitude and acceleration in real time
- Requires the design and implementation of a sensor suite and radio link
  - Comprised of four subsystems: The antennas, transceiver boards, sensor board, and relay and ground station boards
  - Organized into three main modules: The vehicle, the relay station, and the ground station
- Due to unforeseen interruptions by COVID-19, the full system was not fully integrated and tested
- Preliminary system tests were successful and indicate a functional, foundational system

System Requirements

- Rocket will reach apogee at 4,900ft
- Descent is slowed with 2 parachutes
  - One at apogee and the other at 500ft
  - Rocket is split into three sections held together with shock cord
- Real-time data to be transmitted
  - GPS (required by NASA)
  - Barometer readings (altitude)
  - Accelerometer readings
- Data transfer should be maintained through launch, descent, and while lying on the ground
  - Includes long leading wait time on launch pad
- Data should be reported via a ground station user interface

Theory of Operation

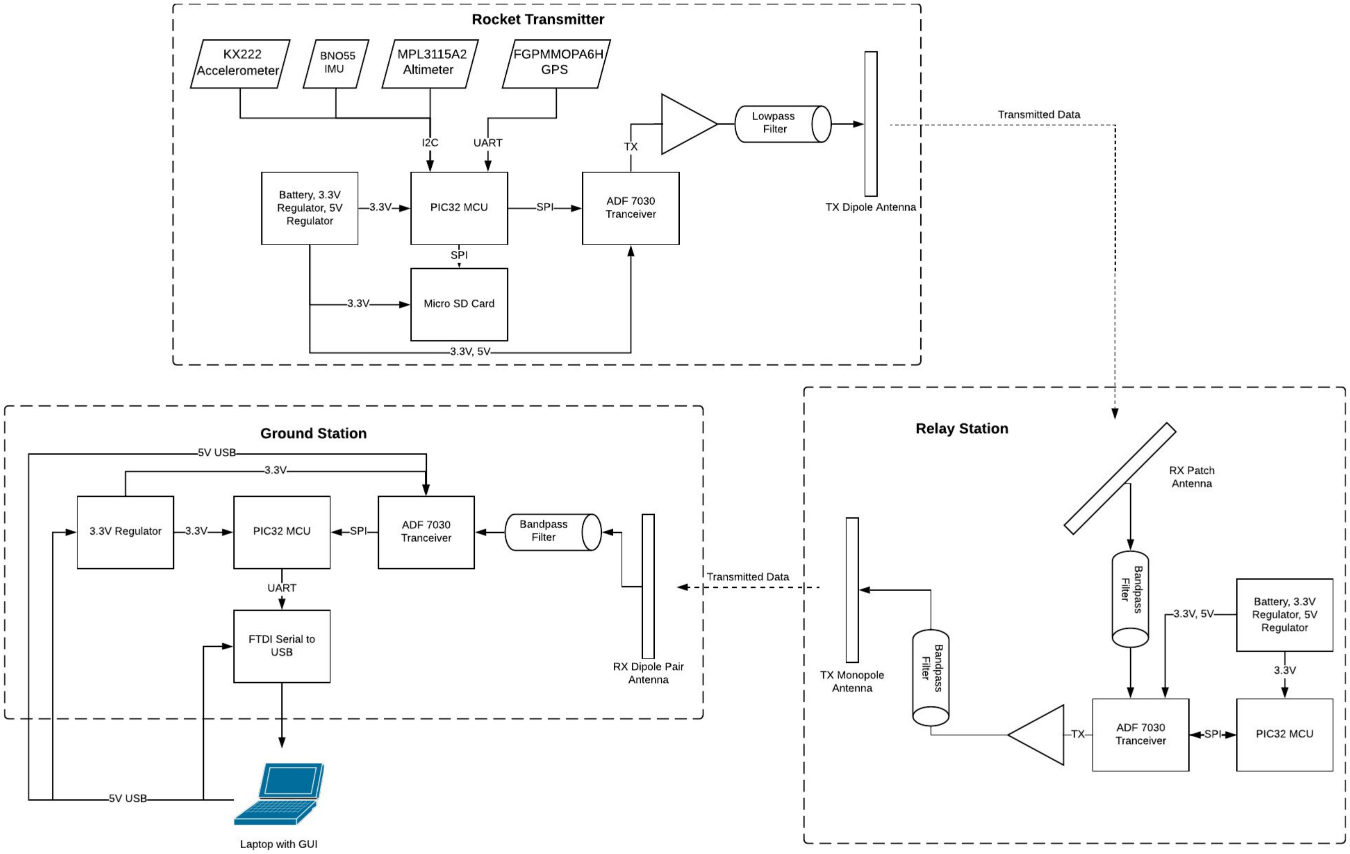
- Solution consists of three modules: Vehicle, relay station, and ground station
- Vehicle
  - Sensor board collects sensor data and organizes into packets
  - Sends packets to transceiver buffer to be transmitted
- Relay Station
  - Packets are received and transmitted using the automatic turnaround configuration
- Ground Station
  - Packets are received by the ground station transceiver
  - Ground station board reads data from transceiver buffer and prints to serial monitor



System Block Diagram

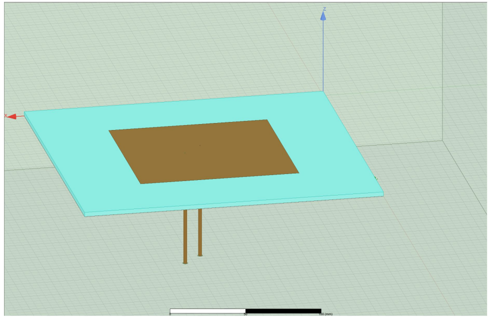
- Modules
  - Vehicle
  - Relay Station
  - Ground Station
- Subsystems
  - Sensor Board
  - Ground/Relay Station Board
  - Transceiver Board
  - Antennas

System Block Diagram

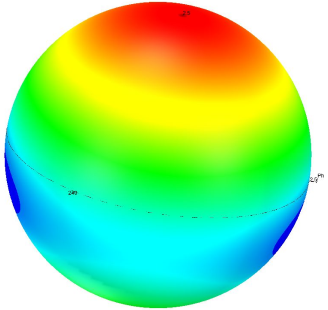


Antennas: Relay Station Receiver

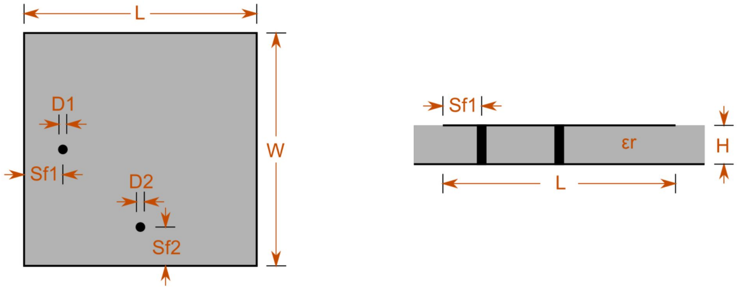
- Circularly-polarized 433 MHz patch antenna
  - Broad radiation pattern above the antenna
  - Receives all incident wave polarization angles
  - Quadrature (90°) hybrid for circular polarization
- Design
  - Antenna Magus initial design
  - Ansys HFSS: Model design, parametrize geometries
  - Parametric sweep for pin locations to minimize S_{11}



A view of the antenna model in HFSS



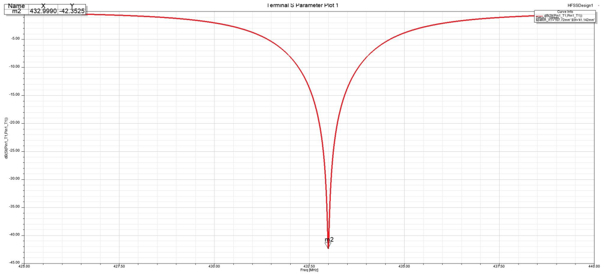
Radiation pattern in HFSS



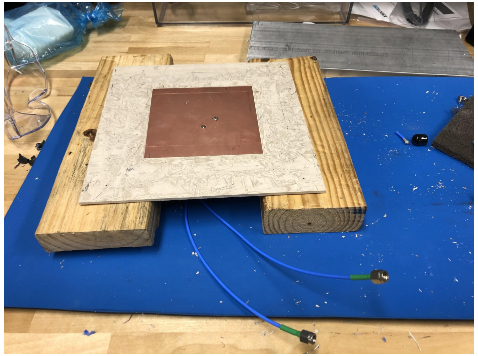
A schematic of the geometric variables studied

Antennas: Relay Station Receiver

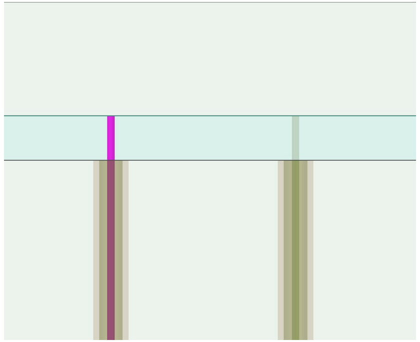
- Antenna fabrication
  - Rogers AD1000 0.12” substrate
    - Thick, high $\varepsilon_r \rightarrow$ smaller
  - Milled in Dr. Chisum’s lab
  - Coaxial cables soldered to ports
- S_{11} measured on VNA
  - Copper tape added to adjust



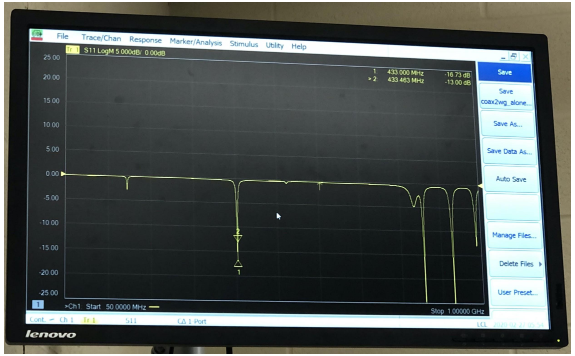
S_{11} plot in HFSS



The completed antenna



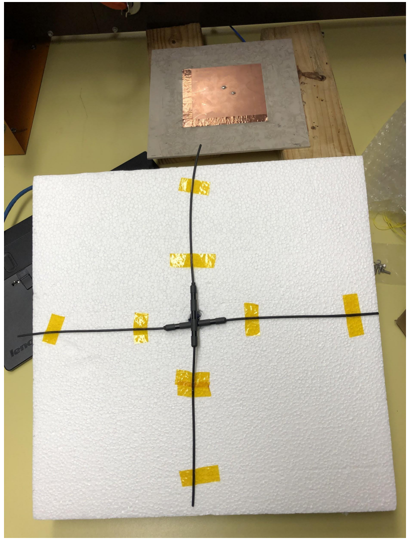
A side view of the antenna construction



VNA measurements

Antennas: Ground Station Receiver

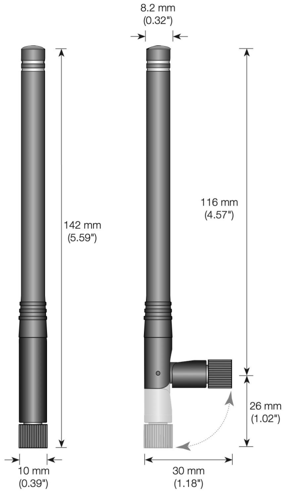
- Ground station antenna constructed but never used beyond initial measurements
- Made from two purchased 433MHz UHF semi-rigid dipole antennas
- Antennas secured in a styrofoam block to be perpendicular to each other
- Antennas feed into a quadrature hybrid, making it circularly polarized
- Easy to produce, wider band than patch antenna



Ground station receive antenna

Antennas: Relay Station, Rocket Transmitters

- Transmit from Relay Station to Ground Station
  - ANT-433-CW-HWR-SMA
  - λ/4 whip monopole by Linx Technologies
  - Included in the ADF7030-1 kit
  - Linear polarization
- Rocket Transmitter
  - Same 433MHz UHF semi-rigid dipole antenna used in the Ground Station receiver
  - Linear polarization
  - SMA connector
  - Purchased to guarantee 433 MHz
  - Flexible

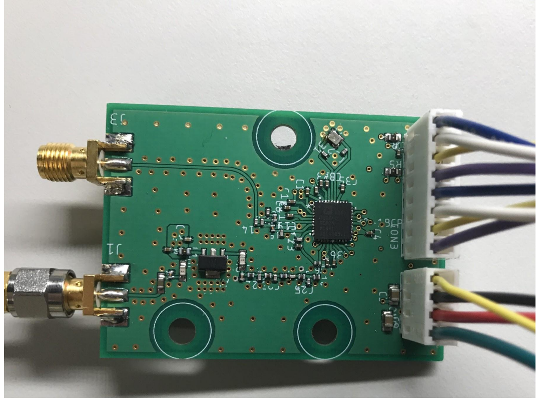


Relay Station transmitter
Source: Linx Technologies

Rocket Transmitter
Source: ReadyMadeRC

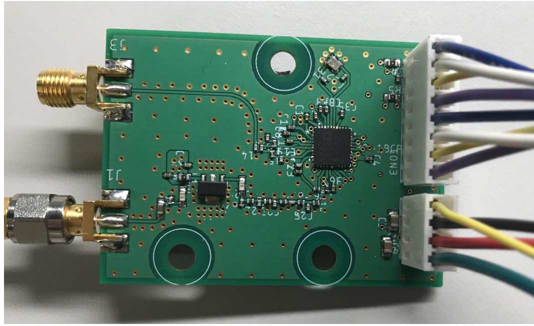
Transceiver Boards

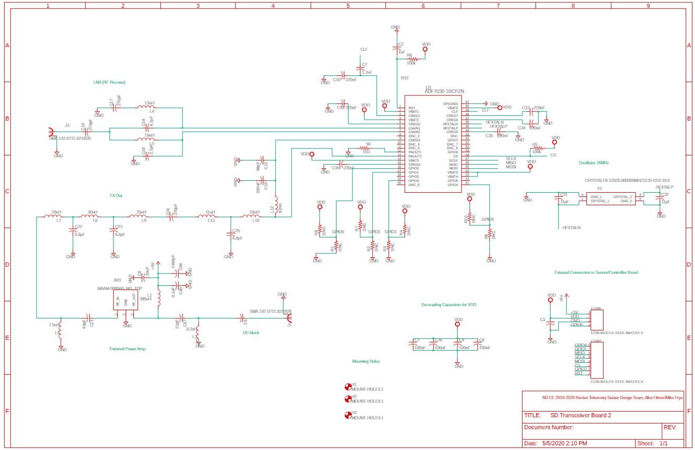
- Designed around Analog Device's ADF7030-1 integrated transceiver
- ADF7030-1 chosen to satisfy project requirements
  - Avoid interference with other transceiver systems
  - Transmit at sufficiently high data rate
  - Output at maximum allowed power
- Interference
  - ADF7030-1 used in 433MHz band
- Data rate
  - Data rate needed for sensors calculated to be 120kbps
  - ADF7030-1 capable of 300kbps
- Output power
  - Wanted to transmit at maximum competition allowed power of 24dBm
  - ADF7030-1's maximum output power is 17dBm
  - Included an external power amplifier



Transceiver Boards

- Important aspects of design around ADF7030-1
  - TX & RX SMA ports
  - 8,4 pin molex connectors for SPI interface, power, GP I/O pins
  - Power amplifier
  - Harmonic filter on TX output
  - RF considerations
    - Matching networks on RX input, TX output, around power amplifier
    - 4 Layer board stackup, trace width, sharp corners





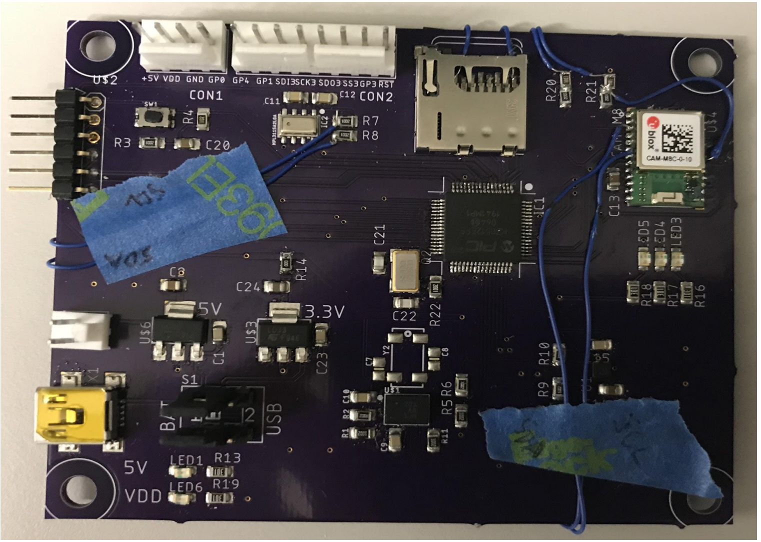
Vehicle Sensor Board

- General hardware:
  - Uses a PIC32MZ0512EFE064 processor and an external 8MHz crystal oscillator
  - PIC32MZ has several serial peripheral ports, providing each sensor with its own I2C, SPI, or UART interface
  - Board can be powered via a 2 cell LiPo battery (7.4V nominal output) or via USB
  - Voltage is regulated to both 5V and 3.3V lines using the LD1117
- Communicates to the vehicle transceiver via SPI interface using a molex connector to provide power, ground, and data
- Stores sensor data locally to micro SD card using SPI interface

Vehicle Sensor Board

- Sensors
  - MPL3115A2: Altitude sensor with a data rate of 38.4 kbps
  - KX222-1054: Accelerometer with a data rate of 76.8kbps
  - BNO055: Acceleration and orientation sensor with a data rate of 38.4kbps
  - FGPMMOPA6H: GPS sensor with a data rate of 0.96kbps

- Minimum required data rate is therefore 120kbps
- First iteration of the sensor board is shown here

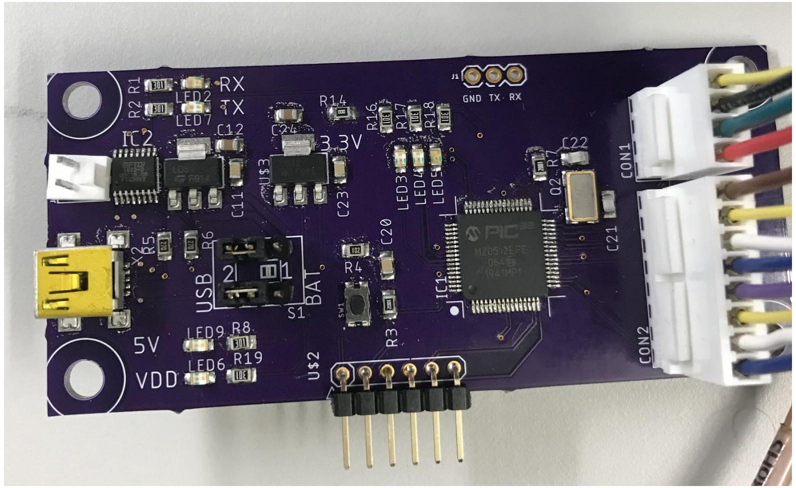


Relay and Ground Station Boards

- Same basic circuitry as the sensor board excluding the sensors themselves
- Uses a PIC32MZ processors with an 8MHz external crystal oscillator
- Same power supply hardware
  - Powered by 2 cell LiPo battery (7.4V nominal output) or USB connection
  - Voltage regulated to 5V and 3.3V lines
- Boards communicate with their respective transceivers via the SPI3 interface on the PIC32MZ with molex connectors providing power, ground, and data lines

Relay and Ground Station Boards

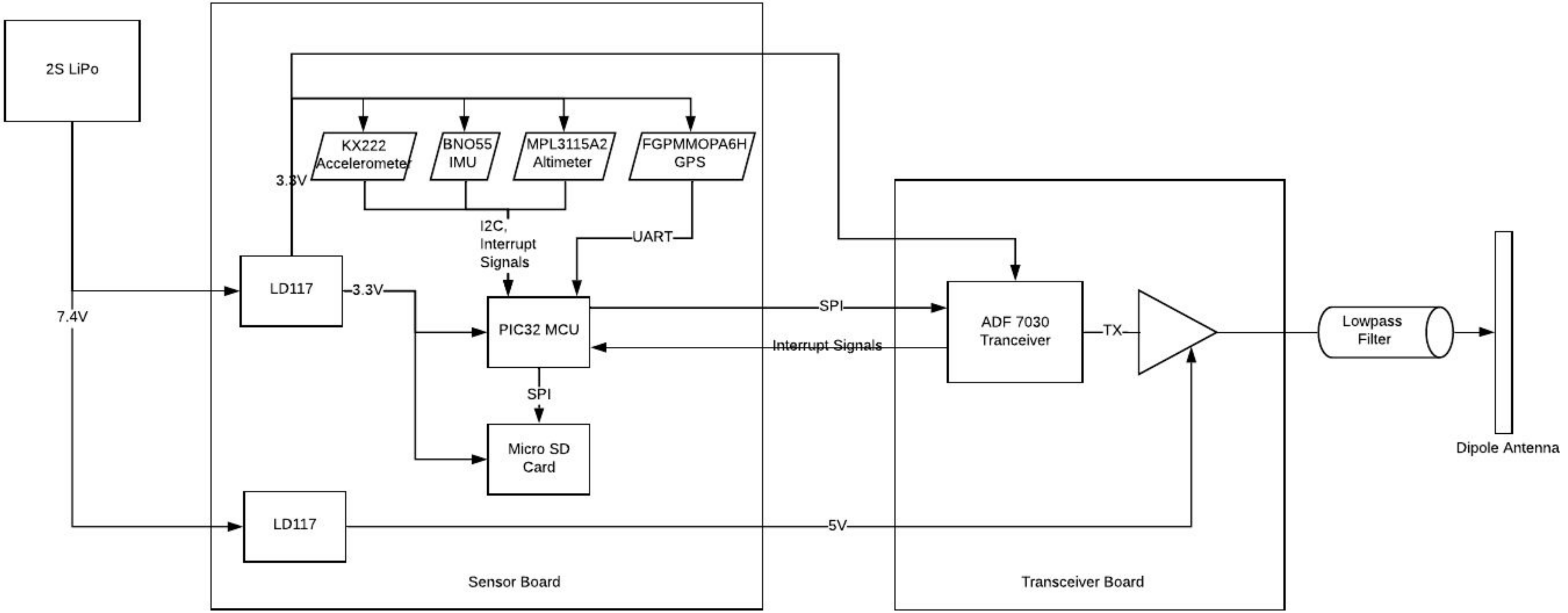
- Primary difference from sensor board is the addition of an FTDI FT230XS USB to UART chip
  - Allows received data to printed to a serial monitor
  - Uses the UART1 interface on the PIC32MZ at a baud rate of 57600 bps



Vehicle Module

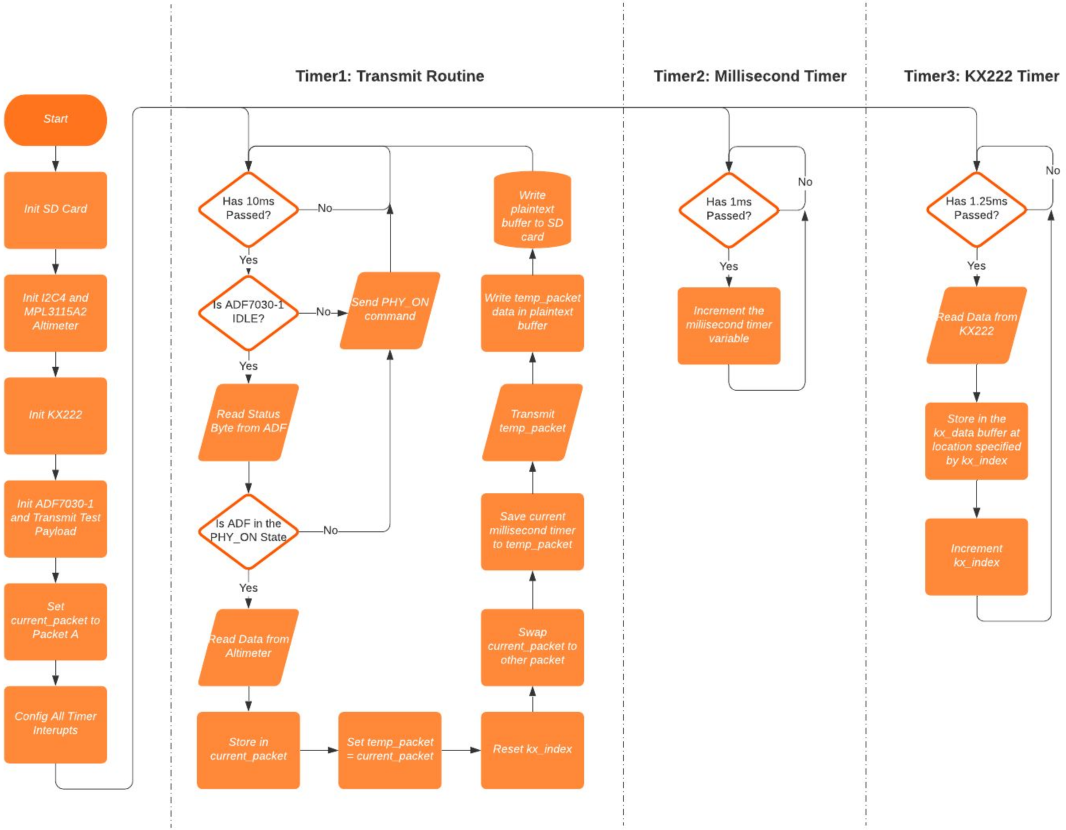
- Composed of
  - Sensor board
  - Transceiver board
  - 2 cell LiPo
  - RF lowpass filters
  - Dipole antenna
- LiPo - connected to sensor board - powers whole module
- 8 and 4 pin MOLEX headers connect boards - SPI, Power, I/O for interrupts
- Transceiver board RF output connected to filter via SMA
- Filter connects to dipole via SMA

Vehicle Module



Vehicle Module

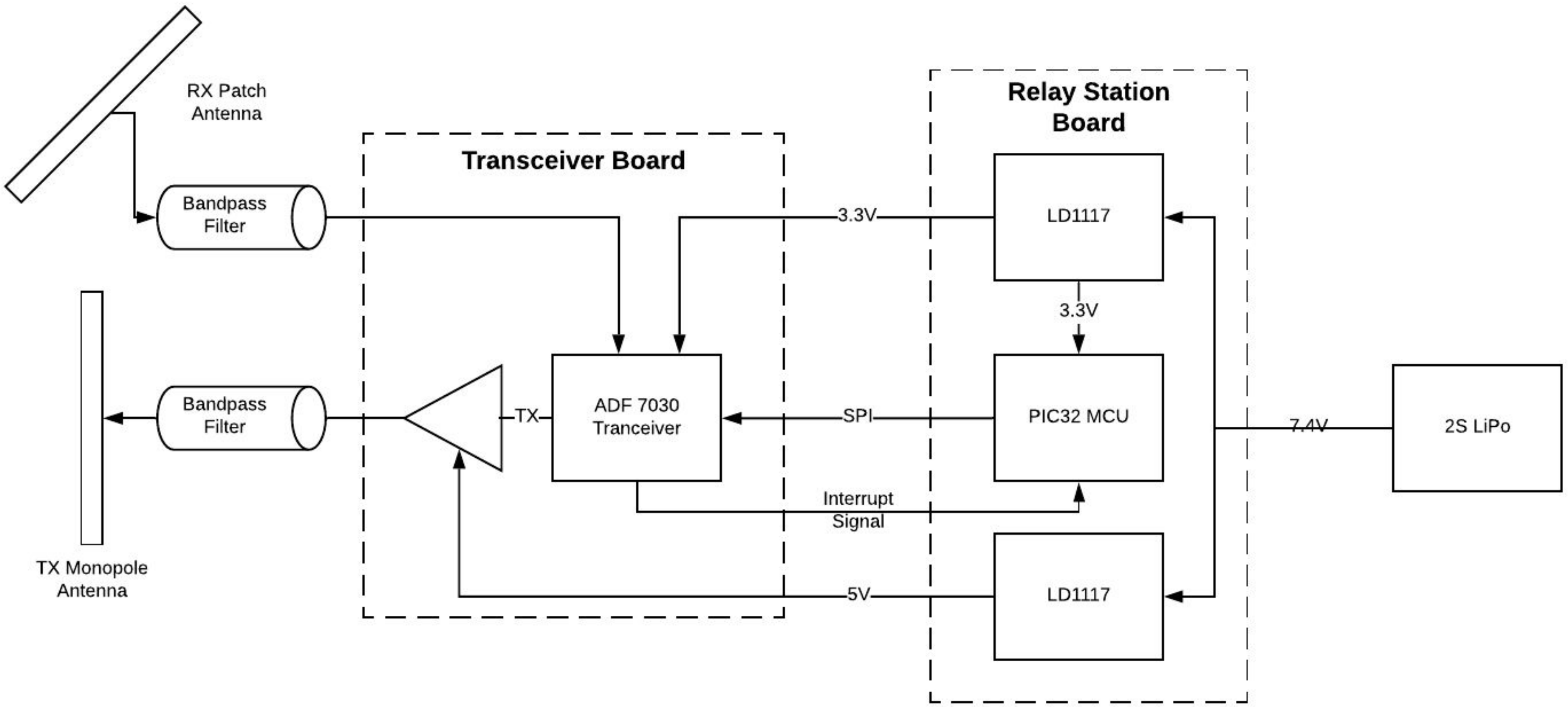
Software Flow



Relay Station Module

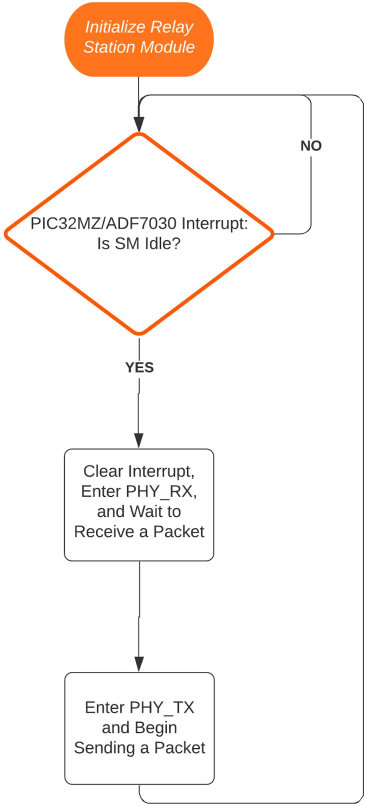
- Composed of
  - Ground/Relay station board
  - Transceiver board
  - 2 RF bandpass filters
  - Circularly polarized patch antenna & quadrature hybrid
  - Whip monopole antenna
  - Optional LiPo
- Station board and transceiver board connected via same MOLEX connector as in Vehicle Module
- Station board can be powered by LiPo or PC
- Patch antenna connects to transceiver board input through hybrid combiner and one BP filter via SMA
- Transceiver board output connects to whip monopole through BP filter via SMA

Relay Station Module



Relay Station Module

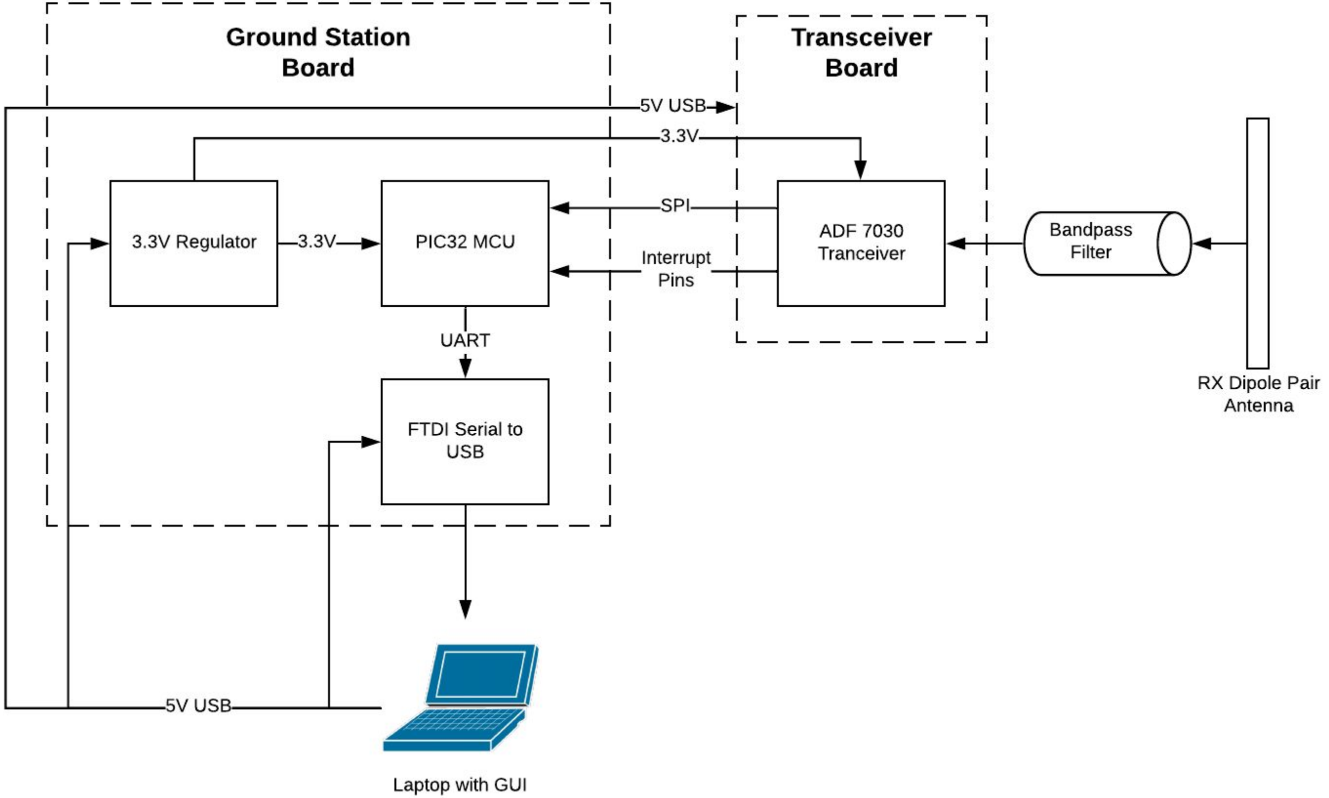
Software Flow



Ground Station Module

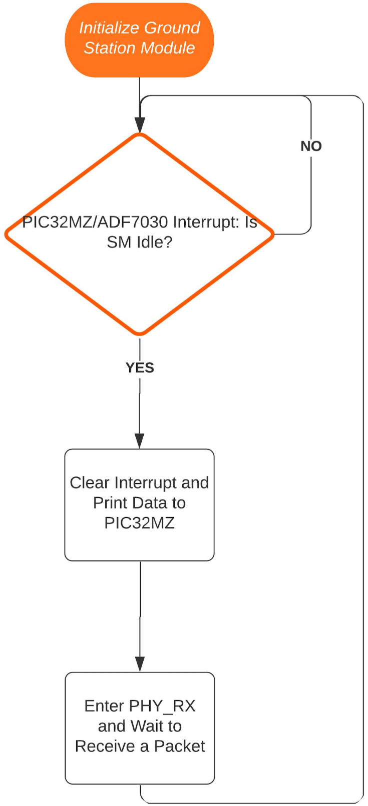
- Composed of
  - Ground/Relay station board
  - Transceiver board
  - RF bandpass filter
  - Circularly polarized dipole pair & quadrature hybrid
- Station board and transceiver board connected via same MOLEX connector as in Vehicle and Relay station modules
- Station board is connected to the PC which runs the display software via USB
  - Power to the board
  - Data to the PC
- Dipole pair connects to transceiver board input through hybrid combiner and BP filter via SMA

Ground Station Module



Ground Station Module

Software Flow



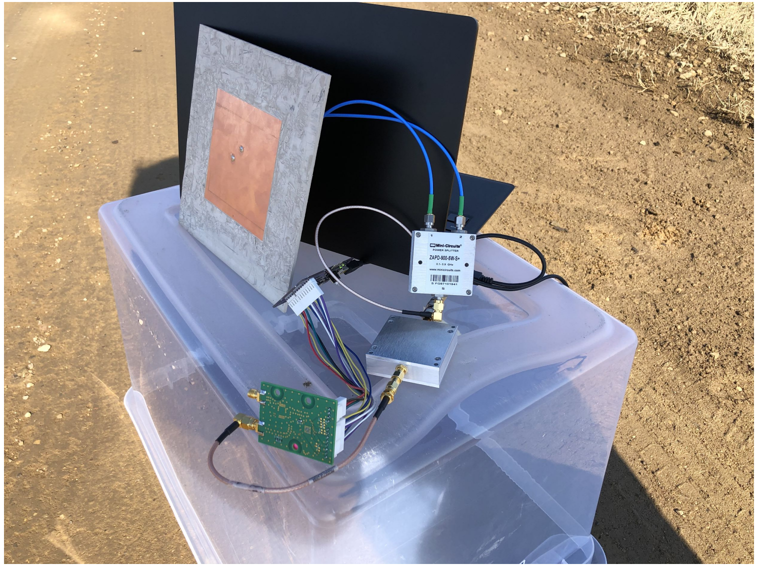
System Integration Testing

- Telemetry Range and Antenna Test
  - Objective: Ensure that the telemetry system will reliably transmit data from launch vehicle during entirety of the mission by evaluating the maximum range of transmission
  - Setup and Procedure:
    - Placed two transceivers at various distances (0.5 and 1 mile) as packets were transmitted between them
    - Maintained line-of-sight between the transmitter module and receiver module to mimic the line-of-sight transmission that will occur during launch vehicle flight
    - The antennas for the transmitter and receiver modules were both held approximately 5 ft above the ground and both modules were power from laptops that collected the data via PuTTY
    - Meant to represent the worst-case scenario due to high path loss along the ground
  - Results:
    - 0.5 Mile - Packet drop rate = 3.23%
    - 1 Mile - Packet drop rate = 8.33%
    - Since in either case the packet success rate exceeded 90%, the test was considered a success
    - Conditions in actual launch will be more favorable (less path loss) so the drop rate will likely decrease

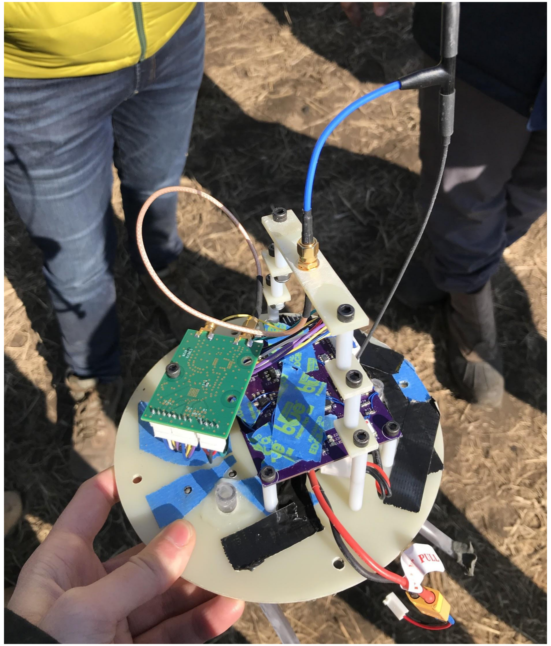
System Integration Testing Cont.

- Full-Scale Launch
  - Objective: Ensure that the telemetry system can reliably transmit, receive, and print data from the launch vehicle to the ground during the entirety of the mission
  - Setup and Procedure:
    - Two receiver modules placed ~0.5 mile away from the launch site
    - One receiver module used a monopole antenna and the other used a dual polarized patch antenna
    - Both antennas were held upright at ~3 ft above the ground and both receiver modules were attached to separate laptops for power and data recording via PuTTY
    - While received data was logged using PuTTY, data was also stored locally on the SD card of the vehicle module
  - Results:
    - Data for elevation and acceleration were continuously transmitted and received throughout the mission
    - Based on our transmitted and received data comparison, the test was successful

Full-Scale Launch Setup



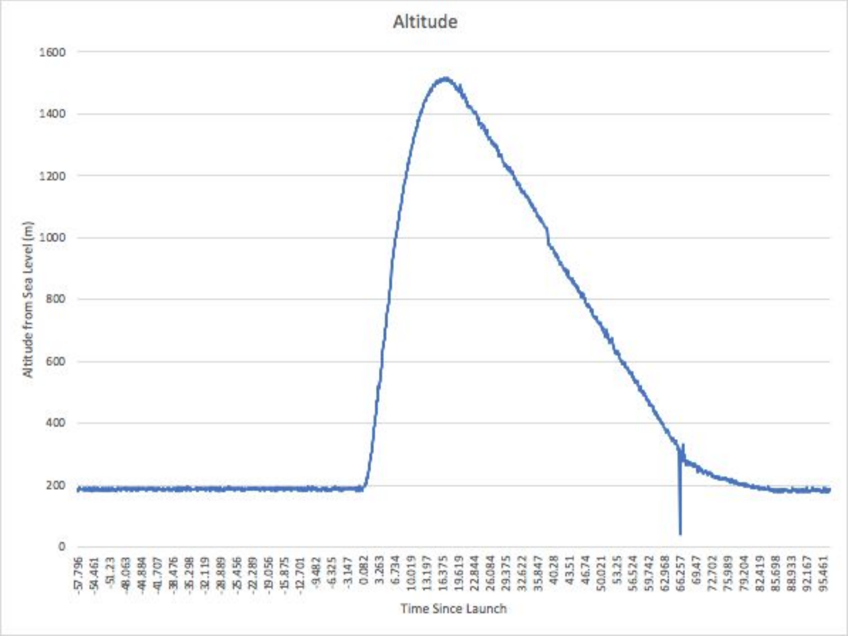
Full ground station setup with polarized patch antenna



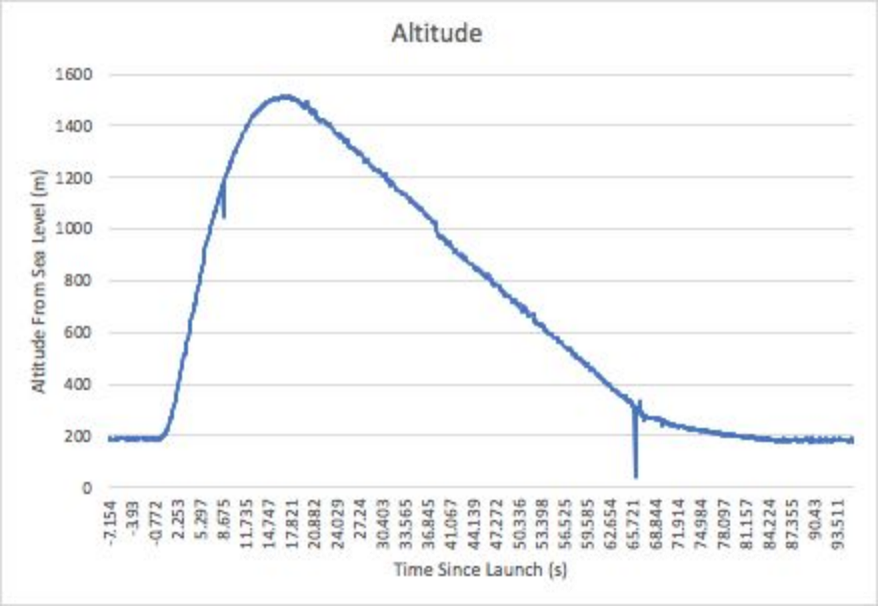
Full vehicle system setup with dipole antenna

Full-Scale Launch Data

- Example of locally saved data versus received altitude data



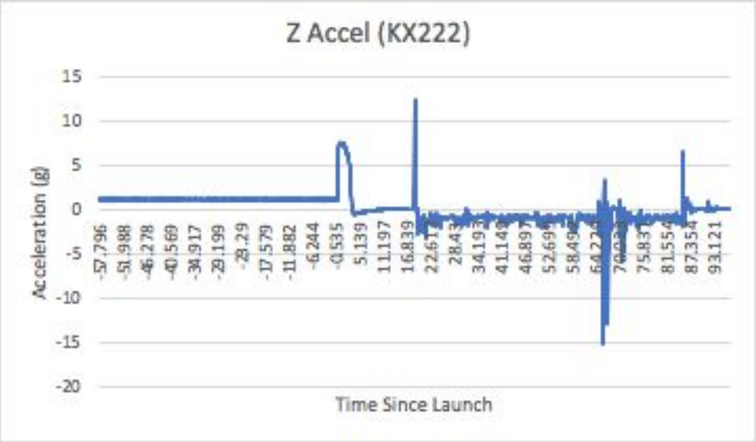
Locally Saved Data



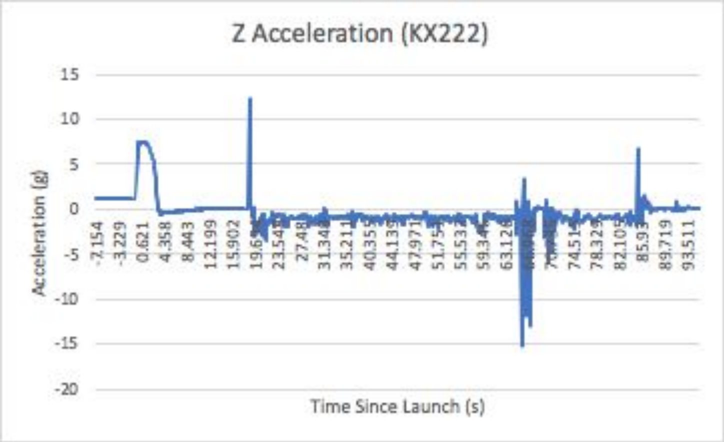
Received Data

Full-Scale Launch Data

- Example of locally saved versus received acceleration data



Locally Saved Data



Received Data

Future Design Changes

Due to the shortened timeline of this project, several changes should be implemented before the system is utilized by the Rocketry Team

- Integrate all sensor modules into the vehicle system
  - Full-scale launch proved the successful implementation of time, altitude and acceleration data
  - BNO055 and FGPMMOPA6H (GPS) modules were successful in preliminary tests, but were never fully integrated and tested in the final system
- Increase data rate to meet minimum 120kbps
  - Preliminary data indicates that the data rate is ~10.36kbps, well below the minimum required
  - Can be improved by increasing clock speeds, writing raw data to the SD card versus text, and converting to hardware interrupts instead of data polling
- Implementation of the relay-to-ground communication link
  - All tests were performed from air to ground; relay module never fully tested
  - Further antenna modifications should also be made at both the relay and ground stations
- Ground station user interface design
  - Would be useful to develop a UI to convey telemetry data in real-time
  - Rocketry team would be able to track rocket position, trajectory, altitude, and acceleration during flight

Conclusions

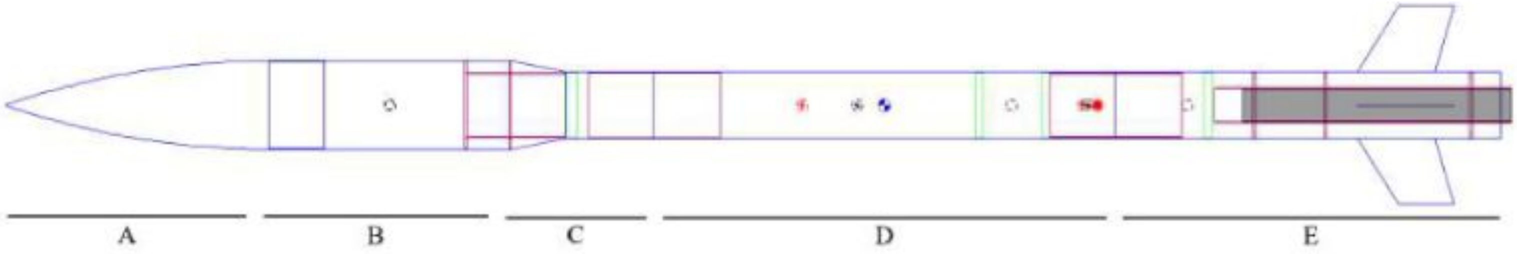
- Despite a shortened timeline due to COVID-19, significant milestones were achieved
  - The communication link meets the conditions of the rocket launch
  - The full-scale test launch demonstrated that altitude and acceleration data can be successfully recorded and transmitted to the ground throughout the duration of the flight
  - The GPS and BNO055 modules are successful as standalone projects
- Following the implementation of the recommended design changes, the system will likely meet NDRT's requirements and goals
- There is significant hope that a future senior design team will complete the project and continue to improve the system for NDRT

Questions?

Backup Slides

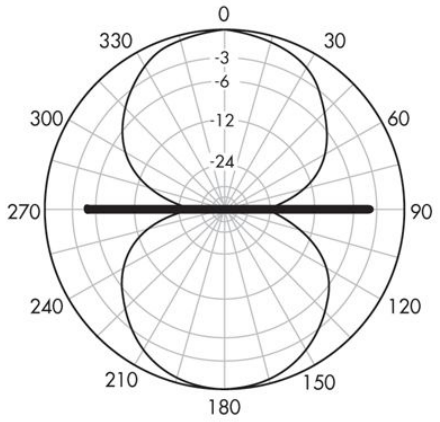
Proposed Solution: Location

- NDRT had space for Telemetry hardware in Nose Cone (A) or Fin Can (E)
- Fin Can is made of carbon fiber
  - Antennas and GPS would need to be mounted outside
- 3D printed nose cone is RF transparent
  - Can leave components inside rocket
  - 2’ long, 8” wide

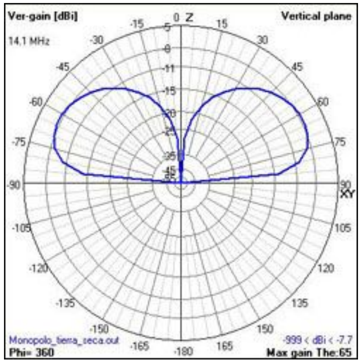


Proposed Solution: Relay Station

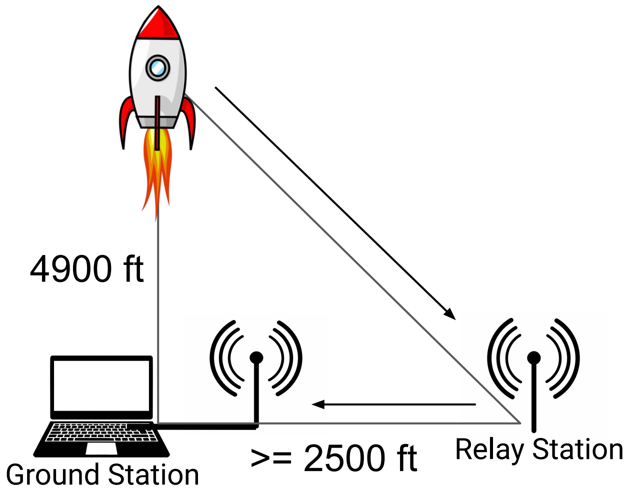
- Serves as an intermediary between rocket and ground station
- Necessary because of the geometry of the problem
  - Ground station ~300ft from launch
  - Rocket 4900ft at apogee
  - 86° angle from ground to rocket



Radiation pattern of a half-wave dipole antenna

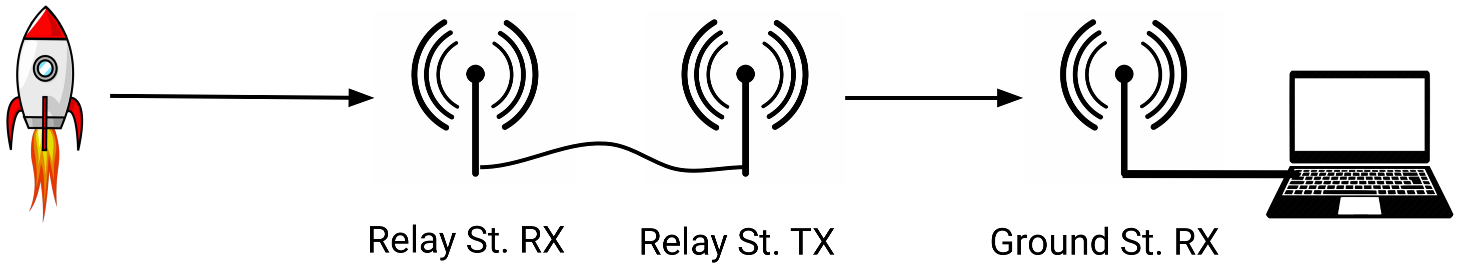


Radiation pattern of a ground plane monopole antenna



Proposed Solution: Ground Station

- Ground station will consist of commercial radio link receiver connected to a laptop
  - Custom-made receiver on relay station will give data to commercial transmitter via wired connection
  - Commercial transmitter will forward to commercial receiver
  - Commercial receiver will provide data to ground station laptop
- Software on laptop will pull data from the link, process it, and display via a GUI



Demonstrated Features

- Functional radio link
  - Demonstrate that readings from stationary rocket can be transmitted and received successfully by ground station
  - Verifies transmitter/receiver hardware and ground station software in real time
- Launch performance
  - Locally store data from the launch to demonstrate successful sensor readings
  - Record the UI feed from the launch and replay during demonstration to demonstrate link functionality in its intended environment