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Controllable Open-source Water Sensing (COWS)

Information

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Nomenclature

A: Area of a Solar Panel

Comms: Communications

CONOPS: Concept of Operations

DCDC: Direct-Current to Direct-Current

DOD: Depth of Discharge

DR: Derived Requirement

e: Elevation Angle

e_{cloudy}: Power Generation Efficiency in a Cloudy Day Compared to a Sunny Day

e_{module}: Solar Energy Conversion Efficiency

FR: Functional Requirement

G: Solar Irradiance

GLONASS: Глобальная навигационная спутниковая система (RU), Global Navigation Satellite System (EN)

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

I: Current

I/O: Input/Output

IR: Interferometric Reflectometry

I^2C: Inter-Integrated Circuit

MicroSD: Micro Secure Digital

P: Power

PC: Power Capacity

PCB: Printed Circuit Board

RF: Radio Frequency

RSD: Remote Sensing Device

SLA: Sealed Lead Acid

SMA: SubMiniature Version A

SNR: Signal to Noise Ratio

UART: Universal Asynchronous Receiver/Transmitter

USART: Universal Synchronous/Asynchronous Receiver/Transmitter

V: Voltage

α: Earth Tilt Angle

β: Solar Elevation Angle

γ: Solar Hour Angle at Sunrise/Sunset

η: Efficiency

θ: Latitude from the Equator

μ: Solar Hour Angle

ϕ: Azimuth Angle

Ω: Ecliptic Latitude

1 Project Purpose

Authors: Ethan Stapp, Toan Lu

With climate change and global warming becoming an ever-present issue across the world in recent years, the need for accurate water level monitoring systems is increasing yearly as sea levels rise and fresh water scarcity become more prevalent issues. Many remote sensing devices are already deployed across the world for monitoring weather. However, these devices are often too expensive for many communities across the world to afford, and they often contain expensive or proprietary software. With the current worldwide availability and coverage of GNSS satellites, and the knowledge of the GNSS-Interferometric Reflectometry (GNSS-IR) technique highlighted in Appendix 4, this provides a unique opportunity to develop a low-cost and open source GNSS-IR water level monitoring system that can be deployed in remote locations across the world and accurately measure changes in water level in near real-time.

The mission objective for this project is to develop a low-cost, open source, near real-time water level monitoring system with high temporal resolution that can be deployed in remote locations across the world and be operable in varying weather conditions. The low-cost nature of this project is made achievable through the GNSS-IR technique. This technique allows for the use of low-precision GNSS receivers that have a lower cost. With this project being both low-cost (less than $800) and open-source, this project will be able to be built and used by anyone around the world for water level or snow level monitoring. The CONOPS for the GNSS-IR system is included below in Figure 1.1.

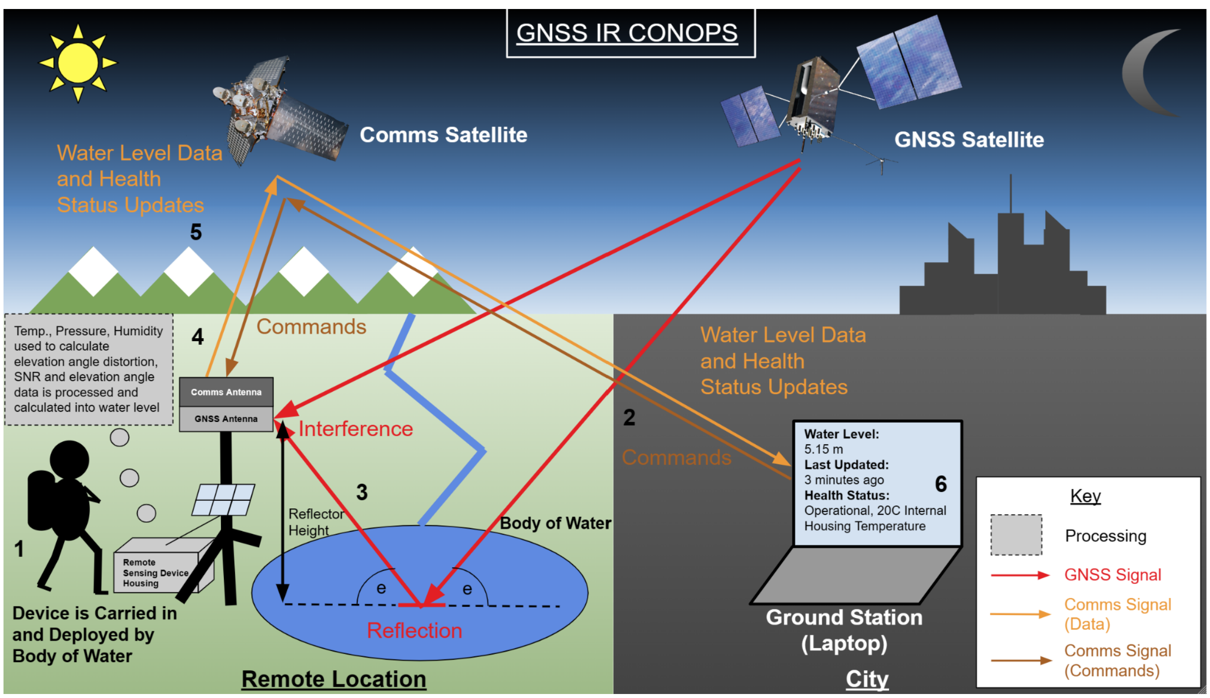

Figure 1.0.1 GNSS-IR CONOPS

The first step to setting up the remote sensing device is backpacking in the GNSS-IR device and deploying it next to a body of water. Second, system configuration commands will be sent from the ground control station to the remote sensing device to specify minimum and maximum azimuth angles, in addition to elevation angles. Third, the remote sensing device will receive the direct and reflected signals through the GNSS antenna and then process them into SNR and elevation angle for further processing. Fourth, the SNR and elevation angle data will be processed on-site through the microprocessor into water level data. After this, onboard temperature, pressure, and humidity sensors will be used to calculate tropospheric elevation angle distortion effects. Fifth, the water level data and health status updates (including internal housing temperature and the operational status of the device) will be sent through the comms module to the comms antenna, over the Iridium satellite network, to the ground control station. Sixth, the ground control station will display the water level data, time when that data was taken, and the health status of the device on a screen for the user. Moreover, data processing option commands (e.g. specifying average vs. instantaneous water height) and system reboot commands (resetting the GNSS receiver and rebooting the comms module) can also be sent by the user.

2 Detailed Design

Authors: Ethan Stapp, Sean Vestecka, Kristyn Grell, Blake Wilson, Toan Lu, Micah Bergeron

2.1 Functional Block Diagram

A detailed functional block diagram (FBD) of the GNSS-IR system is included below in Figure 2.1.1. The FBD includes each of the major components of the system arranged into their respective subsystems and locations. Components are highlighted in blue, subsystems are outlined in dashed gray lines, and locations are outlined in black dashed lines. The FBD also shows the connections between components to the pin level and highlights the signals sent between components, with data signals in black, 3.3V power in light green, 5-18V power in dark green, ground in pink, comms signals in orange, and GNSS signals in red. The system's functionality and subsystems are explained below the figure.

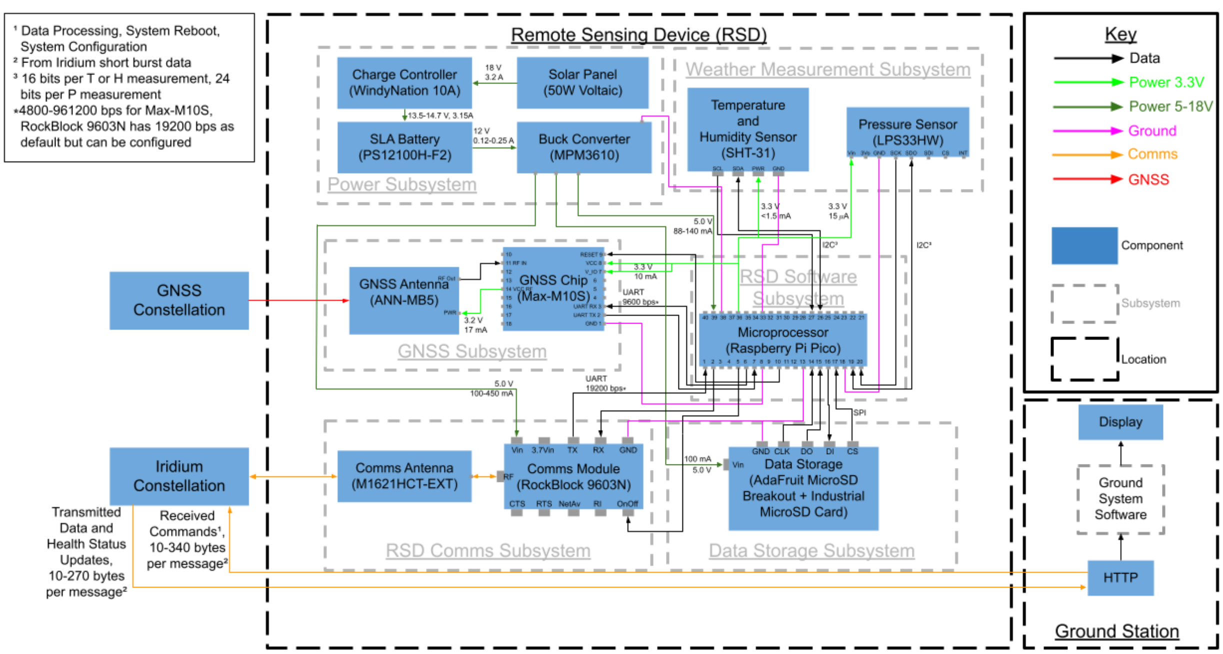

Figure 2.1.1 System Functional Block Diagram

Note: Unless otherwise mentioned, all components are rated within the -30 °C to 55 °C temperature range

The Power Subsystem consists of a solar panel, charge controller, battery, and buck converter. As shown in the FBD, the 50W Voltaic Systems solar panel will supply 18V and 3.2A to the WindyNation 10A charge controller. This charge controller will then take the power supplied by the solar panels and use it to charge the sealed lead-acid (SLA) PS12100-F2 battery between 13.5-14.7V and 3.15A. The battery will then supply 12V and 0.12-0.25A to the MPM3610 buck converter, which converts the 12V from the battery to 5V for the RockBlock 9603N comms module, the Raspberry Pi Pico microcontroller, and the AdaFruit MicroSD Breakout data storage.

The GNSS Subsystem will interact with GNSS constellations to read their signals and deliver them to the microprocessor. Its two components are the GNSS Chip and the GNSS Antenna. The selected GNSS chip is the ublox MAX-M10S. Its purpose is to read the incoming RF signals from the antenna and parse GNSS signals, delivering the result of its parsing in the form of NMEA messages. The chip communicates with a bi-directional UART serial connection with a baud rate of 9600 bps with the microcontroller. The chip will deliver the latest NMEA messages to the microprocessor over this connection. It also receives 3.3V power from the microprocessor's 3.3V rails. Additionally, the chip delivers the required 3.2V power to the antenna for its internal amplification. The selected GNSS antenna is the ublox ANN-MB5. The antenna will read GNSS signals and send them to the GNSS chip.

The Comms Subsystem works with the Iridium satellite communications network. As shown in the FBD, its primary components are the communications antenna and the communications module. The selected communications module, the RockBlock 9603N, is based on an Iridium 9603 module. It acts as receiver and transmitter for messages to and from the network, sending messages from the microprocessor and receiving messages from the ground station. It has a bi-directional UART serial connection with a baud rate of 19200 bps with the microcontroller. It transmits and receives messages over its RF port, which connects to the communications antenna. It also takes in 5V power directly from the buck converter. The selected communications antenna is the Maxtena M1621GCT-EXT. This helical antenna is designed to interact with the Iridium satellite network. It connects to the communications module, delivering it the signals it receives.

The Data Storage Subsystem interfaces with the Remote Sensing Device Software Subsystem, which the Data Storage Subsystem will store the calculated water level height in case the Remote Sensing Device Software Subsystem is unable to communicate with the Ground Station Software Subsystem. The selected Micro SD card is the Kingston Industrial Micro SD card. Its purpose is to store the calculated water level data and interface with the selected Micro SD card reader, Adafruit MicroSD Card Breakout. The Micro SD card reader will interface with the microprocessor through I^2C.

The Remote Sensing Device Software Subsystem consists of the Raspberry Pi Pico microcontroller, as shown in the FBD. This subsystem is responsible for processing SNR, elevation angle, and weather data (air pressure, air temperature, and relative humidity) into water level and sending water level data to the Comms Subsystem for transmission. This subsystem is also responsible for processing system reboot, system configuration, and data processing commands. Because of this required functionality, the subsystem interfaces with the GNSS Subsystem through UART to receive SNR and elevation angle data, interfaces with the Comms Subsystem through UART for sending data and receiving commands, interfaces with the Weather Measurement Subsystem through I^2C for receiving temperature, pressure, and humidity data for tropospheric distortion effects, and interfaces with the power subsystem which powers the microcontroller through the buck converter.

Finally, the Ground Station Software Subsystem consists of the website (HTTP), the ground station software, and the display. The Ground Station Software Subsystem will interface with the Comms Subsystem through the Iridium constellation to transmit system reboot, system configuration, and data processing option commands to the remote sensing device. It will also receive water level data and health status updates from the remote sensing device. The Ground Station Software Subsystem will provide a user interface for the purpose of sending commands to the remote sensing device and viewing near real-time water level data and health status updates.

2.2 Power Subsystem

The Power Subsystem contains the power generation (50W Voltaic Systems Solar Panel), power storage (PS12100H-F2 SLA battery), and power conversion components (i.e. WindyNation 10A Waterproof Solar Charge Controller and MPM3610 DCDC Buck Converter). The Power Subsystem is responsible for generating, storing, and supplying power to the various subsystems and components of the remote sensing device. This includes providing continuous power to the Remote Sensing Device Communication Subsystem, the GNSS Subsystem, the Weather Measurement Subsystem, Data Storage Subsystem, and the Remote Sensing Device Software Subsystem. In the Power Subsystem, batteries and solar panels are essential to ensure the entire system to function in any weather conditions. With a consideration of the allowable temperature range of charging, lead-acid batteries are the most suitable for the remote sensing device. The battery used in this system has a charging temperature range between -20 °C and 50 °C and a discharge temperature range between -40 °C and 60 °C.

2.3 GNSS Subsystem

The GNSS subsystem consists of the GNSS chip (MAX-M10S), SMA connector, GNSS antenna (ANN-MB5), antenna signal conditioning and filtering circuitry, I/O for data communication via UART, and power. The GNSS chip is responsible for receiving GNSS signals, including elevation angle and SNR data, from the antenna via the SMA connection, and is able to receive signals from multiple constellations (GPS, Galileo, GLONASS, BeiDou) at various carrier frequencies. The chip is also able to encode the contents of the message into various formats, including multiple specs of NMEA messages. The GNSS chip will be on a fabricated PCB, which the designs are detailed in Figures 2.3.1, 2.3.2, and 2.3.3. If the fabricated PCB is unsuccessful, the offramp is to use a commercial breakout board (The MAX-M10S GNSS Breakout from Sparkfun). The selected GNSS antenna is designed to receive GPS/Galileo/BeiDou/GLONASS L1, GPS L5, Galileo E5a, BeiDou B2a, and NavIC signals.

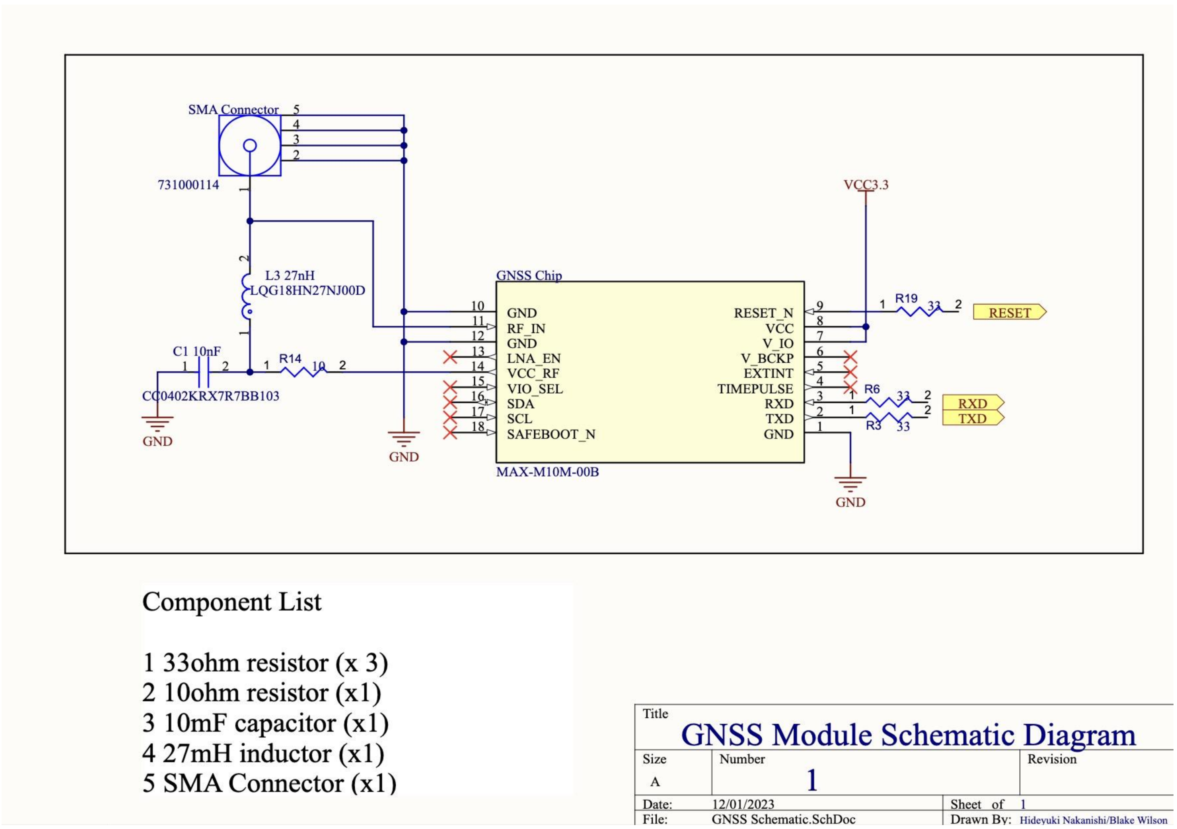

Figure 2.3.1 GNSS Module Schematic Diagram

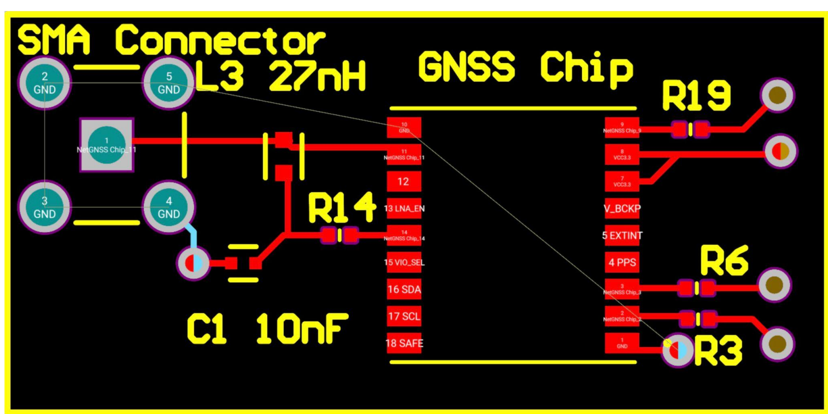

Figure 2.3.2 GNSS PCB Design

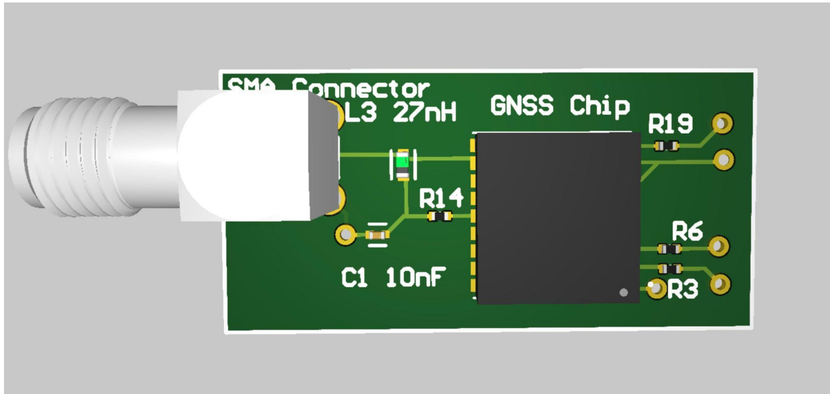

Figure 2.3.3 Realistic Model of GNSS PCB Board

2.4 Remote Sensing Device Communications Subsystem

The Remote Sensing Device Communications Subsystem contains the remote sensing device's communication equipment that includes an antenna (M1621HCT from MAXTENA), amplifiers, filters, SMA connectors, and an Iridium 9603N module. The communication subsystem is primarily on the RockBLOCK 9603N module from Ground Control, which contains the Iridium 9603N module, an SMA connector, a serial connector, and components for signal conditioning and amplification. It is responsible for communication between the remote sensing device and the ground station, this includes sending water level data to the ground station, sending health status updates to the ground station, and receiving commands from the ground station, and vice versa.

2.5 Remote Sensing Device Software Subsystem

The Remote Sensing Device Software Subsystem is the remote sensing device's open source, onboard software. This subsystem only includes the Raspberry Pi Pico microprocessor, which is responsible for calculating the water level (to better than 5 cm accuracy) using the GNSS-IR technique with SNR and elevation angle data from the GNSS-IR sensor, and saving the data to the Data Storage Subsystem, and sending the data to the ground station via the Communications Subsystem. This subsystem will perform tropospheric distortion calculations using data collected from the Weather Measurement Subsystem. Additionally, this subsystem is responsible for interpreting commands sent from the ground control station through the Remote Sensing Device Communications Subsystem and is responsible for configuring the remote sensing device after receiving either system reboot commands, data processing option commands, and system configuration commands. This subsystem is also responsible for sending health status update information to the Remote Sensing Device Communications Subsystem, which is then transmitted to the ground control station. The Pi Pico is rated to -20 °C, so a test will need to be performed to verify functionality at the minimum temperature bound of -30 °C.

2.6 Weather Measurement Subsystem

The Weather Measurement Subsystem will contain temperature, barometric pressure, and humidity sensors, which is responsible for measuring the temperature of the air (T), atmospheric pressure (P), and relative humidity (H) data for tropospheric distortion calculations. These values will be read every 15 minutes and will be sent to the microcontroller via its I^2C bus, and used to calculate the error in elevation caused by tropospheric distortion. This elevation angle correction will be saved in the data storage subsystem if needed for later use. To do this, the system will perform the calculations derived by Feng, Haas, and Elgered[1]. Important equations for this calculation are shown below.

$$\Delta e = 10^{-6} N_0 \frac{cos(e_T)}{sin(e_T)+0.00175\, tan(87.5°-e_T)} \quad (1)$$

$$N_0 = K_1 \frac{P_d}{T} + K_2 \frac{P_w}{T} + K_3 \frac{P_w}{T^2} \quad (2)$$

$$P_w = \frac{H*P_s(T)}{100} \quad (3)$$

In the final equation above, e_T is true elevation angle, P_d is the dry air pressure and P_s is the saturation pressure, which is a function of temperature. K_1 , K_2 , and K_3 are constants. The elevation angle distortion can easily be computed by the microcontroller.

2.7 Data Storage Subsystem

The Data Storage Subsystem includes non-volatile external data storage via a 32GB micro SD card and any additional memory equipment. This subsystem is responsible for collecting and storing data received from the GNSS Subsystem and the Remote Sensing Device Software Subsystem. It will also be responsible to keep the data on the remote sensing device if the Sensing RF Subsystem is unable to communicate with the Ground Control Station Software Subsystem for various reasons (e.g., not having a direct line of sight with Iridium satellite).

2.8 Ground Control Station Software Subsystem

The Ground Control Station Software Subsystem is the ground control station's open source, onboard software for providing an interface to the user for control and data monitoring of the GNSS-IR system. This subsystem is responsible for providing a user interface for and sending system configuration, system reboot, and data processing options commands to the remote sensing device. Furthermore, this subsystem is responsible for receiving and displaying water level data and health status updates from the remote sensing device through a user interface.

2.9 Component Housing and Structure

The structure of the deployable device can be divided into two main sections: housing and mounting. Housing covers how components are stored and protected during deployment, while mounting refers to the attachments of components that are able to exist outside in the elements during the period of deployment, such as the solar panel and the GNSS-IR antenna.

2.9.1 Component Housing

The housing consists of an off the shelf electrical box which has a waterproof rating of IP67 and is made of ABS plastic. It contains all electrical components except for the antennas and charge controller, which will be mounted externally. The housing material allows for holes to be drilled for cable glands and bypasses to be inserted without compromising the integrity of the entire box. The box comes with mounting brackets which can be used in combination with a series of metal stakes to attach the box to the ground. The CAD model of the housing setup is shown in Appendix 2.

Based on the thermal model, colder climates may require insulation to be included in order to keep the internal temperature within operating range. The housing box is sized so that it can be fitted with 1” thick foam insulation as needed for cold climates, but can also be deployed without it for areas that more consistently reach the upper end of the temperature threshold.

2.9.2 Mounting Pole

There are three total components that will be kept separate from the housing box and will therefore be mounted independently. These three components are the solar panel, the GNSS antenna (ANN-MB5), and the communications antenna (M1621HCT from MAXTENA). Each device is secured to a modular mounting pole that will be manufactured in house.

Since different bodies of water require the ANN-MB5 antenna to be positioned at different heights above the surface of the water, the mounting pole is able to adjust to every half meter increment between 0.5 and 2 meters. The pole itself is made of individual pieces of 4-inch diameter PVC connected by 4-inch diameter PVC couplings as needed. Both the M1612HCT and the ANN-MB5 are secured at the top of the pole, while the solar panel is secured at the base of the pole with a mounting bracket from the solar panel manufacturer. The base of the pole also has four right-angle brackets attached to it to act as a stable base. These brackets can in turn be staked to the ground in order to prevent the mounting pole from shifting or tipping in variable weather conditions. A CAD model of the mounting pole setup is shown in Appendix 2.

The 4-inch diameter PVC pipe was determined to be the most optimal material for the mounting pole based on price and strength. Due to the sensitive nature of the ANN-MB5 antenna, the maximum allowable horizontal displacement that the antenna can experience is five centimeters. A model was developed that calculates the antenna displacement based on varying wind speeds and PVC diameters, which includes the effects that the wind acting on the solar panel has on the entire mounting pole. This wind beam deflection model is explained in detail in Appendix 3. The 4-inch diameter PVC pipe was the minimum diameter that was able to withstand high wind speeds while having a tip displacement of less than 5 centimeters.

3 Engineering Models and Prototyping Results

Authors: Hideyuki Nakanishi, Ethan Stapp, Sean Vestecka, Kristyn Grell

Model or Prototype Test	Description	Requirements Verified
Power Model	Using MATLAB, the model looked into power consumption, solar panel generation, battery life, and battery recharge time.	FR 2.0, DR 2.1, DR 2.3
Wind Beam Deflection Model	Using MATLAB, the model calculates the deflection of the tip of the antenna pole due to forces from and the mounted solar panel for a variety of PVC pipe sizes.	FR 3.0, DR 2.1, DR 7.2.1
Thermal Model	Using MATLAB, the model calculates the radiation produced by the components within the housing. The model was also used to verify that the temperature within the housing is still within the temperature requirements.	DR 2.1, DR 7.2.1
GNSS-IR Prototype	Using a SparkFun breakout board for the MAX-M10S and the Raspberry Pi 4, test data was taken to verify the system would meet the 5 cm accuracy requirement without use of an array configuration. The data taken had an error of 1.5 cm.	FR 2.0, DR 2.1, FR 7.0, DR 7.2

Table 3.0.1 Models and Prototype Tests Completed

3.1 Power Model

The power subsystem needed to be modeled in order to verify the required size of the solar panel and battery based on the amount of power that can be generated and stored in varying weather conditions. The power model covered power consumption, power generation, battery life, and battery recharge time in peak sun hours.

3.1.1 Power Consumption

The power consumption by the entire system was calculated by using Ohm's law to ensure the device remains operational for three days without power generation. There is a single GNSS antenna and receiver in the system with an assumption of two received and two transmitted messages per hour. It is assumed that each component is turned on at all times for three days. The total power in Watts was determined by the sum of the power from each component, shown in the following equation.

$$P_{total} = \sum_{i}^{n} I_i \cdot V_i \ \text{[W]} \tag{4}$$

It is also important to highlight the required amount of power that the system draws over a period of three days without power generation. The power capacity in Whr was computed by the product of the total power and the period of three days in hours.

$$PC_{total} = P_{total} \cdot \Delta t \ \text{[Whr]} \tag{5}$$

Total Power Required [W]	1.74
Power Capacity Required [Whr]	125

Table 3.1.1 Total Power Consumed and Power Capacity Required for 3 Days

Based on the datasheet, the battery capacity is 126 Whr, meaning that the system can function theoretically for 3 days without generating power. This is sufficient for DR 2.3.1, the power subsystem requirement for having 3 days of power storage.

3.1.2 Power Generation

The power generation of the solar panel needs to be investigated at different latitudes with varying weather conditions to ensure it can generate enough power to operate the remote device for at least 3 days. In this model, the solar energy during the periods around the summer and winter solstices were particularly examined because these are when the solar energy can be gained at minimum and maximum. Note that a solar panel is positioned hypothetically parallel to the ground. The solar panel selected for the power model is 59.5 cm x 51.5 cm in size and is capable of generating 55W with an efficiency of 20%.

To simplify the model, it was assumed that the mean global normal solar irradiance on Earth 1000 W/m^2 was centered on the ecliptic plane (the plane of Earth's orbit around the Sun). The solar irradiance varies with the ecliptic latitude (the latitude from the ecliptic), which defines as below:

$$\Omega = \theta \mp \alpha \quad [\text{deg}] \tag{6}$$

Where θ is the latitude from the equator; α is the Earth tilt angle.

The max solar irradiance at a certain latitude can be expressed as:

$$G_{max,\theta} = 1000 \cdot cos(\Omega) \quad [W/m^2] \tag{7}$$

Considering the elevation angle of the sun at a certain latitude, the change in solar irradiance during daytime was calculated as:

$$\beta = sin^{-1}(sin(\theta)sin(\alpha) + cos(\theta)cos(\alpha)cos(\mu)) \quad [\text{deg}] \tag{8}$$

Where μ is the solar hour angle.

The solar irradiance varies during daytime, assuming that the peak time is at noon with $G_{max,\theta}$, which can be determined by using the elevation angle β:

$$G_\theta(t) = G_{max,\theta} \cdot sin(\beta) \quad [W/m^2] \tag{9}$$

From there, the change in power generation of a sunny day can be calculated by the product of the change in solar irradiance during a day and the area of the solar panel, considering the solar energy conversion efficiency given by the datasheet:

$$P_{sunny}(t) = e_{module} \cdot G_\theta(t) \cdot A \quad [\text{W}] \tag{10}$$

The worst scenario of power generation is when it is cloudy, rainy, and snowy because the solar energy cannot be collected as much as a sunny day. From the study, the solar power generation efficiency would drop to 20%. Thus, the power generation in a cloudy day would be:

$$P_{cloudy}(t) = 0.2P_{sunny}(t) \quad [\mathrm{W}] \tag{11}$$

It is significant to identify how much power can be stored during a day. Therefore, taking an integral of power generation with respect to sunlight hours, the power capacity of a day is defined.

$$PC_{sunny} = \int_{sunrise}^{sunset} P_{sunny}(t)dt \quad [\mathrm{Whr}] \tag{12}$$

$$PC_{cloudy} = \int_{sunrise}^{sunset} P_{cloudy}(t)dt \quad [\mathrm{Whr}] \tag{13}$$

The sunrise and sunset time can be determined by first finding the solar hour angle at either sunrise or sunset denoted as γ.

$$\gamma = sin^{-1}(tan(\theta)tan(\alpha)) \quad [\mathrm{deg}] \tag{14}$$

$$Sunrise/Sunset = 12 \mp \frac{90^{\circ}+\gamma}{30^{\circ}} \quad [\mathrm{hr}] \tag{15}$$

Based on the derived equations above, the power generation in Boulder at 40 degrees latitude in the summer and winter solstices is shown in Figure 3.1.1. In the summertime, the solar panel can produce power up to 55W during a sunny day. Compared to the wintertime, the solar power significantly decreases since the solar elevation angle gets lower. On a cloudy day, the amount of solar power in both summer and winter drops to 20%.

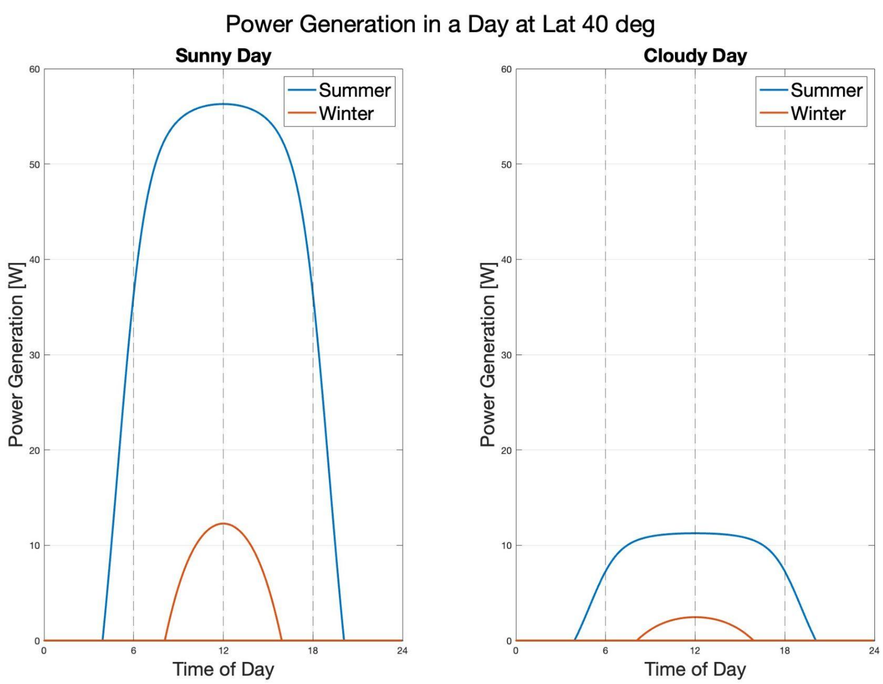

Figure 3.1.1 Solar Power Generation during a Day in Boulder

Evaluating the power capacity during a day in Boulder, there is sufficient sunlight to full-charge the battery on both sunny and cloudy days in the summertime. Recall the total battery capacity is 126 Whr. However, because of the decreasing daylight and sunlight intensity, the power capacity drops down to 66.7 Whr on a sunny day. It could be sufficient enough to recharge the battery with 50% Depth of Discharge. On a cloudy day, it is unable to generate enough power due to a lack of solar irradiance.

Power Capacity	Summer [Whr]	Winter [Whr]
Clear Day	703	66.7
Cloudy Day	141	13.3

Table 3.1.2 Total Power Capacity during a Day in Boulder

Below is the power generation model in Anchorage at 60 degrees latitude, which is the worst case scenario analyzed in terms of sunlight hours and solar intensity. In the summertime, even though sunlight intensity declines from that in Boulder, the amount of power generation in Anchorage is still sufficient enough to recharge the remote sensing device. However, in the wintertime, there is not enough solar irradiance captured as shown in the figure and table below. This means that +/- 60 degrees latitudes in the wintertime, the system needs to be shut down as there would not be enough power in the battery.

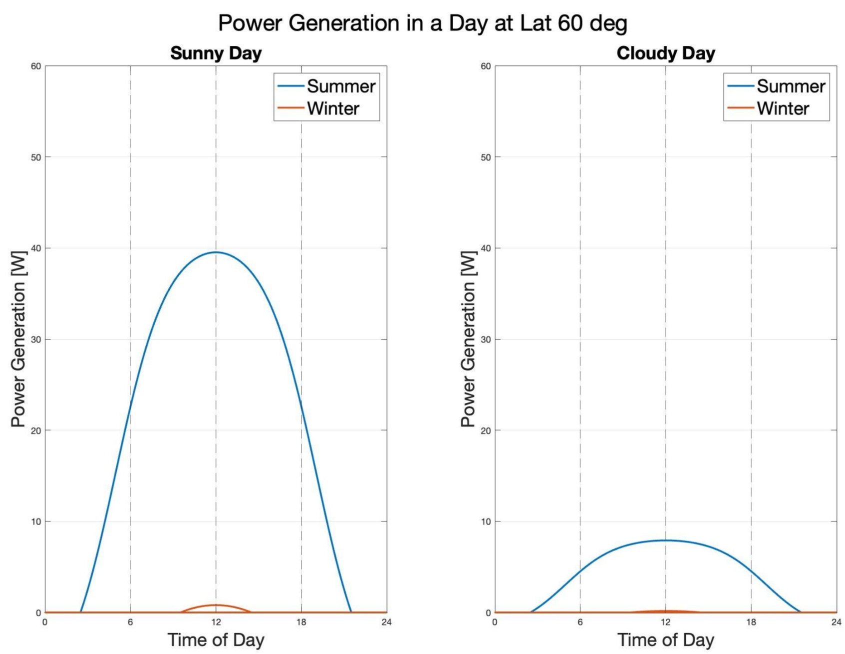

Figure 3.1.2 Solar Power Generation during a Day in Anchorage

Power Capacity	Summer [Whr]	Winter [Whr]
Clear Day	488	2.67
Cloudy Day	97.7	0.534

Table 3.1.3 Total Power Capacity During a Day in Anchorage

3.1.3 Battery Life

Battery life is another important factor when considering the size of a battery and evaluating whether the system is able to operate for 3 days without solar power generation. The selected battery type is lead-acid as it has a large range of allowable charging temperatures. In order to calculate battery life, the ampere-hour of the battery given by the datasheet was divided by the current drawn from the battery, assuming all the components are turned on at all times.

The current drawn from the battery can be expressed as below:

$$\eta_{Buck\ Converter} = \frac{P_{out}}{P_{in}} \cdot 100 \qquad (16)$$

Where $\eta_{buck\ converter}$ is the efficiency of a buck converter that is given by the datasheet.
P_{out} is the output power from a buck converter in Watts.
P_{in} is the input power to a buck converter, which is equivalent to the given output power of a battery in Watts.

$$\eta_{Buck\ Converter} = \frac{V_{out} \cdot I_{out}}{V_{Battery} \cdot I_{Battery}} \cdot 100 \qquad (17)$$

Solving for unknown $I_{Battery}$,

$$I_{Battery} = \frac{\eta_{Buck\ Converter}}{100} \cdot \frac{V_{out} \cdot I_{out}}{V_{Battery}} \ [\mathrm{A}] \qquad (18)$$

Note V_{out}, I_{out}, and $V_{Battery}$ are given by the datasheets.

$$Battery\ Life = \frac{AmpHour_{Battery}}{I_{Battery}} \ [\mathrm{hr}] \qquad (19)$$

With the analysis of battery life, it is essential to analyze the worst and optimal scenarios. For this reason, the minimum and maximum current draw from the components were defined based on the datasheets, which determined the range of battery life without power generation as shown in the table below.

In the optimal condition, the battery is able to supply power for more than 3 days without generating power, whereas in the worst case scenario of using the maximum current draw at all times, the remote sensing device can function for 1.7 days. The worst case scenario was assumed to barely happen since the Comms Subsystem, which draws the most current, does not transmit and receive data at all times.

Battery Life [days]	1.7 ~ 3.7

Table 3.1.4 Battery Life without Power Generation

3.1.4 Battery Recharge Time

Because the remote sensing device needs to operate at varying latitudes and weather conditions, another important consideration for the remote sensing device was battery recharge time. When calculating the battery recharge time for the remote sensing device, the final recharge time is reported in peak sun hours, which is defined as an hour of 1000 W/m^2 or more of solar irradiance. The equations for this model are included below. First, the discharged battery capacity was calculated in Whr, which is the amount of energy in Whr that needs to be recharged by the solar panels. To calculate this, the battery capacity of 126 Whr was multiplied by the depth of discharge (DOD) of 50%. A depth of discharge of 50% was used since the battery charge needs to be kept between 50% and 100% charged for preserving the battery health of the sealed lead acid (SLA) battery.

$$Discharged\ Battery\ Capacity\ =\ (Battery\ Capacity)\cdot DOD\ \ [Whr] \tag{20}$$

After calculating the discharged battery capacity, the discharged battery capacity was divided by the efficiency of lead acid batteries, 85%, to calculate the total required energy for recharging the battery from the solar panel in Whr.

$$Energy\ Required\ for\ Full\ Charge\ =\ \frac{Discharged\ Battery\ Capacity}{Lead\ Acid\ Efficiency}\ \ [Whr] \tag{21}$$

$$Adjusted\ Solar\ Output\ =\ W_{Solar}\cdot (PWM\ Efficiency)\ \ [W] \tag{22}$$

$$Charge\ Time\ =\ \frac{Energy\ Required\ for\ Full\ Charge}{Adjusted\ Solar\ Output}\ \ [hr] \tag{23}$$

The adjusted solar output was then calculated by taking the wattage of the solar panels and multiplying the wattage of the solar panel by the PWM efficiency of the charge controller of 85%. This gave an adjusted solar output from the solar panel in watts. To calculate charge time in peak sun hours, the energy required for full charge in Whr was divided by the adjusted solar output in watts. This gave a battery recharge time of 1.977 peak sun hours. This meets the requirement for the solar panels recharging the batteries in no more than 3 peak sun hours, DR 2.3.2.

Throughout the power model analyses, there are several uncertainties that need to be considered, such as varying current draw from all components over time. This needs to be clarified when all the components are integrated in the next semester. In addition, the solar panel was assumed to be parallel to the ground, so another factor of uncertainty is mounting angle. Depending on the orientation of a solar panel, the solar power could generate more power than is predicted by the model. Furthermore, due to solar irradiance variation with altitude, the solar power can be increased at higher altitude. Varying temperature would affect the battery performance. For this reason, the battery life would be uncertain. Lastly, there may be manufacturing imperfections; currents and voltages on the system may vary from values on datasheets. With all these uncertainties, power tests in the next semester will be clarified.

3.2 GNSS-IR Prototype

A prototype of the GNSS-IR subsystem was created and tested in order to verify that the requirements of the subsystem are able to be met with the selected GNSS receiver chip and GNSS antenna. Specifically, System Requirement DR 7.2: “The system shall calculate the water level variation using SNR and elevation angle data with a precision of better than 5 cm,” which flows down from functional requirement FR 7.0. If successful, the prototype will prove that a single GNSS chip and antenna combination will be enough to meet this requirement. If not, then multiple antenna/chip combinations will need to be used to meet the accuracy requirement by combining their data to reduce randomized error. A photograph showing the prototype setup is included in the document.

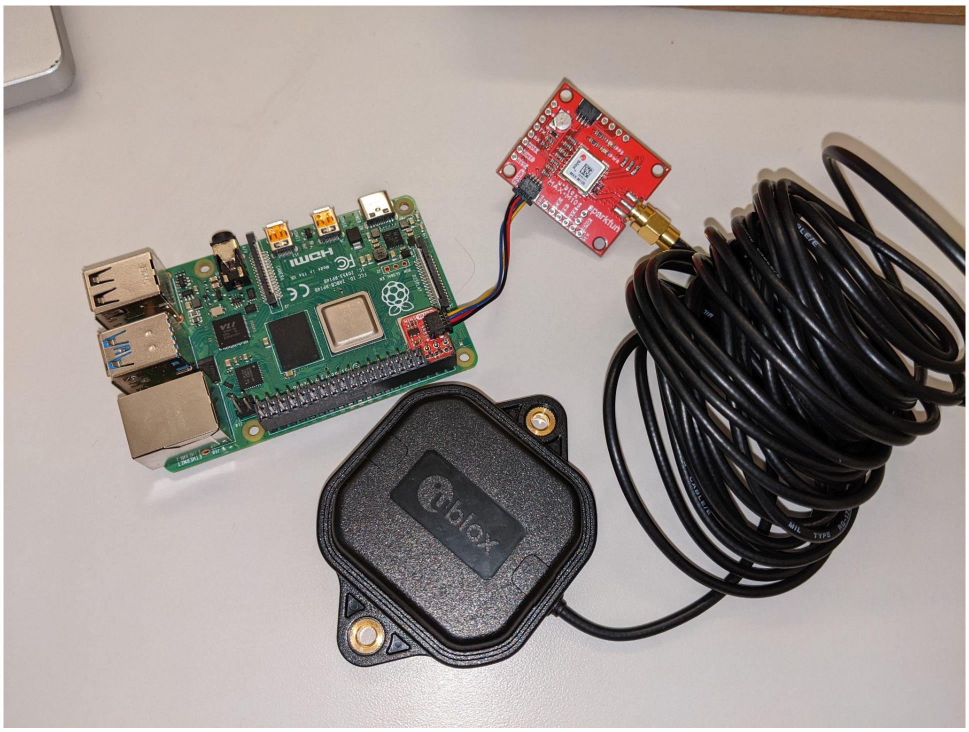

Figure 3.2.1 GNSS-IR System Prototype Including Major Prototype Components

The ublox MAX-M10S GNSS receiver chip and the ublox ANN-MB1 antenna were used in the prototype. A MAX-M10S breakout board and a ublox ANN-MB1 antenna were purchased from SparkFun and Mouser, respectively, in order to perform these tests. The ANN-MB1 antenna is different from the final ANN-MB5 antenna that will be integrated in the final system. These two differences from the final intended system are an important note about this prototype. It is reasonable to believe that even with these surrogate parts in the prototype, the data collected and processed will be an accurate representation of the final system. For the Sparkfun MAX-M10S breakout board, it is using the same GNSS receiver chip as the final system, so it will have the same performance in the final PCB design. For the ANN-MB1, the major difference between this and the final antenna is the gain that the antenna applies to the signal. The ANN-MB1 has a peak gain on the L1 band of 3.8 dBic and a peak gain of 1.3 dBic for the other supported bands (L5, E5a, B2a, NavIC). The ANN-MB5 has a peak gain on the L1 band of 4.5 dBic and a peak gain of 4.0 dBic for the other supported bands (L5, E5a, B2a, NavIC). The ANN-MB1, as a surrogate for prototyping, performs worse in the signal strength it delivers to the GNSS chip, so the actual integration that uses the ANN-MB5 will have superior performance.

A Raspberry Pi 4 was procured from the Electronics Shop, alongside a Qwiic SHIM from Sparkfun. The Qwiic SHIM sat over pins 1-6 of the Raspberry Pi 4, connecting the MAX-M10S board to 3.3V of power, as well as the Pi's I^2C bus. The ANN-MB1 was then connected via the SMA connector on the breakout board. From there, a simple Python script was written to read from the I^2C bus. The MAX-M10S places the latest NMEA messages it has created to its registers on the I^2C bus upon request, which can then be read by the Python script. The messages were saved for later processing. These messages are then placed into Dr. Larson's python GNSS-IR code[2] to calculate the reflector height.

On December 3rd, 2023, this system was deployed outside of the AERO building to collect reflections on the building's lawn. The expected height of the reflections was 96 inches (~2.4 meters). By running the collected NMEA messages through the GNSS-IR code, the found reflection height was 2.435 meters. This proves that the GNSS system can meet the accuracy requirements from the customer.

Figure 3.2.2 Dec 3rd Test of GNSS Subsystem

4 Spring Tests, Schedule, & Budget

Authors: Janelle Nedrow, Gerrell Miller

4.1 Spring Tests

Test ID	Description	Equipment/Facilities	Requirement ID
T1	Conduct an operational test on the Raspberry Pi Pico in a controlled environment to ensure functionality at cold temperatures (-30 °C).	Raspberry Pi Pico, Cooler, Thermocouple, Dry ice	FR 2.0
T2	Conduct a Multi-Constellation Signal Report Test to verify the system's capability to receive and process signals from GPS, GLONASS, Galileo, and BeiDou using L1 carrier frequencies.	MAX-M10S, ANN-MB5, Laptop	FR 3.0
T3	Execute a command response test to assess the system's ability to receive and execute instructions from a ground control station, including system configuration, data processing options, and reboot commands.	Raspberry Pi Pico, RockBlock 9603N, M1621-hct, Laptop	FR 4.0 & FR 5.0
T4	Execute a Health Status Transmission Test to verify the system's capability in sending consistent and accurate health status updates to the ground station.	Raspberry Pi Pico, RockBlock 9603N, M1621-hct, Laptop	FR 6.0
T5	Execute a Water Level Measurement Test to confirm the system's ability to retrieve sub-daily water levels with a precision better than 5 cm.	MAX-M10S, ANN-MB5, Laptop	FR 7.0
T6	Perform a latency Assessment to verify the systems proficiency in estimating water level variations within a two hour timeframe.	MAX-M10S, ANN-MB5, Raspberry Pi Pico, RockBlock 9603N, M1621-hct, Laptop	FR 8.0
T7	Execute a Real-Time Transmission Test to assess the system's capability to transmit SNR data and water level variation results live to a ground control station display.	MAX-M10S, ANN-MB5, Raspberry Pi Pico, RockBlock 9603N, M1621-hct, Laptop	FR 9.0

T8	Conduct a water resistance test to evaluate the systems durability when subjected to direct water exposure.	YETLEBOX, Water hose	FR 2.0
T9	Conduct a deployment test near a body of water to verify system operability for 2 weeks.	Boulder Reservoir, MAX-M10S, ANN-MB5, Raspberry Pi Pico, RockBlock 9603N, M1621-hct, YETLEBOX, PS-12100H battery, Voltaic Systems 50W solar panel, Laptop	FR 2.0

Table 4.1.1 Spring Tests to be Completed

Key tests that will need to be performed from table 4.1 are T1, T3, T7, and T9. Test T1 will focus on evaluating the Raspberry Pi Pico's performance in extreme cold temperatures of -30 °C (-22 °F). It requires a cooler, thermocouple, and dry ice to create the necessary temperature conditions. The goal is to verify the system's functionality under varying thermal stresses, addressing requirement FR 2.0 which states that "The system shall operate independently in remote environments in a temperature range of -30 to 55 °C (-22 to 131 °F)" . A significant safety consideration in this test is the handling of dry ice and the management of extremely low temperatures. Proper safety gear, like insulated gloves and temperature-controlled environments, will be essential to mitigate these risks.

Test T3 will consist of the Raspberry Pi Pico, along with a RockBlock 9603N, M1621-hct, and a laptop, which will be used to assess the system's responsiveness to commands from a ground control station. This includes testing for system configuration, data processing options, and executing reboot commands. This test is critical for ensuring reliable communication and command execution under operational conditions, fulfilling requirements FR 4.0 which states that "The system shall be able to receive and respond to commands from a ground control station regarding system configuration, system reboot, etc." and FR 5.0 which states that "The system shall be able to receive and respond to commands from a ground control station regarding data processing options (e.g., compute daily average of estimated water level data)".

The objective of test T7 is to test the system's ability to transmit SNR data and water level variation results live to a ground control station display. It involves the use of a comprehensive set of equipment including the Raspberry Pi Pico, RockBlock 9603N, M1621-hct, and a laptop. This test is crucial for verifying real-time data transmission capabilities, addressing requirement FR 9.0 which states that "The system shall be able to transmit the SNR data and/or final results (water level variation) to a ground control station (e.g., a laptop) to be displayed live on a screen".

Test T9 involves deploying the system near the Boulder Reservoir to verify its operability over an extended period of two weeks. The test setup includes a variety of equipment like the Raspberry Pi Pico, RockBlock 9603N, M1621-hct, YETLEBOX, PS-12100H battery, Voltaic Systems 50W solar panel, and a laptop. It's designed to ensure system stability and operational reliability in a real-world environment, meeting requirement FR 2.0. The primary safety risks in this scenario include environmental exposure and equipment failure. To mitigate these, it will be necessary to ensure waterproof housing for the equipment and have contingency plans for equipment malfunctions or data loss. Should the equipment malfunction or lose data, the regular health status updates will be able to notify the ground station and will be able to automatically shut off.

4.2 Schedule

Below is the Gantt chart outlining the schedule to be followed in the spring. This includes all of the procurement, integration, manufacturing, testing and class deliverables to be completed.

The Critical Path is lined in maroon and outlines the important tasks that need to be done in order for the whole project to be successfully completed. The Critical Path starts with all of our procurement and then moves along the integration blocks, because we aren’t able to build our system and perform our tests without all of our components and without software written. It then moves to the Test Readiness Review, as this is required by the course for safety and competency reasons prior to testing. The path then follows all the tests and the last two deliverables, being the AES Symposium and the Spring Final report.

The margin for any given task was made based on the beginning date of whatever task is dependent on it. For example, both of our softwares should only take 26 days, but we don’t need them for another 19 days when we perform the multi-constellation test on March 4th.

The two pink stars are representative of the two assignments that are in the middle of testing and manufacturing. These are just to help visualize that the assignments lie in the midst of everything else whereas the other two assignments are at the end of everything and do not interrupt the flow of everything.

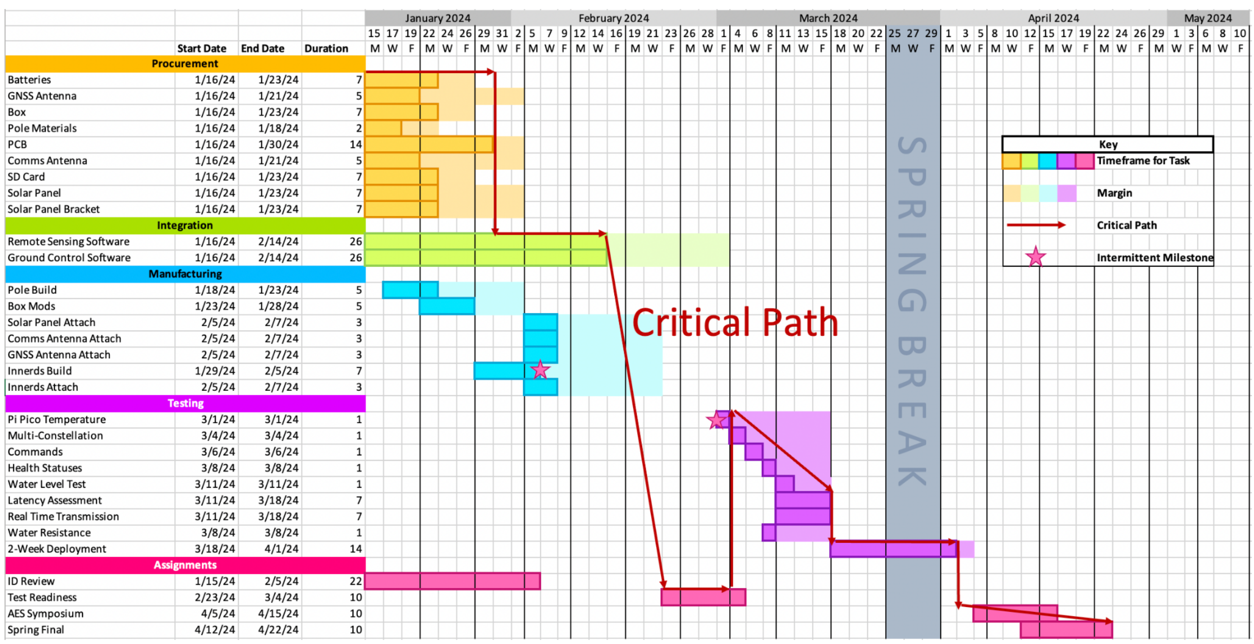

Figure 4.2.1 Gantt Chart

4.3 Budget

Component	Name/Desc	Quantity	Price Per Unit	Margin	Total	Lead Time
GNSS Chip	Max M10s	1.00	$21.00	**20.00%**	**$25.20**	5 days
GNSS Antenna	ANN-MB5	1.00	$34.72	**0.00%**	**$34.72**	5 days
Comms Module	RockBlock 9603N	1.00	$267.00	**0.00%**	**$267.00**	5 days
Comms Antenna	m1621-hct	1.00	$72.00	**0.00%**	**$72.00**	5 days
Microprocessor	Raspberry Pi Pico	1.00	$4.00	**0.00%**	**$4.00**	5 days
Housing	YETLEBOX Waterproof Electrical Box	1.00	$51.70	**10.00%**	**$56.87**	1 week
Data Storage Breakout	Adafruit MicroSD Card Breakout + Kingston Industrial Micro SD card	1.00	$25.68	**10.00%**	**$28.25**	1 week
Energy Storage	PS-12100H-F2 SLA Battery	1.00	$40.44	**20.00%**	**$48.53**	1 week
Power Generaton	Voltaic Systems 50W 18V Solar Panel + Solar Panel Mount + WindyNation 10A PWM Charge Controller	1.00	$152.00	**10.00%**	**$167.20**	1 week
PCB		1.00	$7.00	**100.00%**	**$14.00**	2 weeks
Structure Tower		1.00	$61.46	**30.00%**	**$79.90**	2 days
					TOTAL	
					$797.66	

Expense Summary		Remaining Total	Remaining Required
GNSS Electronics	$77.92		
Comms Components	$367.25	**$2,990.74**	**$2.34**
Structure	$136.77		
Power	$215.73	Note: Total includes extras purchased in Fall	
Total Project Estimate	**$797.66**		

Table 4.3.1 Budget Breakdown

The budget allocation for this project is currently set at $4,000, while the requirement for the full implementation of the system stands at $800. According to the financial analysis presented in Table 4.3, the total calculated budget, inclusive of a carefully considered margin, is approximately $797.66. This margin calculation is an essential component of the budgeting strategy, primarily due to its direct correlation with the variable availability and price fluctuations of necessary components. The project encompasses a range of components, including the GNSS chip, housing, energy storage, power generation, PCB, and the structural tower. For these components, a margin range between 10% and 100% has been allocated. This broad margin is strategically designed to cover potential fluctuations in market prices and additional unforeseen expenses that might arise during the integration of these components into the system. Such incidental expenses typically include, but are not limited to, essential hardware like cables and screws. It is also important to note that certain components have been excluded from this margin calculation. These components are known for their consistent availability and have historically shown no significant fluctuations in pricing. They are readily accessible through reliable suppliers such as Mouser and Sparkfun, which enhances the confidence in their stable costing. Among the array of purchases, the communications module and the power generation components stand out as the most significant in terms of cost. These components are not only the most expensive but are also critically vital for the operational efficacy of the system. The absence or failure of these components could lead to significant system malfunctions or complete operational failure. Another crucial component of this project is the PCB. This element requires custom manufacturing, which introduces a lead time of potentially up to two weeks for delivery. Furthermore, the PCB demands exacting tolerances for it to function optimally within the system. This precision requirement elevates the risk of initial failures, possibly necessitating a redesign and subsequent procurement of additional PCBs. To safeguard against these risks and ensure project continuity, the budget has been structured to include a substantial contingency fund. This fund, amounting to $2,990.74, is earmarked to cover any unexpected challenges or additional expenses that may arise during the project's lifecycle. This financial cushion is a prudent measure, allowing us to adapt and respond effectively to any unforeseen difficulties, thereby ensuring the project's success and sustainability.

5 Individual Report Contributions

Name	Contributions
Ethan Stapp	Wrote requirements, led trade studies, verified proper compatibility between components, made Conops and FBD and explained these in section 2, worked on thermal model and power model, explained these in section 3.
Janelle Nedrow	Reviewed all requirements, powerpoints, papers and trade studies, was the point of contact for Mentor Dr. Minear, Advisor Dr. Ghobadi-Far, Dr. Wingate, and other GNSS-IR teams, created the gantt chart and entire spring plan, reviewed and edited entire report.
Toan Lu	Assisted with writing and reviewing requirements, assisted with GNSS subsystem trade study, assisted Mechanical trade study and design, assisted Power subsystem trade study, assisted with FBD and explanation in section 2, created the CAD models and explanation of colored components in Appendix 2, assisted on thermal model, along with proofreading, editing and formatting.
Hideyuki Nakanishi	Assisted with trade studies and requirements, made solar panel power generation model explained in section 3, worked with Blake on PCB design for the GNSS subsystem explained in section 2.
Gerrell Miller	Wrote the preamble, sections 4.1 and 4.3. Created budget spreadsheet table 4.3.1. Helped create test table 4.1.1. Helped with trade studies and purchased items.
Micah Bergeron	Assisted with Mechanical trade study, developed wind beam deflection model explained in Appendix 4.1, designed and selected modular mounting pole, worked with Toan to select housing and finalize full structural design, wrote sections 2.9 and Appendix 4.1.
Kristyn Grell	Selected weather measurement sensors, assisted with power subsystem component selection, and completed GNSS-IR prototyping with Sean. Wrote section 2.6, various parts of section 3, appendix 3.2, several references, as well as editing.
Sean Vestecka	Wrote GNSS and Comms subsystem FBD description (section 2.1), wrote further GNSS subsystem design information with Blake (section 2.3). Made and used the GNSS-IR subsystem prototype with Kristyn, along with writing section 3.2 together. Wrote Appendix 4 and contributed to cross-checking references. Worked on the GNSS-IR and Comms trade study, particularly on how they interact with the microcontroller.
Blake Wilson	Assisted with requirements. Worked on trade studies for GNSS module, Comms Module, antennas, and power conversion. Worked with Hideyuki to design GNSS schematic and PCB, as well as overall circuitry for the remote sensing device. Worked on subsystem descriptions in the report (sections 2.2 - 2.8)

Appendix

Authors: Sean Vestecka, Micah Bergeron, Ethan Stapp, Kristyn Grell, Toan Lu

Appendix 1: References

[1] Feng, P., Haas, R., and Elgered, G., "A new tropospheric error model for ground-based GNSS interferometric reflectometry: theory and validation," *ESS Open Archive*, 9 Dec. 2023, pp 5, 6.

[2] Kristine Larson's GNSS-IR Reflections code: https://github.com/kristinemlarson/gnssrefl

[3] Song, M., He, X., Wang, X., Zhou, Y., and Xu, X.. 2019. "Study on the Quality Control for Periodogram in the Determination of Water Level Using the GNSS-IR Technique" *Sensors* 19, no. 20: 4524. https://doi.org/10.3390/s19204524

[4] Larson, K. M., Ray, R., Nievinski, F., and Freymueller, J. "The Accidental Tide Gauge: A Case Study of GPS Reflections from Kachemak Bay, Alaska," *IEEE GRSL*, Vol 10, No. 5, 1200-1205, 5 Feb. 2013.

[5] Darin, Koblick. "Vectorized Solar Azimuth and Elevation Estimation." *MathWorks*. www.mathworks.com/matlabcentral/fileexchange/23051-vectorized-solar-azimuth-and-elevation-estimation

Kristen Larson's Reflection Map API: http://gnss-reflections.org/rzones

Appendix 2: Structural and Mechanical Documents

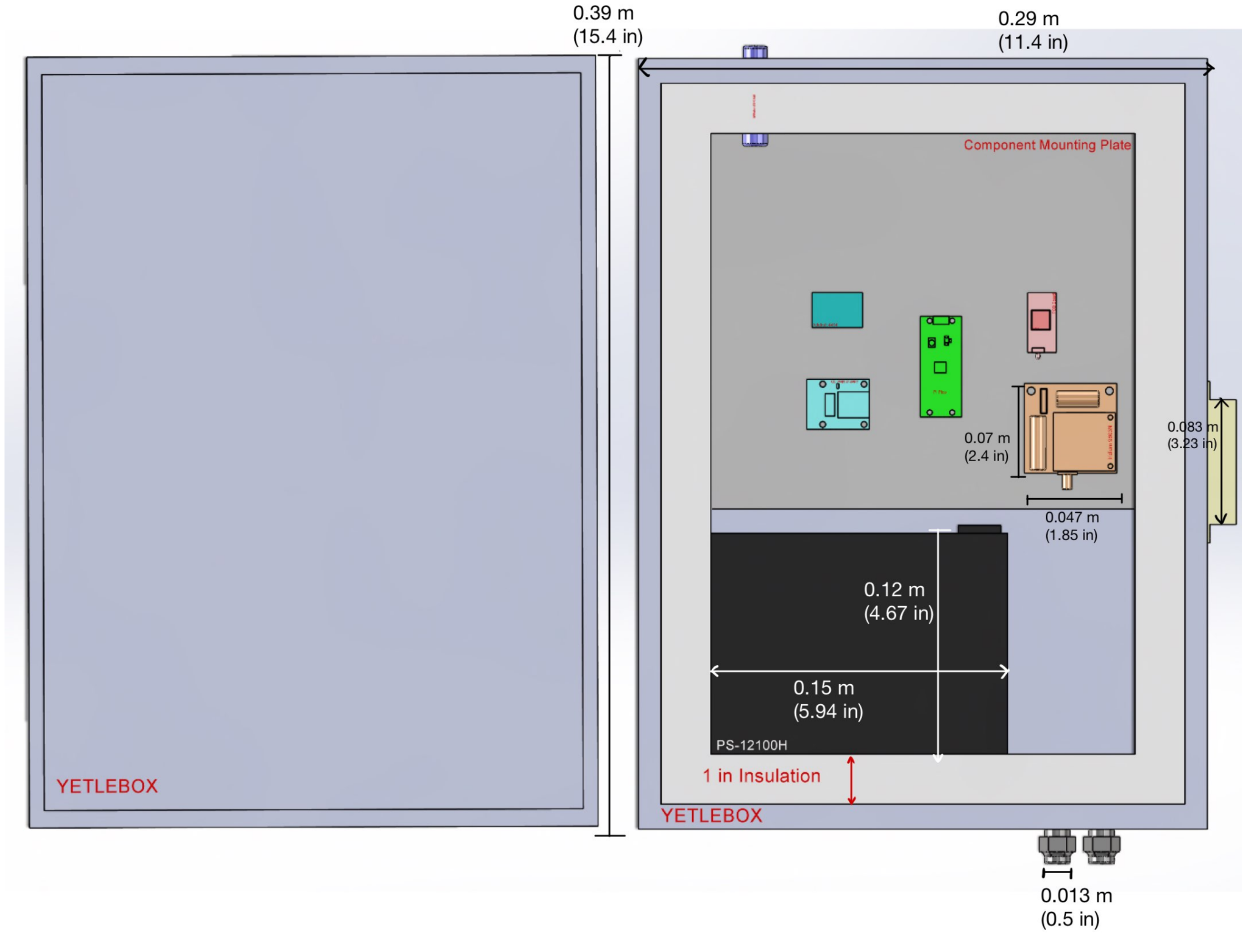

Figure A.2.1 Housing Design CAD Model with Dimensions

For figure A.2.1, the following are the color coordination of the different components that will be placed inside the housing during the manufacturing phase:

Grey - Housing
White (or light gray) - Insulation
Medium Gray - Mounting Plate
Black - PS-12100H F2 Battery
Green - Pi Pico
Red - MAX-M10S GNSS module and PBC
Orange - Comms Module (Iridium 9603N)
Yellow - Charge Controller
Light Blue - Adafruit Micro SD Card Breakout Board
Teal - Adafruit Pressure Sensor
Dark Blue - Temp/Humidity Sensor
Dark Gray - Cable Glands

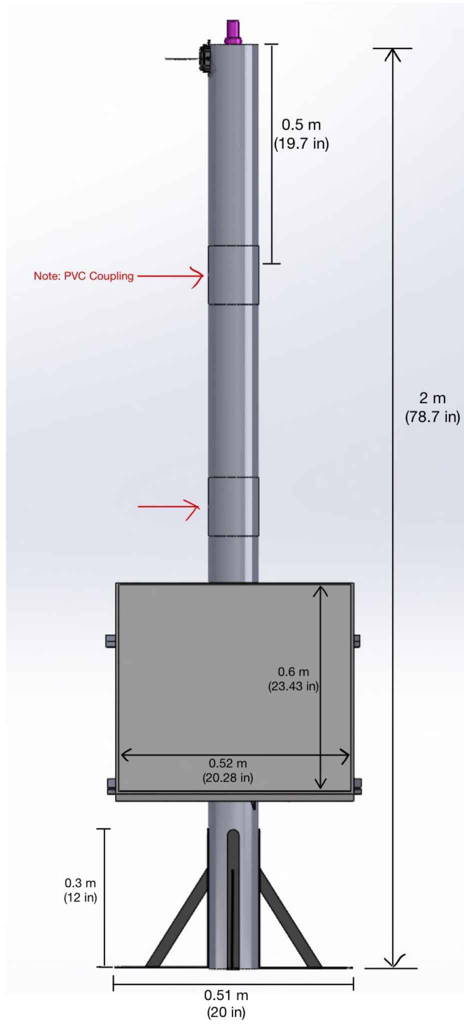

Figure A.2.2 Antenna Pole Design CAD Model with Dimensions

For figure A.2.2, the following are the color coordination of the different components that will be used to manufacture the Antenna Pole:

Gray - PVC Pole and PVC Coupling
Dark Gray - Solar Panel
Bottom Black - 12 in by 8 in Bracket
Top Black - GNSS Antenna (ANN-MB5)
Magenta - Comms Antenna

Appendix 3: Additional Models

Appendix 3.1 Wind Beam Deflection Model

This model was developed and utilized in order to find a PVC diameter for the mounting pole that experiences a maximum tip displacement of five centimeters when exposed to high wind speeds. The model developed assumes that the base of the mounting pole is completely fixed, meaning it experiences no displacement from any applied forces or moments. The force from the wind directly on the pole itself is assumed to be a uniformly distributed load. The force on the solar panel from the wind is also assumed to act on the mounting pole as a uniformly distributed load, acting between the top and bottom attachments of the associated solar panel mounting bracket. The model also assumes that the mounting pole will be at its maximum length of two meters and that the solar panel is mounted at a 90-degree angle perpendicular to the ground.

These assumptions are consistent with the governing equation utilized, which is based on a second-order beam bending model as taught in the course ASEN 3112.

$$EI_{zz}v''(y) = M(y) \tag{4}$$

Where E is the Young's modulus of the PVC pipe.
I_{zz} is the area moment of inertia of the PVC pipe.
$v''(y)$ is the second derivative of the displacement as a function of location along the pole, where $y = 0$ is the fixed base of the pole.
$M(y)$ is the internal moment as a result of any applied forces/moments.

Going through the process of solving for the tip displacement of the pole results in the following equation:

$$v(L) = \frac{1}{EI_{zz}}\left[\frac{-wL^4}{12} - \frac{Lpy_2^3}{3} + py_1^3L + \frac{py_2^4}{4} - \frac{11py_1^4}{12}\right] \tag{5}$$

Where $v(L)$ is the displacement of the tip of the pole.
w is the distributed load due to the wind on the pole.
L is the length of the pole.
p is the distributed load on the pole due to wind effects on the mounted solar panel.
y_1 is the location of the bottom attachment of the solar panel mounting bracket.
y_2 is the location of the top attachment of the solar panel mounting bracket.

From this final displacement equation, the only variable that is impacted by the PVC diameter is the area moment of inertia, I_{zz}. Tip displacements were then plotted for varying wind speeds as well as varying PVC pipe diameters.

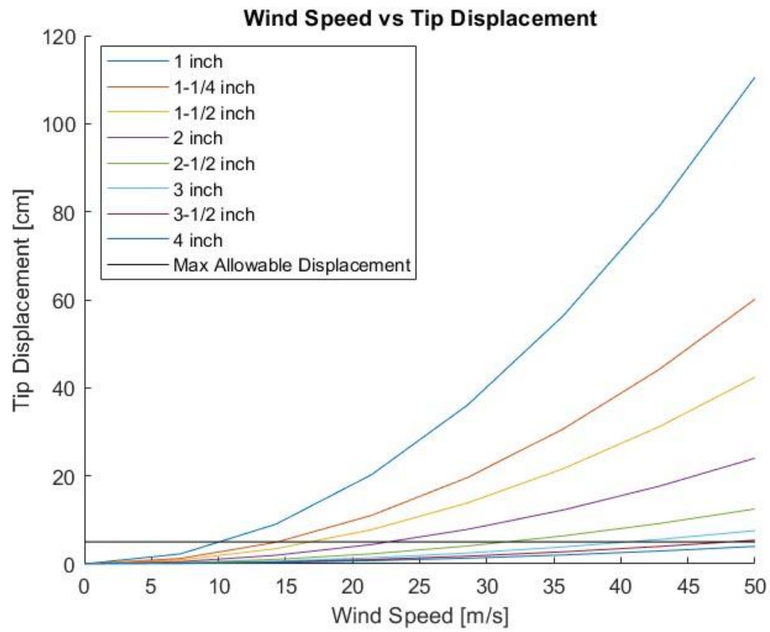

Figure A.3.1 Wind Beam Deflection Results

As can be seen from Figure A.3.1, the 4-inch diameter PVC pipe is the only pipe size that displaces less than than the maximum allowable displacement of five centimeters for all wind speeds tested. Given that the device must be functional for a full calendar year in all types of weather, it is necessary for the pole to be designed to be able to stay within the bounds of the maximum allowable displacement for extreme wind speeds.

Appendix 3.2 Thermal Model

This model was developed in order to ensure that the internal temperature of the housing would stay within the temperature ranges of all components, even at the extreme temperatures of the requirement range. In order to do so, it was assumed that all component power consumed would be converted to heat. This calculation was performed for an ABS housing thickness of 0.185 inches. This model uses a thermal resistance network. At the lowest temperature bound (-30℃), the minimum heat generation was used to verify the worst case scenario. Likewise, at the highest temperature bound (55℃), the highest heat generation was used.

This model does indeed verify that the system will stay within the temperature ranges of all components, with a small caveat. In the event that the system will be deployed in a very cold weather environment, one inch thick styrofoam insulation will keep the system at a reasonable temperature. The graphs calculated at the minimum temperature bound (-30℃) can be seen below with insulation in Figure A.3.2.1, and without in Figure A.3.2.2.

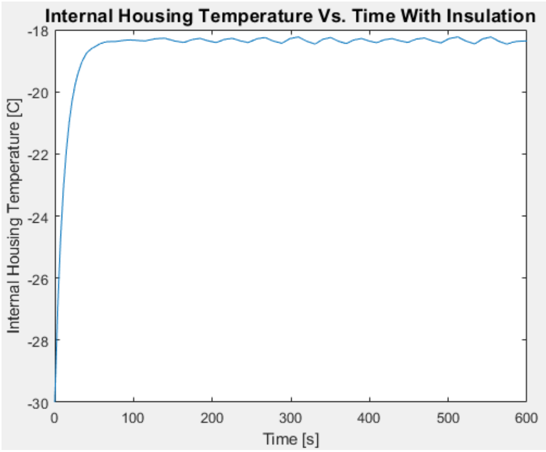

Figure A.3.2.1 -30℃ With Insulation

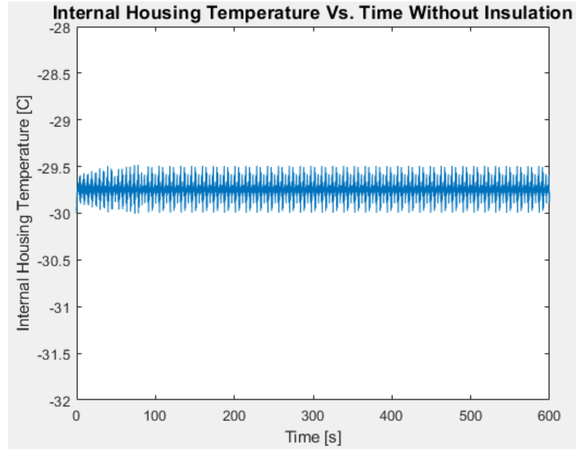

Figure A.3.2.2 -30℃ Without Insulation

Because of the high cost of low temperature batteries, a lead acid battery was selected, as it had the largest charging temperature range. However, it cannot be charged at temperatures below -20℃. This model verifies that with insulation, we should be able to charge the battery at all times.

If the system is deployed towards the high end of the temperature range, this insulation should be taken out. The graph for housing temperature at the high temperature bound (without insulation) can be found below in Figure A.3.2.3.

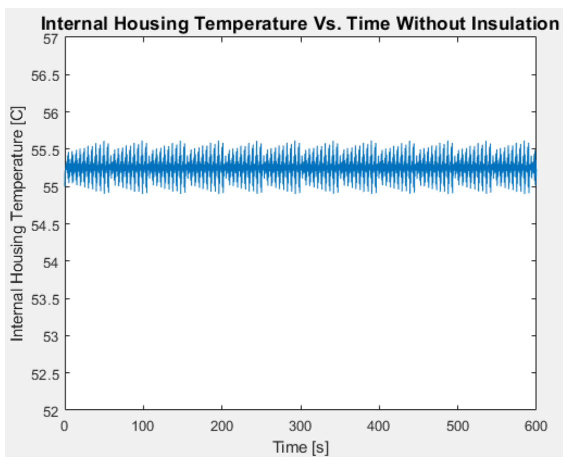

Figure A.3.2.3 55℃ Without Insulation

The selected battery can discharge at temperatures up to 60℃. This model verifies that even at the high end of the required temperature range, the battery will still remain operational, although it cannot charge with temperatures greater than 50℃. The rest of the components are graded to much higher temperatures, and are not of concern.

Appendix 4: The GNSS-IR Technique

The GNSS-IR Technique involves using interferometric reflectometry on the signals produced by GNSS constellations in order to perform measurements. The basics of the technique are shown in the following figure. Signals reflected off of a surface intersect signals that directly reach an antenna. The interference between this reflected signal and the direct line-of-sight signal manifests in the SNR of the signal collected by the antenna. This is demonstrated below in Figure A.4.1.

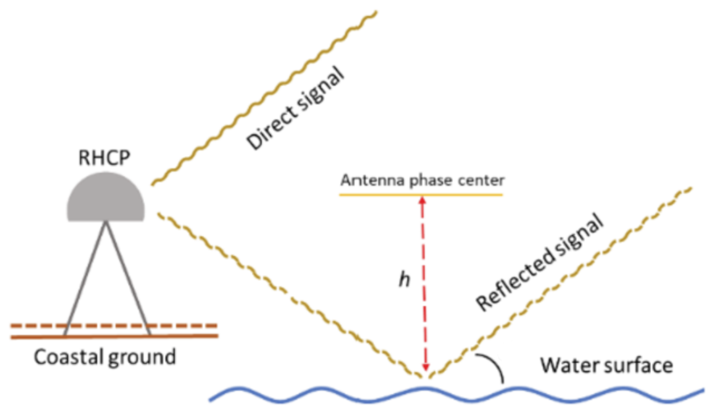

Figure A.4.1 GNSS-IR Reflection Demonstration Image[3]

Looking at the equation for the sinusoid signal and the equation for the signal-to-noise ratio present in the GNSS signal collected by the antenna:

$$x(t) = Acos(2\pi ft + \theta)$$

$$\delta SNR(t) = Acos(\frac{4\pi h}{\lambda} sin[e(t)] + \theta)$$

These equations have a relation in their frequency component that can be used to calculate the height of the reflected signal. By setting them equal to each other, this can solved down to get the following relation for reflector height based on the frequency of the SNR signal:

$$2\pi f = \frac{4\pi h}{\lambda}$$

$$f = \frac{2h}{\lambda}$$

$$h = \frac{\lambda}{2} f$$

The derivation of this relationship is from Larson et al. (2013)[4]. With this relationship, knowing the frequency of the SNR signal and the wavelength of the GNSS carrier waves will return the height of the reflected signal. For the purposes of this project, this reflector height can be used to measure the surface height of bodies of water.

Appendix 5: Requirement Flow-Down

Attached below is the entire list of requirements.

Key	
(yellow)	Critical Requirement
(cyan)	Requirements Verified Through Inspection
(red)	Requirements Verified Through Analysis/Test

Level 0: Functional				
Requirement	Requirement	Parent	Child	Verification
FR 1.0	The system shall cost less than $800 per unit, excluding monthly communication subscription costs.	N/A	DR 1.1	I
FR 2.0	The system shall operate independently in remote environments in a temperature range of -30 to 55 C (-22 to 131 F).	N/A	DR 2.1	I/T
FR 3.0	The system shall be able to receive signals from multiple GNSS constellations (GPS, GLONASS, Galileo, and BeiDou) as well as various frequencies (e.g., L1 and L5 for GPS).	N/A	DR 4.1, DR 4.2, DR 4.3, DR 4.4, DR 4.5	I/D/T
FR 4.0	The system shall be able to receive and respond to commands from a ground control station regarding system configuration, system reboot, etc.	N/A	DR 5.1, DR 5.2, DR 5.3, DR 5.4	D/T
FR 5.0	The system shall be able to receive and respond to commands from a ground control station regarding data processing options (e.g., compute daily average of estimated water level data).	N/A	DR 6.1, DR 6.2	D/T
FR 6.0	The system shall send health status updates to the ground station.	N/A	DR 7.1	D/T
FR 7.0	The system shall retrieve sub-daily water level with a precision better than 5 cm.	N/A	DR 9.1, DR 9.2	D/T
FR 8.0	The system shall be able to estimate water level variations within 2 hours latency.	N/A	DR 10.1	D/T
FR 9.0	The system shall be able to transmit the SNR data and/or final results (water level variation) to a ground control station (e.g., a laptop) to be displayed live on a screen.	N/A	DR 11.1	D/T
Level 1: System Requirements				
Requirement	Requirement	Parent	Child	Verification
DR 1.1	The system shall cost less than $800 per unit, excluding monthly communication subscription costs.	FR 1.0		I
DR 2.1	The system shall have a Mean Time Between Failure (MTBF) of greater than 1 year.	FR 2.0	DR 2.1.1, DR 2.1.2, DR 2.1.3, DR 2.1.4, DR 2.1.5, DR 2.1.6, DR 2.1.7, DR 2.1.8	D/T
DR 2.2	The system shall operate in a temperature range of -30 to 55 C (-22 to 131 F).	FR 2.0	DR 2.2.1, DR 2.2.2, DR 2.2.3, DR 2.2.4, DR 2.2.5, DR 2.2.6, DR 2	I/T
DR 2.3	The system shall operate entirely on its own power.	FR 2.0	DR 2.3.1, DR 2.3.2	D/T
DR 3.1	The system shall receive signals from multiple GNSS constellations (GPS, GLONASS, Galileo, and BeiDou).	FR 3.0	DR 3.1.1, DR 3.1.2, DR 3.1.3, DR 3.1.4	I/D/T
DR 3.2	The system shall receive GNSS signals using L1 C/A, E1-B/C, L10F, B1I, and B1C carrier frequencies.	FR 3.0	DR 3.2.1	I/D/T
DR 3.3	The system shall measure the air temperature for tropospheric distortion calculations.	FR 3.0	DR 3.3.1, DR 3.3.2	I
DR 3.4	The system shall measure the relative humidity for tropospheric distortion calculations.	FR 3.0	DR 3.3.1, DR 3.4.1	I
DR 3.5	The system shall measure the air pressure for tropospheric distortion calculations.	FR 3.0	DR 3.3.1, DR 3.5.1	I
DR 4.1	The system shall receive and respond immediately to system configuration and reboot commands from the ground station.	FR 4.0	DR 4.1.1, DR 4.1.2, DR 4.1.3, DR 4	D/T
DR 5.1	The system shall receive and respond immediately to data processing option commands from the ground station.	FR 5.0	DR 5.1.1, DR 5.1.2, DR 5.1.3, DR 5	D/T
DR 6.1	The system shall send health status updates to the ground control station at least once an hour.	FR 6.0	DR 6.1.1, DR 6.1.2, DR 6.1.3	D/T
DR 7.1	The system shall retrieve sub-hourly water level data.	FR 7.0	DR 7.1.1	D/T
DR 7.2	The system shall calculate the water level variation using SNR and elevation angle data with a precision of better than 5 cm.	FR 7.0	DR 7.2.1	D/T
DR 8.1	The system shall estimate water level variations within 2 hours latency.	FR 8.0	DR 8.1.1	D/T
DR 9.1	The system shall transmit the SNR data or final results (water level variation) to a ground control station (e.g., a laptop) to display most recent water level and time results on a screen.	FR 9.0	DR 9.1.1, DR 9.1.2, DR 9.1.3	D/T
DR 0.1	The system shall weigh less than 50 lbs.	N/A	DR 0.1.1, DR 0.1.2	I
DR 0.2	The system shall have stowed dimensions less than 15.4 x 11.4 x 6.3 in, excluding the solar panel size and antenna pole.	N/A		I
DR 0.3	The system shall be open source.	N/A	DR 0.3.1, DR 0.3.2	I
DR 0.4	The system shall have on site backup storage of water level data in case of transmission delays.	N/A	DR 0.4.1, DR 0.4.2, DR 0.4.3	I
DR 0.5	The system shall operate in precipitation (rain and snow) conditions.	N/A	DR 0.5.1, DR 0.5.2, DR 0.5.3, DR 0	I/T
DR 0.6	The system shall attach to the ground.	N/A	DR 0.6.1	A/T
Level 2: Sub System Requirements				
Requirement	Requirement	Parent	Child	Verification
Power (solar panel(s), battery(s))				
DR 2.3.1	The power subsystem shall supply power continuously for 3 days without power generation.	DR 2.3	DR 2.3.1.1	A/T
DR 0.1.1	The power subsystem shall weigh no more than 20 lbs.	DR 0.1	DR 0.1.1.1, DR 0.1.1.2	I
DR 3.1.1	The power subsystem shall operate in the -30 to 55 C temperature range.	DR 3.1	DR 3.1.1.1, DR 3.1.1.2	I/T
DR 2.1.1	The power subsystem shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.1.1, DR 2.1.1.2	D/T
Remote Sensing Device Comms (communication equipment)				
DR 4.1.1	The remote sensing device comms subsystem shall receive remote sensing device configuration commands from the ground control station.	DR 4.1	DR 4.1.1.1	D/T
DR 4.1.2	The remote sensing device comms subsystem shall receive remote sensing device system reboot commands from the ground control station.	DR 4.1	DR 4.1.2.1	D/T
DR 5.1.1	The remote sensing device comms subsystem shall receive data processing option commands from the ground control station.	DR 5.1	DR 5.1.1.1	D/T
DR 4.1.3	The remote sensing device comms subsystem shall send received system configuration commands to the remote sensing device software subsystem.	DR 4.1	DR 4.1.3.1	D/T
DR 5.1.2	The remote sensing device comms subsystem shall send received data processing option commands to the remote sensing device software subsystem.	DR 5.1	DR 5.1.2.1	D/T
DR 4.1.4	The remote sensing device comms subsystem shall send received system reboot commands to the remote sensing device software subsystem.	DR 4.1	DR 4.1.4.1	D/T
DR 8.1.1	The remote sensing device comms subsystem shall transmit SNR or water level data to the ground control station within 2 hours latency.	DR 8.1	DR 8.1.1.1, DR 8.1.1.2	A/D/T
DR 6.1.1	The remote sensing device comms subsystem shall transmit health status updates to the ground control station at least once an hour.	DR 6.1	DR 6.1.1.1	D/T
DR 2.2.2	The remote sensing device comms subsystem shall operate in the -30 to 55 C temperature range.	DR 2.2	DR 2.2.2.1, DR 2.2.2.2	I/T
DR 0.5.1	The remote sensing device comms subsystem shall operate in precipitation (rain and snow) conditions.	DR 0.5	DR 0.5.1.1	I/T
DR 2.1.2	The remote sensing device comms subsystem shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.2.1, DR 2.1.2.2	D/T
Data Storage (non-volatile drive, any additional memory equipment)				
DR 9.1.2	The data storage subsystem shall have 32 GB of storage for storing SNR and water level data.	DR 9.1	DR 9.1.2.1	I
DR 2.2.3	The data storage subsystem shall operate in the -30 to 55 C temperature range.	DR 2.2	DR 2.2.3.1	I/T
DR 2.1.3	The data storage subsystem shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.3.1	D/T
GNSS (GNSS sensor and equipment)				
DR 3.1.1	The GNSS subsystem shall receive GNSS signals from multiple constellations (GPS, GLONASS, Galileo, and BeiDou).	DR 3.1	DR 3.1.1.1, DR 3.1.1.2	I/D/T
DR 3.2.1	The GNSS subsystem shall receive GNSS signals using L1 C/A, E1-B/C, L10F, B1I, and B1C carrier frequencies.	DR 3.2	DR 3.2.1.1, DR 3.2.1.2	I/D/T
DR 9.1.3	The GNSS subsystem shall send SNR data to the data storage subsystem.	DR 9.1	DR 9.1.3.1	D/T
DR 2.2.4	The GNSS subsystem shall operate in the -30 to 55 C temperature range.	DR 2.2	DR 2.2.4.1, DR 2.2.4.2	I/T
DR 0.5.2	The GNSS subsystem shall operate in precipitation (rain and snow) conditions.	DR 0.5	DR 0.5.2.1	I/T
DR 2.1.4	The GNSS subsystem shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.4.1, DR 2.1.4.2	D/T
Weather Measurement (temperature, pressure, and humidity sensor(s))				
DR 3.3.1	The weather measurement subsystem shall monitor air temperature with an accuracy of 0.2 C.	DR 3.3	DR 3.3.1.1	I

DR 3.5.1	The weather measurement subsystem shall monitor air pressure with an accuracy of 0.1 hPa.	DR 3.5	DR 3.5.1.1	I
DR 3.4.1	The weather measurement subsystem shall monitor relative humidity levels with an accuracy of 2% humidity.	DR 3.4	DR 3.4.1.1	I
DR 3.1.2	The weather measurement subsystem shall take measurements with a sampling frequency every 15 minutes.	DR 3.1	DR 3.1.2.1, DR 3.1.2.2, DR 3.1.2.3	I
DR 0.5.5	The weather measurement subsystem shall operate in precipitation (rain and snow) conditions.	DR 0.5	DR 0.5.5.1, DR 0.5.5.2, DR 0.5.5.3	I/T
DR 2.2.5	The weather measurement subsystem shall operate in the -30 to 55 C temperature range.	DR 2.2	DR 2.2.5.1, DR 2.2.5.2, DR 2.2.5.3	I/T
DR 2.1.5	The weather measurement subsystem shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.5.1, DR 2.1.5.2, DR 2.1.5.3	D/T
Mechanical (sensor container and support)				
DR 0.1.4	The mechanical subsystem shall weigh no more than 30 lbs.	DR 0.1		I
DR 2.2.6	The mechanical subsystem shall withstand the -30 to 55 C temperature range.	DR 2.2	DR 2.2.6.1	A/T
DR 0.5.3	The mechanical subsystem shall be water resistant.	DR 0.5	DR 0.5.3.1, DR 0.5.3.2, DR 0.5.3.3	I/T
DR 2.1.6	The mechanical subsystem shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.6.1	D/T
DR 0.6.1	The mechanical subsystem shall attach to the ground.	DR 0.6	DR 0.6.1.1	A/T
Remote Sensing Device Software (on a microcontroller, Note: We currently have the sensor software calculating the water level)				
DR 0.3.1	The remote sensing device software program shall be open source (e.g. Python, C++).	DR 0.3	DR 0.3.1.1	I
DR 7.2.1	The remote sensing device software shall calculate the water level sub-hourly using SNR and elevation angle data to a precision of better than 5 cm.	DR 7.2	DR 7.2.1.1	D/T
DR 4.1.5	The remote sensing device software shall interpret system configuration commands from the remote sensing device comms subsystem.	DR 4.1		D/T
DR 4.1.6	The remote sensing device software shall interpret system reboot commands from the remote sensing device comms subsystem.	DR 4.1		D/T
DR 5.1.3	The remote sensing device software shall interpret data processing option commands from the remote sensing comms subsystem.	DR 5.1	DR 5.1.3.1	D/T
DR 4.1.7	The remote sensing device software shall configure the system based on elevation angle and azimuth configuration commands.	DR 4.1	DR 4.1.7.1	D/T
DR 4.1.8	The remote sensing device software shall reboot the remote sensing device after receiving reboot commands from the remote sensing device comms subsystem.	DR 4.1	DR 4.1.8.1	D/T
DR 3.3.2	The remote sensing device software shall calculate elevation angle tropospheric distortion effects using onboard temperature, pressure, and humidity data.	DR 3.3, DR 3.4, DR 3.5		D/T
DR 6.1.2	The remote sensing device software shall send health status updates to the remote sensing device comms subsystem at least once an hour.	DR 6.1		D/T
DR 0.4.2	The remote sensing device software shall store daily water level data to the memory drive.	DR 0.4	DR 0.4.2.1	D/T
DR 0.5.1	The remote sensing device software shall clear water level data off of the memory drive once the data is received by the ground control station.	DR 0.5		D/T
DR 2.1.7	The remote sensing device software shall have a MTBF of greater than 1 year.	DR 2.1	DR 2.1.7.1	D/T
Ground Control Station Software (on a laptop)				
DR 0.3.2	The ground control station software shall be open source (e.g. Python, C++).	DR 0.3		I
DR 4.1.9	The ground control station software shall provide a user interface for sending system configuration commands to the remote sensing device.	DR 4.1		D
DR 4.1.10	The ground control station software shall send system configuration commands to the remote sensing device.	DR 4.1		D
DR 4.1.11	The ground control station software shall provide a user interface for sending system reboot commands to the remote sensing device.	DR 4.1		D
DR 4.1.12	The ground control station software shall send system reboot commands to the remote sensing device.	DR 4.1		D
DR 5.1.4	The ground control station software shall provide a user interface for sending data processing option commands.	DR 5.1		D
DR 5.1.5	The ground control station software shall send data processing option commands to the remote sensing device.	DR 5.1		D
DR 7.1.1	The ground control station software shall provide a user interface for displaying sub-hourly water level data.	DR 7.1		D
DR 9.1.1	The ground control station software shall provide a user interface for displaying the most recent water level data.	DR 9.1		D
DR 6.1.3	The ground control station software shall provide a user interface for displaying the most recent health status update.	DR 6.1		D
DR 0.4.3	The ground control station software shall have a database to store operation history.	DR 0.4		D
DR 2.1.8	The ground control station software shall have a MTBF of greater than 1 year.	DR 2.1		D/T
Level 3: Component Requirements:				
Requirement	Requirement	Parent	Child	Verification
GNSS Module				
DR 3.1.1.1	The GNSS Module shall process GNSS signals from GPS, GLONASS, Galileo, and Beidou.	DR 3.1.1		I
DR 3.2.1.1	The GNSS Module shall use L1 C/A, E1-B/C, L10F, B1I, and B1C carrier frequencies.	DR 3.2.1		I
DR 9.1.3.1	The GNSS Module shall output SNR and elevation angle data.	DR 9.1.3		I/D
DR 2.1.4.1	The GNSS Module shall have a MTBF of greater than 1 year.	DR 2.1.4		D/T
DR 2.2.4.1	The GNSS Module shall operate in the -30 to 55 C temperature range.	DR 2.2.4		I/T
GNSS Antenna				
DR 3.1.1.2	The GNSS Antenna shall receive GNSS signals from GPS, GLONASS, Galileo, and Beidou.	DR 3.1.1		I
DR 3.2.1.2	The GNSS Antenna shall use L1 C/A, E1-B/C, L10F, B1I, and B1C carrier frequencies.	DR 3.2.1		I
DR 0.5.2.1	The GNSS Antenna shall be operable in rain and snow conditions.	DR 0.5.2		I/T
DR 2.1.4.2	The GNSS antenna shall have a MTBF of greater than 1 year.	DR 2.1.4		D/T
DR 2.2.4.2	The GNSS antenna shall operate in the -30 to 55 C temperature range.	DR 2.2.4		I/T
Comms Module				
DR 4.1.3.1	The Comms Module shall send system configuration commands to the microprocessor.	DR 4.1.3		D/T
DR 4.1.4.1	The Comms Module shall send system reboot commands to the microprocessor.	DR 4.1.4		D/T
DR 5.1.2.1	The Comms Module shall send data processing option commands to the microprocessor.	DR 5.1.2		D/T
DR 8.1.1.1	The Comms Module shall receive SNR or water level data from the microprocessor.	DR 8.1.1		D/T
DR 2.1.2.1	The Comms Module shall have a MTBF of greater than 1 year.	DR 2.1.2		D/T
DR 2.2.2.1	The Comms Module shall operate in the -30 to 55 C temperature range.	DR 2.2.2		I/T
Comms Antenna				
DR 4.1.1.1	The Comms Antenna shall receive system configuration commands from the ground control station.	DR 4.1.1		D/T
DR 4.1.2.1	The Comms Antenna shall receive system reboot commands from the ground control station.	DR 4.1.2		D/T
DR 5.1.1.1	The Comms Antenna shall receive data processing option commands from the ground control station.	DR 5.1.1		D/T
DR 8.1.1.2	The Comms Antenna shall transmit SNR or water level data to the ground control station within 2 hours latency.	DR 8.1.1		D/T
DR 6.1.1.1	The Comms Antenna shall transmit health status updates to the ground control station at least once an hour.	DR 6.1.1		D/T
DR 0.5.1.1	The Comms Antenna shall operate in precipitation (rain and snow) conditions.	DR 0.5.1		I/T
DR 2.1.2.2	The Comms Antenna shall have a MTBF of greater than 1 year.	DR 2.1.2		D/T
DR 2.2.2.2	The Comms Antenna shall operate in the -30 to 55 C temperature range.	DR 2.2.2		I/T
Microprocessor				
DR 7.2.1.1	The Microprocessor shall calculate the water level sub-hourly using GNSS IR SNR and elevation angle data to a precision of better than 5 cm.	DR 7.2.1		D/T
DR 3.3.2.1	The Microprocessor shall calculate tropospheric elevation angle distortion using temperature, pressure, and humidity data from the Pressure/Humidity/Temp sensors.	DR 3.3.2		D/T
DR 4.1.8.1	The Microprocessor shall reboot the remote sensing device after receiving reboot commands from the Comms Module.	DR 4.1.6		D/T
DR 4.1.7.1	The Microprocessor shall configure the system after receiving system configuration commands from the Comms Module.	DR 4.1.7		D/T
DR 5.1.3.1	The Microprocessor shall update data processing options after receiving data processing option commands from the Comms Module.	DR 5.1.3		D/T
DR 0.3.1.1	The Microprocessor shall use open source software (i.e. Python, C++).	DR 0.3.1		I
DR 0.4.2.1	The Microprocesor shall send water level data from Data Storage and health status to the Comms Module.	DR 0.4.2		D/T
DR 2.1.7.1	The Microprocessor shall have a MTBF of greater than 1 year.	DR 2.1.7		D/T
DR 2.2.7	The Microprocessor shall operate in the -30 to 55 C temperature range.	DR 2.2		I/T

Batteries				
DR 2.3.1.1	The Batteries shall supply power continuously for 3 days without power generation.	DR 2.3.1		I/A/T
DR 0.1.1.1	The Batteries shall weigh no more than 7.5 lbs.	DR 0.1.1		I
DR 2.1.1.1	The Batteries shall have a MTBF of greater than 1 year.	DR 2.1.1		D/T
DR 3.1.1.1	The Batteries shall operate in the -30 to 55 C temperature range.	DR 3.1.1		I/T
Solar Panels				
DR 2.3.2	The Solar Panels shall recharge the batteries in no more than 3 peak sun hours (1000 W/m^2 or more solar irradiance).	DR 2.3		A/T
DR 0.1.1.2	The Solar Panels shall weigh no more than 7.5 lbs.	DR 0.1.1		I
DR 0.5.4	The Solar Panels shall operate in precipitation (rain and snow) conditions.	DR 0.5		I/T
DR 2.1.1.2	The Solar Panels shall have a MTBF of greater than 1 year.	DR 2.1.1		D/T
DR 3.1.1.2	The Solar Panels shall operate in the -30 to 55 C temperature range.	DR 3.1.1		I/T
Data Storage				
DR 9.1.2.1	The Data Storage shall store 32 GB of data.	DR 9.1.2, DR 0.4.1		I
DR 2.1.3.1	The Data Storage shall have a MTBF of greater than 1 year.	DR 2.1.3		D/T
DR 2.2.3.1	The Data Storage shall operate in the -30 to 55 C temperature range.	DR 2.2.3		I/T
Housing				
DR 0.5.3.1	The Housing shall be sealed to prevent humidity from entering the housing and damaging non-waterproof components.	DR 0.5.3		I/T
DR 0.6.1.1	The Housing shall remain attached to the ground.	DR 0.6.1		A/T
DR 0.5.3.2	The Housing shall withstand precipitation (rain and snow) conditions.	DR 0.5.3		I/T
DR 2.1.6.1	The Housing shall have a MTBF of greater than 1 year.	DR 2.1.6		D/T
DR 2.2.6.1	The Housing shall operate in the -30 to 55 C temperature range.	DR 2.2.6		I/T
DR 0.5.3.3	The Housing shall have feedthrough connectors for the external GNSS Antenna, Comms Antenna, Solar Panels, and Pressure/Humidity/Temp Sensors.	DR 0.5.3		I
Pressure Sensor				
DR 3.5.1.1	The Pressure Sensor shall measure pressure to a precision of better than 0.1 hPa.	DR 3.5.1		I
DR 3.1.2.1	The Pressure Sensor shall have a sampling frequency every 15 minutes.	DR 3.1.2		I
DR 0.5.5.1	The Pressure Sensor shall operate in precipitation (rain and snow) conditions.	DR 0.5.5		I/T
DR 2.1.5.1	The Pressure Sensor shall have a MTBF of greater than 1 year.	DR 2.1.5		D/T
DR 2.2.5.1	The Pressure Sensor shall operate in the -30 to 55 C temperature range.	DR 2.2.5		I/T
Humidity Sensor				
DR 3.4.1.1	The Humidity Sensor shall measure relative humidity to a precision of better than 2 percent.	DR 3.4.1		I
DR 3.1.2.2	The Humidity Sensor shall have a sampling frequency every 15 minutes.	DR 3.1.2		I
DR 0.5.5.2	The Humidity Sensor shall operate in precipitation (rain and snow) conditions.	DR 0.5.5		I/T
DR 2.1.5.2	The Humidity Sensor shall have a MTBF of greater than 1 year.	DR 2.1.5		D/T
DR 2.2.5.2	The Humidity Sensor shall operate in the -30 to 55 C temperature range.	DR 2.2.5		I/T
Temperature Sensor				
DR 3.3.1.1	The Temperature Sensor shall measure temperature to a precision of better than 0.2 C.	DR 3.3.1		I
DR 3.1.2.3	The Temperature Sensor shall have a sampling frequency every 15 minutes.	DR 3.1.2		I
DR 0.5.5.3	The Temperature Sensor shall operate in precipitation (rain and snow) conditions.	DR 0.5.5		I/T
DR 2.1.5.3	The Temperature Sensor shall have a MTBF of greater than 1 year.	DR 2.1.5		D/T
DR 2.2.5.3	The Temperature Sensor shall operate in the -30 to 55 C temperature range.	DR 2.2.5		I/T