Controllable Open-source Water Sensing

Spring Final Review

ENVIRONMENTAL REMOTE SENSING USING A LOW-COST GNSS INTERFEROMETRIC REFLECTOMETRY SYSTEM

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Project Purpose and Objectives

Project Background

- Climate Change: Reduced fresh water availability, glacier melting, flooding and sea level rise
  - Need for low cost remote sensing devices that can be deployed in remote locations (no internet or power) and monitor water level in reservoirs, flooding, glacier melting/snow level, and sea level rise
  - Existing remote sensing devices can cost thousands of dollars (tide gauges, high-quality GNSS-IR receivers, etc)

[Credit: NBC Bay Area]

[Credit: Wired]

Project Background

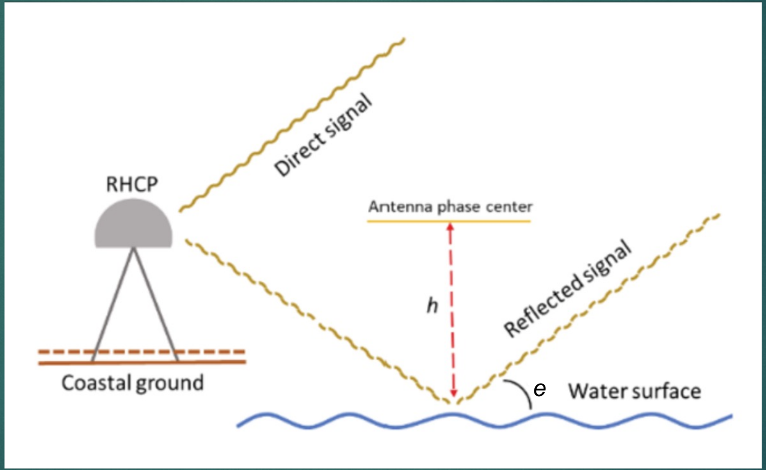
- Opportunity to develop a low-cost (less than $800) open source remote sensing device that will monitor changes in water level or ice/snow height using the GNSS-IR technique
    - Low-cost: able to be built by individuals in low-income communities
    - Open source: no need for additional software development or software subscriptions, software is downloadable from a GitHub repository

Mission Objective

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.

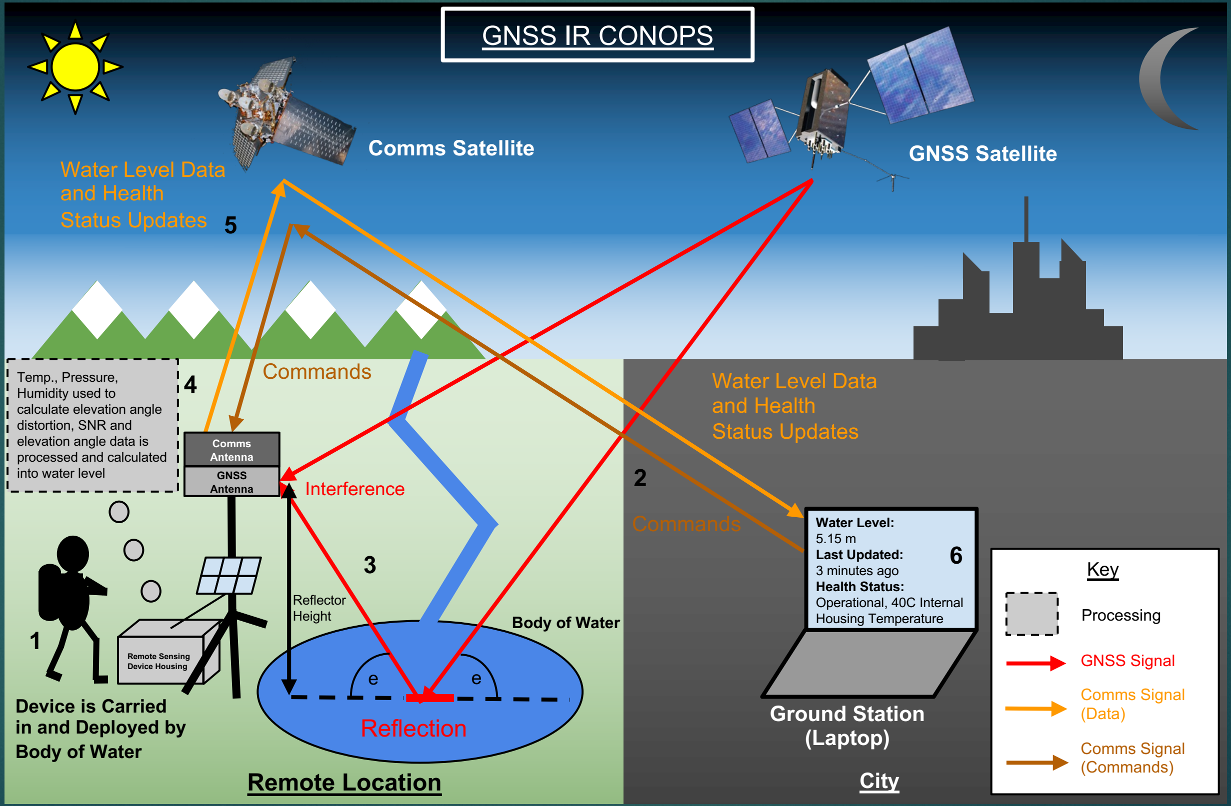
GNSS-IR Background

- GNSS-IR: Global Navigation Satellite System Interferometric Reflectometry
- Reflected GNSS signal interferes with direct signal, showing up in SNR data



[Credit: Song et. al. (2019)]

CONOPS



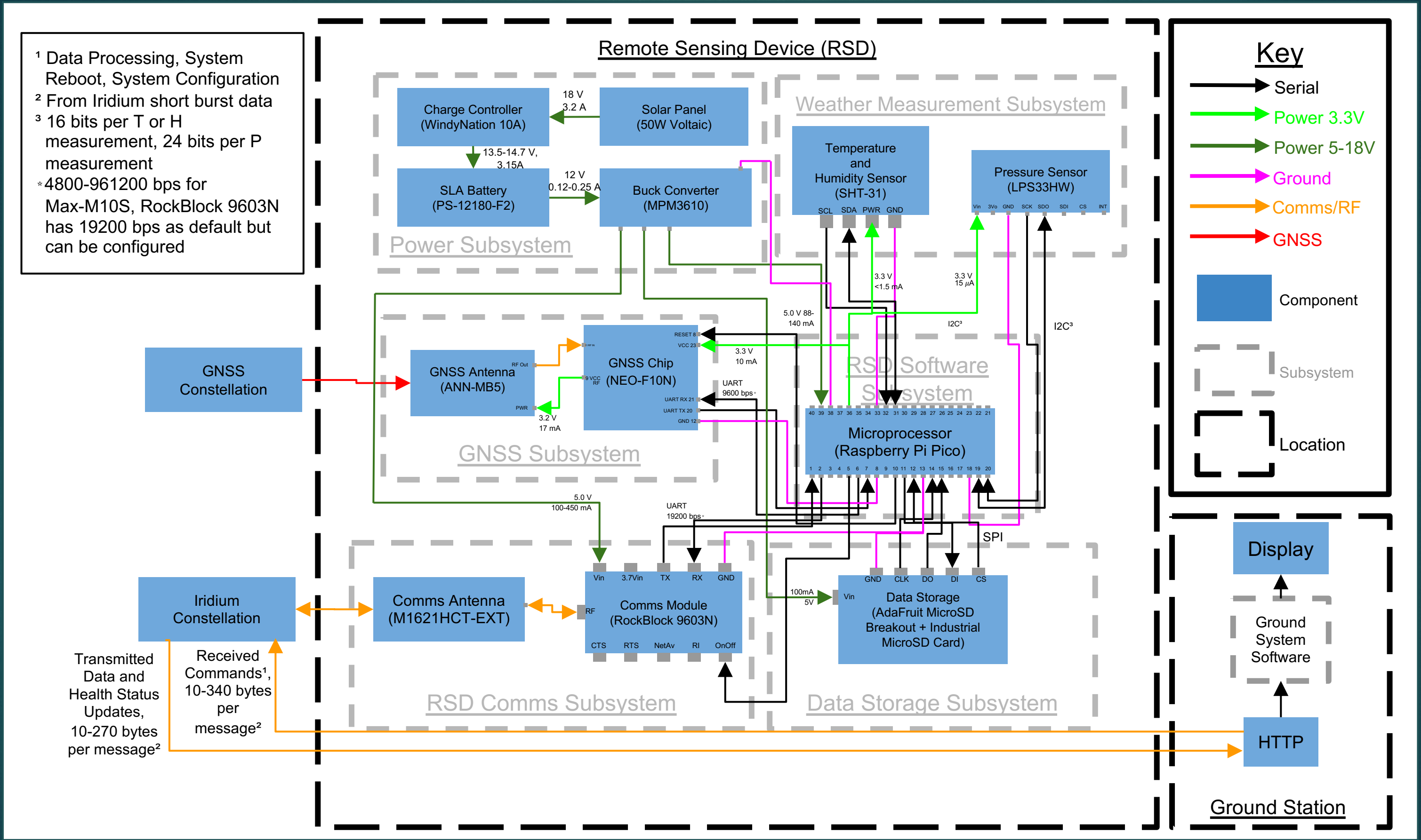
GNSS IR CONOPS
Comms Satellite
GNSS Satellite
Water Level Data and Health Status Updates
5
Temp., Pressure, Humidity used to calculate elevation angle distortion, SNR and elevation angle data is processed and calculated into water level
4
Commands
Comms Antenna
GNSS Antenna
Interference
3
Reflector Height
Remote Sensing Device Housing
1
Device is Carried in and Deployed by Body of Water
e
e
Reflection
Body of Water
Remote Location
Water Level Data and Health Status Updates
2
Commands
Water Level: 5.15 m
Last Updated: 3 minutes ago
Health Status: Operational, 40C Internal Housing Temperature
6
Ground Station (Laptop)
City
Key
Processing
GNSS Signal
Comms Signal (Data)
Comms Signal (Commands)

Key Driving Requirements

Requirement Number	Requirement	Parent Requirement	Child Requirement
FR 1.0	The system shall cost less than $800 per unit, excluding monthly communication subscriptions.	N/A	DR 1.1
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
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
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 2.3	They system shall operate entirely on its own power.	FR 2.0	DR 2.3.1, DR 2.3.2
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

Design Description

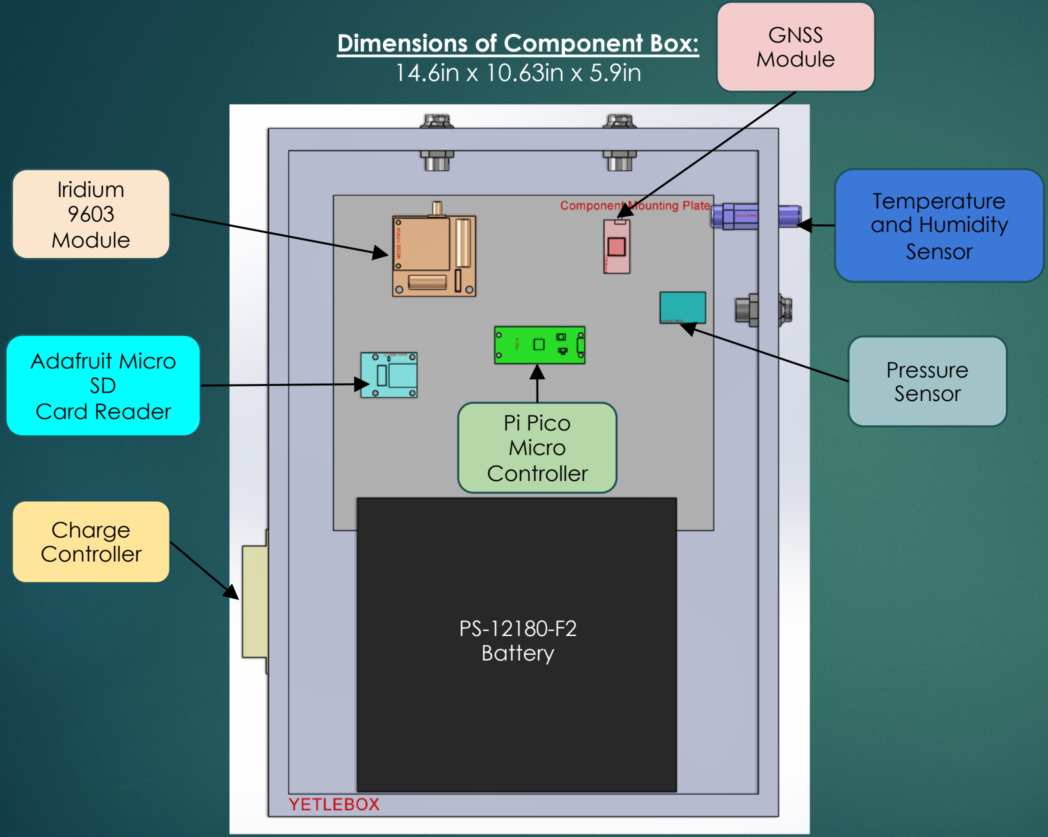
Functional Block Diagram



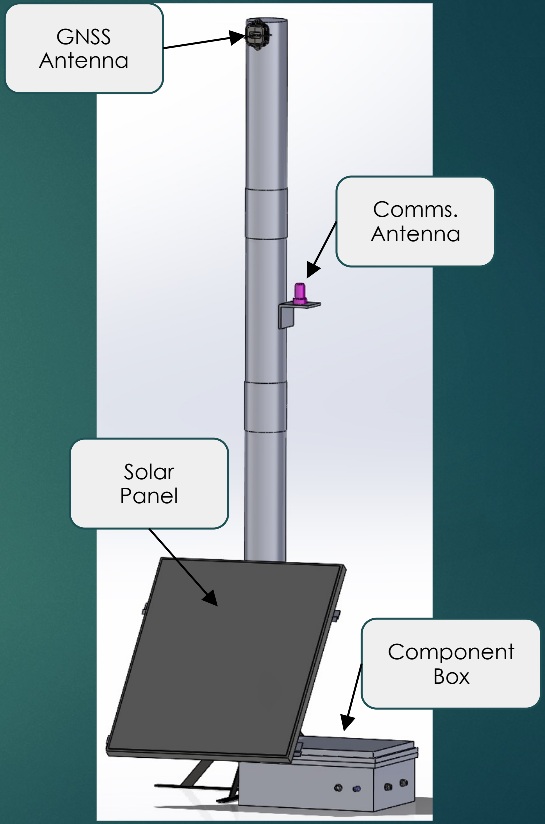
Section 1: Project Overview | Section 2: Design Description | Section 3: Test Overview and Results | Section 4: Program Management

Current Baseline Design

Dimensions of Component Box:
14.6in x 10.63in x 5.9in



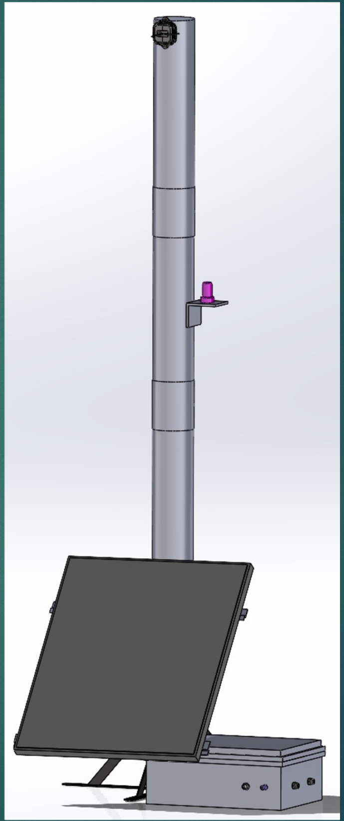
Dimensions of Antenna Pole:
78.7in x 23.72 in x 20.28 in



Note: 2m GNSS-IR antenna height is based off GNSS reflection zone mapping for a large body of water (i.e. Boulder Reservoir)

Major Design Changes from TRR

- Upgraded Battery to an 18 Ahr battery from original 10.5 Ahr for longer battery life
- Changed position of solar panel
- Changed location of communication antenna
- Updated location of component box



Elements Evaluated Via Testing

Elements	Evaluation Via Test
Power	Battery discharge and charge test
Commands	Commands test (system configuration, data processing, system reboot)
Water Level Processing	Real-time transmission, multi-constellation, and two week deployment test
Accuracy	Two week deployment test and antenna height test
Data Transmission /Latency	Real time transmission and two week deployment
Water Resistance	Water resistance test (component housing box)
Durability	Two week deployment
Temperature	Pi pico temperature test

DR 2.3	They system shall operate entirely on its own power.
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.
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).
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).
FR 7.0	The system shall retrieve sub-daily water level with a precision better than 5 cm.
FR 8.0	The system shall be able to estimate water level variations within 2 hours latency.
DR 9.1	The system shall transmit the SNR data or final results (water level variation) to a ground control station to display most recent water level and time results on a screen.
DR 0.5	The system shall operate in precipitation conditions
Dr 2.1	The system shall have Mean TIme Between Failure (MTBF) of greater than 1 year.
DR 2.2	The system shall operate in a temperature range of -30 to 55 C (-22 to 131 F).

Test Overview and Results

All Tests Performed

Test	Description	Successful?
Multi - Constellation	Conduct a multi-constellation signal report test to verify the systems capability to receive and process signals from multiple GNSS constellations using L1 and L5 carrier frequencies.	Yes
Antenna Height	Execute a test to confirm reflector height accuracy to within 5 cm.	Yes
Commands	Execute a command response test to access the system's ability to receive and execute instructions from a ground control station, including system configuration, data processing options, and reboot commands.	Yes
Real Time Transmission	Execute a real-time transmission test to assess the system's capability to transmit SNR and water level data live to a ground control display, verify the system's proficiency in transmitting water level data with a less than two hour latency, and verify system's capability in sending consistent and accurate health status updates to the ground station.	Yes
Water Resistance	Conduct a water resistance test to evaluate the systems durability when subjected to direct water exposure.	Yes
Pi Pico Temperature	Conduct an operational test on Raspberry Pi Pico in a controlled environment to ensure functionality at a -30 C temperature.	Yes
Power	Test charging and discharging of battery to verify battery life and charge time.	Yes
2 - Week Deployment	Conduct a deployment test near a body of water to verify system operability for 2 weeks.	Yes

Note: The results of all tests that are not in yellow are in the backup slides.

All Tests Performed (Component Level)

Test	Description	Successful?
Buck Converter Test	Conducted a test to verify the output voltage of 5V from the buck converter with a 12V input.	Yes
Pressure Sensor Test	Conducted a test to verify correct pressure output and accuracy.	Yes
Temperature and Humidity Sensor Test	Conducted a test to verify correct temperature and humidity outputs and accuracy.	Yes
Communication Module and Antenna Test	Conducted a test to verify that the comms module could transmit and receive properly using the external comms antenna.	Yes
GNSS Module and Antenna Test	Conducted a test to verify the GNSS receiver could properly receive SNR arcs from multiple GNSS constellations and multiple frequencies and output SNR, time, elevation angle, and azimuth data,	Yes

Note: The results of all tests that are not in yellow are in the backup slides.

Critical Test I: Power

Power Test - Verifying our CDR Power Models

Completed testing of the battery life of our lead acid battery and solar panel charging, which validated the Power Models from CDR

- Timed and supervised battery discharging, compared to predicted battery discharge time from CDR power model
- Test performed the 6 days leading up to Symposium, April 12th-18th

Power Test: Requirements

Requirement Number	Requirement	Parent Requirement
DR 2.3	The system shall operate entirely on its own power.	FR 2.0
DR 2.3.1	The power subsystem shall supply power continuously for at least 3 days without power generation.	DR 2.3
DR 2.3.1.1	The Batteries shall supply power continuously for at least 3 days without power generation.	DR 2.3.1
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

Power Test - Test Setup

Sensors	Placement/ Calibration Plans
Stopwatch	• Time discharge of battery to fully discharge, or at least, <50%
Charge Controller (Windynation OD10) 	• Low resolution measurement of battery • <50% charge changes LED color, then <25% (measured from battery voltage) • Solid green LED: > 50% charge • Solid orange LED: 25-50% charge • Solid red LED: < 25% charge

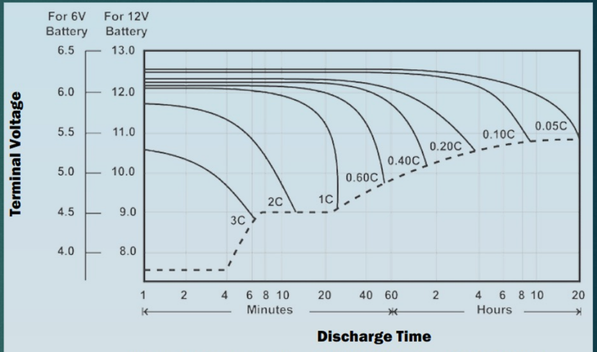


Figure 4: Discharge Characteristic Curves at 20°C (68°F)

Note: In the above discharge curves, C is capacity

Power Model - Equations and Analysis

Power Consumption:

$$P = I \cdot V \ [W]$$

$$Capacity = P \cdot \Delta t \ [Whr]$$

$$Battery\ Capacity = V_{Battery} \cdot I_{Battery\ Capacity} \ [Whr]$$

Battery Charging:

$$Discharged\ Battery\ Capacity = (Battery\ Capacity) \cdot DOD \ [Whr]$$

Note: DOD (Depth of discharge) is the percent that the battery has been depleted relative to the overall battery capacity.

$$Energy\ Required\ for\ Full\ Charge = (Discharged\ Battery\ Capacity)/(Lead\ Acid\ Efficiency) \ [Whr]$$

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

$$Charge\ Time = (Energy\ Required\ for\ Full\ Charge)/(Adjusted\ Solar\ Output) \ [hr]$$

Battery Life:

$$Efficiency_{Buck\ Converter} = P_{out} / P_{in} = (V_{out} \cdot I_{out})/(V_{Battery} \cdot I_{Battery})$$

$$Battery\ Life = I_{Battery\ Capacity} / I_{Battery} \ [hr]$$

Power Model - Predicted Results

- Total power consumption for three days of **126.77 Whr**
  - Battery capacity is 216 Whr (this is with the 18Ah battery)

- Time to charge batteries from 50% depth of discharge of **3.38 peak sun hours**

- **2.296 days** (max current draw) to **4.34 days** (min current draw) battery life
  - Sufficient battery capacity for 3 days without power generation

Power Testing Results

Parameter	Model	Testing Result
Time to charge from 50%	3.38 Sun hours	N/A, more on following slide
Battery life	2.30 - 4.34 Days	> 5.5 days

DR 2.3.1	The power subsystem shall supply power continuously for at least 3 days without power generation.	DR 2.3
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

Differences Between Power Modelling and Testing Results, Uncertainty in Data

Parameter	Model	Testing Result
Time to charge from 50%	3.38 Sun hours	N/A
Battery life	2.30 - 4.34 Days	> 5.5 days

Charge time
- Optimal panel efficiency
- Consistent solar radiation
- We were unable to discharge the battery enough to rigorously test the charge time after battery life test
    - Boulder reservoir test has survived overcast days, but this is not a thorough validation
- Will test for final report

Battery life
- Max load at all times assumption
- Gross overestimation of power needs of Pi Pico and communications module
    - Communications module was not active at all times and has a lower power standby mode

Power Testing - Validation of Project Mission Objectives

- Verified the ability of our system to operate in remote environments off of its own power
  - Greater than 3 day battery life (in case storm moves in and blocks out sun for solar power generation)
  - Less than 3 hours solar charge time for 50% depth of discharge (ensures fast charging of battery in minimal amount of time, ensuring system operability in varying weather conditions)

Critical Test II: Two Week Deployment

Two Week Deployment Test - What is being Tested and Why

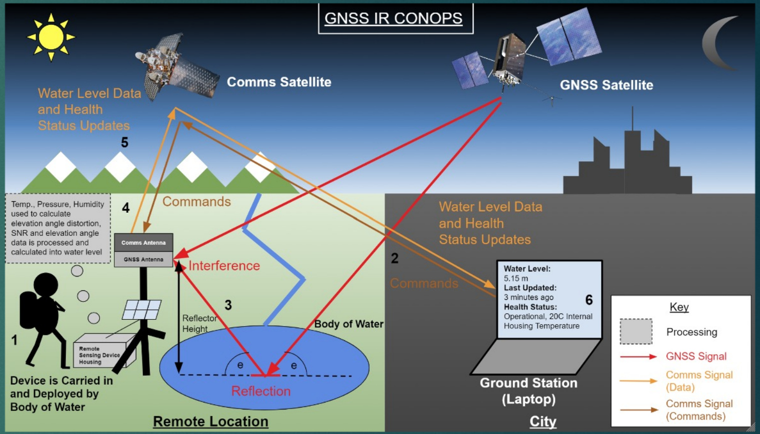
Day in The Life Test:

a) Verify that the Remote Sensing Device (RSD) **works for a two week period at a remote location without any failures** between the RSD and the ground control station (GCS)

b) Verify functionality of calculating water level with an **accuracy of better than 5 cm**

c) Verify **mean time between failure of greater than 1 year** by verifying system operability for a two week test period

d) Verify **functionality of mechanical subsystem** (i.e. pole and housing remain attached to ground)



Two Week Deployment Test - Requirements

Requirement Number	Requirement
FR 2.0	The system shall operate independently in remote environments in a temperature range of -30 to 55 C (-22 to 131 F).
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.
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).
FR 6.0	The system shall send health status updates to the ground station.
FR 7.0	The system shall retrieve sub-daily water level with a precision better than 5 cm.
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.
DR 2.1	The system shall have a Mean Time Between Failure (MTBF) of greater than 1 year.
DR 2.3	The system shall operate entirely on its own power.
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.

Two Week Deployment Test - Requirements (Continued)

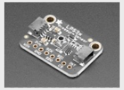
Requirement Number	Requirement
DR 0.6	The system shall attach to the ground.
DR 2.1.1	The power subsystem shall have a MTBF of greater than 1 year.
DR 2.1.2	The remote sensing device comms subsystem shall have a MTBF of greater than 1 year.
DR 2.1.3	The data storage subsystem shall have a MTBF of greater than 1 year.
DR 9.1.3	The GNSS subsystem shall send SNR data to the data storage subsystem.
DR 2.1.4	The GNSS subsystem shall have a MTBF of greater than 1 year.
DR 2.1.5	The weather measurement subsystem shall have a MTBF of greater than 1 year.
DR 2.1.6	The mechanical subsystem shall have a MTBF of greater than 1 year.
DR 0.6.1	The mechanical subsystem shall attach to the ground.
DR 0.4.2	The remote sensing device software shall store daily water level data to the memory drive.

Two Week Deployment Test - Requirements (Continued)

Requirement Number	Requirement
DR 0.4.1	The remote sensing device software shall clear unnecessary data off of the memory drive once the water level data is received by the ground control station.
DR 0.5	The system shall operate in precipitation (rain and snow) conditions.
DR 8.1	The system shall estimate water level variations within 2 hours latency.
DR 2.1.7	The remote sensing device software shall have a MTBF of greater than 1 year.
DR 2.1.8	The ground control station software shall have a MTBF of greater than 1 year.

Note: We are in agreement with our faculty advisor that the 2 week deployment test is sufficient to verify our MTBF of 1 year requirements. This test will also verify applicable component requirements (not listed).

Two Week Deployment Test - Test Setup

Sensors	Placement/ Calibration Plans
GNSS Receiver (NEO-F10N) 	• 5, 10, and 15 degree elevation angles (shown in yellow, blue, and red on the right) • 67 to 235 degree azimuth angles
GNSS Antenna (ANN-MB5) 	• Was positioned south-facing towards Boulder Reservoir • 2 m reflector height
Temperature and Humidity Sensor (SHT-31) 	• External mount on electrical box • Comes factory calibrated, we verified accuracy meets requirements DR 3.3.1 and DR 3.5.1
Pressure Sensor (LPS33HW) 	• Open to outside air via silicone tube • Was tested for accuracy ahead of time, compared pressure measurements with barometric pressure in Boulder

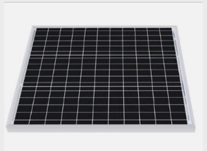
Two Week Deployment Test - Test Setup

Sensors → Placement/ Calibration Plans

Antenna Pole
(PVC Pipe & Coupling)

- Positioned perpendicular to water surface
- Set antenna at a height of 2m from the ground

Solar Panel
(Renogy 50W)



- Positioned south-facing (sun is south in northern hemisphere)
- Angle of 45 degrees relative to the ground

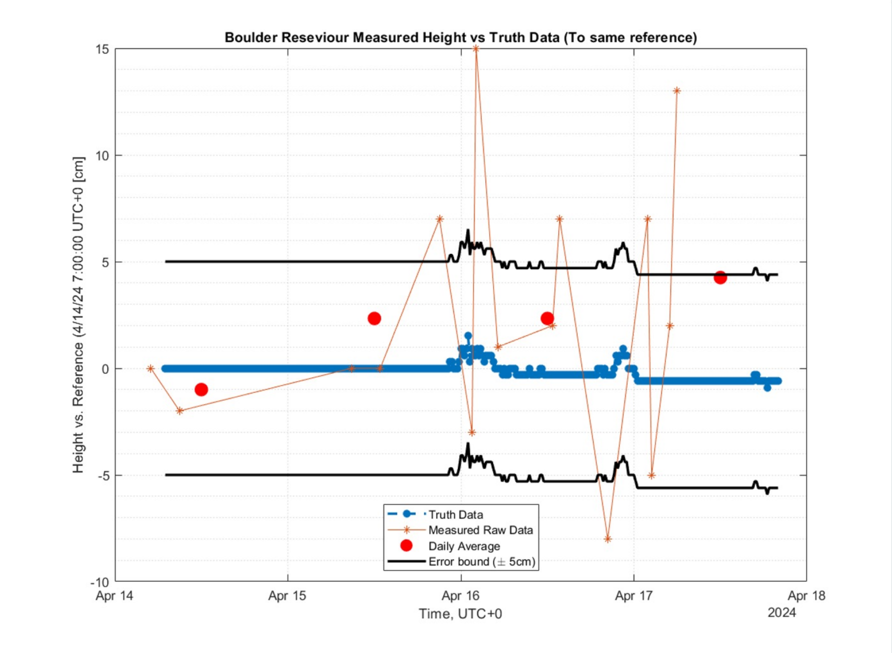
Comms Antenna
(M1621HCT-EXT)

- Positioned on L-bracket on antenna pole, clear line of sight to sky and Iridium satellites

2-Week Deployment Test: Results

- Truth data for Boulder Reservoir water height is from Northern Water's website, which is reported to 1/100th of a foot

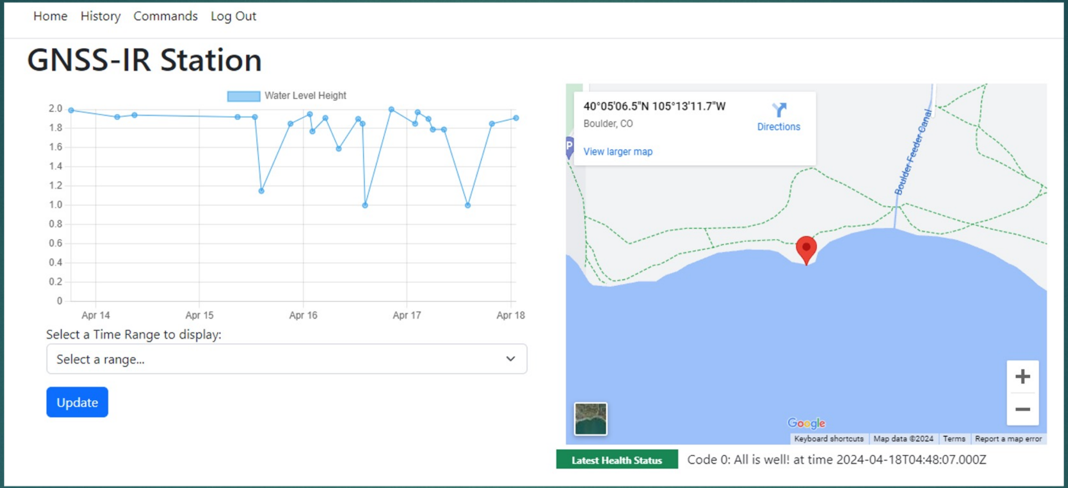
- Data collected from Apr 14-17 is plotted vs truth data, excluding outliers > 40cm
- Daily Average taken to account for inaccuracy from real-time GNSS-IR implementation
  - Meets < 5cm accuracy during 1-day period requirement



FR 7.0	The system shall retrieve sub-daily water level with a precision better than 5 cm.

2-Week Deployment Test: Results

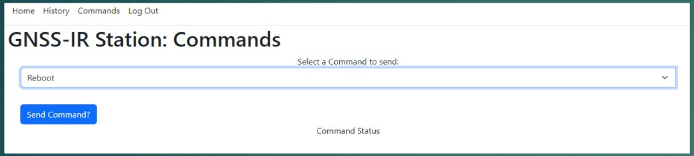
Home Page

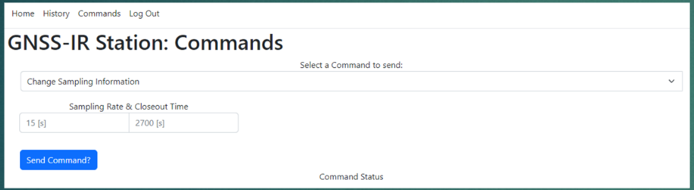


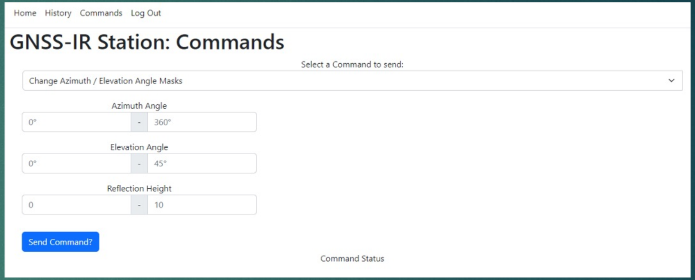
FR 6.0	The system shall send health status updates to the ground station.
FR 7.0	The system shall retrieve sub-daily water level with a precision better than 5 cm.
FR 9.0	The system shall be able to transmit the SNR data and/or final results (water level variation) to a ground control station (e.g., a laptop) to be displayed live on a screen.

2-Week Deployment Test: Results

Commands Page







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.
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).

2-Week Deployment Test: Results

- **System remained attached to ground** over entire two week period
  - **80-90 mph wind** storm over two days (April 6th and 7th) occurred during the two week deployment period

- **All components remained functional during several rain storms** and over entire two week period (no water got into the electrical box)

- **Power system remained operational** during the entire two week period
  - Over several site visits over the two week deployment period, the battery light on our charge controller remained green (above 50% battery)
  - Verified that the solar panel was able to charge the battery sufficiently charged above 50% battery

FR 2.0	The system shall operate independently in remote environments in a temperature range of -30 to 55 C (-22 to 131 F).
DR 0.6	The system shall attach to the ground.
DR 0.5	The system shall operate in precipitation (rain and snow) conditions.
DR 2.3	The system shall operate entirely on its own power.
DR 2.1	The system shall have a Mean Time Between Failure (MTBF) of greater than 1 year.

2-Week Deployment: Results

Water Level Message Time	Latency (hr:min:sec)
Minimum	00:30:08
Maximum	1:00:44
Average	00:44:40

```
Water Level Message time from Collection to Display on Ground Station
Average: [hh:mm:ss]
    00:44:40

Maximum: [hh:mm:ss]
    01:00:44

Minimum: [hh:mm:ss]
    00:30:08
```

DR 8.1	The system shall estimate water level variations within 2 hours latency.

2-Week Deployment: Issues

Memory allocation errors on the Pi Pico

- System stopped working after 6 hours
- Unable to handle data-processing

→

Resolved by:

- Altering how data was stored/accessed
- Downsampling GNSS data from 15s to 30s to reduce the number of data points collected

```
MemoryError: memory allocation failed, allocating 4096 bytes
Traceback (most recent call last):
  File "mainClass.py", line 405, in closeout_curve
  File "Reflection_Height.py", line 27, in reflection_height
  File "Reflection_Height.py", line 115, in flat_snr
  File "umatrix.py", line 11, in zeros
  File "umatrix.py", line 8, in fill
  File "umatrix.py", line 26, in __init__
  File "umatrix.py", line 26, in <listcomp>
MemoryError: memory allocation failed, allocating 4096 bytes
Traceback (most recent call last):
  File "mainClass.py", line 318, in gnss_handler
  File "mainClass.py", line 505, in write_gnss
MemoryError: memory allocation failed, allocating 232 bytes
```

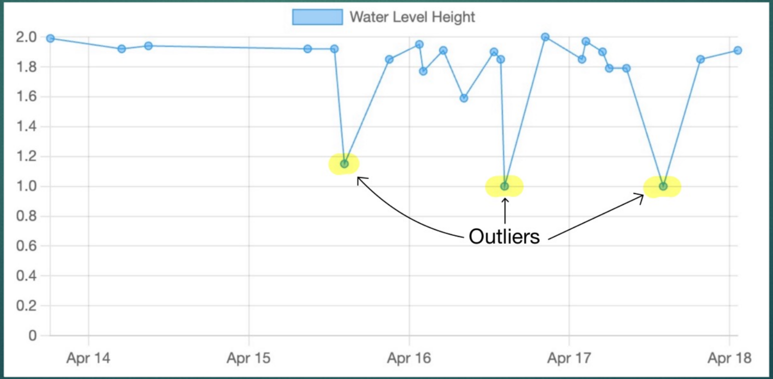
2-Week Deployment: Issues

Encountered several outlier data points

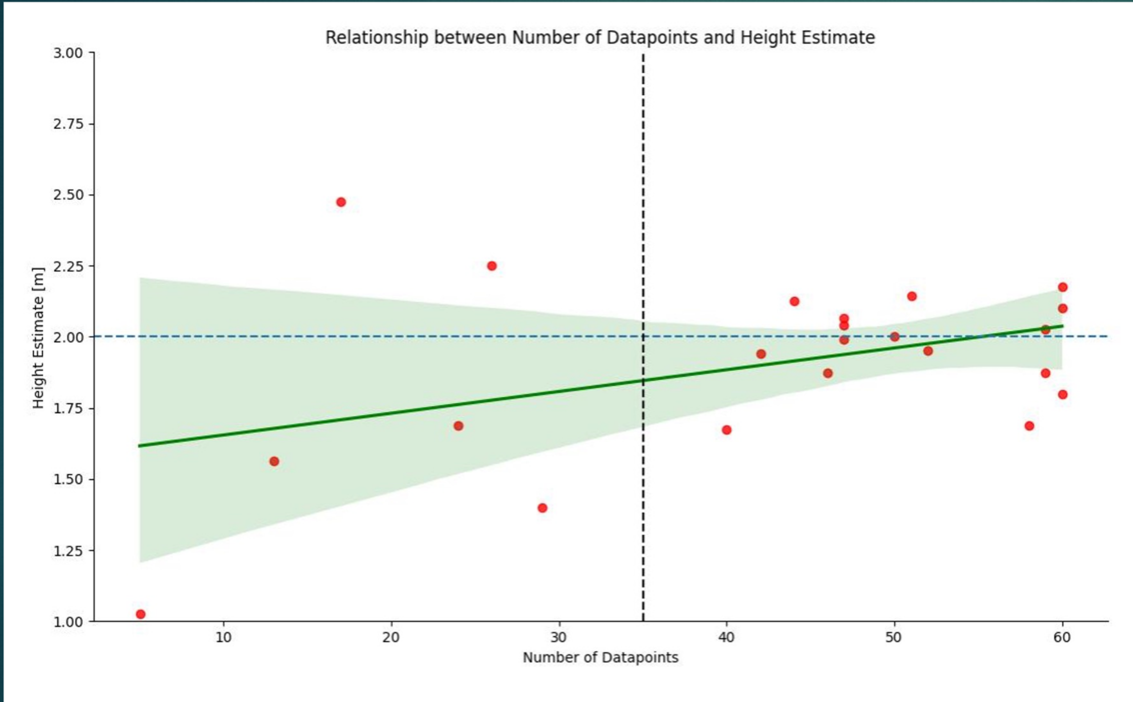
- With real-time processing, some datasets will be better than others
- Leads to occasional outliers in reflector height data points

Resolved by:

- Better filtering of elevation angles
- Utilizing stricter minimum/maximum reflector height masking
- Filtering the number of data points after masks
- Averaging over 1 day period



2-Week Deployment: Issues



Data Information

Date: April 3rd, 2024
Location: Boulder Reservoir
Satellite: GPS
True Height: 2 m reflector height

For our quality control, we decided to use data that contain more than 35 points, which increases the overall accuracy of height estimation.

2-Week Deployment - Mission Achievement

Verified the functionality of our system for a long period in a remote location, meeting the following requirements:

- Sufficient power to operate the system more than 3 days
- Near-real time transmission of both data and commands in 30-60 mins
- Durability of our mechanical subsystem under severe weather conditions
- Better than 5cm accuracy in measuring variation of water level
- Test extension approved by Boulder Reservoir, will continue until Friday May 3rd

Program Management and Systems Engineering

Main Challenges and Successes

- **Challenges:**
  1) Software development with limited RAM on a Pi Pico
  2) Managing a $800 budget for our system
  3) Software development delayed some tests

- **Successes:** Created a reliable remote sensing device that:
  1) Receives and stores GPS NMEA data in real time
  2) Processes data into water level using on-node processing on a Pi Pico Microcontroller with limited RAM and store water level data on a micro SD card
  3) Transmits water level data to a user interface over Iridium communications satellites to be displayed on a screen to a user within 2 hours latency
  4) Receives and responds to system configuration, data processing, and system reboot commands sent remotely by a user through the ground station over Iridium communication satellites
  5) Operates in varying weather conditions (i.e. rain storms and severe wind)
  6) Has a low-cost of close to $800 with COTS components (our system cost $850.49)
  7) Uses open source software (Micropython)

Budget

CDR Estimated Budget

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

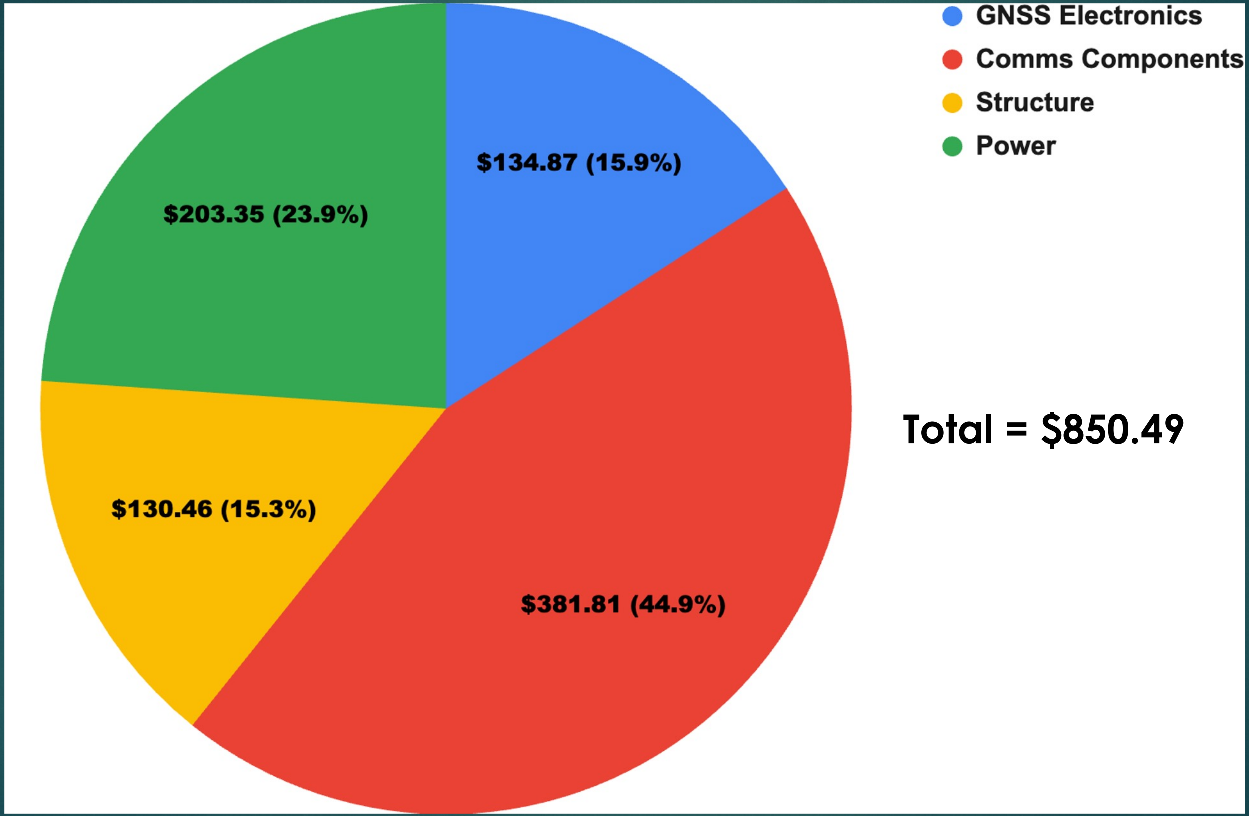
Actual Budget

Component	Name/Desc	Quantity	Price Per Unit	Total
GNSS Chip	NEO-F10N	1.00	$63.75	$63.75
GNSS Antenna	ANN-MB5	1.00	$34.72	$34.72
Comms Module	RockBlock 9603N	1.00	$267.00	$267.00
Comms Antenna	M1621-HCT	1.00	$72.00	$72.00
Microprocessor	Raspberry Pi Pico	1.00	$4.00	$4.00
Housing	YETLEBOX Waterproof Electrical Box	1.00	$44.00	$44.00
Data Storage Breakout	Adafruit MicroSD Card Breakout + Kingston Industrial Micro 32GB SD	1.00	$42.81	$42.81
Energy Storage	PS-12180-F2 SLA Battery	1.00	$45.40	$45.40
Power Generaton	Voltaic Systems 50W 18V Solar Panel + Solar Panel Mount + WindyNation 10A PWM Charge Controller	1.00	$151.00	$151.00
PCB	Did not purchase	0.00	$7.00	$0.00
Structure Tower	PVC pipe, couplings, clamps, brackets	1.00	$61.46	$61.46
Pressure sensor	LPS33HW pressure sensor	1.00	$12.50	$12.50
Temperature sensor	SHT31 temperature sensor	1.00	$19.90	$19.90
Buck converter	MPM3610 5V	1.00	$6.95	$6.95
Miscellaneous	Screws, Cables, Glue, etc.	1.00	$25.00	$25.00
				TOTAL
				$850.49

Total Budget Remaining:	$ 35.14

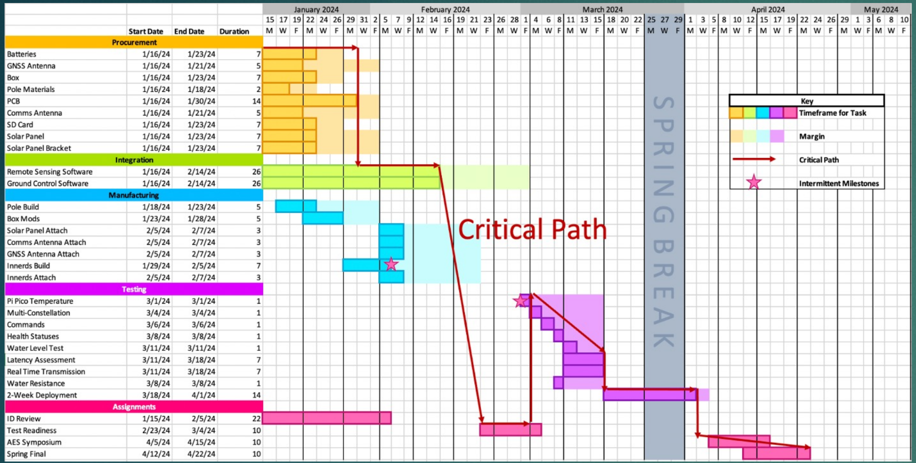
-Build of TWO systems was largest cost ($850.49/ea)

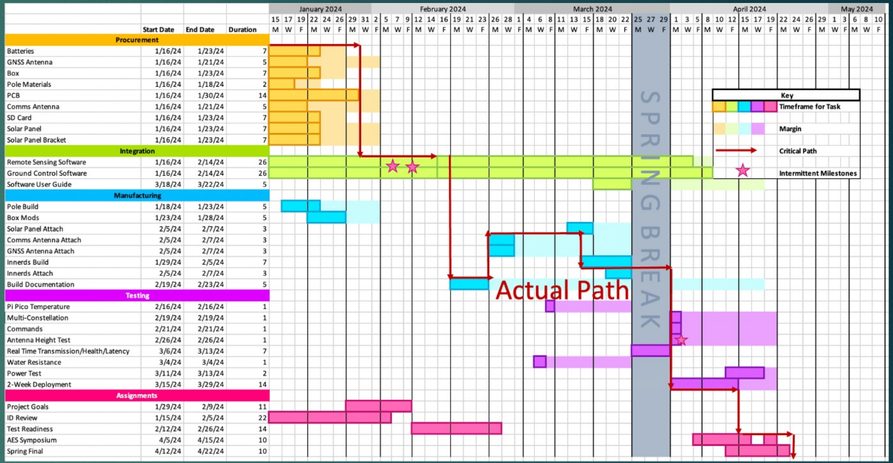
Budget



GNSS Electronics
Comms Components
Structure
Power
$134.87 (15.9%)
$381.81 (44.9%)
$130.46 (15.3%)
$203.35 (23.9%)
Total = $850.49

Planned Schedule vs. Actual





<u>3 Major Deviations:</u> Innards Attach (waiting for parts to ship), Software crunch (real-time implementation of GNSS-IR), Boulder Res testing delay by 2 weeks

Industrial Cost

456 hours x 9 people = **4,104 Total hours worked**
$36.06 per hour x 4,104 = **$147,990 Wages**
Material cost = $3,965

Industry cost = ($147,990 x 1.7) + ($3,965) = **$255,548**

Thank you! Questions?

Backup Slides

Component Data Sheets

Component	Data Sheet Link
Solar Panel	P150_dwg.pdf (mybigcommerce.com)
Charge Controller	TrakMax Owners Manual (shopify.com)
Battery	PS_12100H_F2-1350745.pdf (mouser.com)
Buck Converter	monolithicpower.com/en/documentview/productdocument/index/version/2/document_type/Datasheet/lang/en/sku/MPM3610GQV-Z/document_id/2090/
Comms Module	RockBLOCK-9603-Data-Sheet.pdf (groundcontrol.com)
Comms Antenna	https://www.mouser.com/datasheet/2/1055/m1621hct-ext-1880193.pdf
GNSS Receiver	NEO-F10N Data sheet (u-blox.com)
GNSS Antenna	ANN-MB5 (u-blox.com)
Microprocessor	Raspberry Pi Documentation - Raspberry Pi Pico and Pico W
Data Storage	Download | Micro SD Card Breakout Board Tutorial | Adafruit Learning System
Temperature/Humidity Sensor	SEN0385 DFRobot | Mouser
Pressure Sensor	Adafruit LPS35HW Water Resistant Pressure Sensor [STEMMA QT] : ID 4258 : $12.50 : Adafruit Industries, Unique & fun DIY electronics and kits
Housing	https://www.amazon.com/YETLEBOX-Waterproof-Electrical-220x170x110mm-Electronics/dp

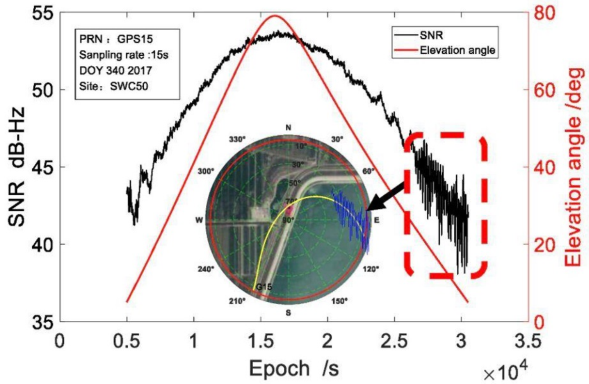
Dynamic Height Correction

GNSS-IR: reflector height estimation from SNR data w.r.t. sin(e)

$$\delta SNR(t) = A \cdot cos\left(\frac{4\pi h}{\lambda} sin(e(t)) + \theta\right)$$

LSP of SNR data w.r.t. sin(e)

$$h = \left(\frac{\lambda}{2}\right) f$$



Dynamic Height Correction

Frequency analysis

$$x(t) = A \cdot cos(2\pi f t + \theta)$$

$$x(t) = A \cdot cos(\psi(t) + \theta)$$

$$2\pi f = \frac{d\psi(t)}{dt}$$

$$\delta SNR(t) = A \cdot cos(\psi(t) + \theta);$$

$$w(t) = sin(e(t))$$

$$\psi(t) = \frac{4\pi h}{\lambda} sin(e(t)) = \frac{4\pi h}{\lambda} w(t)$$

$$2\pi f = \frac{d\psi(t)}{dw(t)} = \frac{d\psi(t)}{dt}\frac{dt}{dw(t)}$$

$$\frac{d\psi(t)}{dt} = \frac{4\pi}{\lambda}[\dot{h} \cdot sin(e(t)) + h \cdot cos(e(t)) \cdot \dot{e}(t)]$$

$$\frac{dw(t)}{dt} = \frac{d(sin(e(t)))}{dt} = cos(e(t)) \cdot \dot{e}(t) \Rightarrow$$

$$\frac{dt}{dw(t)} = \frac{1}{cos(e(t)) \cdot \dot{e}(t)}$$

Dynamic Height Correction

Frequency analysis

$$2\pi f = \frac{d\psi(t)}{dw(t)} = \frac{d\psi(t)}{dt}\frac{dt}{dw(t)}$$

$$\frac{d\psi(t)}{dt} = \frac{4\pi}{\lambda}[\dot{h} \cdot sin(e(t)) + h \cdot cos(e(t)) \cdot \dot{e}(t)]$$

$$\frac{dt}{dw(t)} = \frac{1}{cos(e(t)) \cdot \dot{e}(t)}$$

$$2\pi f = \frac{4\pi}{\lambda}\left[\mathrm{h} + \frac{\dot{h} \cdot tan(e(t))}{\dot{e}(t)}\right] \Rightarrow \frac{\lambda}{2}f = \mathrm{h} + \frac{\dot{h} \cdot tan(e(t))}{\dot{e}(t)}$$

$$\bar{h} = \mathrm{h} + \dot{h}\frac{tan(e(t))}{\dot{e}(t)}$$

$\bar{h}$: estimated from LSP of SNR data wr.t. sin(e)

Dynamic Height Correction

Least squares estimation of h and $\dot{h}$

$$\bar{h} = h + \dot{h}\,\frac{tan(e(t_1))}{\dot{e}(t_1)}$$

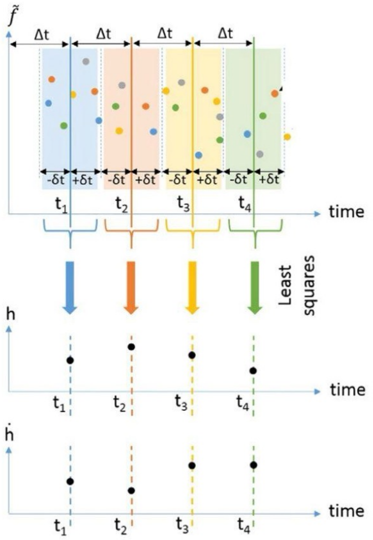
$$\bar{h} = h + \dot{h}\,\frac{tan(e(t_2))}{\dot{e}(t_2)}$$

$$\dots$$

$$\bar{h} = h + \dot{h}\,\frac{tan(e(t_N))}{\dot{e}(t_N)}$$

$$\begin{bmatrix}\bar{h}_1\\ \bar{h}_2\\ \dots\\ \bar{h}_N\end{bmatrix} = \begin{bmatrix}1 & \frac{tan(e(t_1))}{\dot{e}(t_1)}\\ 1 & \frac{tan(e(t_2))}{\dot{e}(t_2)}\\ \dots & \dots\\ 1 & \frac{tan(e(t_N))}{\dot{e}(t_N)}\end{bmatrix}\begin{bmatrix}h\\ \dot{h}\end{bmatrix} \Rightarrow L = Ax \Rightarrow \hat{x} = \left(A^T A\right)^{-1}\left(A^T L\right)$$

$$h = \bar{h} - \dot{h}\,\frac{tan(e(t))}{\dot{e}(t)}$$



Elevation Angle Correction Model

Since our reflection height model is dependent on elevation angle, a correction factor is necessary for the elevation angle value to enhance the accuracy of height estimation.

Tropospheric Error Equation

$$\Delta e = 10^{-6} N_0 \frac{cos(e)}{sin(e) + 0.00175tan(87.5^\circ - e)}$$

where

$$N_0 = K_1 \frac{P_d}{T_K} + K_2 \frac{P_w}{T_K} + K_3 \frac{P_w}{T_K^2}$$

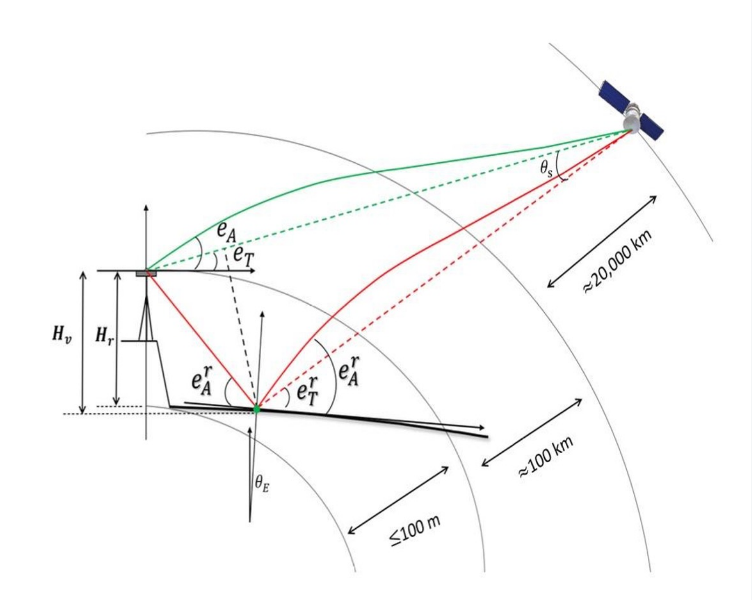
$K_1 = 77.689$ [K/hPa]

$K_2 = 71.2952$ [K/hPa]

$K_3 = 375463$ [K^2/hPa]

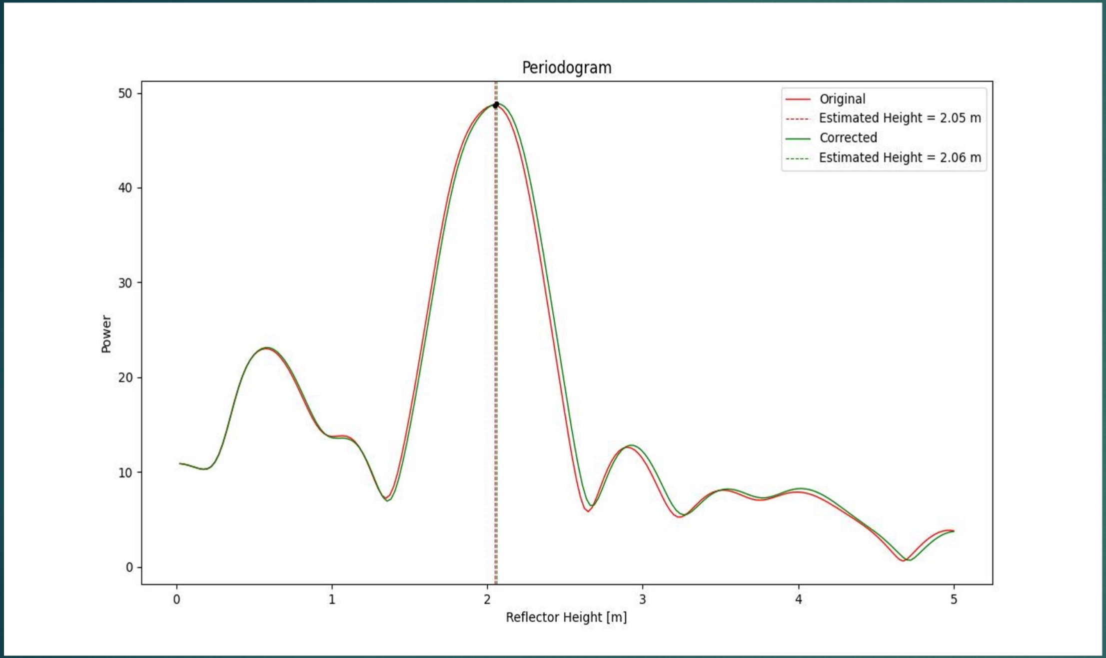
$$P_w = P_{sat} \frac{humidity}{100}$$

$$P_{sat} = 6.1094\exp(\frac{17.625 T_C}{T_C + 243.04})$$



[Credit: Feng, Haas, and Elgered (2023)]

Elevation Angle Correction Impact

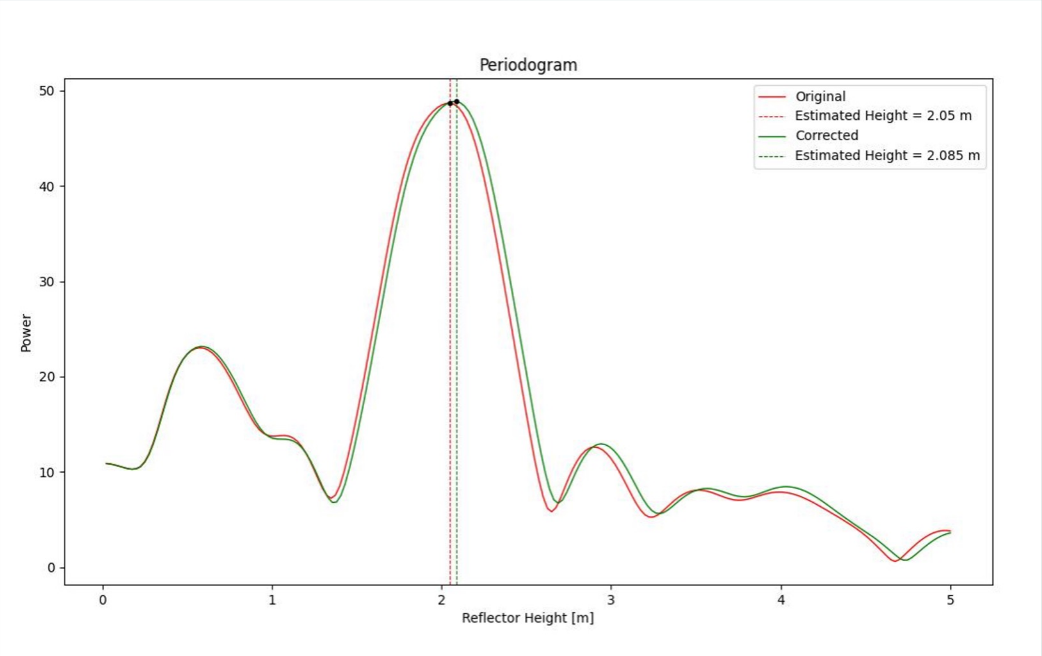


Note: Sample rate is 15s

Location	Boulder
Ambient Temperature	20 C
Ambient Pressure	840 hPa
Relative Humidity	40 %

Original	2.05 m
Corrected	2.06 m

Elevation Angle Correction Impact

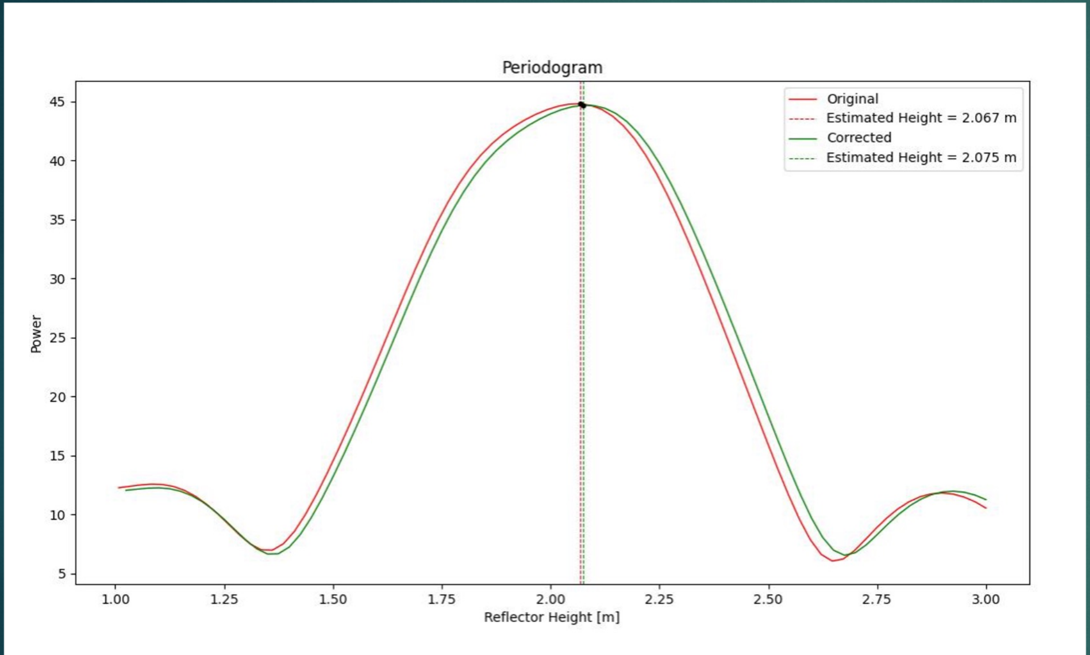


Note: Sample rate is 15s

Location	Hawaii
Ambient Temperature	32 C
Ambient Pressure	1010 hPa
Relative Humidity	72 %

Original	2.05 m
Corrected	2.085 m

Elevation Angle Correction Impact

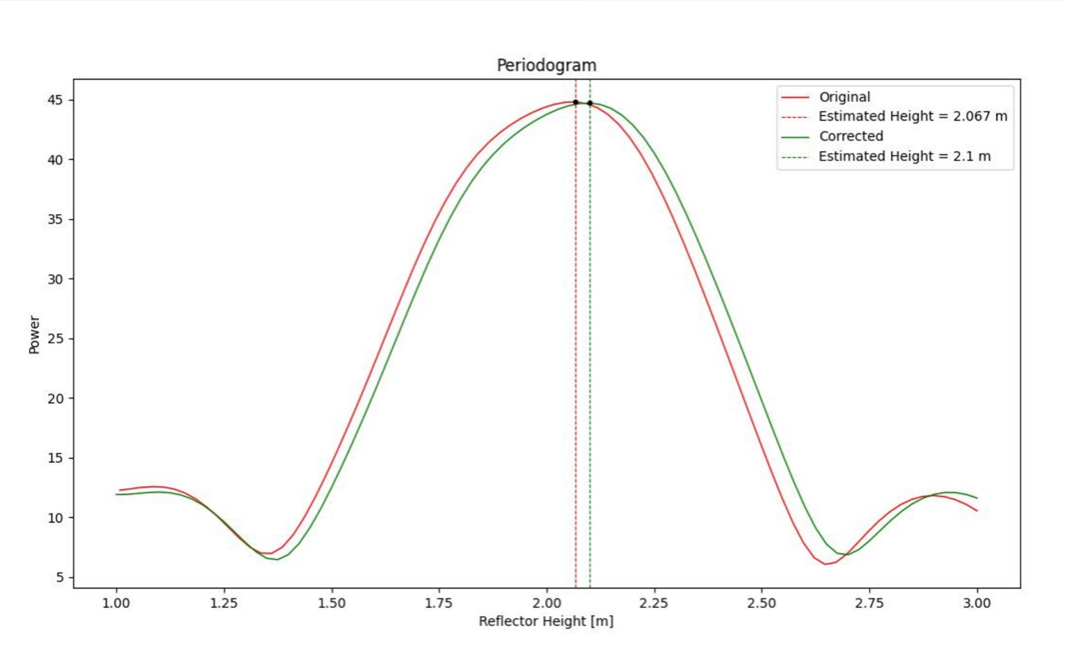


Note: Sample Rate is 30s

Location	Boulder
Ambient Temperature	20 C
Ambient Pressure	840 hPa
Relative Humidity	40 %

Original	2.067 m
Corrected	2.075 m

Elevation Angle Correction Impact



Note: Sample Rate is 30s

Location	Hawaii
Ambient Temperature	32 C
Ambient Pressure	1010 hPa
Relative Humidity	72 %

Original	2.067 m
Corrected	2.10 m

Power Model - Equations

e_{module} = Module efficiency

e_{cloudy} = Power generation efficiency in a cloudy day compared to a sunny day

A = Area of solar panel $[m^2]$

Change in power generation of a day in a sunny and a cloudy day [W]

$$P_{sunny} = e_{module} \cdot G_\theta \cdot A$$

$$P_{cloudy} = e_{cloudy} \cdot P_{sunny}$$

θ = Latitude angle relative to the equatorial plane [deg]

α = Earth tilt angle relative to the perpendicular to the solar plane [deg]

Angle of sun at sunrise relative to the equatorial plane [deg]

$$\gamma = \sin^{-1}(tan(\theta)tan(\alpha))$$

Sunrise and sunset time [hr]

$$sunrise/sunset = 12 \mp \frac{90° + \gamma}{30°}$$

Power capacity of a day in a sunny and a cloudy day [Whr]

$$PC_{sunny} = \int_{sunrise}^{sunset} P_{sunny}\, dt$$

$$PC_{cloudy} = \int_{sunrise}^{sunset} P_{cloudy}\, dt$$

Power Model - Equations

Power Consumption:

$$P = I \cdot V \ [W]$$

$$Capacity = P \cdot \Delta t \ [Whr]$$

$$Battery\ Capacity = V_{Battery} \cdot I_{Battery\ Capacity} \ [Whr]$$

Battery Charging:

$$Discharged\ Battery\ Capacity = (Battery\ Capacity) \cdot DOD \ [Whr]$$

Note: DOD (Depth of discharge) is the percent that the battery has been depleted relative to the overall battery capacity.

$$Energy\ Required\ for\ Full\ Charge = (Discharged\ Battery\ Capacity)/(Lead\ Acid\ Efficiency) \ [Whr]$$

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

$$Charge\ Time = (Energy\ Required\ for\ Full\ Charge)/(Adjusted\ Solar\ Output) \ [hr]$$

Battery Life:

$$Efficiency_{Buck\ Converter} = P_{out} / P_{in} = (V_{out} \cdot I_{out})/(V_{Battery} \cdot I_{Battery})$$

$$Battery\ Life = I_{Battery\ Capacity} / I_{Battery} \ [hr]$$

Power Generation

θ = Latitude angle relative to the equatorial plane [deg]

α = Earth tilt angle relative to the perpendicular to the solar plane [deg]

Latitude angle relative to the solar plane [deg]

$$\Omega = \theta \mp \alpha$$

Solar irradiance at altitude during daylight hours $[W/m^2]$

$$G_\theta = at^2 + bt + c$$

To find the coefficients a, b, and c

$$\begin{bmatrix} G_{\theta,1} \\ G_{\theta,2} \\ G_{\theta,3} \end{bmatrix} = \begin{bmatrix} t_1^2 & t_1 & 1 \\ t_2^2 & t_2 & 1 \\ t_3^2 & t_3 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

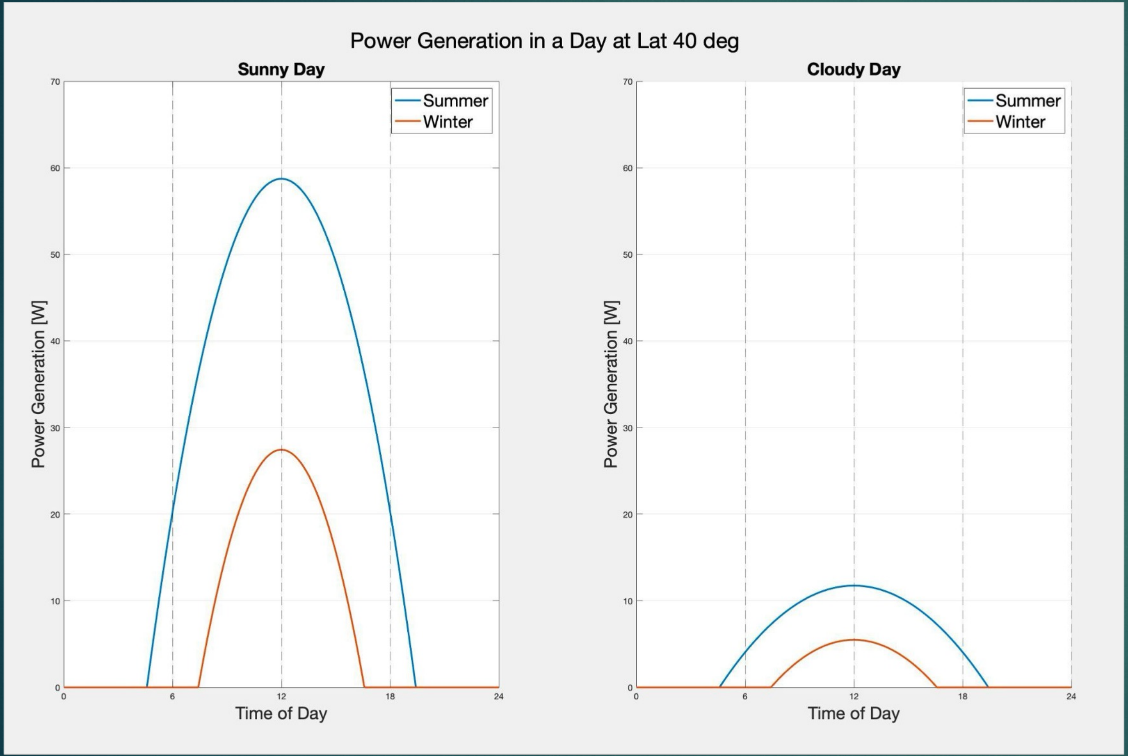
Maximum solar irradiance $G_{max,\theta} = G_{max} \cos\Omega \ [W/m^2]$

t_i = Sunrise time, t_m = Sun peak, t_e = Sunset time

$$\begin{bmatrix} 0 \\ G_{\max,\theta} \\ 0 \end{bmatrix} = \begin{bmatrix} t_i^2 & t_i & 1 \\ t_m^2 & t_m & 1 \\ t_e^2 & t_e & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} t_i^2 & t_1 & 1 \\ t_m^2 & t_2 & 1 \\ t_e^2 & t_3 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ G_{\max,\theta} \\ 0 \end{bmatrix}$$

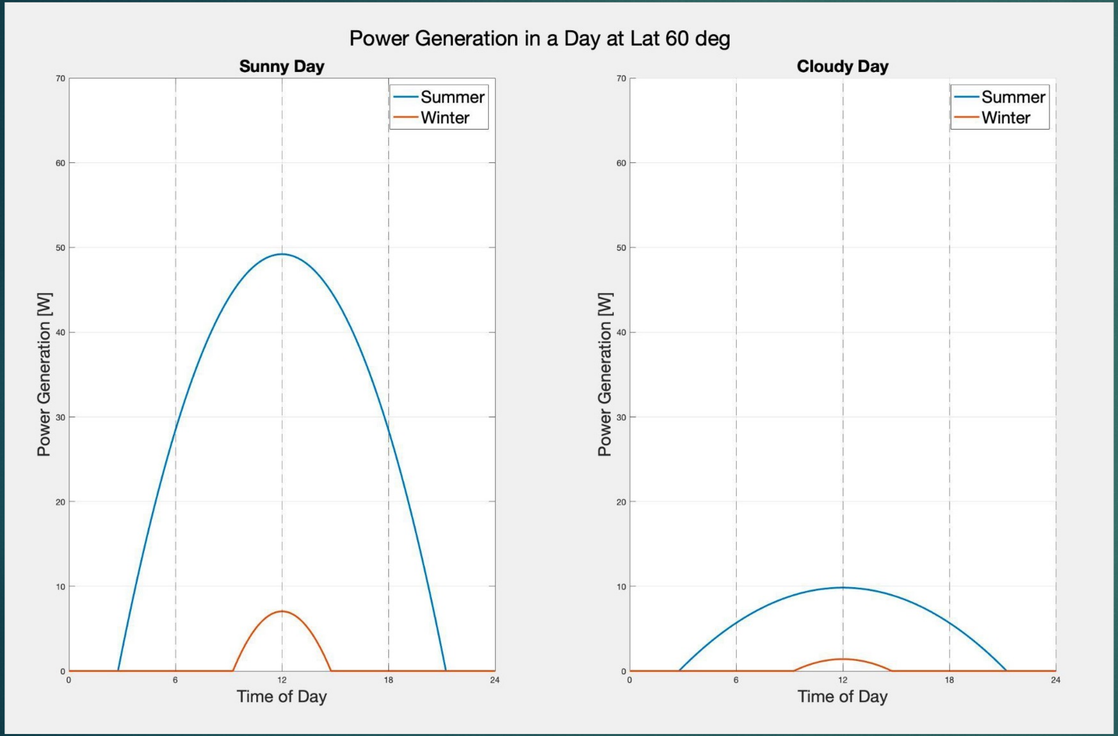
Power Model - Graphs (Location at Lat 40 deg)



Boulder at Latitude 40 deg North		
Power Capacity	**Summer [Whr]**	**Winter [Whr]**
Clear Day	581	168
Cloudy Day	116	33.5

<u>Note:</u> Our total battery capacity is 126 Whr

Power Model - Graphs (Location at Lat 60 Deg)



Anchorage at Latitude 60 deg North		
Power Capacity	**Summer [Whr]**	**Winter [Whr]**
Clear Day	606	26.0
Cloudy Day	121	5.19

Note: Our total battery capacity is 126 Whr

Power Model - Uncertainty

- Current draw from all components will vary over time
- Solar irradiance variation with altitude
- Solar panel mounting angle (we assumed worst case and flat)
- Manufacturing imperfections (currents and voltages from datasheets may vary from values on spec sheets)

Multi Constellation / Multi Band Test

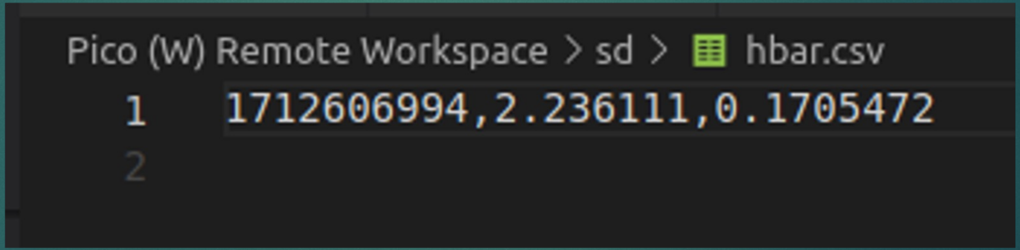
We were able to collect signals from multiple constellations such as GPS and Galileo, denoted respectively as “GPGSV” and “GAGSV”

The GPS signal with ID 1 indicates the L1 band (1575.42 MHz)
The GPS signal with ID 8 indicates the L5 band (1176.45 MHz)
The GAL signal with ID 7 indicates the L1 band (1575.42 MHz)

Signal ID	PRN Number	Satellite Type	Initial Time Point (s)
1	5	GPGSV	1712192846
0	40	48	46
8	6	GPGSV	1712351420
0	40	46	43
7	5	GAGSV	1712193541
0	12	37	26

Antenna Height Test

- GNSS Antenna and system set up outside on grass
- Antenna placed at a height of 2.27 meters off the ground
- System measures height of 2.23 meters, which falls within the 5 cm accuracy range



Measured Reflector height

Commands Test

```
1712612217: Message send success, status 0
1712612217: Reboot command recieved, spawning reboot event
1712612224: <- The epoch
1712612224: GNSS Handler, Message Sender, and 6hr Cleanup initialized
```

Reboot Command

Pico (W) Remote Workspace > sd > mask.csv

```
0,360
0,45
0,5
```

Mask Angles Pre-Command

Pico (W) Remote Workspace > sd > mask.csv

```
90,180
5,35
1,6
```

Mask Angles Post-Command

- Reboot and Mask Angle commands sent from the ground station to the system
- Success determined by system response to commands (Latency ~1.5hr)

Select a Command to send:

Reboot

Send Command?

Command Status

Success Response recieved from Ground Control: OK!

Success Response recieved from RSD: Reboot Success!

Real Time Transmission Test

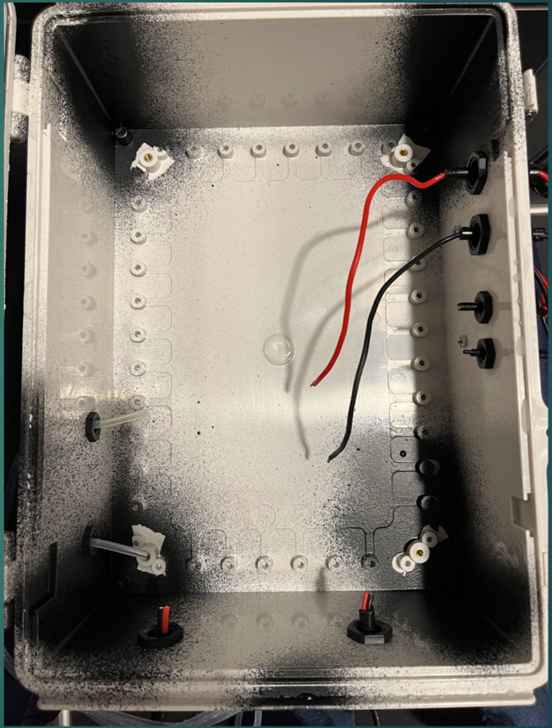
- During two week deployment, health status updates were received by ground station once every hour
- Latency Average: 44:36
  - Max: 1:00:44, Min: 30:08
- Verified that the requirement of maximum 2 hours latency is met

```
Water Level Message time from Collection to Display on Ground Station
Average: [hh:mm:ss]
   00:44:40

Maximum: [hh:mm:ss]
   01:00:44

Minimum: [hh:mm:ss]
   00:30:08
```

Message Latency Calculation Results

Water Resistance Test

- Component box subjected to constant water flow via shower head, with each face of the box oriented towards the water source for a period
- First test had minor leakage, applied flex seal and reattempted
- Second test had no leakage



Interior of component box after second test

Pi Pico Temperature Test

- Pi Pico placed in cooler with dry ice to simulate low operating temperatures
- Pi Pico was able to complete computations in temperatures of -37 C
- Ensures Pi Pico meets temperature range operation conditions (-30 C to 50 C)

Temperature Readout from Pi Pico Dry Ice Environment

Buck Converter Test

2/9/2024: Test was performed with MPM3610 buck converter

- Verified 5V output with 12V input
- Input 12V from power supply directly into buck converter
- Verified 5V output using a multimeter