RNO-G

Radio Neutrino Observatory - Greenland

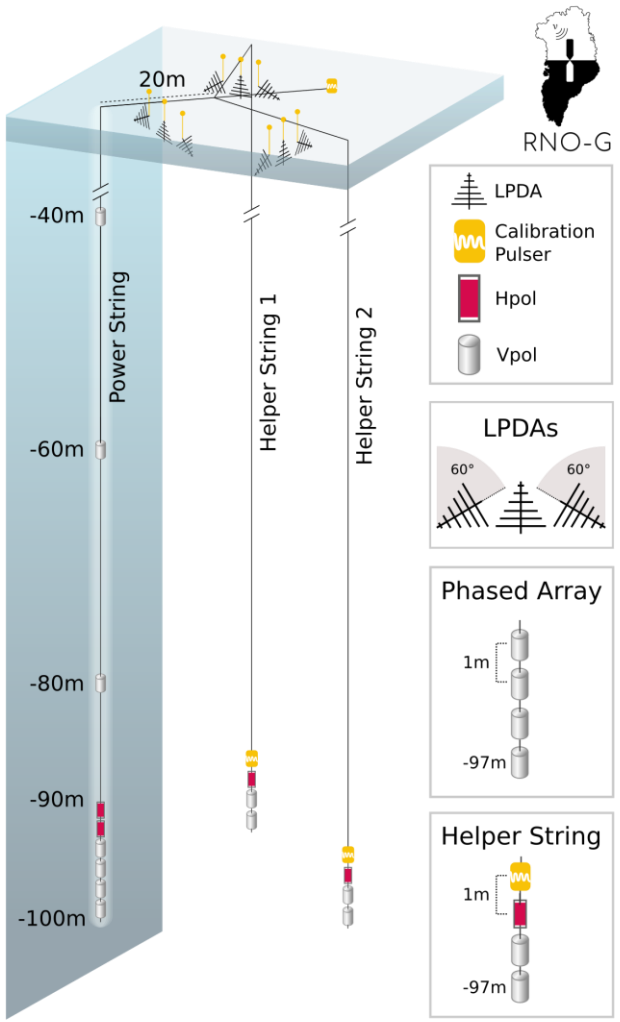
PennState

Hardware Overview of the Radio Neutrino Observatory in Greenland

ARENA – 2024

Ryan Krebs on behalf of the RNO-G Collaboration

RNO-G



Design Targets

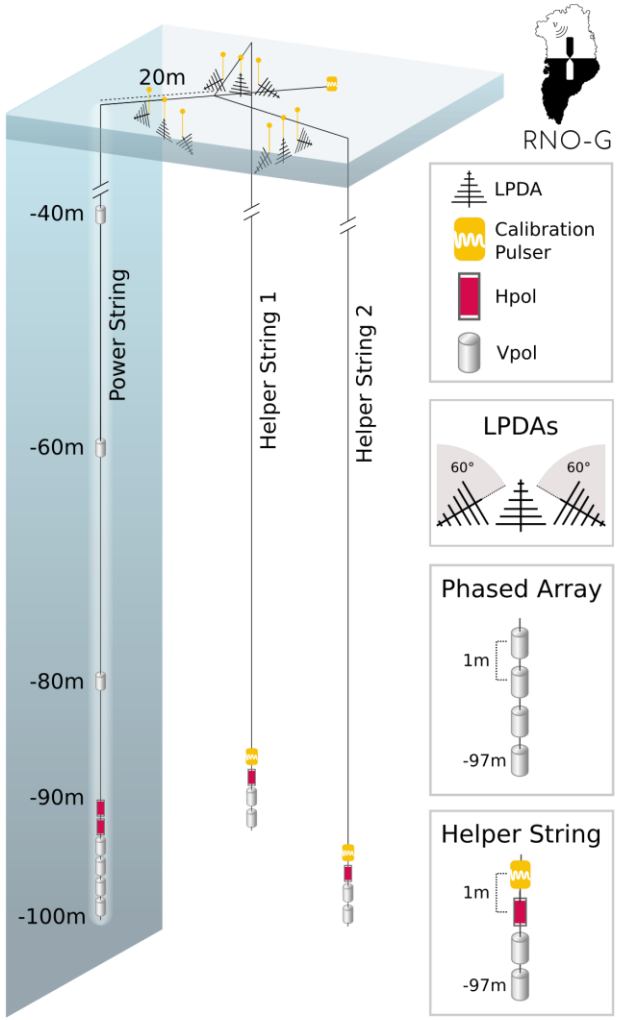
- Independent & Autonomous Stations
- Low Power
- Renewable Energy
- Complementary Surface and Deep Components

Environmental Box

Station Surface

Instrument Box

RNO-G



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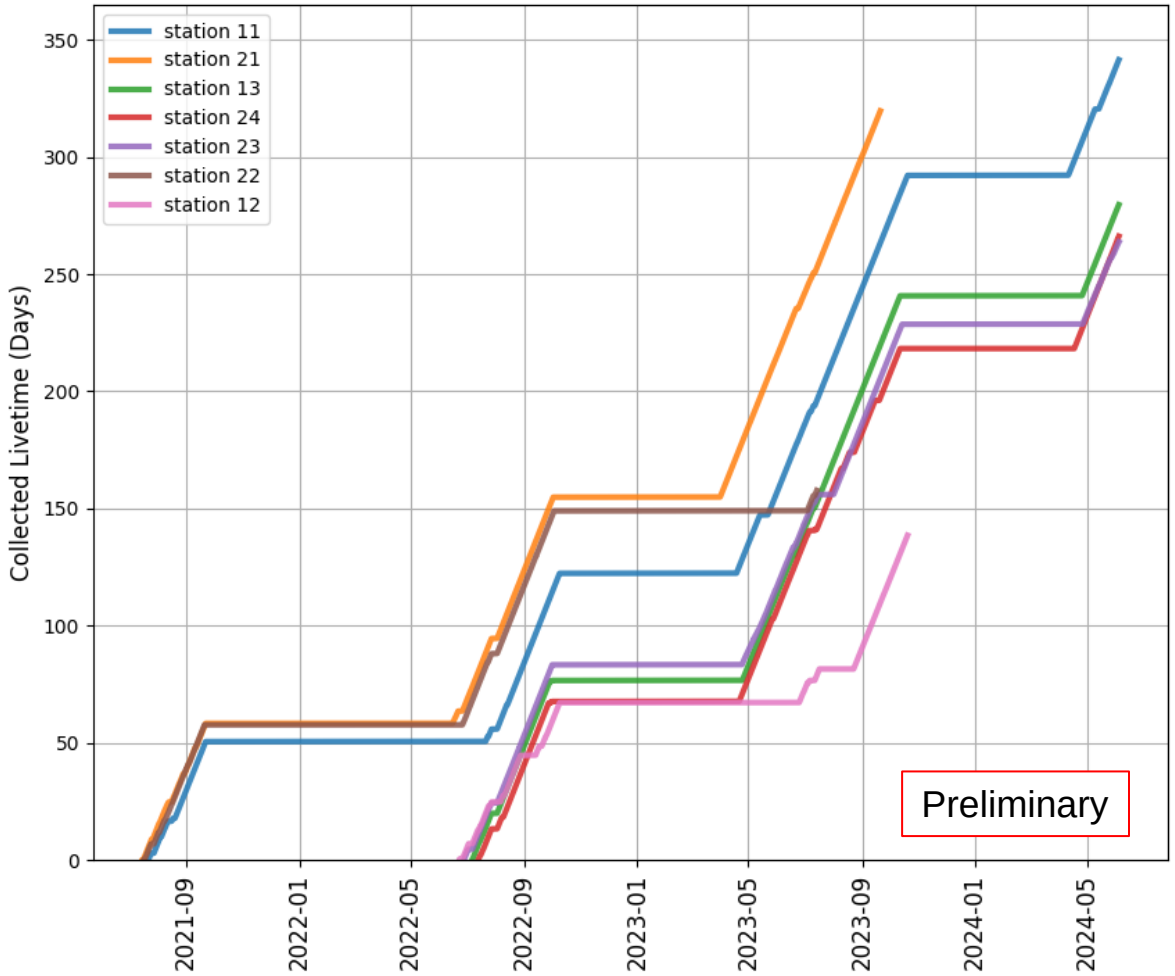
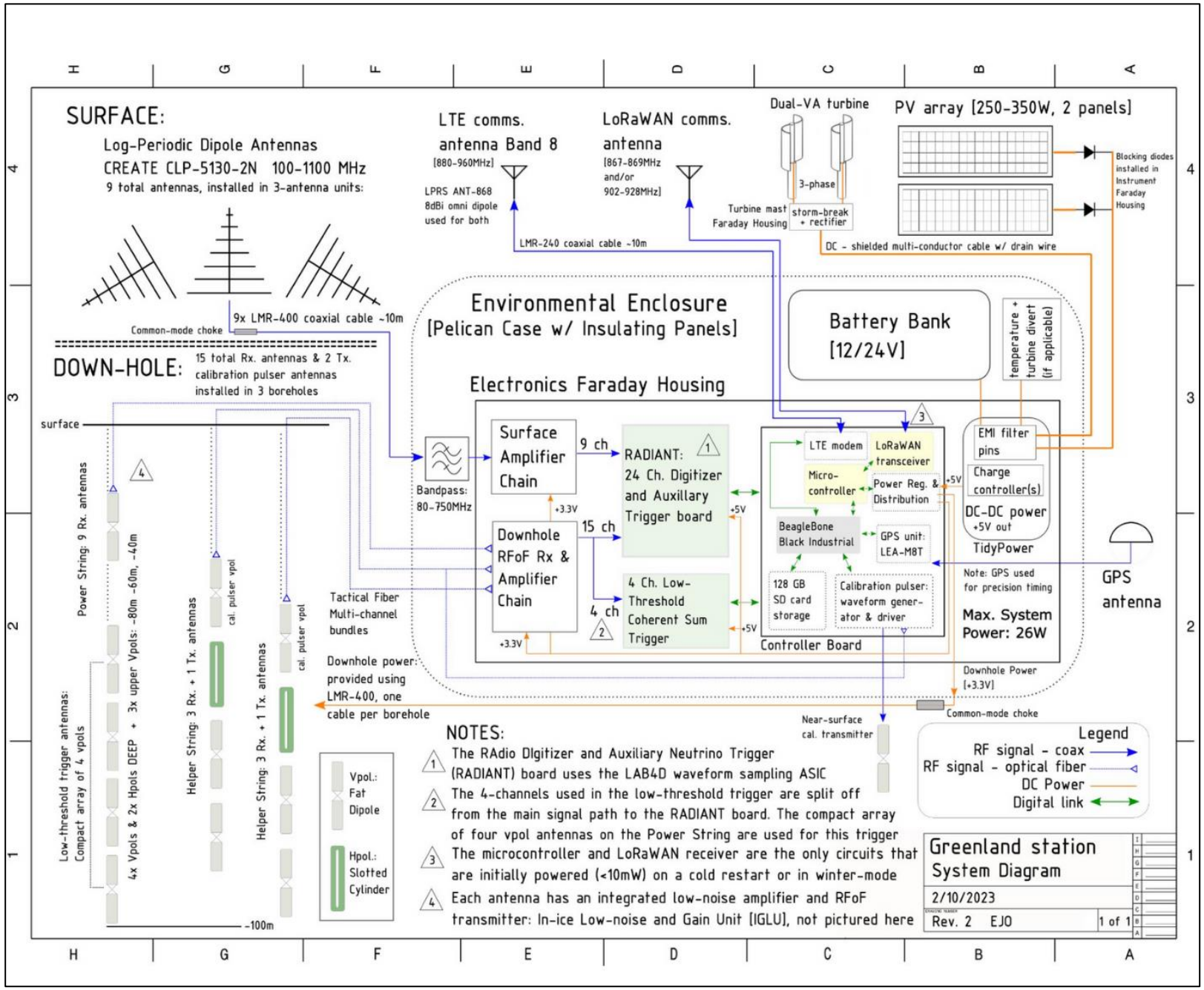


RNO-G

- Amplifiers
- Digitizer
- Trigger
- Power



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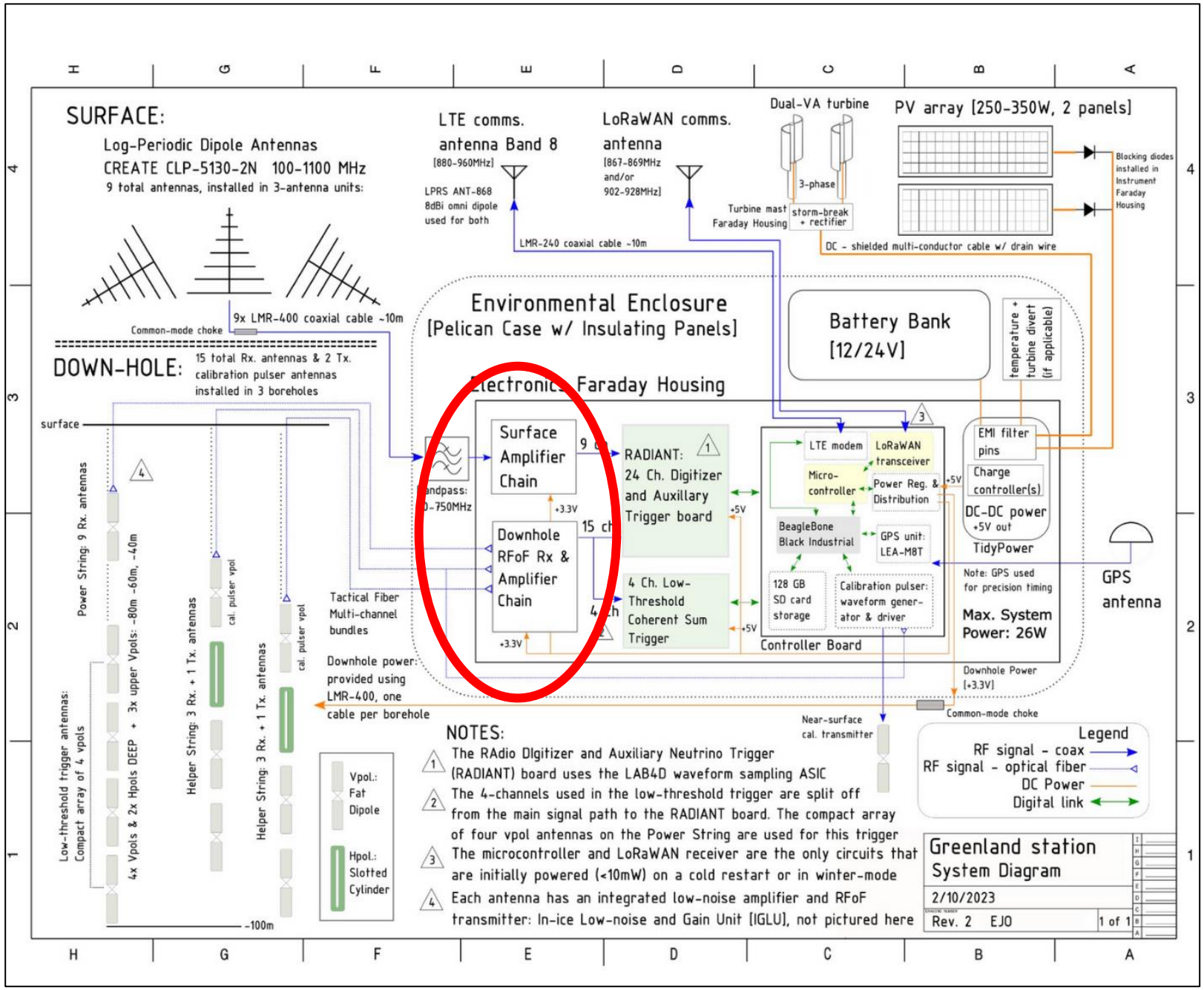
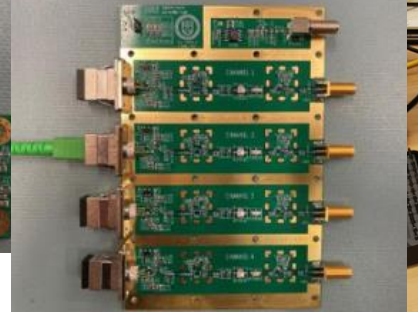
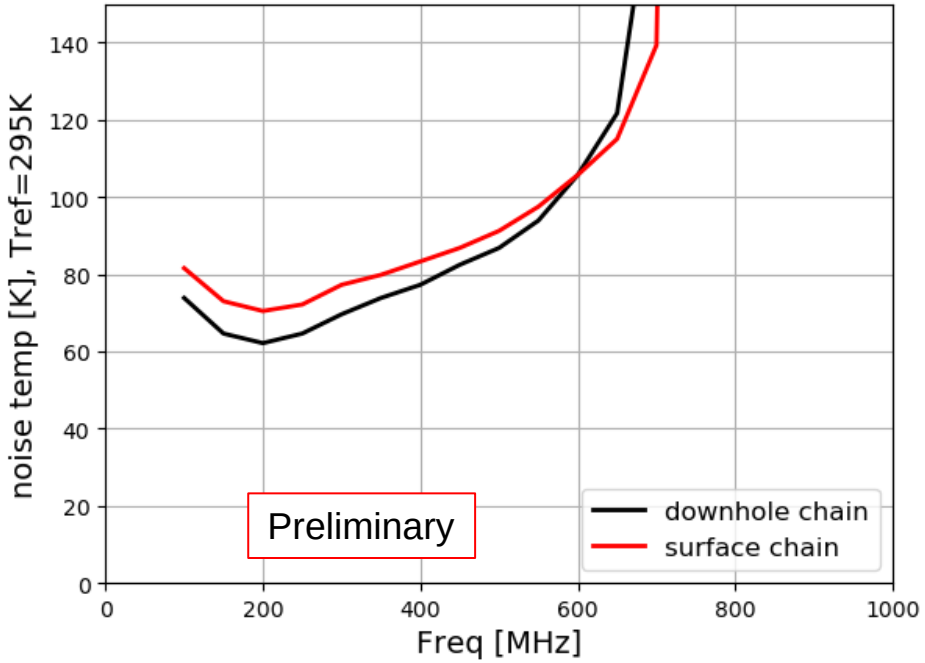


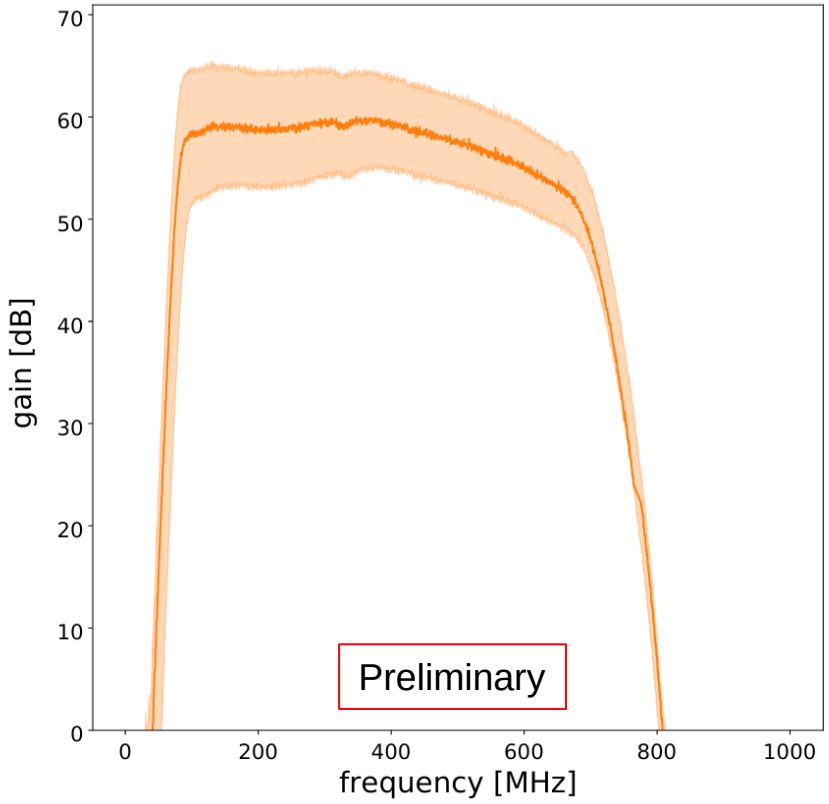
Amplifiers



- Deep Channels (V-Pol and H-Pol Antennas) (~0.24W/ch)
  - **I**n-Ice **G**ain and **L**ow-Power **U**nit (IGLU)
    - Front end on antennas. Amplifies signals and converts to RFoF
  - **D**ownhole **R**eceiver and **A**mplifier **B**oard (DRAB)
    - Converts RFoF backs to electrical and amplifies further
- Surface Channels (LPDA) (~0.22W/ch)
  - Surface Amplifier



In-Ice Signal Chain



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  - **D**ownhole **R**eceiver and **A**mplifier **B**oard (DRAB)
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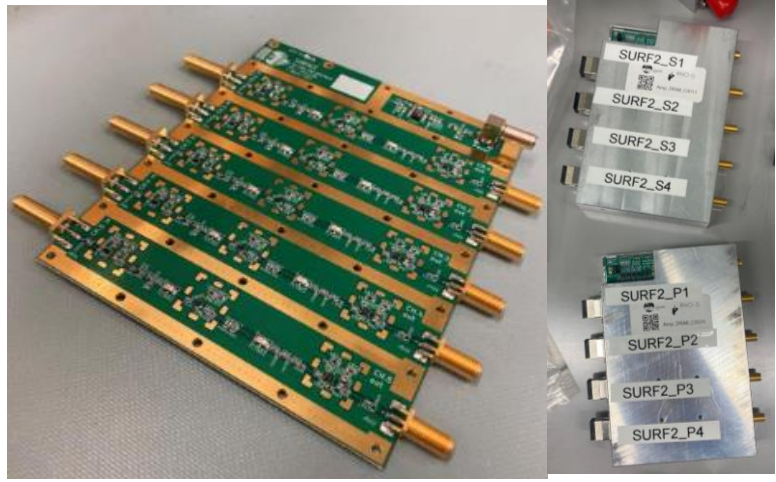
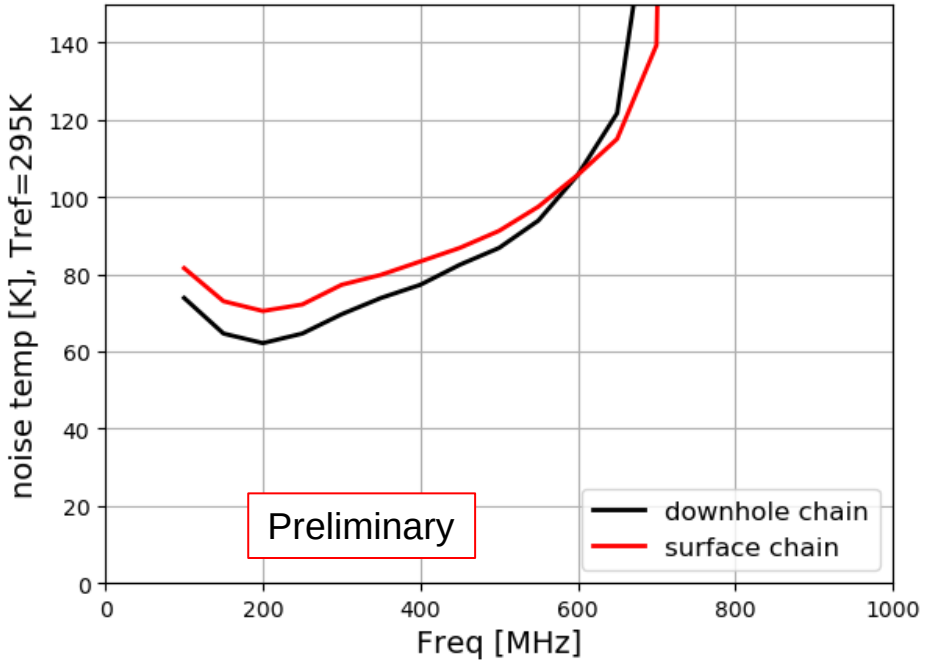
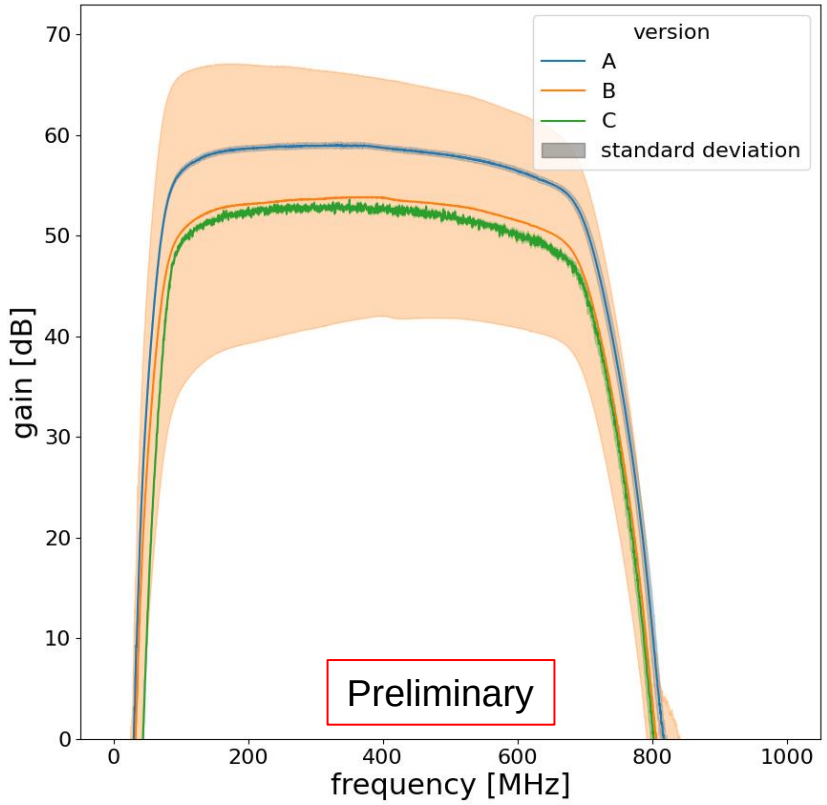
- Surface Channels (LPDAs) (~0.22W/ch)
  - Surface Amplifier





Surface Signal Chain



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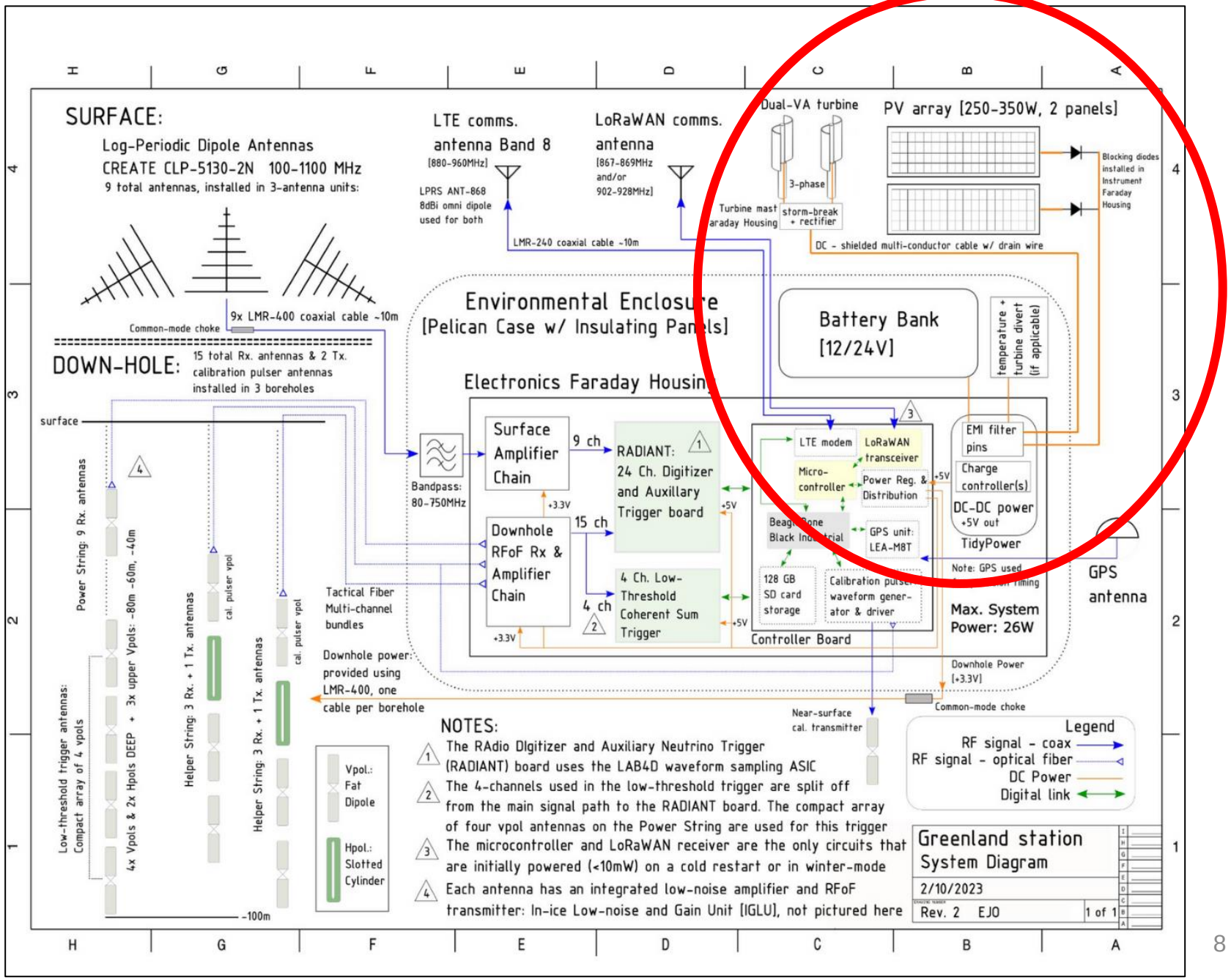
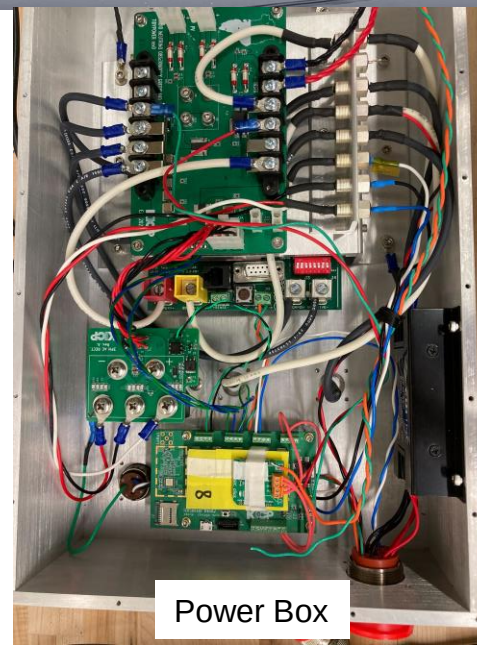


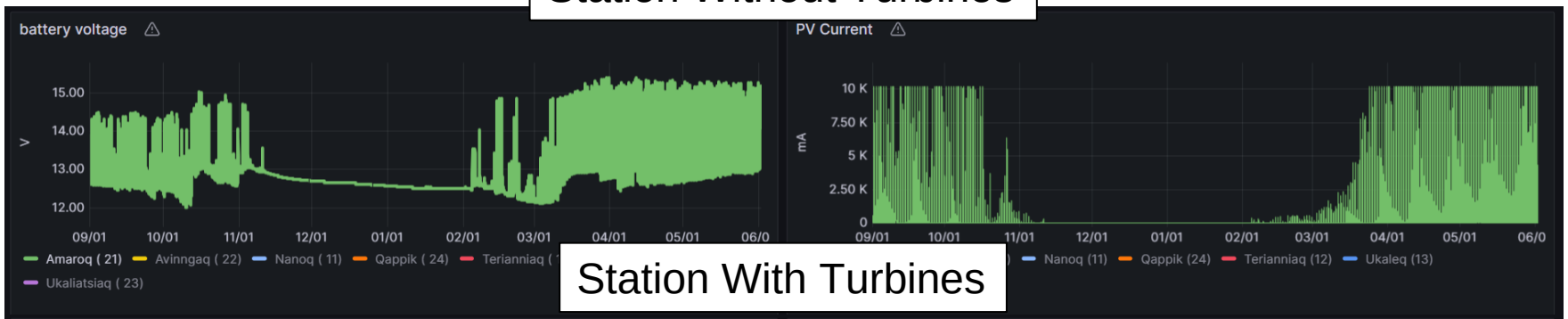
Power

- Target Uptime ~80% (~28W station power)
  - 2x ~120 Watt Solar Panels ~50-60% Uptime
  - Experimental Wind Turbines
- Maintenance and access
  - Movable Power Box - *Tidy Power*
  - Stackable Towers

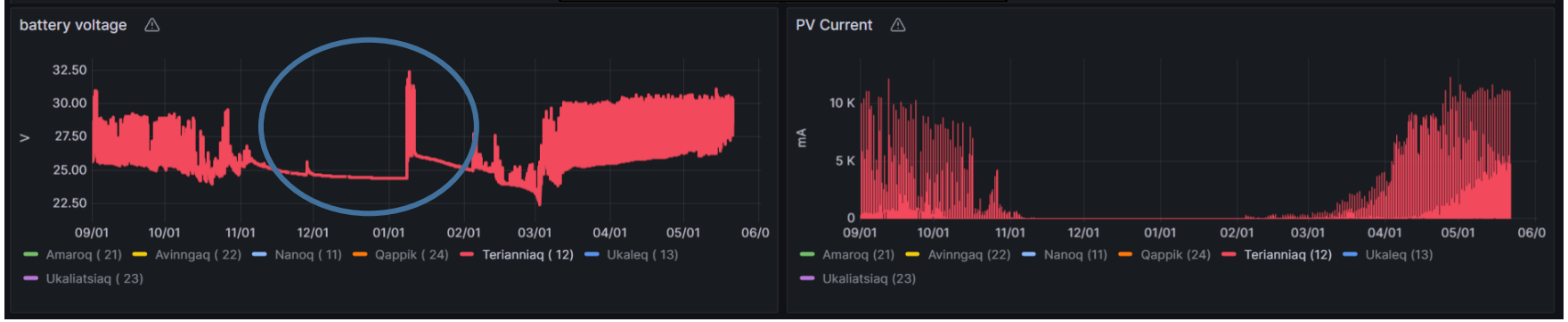


Power Box

Station Without Turbines



Station With Turbines



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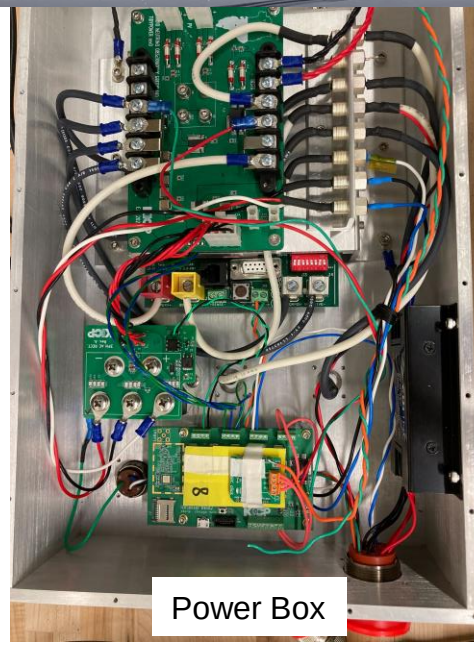

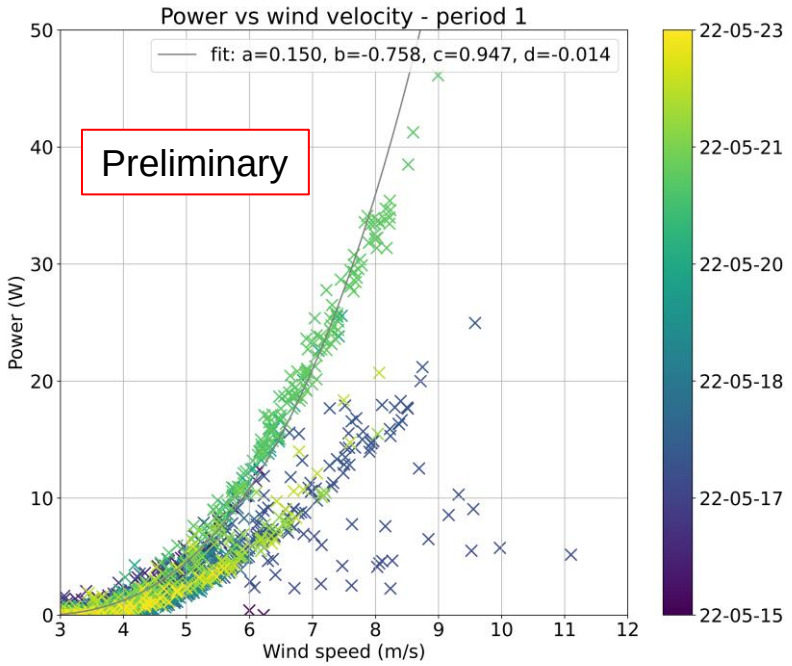

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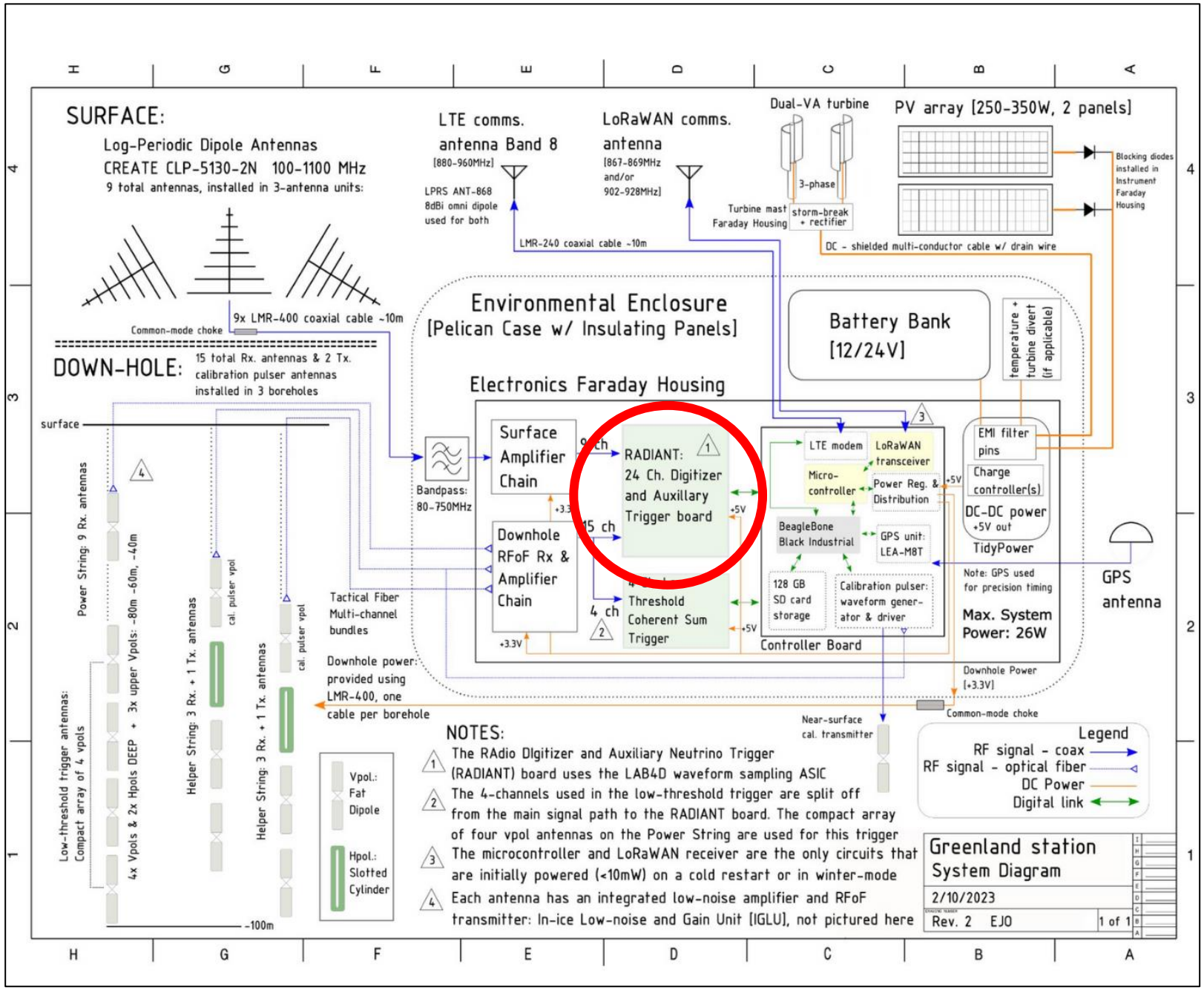
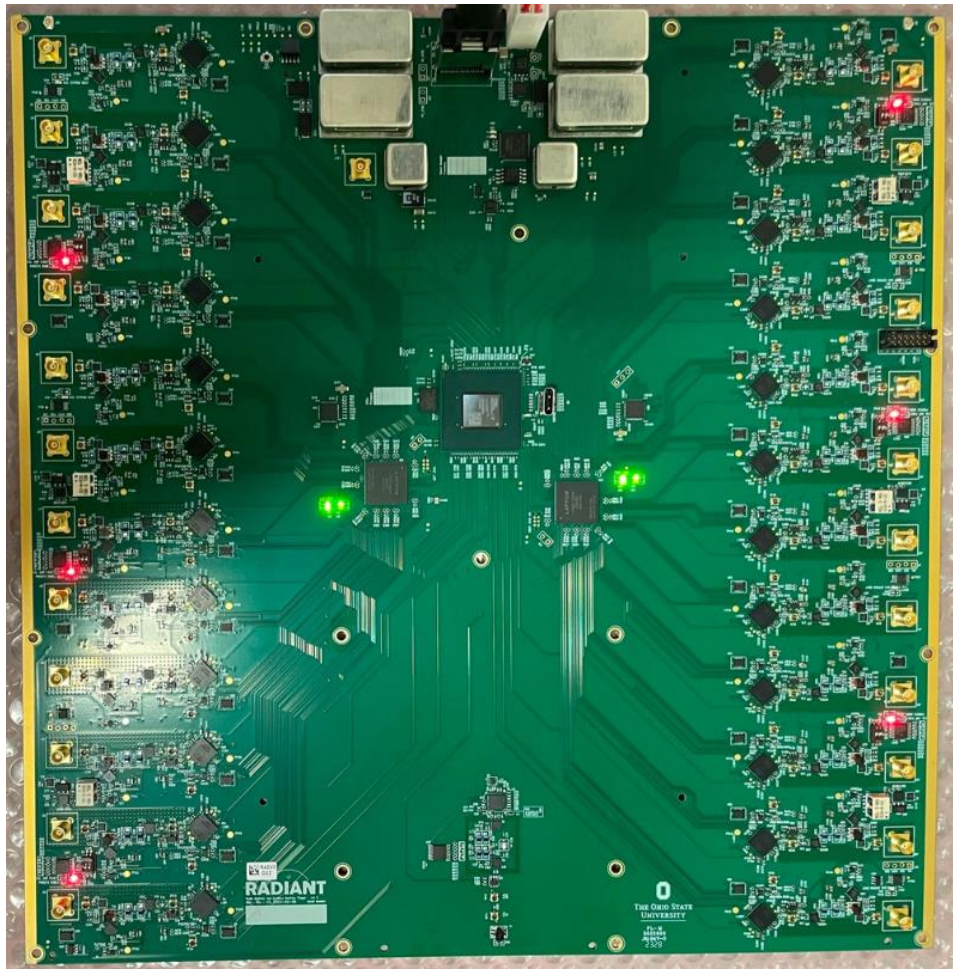


Digitizer

- **Ra**dio **Di**gitizer and **A**uxillary **N**eutrino **T**rigger (RADIANT)
  - 24 channels digitized using LAB4D ASICs (arXiv:1803.04600)
  - 2048 Sample Buffer Length
  - Sampling Rate of 3.2 GHz (2.4GHz)
  - ASICs integrated with breakout CPLDs and Artix 7 FPGA
  - Capable of **in-situ timing and voltage calibration**[1]
  - Diode-Based Power “Integration” Trigger
- Supplementary Triggers
  - **Upward looking** surface (using LPDAs) trigger for cosmic ray science[2], cosmic ray veto, noise analysis[3], and solar flares[4]
  - **Downward looking** surface trigger to supplement the low-threshold triggers
- Recent Firmware Upgrades
  - Sampling rate optimization from 3.2 GHz to 2.4 GHz
  - Adjustable Readout Windows



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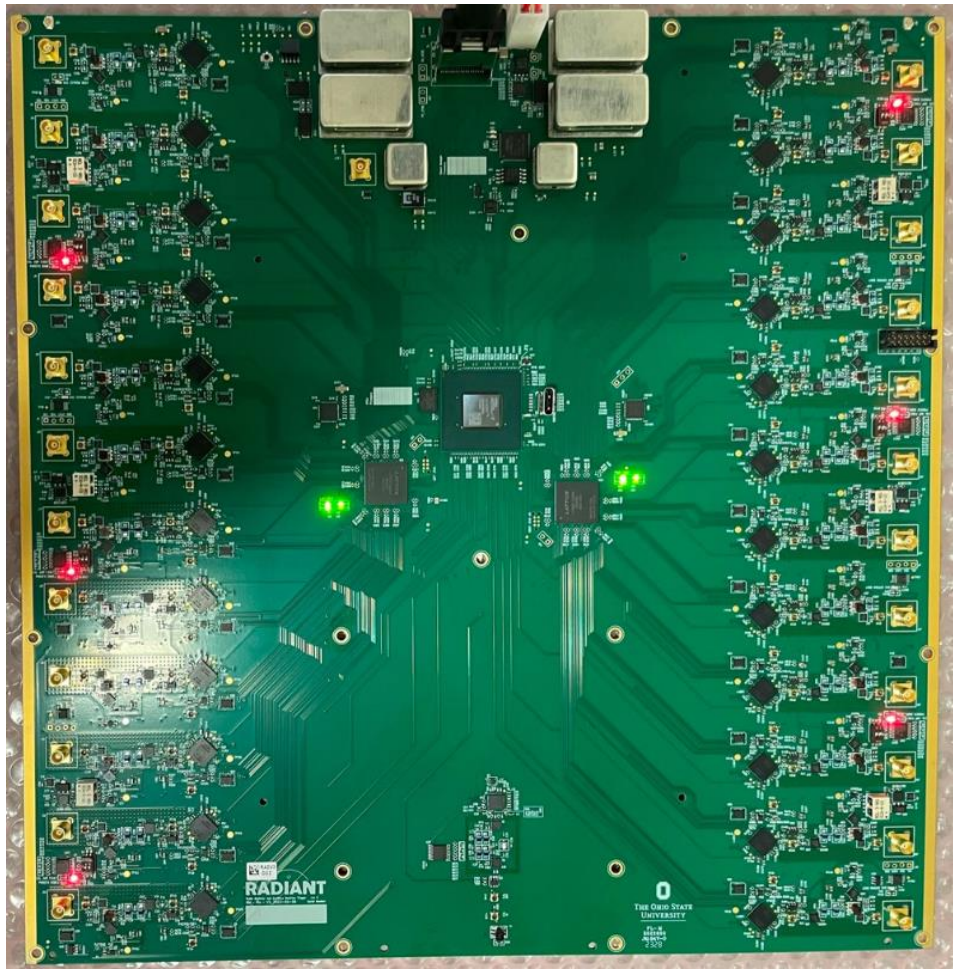

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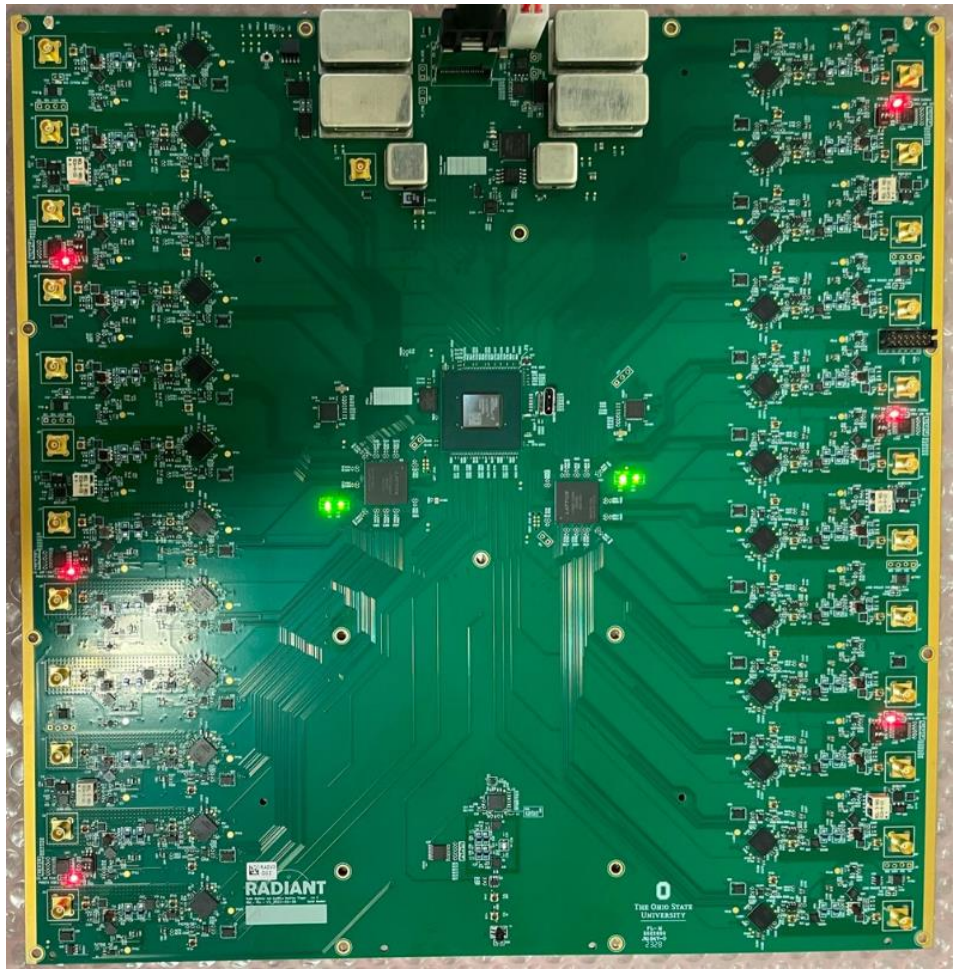

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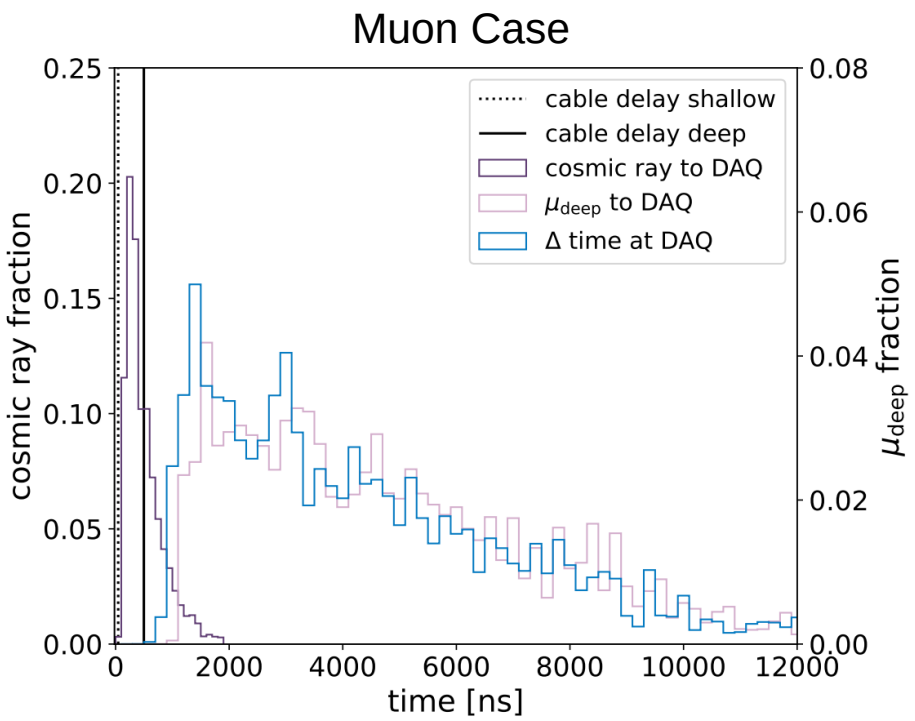
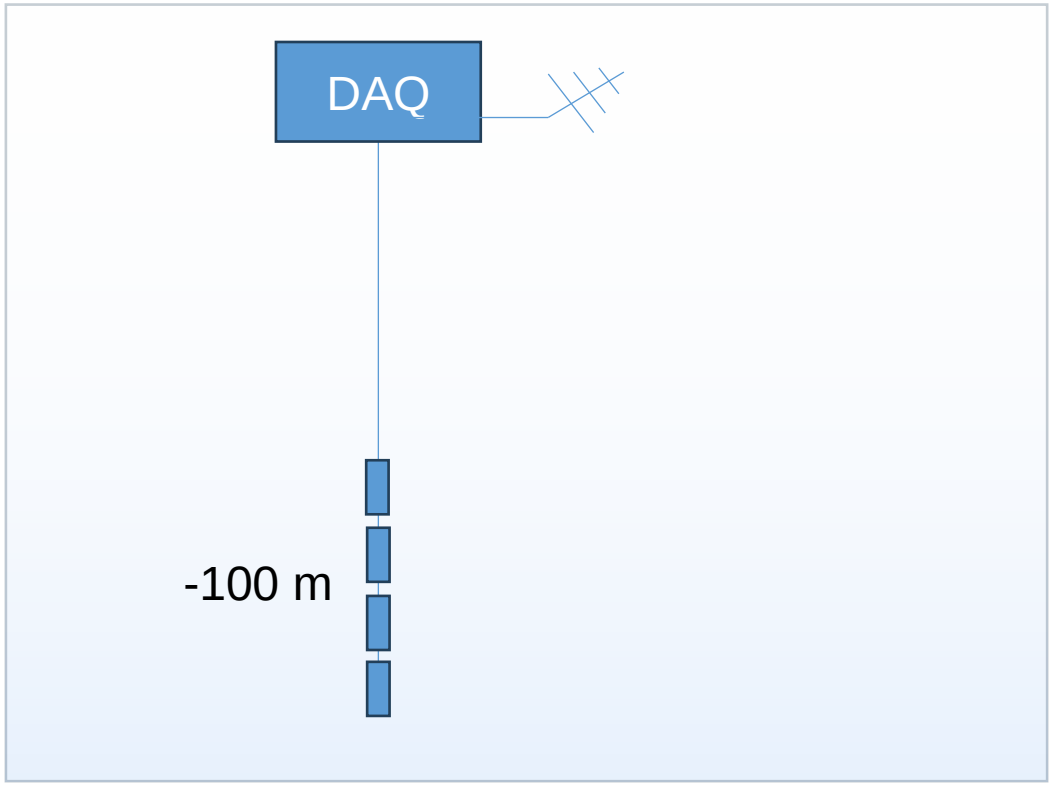
RADIANT Firmware For Cosmic Rays

- Cosmic Ray “Veto” Trigger Eliminates Signature from Deep Channels
  - All 24 Channels are Read Simultaneously
  - Limited buffer length 640 ns (@3.2GHz)
  - Signal propagation through ice and cable delay deep signals past the readout window



(Pyras et al. - arXiv:2307.04736)



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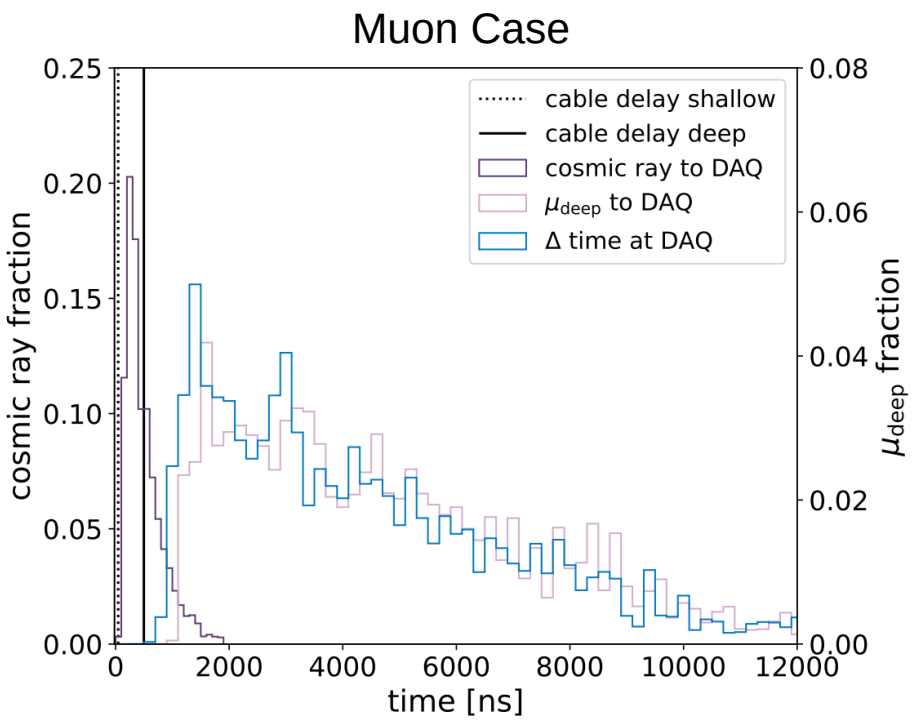

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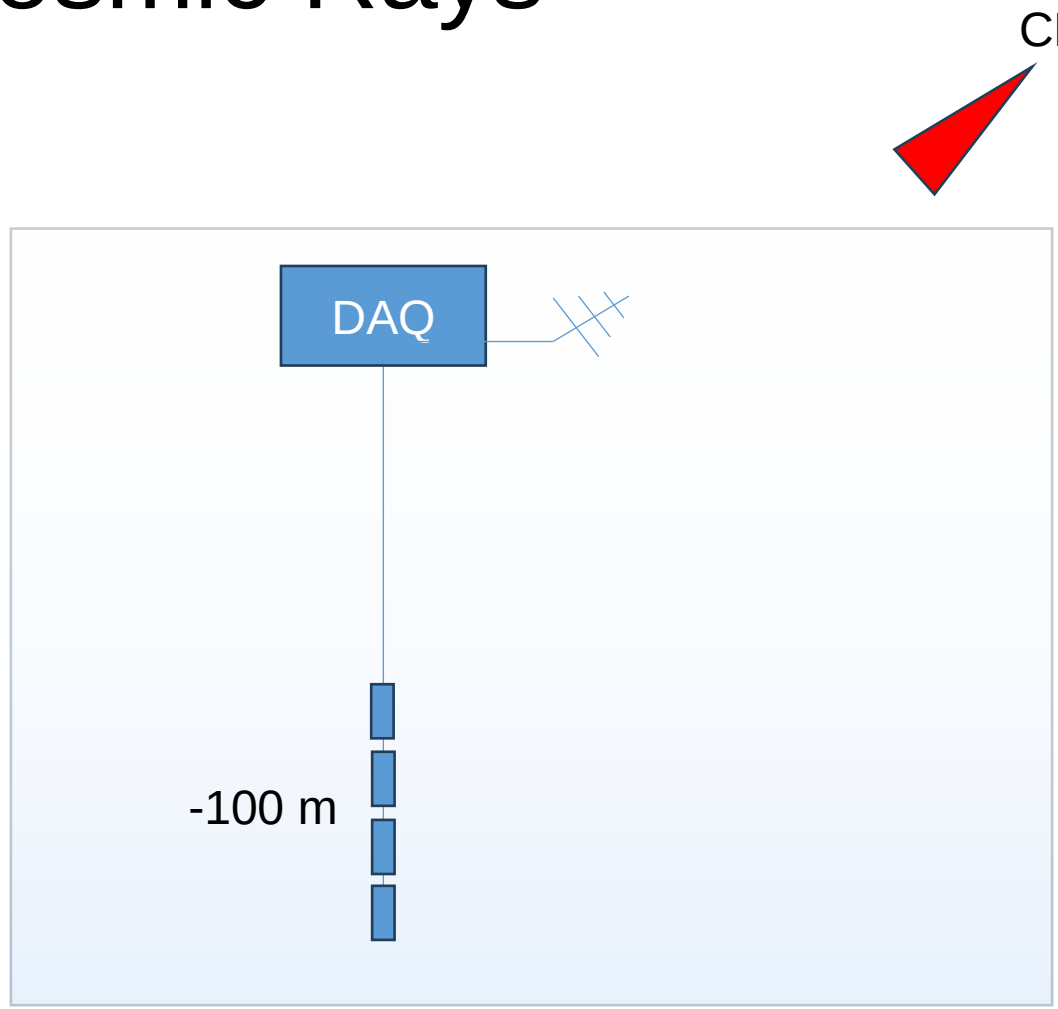

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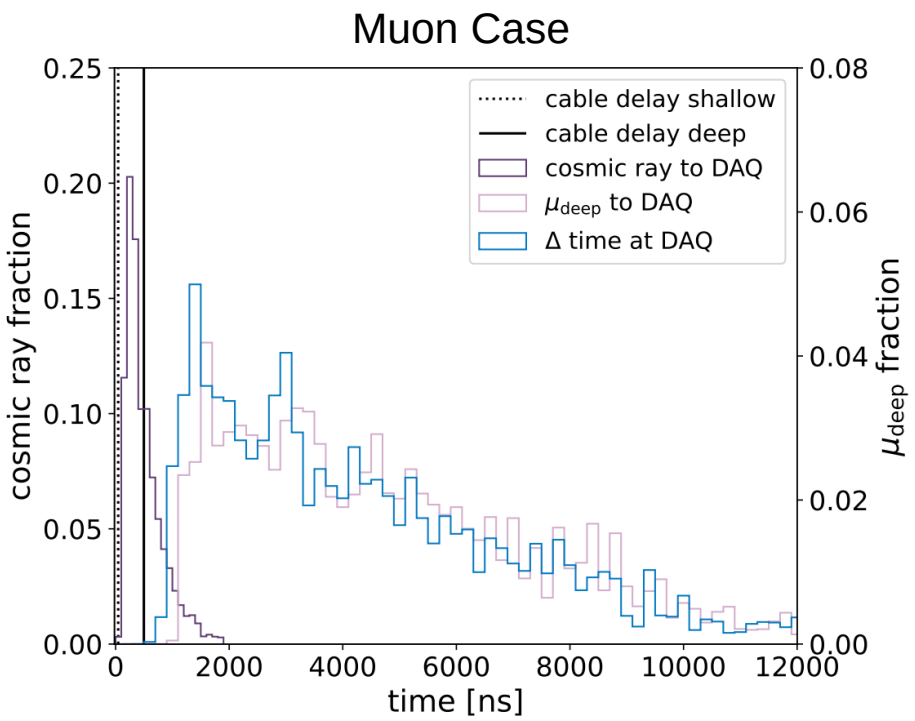

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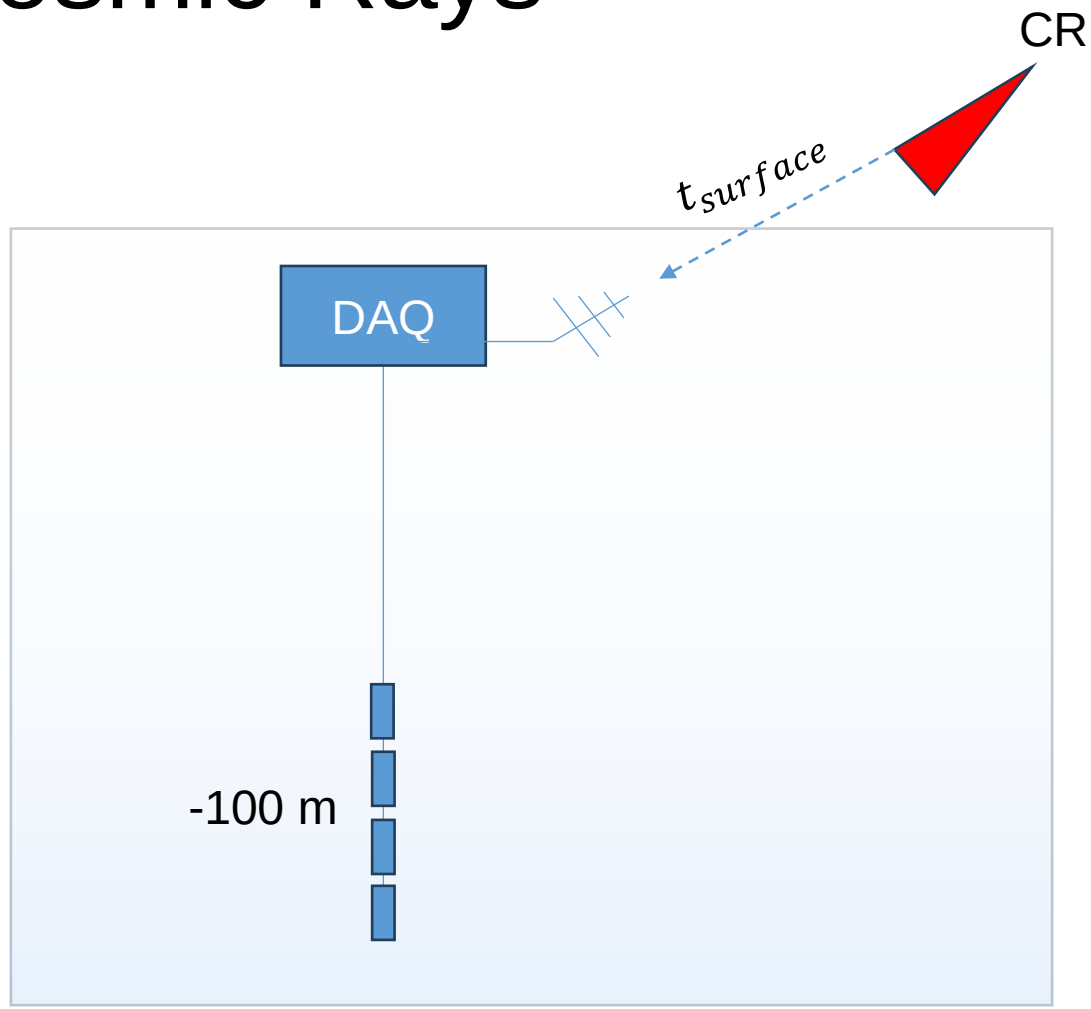

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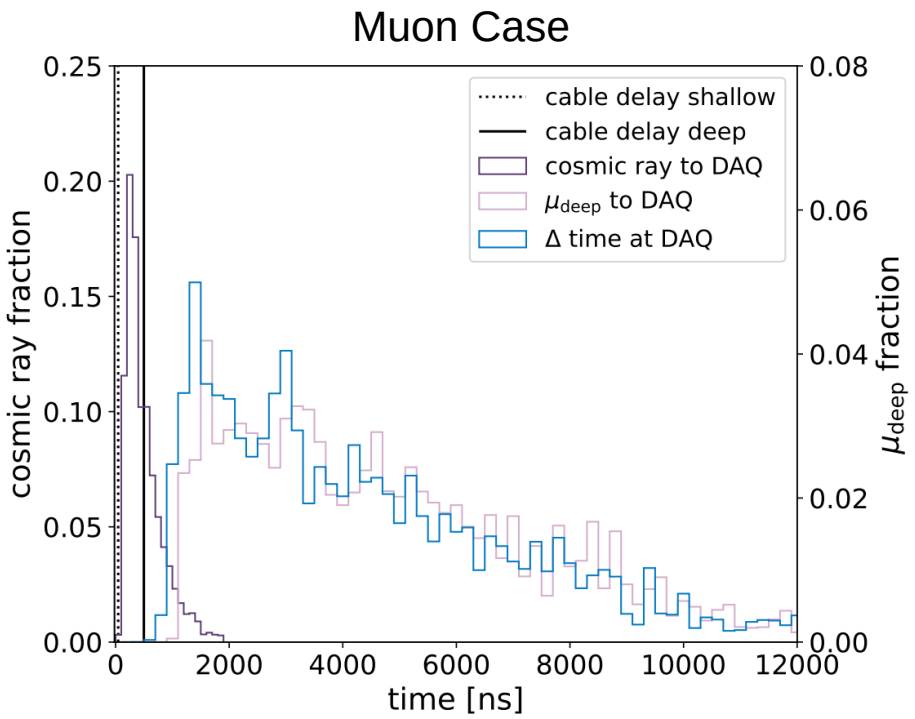

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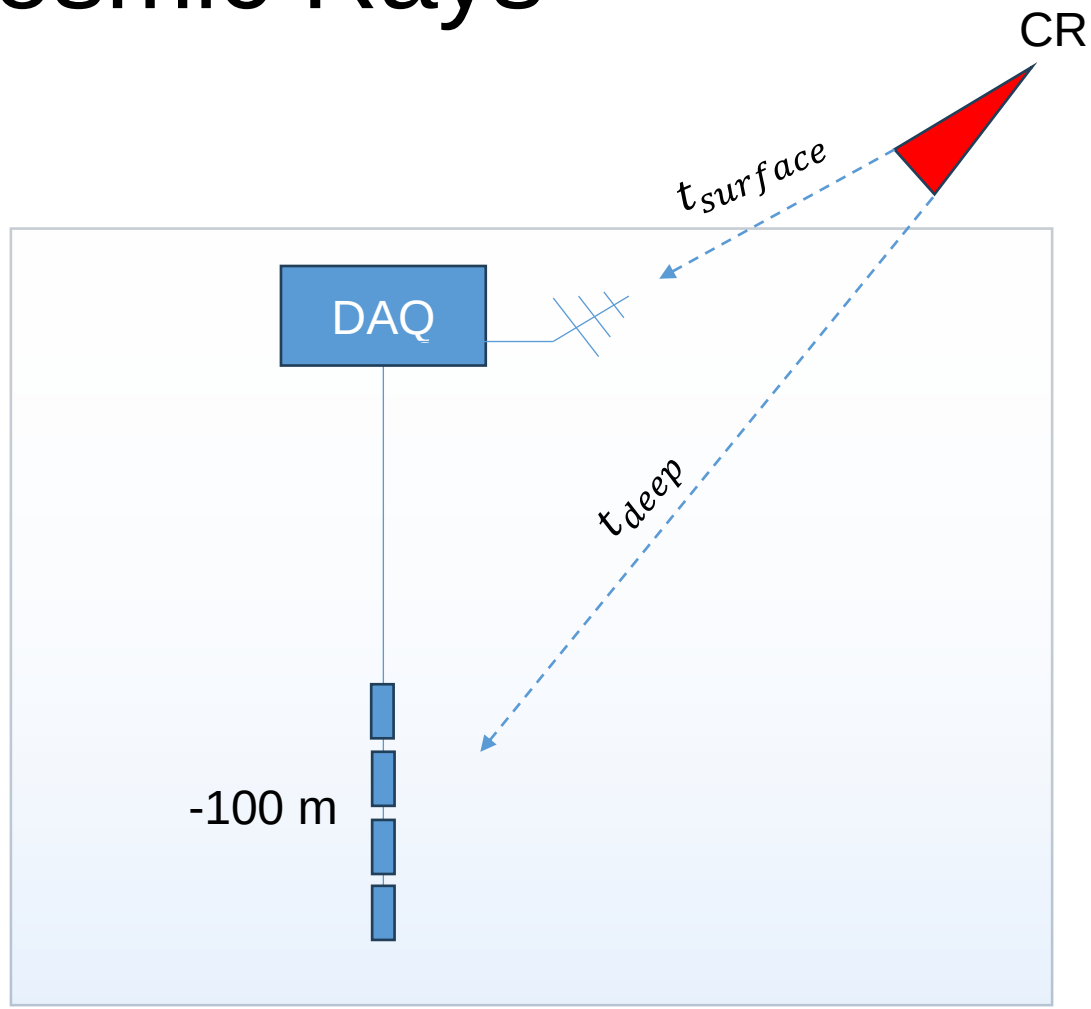

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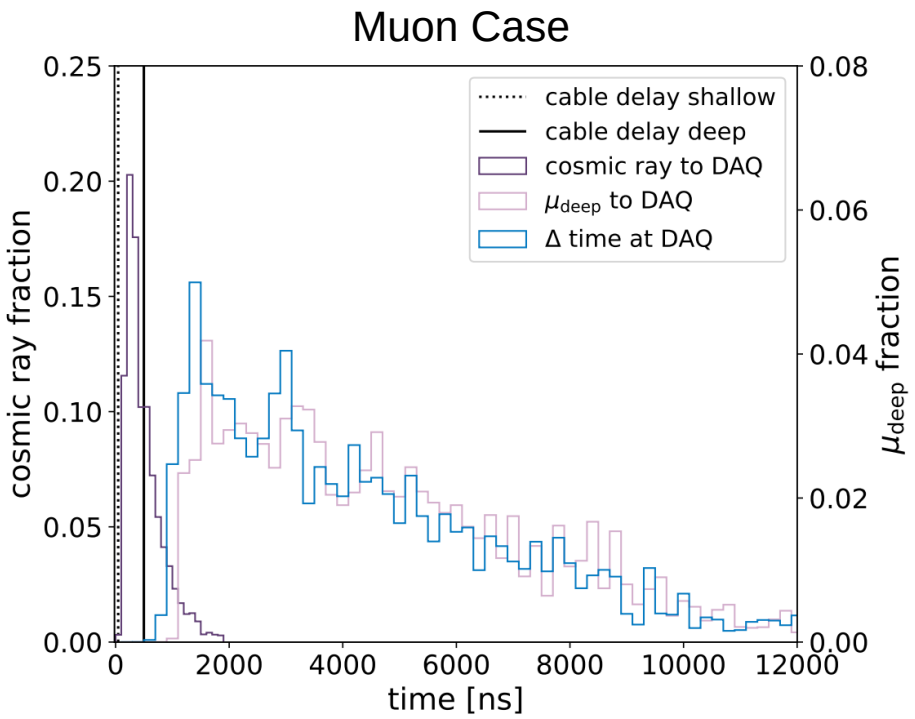

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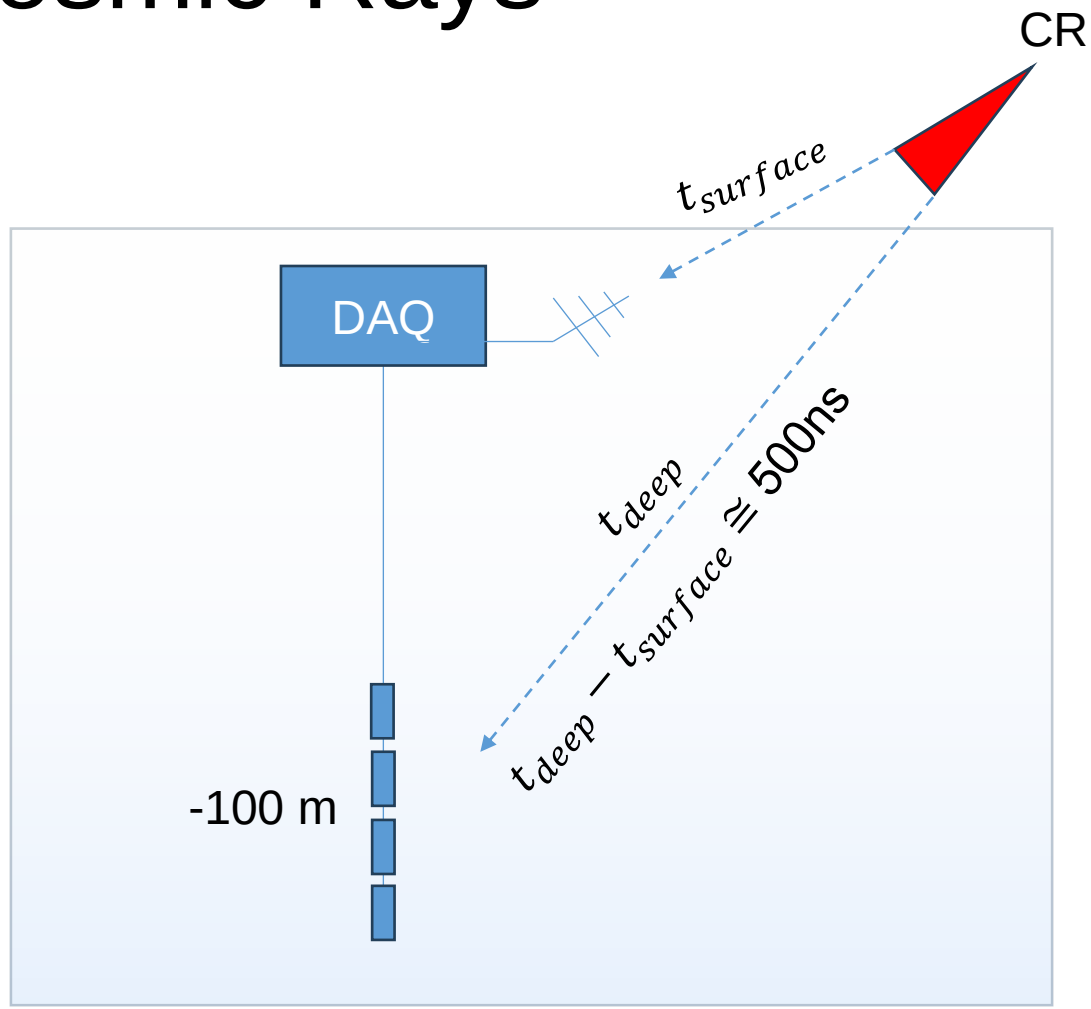

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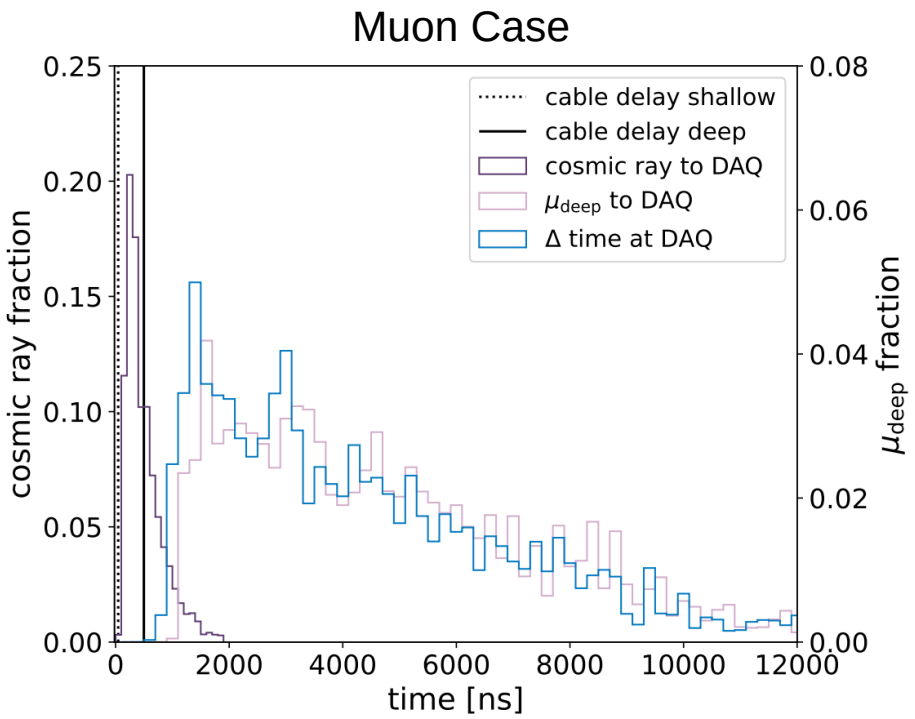

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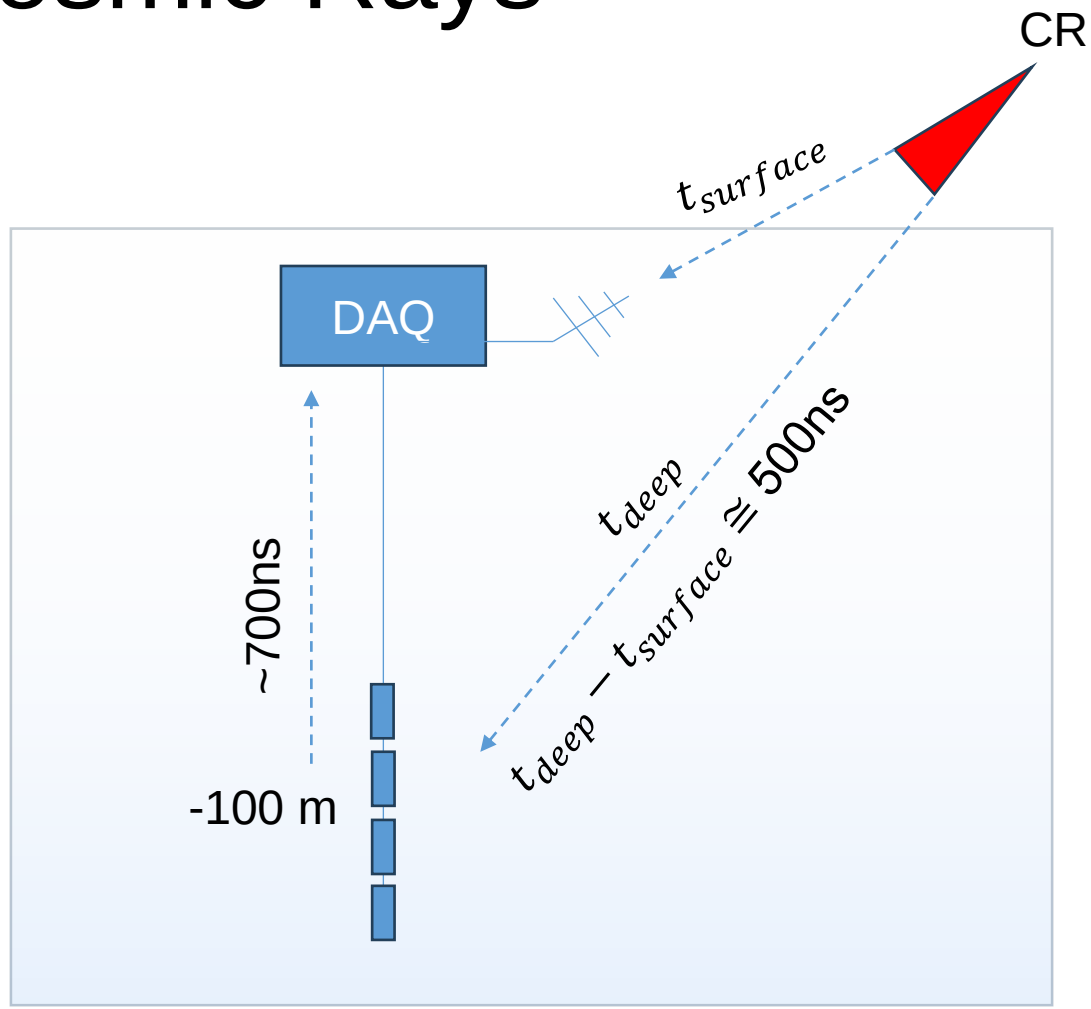

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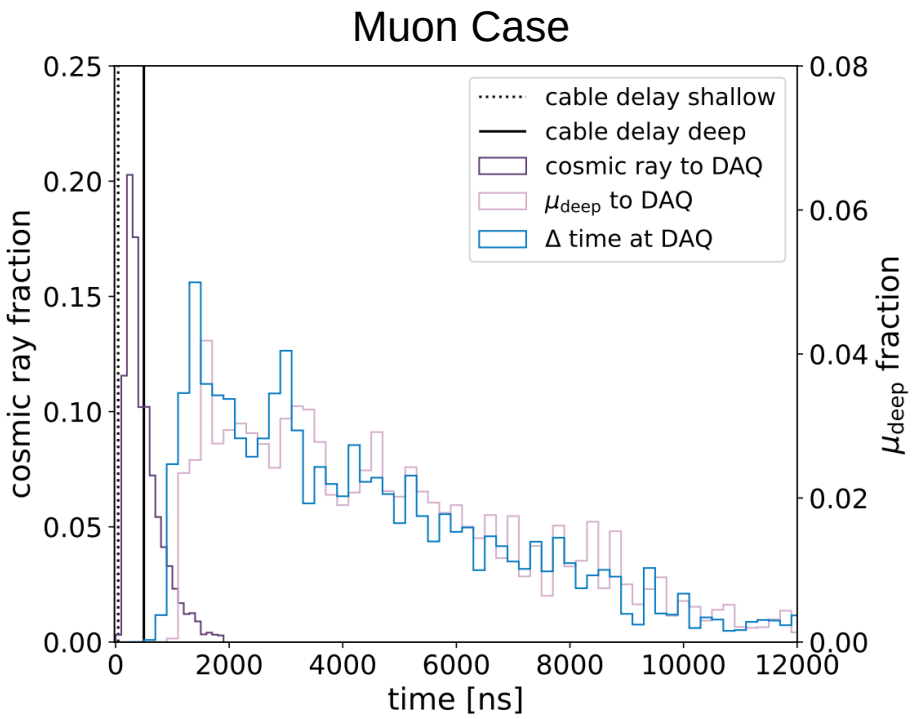

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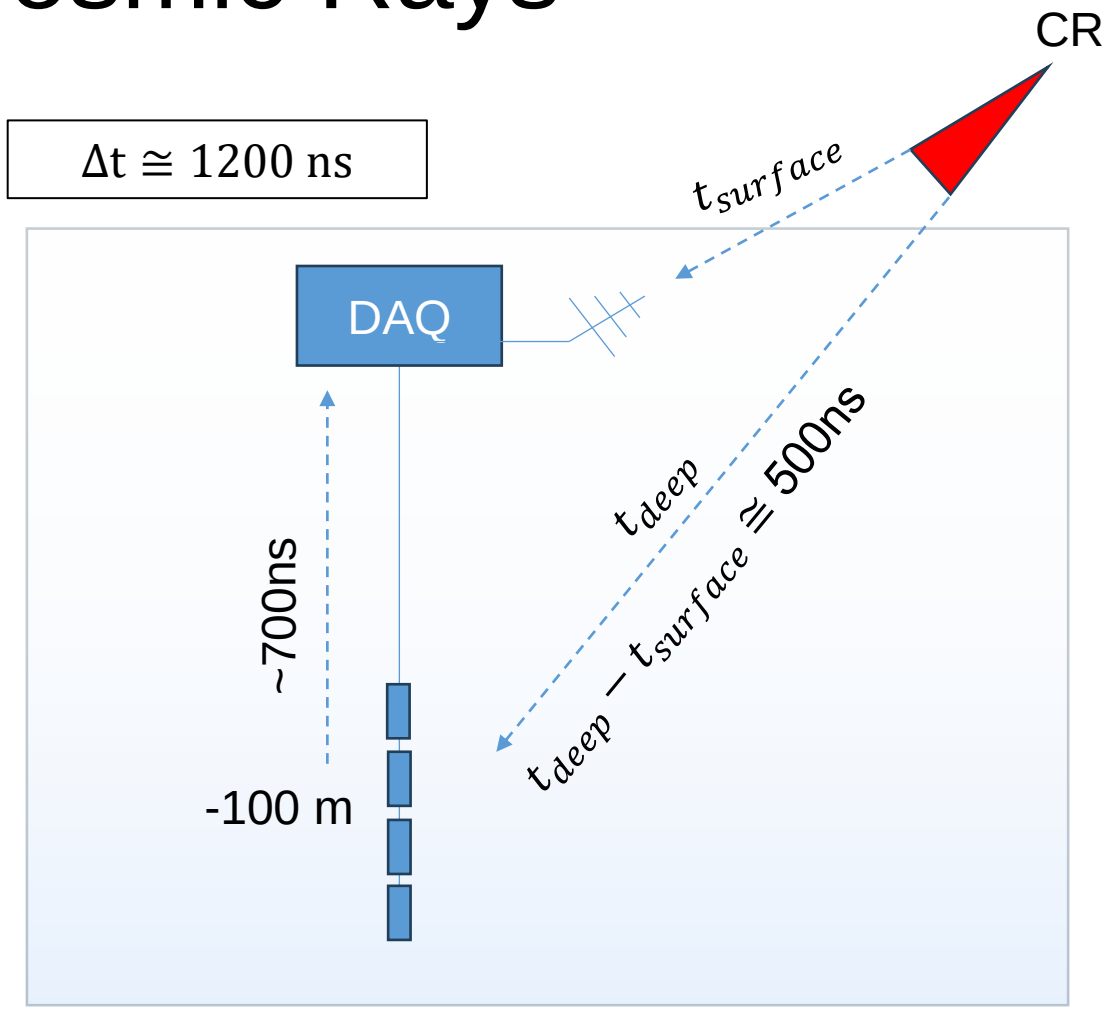

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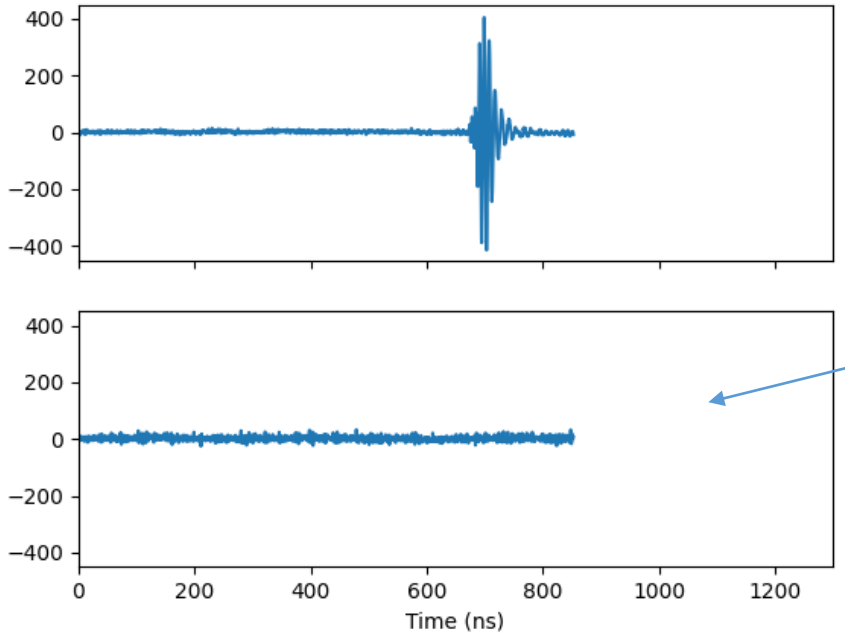
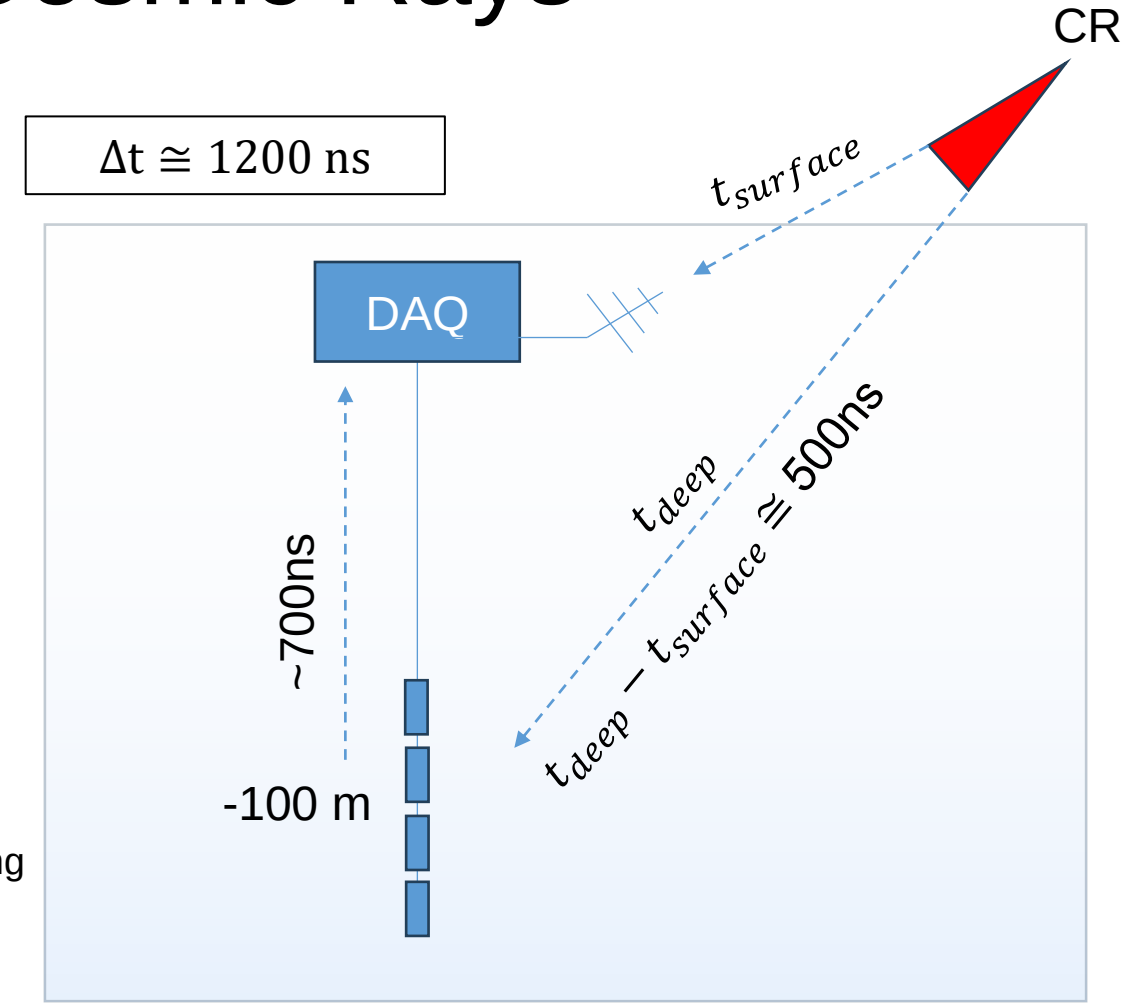
Lab Test Using Time Delayed Signals



Expect something here

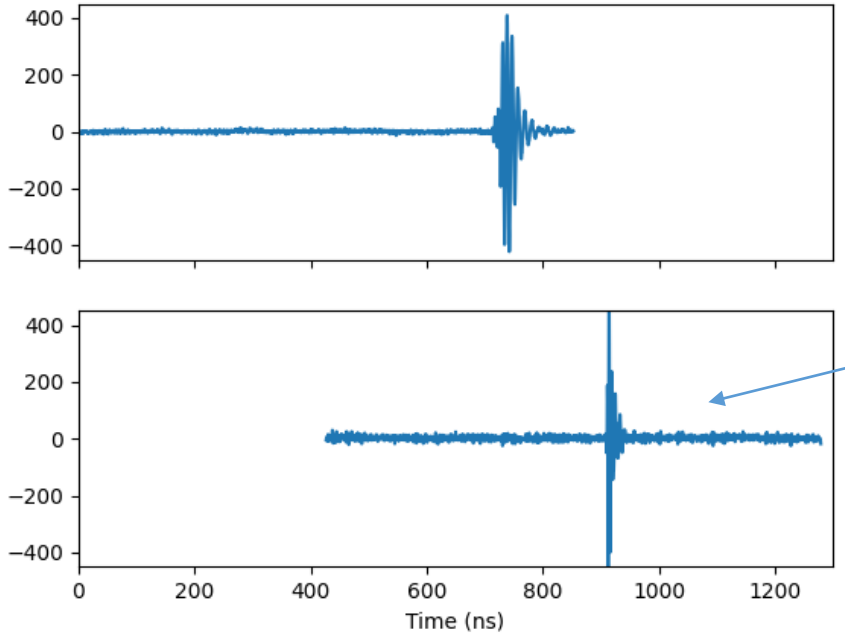


(See Anna Nelles’ Talk)

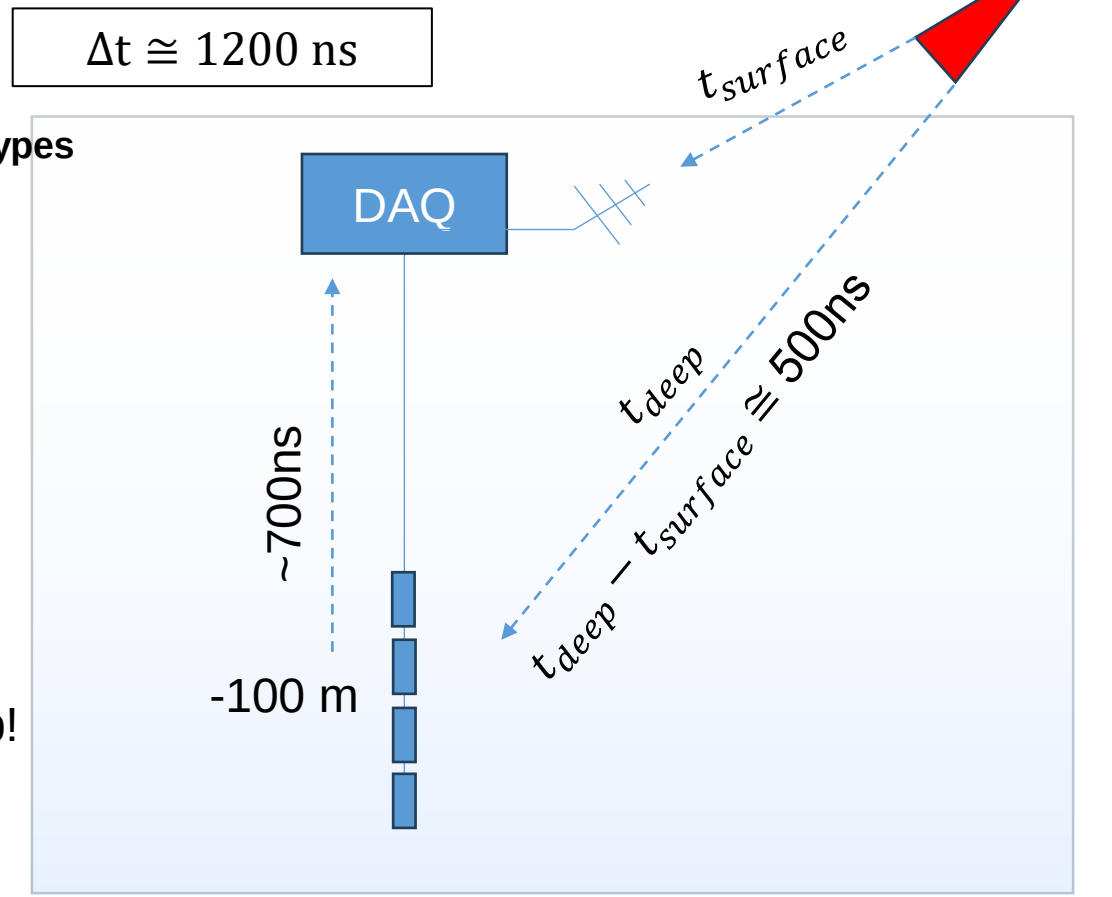
RADIANT Firmware For Cosmic Rays

- Cosmic Ray “Veto” Trigger Eliminates Signature from Deep Channels
  - All 24 Channels are Read ~~Simultaneously~~ **At variable times for different trigger types**
  - Limited buffer length ~~640 ns~~ **853 ns**
  - Signal propagation through ice and cable delay deep signals past the readout window

Lab Test Using Time Delayed Signals



It shows up!



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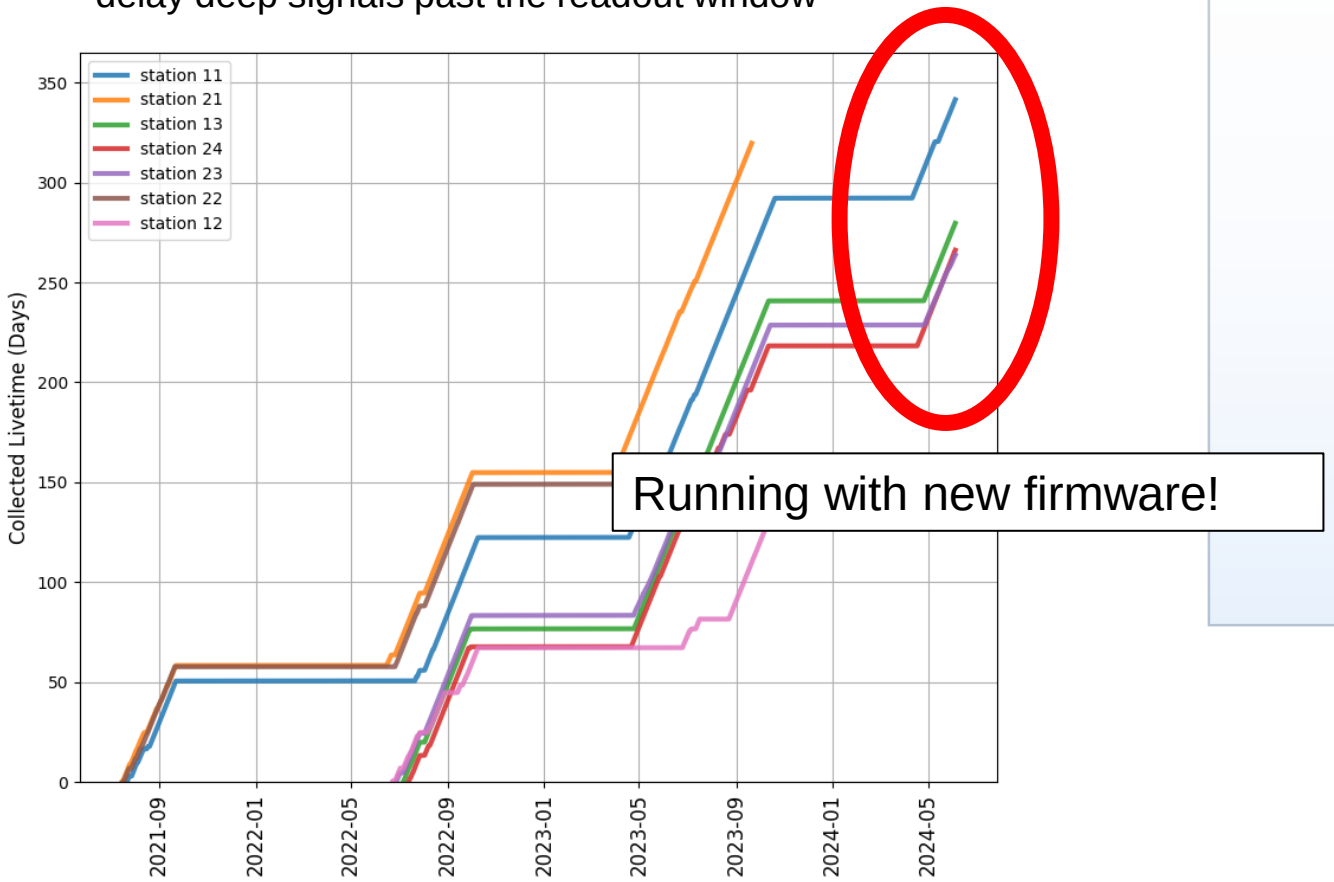
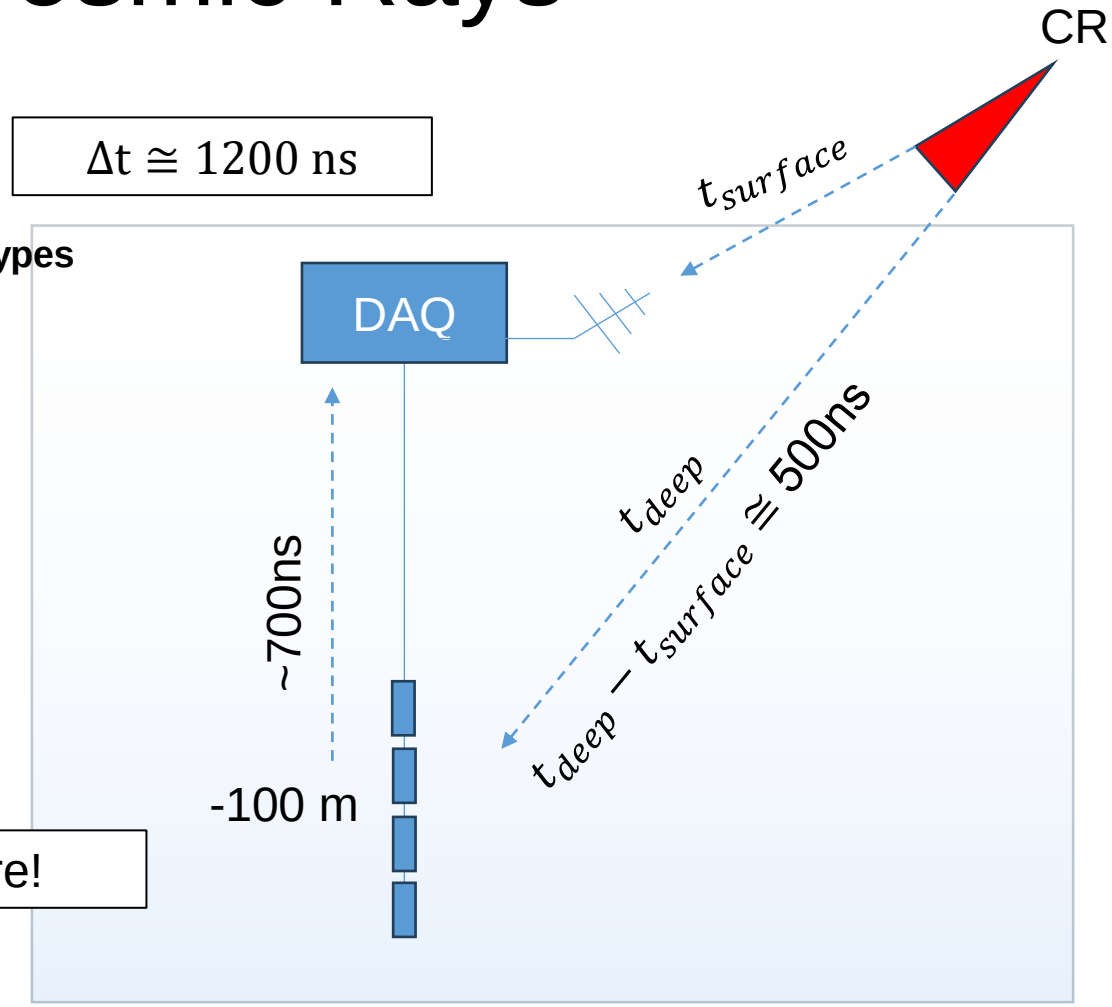


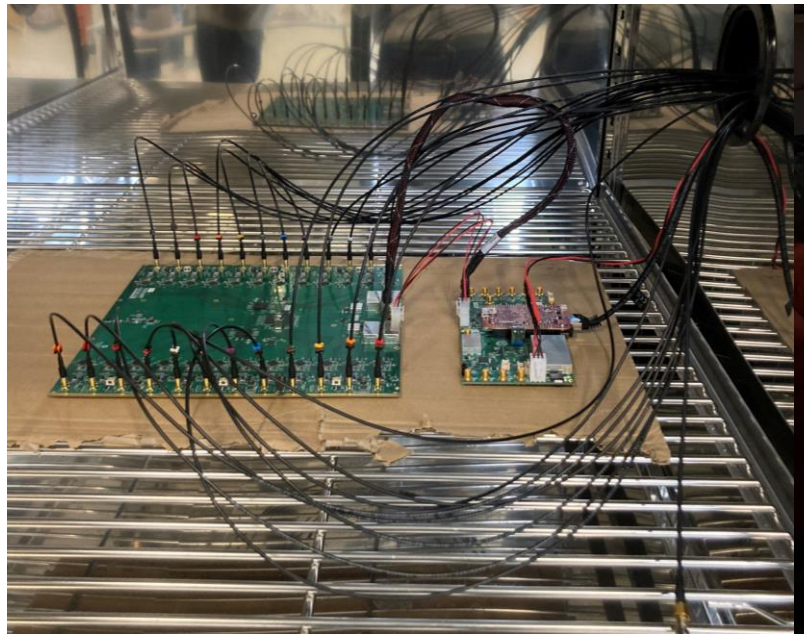
Running with new firmware!

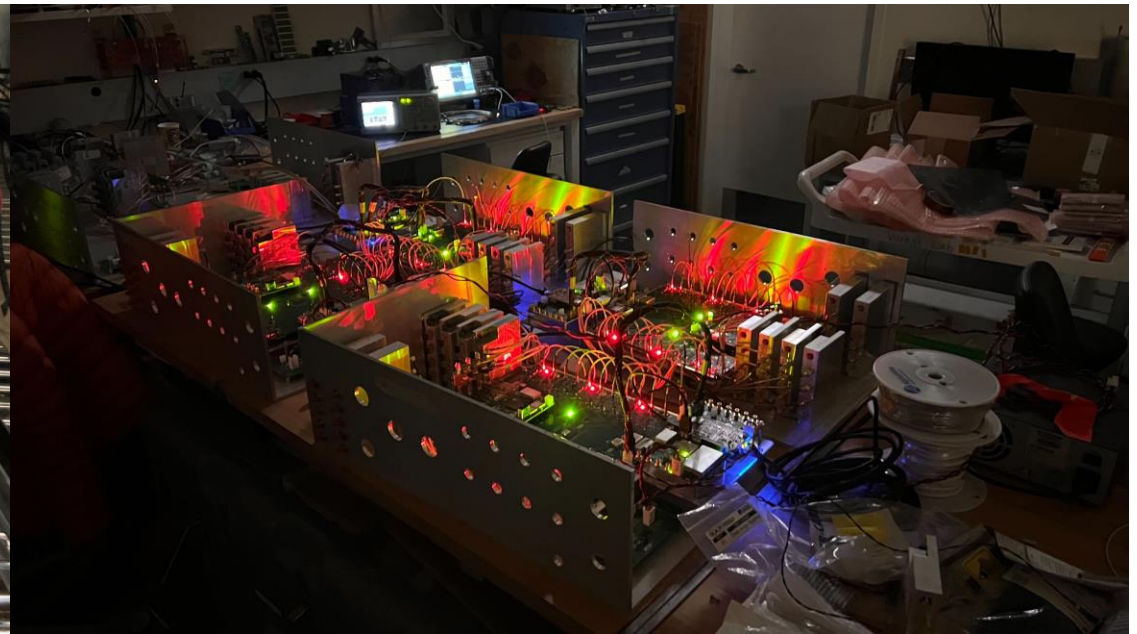


(See Anna Nelles’ Talk)

Station Upgrades and RADIANT Testing

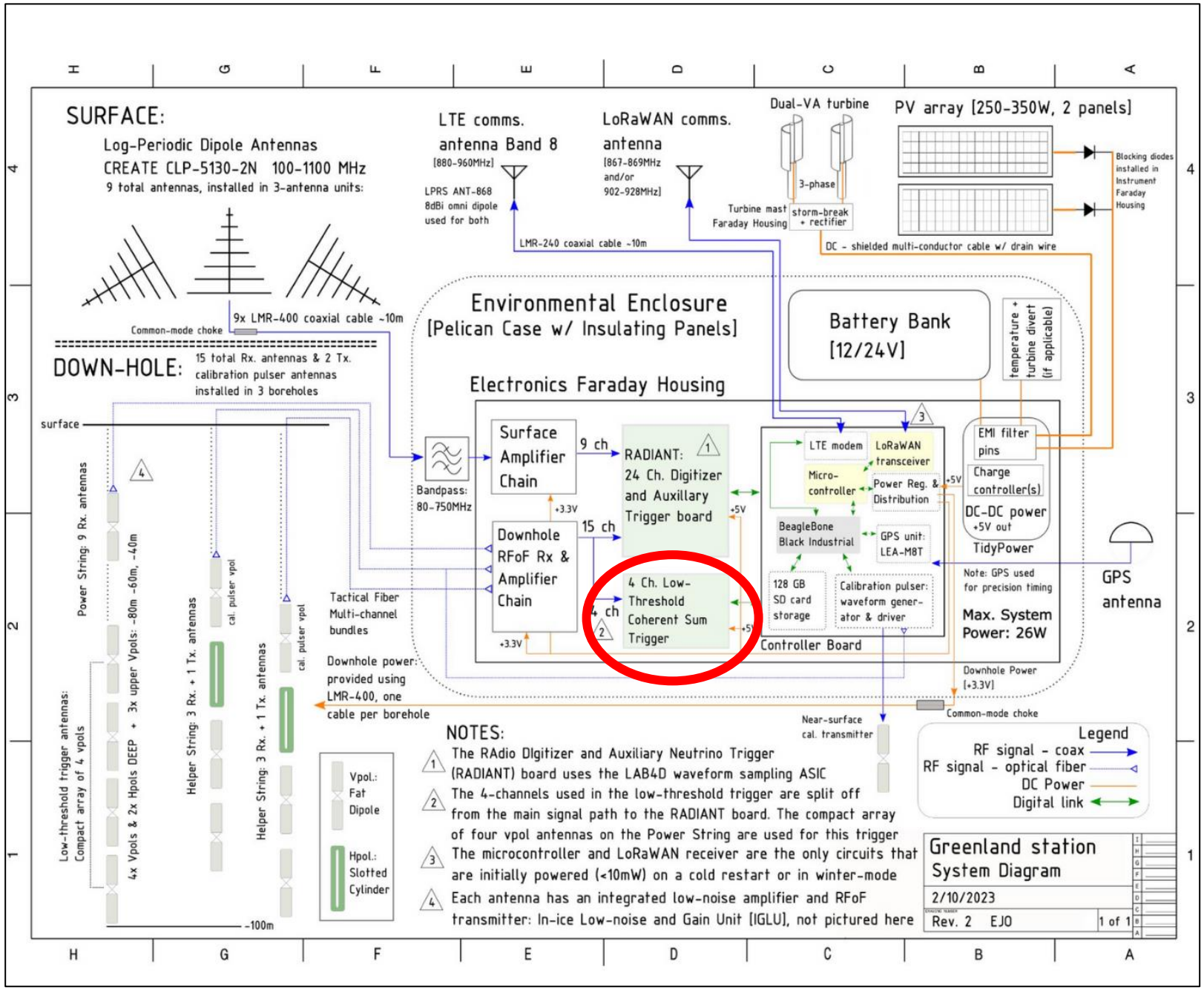
- 2024 Season we will be refurbishing current 7 DAQ’s
  - Revamped calibration pulser and external power box
  - **Upgrades** to RADIANT V3
    - Power rail stability
    - Increased splitter fraction for surface trigger path
    - Months of quality control, testing, and validation to ensure these perform well and last!





RNO-G

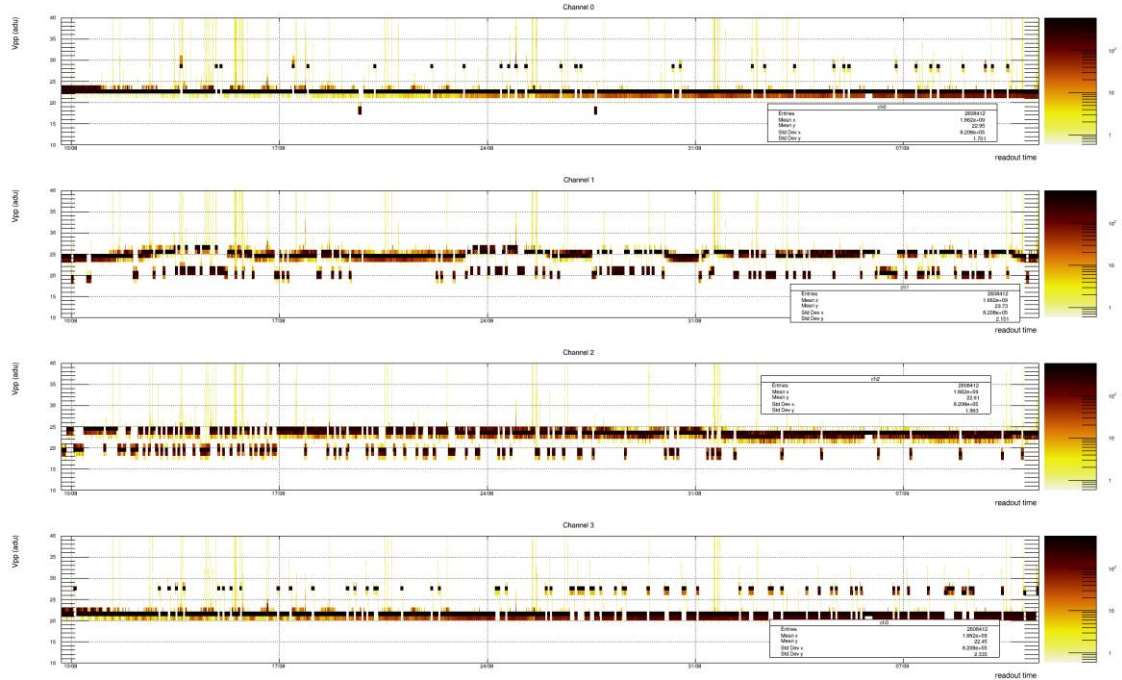
- Amplifiers
- Power
- Digitizer
- Trigger



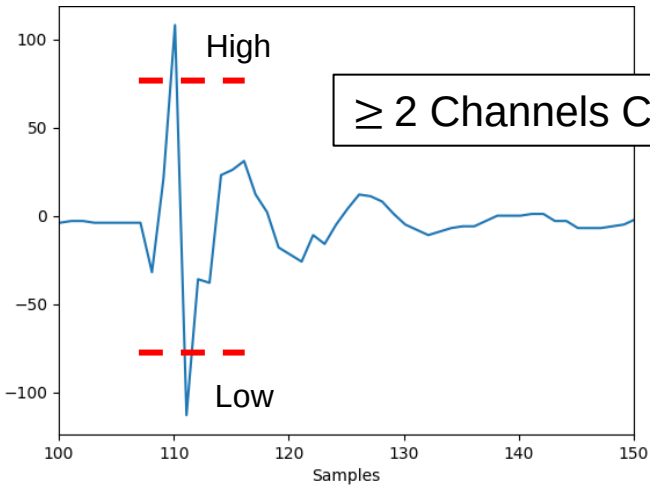
Low-Threshold Trigger

- **Fl**exible **O**ctal **W**av**e**form **R**ecorder (FLOWER)
  - 2x HMCAD 1511 Streaming Digitizers to a Cyclone V FPGA
  - Configured as 472 MHz sampling rate on the 4 lowest V-Pol Antennas (AKA Phased Array)
- Triggers
  - 2021-2024: Hi-Low Coincidence Trigger – 2.4σ
  - 2024+: Fully Phased Power Threshold Trigger -> 2σ?

V_{pp} ~ 24 ADC →2.4σ

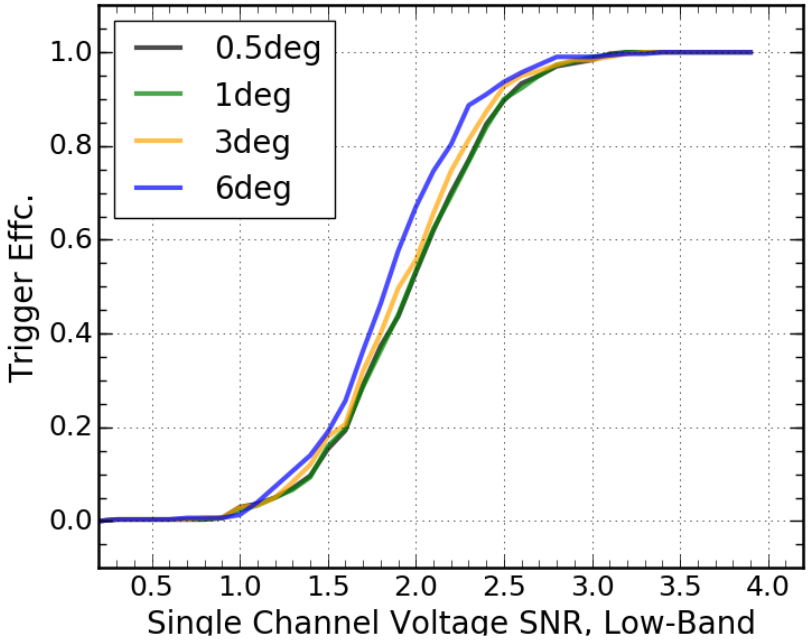


Hi-Low Trigger

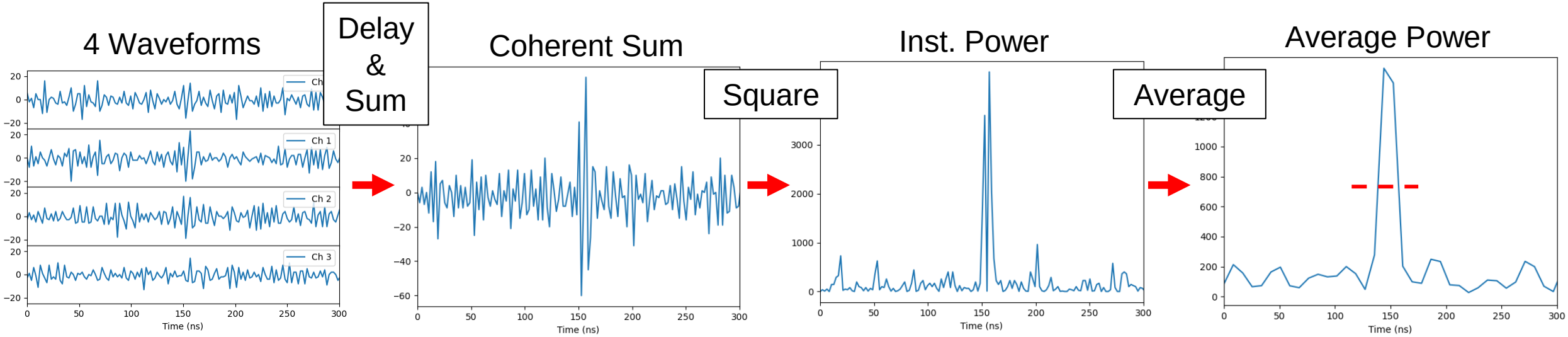


Phased Array Trigger

(RNO-G Collab. - arXiv:2010.12279)

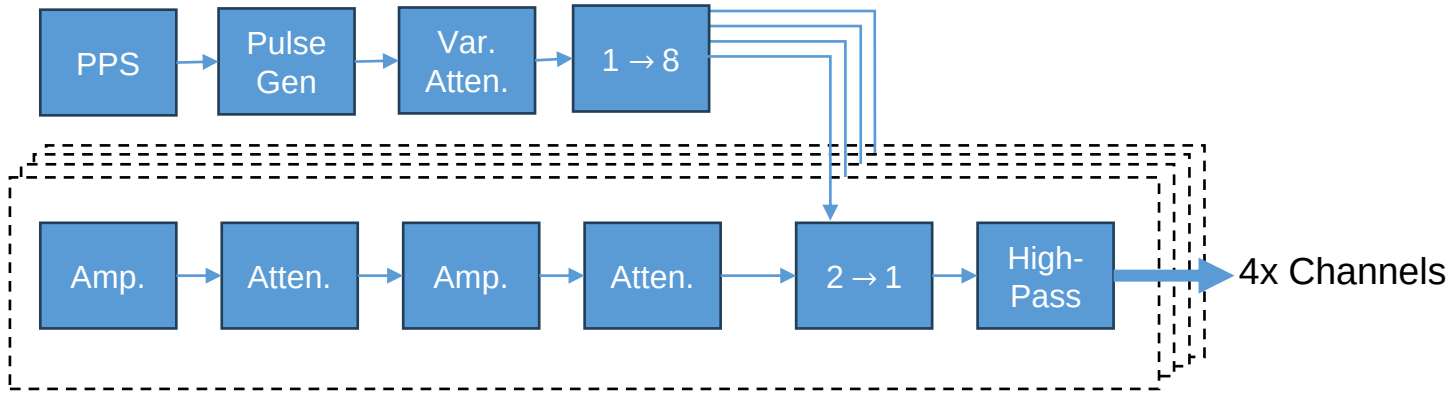


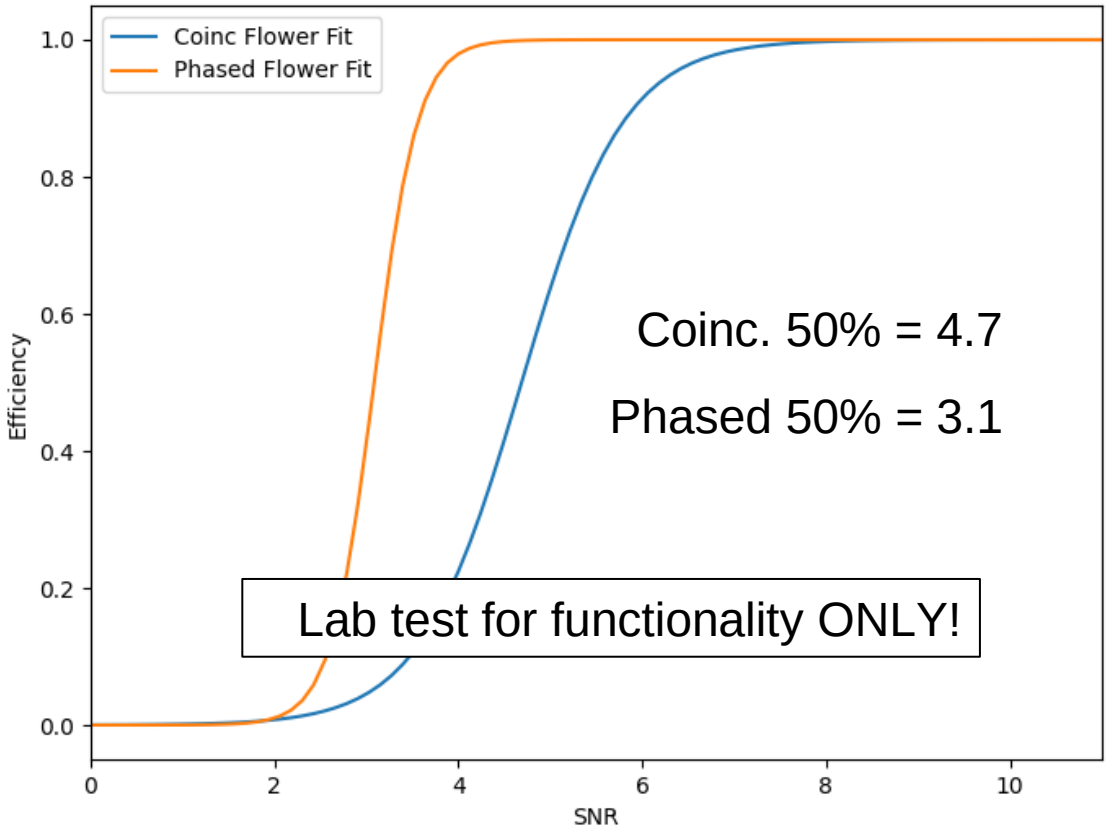
- Integrated Power Threshold Trigger on Beamformed Waveforms
- 8 beams equally spaced between elevation angles of [-60°,60°]
- 4x linearly interpolation to form beams constrained by sampling rate



Phased Array Trigger Lab Testing

- Trigger Efficiency Scans
  - Emulated the signal chain using amplifier noise and a fast pulse through a high pass filter
  - Set thresholds to match field trigger rate of 1Hz
  - Compare current high-low threshold trigger to a new phased array trigger





SNR highly sensitive to pulse and RF chain spectra!

Phased Array Trigger Lab Testing

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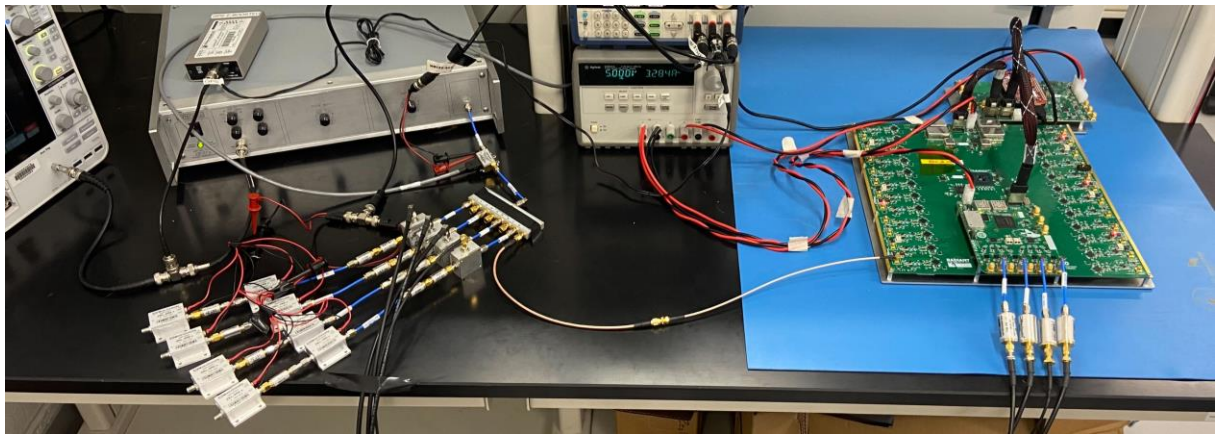
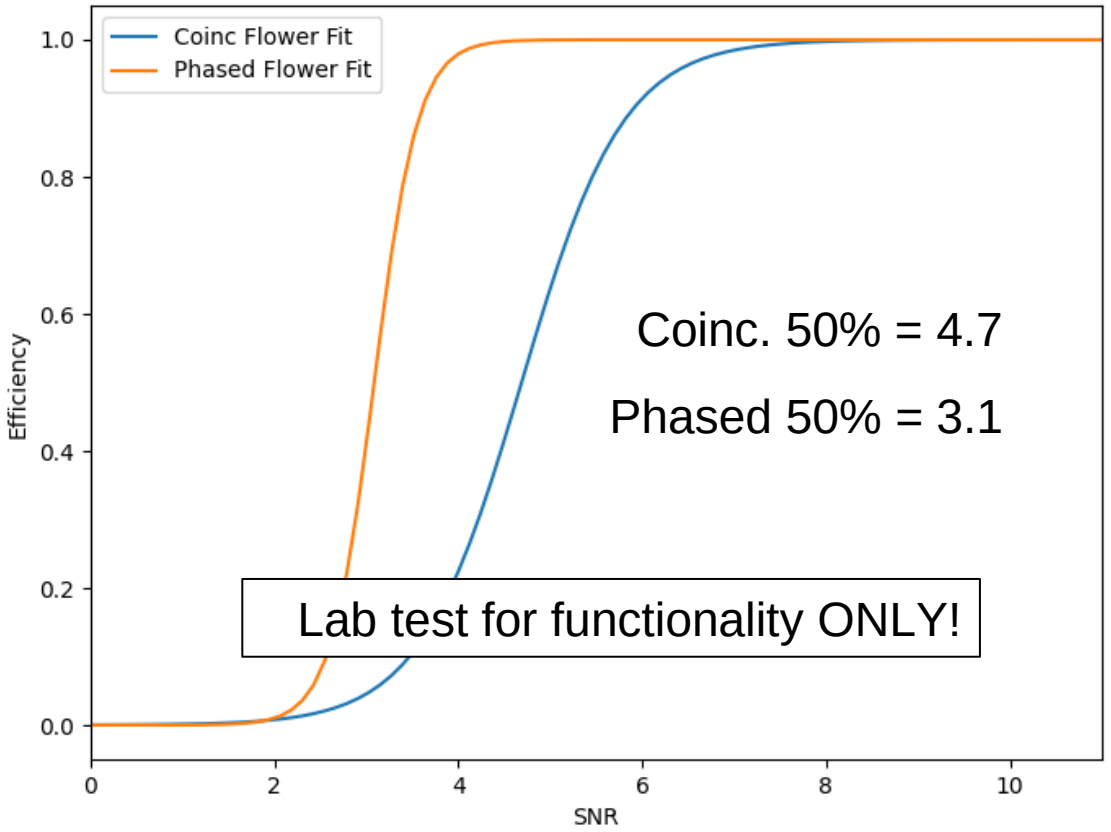
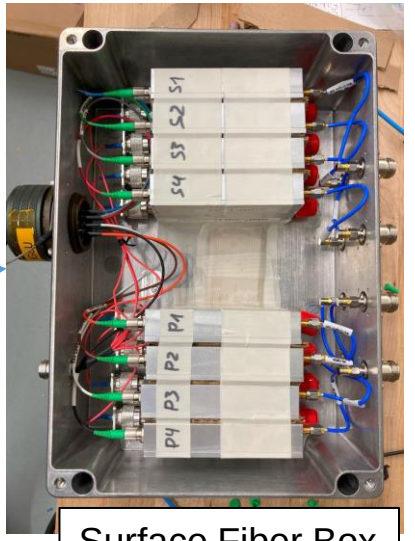




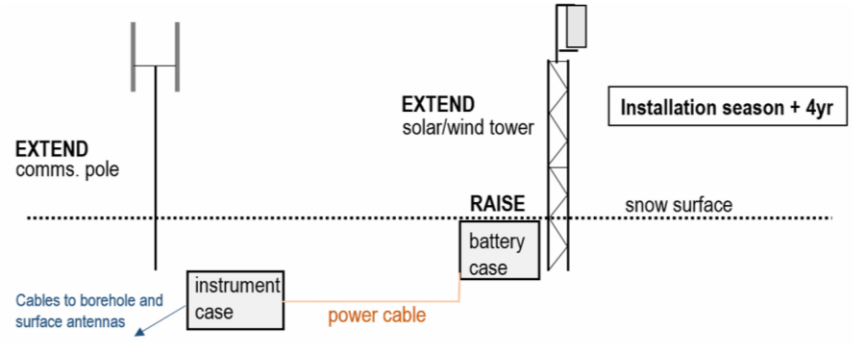
SNR highly sensitive to pulse and RF chain spectra!

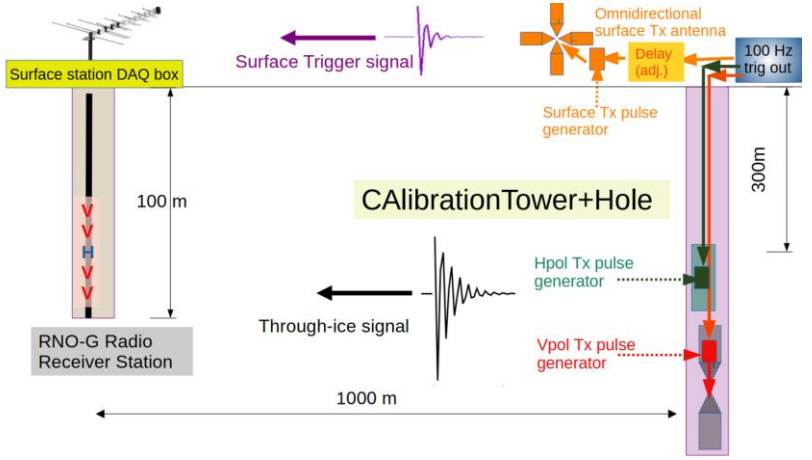
Future Work

- Rollout of Phased Array Trigger w/ In-Situ Testing
- Deep Learning Trigger – (Coleman et al. - PoS(ICRC2023)1100)
- Full fiber stations to reduce time delay between deep and surface channels
- Decentralized DAQ – move a source of RF noise away from the antennas
- Dual RX/TX IGLU amplifiers transform every antenna to a **calibration source**
- Calibration Tower For Pulsing to **Many** Stations
- New DAQ designs using new ASICs or streaming digitizers (see Stephanie Wissel's Gen-2 Talk)



Surface Fiber Box





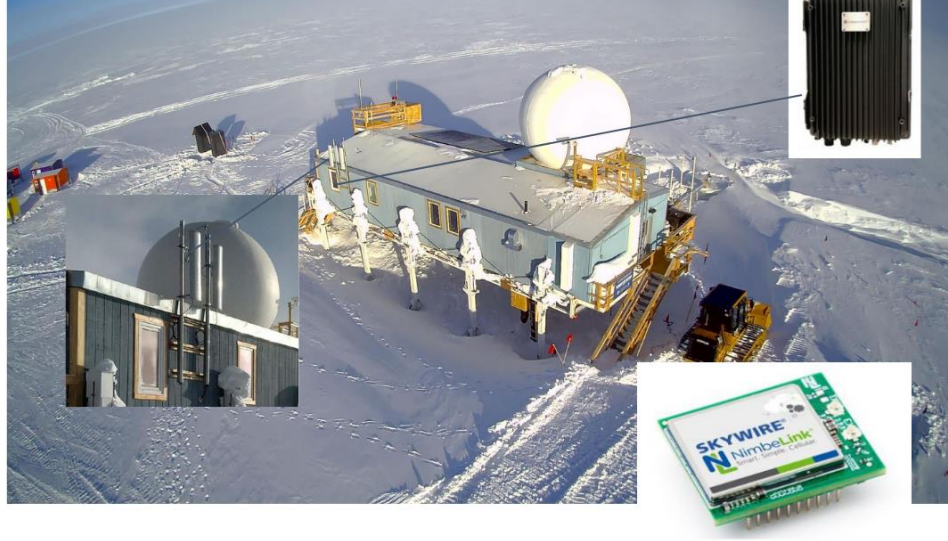
Conclusions

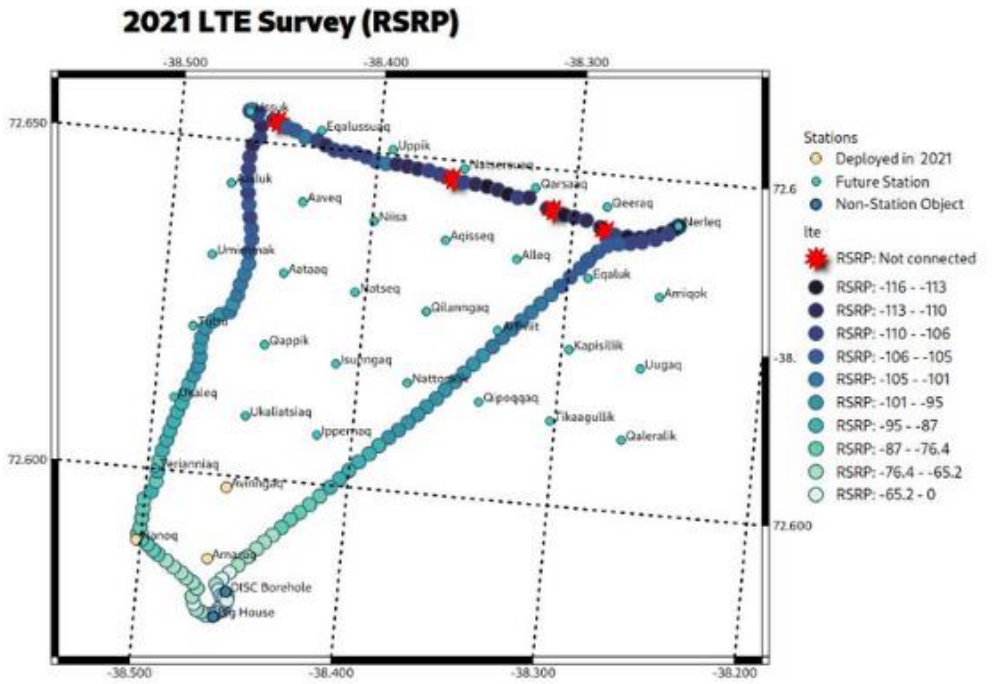
- Robust and maturing design, learning from currently deployed stations
- Low-power RF systems and modular power pushing to increase live-time
- Extensively tested RF and DAQ systems to better constrain systematics
- Firmware upgrades to better understand cosmic rays in our detector and to improve neutrino sensitivity

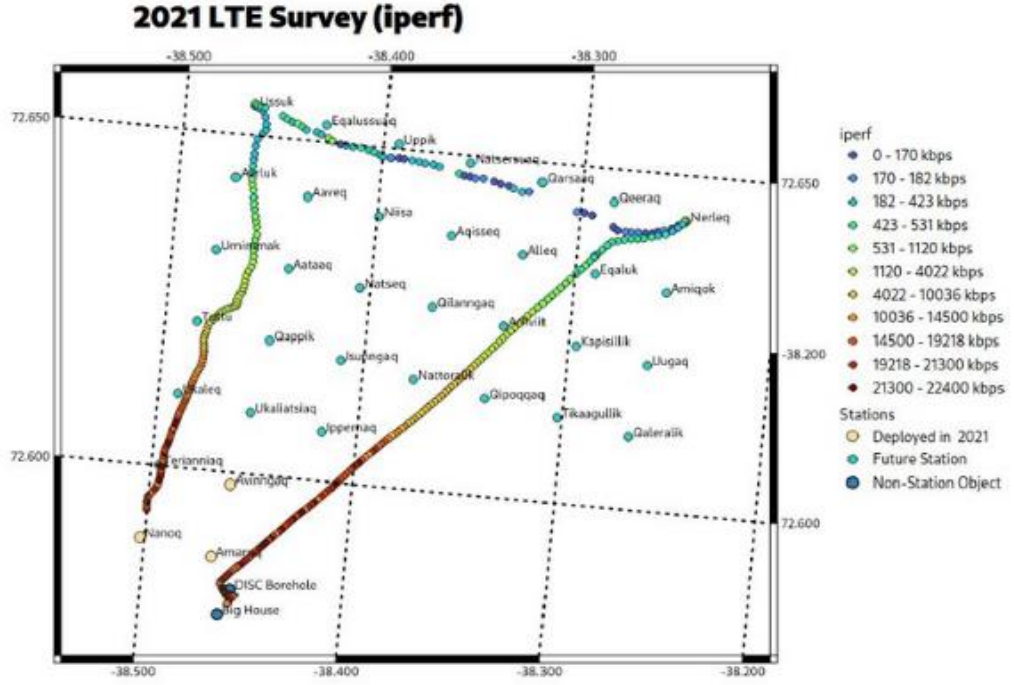
Backup Slides

Communications

- LoRaWAN
  - Lower-level housekeeping + low power station control
- Local LTE Network
  - For full station I/O and data collection
- Satellite Link
  - Fractional data transfer for monitoring and future multi-messenger work

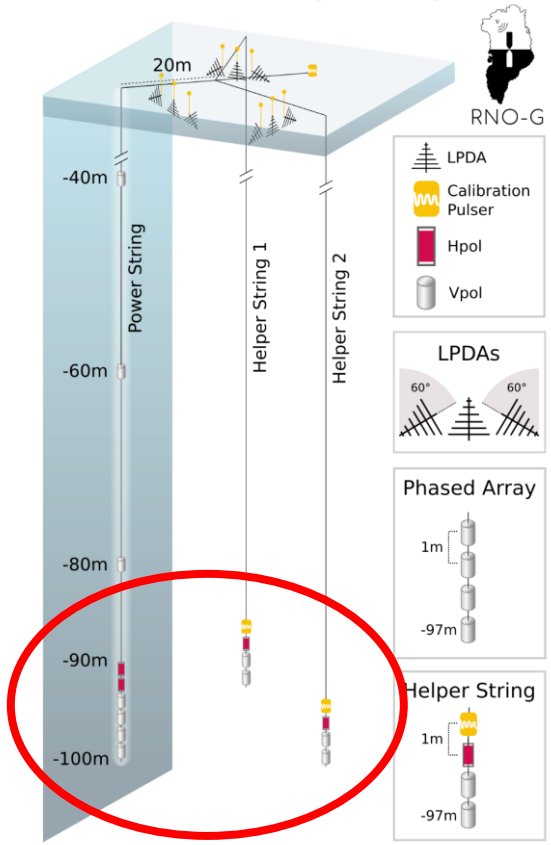




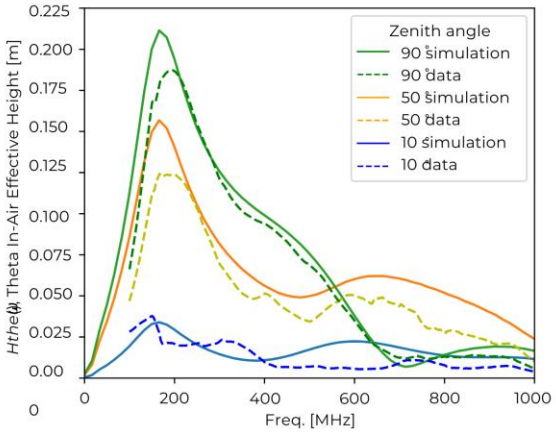


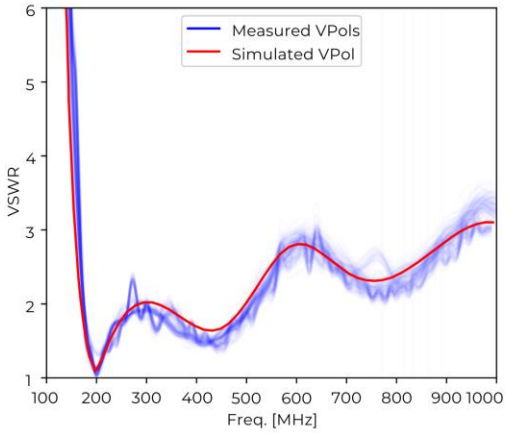
Antennas

- Vertically Polarized Antennas (Dipole)
- Horizontally Polarized Antennas (Quad Slot)
- Surface Antennas (LPDA)

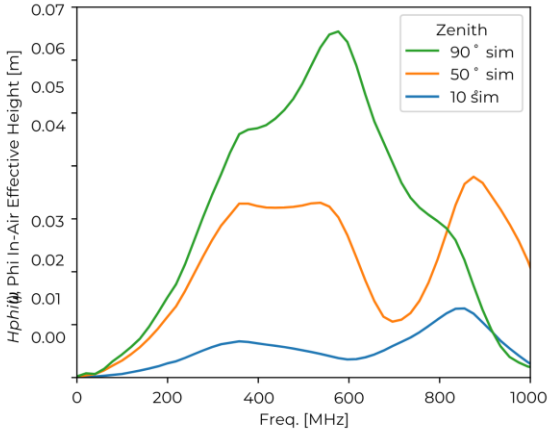


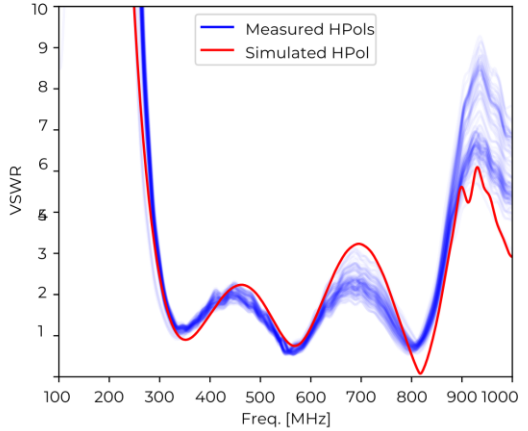
V-Pol





H-Pol

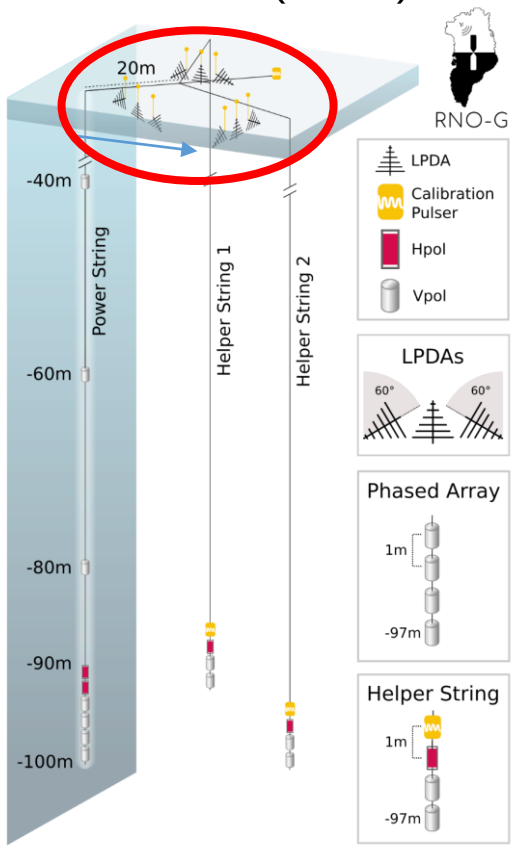


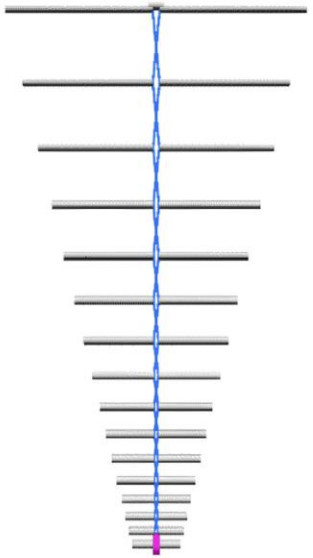


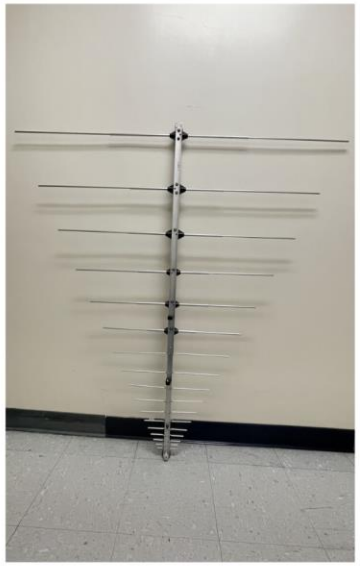
Preliminary

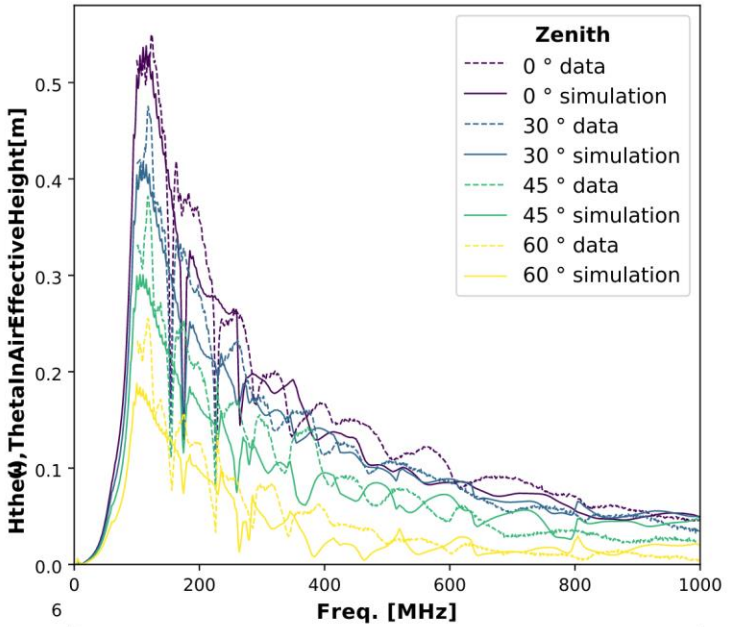
Antennas

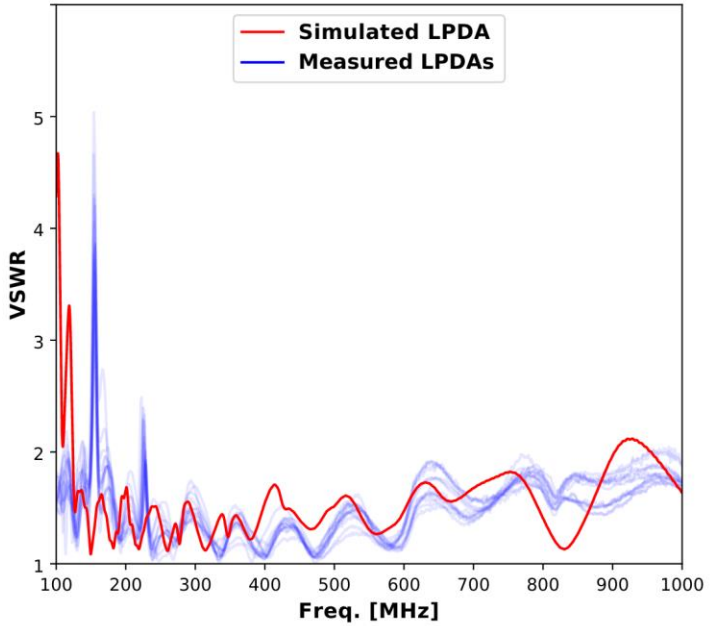
- Vertically Polarized Antennas (Fat Dipole)
- Horizontally Polarized Antennas (Quad Slot)
- Surface Antennas (LPDA)











Preliminary

In-Situ Digitizer Delays

- When triggering on a calibration pulser on a helper string, the deep power string antennas are late.
- By applying readout delays they now show up in the readout window!