Searching for RF-Only Triggered Cosmic Ray Events with the High-Elevation BEACON Prototype

Daniel Southall – ICRC 2021

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BEACON

BEACON

- Concept for mountaintop radio array designed for measuring astrophysical ν_τ flux
- Utilizes phased radio antenna trigger for lower trigger threshold and directional RFI rejection
- Sub-degree angular resolution
- Optimized for scalability
  - Stations are independent, can result in broad sky coverage

This talk discusses the BEACON prototype and data analysis efforts that are underway – focusing on position calibration and an RF-Only trigger based cosmic ray search

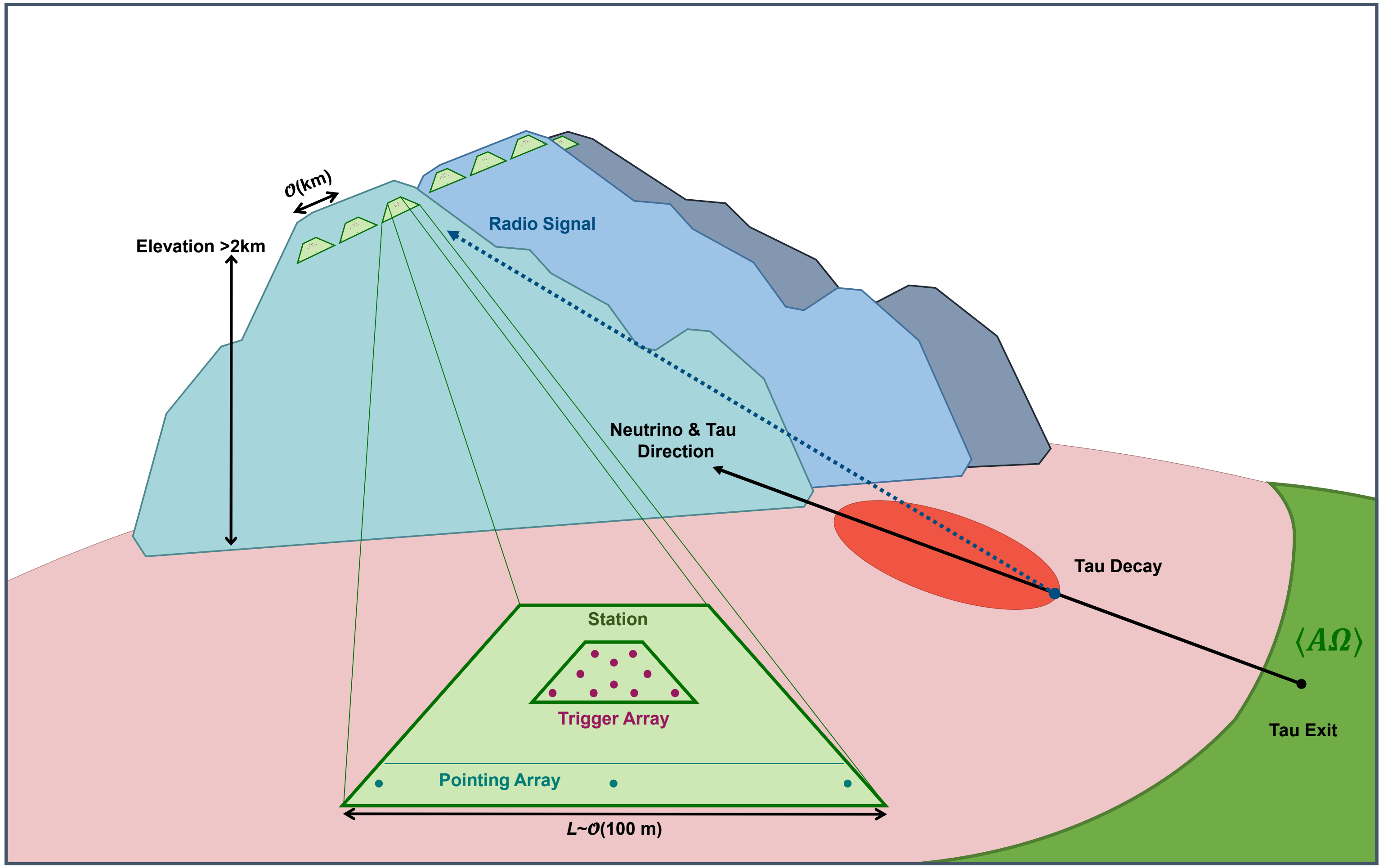
Motivation

- ν events have been observed with up to 10 PeV (10^{16}eV), with cosmic ray events suggesting higher energies should exist
- BEACON could provide a unique unambiguous measure ν_τ flavor-specific flux
- Current estimates → Full BEACON array consisting of 1000 stations sensitive to iron-dominated cosmogenic models*
- Measuring a flux of cosmic rays with the BEACON prototype could serve as an excellent proof of concept and enable refinement of full-scale sensitivity predictions

*Estimate presented in JCAP11(2020)065

Technique Methodology

- $\nu_\tau \rightarrow \tau \rightarrow air\ shower \rightarrow$ detected by radio array
- Sensitive to only ν_τ
- High-Elevation sites (> 2 km prominence) are selected for large visible area for near horizon events
- Multiple stations in various locations for broad sky coverage
- Trigger array uses phasing to reject anthropogenic noise



BEACON Performance

Poster

- For more simulation information please see the ICRC 2021 Poster by Andrew Zeolla: *Modeling and Validating RF-Only Interferometric Triggering with Cosmic Rays for BEACON*

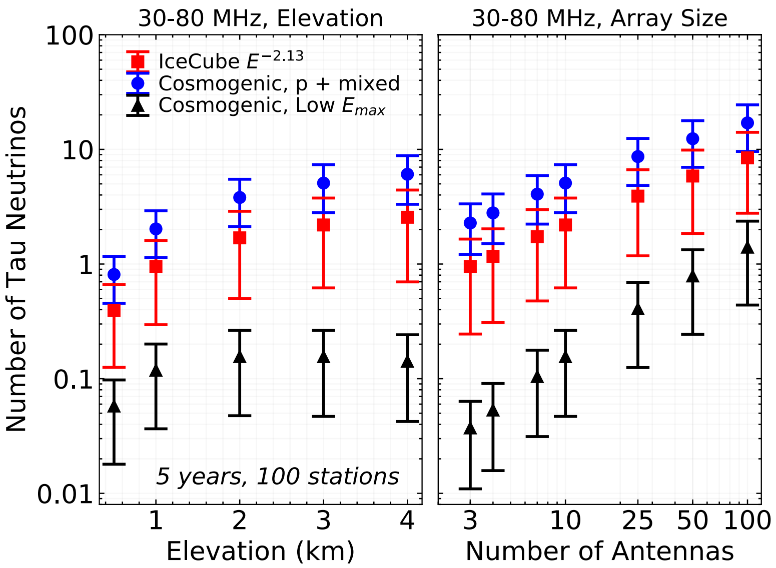
Array Design

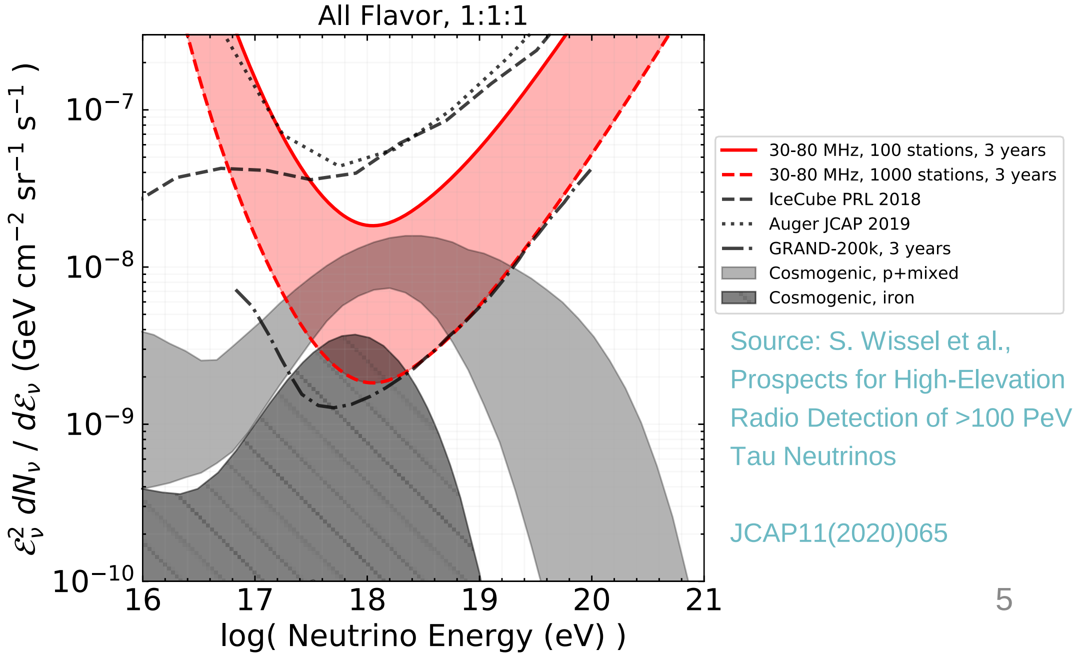
- Elevation of 2-3 km is ideal
- 10 antennas/trigger array strikes balance of practicality and sensitivity

Predicted Performance*

- Current estimates → Full BEACON array consisting of 1000 stations sensitive to iron-dominated cosmogenic models

*Simulations assume 120° FOV and trigger threshold of 5σ SNR in beam voltage



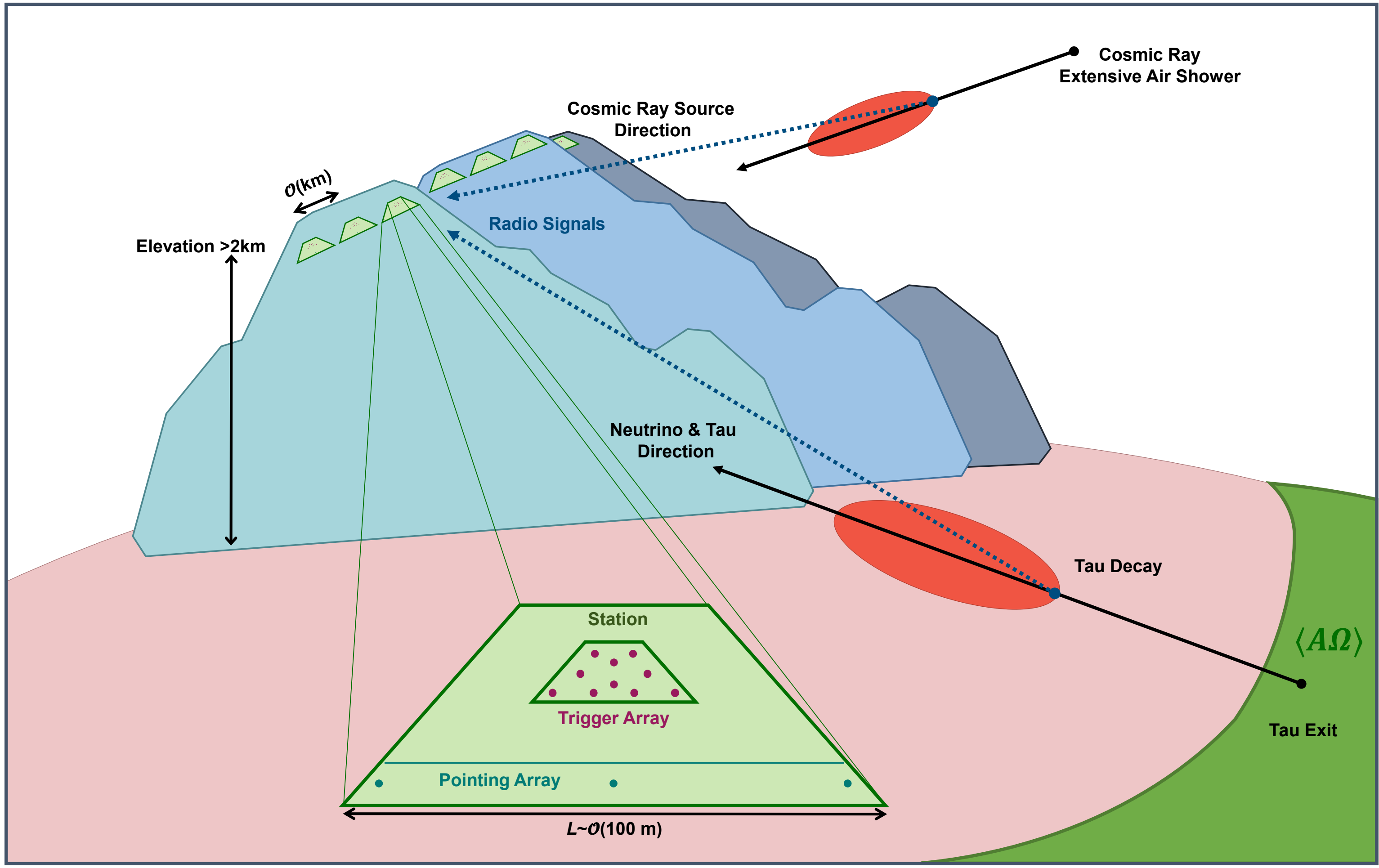


Source: S. Wissel et al., Prospects for High-Elevation Radio Detection of >100 PeV Tau Neutrinos

JCAP11(2020)065

Cosmic Ray Backgrounds

- Cosmic rays are the main expected astrophysical background for BEACON
- They have many similar characteristics to a ν_τ event but are distinguishable based on direction and polarity
- RF-only triggers on cosmic rays have been demonstrated at OVRO-LWA, TREND *

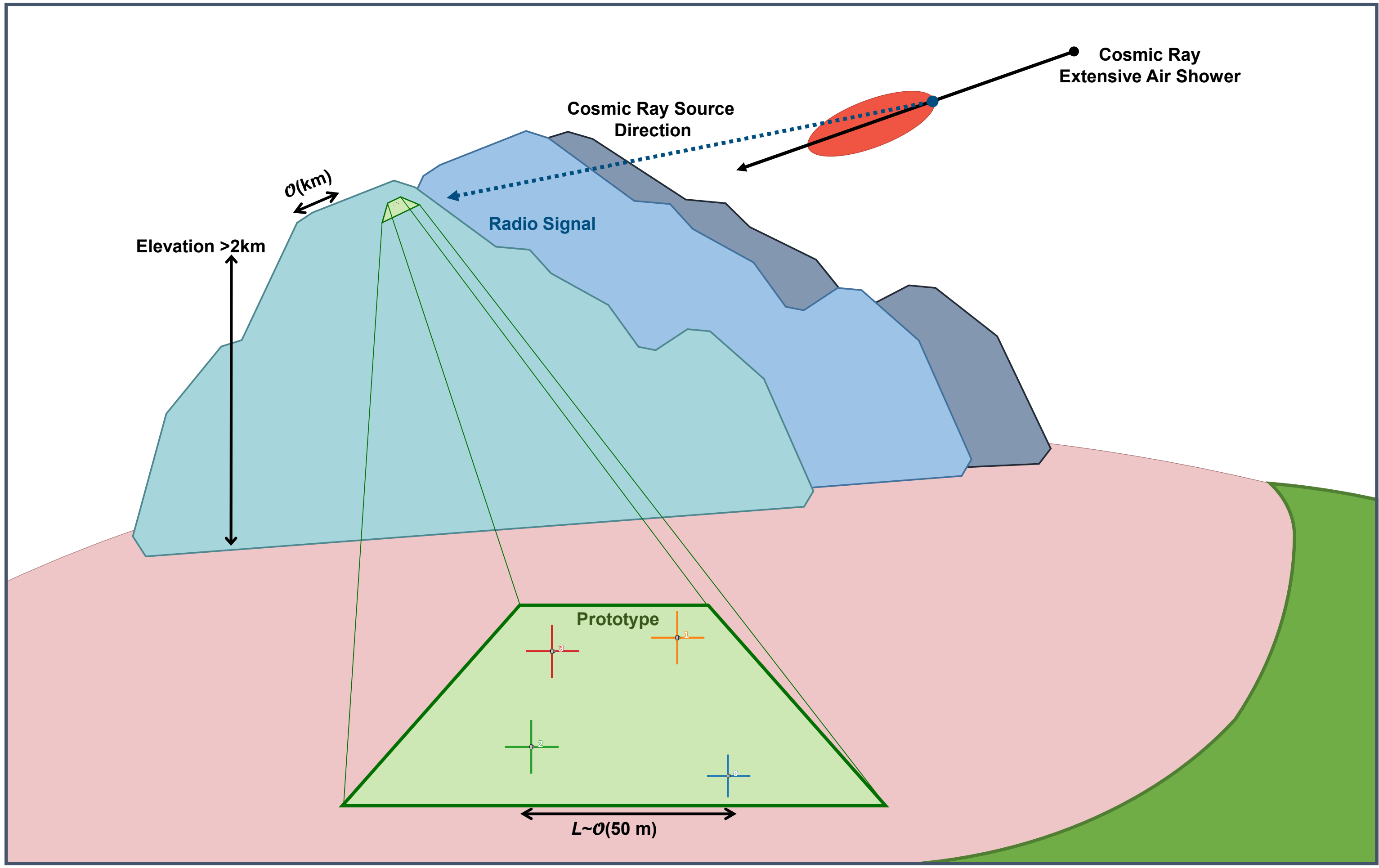


* R. Monroe, A.R. Wolf, G. Hallinan, A. Nelles, M. Eastwood, M. Anderson et al., *Self-triggered radio detection and identification of cosmic air showers with the ovro-lwa, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **953** (2020) 163086.

D. Charrier, K.D. de Vries, Q. Gou, J. Gu, H. Hu, Y. Huang et al., *Autonomous radio detection of air showers with the trend50 antenna array, Astroparticle Physics* **110** (2019) 15.

Prototype

- Consists of 4 crossed short-dipole antennas
- Aims to use measurements of cosmic rays to provide a proof of concept
- The observed rate will also help refine the predicted BEACON sensitivity



Prototype - Goal

Development Towards First Station:

- In situ testing of systems and hardware
- Development of RFI rejection techniques

Demonstrate Technique:

- High array live time
- Directional beam-forming trigger
- Low thresholds
- Ability to RF trigger on cosmic rays

Prototype Site

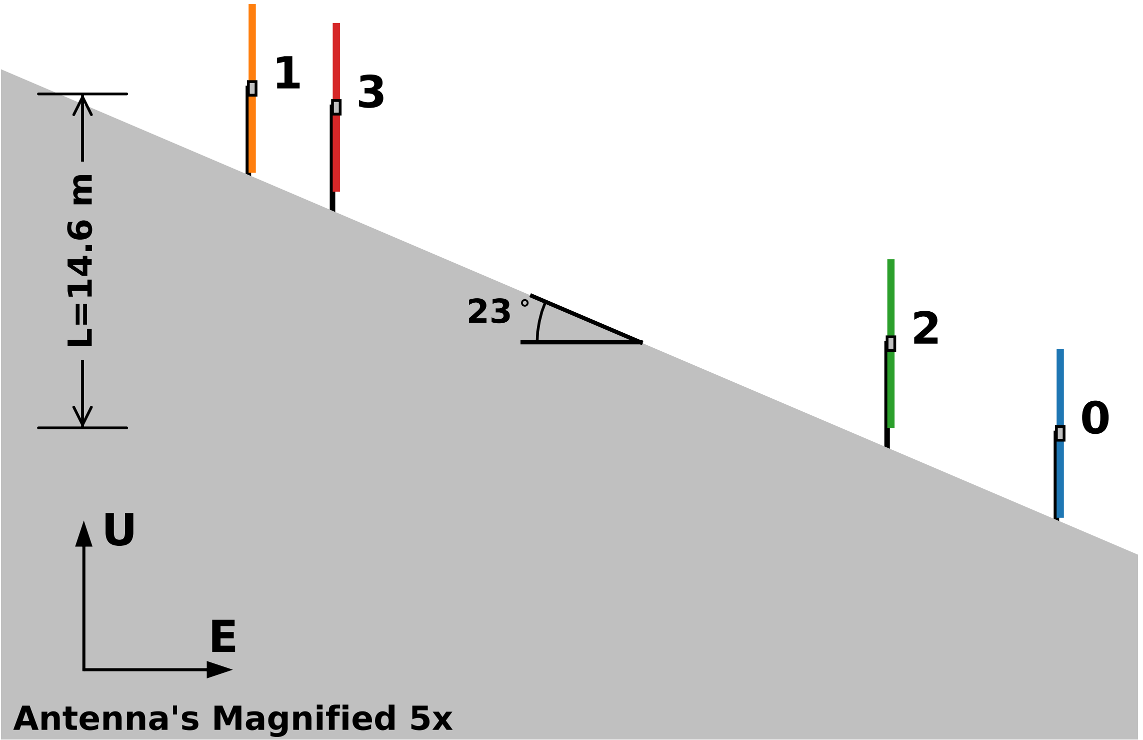
White Mountain Research Station (WMRS)
Barcroft Field Station, California

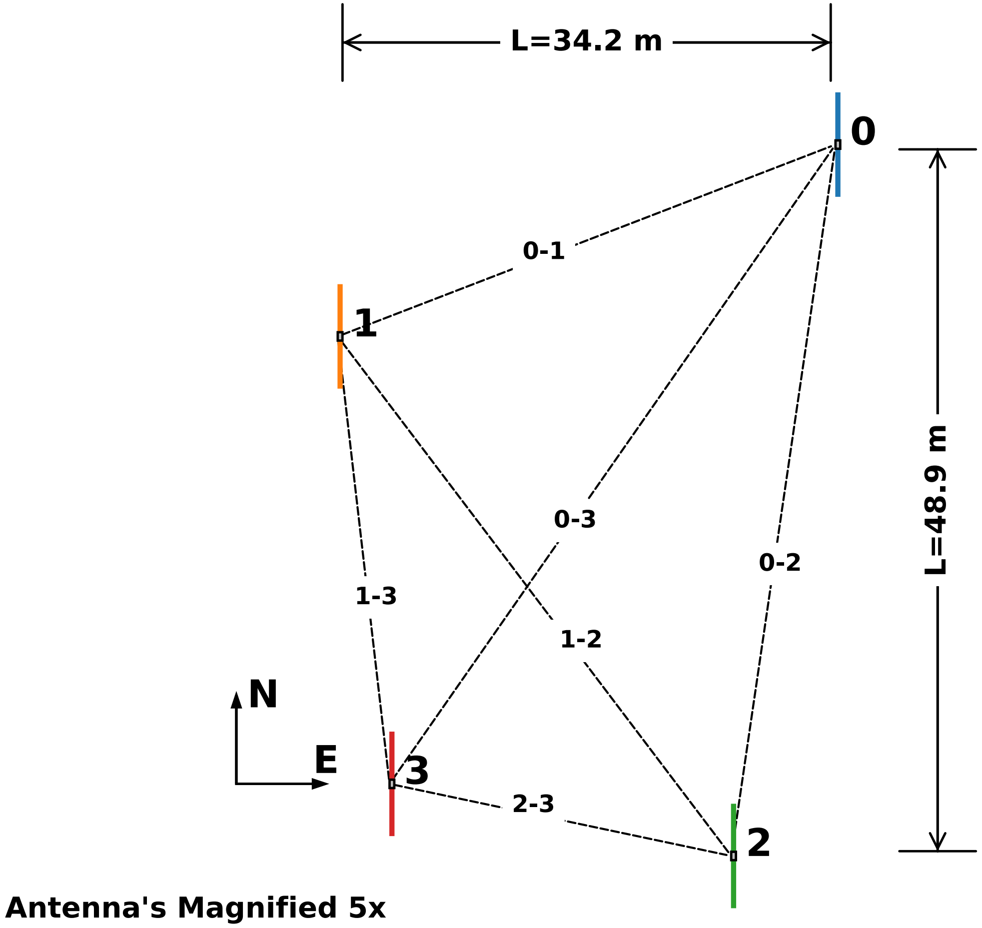
- Accessible, internet, power, amazing staff! (Thanks WMRS Staff!)
- Site has > 2 km prominence to Fish Lake Valley
- Site survey showed indicated site would be suitable for 30-80 MHz

Taken during the June 2021 deployment before new hardware deployed. Taken just west of Antenna mast 3, facing east.

Taken during the June 2021 deployment. Taken just north-east of Antenna mast 0, facing south-west.

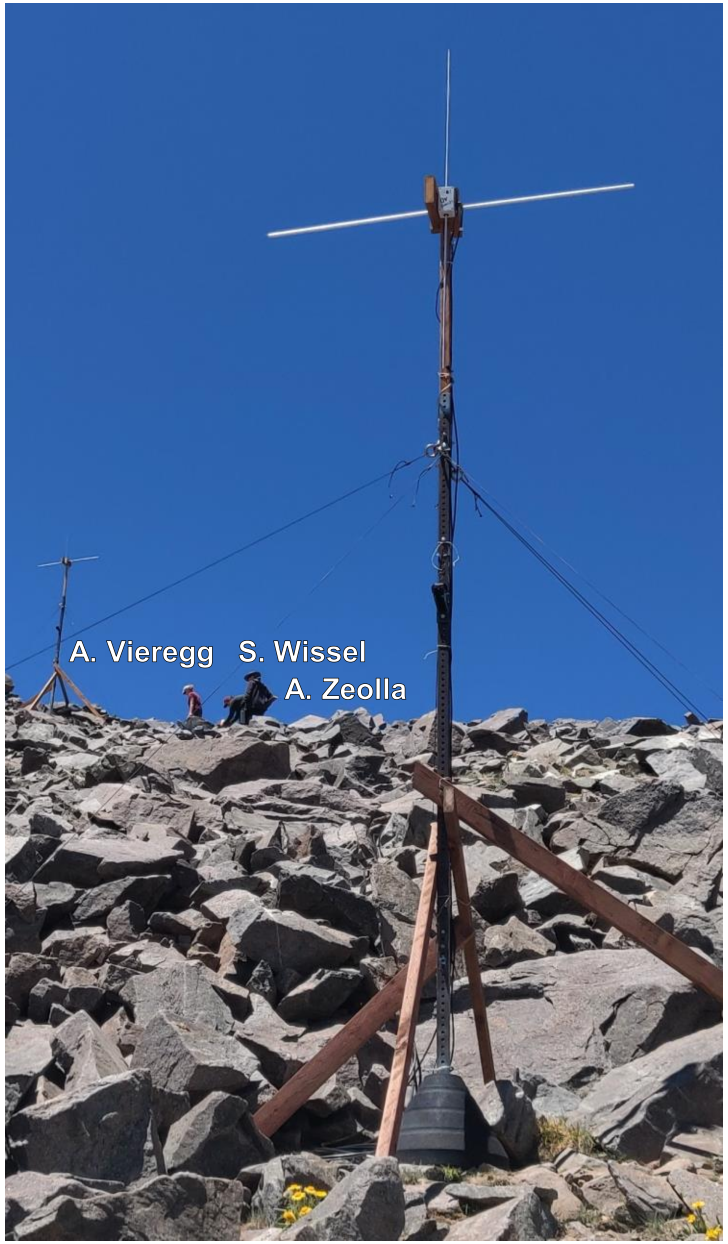
Prototype Layout





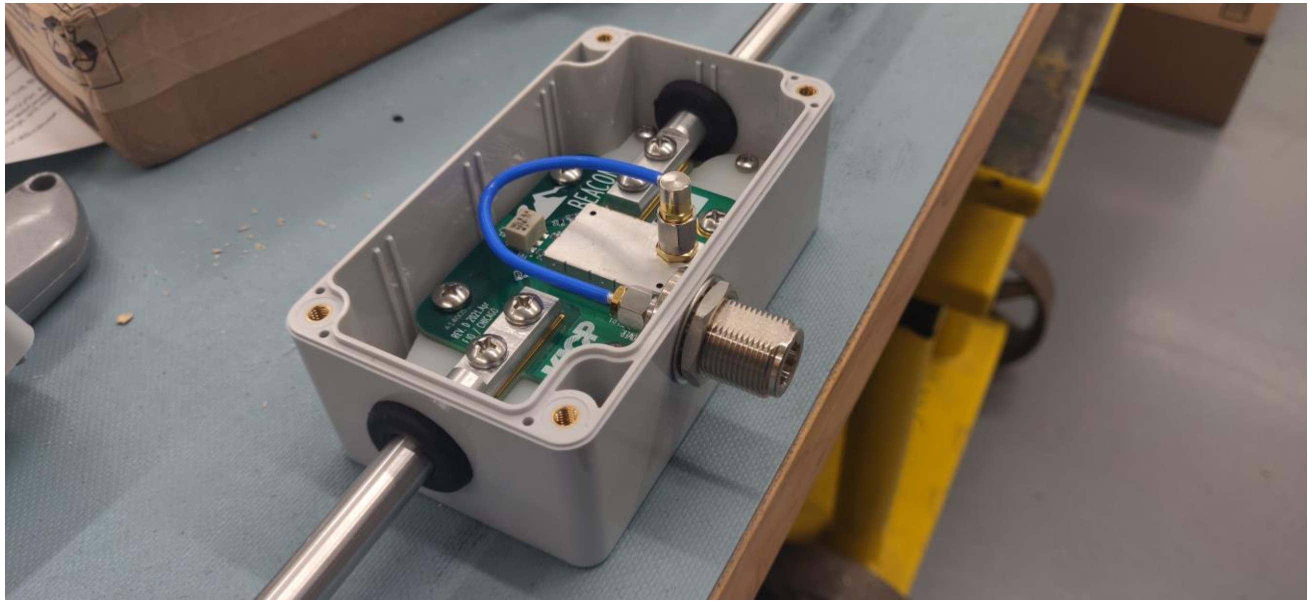
Prototype

- Uses inexpensive custom short dipole antennas (30-80 MHz range)
- A custom feed board contains balun, filters, pre-amp, and signal readout
- Antennas are configured in cross and raised ~3.6 m to minimize impact of the ground on the antenna performance
- Antenna signals amplified in two stages and read out by custom DAQ using a beam forming trigger

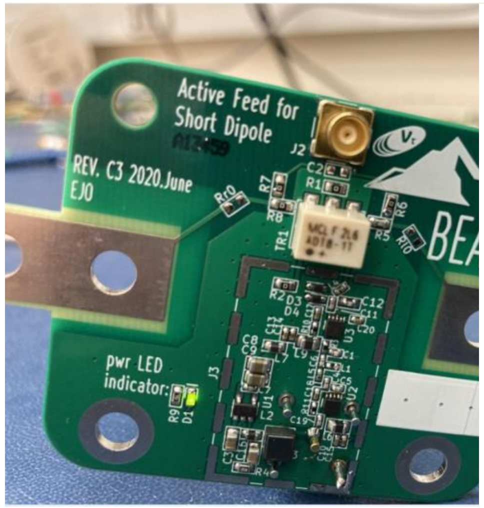


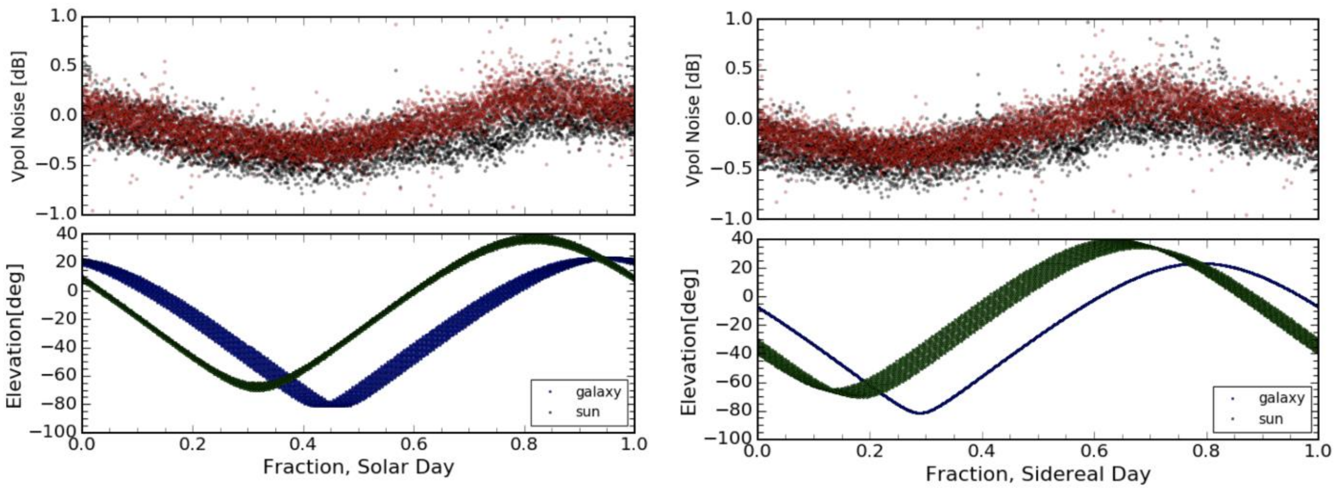
Antennas

- 2018 Deployment used crossed-V dipoles from LWA-OVRO
- 2019 onward have used iterative designs of custom short dipole antennas with active feeds
  - Both high-impedance and balun transformer matching circuits have been tested
  - Each iteration has seen both performance and durability improvements



A short dipole active feed enclosure (open for display). This antenna was installed during the June 2021 deployment.

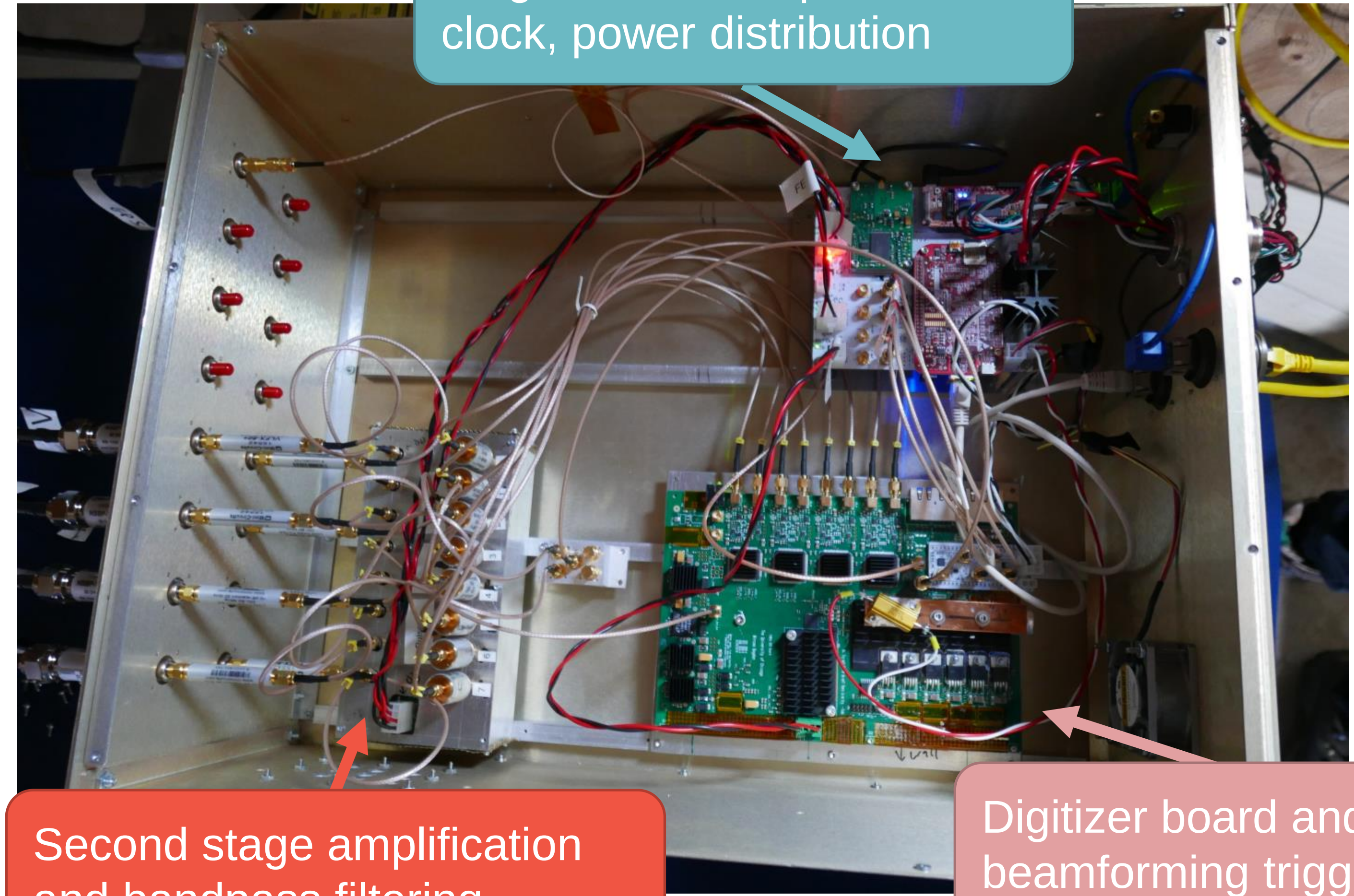




Left: The custom-designed active feed for the BEACON antennas. Right: The root-mean-squared noise measured on the two of the electrically short vertically polarized antennas used in the BEACON prototype in 2020 compared with the elevation of the sun and the galactic center. While the RMS noise is expected to vary with temperature, which is driven by solar heating, the galactic center appears visible to these antennas. Source: Eric Oberla

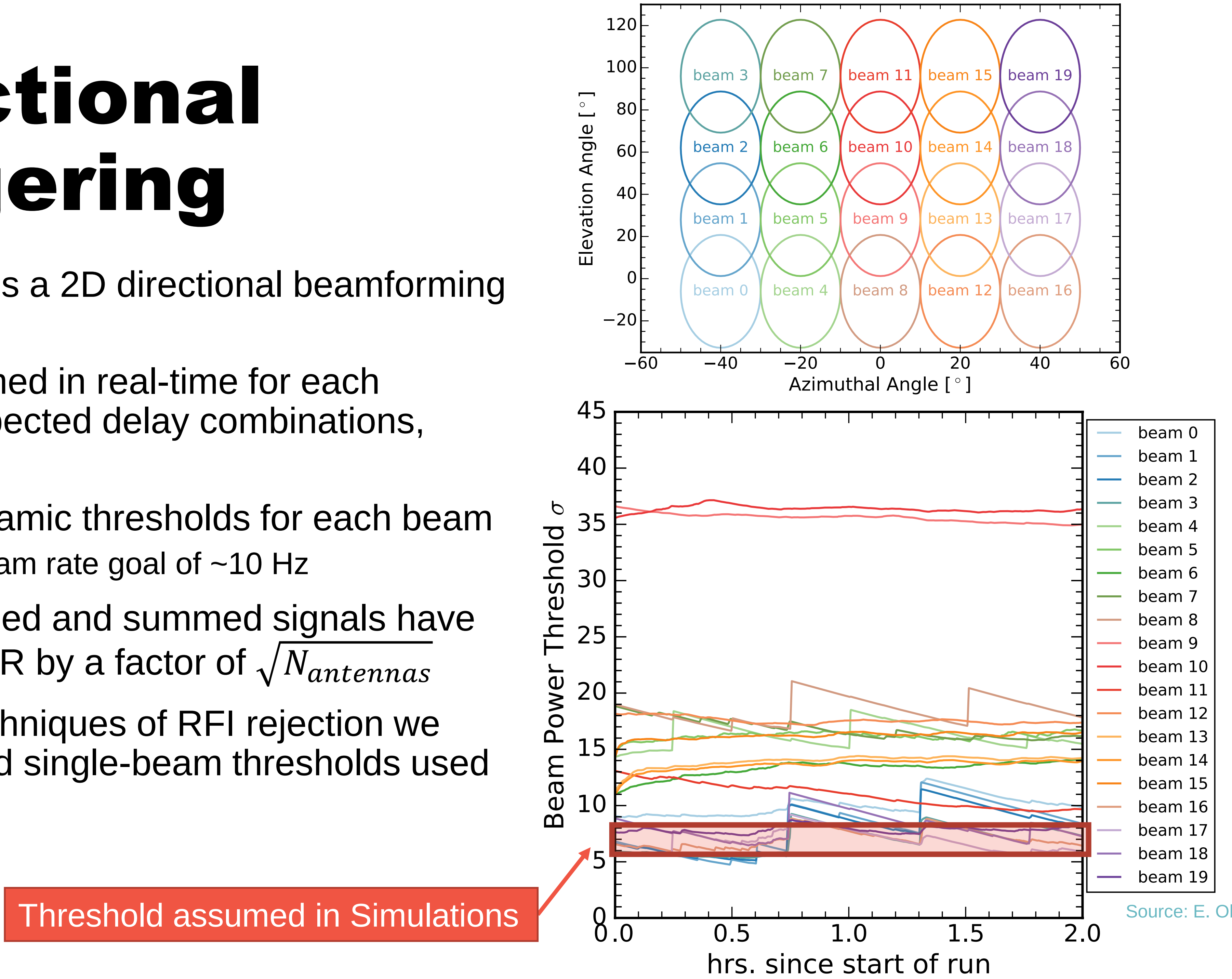
DAQ

- Stored in the observatory, solar powered
- Live monitoring possible for signals, rates, battery charge, temperatures, etc.
- Long live-time: Solar capacity largely outweighs daily usage, resulting in 24/7/365 live time when operational except in extended cloud cover or excessive snow lasting > 5 days
- Current system is ~40 W, will be brought to ~10 W for future autonomous stations



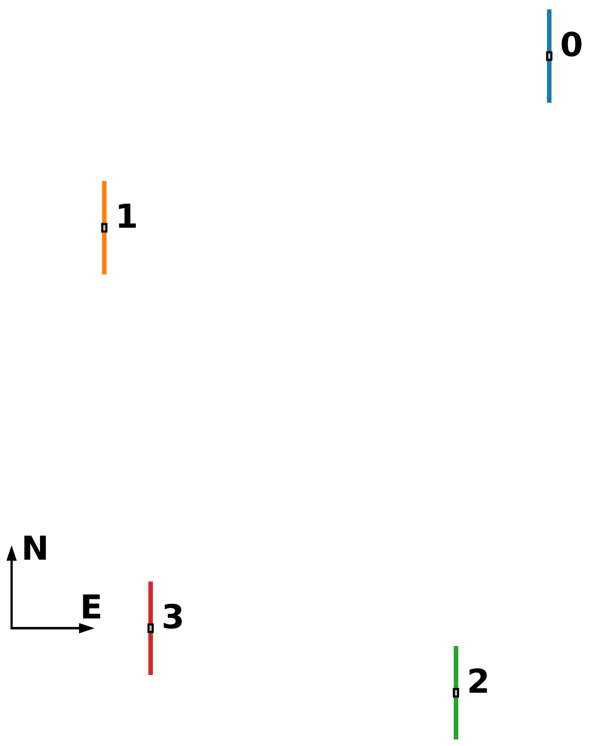
Directional Triggering

- BEACON uses a 2D directional beamforming trigger
- Signals summed in real-time for each directions expected delay combinations, “beam”
- Separate dynamic thresholds for each beam
    - Total all-beam rate goal of ~10 Hz
- Properly aligned and summed signals have enhanced SNR by a factor of $\sqrt{N_{antennas}}$
- With early techniques of RFI rejection we have achieved single-beam thresholds used in simulations

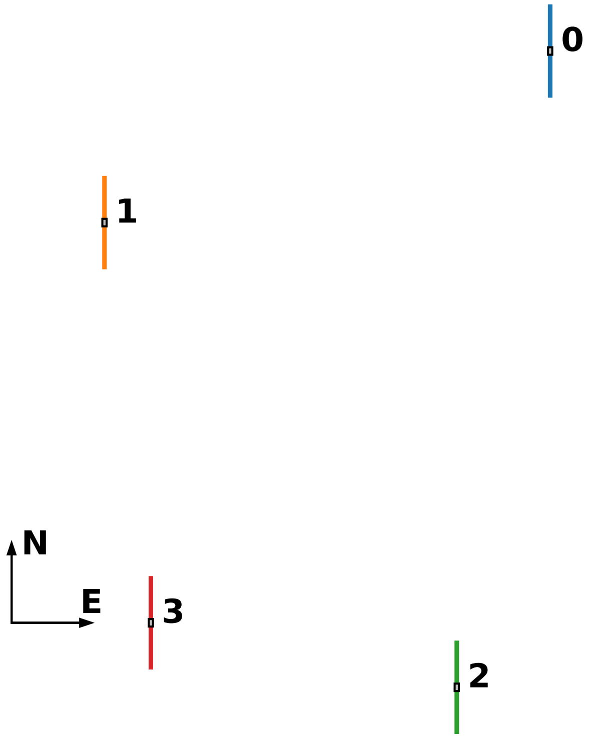


Source: E. Oberla

Calibration Pulsing



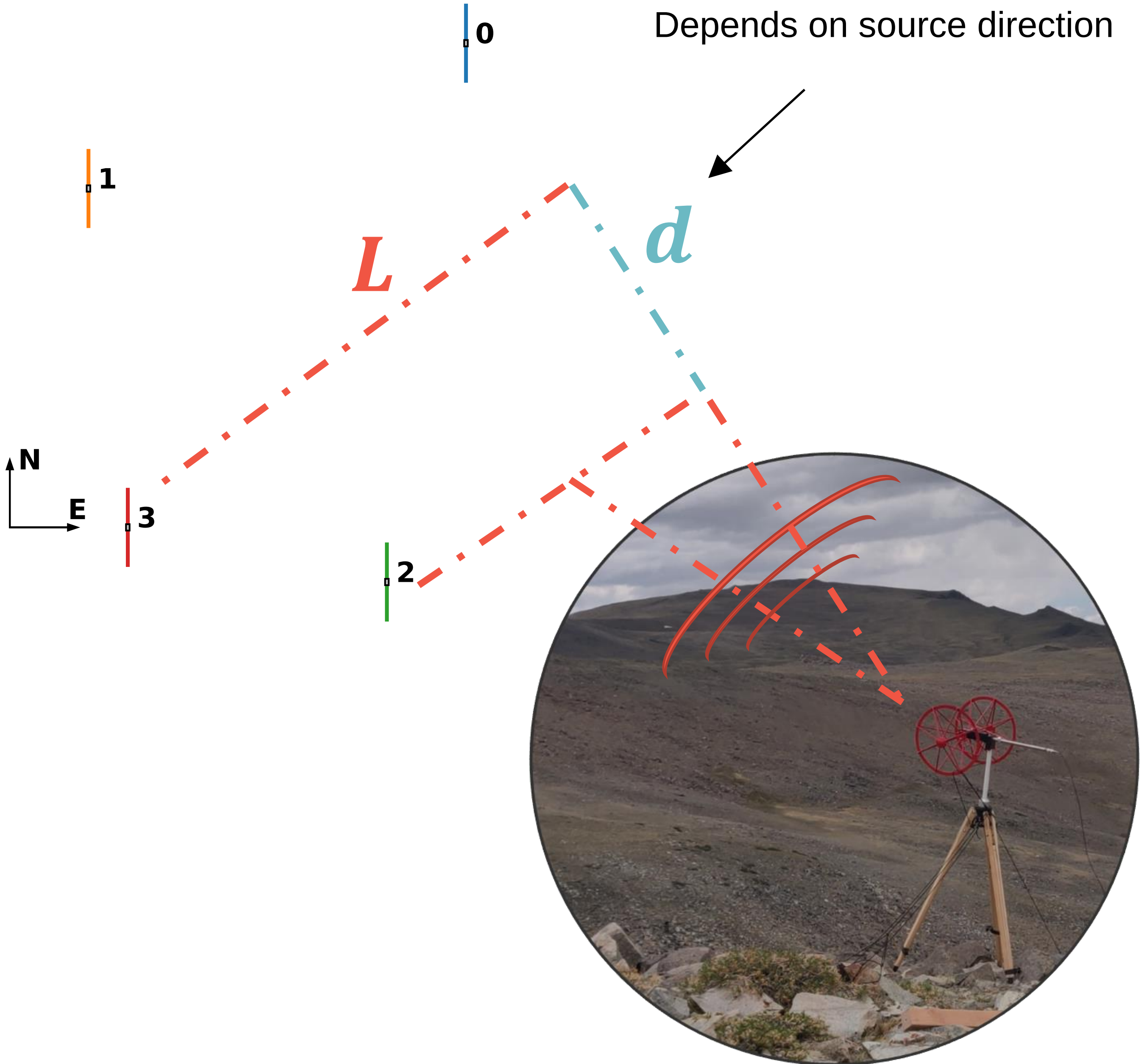
Calibration Pulsing



Calibration Pulsing

Time Delay $(i,j) = \frac{d}{c} + \delta l_{ij}$

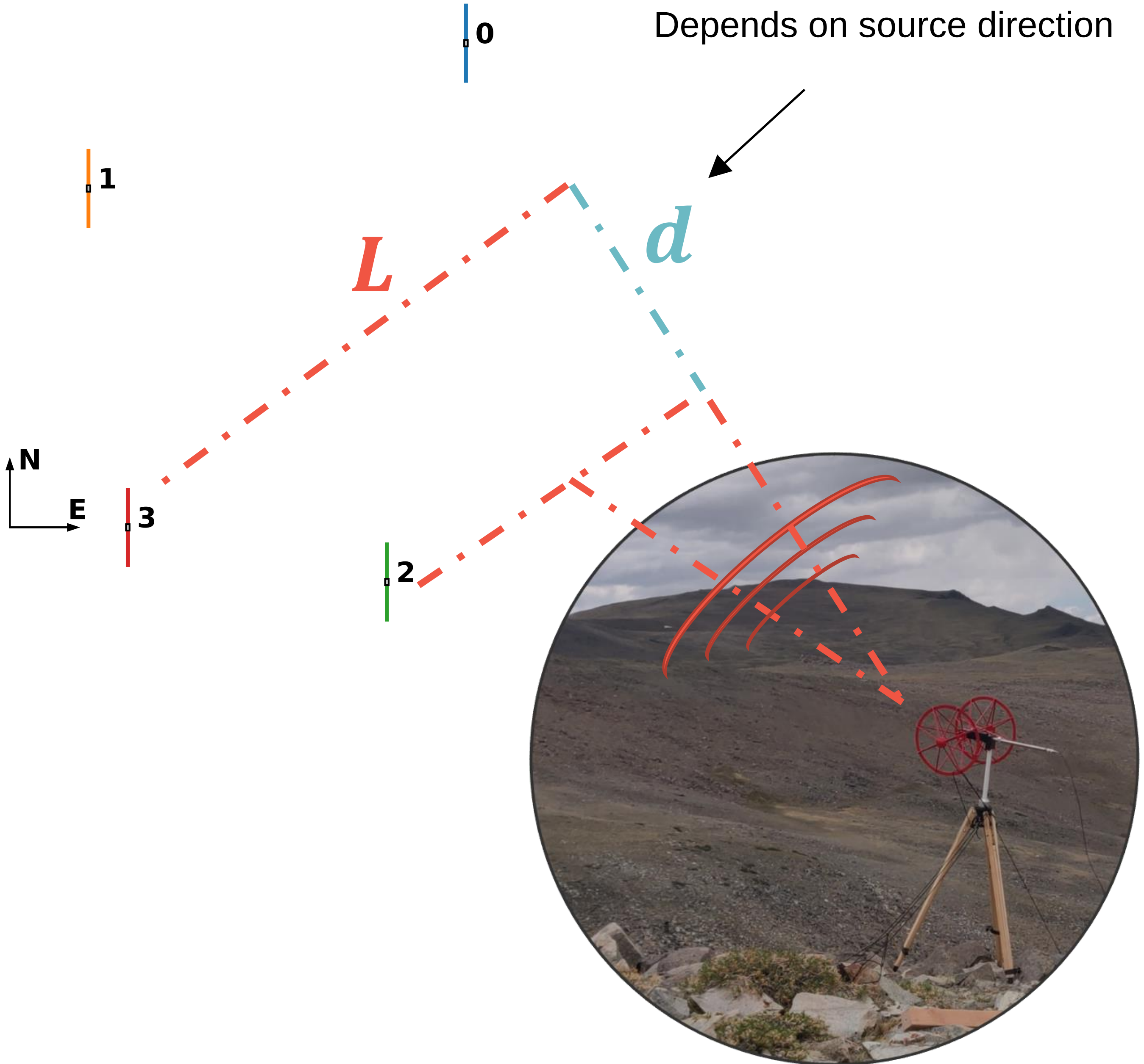
δl_{ij} is the difference in readout cable lengths



Calibration Pulsing

$$\text{Time Delay}\,(i,j) = \frac{d}{c} + \delta l_{ij}$$

Depends on source direction



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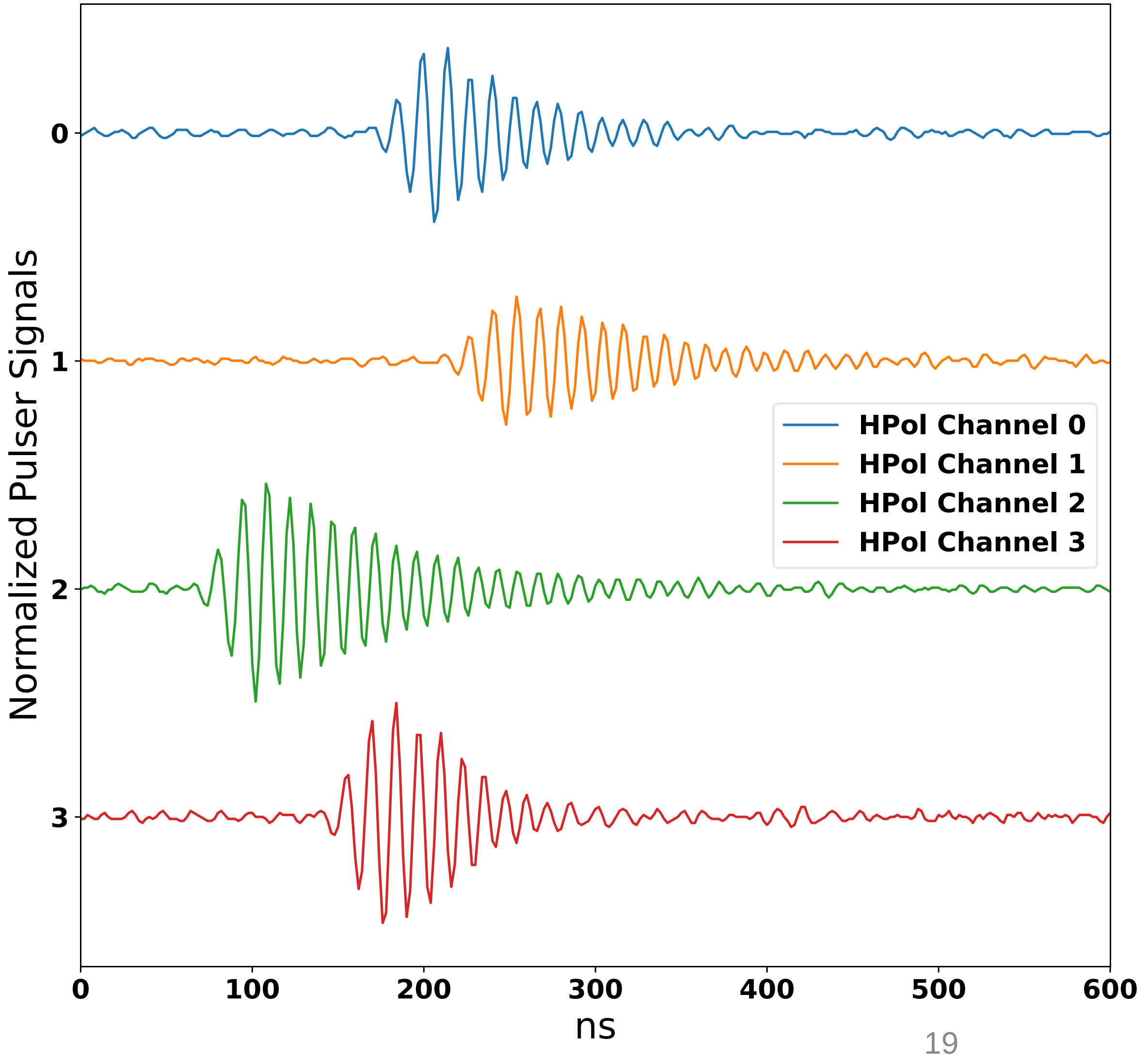
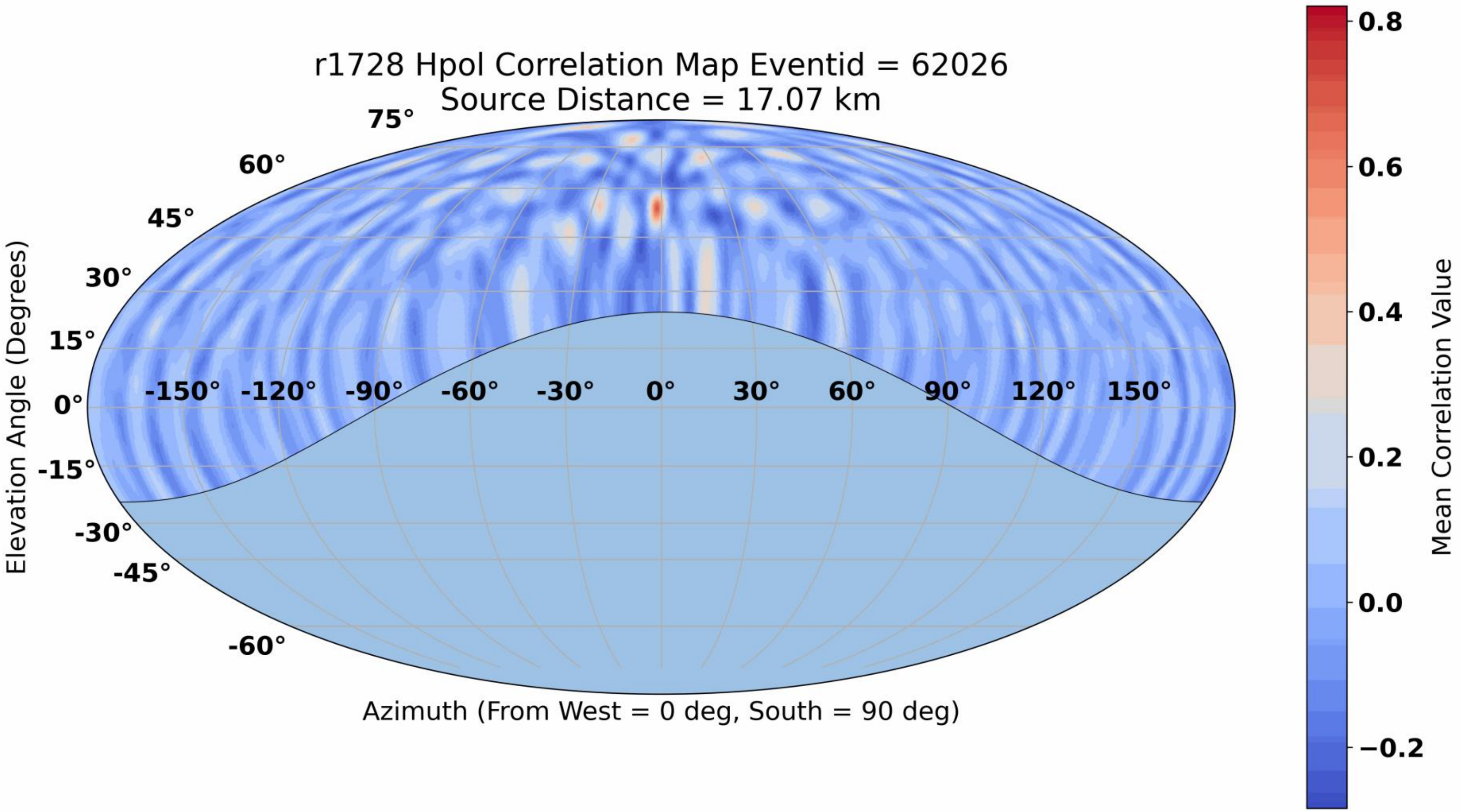


Calibration Efforts

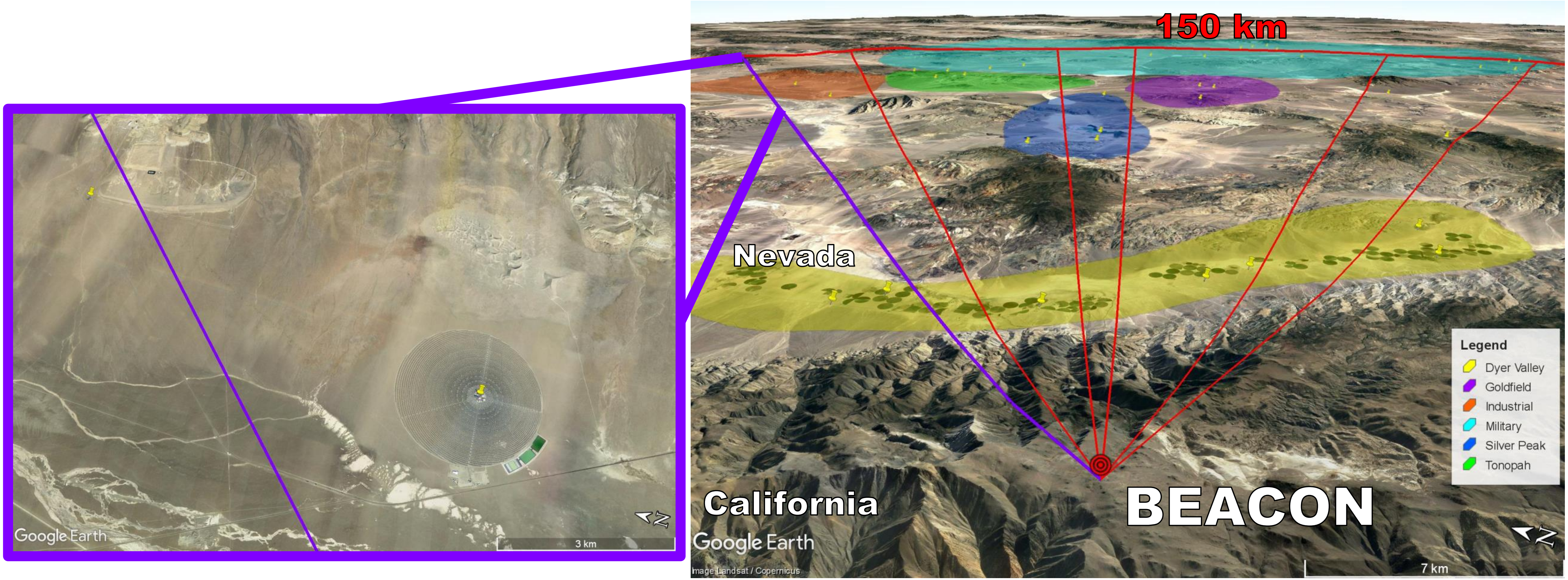
- Pulsing sites chosen in 2019 had large uncertainty, and were ultimately included in χ^2minimizations as free parameters
- Without access to site for refined measurements, both static and transient RFI sources were used as *effective* pulsing sites, each constraining a net 4 degrees of freedom*

*Each source provides 6 time-delay measurements, though from unknown θ and ϕ, reducing net constraining power to 4 degrees of freedom

Airplanes as Self-Triggered RFI



- Airplanes events demonstrate BEACON's ability to trigger on impulsive signals, and can provide additional source information for calibration
- Tracking data can be used to distinguish impulsive RFI from airplanes

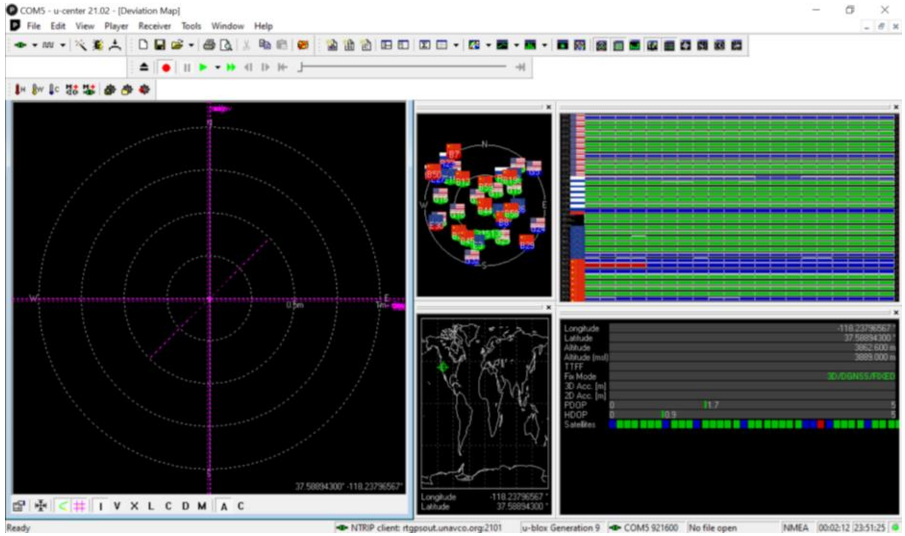


An aerial view map of the visible area from the BEACON prototype site, including directions with some prominent RFI sources (rays), and general area descriptions. An example potential source is highlighted by the purple ray, which is believed to be related to the Crescent Dunes Solar Energy Project (visible in the pop-out image on the left).

Calibration Efforts

- Pulsing sites chosen in 2019 had large uncertainty, and were ultimately included in χ^2 minimizations as free parameters
- Without access to site for refined measurements, both static and transient RFI sources were used as *effective* pulsing sites, each constraining a net 4 degrees of freedom*
- High precision RTK-GPS measurements were made in June 2021 which validated the calibration derived from RFI sources

NTRIP Corrective GPS data provided by UNAVCO GPS Station P652, conveniently installed ~ 30m from our closest BEACON prototype mast

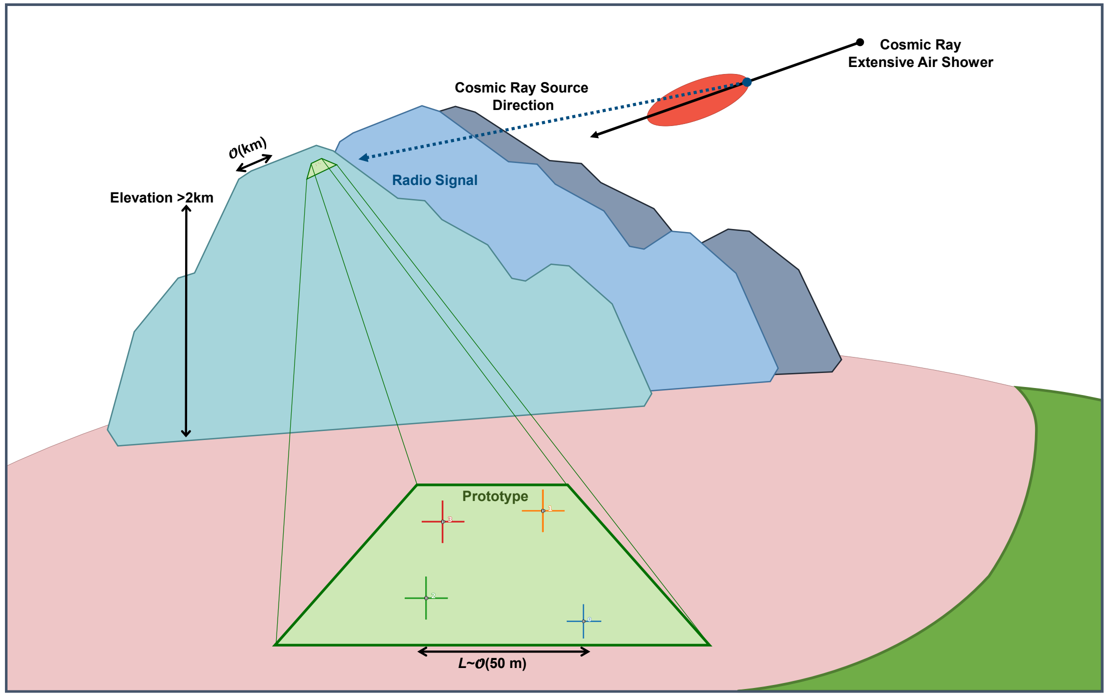


RTK GPS measurements taken using Ublox GPS patch antennas installed on each mast, with data being taken and processed via a Ublox C099-F9P application board and u-center software.

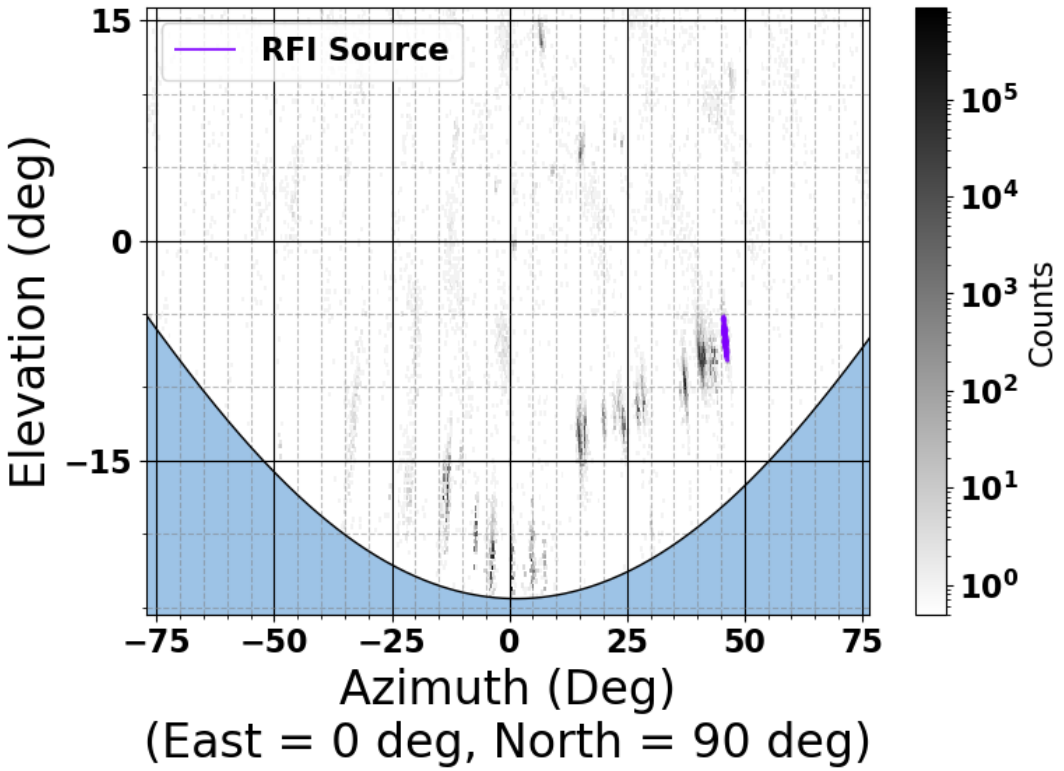
*Each source provides 6 time-delay measurements, though from unknown θ and ϕ, reducing net constraining power to 4 degrees of freedom

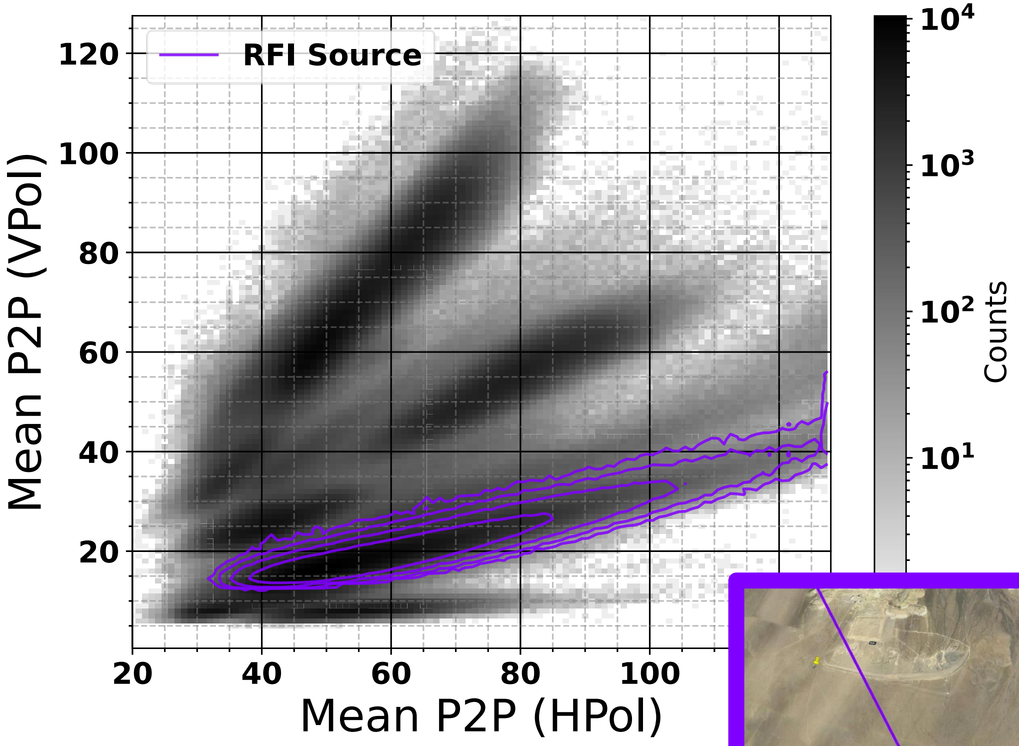
CR Search

- Analysis is ongoing
- Thorough background RFI cuts will be done using:
  - Source direction
  - Spatial and temporal clustering
  - Zenith information (CR’s expected above horizon)
  - Cosmic ray template cross correlations
  - Polarization
  - Etc.
- A framework has been developed to cluster and cut on any N dimensions of this measurable phase space, allowing for of these



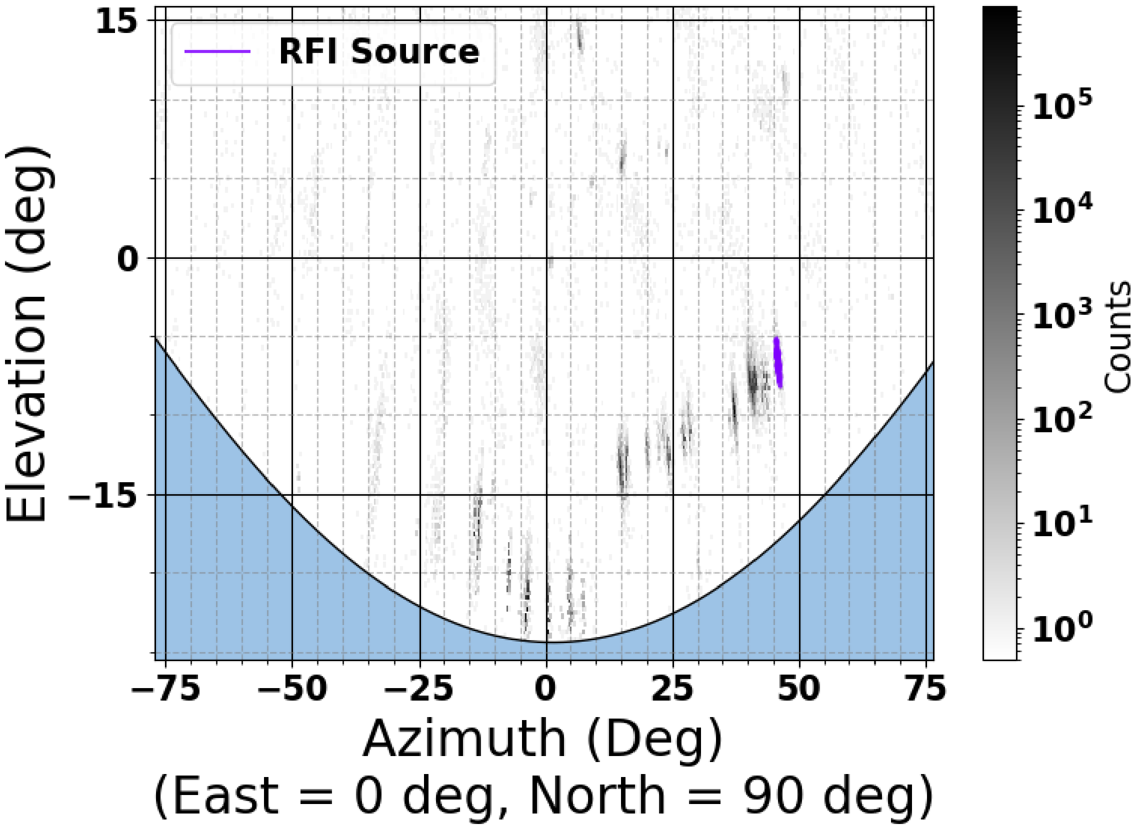
Event Characterization

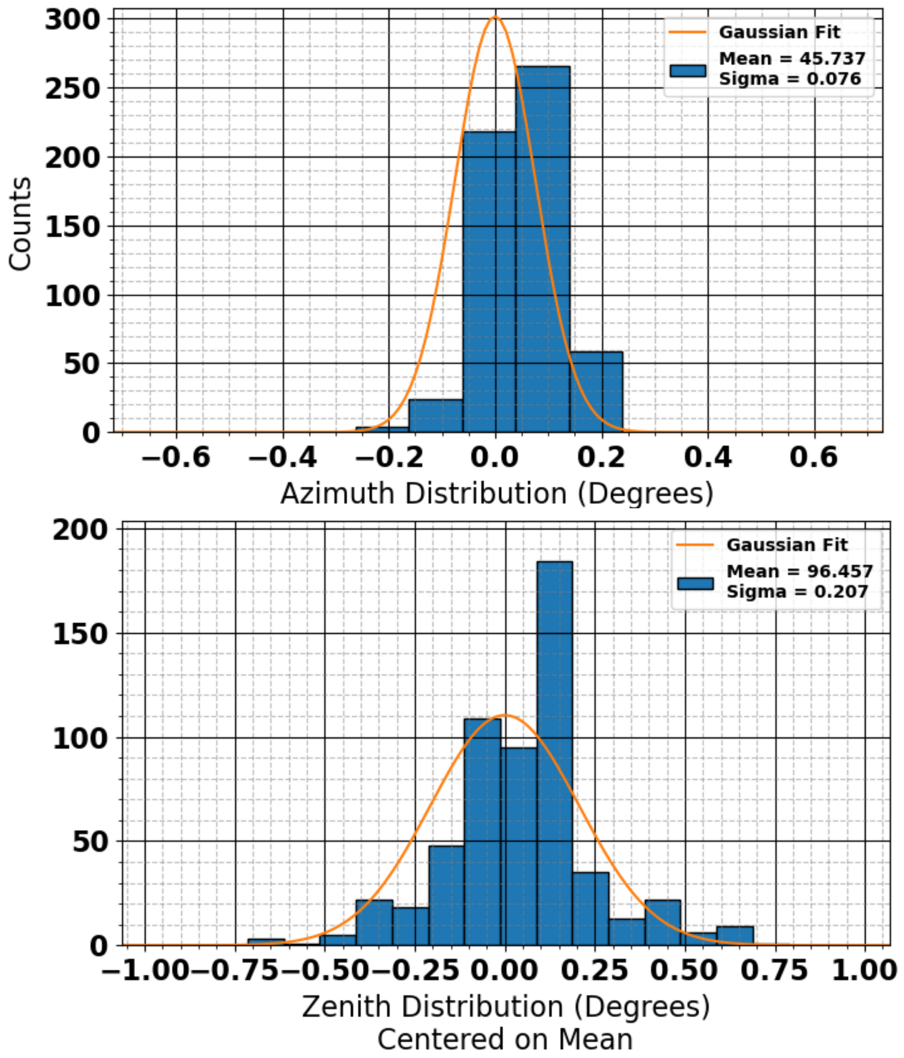




Left: The reconstruction direction of RF triggered events from early runs in the 2019 deployment.
Right: The peak-to-peak (P2P) values of both horizontal and vertical antennas for each event, illustrating clear separation of signal properties for disparate RFI sources.

The Crescent Dunes Solar Project, highlighted as an example of a potential static RFI source





Left: The reconstruction direction of RF triggered events from early runs in the 2019 deployment.
Right: Reconstruction direction histograms for 1 hour of data from the highlighted RFI source shows clear sub-degree precision for pointing near the horizon. The resolution is direction-dependent, with higher precision achievable where longer projected baselines are visible

Achieved Goals

✓ In situ testing of systems with improved mechanical durability and design

✓ Demonstrate directional trigger and low antenna noise

✓ Demonstrate position calibration and resulting pointing capabilities, alongside parameter clustering and RFI rejection techniques

Ongoing Efforts

Analysis:

❑ Cosmic Ray Search

Hardware:

❑ Developments of prototype and planning for full-scale station systems, including plans for future deployment of scintillating detectors

❑ Improve deployment efficiency (drone pulser, site survey kits, etc.)

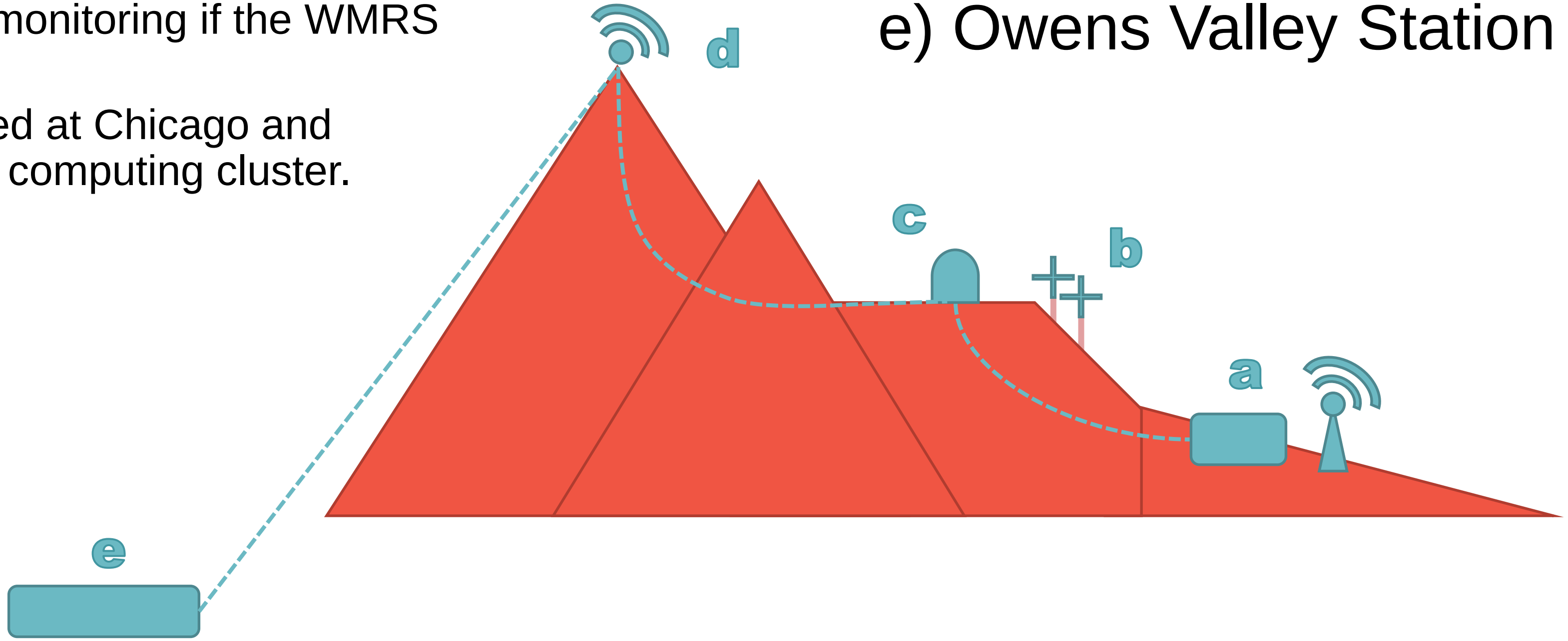
Thanks!

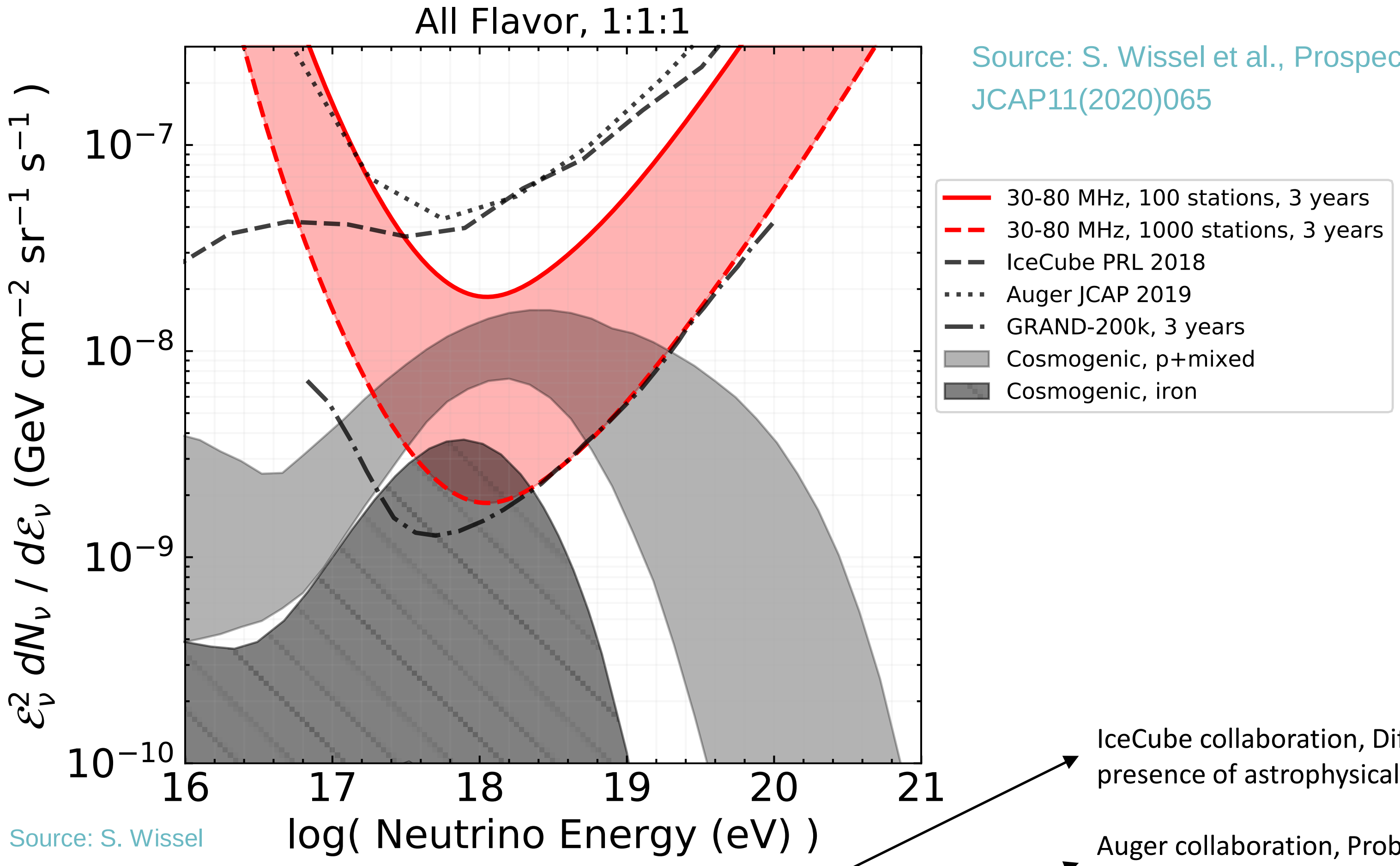
BACKUP

Data Network at Barcroft

- Data taken from antennas at b) are digitized by the DAQ at c), before being sent to an archive computer at a).
- Barcroft a) is connected to internet through a ground cables connecting the station and White Mountain summit d), which has a communication link to e).
- As a backup system we installed a cellular connection at a) which can be used for emergency monitoring if the WMRS network goes down.
- Data is transmitted offsite and stored at Chicago and processed using the Midway super computing cluster.

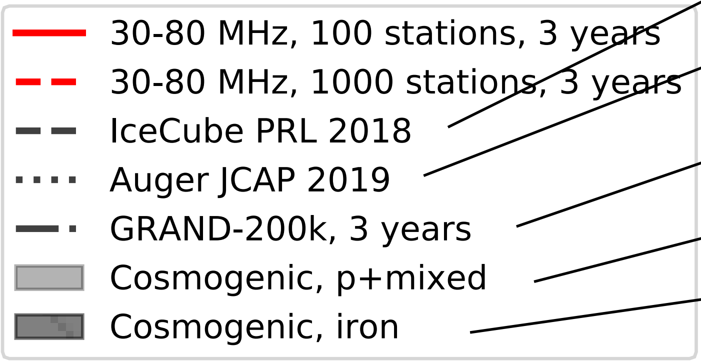
a) Barcroft Station
b) Antenna Array
c) Observatory Dome
d) White Mountain Summit
e) Owens Valley Station





Source: S. Wissel et al., Prospects for High-Elevation Radio Detection of >100 PeV Tau Neutrinos JCAP11(2020)065

Source: S. Wissel



IceCube collaboration, Differential limit on the extremely-high-energy cosmic neutrino flux in the presence of astrophysical background from nine years of IceCube data, Phys. Rev. D 98 (2018) 062003.

Auger collaboration, Probing the origin of ultra-high-energy cosmic rays with neutrinos in the EeV energy range using the Pierre Auger Observatory, JCAP 10 (2019) 022 [1906.07422].

GRAND collaboration, The Giant Radio Array for Neutrino Detection (GRAND):science and design, Sci. China Phys. Mech. Astron. 63 (2020) 219501 [1810.09994].

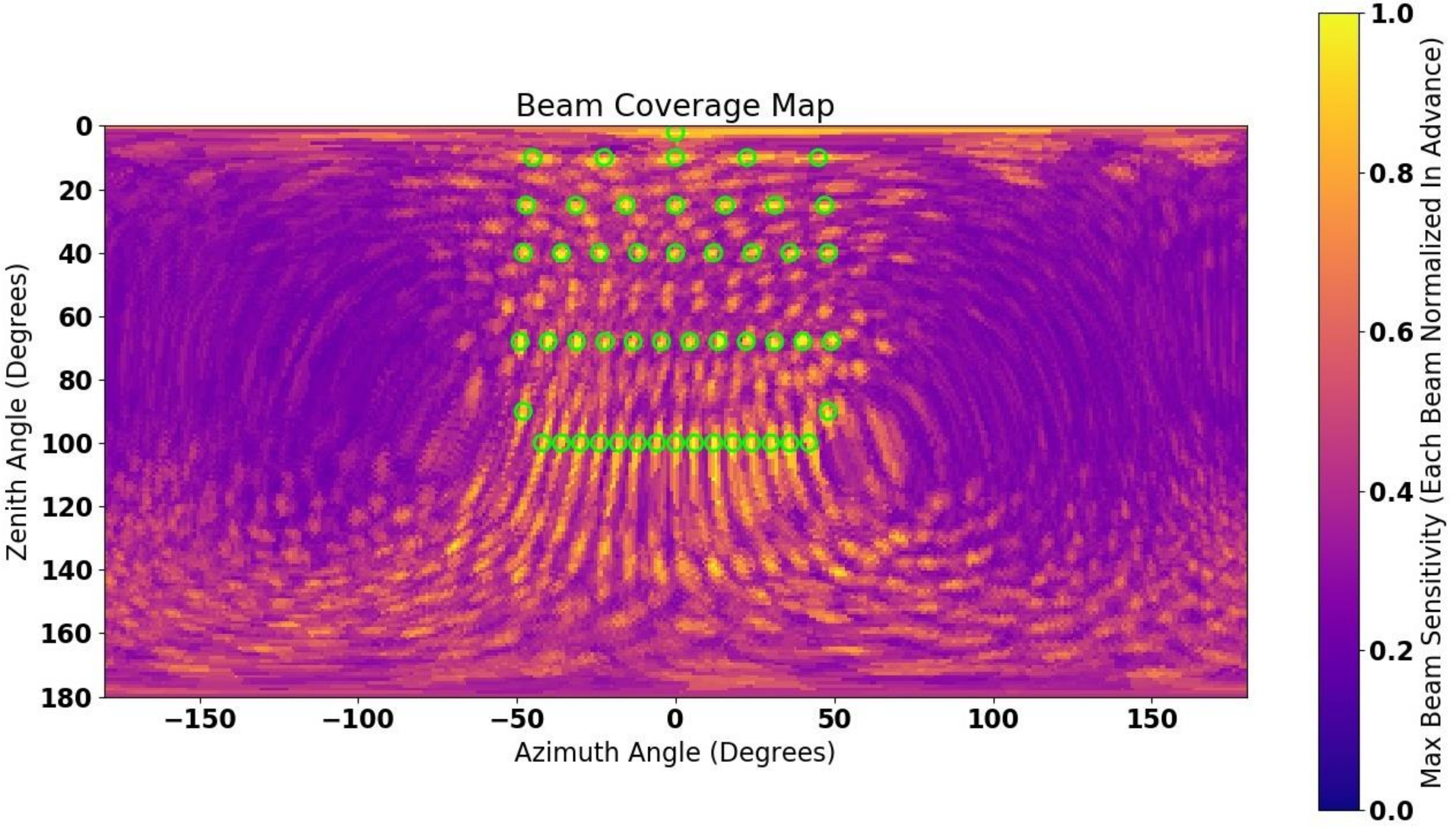
K. Kotera, D. Allard and A. V. Olinto, Cosmogenic neutrinos: parameter space and detectability from PeV to ZeV, JCAP 1010 (2010) 013 [1009.1382].

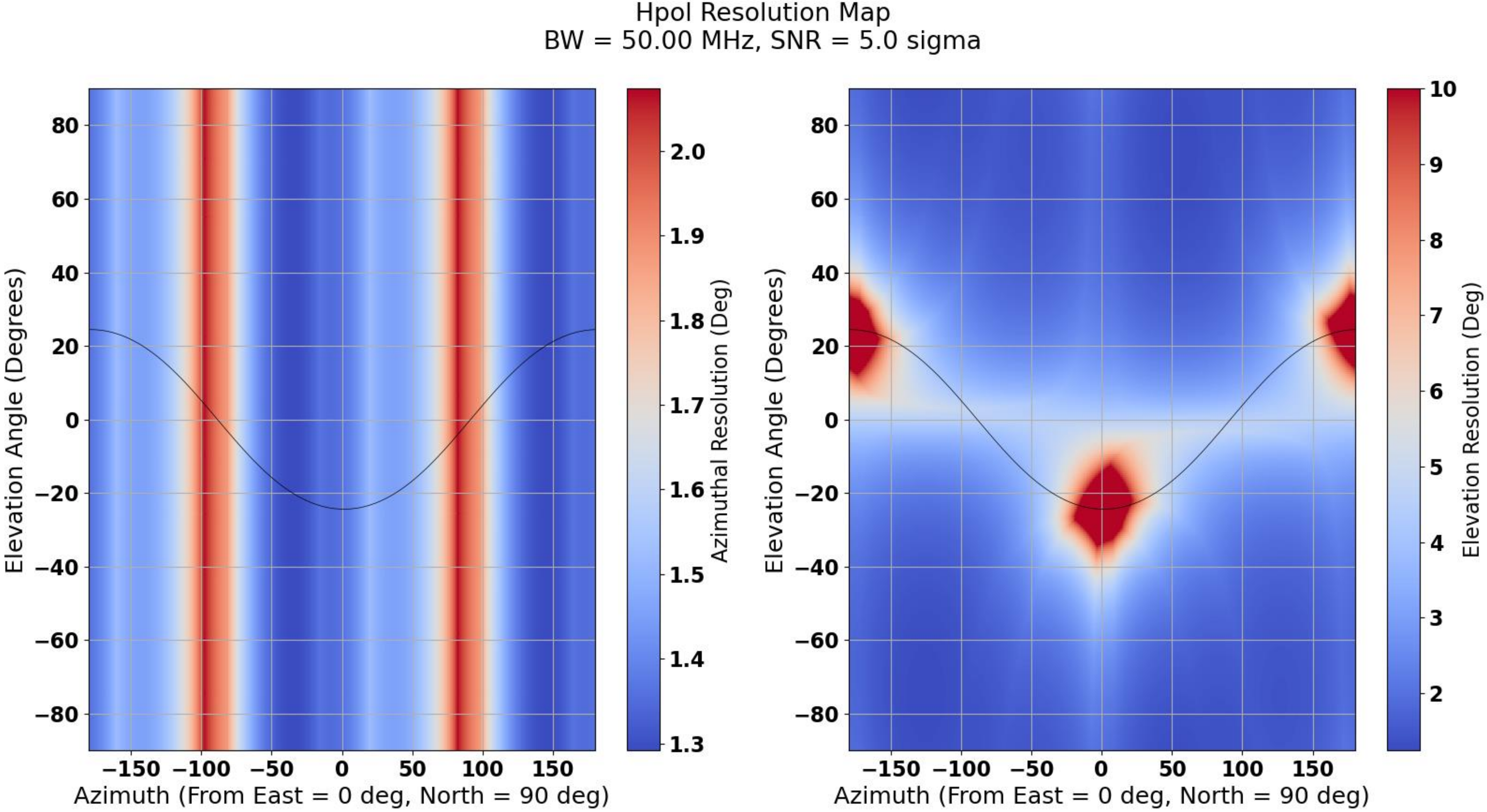
K.-H. Kampert and M. Unger, Measurements of the cosmic ray composition with air shower experiments, Astropart. Phys. 35 (2012) 660 [1201.0018]

Proposed Beams

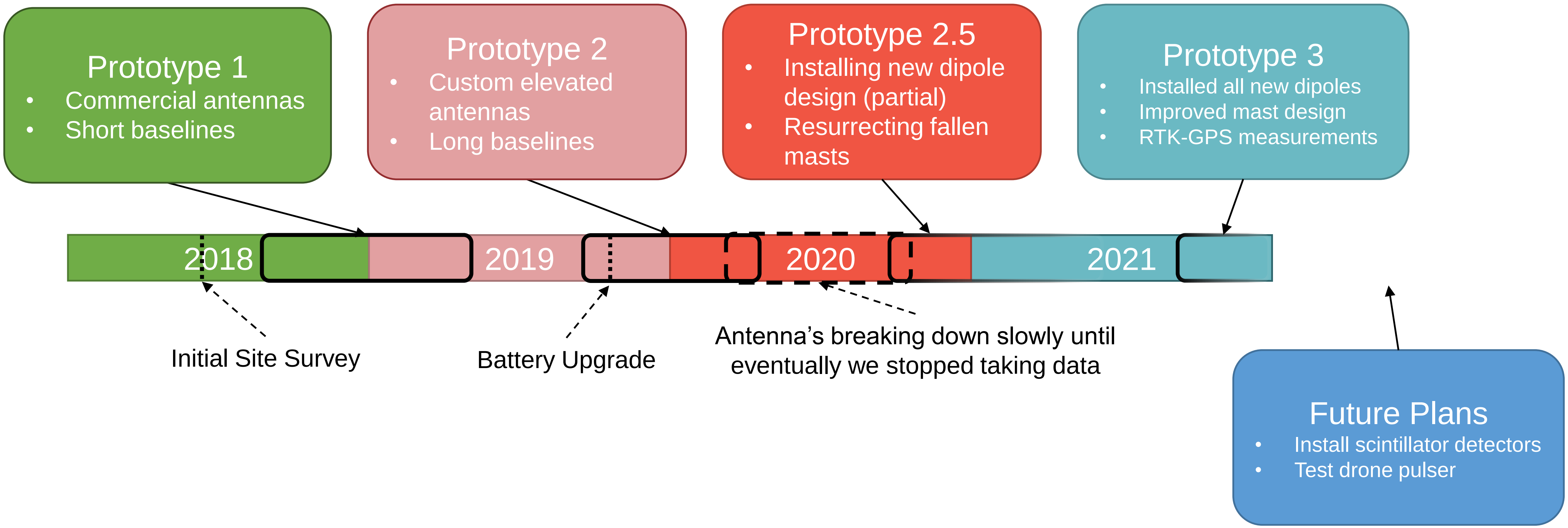
The plot on the right shows the resulting sensitivity for beams centered on each of the green circles. This was created assuming a limit of 51 beams, and a desired viewing angle trigger area from -50→50 in azimuth, and 0 → 110 in zenith.

With only four antennas at long baselines, beams are quite narrow and have prominent sidelobe contributions. As the number of antennas goes up (with some resulting in shorter baselines) the beams can be tweaked to cover more reasonable angular areas, with smaller sidelobe contributions.





Theoretical calculations using simplified BW and SNR, where $d\theta \approx \frac{c}{L} \cdot \mathrm{SNR} \cdot \mathrm{BW}$ where L is the longest projected baseline from that perspective



Prototype 1
Commercial antennas
Short baselines
Prototype 2
Custom elevated antennas
Long baselines
Prototype 2.5
Installing new dipole design (partial)
Resurrecting fallen masts
Prototype 3
Installed all new dipoles
Improved mast design
RTK-GPS measurements
2018
2019
2020
2021
Initial Site Survey
Battery Upgrade
Antenna’s breaking down slowly until eventually we stopped taking data
Future Plans
Install scintillator detectors
Test drone pulser

Zoom Camera Location