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Towards Interferometric Triggering on Air Showers Induced by Tau Neutrino Interactions

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The Beamforming Elevated Array for COsmic Neutrinos (BEACON) Experiment aims to implement a new interferometric trigger targeting air showers initiated by the decay of tau leptons created during neutrino interactions in the earth at energies greater than 100 PeV. Over the past decade, interferometric techniques have been successfully implemented in analysis for many of the leading UHE particle experiments. BEACON has included interferometry at the trigger level, by implementing a beamforming technique in which signals are coherently summed, improving overall sensitivity and providing robust rejection against man-made backgrounds. A two-antenna short-term interferometer and a four-antenna long-term interferometer, both targeting the 30-80 MHz range, were installed on White Mountain near Bishop, California, as part of a months-long site study of man-made backgrounds and rates. Successfully suppressing man-made backgrounds will lead future iterations of BEACON to trigger on both cosmic rays from above and tau lepton air showers from tau neutrino interactions near the horizon.

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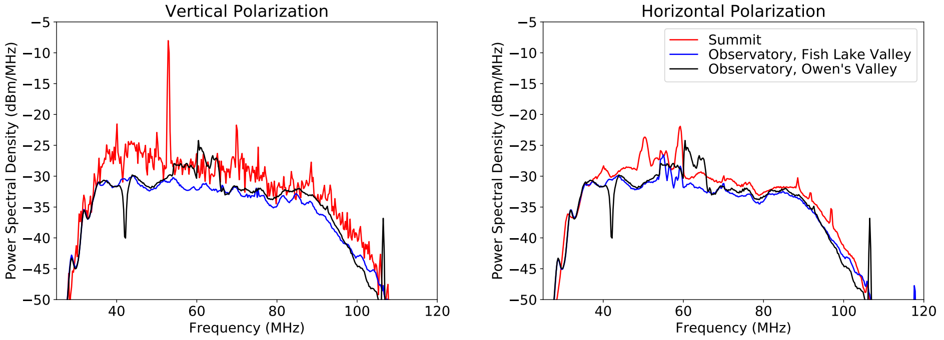
1. Motivation

Detecting neutrinos with energies above 100 PeV is the crucial next step towards understanding both the cosmogenic neutrino production mechanisms and the diffuse astrophysical neutrino flux at the highest energies [1]. While experiments such as IceCube have directly measured neutrino events up to energies of nearly 10 PeV, higher energy neutrinos have thus far been elusive [2, 3, 4, 5]. One feasible detection mechanism for tau neutrino interactions requires building a radio detector sensitive to radiation from both cosmic ray air showers and upward going tau lepton-induced showers caused by tau neutrino interactions in the Earth.

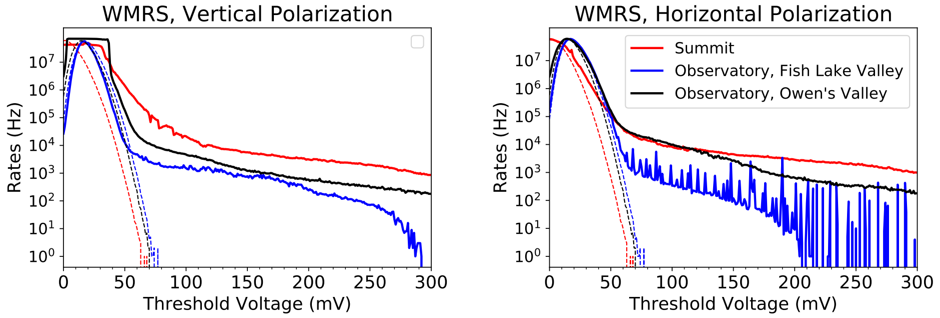
Called the Beamforming Elevated Array for COsmic Neutrinos (BEACON) Experiment, this project would be the first to implement an interferometric trigger on a project searching for tau-lepton induced showers. This type of trigger enables both efficient radio detection in the presence of anthropogenic backgrounds, and a high duty cycle compared to optical air shower detectors. BEACON also benefits from high-elevation stations that enhance the acceptance of tau lepton showers.

The interferometric triggering technique has recently been demonstrated as part of the Askaryan Radio Array experiment [6]. Here, we report on the deployment of an interferometric trigger as part of a year-long, BEACON prototype system, while also thinking ahead about the feasibility of a future larger-scale BEACON experiment.



(a) Spectra from Vertical Polarization. The summit shows a single spectral run, while the observatory shows the averages of 50 spectra.

(b) Spectra from Horizontal Polarization, averaged over 50 spectra.



(c) Rates from Vertical Polarization.

(d) Rates from Horizontal Polarization.

Figure 1: Spectra and Rates from White Mountain Site Study.

2. White Mountain Site Study

The Barcroft Research Station [7] on White Mountain in California was chosen as a potential site due to its high elevation, existing power infrastructure, extensive views into both Owens Valley to the West and Fish Lake Valley to the East, and its proximity to collaborators at many California institutions. The Observatory site at WMRS, which includes a longer mountain ridge, reaches a prominence over the Owen's Valley of 2.6 km and of 2.4 km over the Fish Lake Valley. The Summit site at White Mountain Peak is 466 m higher than the Observatory.

Electrically-short bicone antennas (ETS-Lindgren 3180C), sensitive from 30-1000 MHz, were used to measure the local radio-frequency interference (RFI). Filters selected two frequency ranges: 30-90 MHz and 200-1200 MHz. Signals were amplified in two stages with an overall gain of 79.5 dB and noise figure of 1.5 dB for the lower frequency band. The higher frequency band was amplified with gain of 79.5 dB at 200 MHz, linearly falling to 64 dB across the band and with a noise figure of 2 dB. Regular CW pulse packets at 42.5 MHz dominated the spectrum, so a notch filter was applied using a tunable tank filter. Previous internal studies from the valley indicated that the 30-80 MHz band was the quietest; this was confirmed with the following measurements.

A spectrum analyzer was used to measure the local continuous wave (CW) spectra in 0.2 s intervals. The average of 50 such measurements is shown in Figure 1. The power in the band from the East was lower than in the West by nearly 10 dB in some instances. The power in the horizontal and vertical polarizations were on average the same, with the exception of high powered spikes in the horizontal polarization between 55-60 MHz to the East, and 60-65 MHz to the West. Broad-spectrum RFI was observed in the UHF over 50-100 MHz bands; less than 400 MHz total bandwidth was consistent with the expectation from thermal backgrounds, making the band effectively unusable at this site for triggering [8]. Additionally, the spectrum at the Summit site contained the most RFI across the band.

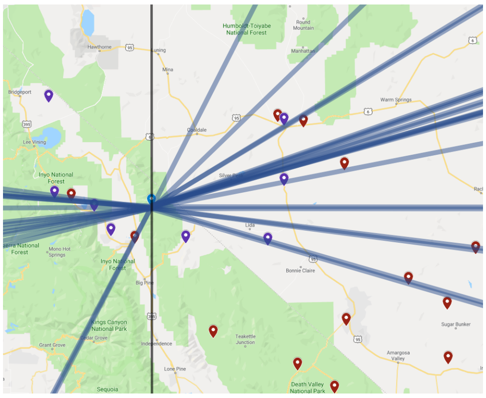


Figure 2: A map of the source directions as found by the single baseline interferometer. Lines to the left of center represent data taken while the interferometer was placed overlooking the West Valley, and lines to the right are from the East.

Additionally, a pulse counter was used to measure the rates of impulsive, transient pulses. The rates measured were compared to a terminated input, a proxy for thermal noise. From Figure 1, the rates in either the East or the West Valley are much higher than the terminated input at 10 Hz. Thus, the trigger must reduce the transient backgrounds by at least a factor of 1000.

The results of this site study confirmed that the BEACON prototype should overlook Fish Lake Valley to the East, as the spectra was cleaner and the transient rates were lower than in Owens Valley and that the Observatory site is better than the Summit site. However, even in the case of an East facing array, significant vetoing capabilities must be built into the trigger to reject anthropogenic RFI. The year-long interferometer described below details the development of such a system.

3. Interferometry Studies

Two different interferometry studies were conducted on White Mountain: first, a two-day long, single baseline interferometer; and second, a year-long, four-antenna interferometer with a phased array trigger, referred to here as the BEACON prototype. This section describes each in detail.

3.1 A Two-Antenna Short Term Interferometer

The bicones used for the site study were reused here to create a short term, single basline interferometer, with filters selecting the 30-80 MHz range. The interferometer was placed two separate times, once overlooking the West valley and once overlooking the East. Each antenna was at approximately the same height, causing the time difference between each antenna to be directly related to the azimuthal angle at which the signal arrived. Because there are only two antennas, the source could equally be reconstructed on either side of the antenna pair. However, here the source direction was chosen as the solution that pointed back out towards the valley at the time. This choice was due to the placement of the bicones down the ridge of the mountain, obscuring the view from the opposite valley.

Waveforms were recorded in varying time windows, with the longest being 20 ms, sampled at 0.4 ns. These were then broken into smaller time windows and analyzed for pulses using cross correlation. Pulses that were identified could then be used to calculate the arrival angle. This was done for all pulses for both Owens Valley and Fish Lake Valley.

In Figure 2, some source arrival directions do correlate with known locations of local towns and airports. Additionally, expected background rates were extrapolated from this data set; for a thermal event rate of 1-100 Hz, the expected background rate is 250 Hz. This presents a clear challenge to design a experimental system capable of rejecting a high level of RFI contamination.

Figure 3: View of BEACON prototype from above the mountain ridge. Antennas were camouflaged to minimize environmental impact.

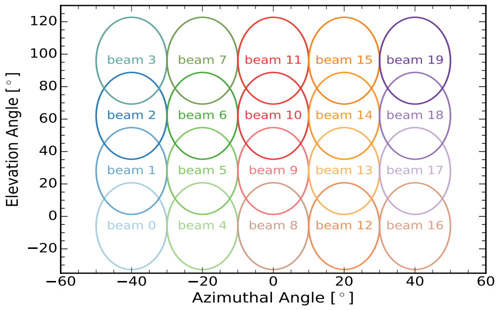


Figure 4: Approximate beam directions of the BEACON prototype. Here due East corresponds to 0 °Azimuth.

3.2 The BEACON Prototype: A Four-Antenna, Year-Long Interferometer

Following the White Mountain Site Study, a four-antenna station was set up facing the Fish Lake Valley. The antennas chosen for the BEACON prototype were inverted-V cross dipole antennas, as shown in Figure 3, also used as part of the Long Wavelength Array (LWA) experiment at the Owens Valley Radio Observatory [9]. This antenna was chosen for its sensitivity to 30-80 MHz frequencies, as well as its active balun that includes conversion to a coaxial cable line and 35 dB of amplification [10].

Each antenna was installed on the slope of White Mountain along a 20° gradient. However, the beam pattern greatly favors signals coming from directly above the antenna; though installing the antennas on a slope of 20° improves the response at the horizon slightly, there is still a loss of 5-7 dB. Current development work is being done to improve the antenna design for future iterations.

Additionally, the BEACON prototype was equipped with a phased array trigger system, using the same underlying framework as the interferometric trigger designed and deployed as part of the ARA5 station [6]. By pre-arranging sets of time delays into beams that each cover areas of the field of view, waveforms can be coherently summed in each beam prior to the trigger. This has two main advantages. One: the system is more sensitive to low-power impulsive signals that may not have met a traditionally set power threshold, but can meet a threshold after being coherently summed. Two: each beam can be given its own rate goal, which will lead to independently determined trigger thresholds depending on the RF content of that beam. The BEACON prototype system has a total of 20 beams, with approximate directions shown in Figure 4.

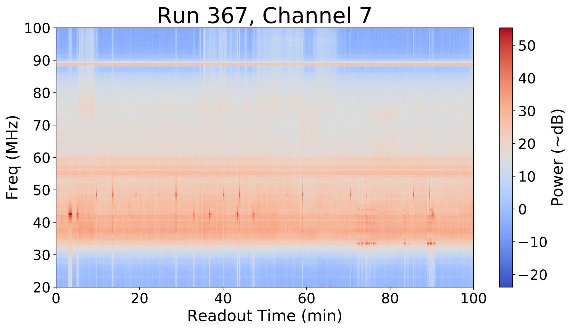


Figure 5: A spectrogram showing the changing frequency content over the course of 100 minutes.

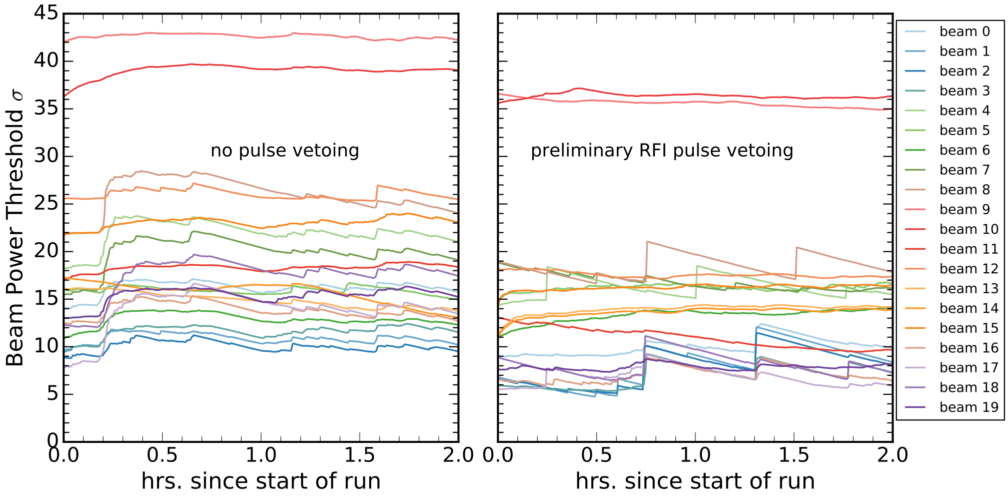


Figure 6: A comparison of the thresholds of each beam formed with the BEACON prototype system. One σ on this plot corresponds to the average power over 16 samples of a typical noise trigger.

The trigger threshold on each beam changes with time as the RF environment changes, as is evident in Figure 6. A few known sources, such as a strong 48 MHz CW signal caused by local towers, are known to turn on and off every 30-60 minutes. Evidence of this and other repeating sources can be seen in Figure 5. In an effort to cut down on the high volume of local RFI, a number of RF vetos were added to the software at the trigger level. These vetos enabled the BEACON prototype to ignore events that were overly saturated, had significant CW content, or had high voltage on some antennas but not others. Notably, after these RF vetos were added to the trigger, the thresholds on most beams lowered to between 5-20 σ . The two outlier beams are the ones most directly facing into Fish Lake Valley.

4. Understanding Local RFI

4.1 High-Voltage Power Lines

One of the most prevalent types of triggered events are repeating, poorly correlating events that occur in intervals of approximately 60 Hz spacing, as seen in Figure 7. This 60 Hz structure in the trigger time is directly related to the frequency that is carried on power lines in the United States. This hypothesis was confirmed in the field using a log-periodic dipole antenna (LPDA) and an oscilloscope at a power substation along the high-voltage lines in the Fish Lake Valley.

Because at least 10 percent of triggered events appear to be caused by this 60 Hz background, it is imperative that future iterations of BEACON are able to veto this type of event. Likely this can be done on the trigger level; this is an area of active development.

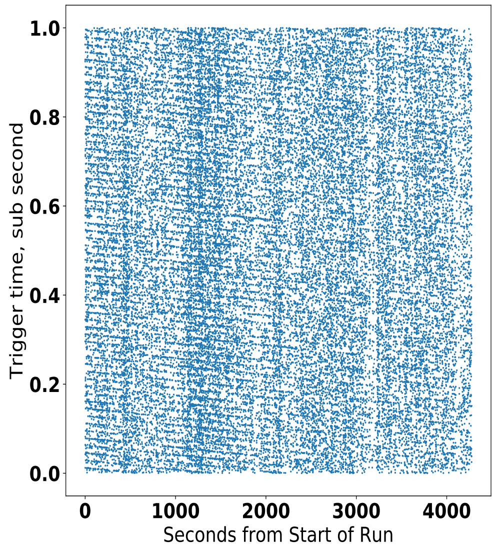


Figure 7: Example of the 60 Hz structure that appears during data taking.

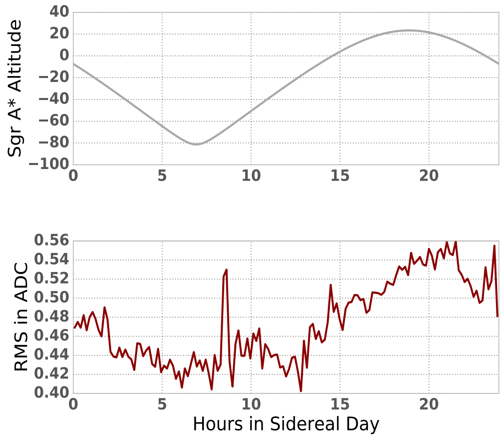


Figure 8: Evidence that the BEACON prototype is sensitive to radio from the galactic center. Here the altitude of Sgr A* is compared to the median RMS of noise trigger events after undergoing a low pass filter.

4.2 Galactic Noise

As the BEACON prototype is most sensitive between 30-80 MHz, it is expected that the radio emission from the galactic center should be visible. One way to find the galactic center would be to construct the average correlation map of many forced trigger events in celestial coordinates; however, this method requires the antenna positions to be well calibrated and farther apart for more precise correlation maps.

An easier solution is to calculate the median RMS of all forced trigger events over the course of many day. If the galactic center is visible, the RMS should increase as the galactic center rises, and fall as it sets. From Figure 8, the median RMS is correlated with the rising and setting of the galactic center, which is evidence that it is visible.

4.3 Airplane Tracks

The BEACON prototype is also sensitive to RFI from airplanes as they move into and out of its field of view. While airplanes themselves broadcast at frequencies higher than 80 MHz, radio emission from the ground is reflected by the body of the airplanes, making them possible to detect.

Candidate airplane events were found by clustering causal events, i.e. events that returned physically possible time delays based on the physical spacing of the baselines, by their time delays across each baseline of antennas. Events were considered clustered if all six time delays were within 2 ns. Events were removed if from one of the top 25 largest clusters, each containing more than 1000 events in the analyzed sample.

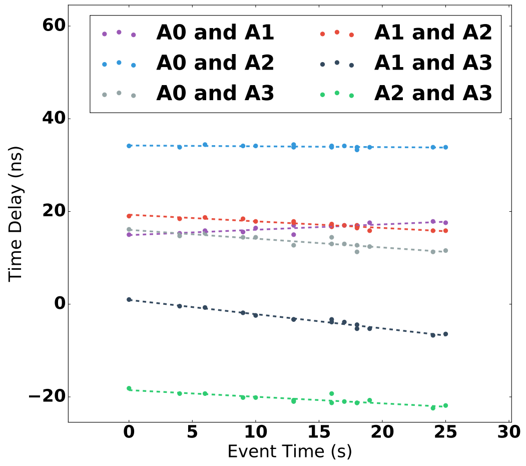


Figure 9: Time delays for each baseline as a function of readout time, using vertically-polarized channels. The sloped nature of the lines is evidence that the source is moving over the course of 25 seconds.

The remaining events were then sorted based on "impulsivity", an observable borrowed from ANITA [11]. Highly impulsive events contain a high fraction of power around the peak of the coherently summed waveform. A set of high-impulsivity events were found with slowly changing time delays across all baselines over the course of around 30 seconds. Four planes were identified using this method over the course of two days of data. An example set of airplane events is shown in Figure 9, providing clear evidence that the BEACON prototype can trigger on impulsive transient events.

Airplane events are easy to spot when multiple events are recorded and can be tracked; it is much more challenging to select airplane events in which only one or two events are detected. To assist with detecting all plane events, a flight tracker was installed this summer that detects and records the time, latitude, longitude, and altitude of each airplane, which is broadcast from the airplane every second at 1090 MHz [12]. This setup will make it possible to detect and verify all airplane events.

5. Future Implementation

The next iteration of BEACON, planned for the fall of 2019, will build off the system previously deployed. The most notable upgrade will be installing custom-built dipole antennas designed specifically to be more sensitive at the horizon. An improved trigger system can likely reduce the amount of man-made triggers, especially those caused by high-voltage power lines. Future iterations of BEACON may also include UHF antennas for better energy and direction reconstruction.

6. Acknowledgements

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References

[1] M. Ackermann *et al.*, Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos, *Bulletin of the American Astronomical Society* **51 (3)**, 185 (2019).

[2] IceCube, Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector, *Science* **342**, 1242856 (2013).

[3] P. W. Gorham *et al.*, Constraints on the ultra-high energy cosmic neutrino flux from the fourth flight of ANITA, *Phys. Rev. D* **99**, 122001 (2019).

[4] E. Zas, Searches for neutrino fluxes in the EeV regime with the Pierre Auger Observatory, *Proc. ICRC* **301**, 972 (2017).

[5] P. Allison *et al.*, ARA, Performance of two Askaryan Radio Array stations and first results in the search for ultrahigh energy neutrinos, *Phys. Rev.* **D93**, 082003 (2016).

[6] P. Allison *et al.*, Design and performance of an interferometric trigger array for radio detection of high-energy neutrinos, *NIM-A* **930**, 112 (2019).

[7] The white mountain research station, https://www.wmrc.edu/.

[8] S. Wissel *et al.*, Concept Study for the Beamforming Elevated Arrayfor Cosmic Neutrinos (BEACON), *ICRC Conference Proceedings* (2019).

[9] M. W. Eastwood, M. M. Anderson, R. M. Monroe, G. Hallinan, B. R. Barsdell, S. A. Bourke, M. A. Clark, S. W. Ellingson, J. Dowell, and H. Garsden, The Radio Sky at Meter Wavelengths: m-mode Analysis Imaging with the OVRO-LWA, *Astron. J.* **156**, 32 (2018).

[10] In-situ testing of frequency labeling and aliasing of DP and measurement of signal cross-coupling at LWA1, (2014).

[11] P. W. Gorham *et al.*, ANITA, Constraints on the diffuse high-energy neutrino flux from the third flight of ANITA, *Phys. Rev.* **D98**, 022001 (2018).

[12] S. Cabler, Airworthiness approval of automatic dependents surveillance- broadcast out systems, 2015.