Isolating cosmic ray candidates with the BEACON prototype

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The Beamforming Elevated Array for COsmic Neutrinos (BEACON) is a concept for a neutrino telescope designed to detect radio emission from upgoing air showers induced by tau leptons that are generated by ultra-high energy tau neutrino interactions in the Earth. This detection mechanism provides a pure measurement of the tau flavor of cosmogenic and astrophysical neutrinos, which could be used to set limits on the observed flavor ratios in a manner complimentary to the all-flavor neutrino flux measurements made by other experiments. A BEACON prototype has been installed at high elevation at Barcroft Field Station for several years and consists of 4 crossed-dipole antennas operating in the 30-80 MHz band and connected to a custom DAQ. The BEACON prototype is at high elevation to maximize effective volume and uses a directional beamforming trigger to reduce man-made background signals at the trigger level. This prototype system is expected to be capable of detecting downgoing cosmic ray air showers, a signal like the upgoing tau lepton air shower, but distinguishable chiefly by arrival direction. Here we give an overview of the BEACON experiment and present an ongoing cosmic ray search with data from the BEACON prototype. Cosmic ray candidates that are identified by this search will be used to experimentally determine the sensitivity of the BEACON concept to the known cosmic ray flux, which can then be used to predict the sensitivity of a full-scale BEACON array to the cosmogenic and astrophysical neutrino fluxes.

1 Motivation

A cutoff in the ultra-high energy (UHE) cosmic ray spectrum has been observed at $\sim 10^{19.5}$ eV [1], consistent with the GZK limit [2,3]. These measurements imply the existence of cosmogenic UHE neutrinos originating from decaying pions which are produced in interactions of UHE cosmic rays with cosmic microwave background (CMB) photons:

$$\gamma_{\text{CMB}} + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\pi^+ \rightarrow \nu_e + \nu_\mu + \overline{\nu}_\mu$$

In addition to the predicted cosmogenic neutrino flux, recent discoveries of a diffuse flux of astrophysical neutrinos [4,5] and a candidate for an extra-galactic source of neutrinos [6,7] create strong motivation for expanding the capabilities of UHE neutrino searches. Though only ν_e and ν_μ are expected to be produced at the sources, flavor oscillations over the relevant astrophysical baselines should result in an observed flavor ratio flux at Earth of 1:1:1. An exclusive measurement of the ν_τ flavor would yield both flux and flavor ratio information for testing both cosmogenic and astrophysical neutrino models.

The Beamforming Elevated Array for COsmic Neutrinos (BEACON) concept consists of mountaintop phased radio antennas that are designed for measuring the flux of ν_τ above 100 PeV [8]. When a ν_τ interacts with the surface of the Earth it can produce a τ lepton, which can escape the Earth's crust and decay in the atmosphere. This decay creates an upgoing extensive air shower that will produce an impulsive radio signal that is dominated by geomagnetic radiation, with contributions from Askaryan radiation [9]. A full-scale BEACON array would consist of hundreds of independent stations, creating a global network of low-cost high-elevation mountaintop radio arrays designed to search for these signals. The high elevation and topographical prominence provide the optimal field of view for horizon-based searches, while a noise-riding phased directional trigger provides anthropogenic radio frequency interference (RFI) rejection that helps maintain sensitivity to the expected diffuse flux while in noisy environments.

The BEACON prototype has seen ongoing development and support since 2018 [10]. These proceedings discuss the BEACON prototype, with significant emphasis on details of the analysis of the 2021 dataset, including discussion of background RFI distributions and efforts towards isolating cosmic ray candidates. Additional details about the design of a full-scale BEACON array are available in our original concept study [8].

2 The BEACON Prototype

The BEACON prototype is located near Barcroft Field Station, in the White Mountains near Bishop, California, USA. The first installation in 2018 used crossed inverted-V dipoles, which were also used as part of the Long Wavelength Array (LWA) experiment at the Owens Valley Radio Observatory [11]. Since 2019 the prototype has consisted of 4 crossed electrically-short-dipole antennas, each driven by an active feed and is sensitive in the 30-80 MHz range. Each crossed-dipole pair contains one horizontally-polarized (HPol) dipole aligned from North-to-South (with maximum sensitivity in the East to West directions), and one vertically-polarized (VPol) dipole aligned upright, with uniform azimuthal symmetry. The antenna feeds are connected to active on-board pre-amplifiers, filters, and baluns, with additional downstream band-pass filters. The signals are digitized at 500 MSa/s by the data acquisition system (DAQ). Each singular dipole consists of 2x76.2 cm (2x30 in) tines connected to a central active balun, with the crossed-dipole pairs being elevated ~ 3.7 m (12 ft) above the mountainside via masts constructed of both wood (for low-interference structural support near the antenna) and steel signposts (for structural support and grounding). In order to withstand the extreme weather with gusts of up to 130 km/h at the prototype site, the masts are secured by ≥ 6 guy-lines, 4 weather-treated wooden struts, and a 37 kg (70 lb) rubber base each as seen in Figure 1. The struts are cut to length on-site such that they can be wedged securely into the local terrain. This design has proven to be stable in locations of extremely irregular terrain, where drilling or pouring cement is not an option, and is flexible enough to support different terrains.

A full BEACON station would consist of 10 crossed-dipoles in the main trigger array, with at least 3 outlying crossed-dipoles with increased spacing (extending maximum baselines to ≥ 100 meters) to improve pointing resolution. The prototype has only 4 antennas, with a maximum baseline of $\sim$50 meters. Performance characteristics of the prototype array will validate the concept, but we expect the performance of a full station to be significantly better. Measurements of peak-to-sidelobe, signal-to-noise ratio, pointing resolution, and trigger thresholds all benefit from the additional antennas and longer baselines of a full station.

Just like a full BEACON station, the prototype uses a phased trigger system designed originally for the ARA Station 5 phased array [12]. This trigger has a field programmable gate array (FPGA) which uses a pre-calculated table of expected arrival time differences between the antennas to delay signals before performing a power sum on the resulting net signal. Each set of time delays corresponds to a particular direction, referred to as a "beam", and is sensitive to signals arriving from the specific direction where the delays result in coherently summed signals. This coherent sum increases the signal's magnitude by a factor of N_{antenna} (the number of summed antennas), while the noise adds incoherently and only increases by $\sqrt{N_{\text{antenna}}}$, resulting in a net signal-to-noise ratio (SNR) increase of $\sqrt{N_{\text{antenna}}}$ [12]. Trigger thresholds are noise riding, with thresholds rising automatically for noisy beams such that a global trigger rate of 10 Hz

Figure 1 – Left: A top-down view of the calibrated HPol phase center positions in local East-North-Up (ENU) coordinates. The mountainside slopes upward to the West with an inclination angle of $\sim 22°$. Relative to the lowest antenna (mast 0), the heights of 1, 2, and 3 are approximately 15.9 m, 4.0 m, and 13.7 m respectively. The size of each antenna has been magnified $5\times$ compared to baselines for visibility. Center: Close-up of the 2021 antenna feed enclosure with lid removed. Right: BEACON prototype antenna mast 0. The mast is held upright via ≥ 6 guy-lines, 4 weather-treated wooden struts, and a 37 kg (70 lb) rubber base, all visible. The science antennas are bolted to a wooden masthead, attached to readout and lightning grounding cables which are fed to the base of the mast with strain relief. The mast also has an attached GPS patch antenna which can be used for position calibration.

is maintained. This directional trigger is essential in noisy environments and has allowed the BEACON prototype to maintain low thresholds in most beams despite a high rate of RFI events.

Directional reconstruction like that used in the trigger and more precisely in offline event reconstruction analysis depends on accurate knowledge of the location of the antenna phase centers relative to each other. Initial antenna positions were measured using both a theodolite and GPS measurements corrected using real time kinematic (RTK) data provided by a nearby UNAVCO base station. A calibration campaign was then conducted to send impulsive radio calibration signals to the array from 6 static locations on the mountainside[13]. We then ran a χ^2 minimization to find the true antenna phase center locations, using measured locations as a starting point in the minimization algorithm, optimizing for the matching between expected geometrical arrival time differences and those observed from the calibration pulser data.

We determine the arrival direction of signals by constructing a correlation map for each polarization, where each direction in the map is the average correlation value of all possible antenna waveform pairs when sampled at the appropriate expected arrival time difference for that given direction. Directions in this map that correspond to the actual arrival direction of the signal will thus sample at the maxima of the correlations, resulting in a larger value on the map. The position calibration of the antennas is required for correct mapping of expected arrival time delays for each direction on the map. The angular pointing resolution of the prototype has been experimentally determined by reconstructing arrival directions of below-horizon RFI sources, the majority of which arrive from a smaller number of stationary emitters. A 2D Gaussian was fit to 7 of the most dominant sources, with an average 90% fit integral area of < 0.1 sq. degrees (see Figure 2).

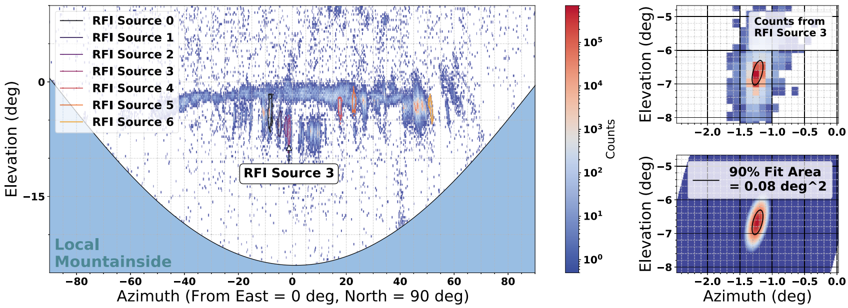

Figure 2 – Left: Reconstruction direction of events from a week in September 2021. Seven of the most populated RFI sources have been highlighted. Events within these regions were isolated, with the 90% integral area being calculated based on a 2D Gaussian fit. Top Right: Isolated events from RFI Source 3 (arbitrarily chosen as an example). Bottom Right: 2D Gaussian fit (color map), with outline of the 90% integral area of the fit plotted on top. Note that the color scale is logarithmic and represents counts for all 3 plots. The average fit 90% integral area for all 7 sources was < 0.1 sq. degrees.

3 Exploratory Cosmic Ray Search

Though the prototype array has insufficient sensitivity to detect ν_τs, our custom Monté Carlo cosmic ray simulation package, Cranberry, predicts that cosmic ray air showers should be detectable with the prototype array at reasonable rates (Figure 3). These cosmic ray air shower events are the closest possible signature to the desired ν_τ events, mainly differing by their arrival direction: cosmic rays are downgoing, whereas ν_τs would be upgoing. In a full-scale BEACON, cosmic rays will be a background to the ν_τ search, sharing many characteristics with the expected ν_τ signals, but distinguishable based on direction. The observed rate will be used in future analyses to determine both experimental and analysis thresholds, and set the expected sensitivity for a full-scale BEACON - pending finalization of the cosmic ray simulation.

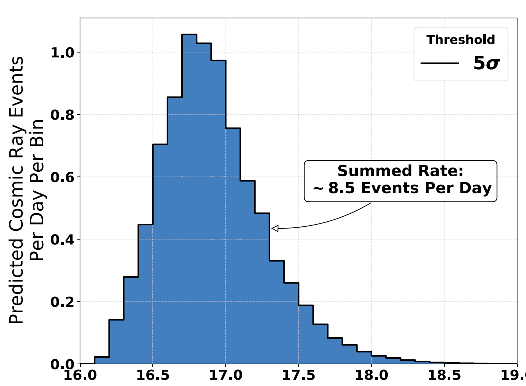

Figure 3 – Preliminary simulation results showing the predicted observation rate of cosmic rays at various energies with the BEACON prototype, with rates scaled to match the ~110 day span inspected by the ongoing cosmic ray search. Events are generated using ZHAireS and the radio morphing technique; signals are propagated through a combination of measured system responses and XFdtd-determined antenna models before being processed through a simplified DAQ [14], where 5σ refers to a simplified voltage SNR threshold. The simulation is still undergoing active development, so rates are preliminary and approximate.

A background-driven search has been conducted which uses preliminary input from the simulation for expectation and validation of results. This search aims to isolate cosmic ray candidates by isolating events that reconstruct above horizontal, and systematically removing identifiable background RFI events, before correlating the remaining events with cosmic ray templates from the simulation. Cosmic rays are expected to be impulsive signals that correlate well with templates, have polarization's consistent with source direction and geomagnetic radiation in the local Earth's magnetic field, and should have above-horizontal arrival directions which show no spatial or temporal clustering. This search spans ∼110 days of prototype data taken from the beginning of September 2021 to the end of December 2021 (corresponding to ∼100 million RF-triggered events).

Events first undergo additional band-pass, notch, and sine-subtraction filtering. Correlation maps are then constructed to determine the most likely arrival direction of each signal. Approximately 99% of background RFI events were removed by directional cuts alone, because the majority of RFI comes from below the horizon. A series parameter cuts were then designed to reduce the remaining ∼1 million events down to ∼5400. These cuts are intended to be conservative, only removing events with sufficiently low signal or map quality that their above horizon reconstructions cannot be strongly trusted. Most of these low-quality signals are likely from below the horizon given the RFI rate from below the horizon. These parameter cuts are summarized below:

1. *Time Delay Similarity Count*: Remove events that have more than 10 events within the same run (∼1.5 hours) showing the same calculated arrival time delays.

2. *Peak-to-Sidelobe Ratio*: Remove events for which the peak-to-sidelobe ratio of the HPol and VPol correlation maps sums to less than 2.15, where the peak-to-sidelobe ratio is defined as the ratio between the maximum value peak of a correlation map to the next most prominent peak in the map. A ratio near 1 for a single polarization indicates no distinguishable primary peak, so requiring a sum of HPol and VPol near 2 targets events with difficult to interpret pointing.

3. *Impulsivity*: Remove events which have summed HPol and VPol impulsivities ($\mathcal{I}$) below 0.3. $\mathcal{I}$ is a metric for measuring the temporal compactness of signal's power used by the ANITA collaboration [15], defined here as $\mathcal{I} = 2A - 1$, where A is the average of the cumulative distribution of fractional power contained within a 400 ns window centered on the peak of the Hilbert envelope of $\overline{\mathrm{WF}}$, with $\overline{\mathrm{WF}}$ denoting the aligned and averaged waveforms for a particular polarization.

4. *Simple Cosmic Ray Model Correlation*: Remove events for which neither polarization correlates above 0.4 with a simplified cosmic ray template. The template used was a bi-polar delta function with duration and heights motivated by an off-axis angle of 1.37° for a slightly up-going airshower [16]. Specifically the bi-polar delta integrates to a value of 1, with an initial negative impulse lasting 5 ns, and a positive tail lasting 28 ns. This signal is then convolved with the appropriate channel-dependent responses of the BEACON prototype, before undergoing the same filtration and cleaning as the waveforms.

5. *Targeted Box Cuts*: In order to remove events misreconstructing above horizon due to prominent sidelobes of below horizon sources, a subset of problematic below horizon sources were identified. Events are cut if their below horizon reconstruction direction (when above horizon is masked out) lies within targeted boxes encompassing these sources.

6. *Normalized Map Peak Value*: Remove events which do not achieve a threshold percentage of their optimal achievable map value. If the normalized map peak value is m, then events are cut if they fall below the line $m_{\mathrm{V}} = -1.2m_{\mathrm{H}} + 1.5$, effectively keeping events in the upper-right portion of the phase space corresponding to good HPol and VPol map

maximization. This and the following cut were added following by-eye inspection of data passing all other cuts for a 1-month subset.

7. *Peak-To-Peak / Standard Deviation*: Remove events where the peak-to-peak value is not sufficiently above the standard deviation of the observed ADU counts in that waveform (with the cut being applied on the ratio of the two values[a]). If this ratio is r, then events are cut if they fall below the line $r_{\mathrm{V}} = -(11/6)r_{\mathrm{H}} + 11$, effectively keeping events in the upper-right portion of the phase space corresponding to a high peak-to-peak relative to the overall noise level of that event.

Events that pass these cuts were then inspected by eye to visually remove any misreconstructed events (due to prominent sidelobes or anomalous behavior). Events are also temporally and spatially correlated with airplane trajectories from The OpenSky Network[17], which contains an extensive database of ADS-B airplane data which the majority of airplanes are required to transmit. Of these, 64 individual airplanes showed at least 4 triggered events, with 6 airplanes having 50 or more triggered events. Of the ~ 5400 passing events, $\sim 75\%$ were sorted by eye as possible misreconstructions, anomalous behavior, or ambiguous. Roughly 24% are believed to be airplanes, with only $< 1\%$ ($\sim$50 events) showing no clustering or association with known airplanes.

It is not believed that all triggered cosmic rays would pass all specified cuts or that all passing events are cosmic rays. Further analysis is planned that will report a total observed cosmic ray rate for the prototype array, however in Figure 4 we present our most promising candidate from this exploratory cosmic ray search. This event correlates well with templates (best among all uncategorized passing events), has high impulsivity ($\mathcal{I}_{\mathrm{HPol}} = 0.59$, $\mathcal{I}_{\mathrm{VPol}} = 0.66$), high peak-to-sidelobe ratio (> 1.7 for each polarization), and an arrival direction and polarization angle consistent with expectations. Figure 5 shows this alongside an event generated with the cosmic ray simulation, as well as the polarization angle compared to the predicted polarization angle distribution, where polarization angle ϕ is calculated in the frame of the antennas as:

$$\phi = \arctan\left(\frac{\max\left(\left|\overline{\mathrm{WF}}_{\mathrm{VPol}}\right|\right)}{\max\left(\left|\overline{\mathrm{WF}}_{\mathrm{HPol}}\right|\right)}\right)$$

where $\overline{\mathrm{WF}}$ is the aligned and averaged waveform of all signals for a particular polarization.

4 Conclusion

The BEACON prototype has been in operation since 2018 and has seen continual upgrades that lead towards an inexpensive and robust station design that is scalable for a full BEACON array implementation. Data from the prototype array been used to understand backgrounds, develop analysis techniques, identify above horizon RFI sources such as airplanes, and to isolate events consistent with the expected properties of a cosmic ray. The results of this analysis have already validated the phased trigger's ability to maintain sensitivity to above horizon events using a small number of antennas in a noise-dominated environment like California. The ongoing development of the cosmic ray simulation will enable future estimates of experimental and analysis thresholds for the BEACON prototype to cosmic rays, which will be used to refine the predicted neutrino sensitivity of a full-scale BEACON array.

[a] Standard deviation is applied to the entire waveform including the signal, so this metric is distinct from SNR

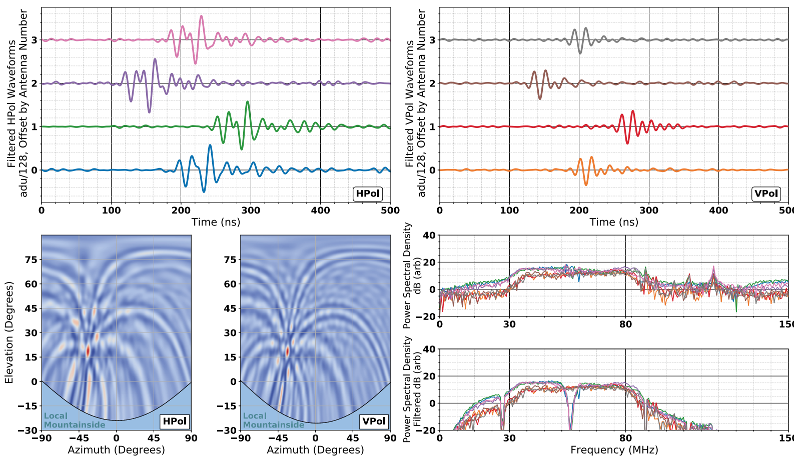

Figure 4 – Event display for the current most promising cosmic ray candidate. Top: Each of the 8 channels, normalized and offset such that the y-scale indicates the mast number for each waveform (left being HPol channels and right being VPol). Bottom Left: HPol and VPol correlation maps, where the colors of each map is individually normalized to illustrate each polarization's best-reconstruction location; the region of the maps associated with the mountainside being masked out. Bottom Right: Event spectra before and after filtration, in arbitrarily offset dB units (a conversion between ADU and volts has not been performed).

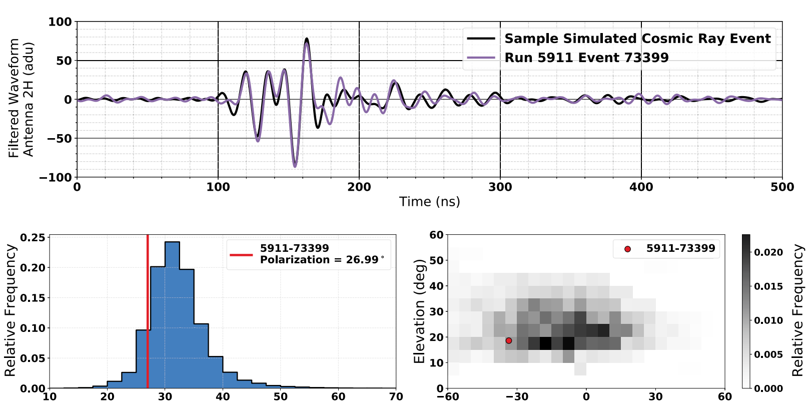

Figure 5 – Top: Waveform from Antenna 2H from Figure 4 shown alongside a sample simulated cosmic ray signal. The simulated event is processed with the measured system response and signal chain of the prototype for the same channel, and has thermal noise added at a realistic level to match the prototype array. Both waveforms are filtered as described in Figure 4. Bottom: The distributions of expected relative frequency of occurrence for the observable angles of triggered simulated events, with vertical red lines indicating the values of the real cosmic ray candidate event 5911-73399.

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