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The Beamforming Elevated Array for COsmic Neutrinos (BEACON): A Radio Detector for Earth-Skimming Tau Neutrinos

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When ultrahigh energy tau neutrinos skim the Earth, they can generate tau leptons that then decay in the atmosphere, forming upgoing extensive air showers. The Beamforming Elevated Array for COsmic Neutrinos (BEACON) is a novel detector concept that utilizes a mountaintop radio interferometer to search for the radio emission due to these extensive air showers. The prototype, located at the White Mountain Research Station in California, consists of 4 custom crossed-dipole antennas operating in the 30-80 MHz range and uses a directional interferometric trigger to achieve reduced thresholds and background rejection. The prototype will first be used to detect extensive air showers from down-going cosmic rays to validate the detector model. In this talk, we give an overview of the BEACON concept and the status of its prototype. We also discuss the ongoing cosmic ray search which utilizes both data analysis and simulation.

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1. Introduction

The interaction of ultrahigh energy cosmic rays with photons is expected to produce neutrinos with energies exceeding 100 PeV. These interactions can occur at the cosmic ray source [1], or while the cosmic rays propagate through the cosmic microwave background [2]. While many ultrahigh energy cosmic rays have been detected, the existence of the ultrahigh energy (UHE) neutrinos they are expected to produce remains unproven.

UHE neutrinos which skim the Earth have a chance that their interaction products will escape into the atmosphere, producing detectable up-going particle air showers [3]. Tau neutrinos are particularly suited for this, due to the long propagation length and short lifetime of the τ lepton. Tau neutrinos are not expected to be produced at astrophysical sources, however due to flavor oscillation over astrophysical distances the neutrino flux is expected to have an even flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at Earth [4]. Earth-skimming events are therefore very likely to be astrophysical in nature, and provide an exclusive measurement of the tau neutrino flux. The up-going extensive air showers created by the decays of the τ leptons emit an impulsive radio signal. This is due to the geomagnetic effect, in which the deflection of charges by Earth's magnetic field creates a time-varying current, and the Askaryan effect, which is subdominant for air showers [5].

The Beamforming Elevated Array for COsmic Neutrinos (BEACON) is a novel detector concept consisting of multiple radio interferometers placed on mountaintops, searching for these impulsive radio signals [6]. The use of phased arrays at the trigger level lowers the trigger threshold and allows the directional rejection of noise. The high elevation site and long propagation length of radio provides BEACON with a large viewing area for up-going extensive air showers. Additionally, the use of radio antennas is low cost and allows a nearly continuous duty cycle. BEACON consists of multiple phased antenna arrays, each independent of the other. As a result, the stations can be placed around the globe leading to full-sky coverage. A full-scale BEACON is planned to consist of $O(1000)$ autonomous 10-antenna stations. This design can achieve sensitivity to diffuse ultrahigh energy neutrino models which assume cosmic rays are purely protons or iron [6].

In these proceedings, we first discuss the design and goals of the BEACON prototype in Section 2. We then discuss simulations which have been developed to estimate the sensitivity of the prototype to cosmic rays in Section 3. Lastly, we discuss the performance of the BEACON prototype and a potential cosmic ray event in Section 4.

2. Design and Goals of the Prototype

The BEACON prototype is located near Barcroft Field Station within the White Mountains of California and has been operating since 2018. The antenna array sits at an altitude of 3.8 km, overlooking a valley to the East with an altitude of 1.5 km. A map of the surroundings of the prototype site is shown in Fig. 1. The site has road access, a solar-battery hybrid power system, an observatory dome in which electronics can be stored, and internet access.

The prototype consists of four custom crossed-dipole antennas operating in the 30-80 MHz range, one of which is pictured on the left in Fig. 2. Each antenna has two channels, one horizontally-polarized, the other vertically-polarized, for a total of eight. The antennas are elevated 13 ft above the ground so as to reduce interference from the ground, and are pointed East, where the geomagnetic

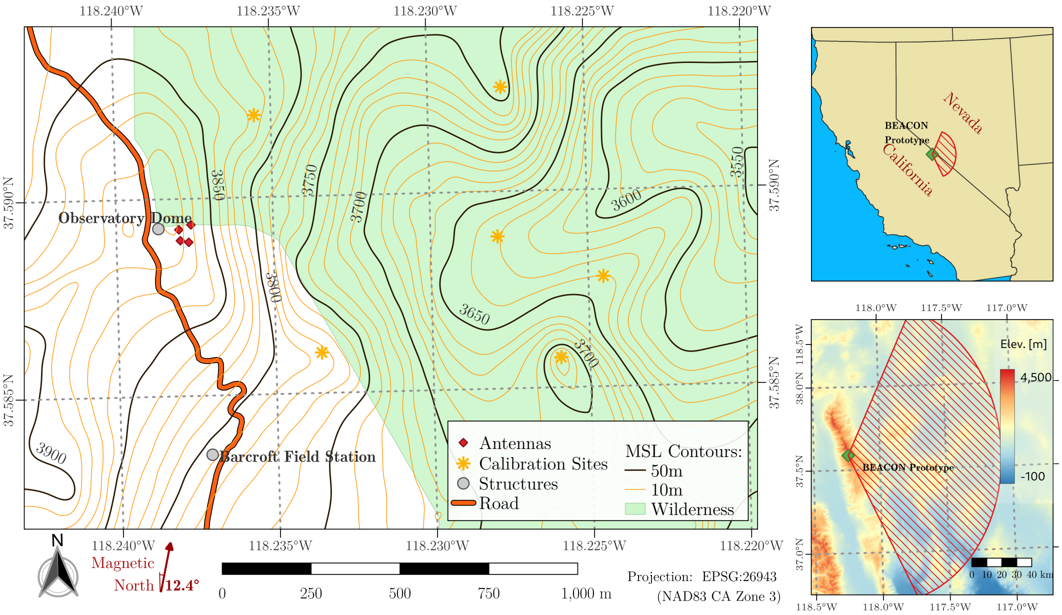

Figure 1: Left: A topographic map of the BEACON prototype site within the White Mountains of California. Top Right: A map showing the location of the BEACON prototype. Bottom Right: A map showing the elevation profile of the region. A cone with a radius of 100 km and spanning ±60° of East has been added to illustrate the field-of-view of the BEACON prototype. Figure sourced from [7]

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effect is maximized. The antenna tines are fed into an active balun, consisting of a 4:1 transformer and 50 Ω low-noise amplifier (LNA), shown on the right in Fig. 2. Coaxial cables carry both the amplified signal to the DAQ housed in the observatory dome, and provide power to the LNAs using internal bias tees.

At the DAQ, the signals are further amplified and then filtered. Filters include bandpass filters and FM notch filters. The signals are then passed to the digitizer and beamforming trigger board, which digitizes the 8 channels at 500 MSPS with 7-bit resolution. A FPGA controls the trigger and buffers up to 2048 samples per channel for readout. A timing GPS is used to provide a precise timestamp for each trigger. A BeagleboneBlack single board computer is used to configure and readout the digitizer and beamforming trigger board. The power draw of this setup is ~ 40 W.

The trigger currently implemented is a beamforming (AKA phased array) trigger. For any given source direction, signals will arrive at each antenna at a different time. A beamforming trigger delays each channel by a pre-calculated table of these arrival time differences. Each entry in the table, called a beam, corresponds to a particular direction. Signals arriving from within a beam will be coherently summed, while noise will be incoherently summed. Ultimately, this improves the SNR by a factor of $\sqrt{N_{antennas}}$, where $N_{antennas}$ is the number of phased antennas. The prototype currently uses 20 beams spanning nearly 120° in azimuth and 80° in elevation. The trigger threshold can be set per beam, allowing noise to be rejected directionally, and is automatically adjusted to be noise-riding to allow peak sensitivity.

Figure 2: Left: One of the BEACON prototype crossed-dipole antennas. The antenna is elevated 13 ft off the ground and is pointed towards the valley to the East. Right: The BEACON active balun consisting of a 4:1 transformer fed into a 50 Ω LNA, housed in a Polycase enclosure. The antenna tines pass through water-tight grommets and are connected directly to the front-end board. Pictures sourced from [7].

The antenna construction, DAQ, and trigger implementation are described in greater detail in [7]. One goal of the prototype is to demonstrate the capability of triggering on impulsive signals using the interferometric trigger a noise environment like California. Additionally, while BEACON is intended to detect up-going showers initiated by Earth-skimming tau neutrinos, it will also be sensitive to the down-going showers initiated by cosmic rays. While the prototype is unlikely to detect any neutrinos, it is likely to detect cosmic rays. A goal then is to use the observed cosmic ray flux, in conjunction with the well-measured cosmic ray flux, to determine the sensitivity of the prototype array. From there, we can then predict how well a full-scale BEACON will perform in detecting UHE neutrinos.

3. Cosmic Ray Simulation

A Monte Carlo simulation named Cranberry was developed to predict the acceptance of the prototype array to cosmic rays, and from there, the number of expected events. The acceptance at a given cosmic ray energy is given by

$$\langle A\Omega(E)\rangle = \iint_{\Omega} d\Omega \iint_{A} dA\, \hat{n}\cdot\hat{r}\, P_{obs} = \pi \times (\text{test area}) \times \left(\frac{\text{\# of showers that trigger}}{\text{total \# of showers}}\right), \qquad (1)$$

where $\hat{n}$ is a vector normal to the test area and $\hat{r}$ is a vector along the shower axis. Cranberry calculates the acceptance of the BEACON prototype by generating extensive air showers with random geometries in an area around the area, and counting the number of triggered events.

The time-domain radio emission of each air shower in each channel is determined by the bilinear interpolation of ZHAireS simulations, a process similar to radio-morphing [8], and which is described in detail in [9]. The time-domain electric fields $E(t)$ are then Fourier transformed, and converted to voltage via the formula

$$V(f) = \frac{2c}{f} \frac{|Z_L|}{|Z_A + Z_L|} E(f) \sqrt{\frac{G(f,\theta,\phi)}{4\pi} \frac{R_A}{\eta} (1 - |\Gamma|^2)}, \tag{2}$$

where f is frequency, c is the speed of light, Z_L is the impedance at the load, Z_A is the impedance of the antenna, G is the gain, R_A is the resistance of the antenna, η is the impedance of free space, and Γ is the reflection coefficient [6]. The gain, impedance, and reflection coefficient are determined using XFdtd simulations of the crossed-dipole prototype. $V(f)$ is then convolved with the amplifier and filter signal-chain, and inverse Fourier transformed to the time-domain.

A power sum trigger, utilizing the same beam pattern used by the prototype, is then performed. The time-domain voltage waveforms are squared, delayed in time according to the beam layout, and then summed. Thermal noise is modeled using the Dulk parameterization of galactic sky noise [10] in addition to the instrument noise which is dominated by the amplifiers (100 K, nominally). If the power-SNR exceeds a chosen threshold than a trigger is determined to have taken place and the 8-channel voltage waveforms are saved for use in later analysis.

The results of Cranberry are shown in Fig. 3. On the left is the acceptance as calculated by Eq. 1 for a power-SNR threshold of 10 (comparable to a voltage-SNR threshold of 5). The cosmic ray energy threshold of the prototype is seen to be ~ 60 PeV. Using the cosmic ray flux as measured by Auger [11] the number of events per day as a function of energy can be calculated using the acceptance. This calculation is shown on the right in Fig. 3. Integrated over all energy bins, a total of ~ 0.3 cosmic ray events per day are expected.

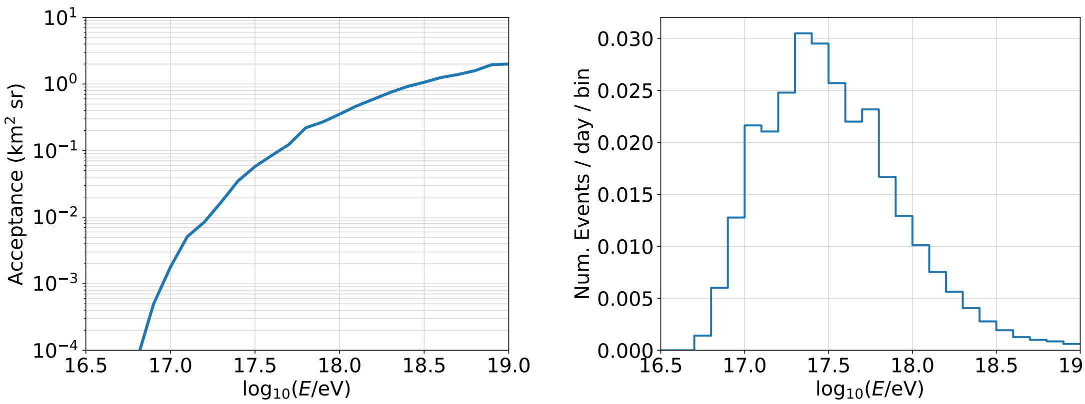

Figure 3: Left: The acceptance (km^2 sr) of the BEACON prototype array to cosmic arrays as a function of cosmic ray energy for a power-SNR threshold of 10. Right: The expected number of cosmic ray events per day as a function of energy assuming the cosmic ray flux measured by Auger [11]. ~ 0.3 events per day are expected total.

4. Performance of the Prototype

Being an interferometer, BEACON is capable of reconstructing the direction of sources, however this requires knowing precisely the location of each antenna and the signal propagation

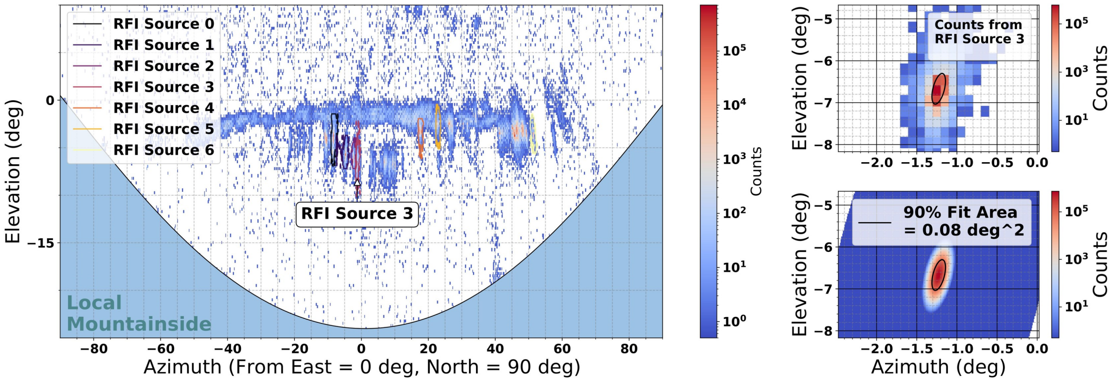

Figure 4: Left: 2D histogram of events from one week in September 2021. Seven of the most populated RFI sources have been highlighted. Top Right: Isolated events from RFI Source 3. Bottom Right: 2D Gaussian fit (color map), with the outline of the 90% integral area. The average fit 90% integral area for all 7 sources was < 0.1 sq. degrees. Figure sourced from [7].

time through each of the cables. A calibration campaign was carried out in 2021 in which these measurements were made for the prototype array. A high-voltage pulser, triggered with nanosecond accuracy by a GPS-synced timer, drove a biconical antenna located at different sites around the array (the yellow stars in Fig. 1). Pulses arriving at the array from these sites have arrival time differences which can be predicted since the location of the pulsing sites are known. A χ^2 minimization can then be performed, in which the positions of the antennas relative to each other, as well as the cable lengths, are adjusted so that the measured arrival time differences match those predicted.

The post-calibration pointing resolution of the prototype was measured by reconstructing the arrival direction of multiple below-horizon RFI sources. A 2D Gaussian was fit to 7 of the RFI sources, with an average 90% integral area of less than 0.1 square degrees. This process is illustrated in Fig. 4.

There are multiple categories which background events can be placed into. The most common category is static sources, like those in Fig. 4. This category is relatively easy to cut from event searches since the events are spatially clustered. Another category is continuous wave (CW) sources, such as TV stations or communication systems. These sources rarely trigger the array themselves, however their signals can appear in triggered events. CW noise can be removed from the data during analysis using notch filters and a technique known as sine subtraction. A third category of background is periodic noise sources. These sources arrive with time differences corresponding to multiples of 1/(60 Hz) and are thus associated with discharges from the US power grid. An algorithm, described in detail in [7], was developed to cut out these background events. The last major category of background events is reflections off airplanes. These events cluster spatially and temporally as the airplane flies across the prototype's field-of-view. An airplane tracker is also used to cross-check whether or not events come from airplanes.

As a precursor to a rigorous cosmic ray search, we have begun classifying a subset of above-horizon impulsive events. $\sim$ 100 million RF-triggered events, collected over 112 days (beginning of September to the end of December 2021), were analyzed. These events were first filtered at known frequencies of anthropogenic noise and then sine subtracted. Events outside $[-90°, 90°]$ in

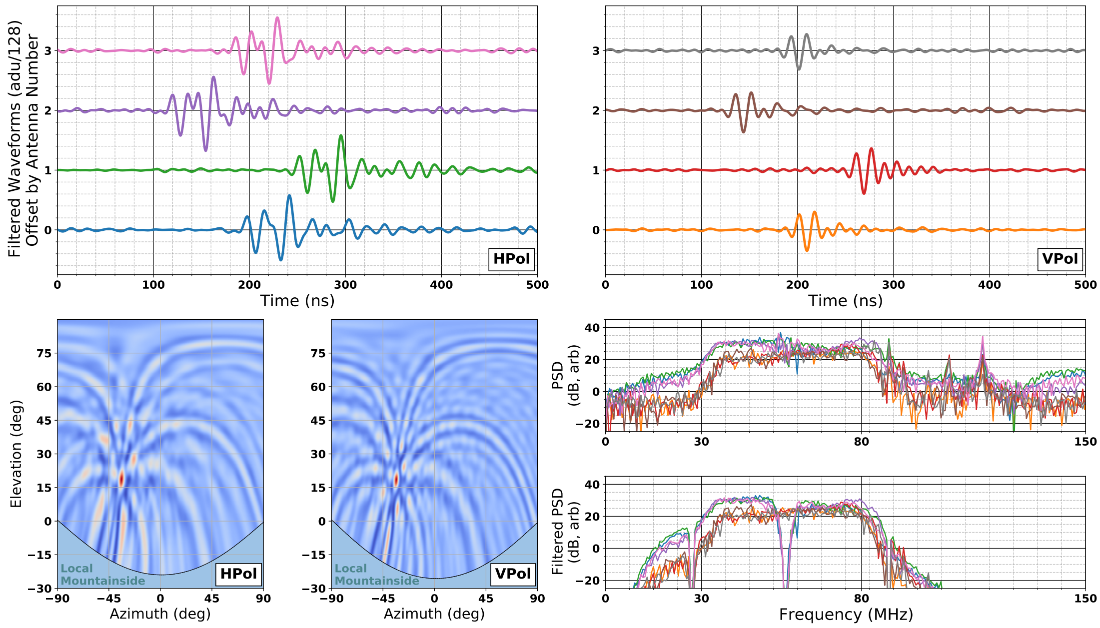

Figure 5: Event display for a likely cosmic ray event (Event 5911-73399). Top: Waveforms from each of the 8 channels, normalized and offset such that the y-scale indicates the antenna number for each waveform. Bottom Left: HPol and VPol correlation maps, individually normalized. Bottom Right: The Power Spectral Density (PSD) before and after filtering. Figure sourced from [7].

azimuth and $[10°, 90°]$ in elevation were cut. This eliminates below-horizon static sources of noise like those in Fig. 4, and restricts the search to azimuths at which the prototype is most sensitive. A series of cuts, described in detail in [7], were then preformed to eliminate any non-impulsive, weak, or otherwise anomalous events.

The remaining 5,440 events were then inspected by hand. 4,081 of the events were likely misreconstructions of below-horizon RFI sources, or instability in the amplifier chain. 1,323 events were associated with known airplane trajectories. 36 events do not belong to either of these two categories, a subset of which could possibly be cosmic rays. One event (event 5911-73399), shown in Fig. 5, is likely a cosmic ray event. The event is highly impulsive, correlates well with simulated cosmic ray waveforms output by Cranberry, and has a polarization angle ($\sim 27°$) consistent with that predicted by the geomagnetic effect for a shower in this direction ($\sim 30°$).

5. Conclusions

The BEACON prototype has demonstrated the ability to trigger on impulsive RF events in a noise-dominated environment like California with 36 above-horizon impulsive events identified in 112 days of data, at least one of which is likely a cosmic ray. A cosmic ray search, utilizing a convolutional neural network trained on simulated cosmic ray waveforms, is planned for the future. Potential hardware upgrades to the prototype, such as an updated DAQ and scintillator panels, are also being explored. These future plans will further improve our understanding of the BEACON prototype, and in turn, allow us to predict the sensitivity of a full-scale BEACON to ultrahigh energy neutrinos.

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