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Searching for Cosmic Rays with the BEACON Prototype

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A cosmic ray search with the prototype for the Beamforming Elevated Array for COsmic Neutrinos (BEACON) helps characterize the BEACON instrument, including the RF trigger that is ultimately crucial for detecting tau-neutrino induced geomagnetic emission with this mountaintop array. The well-studied cosmic ray flux allows us to quantify the detector's performance and discrimination against backgrounds. Detection and characterization of a well-understood population of cosmic-ray events seen by the detector can be used to optimize the RF trigger on a full-scale BEACON experiment. Presented here are the preliminary results of a cosmic ray search using the 2021 detector, and the motivation for a detector upgrade in October 2023. These detector upgrades introduced a new antenna design, new modular data acquisition hardware, and an independent scintillator array detector. The scintillator array provides an independent detection of cosmic rays, yielding a sample of cosmic ray events with coincident RF triggers to characterize the RF trigger. The progress for a cosmic ray search with the 2023 detector using coincident scintillator and RF signals is presented.

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1. Introduction

The Beamforming Elevated Array for COsmic Neutrinos (BEACON) is a detector concept of phased radio arrays on mountaintops designed for sensitivity to up-going radio frequency (RF) emitting showers induced by τ_ν's of energies above 100 PeV [1]. The phenomena is caused by the double cascade mechanism whereby a τ_ν interacts in the Earth which produces a Lorentz-boosted τ-lepton that lives long enough to escape the Earth and decay in the atmosphere.

A prototype for BEACON has been operational since 2018, consisting of four dual-polarized dipole antennas, allowing four H-polarized and four V-polarized channels [2, 3]. The prototype has a 2.4 km prominence overlooking the Eastwards horizon in the White Mountains of California, near White Mountain Research Center's (WMRC) Barcroft Field Station at a 3.8 km altitude. There have been follow-up deployments in 2020 and 2021 to improve structural integrity against the extreme high altitude weather. The prototype of 2021 ran until upgrades in 2023 that brought the array to six newly designed antennas which replaced the prior four, a new data acquisition system (DAQ) and RF chain, and an independent scintillator array as discussed in Section 2.

The goal of the BEACON prototype is to validate the estimated full instrument sensitivity to τ_ν-induced RF showers [1] by verifying the prototype's sensitivities to cosmic ray air showers, whose radio signatures are similarly impulsive and polarized.

2. BEACON Prototype & Upgrades

The BEACON prototype antennas are dipoles sensitive to the 30 - 80 MHz band. This is because at EeV energies, the air shower radio spectrum is low frequency dominated. It was also found that this band is the most quiet for the site's radio-frequency interference (RFI) [2].

The data acquisition system stems from the Askaryan Radio Array (ARA) DAQ and is capable of a beamforming trigger with an FPGA [4]. The radio-frequency (RF) chain consisted of a pre-amplifier at the antenna followed by amplification with bandpass filters at the DAQ. The instrument recorded a fixed rate of forced triggers for background events, and used an RF trigger on 20 beams optimized in the region above the horizon expected to be populated by cosmic rays [3].

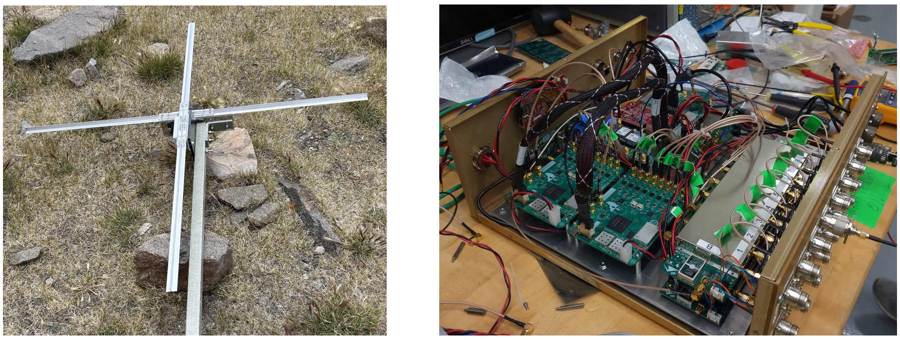


Figure 1: Left: New T-bar antennas and fiberglass mast for the 2023 upgrades. Right: The 2023 DAQ; It contains two modular 8-channel digitization boards on the bottom left, two 8-channel RF receiver boards on the bottom right, and the main computer and FPGA in the back. Photos of the prior hardware can be found in the BEACON 2021 prototype performance paper [3].

In 2023, the BEACON prototype was upgraded with new antennas and electronics. The antenna tines were replaced with T-Bar tines, and the wooden and steel masts were replaced with fiberglass masts to strengthen the antennas from shearing and snapping caused by extreme weather. The antenna pre-amplifiers implemented GPS capabilities that utilized a bandwidth outside of the science band in order to improve reconstruction by improving antenna position determination. Two antenna masts were added to the array, totaling to six antennas, or 12 channels, improving sensitivity and reconstruction capabilities. The DAQ components were replaced with two modular 8-channel 250 MS/s digitization boards with an onboard CycloneV-5CEFA5F23I7N FPGA, capable of beamforming phased triggers and channel coincidence triggers.

A scintillator array consisting of four IceTop scintillators [5] was added as an independent detector for cosmic ray events via secondary muons. The analog output is digitized at the BEACON DAQ to match the sampling rate of the RF channels.

To trigger the scintillator array, at least three of the four scintillators must detect coincident pulses, reducing the likelihood of dark counts or other background noise from individual scintillators.

3. Cosmic Ray Radio Simulation Results

Cosmic ray events are simulated from a Monte Carlo simulation process named the **C**osmic **Ra**y Simulatio**n** for a **B**eamforming **E**levated A**rr**ay (Cranberry) [6]. From Cranberry, we obtain spatial distributions, signal waveforms, event rates, and the acceptance of BEACON to cosmic ray events.

Cranberry utilizes generated geomagnetic and Askaryan electric fields produced by charged particle showers in ZHAireS [7] that are then combined with the antenna model constructed from scattering matrix parameter measurements and XFDTD modeling in order to generate waveforms and estimate acceptance. The cosmic ray flux spectrum from Pierre Auger [8] is then used to gather the rates and distribution of events at the detector.

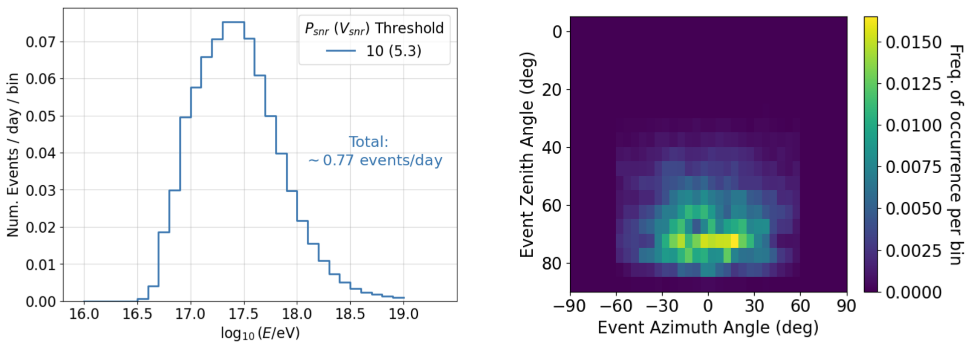


Figure 2: Simulated cosmic ray distributions from Cranberry of RF events expected to be seen by the BEACON 2021 prototype. On the left shows the expected rates depending on energy for a given trigger signal-to-noise ratio (SNR) threshold of 10 in power, or 5.3 in voltage. The cumulative event rate at any energy is 0.77 events per day. The right shows the expected distribution of arrival directions, centered on the East at 0°.

The resulting distributions of event rate dependence on energy and arrival direction are shown in Figure 2. For the 2021 BEACON prototype, the distribution shows a cumulative event rate of 0.77 events per day, expected just above horizon and from the East. Highly inclined Eastward events are favorable due to the high altitude atmosphere density profile, as well as the orientation of the antenna array which faces Eastwards down the slope of the mountain to the horizon.

The simulation also holds waveform and polarity information which can be combined with the expected event distributions to form templates that can be used in the cosmic ray search.

4. Cosmic Ray Search with BEACON Prototype 2021

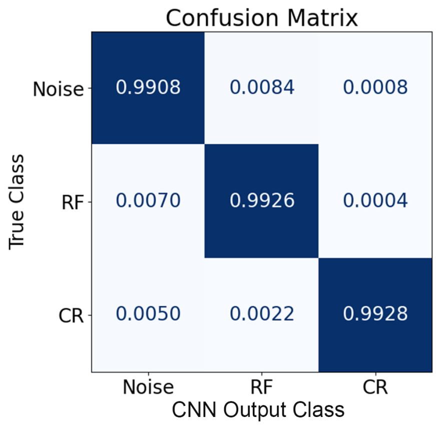
The cosmic ray search led by Dan Southall for the 2021 configuration of the BEACON prototype consisted of carefully constructed cuts, chosen to reduce the number of passing events to the more probable cosmic ray candidates [3]. The cuts were based on waveform quality, arrival direction, and impulsivity characteristics. These cuts narrowed 96,483,288 events down to 5,440 events, of which 99% of them were manually identified to be caused by airplanes or probable mis-reconstructions of RFI from below the horizon. Of the remaining 36 events, one has matched well to a simulated cosmic ray event [3].

Since a full-scale BEACON instrument would be expected to handle hundreds of millions of events, a streamlined approach is in development that implements convolutional neural networks (CNN) trained for waveform denoising, and classification of noise, cosmic ray, and other RF sources. To tune the search parameters, the data used for training and validation come from the same data set used in the prior search.

The classification training takes 20,000 events for each class which consist of data from force triggered data labeled as noise, RF triggered data labeled as other RF sources, and simulated cosmic ray waveforms with added noise from other force triggered data labeled as cosmic rays. The network architecture follows the design of other CNN's used to classify time-series data [9]. The confusion matrix for the classifier and event reduction based on different class probability cuts is shown in Figure 3. A cosmic ray event can be correctly identified 99.28% of the time, with a 0.12% false positive rate. Based on the false positive rate, we anticipate reducing data sets of millions of events down to thousands of events which can be further classified using the expected cosmic ray event characteristics.

Since reconstructed direction comes from correlating RF signals [3], noise increases the chance to mis-reconstruct events near the horizon, where a reconstruction cut is placed. This is the importance of the denoiser. The denoiser architecture has layers similar to the classifier's, but includes upsampling layers at the end to output a waveform. It is optimized to minimize the loss comparing inputs of simulated CRs with force trigger noise to noiseless simulated CR waveforms. The same CR simulation and noise dataset used for the classifier also train and validate the denoiser. As shown in Figure 4, the denoiser improves the reconstruction precision by an order of magnitude as compared to the prior sine-subtraction method.

Optimizing the effectiveness of CNN's for classification and denoising is currently being investigated. The CNN cuts still pass questionable events, but has always successfully passed the cosmic ray candidate from the previous search. Combining the CNNs with the parameters used in the prior search could also help to finalize a search technique. With the advent of the



p_{CR} Cutc	Events Remaining	% of Events Cut
0.5	17,092	99.85%
0.75	12,263	99.89%
0.9	9,050	99.92%
0.95	7,452	99.94%
0.99	5,203	99.95%

Figure 3: Performance of the classifier CNN trained to distinguish noise, cosmic ray, and other RF source waveforms. The left displays the confusion matrix which identifies how often the classifier labels a waveform correctly or incorrectly. The right displays the effectiveness of cuts for different thresholds of probability that a given event is classified as a cosmic ray.

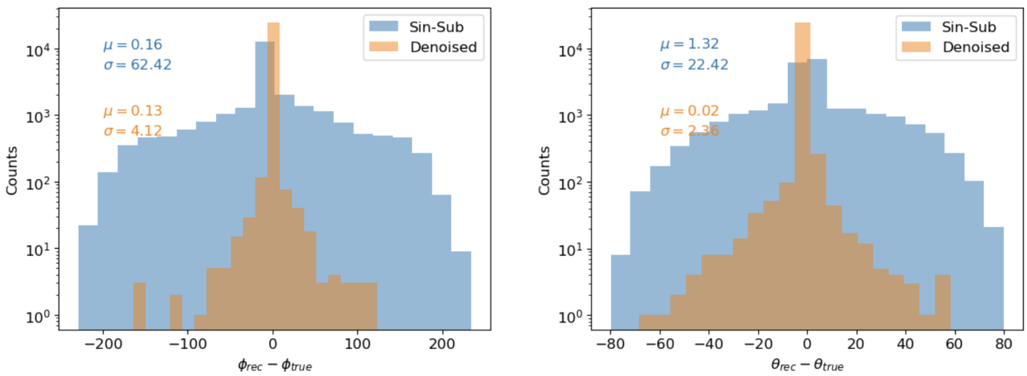


Figure 4: The performance of the CNN denoiser on the reconstructed arrival azimuths (left) and zeniths (right), compared to a sine-subtraction method. Both methods reconstruct using correlation of waveforms on the array and fitting a plane wave. When denoised, the correlation peak width decreases and sidelobes are suppressed, resulting in a more precise reconstruction indicated by the lower standard deviation marked by σ.

2023 deployment of the BEACON prototype, these methods can be validated even further with an independent population of CR's identified from muon fluxes in a scintillator array.

5. Cosmic Ray Search with BEACON Prototype 2023

The goal of the 2023 BEACON prototype is to validate RF-only search methods by comparing against CR populations obtained using secondary muons in the scintillator array. The scintillator array is placed amongst the radio antennas, and are tilted towards the East at nearly 15° to match the slope. While a better sensitivity overlap could be achieved by facing the scintillator panels directly East like the radio antennas, the scintillators would likely face structural integrity challenges in the high altitude winds.

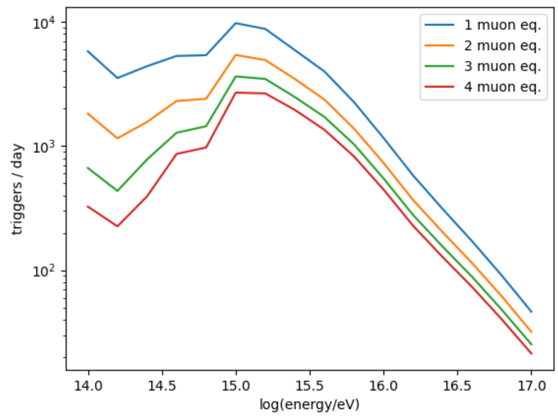


Figure 5: An estimate event rate for the 2023 BEACON prototype scintillator array, obtained from simulations in CORSIKA and GEANT-4. Extrapolating to higher energies, we expect roughly 0.1 to 100 events per day (compared to 0.77 events per day in RF).

In the context of verifying RF methods, a cosmic ray search with the scintillators is not necessary for all events. Simulations using CORSIKA and GEANT-4 for a simplified scintillator model give an estimated event rate shown in Figure 5. Extrapolating to the RF-sensitive region shown previously in Figure 2, the expected scintillator triggers for high energy CRs is 0.1 to 100 events per day, which may be considerably higher than the expected 0.77 events per day in RF. Combined with the expected 1000's of events from lower energies, a CR population for all events would not be meaningful for the RF optimization. To obtain a CR population that can be used to verify RF-only search methods, we prioritize the scintillator CR search to CR candidates that would give rise to RF likely seen in the radio array. The distribution of these events is expected to be dominated by the RF constraints, and thus should be highly energetic and highly inclined.

The event direction reconstruction with the scintillator array is calculated using arrival time differences of scintillator pulses with respect to one another. Then we minimize the loss function at each azimuth and zenith bin,

$$\chi(\theta,\phi)^2 = \sum_{ij} \frac{(\Delta t_{\mathrm{meas},ij}(\theta,\phi) - \Delta t_{\mathrm{exp},ij}(\theta,\phi))^2}{\delta(\Delta t_{\mathrm{meas},ij}(\theta,\phi))^2}$$

where the expected time differences $\Delta t_{\mathrm{exp},ij}$ are obtained using calibrated antenna positions and a plane wave assumption.

The reconstruction distribution of all scintillator events is shown on the left in Figure 6. It is centered nearly at 30° zenith and dips towards the horizon at the East. While not yet extensively studied, the distribution is expected to be the result of the scintillator orientation and high altitude effects on the muonic flux [10].

To search for a CR population with the scintillator array, we start with quality and reconstruction cuts. The digitized V_{max} is constrained within 10 and 120 ADU (127 is the DAQ maximum) to prevent low and saturated pulses. The number of peaks appearing in an event waveform is constrained to less than 5 peaks, conservatively allowing the possibility of a strong air shower producing multiple

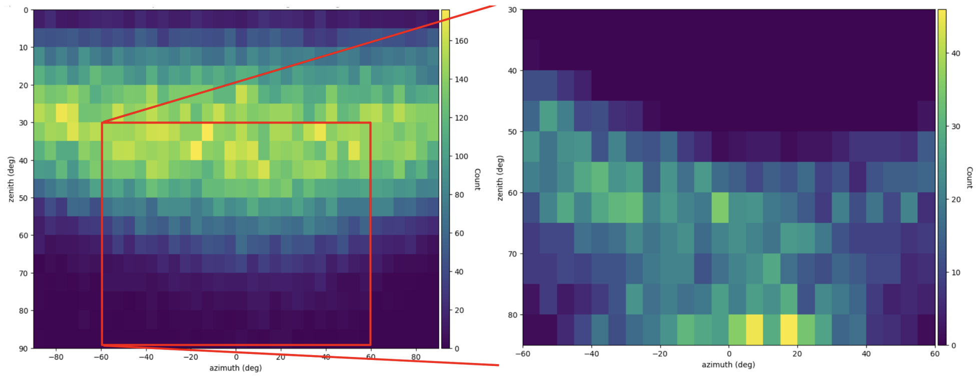


Figure 6: The distribution of all triggered scintillator events over about 70 days on the left and the distribution after a few test quality cuts based on optimizing for a CR population that could produce RF seen in the radio array.

peaks, and cutting events with abnormal signals (e.g. lightning strikes or unknown glitches). Finally, the direction reconstruction is constrained to $\chi^2 < 1$, based on the data χ^2 distributions. For data from the first few months of observing, the distribution, as shown on the right in Figure 6, is in better agreement with the RF distribution shown previously in Figure 2. The optimization and addition of cuts for deciding final cut parameters are being investigated.

Upon inspection, most of the remaining events from these initial cuts have either no coincident RF signal, or have RF signals that do not have the expected cosmic ray characteristics. Triggering on events with three or four pulses in the scintillators mitigates chance coincidences from dark counts, but additional study on the scintillator electronics will be needed to quantify the statistics of such events. Further, a study on the statistical backgrounds using forced triggers will be needed to quantify chance coincidences of scintillators with frequent RFI. Calibration of the scintillators to obtain a map of event waveforms to energies is in progress, which can introduce a cut on energy. Further, simulations of RF and scintillator coincident events are being developed which will validate the obtained distributions and events, and provide templates to check candidate events.

6. Conclusion

The results from the 2021 BEACON prototype's cosmic ray search demonstrate the instrument's ability to detect RF impulsive events. The use of CNNs for waveform classification and denoising look promising as a dedicated process to pass probable cosmic ray events, which is essential when handling the large data volumes that could be expected from a full BEACON instrument.

The addition of a scintillator array in the 2023 upgrades can eventually provide an independent population of cosmic rays, that can be used to refine the techniques of an RF-only search. Developments to optimize this CR search from the muonic component of air showers are in progress. The improved search should identify and characterize a cosmic ray population that can be validated with the expected flux measurements and thus provide experimental evidence of a full BEACON instrument's sensitivity to RF showers induced by highly energetic τ_ν's.

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References

[1] S. Wissel et al., *Prospects for high-elevation radio detection of >100 PeV tau neutrinos*, *JCAP* **11** (2020) 065 [2004.12718].

[2] K. Hughes, J. Alvarez-Muniz, A. Cummings, W.C. Jr., C. Deaconu, G. Hallinan et al., *Towards Interferometric Triggering on Air Showers Induced by Tau Neutrino Interactions*, in *Proceedings of 36th International Cosmic Ray Conference — PoS(ICRC2019)*, vol. 358, p. 917, 2019, DOI.

[3] D. Southall, C. Deaconu, V. Decoene, E. Oberla, A. Zeolla, J. Alvarez-Muñiz et al., *Design and initial performance of the prototype for the beacon instrument for detection of ultrahigh energy particles*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **1048** (2023) 167889.

[4] P. Allison, S. Archambault, R. Bard, J. Beatty, M. Beheler-Amass, D. Besson et al., *Design and performance of an interferometric trigger array for radio detection of high-energy neutrinos*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **930** (2019) 112.

[5] T. Huber, J. Kelley, S. Kunwar and D. Tosi, *The IceTop Scintillator Upgrade*, in *Proceedings of 35th International Cosmic Ray Conference — PoS(ICRC2017)*, vol. 301, p. 401, 2017, DOI.

[6] A. Zeolla, S.A. Wissel, J. Alvarez-Muñiz, W. Carvalho Jr., A.C. Cummings, Z. Curtis-Ginsberg et al., *Modeling and Validating RF-Only Interferometric Triggering with Cosmic Rays for BEACON*, in *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, vol. 395, p. 1072, 2021, DOI.

[7] J. Alvarez-Muñiz, W.R. Carvalho and E. Zas, *Monte carlo simulations of radio pulses in atmospheric showers using zhaires*, *Astroparticle Physics* **35** (2012) 325–341.

[8] T.P.A. Collaboration, A. Aab, P. Abreu, M. Aglietta, I.F.M. Albuquerque, I. Allekotte et al., *The pierre auger observatory: Contributions to the 35th international cosmic ray conference (icrc 2017)*, 2017.

[9] Z. Wang, W. Yan and T. Oates, *Time series classification from scratch with deep neural networks: A strong baseline*, 2016.

[10] Particle Data Group collaboration, *Review of particle physics*, *Phys. Rev. D* **110** (2024) 030001.