Mountaintop Neutrino Detection: a $\nu_\tau$ concept

By

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Abstract

High-energy neutrinos traveling from the distant universe produce detectable signals at radio frequencies after interacting with the earth or its atmosphere. This is the principle behind a new experiment, the BEamforming Elevated Array for COsmogenic Neutrinos, or BEACON. BEACON will be a high altitude array of antennas that is sensitive to up-going tau neutrinos ($\nu_\tau$). These elementary particles serve as sources of information about the extraordinarily high energy events in the universe that create them, and also the laws of particle physics that govern their behavior. This report details the construction of a transient detector used to characterize site locations for future BEACON arrays. This transient detector and used in a field test at Owen’s Valley to assess the suitability of White Mountain Research Station as a potential site location and to motivate future design parameters for the first BEACON array to be built summer 2018.

1 Introduction

Neutrino astrophysics is an emerging field of physics seeking to utilize neutrinos as a source of information about the highest energy events in the universe. Neutrinos are elementary particles that interact with other particles of matter through the weak force. Because weak interactions occur only at sub-atomic distances, high-energy neutrinos produced by extremely distant sources are undeflected by other matter as they travel through space, carrying with them information about high-energy cosmic events far off in our universe.

A new experiment, the BEamforming Elevated Array for COsmogenic Neutrinos (BEACON), proposes to detect and measure the flux of high-energy (100 PeV to 10 EeV) tau neutrinos from outside of our galaxy. The current goal of BEACON is to design and build many antenna arrays at high elevation sites around the world, allowing for a large field of view. Given the low flux of neutrinos, combined with the difficulty of detecting an interaction, a large area is necessary to increase the number of potentially discoverable neutrinos. BEACON would provide an additional method of multi-messenger astronomy, a growing field correlating astronomical observations of many different messengers, ie. gamma rays, neutrinos, and even gravitational waves, to a single source or event. The first example of multi-messenger astronomy came with recent campaign to correlate neutrinos discovered by IceCube with the location of a known blazar, proving blazars are a source of astrophysical neutrinos [7] [20].

Radio-frequency (RF) experiments like BEACON face a great challenge in lowering their noise background due to the prevalence of RF technology. Many types of applications broadcast in the RF band, including cell phone signals, car radios, weather radar, and many more. This RF interference (RFI)
makes detecting a single neutrino impulse extremely difficult. To limit this, site locations are selected
that are as radio-quiet as possible, and what noise backgrounds exist must be carefully measured. In
order to facilitate this process, a transient detector that can measure impulsive waveforms and rates and
power spectra was designed and built here at Cal Poly. This transient detector was taken to a potential
site location at the Owen’s Valley Radio Observatory for initial field testing. The design of the detector
and site characterization results are the main results of this project.

2 BEACON

2.1 The Tau Neutrino and its Implications

Neutrinos are elementary particles that interact very weakly with other particles of matter. Because they
interact rarely, the highest-energy (>PeV) cosmogenic neutrinos produced by extremely distant sources
can reach Earth unimpeded, carrying with them information about high-energy cosmic events far off in
our universe. These high energy neutrinos are produced by Ultra High Energy Cosmic Ray (UHECR)
interactions; UHECRs are particles, primarily protons or some heavier nuclei with energies that can reach
above $10^{20}$ eV. The sources of these particles are unknown, but Figure 1 shows the potential accelerators
that could produce such high energy cosmic rays and cosmogenic neutrinos. The most likely candidates
include active galactic nuclei (AGN) and gamma ray bursts (GRBs). For comparison, the largest particle
accelerator on Earth, the LHC at CERN, has a radius of $4.5 \times 10^5$ cm and uses $B = 8 \times 10^4$ G, so with the
same magnetic field strength, the LHC would need to be a factor of $10^{10}$ bigger. Thus the energy scales
of these processes is far greater than anything possible on earth, so the detection of cosmic neutrinos is
imperative to understanding them.

Creation of a cosmogenic neutrino first involves an accelerator producing an Ultra-High Energy
Cosmic Ray (UHECR), an atomic nucleus with energies between $10^{18}$ to $10^{20}$ eV. During their travel,
UHECRs interact with the Cosmic Microwave Background (CMB) and the Extragalactic Background
Light (EBL). In this interaction, a cosmogenic neutrino can be produced two processes: first by the
decay of charged pions produced by photo-pion production

$$\pi^\pm \rightarrow \mu^\pm + \nu_\tau (\bar{\nu}_\tau)$$
and the subsequent muon decay
\[ \mu^\pm \rightarrow e^\pm + \bar{\nu}_\tau (\nu_\tau) + \nu_e (\bar{\nu}_e) \]
and second, by the beta decay of neutrons and nuclei produced by photo-disintegration:
\[ n \rightarrow p + e^- + \bar{\nu}_e \]
again followed by muon decay. Each of these processes has a probability to produce neutrinos in different energy ranges. Neutrinos produced by interactions with EBL have energies of $10^{15}$ eV in the case of photo-pion production and $10^{14}$ eV in neutron decay. These lower energy neutrinos are suppressed compared to the higher energy neutrinos produced by UHECR interactions with the CMB, which have energies at $10^{18}$ and $10^{16}$ eV for the two processes [8].

Neutrinos are produced by sources inside our galaxy as well. The sun produces a flux of about $7 \times 10^{10}$ particles $\cdot$ cm$^{-2} \cdot$ s$^{-1}$, though these neutrinos are much lower energy in the keV to MeV range [14]. Another type of neutrino is produced by cosmic ray interactions in the atmosphere. Called atmospheric neutrinos, they dominate the spectra below 100 TeV and make up the vast majority of neutrinos detected by IceCube [6]. Interestingly, however, IceCube has detected a flux at $> 10^{15}$ eV that is above the expected background of neutrinos produced through this mechanism [1]. Because the spectra of atmospheric neutrinos drops sharply after 100 TeV, it is possible this flux is astrophysical in origin; however,
atmospheric production cannot be excluded by energy alone [2], and another method of determining the origin is necessary.

Figure 2: Expected flux of neutrinos from different sources [17]. Note the overlap in atmospheric and astrophysical neutrinos at the TeV range.

Determining a detected neutrino’s origin is its own challenge, however, and can done by measuring the neutrino’s flavor. Astrophysical neutrinos are expected to be produced in predominantly $\nu_e$ and $\nu_\mu$ flavors, but as neutrinos propagate they change flavor, resulting in a flux at earth that has an equal flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ [12]. However, cosmic ray interactions are not expected to produce $\tau$ neutrinos, and since the interaction occurs in the atmosphere there is not enough distance for the neutrino to change flavor into a $\tau$ [12]. The same is true for solar neutrinos, where the propagation distance is again too small for significant mixing. Therefore, any $\tau$ neutrino detected at earth would be unambiguously cosmogenic in origin. Currently, the IceCube detector is not sensitive to neutrino flavor [5], and therefore cannot constrain the sources of their discovered flux. The goal of BEACON is to build a detector that is sensitive to $\tau$ neutrinos with a high degree of certainty, which would allow confirmation of the IceCube flux and open a window for neutrino astronomy.

2.2 BEACON’s concept

One of the most promising neutrino detection techniques is radio detection. When high-energy particle decays, it produces a cascade of charged particles that scales with energy in GeV. The earth’s magnetic
Figure 3:
A schematic of the BEACON concept: a upgoing $\tau$ neutrino interacts in the earth, producing a $\tau$ lepton which decays upon exit, producing an air shower and subsequently a radio impulse that is detected by a high elevation antenna [22].

Field acts on the charged particles in the shower in a process called the geomagnetic effect, separating the particles and creating a changing current, and thus electromagnetic radiation. Additionally, particle separation due to excess charge creates currents within the particle shower, called Askaryan radiation [13]. Both these effects generate coherent radio-frequency radiation, and the strength and polarization of this radiation is influenced both by the total charge of the shower and the Earth’s magnetic field [10]. Additionally, the electric field strength of the impulse scales linearly with the energy of the original particle and the inverse of the distance. The field strength also depends strongly on the angle of measurement from the original interaction, with signal strength decreasing away from the Cherenkov angle given by $\cos \theta_C = \frac{1}{\beta n}$ where $n$ is the refractive index of the material and $\beta = v/c$ [15]. These impulses can be detected by specialized antennas, sensitive in the broadband range of the signals produced.

BEACON proposes to utilize radio detection techniques to measure cosmogenic $\tau$ neutrinos by using the Earth as a filter. In the model, a cosmogenic $\tau$ neutrino interacts within the earth. This produces a $\tau$ lepton which continues to propagate, as shown in Figure 4. If it exits the earth, the $\tau$ lepton decays after distance $r_{\text{decay}}$ with probability density function $p_{\text{decay}}(r_{\text{decay}} | E_\tau) = \exp -r_{\text{decay}} / D(E_\tau)$, where $D(E_\tau) = 4.9 \text{ km} \ (E_\tau/10^{17} \text{ eV})$, determined from the $\tau$ lepton lifetime [22]. This decay then produces an air shower via the geomagnetic effect and Askaryan radiation, and the decay altitude and signal strength scale with energy of the incident $\nu_\tau$.

BEACON consists of a phased array of antennas, which allows for geometric reconstruction of an event. When a signal reaches the detector, any distance between antennas translates to a difference in
Simulation geometry for a $\nu_\tau$ entering the Earth with incidence angle $\theta$ assuming a sphere of radius $R_{\text{earth}}$ and adjustable ocean or ice depth $D$. The $\nu_\tau$ interacts in the earth and a $\tau$ lepton exits with emergence angle $\bar{\theta}$ [9].

Arrival time at the antennas, shown in Figure 5. We define the position vectors of two antennas as $\vec{R}_i$ and $\vec{R}_j$ with the baseline vector $\vec{R}_i - \vec{R}_j$. For a signal arriving in direction $\vec{r}$, the delay $\Delta \tau$ between the two antennas is given by $c \Delta \tau = \vec{r} \cdot (\vec{R}_j - \vec{R}_i)$ where $c$ is the speed of light. This can be applied to horizontal antennas as well, allowing for directional reconstruction in both $\theta$ and $\phi$. This allows for geometrical discrimination and rejection of any non-upgoing events, a vital characteristic of $\nu_\tau$ interactions, and a way to distinguish tau neutrinos from cosmic ray signals.

Figure 5: Antenna arrays allow for geometric reconstruction of events by utilizing time differences of signals incident on adjacent antennas.

If run for 3 years, BEACON’s expected number of detections depends on the model for expected
neutrino flux at Earth. Figure 6 shows the projected sensitivity of BEACON against neutrino energy and three flux models. In the Kotera flux model, the upper and lower curves correspond to the upper and lower fluxes assuming a mixed cosmic ray composition presented in [18]. The IceCube flux is extrapolated from IceCube 2015 and 2016 search results with the upper and lower curves corresponding to 68% confidence interval power law fits [3] [4]. The upper and lower bound of the Romero-Wolf & Ave flux correspond to the 68% confidence interval in the posterior distribution of flux curves given their constraints on cosmogenic model parameters [19]. The UHF (200-1200 MHz) band is more sensitive to low energy events, while the VHF (30-300 MHz) band is more sensitive to higher energy events. With both bands carrying potential information, determination of which band to implement in the first stage design will be a product of field testing, as it is likely that one band will be noisier than the other.

![BEACON 3 Years](image)

Figure 6: Flux vs. predicted sensitivity for BEACON given design variations.

Figure 7 shows the expected number of events expected given a frequency band, number of antennas, array elevation, and flux model. The red shaded regions are VHF (30-300 MHz) and blue are UHF (200-1200 MHz). For both bands, additional antennas increases the likelihood of a detection (Figure 7b). The altitude of the array also affects the chance of detection, as shown in Figure 7a. Given an array of 10 antennas at 3 km, BEACON could expect to detect 1-5 neutrinos in a 3 year period, or reject the mixed composition Kotera models. While a neutrino detection is the preferable result, model rejection would
constrain the possible types and maximum energies of cosmogenic neutrino sources.

Figure 7: Number of events expected in a 3-year period depending on elevation and number of antennas, assuming a 120° field of view over rock [22].

An important advantage of BEACON is scalability. Antenna arrays are cheap and easy to implement, and high altitude, RF quiet sites are easier to access and more common than comparable experiments’ locations, like IceCube and ARA in Antarctica. The easiest way to increase BEACON’s likelihood of detection is to add more stations, increasing BEACON’s field of view and therefore sensitivity. Multiple arrays could be potentially even be built within one high-elevation site, which would make increasing sensitivity even easier. A calculation can be made of how far apart each station has to be to be completely independent, ie. have no chance of two stations detecting the same event. Simulations of $\nu_\tau$ interactions and subsequent air showers show that the beam width of the shower is $2.5^\circ$ for VHF. For UHF, the beam is centered at $1.25^\circ$ with the signal breaking into two $0.5^\circ$ cones $0.25^\circ$ from the shower direction. The distance from the detector to the horizon is given, in km, by $d_H = 3.57\sqrt{a}$. For an altitude $a = 3$ km, $d_H = 196$ km, which is effectively the furthest event the detector can see. Using this distance and the beam width to draw a triangle, as shown in Figure 8, the opposite side can be found to be 8.5 km for VHF and 5.1 km for UHF. Therefore, for a station to be independent in both frequency bands, it should be at least 8.5 km away from the nearest station. This calculation assumes that the $\tau$ lepton decays at ground level, which is justifiable for low energy particles which have smaller decay lengths. For higher energy particles with higher altitude decays, the distance between stations would need to be increased. However, this calculation shows that multiple arrays could be easily be set in the same mountain range, simplifying the logistics of increasing BEACON’s effective area.
2.3 Site Characterization

Before any BEACON array can be built, the RF noise environment of a potential site must be characterized. There are many uses of RF signals, including telecommunications, radio stations, weather reports, local police channels, etc. This makes finding a radio-quiet area extremely difficult, and a completely noise-free area impossible near populated areas. However, experiments can combat this by thoroughly measuring and understanding the background at each site. This involves measuring the continuous-wave (CW) and impulsive noise present at the site. All of these characteristics go into determining whether the site is suitable for a BEACON array and the final array design. It is possible to limit the noise background of a potential site in a few ways. First, the location of the array can be placed in as remote of an area as possible, limiting the amount of human-generated noise. Second, the antennas can be pointed away from the strongest sources of noise, like nearby cities, power lines, or cell phone towers. Third, the antennas and frequency band of the array can be specifically chosen in a radio-quiet band, and notch filters can be added to the system to cut out any persistent single-frequency signals. Fourth, the trigger can be designed to reject known sources of RFI. Of course, this requires a thorough understanding of the sources and characteristics of the background at any potential site before final design choices are made.

Other than anthropogenic, or human-caused noise, there are three main sources of noise in radio detection: galactic, system, and ground noise. System noise arises from thermal noise from components of the system, and can be mitigated by choosing low-noise amplifiers and other high-quality components. The system noise is quantified by its noise factor, which is found by taking the ratio of the noise output of
the system to the noise output of an “ideal” system, given identical gain, bandwidth, and matched sources at the standard noise temperature \( T_0 = 290 \, \text{K} \). We can define the noise factor, \( F \), by the Signal-to-Noise Ratio (SNR) of the signal going into the system over the SNR of the signal coming out of the system:

\[
F = \frac{\text{SNR}_{\text{in}}}{\text{SNR}_{\text{out}}} \tag{1}
\]

The noise factor \( F \) is related to the noise temperature by the equation

\[
F = \frac{T + T_0}{T_0} \tag{2}
\]

where \( F \) is the noise factor, \( T \) is the noise temperature in K, and \( T_0 = 290\,\text{K} \). The noise figure (NF) is defined as the noise factor in dB,

\[
NF = 10 \log_{10} F \tag{3}
\]

When a system involves a single load, the noise power is given by \( kTB \), where \( k \) is Boltzmann’s constant, \( T \) is the noise temperature of the load, and \( B \) is the measurement bandwidth. The noise factor of a system with multiple active components is calculated using the Friis formula,

\[
F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots + \frac{F_n - 1}{G_1G_2G_3 \cdots G_{n-1}} \tag{4}
\]

The next type of noise is galactic noise, which originates from synchrotron emission in the galaxy. Measurements of this noise in the frequency range of interest has been measured and modeled by many sources [11], and can be defined by the equation:

\[
I_\nu = I_g \nu^{-0.52} \frac{1 - \exp[\tau(\nu)]}{\tau(\nu)} + I_{eg} \nu^{-0.80} \exp[-\tau(\nu)] \tag{5}
\]

where \( \nu \) is the frequency in MHz, the first term describes the galactic contribution, \( I_g = 2.48 \times 10^{-20} \), the second term describes the extragalactic contribution, \( I_{eg} = 1.06 \times 10^{-20} \) and \( \tau(\nu) \) is the opacity in the polar direction, \( \tau(\nu) = 5.0 \nu^{-2.1} \) in units of W m\(^2\) Hz\(^{-1}\) sr\(^{-1}\) [11].

Finally, ground, or thermal, noise is present in the system, which is thermal radiation picked up by the antenna from the ground. This temperature distribution will be written as \( T(\theta, \phi) \). The amount of thermal noise picked up depends on the direction of the antenna and its radiation pattern, which defines the variation in power radiated by an antenna as a function of the direction and distance from the antenna.
For an antenna with a radiation pattern given by \( R(\theta, \phi) \), the ground noise temperature is defined as:

\[
T_{\text{ground}}(\theta, \phi) = \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi R(\theta, \phi) T(\theta, \phi) \sin \theta d\theta d\phi
\]  

(6)

This integrates the thermal noise around the antenna over a sphere, weighted by the radiation pattern. We can re-express the noise power received by the antenna in terms of the antenna’s bandwidth, \( B \),

\[
P_{\text{ground}} = k_B T_{\text{ground}} B
\]  

(7)

In the above equation, \( k_B \) is Boltzmann’s constant \((k_B = 1.38 \times 10^{-23} \text{ Joules/Kelvin} = J/K)\).

The total noise of the system is a combination of each of these noise sources, adding linearly in power. In order for a site to be a good candidate for a BEACON array, the noise level should be thermal-noise limited. This means that the amount of noise present in the system is close to the minimum amount of noise possible, with minimal contributions from anthropogenic noise. A model is required to make that predicts the total noise expected in an ideal environment, including only system, galactic, and ground noise. The system noise is the unknown, as it depends on each component and connection in your signal chain. Once there exists an accurate model of expected noise, measurements of noise at the site will tell you if the noise level is at or above thermal noise. If it is much above thermal noise across the band, it is likely that site is unsuitable for a BEACON array, as any potential neutrino signal would be buried.

3 The Transient Detector

3.1 Design

A transient detector was designed specifically for site characterizations. This detector was built to be taken up to a potential site and record data; it needed to be able to measure the noise background of the site including information like which bands were producing lots of noise, any directionality to the noise, and any transient signal rates.

The resultant transient detector design is shown in Figure 9. Signals are received by either a Seavey horn antenna sensitive in the 200-1200 MHz range or a mini bicone antenna sensitive in the 30MHz - 1 GHz range. After the antenna comes two stages of bandpass filtering and amplification, shown in Figure 10. There were two boxes built in each stage: one for the VHF (30-300 MHz) and one for the
UHF (200-1200) MHz. After the conditioning, the signal is sent into a tunnel diode. The tunnel diode acts as a power integrator, returning the envelope of the impulsive signal. This signal is then passed into a photon counter, which is set to count the number of pulses above a set threshold that it receives in a given period. Additionally, the output from the tunnel diode is recorded on the oscilloscope or a spectrum analyzer. This allows for viewing both the noise background and, by triggering on the envelope of the signal, the shape of any observed transients.

Stage 1: Initial amplification and bandpass filtering

VHF Band (30-300 MHz)

UHF Band (200-1200 MHz)

The components in each stage were placed into RF shielded enclosures to limit any external noise.
picked up by the amplifiers. An additional challenge was the voltage requirements of the amplifiers. All the amplifiers required 12 VDC in, except the low noise amplifiers in UHF Stage 1 which required 5 VDC. To accommodate this, a voltage regulator was added to UHF Stage 2 before the bias-tee. This allows a single power supply to power all the boxes and simplifies the set up procedure. The voltage regulator was soldered onto a prototyping board with capacitors on the input and outputs to help stabilize the output and protect against transients, then the board was glued into the box with standoffs. Two sets of boxes were made for each band, so that if any component failed in the field, another box could be easily substituted in. The finished boxes are shown in Figure 11.
Figure 11: Amplifier boxes for VHF Stage 1 and Stage 2. The signal from the antenna (RF In) is bandpass filtered (BPF) before being amplified by a low noise amplifier (LNA), which is powered by a 12 VDC signal fed in through box 2 and coupled to the RF by a bias-tee in each box. In Stage 2, the RF signal is again bandpass filtered before the second stage amp, and then exits to the rest of the signal chain.

3.2 Lab Verification & Calibration

Prior to bringing the amplifier boxes to the field, each one’s gain and noise figure was measured in the lab. The noise figure and gain measurements for each box are shown in Figures 12 and 13.

These measurements dictate the expected noise of our detector. By cascading the measured noise figure and gain, including the antenna response, each box, and 3 dB splitter in the signal chain, using equation 4, we can find the expected system noise. Using equations 5 and 6, we can calculate the expected ground and galactic noise, respectively. Adding these three contributions in power, we can estimate the expected level of our measured noise. This is shown in Figure 14.
Another important characteristic of the transient detector system is its trigger efficiency. For example, if there are 100 pulses sent into the detector, and it records 85 of them, the system would have a trigger efficiency of 85%. The trigger efficiency is mostly dependent on the tunnel diode. The tunnel diode acts as a power integrator, returning the envelope of the signal (see Figure 15). This makes it easier to trigger on neutrino signals, which are < 1 ns wide bipolar signals, requiring a fast trigger. Tunnel diodes are used in RF applications as power integrators due to their extremely fast rise time characteristics; however, the trigger efficiency depends on the SNR of the input signal. In the transient detector, pulses from the tunnel diode are sent into the photon counter. The photon counter has a set discriminator threshold and counting period; it counts every time it receives a pulse with an amplitude above that threshold for the duration of the period. With a high discriminator threshold, very few counts will be triggered by thermal noise, but some pulses may be missed. The system’s trigger efficiency was tested at multiple SNRs. This was done by feeding a noise diode with different Excess Noise Ratios (ENRs) through the transient detector, while coupling a pulse in at a set rate. The ENR is a measure of how much higher the noise produced by
Figure 13: Measured insertion gain for each amplifier stage in both frequency bands and both boxes.

Figure 14: Predicted noise power contributions from thermal, galactic, and system noise.

the noise diode is above thermal noise. With a higher ENR, the SNR seen by the noise diode is lower, meaning that it’s more difficult to distinguish a pulse from noise.
Figure 15: The output of the tunnel diode (blue) is the envelope of the input bipolar pulse (pink).

Figure 16: The tunnel diode response curves at various low Signal to Noise Ratio (SNR). At higher SNRs, better trigger efficiency can be attained at lower discriminator levels.

4 Owen’s Valley Field Test & Site Characterization Results

On May 27 and 28th, the transient detector was taken to Owen’s Valley for an initial field test. The goal of this experiment was to verify the transient detector and find potential improvements to the design for later site characterizations in August, as well as to measure preliminary radio backgrounds in the valley overlooked by the White Mountain Research Station. This characterization will inform final design decisions for a semi-permanent prototype array to be installed in August.

The Owen’s Valley site was located near OVRO (Owen’s Valley Radio Observatory) at a lower
elevation (4480 ft) than the August site, which is near 12,000 ft at Barcroft research station. The transient
detector was set up such that the antenna overlooked the valley and we recorded spectra, spectrograms,
sample waveforms, and impulsive rates in both the VHF and UHF bands. The first day of testing allowed
for troubleshooting of the system and minor adjustments; for instance, we found that the noise power
in the FM band was much stronger than expected, so we added a FM notch filter after the antenna and
before the first stage amp to diminish this effect. The second day of data taking therefore produced more
useful data, and is the focus of the analysis.

Figure 17: VHF antenna overlooking Owen’s Valley during field testing.

Included in Figures 18 and 19 are measured spectra in the horizontal polarization (HPOL) for both
UHF and VHF bands. The highest peaks in each have been identified; most peaks belong to a well-
known RF usage, like FM or TV broadcasting. In the field, we tried to identify a clean (flat and free of
peaks), 50 MHz band in VHF and > 200 MHz band in UHF that could be used for BEACON. We found
that such a band did not exist in the UHF, which was populated by many more narrow spikes, as well
as strong, broadband signals in the cell phone and TV bands. Additionally, the spikes in the UHF band
are much more significant, about 30 dBm higher than those in the VHF band. In contrast, in the VHF
band there were few large spikes below about 90 MHz, leaving a relatively quiet band at 30-80 MHz.
This band still had some small spikes of RFI; there was a large peak at 42.1 MHz that came and went
throughout our measurements which we identified as a highway patrol radio frequency. We were able to
mitigate the signal by adding a tuneable notch filter, but a small spike remained. It was stronger in HPOL than VPOL, and can be seen in Figure 20. We found additional RFI throughout the 30-80 band, though the signal strength was weak, approximately 2-5 dB above baseline, including peaks at 70, 55, and 88.4 MHz which were persistent but variable in amplitude. The 54-88 MHz band is classified as I-band, and is used for local TV broadcasting in the US. Especially of note is the peak at 70MHz, which is a popular amateur radio band. The 70 MHz signal was the strongest in I-band, reaching -50 dBm in HPOL and -45 dBm in VPOL 2021. While RFI exists in the 30-80 MHz band, the signal strength of even the largest peaks was only approximately 5 dB above baseline in VPOL and 10 dB above baseline for HPOL, and they were mostly constant. This makes them easy to filter out with background measurements and either physical RF filters or software filters post-processing. A similar noise characterization will be done at the site of each BEACON array to determine the precise sources of RFI at that location and how to best mitigate them.

<table>
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<th>Use</th>
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<tr>
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<td>FM Radio</td>
</tr>
<tr>
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<td>166.34</td>
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</table>

Figure 18: Spectra in the VHF band, with identified peaks.

After the initial measurement of the spectra, we focused in on the clean band in VHF from 30-80 MHz. To do this, we added two low pass filters with critical frequency $f_{co} = 70$ MHz after the second stage amplifier box. Included in Figures 20-22b are spectra and spectrograms for this band. We found that this frequency range was quiet in both the vertically and horizontally polarized channels, though the VPOL had more transients. This can be seen in the spectrograms, Figures 22a and 22b, which show the change in the power spectrum over time. A spectrogram integrates the power in each frequency bin over a set time interval, and represents the total power in a visual color map, where lighter colors indicate more power. The HPOL spectrogram has far fewer horizontal lines of color variation, which indicate a
broadband signal turning on and off. These broadband transients suggest there are more anthropogenic sources in VPOL. This observation is shown in our measurements of impulsive rates as well. From Figure 23 we can see that the 100 Hz point (where the detector measures a rate of 100 Hz) is at 54 mV in HPOL and 108 mV in VPOL. This indicates that in VPOL, the detector’s threshold would need to be set much higher in order to cut out the majority of transient noise, which would inhibit the detection of low-power signals like neutrinos.

The main result of the Owen’s Valley field testing is the suitability of each of the frequency bands. We found that the VHF band had fewer transients than the UHF band, and was clean in the 30-80 MHz band. This discovery has informed the design of the first BEACON array, which will consist of four dual polarized VHF LWA antennas. Additional takeaways include the successful function of the transient

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<th>Frequency (MHz)</th>
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</tr>
<tr>
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<td>740.0</td>
<td>LPTV</td>
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<tr>
<td>935.5</td>
<td>Fixed Business</td>
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</tbody>
</table>

Figure 20: Measured spectra for the VHF band in HPOL
Figure 21: Measured spectra for the VHF band in VPOL.

(a) HPOL

(b) VPOL

Figure 22: Spectrogram of the 20-100 MHz band in both polarizations.

Figure 23: Threshold scans for both HPOL and VPOL show higher transient activity in VPOL.
detector, which acquired the desired CW and impulsive data. The transient detector will be used again
to do site characterizations at the array location before initial installation. A future focus will be on
improving the portability of the detector and implementing more rugged software for data collection and
in-situ analysis.

5 Conclusion

This project successfully designed and implemented a transient detector for use in BEACON, a new RF
neutrino detection experiment searching for unambiguously cosmogenic tau neutrinos. The BEACON
concept relies on the existence of high-altitude, RF quiet locations for antenna arrays looking down to
detect upward-going showers. The work in this project has shown that such a site exists in the White
Mountains, given that the measured noise levels at a low altitude were thermal-noise-dominated. Future
site testing in August will provide a more thorough analysis of the noise environment, but through this
work, the collaboration has decided to go ahead with a semi-permanent antenna array to be installed in
August, called Proto-BEACON.

As a direct result of the noise measurements in Owen’s Valley, the array will consist of four VHF
antennas, as this was the determined to be the cleaner band. Additional insights provided by the transient
detector field test included the addition of FM notch filters within the Stage 1 box and a greater focus on
portability and ease of use. This improved detector design will be used for site characterization ahead
of the Proto-BEACON installation, as well as during determinations of future potential sites, such as
Hawaii. Although optimistic, a single 10 antenna BEACON array could either conclusively detect a
cosmogenic \( \tau \) neutrino, or disprove one of the most promising models for the neutrino flux. Given the
relative ease and inexpensiveness of installation compared to similar experiments of its kind, BEACON
is an promising new experiment in the field of multi-messenger particle astrophysics.

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References


