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A New Trigger for Detection of PeV to EeV Neutrinos Using a Phased Radio Array

Keith Bechtol*
Wisconsin IceCube Particle Physics Center (WIPAC), Madison, WI 53703, USA
Department of Physics, University of Wisconsin–Madison, Madison, WI 53706, USA
E-mail: keith.bechtol@icecube.wisc.edu

Abigail Vieregg
Department of Physics, Enrico Fermi Institute, University of Chicago, 5640 S Ellis Avenue, Chicago, IL 60637, USA
Kavli Institute for Cosmological Physics, University of Chicago, 933 E 56th Street, Chicago, IL 60637, USA

Andres Romero-Wolf
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

Stephanie Wissel
Department of Physics and Astronomy, University of California, Los Angeles, Los Angeles, CA 90095, USA

The detection of high energy neutrinos (10^{15} – 10^{20} eV or $1 - 10^5$ PeV) is an important step toward understanding the most energetic cosmic accelerators, and would enable tests of fundamental physics at energy scales that cannot easily be achieved on Earth. In this energy range, there are two expected populations of neutrinos: the astrophysical flux observed with IceCube at lower energies ($\sim$ 1 PeV) and the predicted cosmogenic flux at higher energies ($\sim 10^{18}$ eV). Radio detector arrays such as RICE, ANITA, ARA, and ARIANNA exploit the Askaryan effect and the radio transparency of glacial ice, which together enable enormous volumes of ice to be monitored with sparse instrumentation. We describe here the design for a phased radio array that would lower the energy threshold of radio techniques to the PeV scale, allowing measurement of the astrophysical flux observed with IceCube over an extended energy range. Meaningful energy overlap with optical Cherenkov experiments could be used for energy calibration. The phased radio array design would also provide efficient coverage of the large effective volume required to discover cosmogenic neutrinos.

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*Speaker.

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1. Introduction

Ultra-high energy (UHE, > 100 PeV) cosmic neutrinos are anticipated to reveal the most distant, most obscured, and highest energy particle accelerators in the Universe. UHE neutrinos are expected from interactions of UHE cosmic rays with the cosmic microwave background (1), and additional contributions may arise from prompt emission at individual sources. The spectrum of UHE neutrinos is a sensitive discriminator of the cosmological evolution of UHE sources, as well as the composition of UHE cosmic rays (2). UHE neutrinos may also enable several tests of fundamental physics, including constraints on the neutrino-nucleon interaction cross section at center-of-momentum energies ~ 100 TeV (3; 4), and searches for Lorentz invariance violation (5).

One promising way to detect the highest energy neutrinos is through the coherent, impulsive radio emission from electromagnetic showers induced by neutrino interactions in a dielectric — the Askaryan effect (6). Beam test measurements (7; 8; 9) confirm that the Cherenkov power scales as the square of the particle cascade energy at frequencies below 1 GHz and validate the expected angular emission pattern and frequency dependence from numerical simulations (10). Glacial ice is an excellent medium for detection of high energy neutrinos with a radio attenuation length $L_\alpha \sim 1$ km (11; 12) which allows large volumes to be monitored with sparse instrumentation.

Current radio detector arrays have energy thresholds matched to the energy scale of cosmogenic neutrinos, $\gtrsim 50$ PeV. Here, we describe a trigger configuration using phased radio arrays to detect neutrinos at an energy scale of ~ 1 PeV. This lower energy threshold would provide meaningful overlap with optical Cherenkov detectors for energy calibration, and importantly, may provide an efficient means to achieve the large effective volume needed to study the astrophysical neutrino flux reported by IceCube, which extends to at least 2 PeV (13). At the same time, the proposed trigger configuration would increase the acceptance for UHE neutrinos.

2. Phased Array Concept

The ARA (14) and ARIANNA (15) experiments are ground-based radio arrays in early stages of development with a small number of stations deployed in Antarctica. ARA and ARIANNA both use a similar fundamental experimental design: an array of antennas (16 in the case of ARA) and a data acquisition system comprise a single station. The stations are quasi-independent in that each individual station can reconstruct a neutrino event. For ground-based experiments, multiple stations can be positioned several kilometers apart to cover large volumes of ice, and the neutrino event rate increases linearly with the number of stations.

In current and previously-deployed experiments, a threshold-crossing trigger is used to determine when individual antennas receive an excess in power above typical thermal noise (16; 17). If a sufficient number of coincident antenna-level triggers occur within a short time window, a station-level trigger is formed, and the antenna waveforms of the candidate neutrino event are digitized and recorded. Essentially this type of combinatoric threshold-crossing trigger is only sensitive to the power seen by individual antennas as a function of time.

The key to lowering the energy threshold of a radio experiment and increasing sensitivity at higher energies is the ability to distinguish weak neutrino-induced impulsive signals from thermal noise. For antennas triggering independently, the amplitude of the thermal noise is determined by the temperature of the ice and the noise temperature of the amplifiers. Combining signals from many antennas in a *phased array configuration* averages down the uncorrelated thermal noise from each antenna while maintaining the same signal strength for real plane-wave signals. If we combine the signals from multiple antennas with the proper time delays to account for the distance between antennas, we can effectively increase the gain of the system of antennas for incoming plane waves from a given direction. Many different sets of delays with the same antennas can create multiple effective antenna beam patterns that would together cover the same solid angle as each individual antenna but with much higher gain. The effective gain G_{eff} of the system is determined by the gain of each individual antenna, G, and the number of antennas, N, by:

$$G_{\mathrm{eff}} = 10\log_{10}(N \times 10^{G/10}). \tag{2.1}$$

Such interferometric techniques have been extensively used in radio astronomy (reviewed by 18).

The trigger threshold of radio detectors is typically set by the maximum rate at which antenna waveforms can be digitized and recorded while maintaining a high livetime fraction. For a phased array, *each trigger channel corresponds to a single effective beam*, and the station-level trigger is the union of simple threshold-crossing triggers on the individual effective beams of the phased array, rather than individual antennas. In this configuration, the threshold on the electric field could be reduced by roughly the square root of the number of antennas that are phased together while maintaining the same overall trigger rate per trigger channel. Since the electric field produced at the antenna from Askaryan emission scales linearly with the energy in the particle cascade, this reduction in the effective electric field threshold directly translates into a lower energy threshold for finding neutrinos. Equivalently, the effective volume of the detector is increased at fixed neutrino energy since events could be detected from farther away. To minimize the number of trigger channels, the phased array that provides the trigger needs to be as closely packed as possible such that each effective beam covers a large solid angle.

Further sensitivity gains may be possible by recognizing that the antennas that form the trigger do not have to be the same antennas used for detailed event analysis. Indeed, it is advantageous to construct two distinct, co-located antenna arrays. The first is the phased array that is as closely packed as possible and provides the most sensitive trigger possible (the "trigger array"). The second array is a set of antennas that are spaced further apart to provide the best pointing resolution and energy resolution possible for neutrino events (the "pointing array"). This two-component station design represents a departure from all previous radio detector neutrino experiments.

2.1 Example: a 16-channel station

We describe here the example of a 16-channel station that uses dipole-like antennas deployed down boreholes beneath the firn layer of a deep glacier. Possible sites for such a station, or set of stations, include the South Pole, where the array would be $\sim$ 200 m below the surface and the ice is $\sim$ 2.8 km deep, and Summit Station in Greenland, where the array would be $\sim$ 100 m below the surface and the ice is $\sim$ 3.0 km deep.

One possible station layout is shown in Figure 1. A trigger array is constructed of 16 dipole antennas strung vertically down one borehole as close together as possible. This configuration would naturally be sensitive to vertically-polarized signals, although one could combine signals

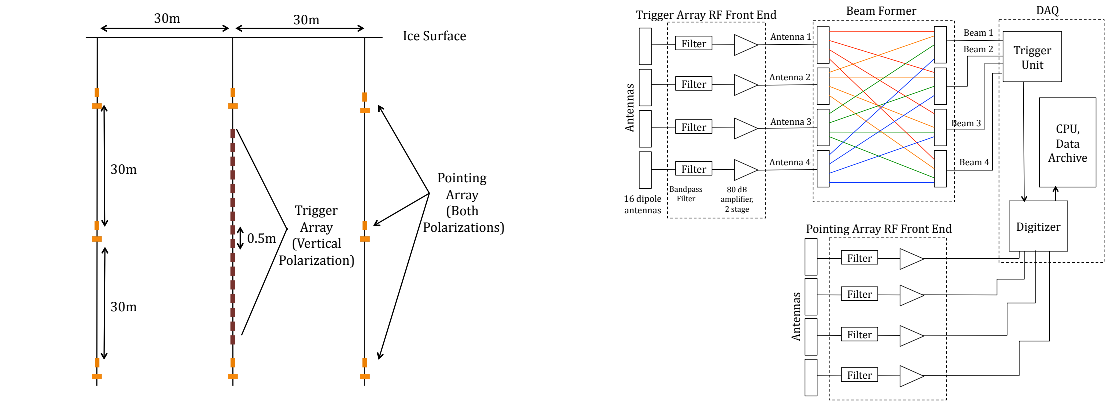

Figure 1: *Left*: An example station layout for a 16-antenna phased trigger array and accompanying pointing array. *Right*: An example layout of the radio frequency chain of a 16-antenna phased trigger array and accompanying pointing array. For simplicity, not all channel paths are depicted.

from orthogonally-polarized antennas to create an unpolarized trigger. The pointing array would be constructed of additional antennas, with both horizontal and vertical polarization sensitivity, and would require at least two additional boreholes to uniquely determine the incident direction, timing, and polarization of the radio emission and thus the incoming direction of the neutrino. We would only need to digitize the signals from the pointing array antennas.

The effective gain of such a 16-channel trigger array of dipole antennas calculated using Equation 2.1 is 14.2 dBi (compared to 2.15 dBi for a single dipole), which corresponds to a factor of $\sim$4 in electric field threshold. The FWHM of the beam of a single trigger channel is 5.4° in elevation with complete azimuthal coverage for this configuration. By adjusting the delays among antennas in different trigger channels, we can cover the relevant range of solid angle for incoming emission from visible neutrino events with only $\sim$15 beams.

2.2 Achieving An Energy Threshold of 1 PeV

The phased array design is scalable and can be configured to achieve an even lower energy threshold. For example, a phased array with 400 dipole antennas would have an effective gain of 28.2 dBi, and would push the electric field threshold down by a factor of $\sim$20 compared to currently-implemented techniques. For large numbers of antennas, the single-borehole configuration for the trigger array is no longer optimal. To keep the size of the trigger array compact, trigger antennas would be deployed down multiple boreholes.

3. Expected Performance

We have developed a Monte Carlo simulation package to quantify the acceptance of various radio detector configurations, and more specifically, investigate the advantages of a phased array design. The simulation formalism and assumed physics input are described in (19). Rather than focusing on specific antenna designs, signal processing chains, and analysis algorithms, we have kept the simulations general by defining signal detection thresholds in terms of the electric field

Station Configuration	Power Law	Power Law with Cutoff	Optimistic Cosmogenic	Pessimistic Cosmogenic
16-antenna	0.9	0.0	7.7	2.3
16-antenna, phased	3.8	0.1	19.6	6.0
400-antenna, phased	18.4	2.2	52.9	15.6

Table 1: Expectation values for the total number of events detected in 3 years for 10 stations in different configurations for spectra based on IceCube observations (13) and for cosmogenic models (2).

strength arriving at the antennas. In this case, different station configurations correspond to different electric field thresholds, as described above. Depending on the particular system deployed, the overall results could shift up or down (by less than a factor of two), but the relative comparisons between configurations are valid.

For this study, we have chosen to simulate the experiment at Summit Station in Greenland with antennas 100 m below the surface. Moving the detectors to South Pole at a depth of 200 m below the surface would increase the acceptance by $< 20\%$ due to a longer radio attenuation length in ice at the South Pole (11). We have chosen to simulate 10 stations for this study, but we note that the acceptance changes linearly with the number of stations, since stations trigger independently.

Figure 2 shows the volumetric acceptance of a 10-station detector as a function of energy for three different station configurations. We also show for comparison the acceptance corresponding to two IceCube analyses optimized for different energy ranges (20; 21). The IceCube curves in the figure include analysis efficiency, whereas the results of our simulation do not, so the curves are not directly comparable. The standard method, shown with the yellow line in Figure 2, is comparable to the approach of the ARA experiment but with only 10 stations.

Figure 3 shows the number of events detected as a function of energy for the same three detector configurations shown in Figure 2 for a variety of astrophysical and cosmogenic models. We show event rates for an $E^{-2.3}$ power law based on IceCube observations (13), an $E^{-2.3}$ power law with a 1 PeV exponential cutoff (13), and optimistic and pessimistic cosmogenic models (2). Table 1 summarizes the expected total number of events detected with each detector configuration for each model. A harder spectrum for PeV-scale neutrinos would yield a higher event rate.

By phasing the antennas in a 16-antenna array, the UHE neutrino event rate could be increased by more than a factor of two over the non-phased case, and sensitivity extended to lower energies. The 16-antenna phased configuration achieves a low enough energy threshold to distinguish an $E^{-2.3}$ power law extrapolation of the observed IceCube spectrum from one that has a cutoff at the PeV scale. Phasing more antennas lowers the threshold even further, and makes marked improvements in event rates.As is evident in Figure 2, 10 stations of 16-antenna phased arrays have a larger acceptance than IceCube above 30 PeV, and the acceptance grows faster with energy than IceCube, so that by 10^{18} eV the acceptance is an order of magnitude more than IceCube. 10 stations of the 400-antenna phased arrays have a larger acceptance than IceCube above 1 PeV.

4. Conclusions

We have described a new trigger for an in-ice phased radio array that is designed to achieve

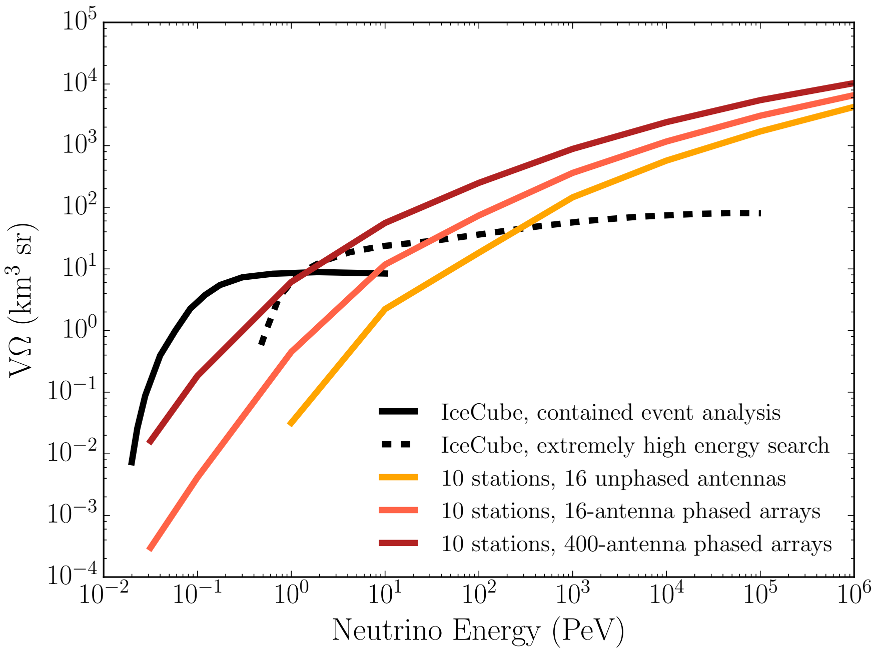

Figure 2: Effective Volume vs. Energy for 10 stations installed 100 m below the surface at Summit Station, Greenland. The yellow line is for 16-channel stations with no phasing, the orange line is for similar stations but with phasing, and the red line is for 400-antenna phased array stations. For each radio array configuration, the volumetric acceptance is presented at the trigger level. Black curves indicate the volumetric acceptance for two difference analyses with IceCube optimized for different energy ranges (20; 21).

sensitivity to the astrophysical neutrino flux at 1 PeV and above, provide energy overlap with IceCube for calibration, and discover cosmogenic neutrinos in an efficient way. The reconstruction of triggered events with low signal-to-noise in individual antennas is a topic of further investigation and may limit the gains in sensitivity that can be achieved in practice. A prototype phased array has been deployed at Summit Station, Greenland in June 2015 to explore this and other potential challenges of the phased-array design (22).

It is worth noting the scalability of the radio technique for increasing acceptance at all energies. The acceptance increases linearly with the number of stations, and further gains can be realized by phasing more antennas in each station, particularly at PeV neutrino energies. An array of 100 stations each with 400-antenna phased arrays could detect hundreds of neutrinos at PeV energies and above each year.

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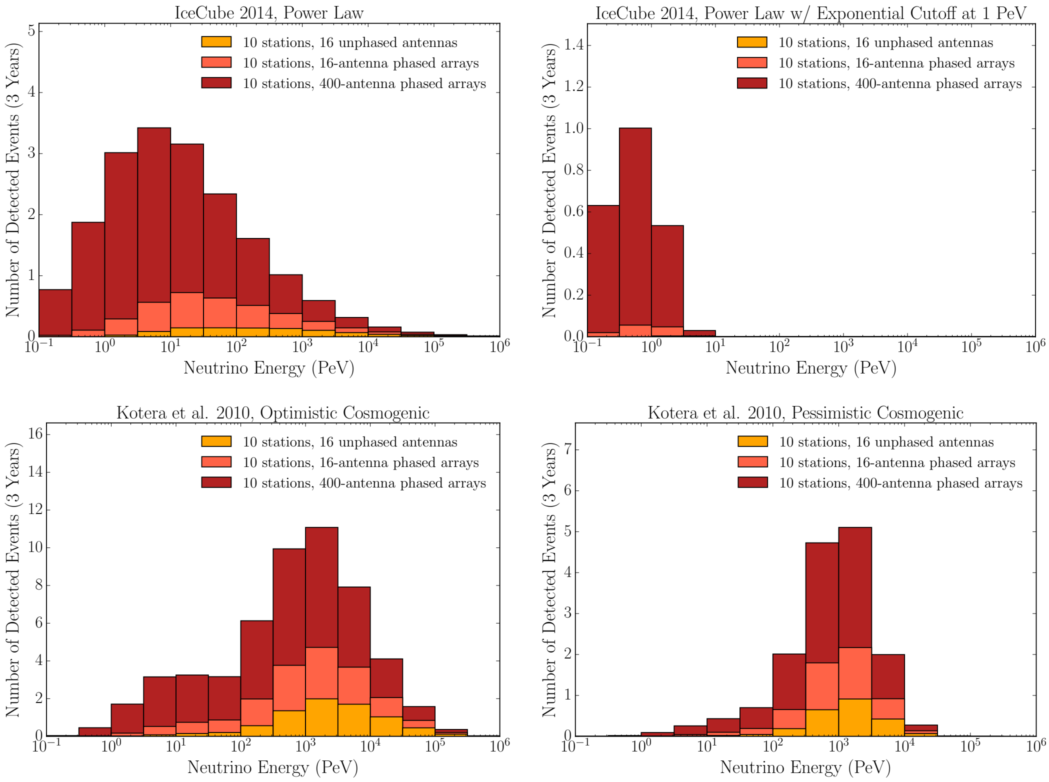

Figure 3: Event Rates vs. Energy for a variety of neutrino models. Event rates for three years of observation for 10 stations installed 100 m below the surface at Summit Station, Greenland. 16-channel stations with no phasing are shown in yellow, 16-channel stations with phasing are shown in orange, and stations with 400 phased antennas are shown in red. The top two panels show event rates based on two possible neutrino spectra based on the IceCube observed neutrino flux (13). The top left panel is an $E^{-2.3}$ power law, and the top right panel is an $E^{-2.3}$ power law with an exponential cutoff at 1 PeV. The bottom two panels show event rates based on optimistic and pessimistic cosmogenic fluxes (2).

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