Phased Antenna Arrays for Radio Detection
of Extremely-High-Energy Neutrinos

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Extremely-High-Energy Neutrinos

Ultra-High-Energy Cosmic Rays (UHECRs) have been detected up to enormous energies, but the production mechanisms remain unknown. At these energies, cosmic rays interact with the cosmic microwave background (CMB) via the Greisen-Zatsepin-Kuzmin (GZK) process:

\[ \nu + \nu_{\text{CMB}} \rightarrow \Delta \rightarrow p + \bar{p} + p + 2 \gamma \]

producing so-called cosmogenic neutrinos at EeV energies. Not only are they excellent cosmic messengers, they are the highest-energy neutrinos we have access to.

In the last few years, IceCube has evinced astrophysical neutrinos at PeV energies. This population, separate from the higher-energy cosmogenics, is of unknown origin.

Radio Detection Mechanism

The low rates and small cross-sections pose immense practical challenges for detecting cosmogenics. One detection mechanism is the Askaryan Effect in dielectric media, such as ice. The cascade produced by an interacting neutrino in the medium has a charge excess moving faster than the speed of light in the medium. This produces radiation coherent at wavelengths larger than the avalanche width (about 10 cm, in ice). Glacial ice is abundant (in Antarctica and Greenland) and also relatively radiotransparent, with km-scale attenuation lengths, thus allowing instrumenting large volumes of ice with few antennas. Examples of experiments using this detection technique are ANTIA, ARIANNA, and ARA.

Phased Antenna Arrays

For the lowest energy threshold, the antennas must be placed in the ice. However, the varying index of refraction near the surface of glacial ice produces shadowing effects, thus requiring burying the antennas deep for maximum effective volume. The small profile required cannot accommodate high-gain antennas, so the threshold cannot be pushed below ~50 PeV, rendering the astrophysical neutrinos invisible.

A phased antenna array delays and adds together the signals from multiple antennas, effectively creating a single high-gain antenna. Each set of delays corresponds to an incoming plane wave direction, which we call a beam. Plane wave signals add coherently in the correct beam, while uncorrelated thermal noise adds incoherently, so the effective SNR increases with the square root of array size.

Expected counts of astrophysical (two different IceCube power laws) and cosmogenic neutrinos (two models) measured in 3 years. As many effects are neglected in this calculation, this should be considered an upper bound.

Development

In two missions to Summit Station in Greenland, a potential detector site, we measured the radio attenuation and deployed a test phased array with an analog beam-former in the ice, measuring the RF noise environment and array performance.

We have also conducted a number of tests in an anechoic chamber, ensuring thermal noise in adjacent antennas is uncorrelated and validating the expected improvement in trigger efficiency.

Next Steps

The next stage is the construction of a phased-array external trigger for an ARA station at the South Pole during the 2017-2018 Antarctic season. This setup will allow direct comparison between a phased and unphased trigger. Unlike the test deployment in Greenland, this deployment will use a digital beam-former, where the signals are digitized and beams are formed in an FPGA in real-time (see Eric Oberla’s poster for details on the hardware).

Pending successful demonstration of the technique a larger phased array deployment will be proposed either at the South Pole or in Greenland. Such a phased array is expected to be sensitive both to the IceCube range of astrophysical neutrinos and the higher-energy cosmogenics.

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