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Development toward a ground-based interferometric phased array for radio detection of high energy neutrinos

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ABSTRACT

The in-ice radio interferometric phased array technique for detection of high energy neutrinos looks for Askaryan emission from neutrinos interacting in large volumes of glacial ice, and is being developed as a way to achieve a low energy threshold and a large effective volume at high energies. The technique is based on coherently summing the impulsive Askaryan signal from multiple antennas, which increases the signal-to-noise ratio for weak signals. We report here on measurements and a simulation of thermal noise correlations between nearby antennas, beamforming of impulsive signals, and a measurement of the expected improvement in trigger efficiency through the phased array technique. We also discuss the noise environment observed with an analog phased array at Summit Station, Greenland, a possible site for an interferometric phased array for radio detection of high energy neutrinos.

1. Introduction

In recent years, the IceCube experiment has detected a population of astrophysical neutrinos with energies up to ~10 PeV [1,2]. The sources of these astrophysical neutrinos remain a mystery, their spectral index remains uncertain, and although there is no evidence for a spectral cutoff, the behavior at higher energies remains unknown [3]. In addition to the astrophysical population discovered by IceCube, there is a separate population of cosmogenic ultra-high energy (UHE) neutrinos ($E > 10^{17}$ eV), created as a byproduct of the GZK process (the interaction of UHE cosmic rays with the cosmic microwave background), that awaits discovery [4–6]. The twin science goals of following up on the IceCube measurement of astrophysical neutrinos at and above PeV energies, and discovering the highest energy cosmogenic neutrinos drive the design of developing and proposed experiments that aim to detect high energy neutrinos.

One promising method for detection of high energy neutrinos is via the Askaryan effect: the coherent, impulsive radio emission from electromagnetic showers induced by neutrinos in a dielectric [7]. At long wavelengths (frequency less than a few GHz), the emission is coherent, so for high energy showers, the long-wavelength radio emission dominates. A large volume of a dielectric material with a long radio attenuation length ($L_\alpha \sim 1$ km), such as glacial ice, is required to

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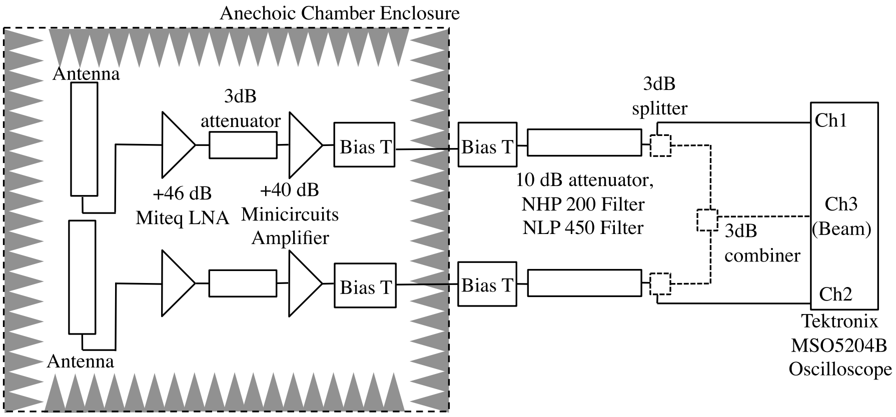

Fig. 1. A schematic of the setup in the anechoic chamber for thermal noise correlation testing and validation of beamforming. For thermal noise correlation testing, there were no splitters or combiners before the oscilloscope. For validation of beamforming, described in Section 3, we added 3 dB splitters to each antenna channel and combined the signals to form a beam in hardware (shown with the dashed lines). We also set up a transmitter 4 m away inside the chamber for the measurements described in Section 3, which is shown schematically in Fig. 6.

detect a significant rate of high energy astrophysical and cosmogenic neutrinos.

There are a variety of current and proposed experiments that search for Askaryan emission from high energy neutrino showers. The ANITA high altitude balloon experiment currently holds the best constraints on the flux of neutrinos above $10^{19.5}$ eV, and the proposed balloon-borne EVA experiment is a novel way to improve sensitivity at these highest energies [8,9]. The ARA and ARIANNA experiments, ground-based radio arrays in early stages of development each with a small number of stations deployed in Antarctica, have energy thresholds $\gtrsim$100 PeV, probing the heart of the cosmogenic neutrino regime [10,11].

The concept for an in-ice radio interferometric phased array for detection of high energy neutrinos was introduced in Ref. [12] and is being explored as a way to push the energy threshold of radio detection down to the PeV scale while increasing the achievable effective volume at the highest energies. Interferometric techniques have been extensively used in radio astronomy (for a review, see [13]) to image radio sources, and here we apply an interferometric technique to improve sensitivity to broadband, impulsive radio signals. Rather than imaging, we are interested in achieving high instantaneous sensitivity to a large solid angle.

An in-ice interferometric phased array coherently combines signals from multiple low-gain antennas deployed down sub-surface boreholes with proper time delays to account for distances between antennas to effectively increase the gain of the system of antennas for incoming plane waves from a given direction. Many different sets of delays of signals from 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 closer the antennas are physically, the fewer beams are needed to cover a given solid angle.

This paper addresses the assumption that a phased array made of closely packed antennas receives uncorrelated noise in each antenna. We show using realistic detector designs in both an anechoic chamber and in the ice in Greenland that thermal noise is uncorrelated between antennas. In developing phased arrays for use in the lab, we also demonstrate how the beamforming technique can be used for impulsive signals in practice.

In Section 2, we discuss measurements of thermal noise correlation between closely-spaced antennas, relevant for an interferometric phased array trigger. Section 3 details a validation of the beamforming technique for impulsive signals in an anechoic chamber. In Section 4, we discuss the implications of beamforming for a realistic triggering scheme. Section 5 reviews and details new measurements of the relevant ice and noise characteristics of Summit Station, Greenland, the site where we performed an *in situ* noise correlation studies of a prototype detector. We conclude in Section 6.

2. Thermal noise correlation studies

One of the underlying assumptions in the interferometric phased array calculations is that the thermal noise measured by each antenna in the array is uncorrelated with the thermal noise measured in its nearest neighboring antenna. The level at which thermal noise signals are correlated between antenna channels is one factor that determines the effective gain achieved by phasing together many antennas. In the limit of fully overlapping antennas, the thermal noise observed from the ice ($\sim$250 K) would be completely correlated, and the noise from the system would be completely uncorrelated ($\sim$75 K for the systems described in this paper). To determine how closely packed the antennas in a phased array can be without introducing a significant correlated noise contribution, we performed tests in an anechoic chamber and designed a simulation of thermal noise to compare to the measurements.

2.1. Noise correlation measurements in an anechoic chamber

2.1.1. Measurement setup

We performed noise correlation measurements using a simple system in an anechoic chamber. Fig. 1 shows a schematic diagram of the system setup, which consists of two antennas laid out end-to-end, with each antenna in its neighbor's null. Signals from each antenna were amplified by a dual-stage front-end amplifier chain that included a 46 dB low-noise amplifier (MITEQ AFS4-00100200-10-15P-4) and a 40 dB amplifier (Mini-Circuits ZKL-1R5) separated by a 3 dB attenuator. DC power for the amplifiers was carried through the radio frequency (RF) cable, coupled by bias tees inside and outside the anechoic chamber. Signals were then filtered using a Mini-Circuits NHP-200 and NLP-450 or NLP-600, depending on the type of antenna used for the test. For all antenna types, which we discuss in Section 2.1.2, we used the NLP-600, except for the broadband dipole antennas that we developed, where we used an NLP-450. We used Times Microwave LMR-240 and LMR-400 cable, and cable lengths were identical in each signal chain. The noise temperature of each channel was $\sim$75 K, dominated by noise from the front-end amplifier. Signals were then read out using a Tektronix MSO5204B oscilloscope, sampling at 5 GSa/s. The walls of the anechoic chamber were between 1 and 3 m from the antennas.

We changed the spacing between the antennas, ranging from as close as physically possible to a distance of over 1.5 m between antenna feeds, to measure the level of correlated noise between channels as a function of the distance between the antennas.