Development Toward a Ground-Based Interferometric Phased Array for Radio Detection of High Energy Neutrinos

J. Avva\textsuperscript{a,b}, K. Bechtol\textsuperscript{c,b}, T. Chesebro\textsuperscript{d}, L. Cremonesi\textsuperscript{e}, C. Deaconu\textsuperscript{h}, A. Gupta\textsuperscript{a}, A. Ludwig\textsuperscript{f,b}, W. Messino\textsuperscript{g}, C. Miki\textsuperscript{e}, R. Nichol\textsuperscript{e}, E. Oberla\textsuperscript{b}, M. Ransom\textsuperscript{a}, A. Romero-Wolf\textsuperscript{f}, D. Saltzberg\textsuperscript{d}, C. Schlupf\textsuperscript{d}, N. Shipp\textsuperscript{b}, G. Varner\textsuperscript{h}, A. G. Vieregg\textsuperscript{f,k,b}, S. A. Wissel\textsuperscript{d}

\textsuperscript{a}Dept. of Physics, University of California Berkeley, Berkeley, CA 94720, USA
\textsuperscript{b}Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
\textsuperscript{c}Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53703, USA
\textsuperscript{d}Dept. of Physics and Astronomy, University of California Los Angeles, Los Angeles, CA 90095, USA
\textsuperscript{e}Dept. of Physics and Astronomy, University College London, London, United Kingdom
\textsuperscript{h}Dept. of Physics, University of Chicago, Chicago, IL 60637, USA
\textsuperscript{g}Electrical Engineering Dept., California Polytechnic State University, San Luis Obispo, CA 93407, USA
\textsuperscript{i}Dept. of Physics and Astronomy, University of Hawaii, Manoa, HI 96822, USA
\textsuperscript{j}Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
\textsuperscript{k}Dept. of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
\textsuperscript{l}Enrico Fermi Institute, University of Chicago, Chicago, IL 60657, USA
\textsuperscript{m}Physics Dept., California Polytechnic State University, San Luis Obispo, CA 93407, USA

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.

Keywords: Ultra-high energy neutrinos, radio detection, phased array

1. Introduction

In recent years, the IceCube experiment has detected a population of astrophysical neutrinos with energies up to ~ 10 PeV \cite{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 \cite{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 \cite{4,5,6}. 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 \cite{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 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 \cite{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 \cite{10,11}.

The concept for an in-ice radio interferometric phased array for detection of high energy neutrinos was introduced in Reference \cite{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 \cite{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 2.1.1, we discuss measurements of thermal noise correlation between closely-spaced antennas, relevant for an interferometric phased array trigger. Section 2.1.2 details a validation of the beamforming technique for impulsive signals in an anechoic chamber. In Section 2.2, we discuss the implications of beamforming for a realistic triggering scheme. Section 3 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 (∼250 K) would be completely correlated, and the noise from the system would be completely uncorrelated (∼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. Figure 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 ∼75 K, dominated by noise from the front-end amplifier. Signals were then read out using a Tektronix MSO5204B oscilloscope, sampling at 5 GSa/sec. The walls of the anechoic chamber were between 1 m 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.

2.1.2. Antennas Used

We used five different pairs of antennas for measurements in the anechoic chamber. We used two types of commercial antennas: folded dipole antennas from Telewave, Inc. (ANT275D and ANT400D) with bandpasses at 230-330 MHz and 360-450 MHz respectively. We also took data with two types of antennas that have been developed for the ARA experiment. The first is a broadband bicone antenna, used by ARA to detect vertically-polarized signals, and the second is a slot antenna that is sensitive to horizontal polarization when the antennas are deployed in boreholes. The bicone antennas have a bandpass of 150-850 MHz and the slot antennas span 200-850 MHz.

Additionally, we took data with broadband dipole antennas that we developed, which we describe in detail here. Each antenna consists of two 20 cm copper cylinders, each with a diameter of 8 cm. The two sides of the antenna are connected at the feed with 0.64 cm copper rods. The antennas are read out via a 1.3 cm diameter Heliax cable. A 5.1 cm polyvinyl chloride collar separates the two halves of the antenna and provides strain relief at the feed. An antenna and the simulated design are shown in Figure 2.

The antenna frequency range is chosen to match the expected Askaryan emission and the physical constraints of in-ice deployment in boreholes. The Askaryan signal is coherent up to a few GHz, but undergoes less propagation loss at low frequencies in glacial ice, so we preferred antennas in the 100-600 MHz range. The diameter of the dipoles was chosen to increase the bandwidth while ensuring that they would fit within reasonable sub-surface in-ice boreholes.

1http://www.telewave.com/products/antennas/pdfs/TWDS-7048.pdf
2http://www.telewave.com/products/antennas/pdfs/TWDS-7079.pdf
Figure 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 Figure 2.

Figure 2: (a) A simulated (using HFSS, left) and constructed (right) broadband dipole. (b) The reflective S-parameter ($S_{11}$) for all the constructed antennas (colored, solid lines) in air compared with the HFSS simulation (dashed). These antennas have good transmission response from 230 MHz to 800 MHz, demonstrated by the small (< $-6$ dB) $S_{11}$ value over that frequency range. (c) Radiation patterns (solid lines) compared with HFSS simulations (dashed lines).
The antenna response, represented by the reflective S-parameter ($S_{11}$) in Figure 2b, reaches its first resonance at 262 MHz in air, which is reduced to 196 MHz when surrounded by glacial ice ($n = 1.78$). A simulation of the antenna response, constructed using HFSS is shown with a dashed line in Figure 2b. The higher-frequency dip corresponds to a second mode of the antenna. Simulations of the beam pattern in the antenna’s E-plane indicate that the beam pattern becomes slightly more directive with increasing frequency, rather than forming an additional null. However, the measured E-plane radiation pattern is no longer azimuthally symmetric above 450 MHz. The bore-sight gain is within 3 dB of its maximum of 2.9 dBi between 220 MHz and 755 MHz.

2.2. Thermal Noise Simulation

We model thermal noise in a multiple antenna system as the sum of multiple noisy transmitters following Reference [15]. Consider antennas $A$ and $B$ located distances $r_{An}$ and $r_{Bn}$ from a transmitter $n$ with random uncorrelated phases but equal amplitudes $\psi_n$. The statistical average of the cross-correlation coefficient, $(C_{AB})$, of many sources is non-zero only when considering terms from a single transmitter, giving an average cross-correlation coefficient of

$$C_{AB} = \psi_n^2 \sum_{n=1}^{N} \frac{e^{-j(kz_{An} - kz_{Bn})}}{r_{An}r_{Bn}}.$$  

(1)

Two cases may result in correlation between the antennas. If the transmitters are arranged in an arbitrary configuration, but there are boundaries, such as the ice-sky horizon that is relevant for balloon-borne neutrino experiments, partial correlation exists near the bounds. When the antenna separation and distance between the transmitters are much smaller than a wavelength, the source is unresolved and the average correlation is non-zero, as may be found with a closely packed phased array deployed down a borehole. Generally speaking, the correlation of the noise between a pair of antennas depends on a combination of the antenna separation and spatial distribution of the transmitters.

For comparison to the anechoic chamber measurements, we treat sources of thermal noise as oscillators each with an amplitude drawn from a Rayleigh distribution corresponding to a temperature of 300 K and a random phase drawn from a uniform distribution. We create $10^5$ of these oscillators, each with a frequency drawn from a uniform distribution over a 2 GHz bandwidth. The oscillators are thrown uniformly on a spherical shell that has a radius of 5 m and is centered on the point between two simulated antennas. We weight the amplitude of each oscillator by the sine of the incident angle on the antenna feed, where a zenith angle of zero corresponds to the location of the null of the antenna, to approximate a dipole antenna beam pattern. We add the electric fields, weighted by the sine of the phase at each antenna, for all generated oscillators in Fourier space for each antenna and filter the result using the magnitude of the frequency response of the filters we used in thermal noise correlation measurements (see Section 2.1). Because the phase of each oscillator is chosen randomly from a uniform distribution, we do not need to take into account the phase response of the filters, since the resulting phase would still be randomly drawn from a uniform distribution. Uncorrelated noise is added to the simulated thermal noise over the same bandwidth for each channel that corresponds to the 75 K system temperature for each channel by generating noise with a spectral amplitude drawn from a Rayleigh distribution and a random phase drawn from a uniform distribution over the same bandwidth as the thermal noise. We generate simulated noise traces at each antenna by taking the inverse Fourier transform of the filtered spectra. By generating many sets of noise traces for antennas with different feed-to-feed spacings, we can make direct comparisons with measurements.

We developed two independent simulations, which we used as a validation technique, and the results of the simulations are consistent with each other.

2.3. Results

We run identical analyses on simulated noise data sets and on noise correlation data taken in the anechoic chamber. Figure 3 shows the results of the noise correlation measurements for the ARA bicone antennas spaced as closely as physically possible (a feed-to-feed distance of 0.73 m), compared to measurements with the inputs to the front-end amplifiers terminated with a 50 Ω load and results from the thermal noise simulation. The configuration with terminated amplifier inputs is used as a measure of the baseline level of correlated noise in the system between the two antenna channels.

The left-hand panel of Figure 3 is a histogram showing the cross-correlation coefficient between the two antenna channels over a causal time window (±2.4 ns) for each of ~500 recorded events. This causal time window corresponds to possible time differences between antennas for incident plane wave signals from an arbitrary direction, determined by the spacing between the antenna feeds. The causal time window ($\Delta t$) is determined by $\Delta t = \Delta d/c$, where $\Delta d$ is the feed-to-feed spacing between the antennas (0.73 m), and $c$ is the speed of light. We define the cross-correlation coefficient, $C$, between two time-domain waveforms, $x(t)$ and $y(t)$, at a relative time delay $\tau$ between the waveforms, as

$$C(x(t), y(t), \tau) = \frac{1}{N\sigma_x\sigma_y} \sum_{i=1}^{N} (x(t_i) - \bar{x})(y(t_i + \tau) - \bar{y}),$$  

(2)

where $N$ is the number of points in each waveform, $\sigma_x$ and $\sigma_y$ are the standard deviation of each waveform, and $\bar{x}$ and $\bar{y}$ are the mean of each waveform. Since the causal time window (±2.4 ns) is much smaller than the length of each trace (2000 ns), the bias of the cross-correlation across the causal window is small (~ 0.2%).

The right-hand panel of Figure 3 is a histogram of the maximum of the absolute value of cross-correlation coefficient values shown in the left-hand plot for each recorded event. The
three overlaid histograms are consistent within statistical errors, shown on the histograms. There is no significant correlation seen between the two channels when compared to the data taken with terminated amplifier inputs, even when the antennas were spaced as closely as physically possible. The correlation observed is consistent with simulated uncorrelated noise, shown by the black line in Figure 3.

We repeated this measurement with the antennas spaced farther apart and with a variety of types of antennas (Telewave ANT275D, Telewave ANT400D, and the ARA bicone antennas), and all results are consistent with no observed correlation between adjacent antennas. Figure 4 shows the results of a comparison between the thermal noise simulation and data taken with each of the types of antennas at a variety of feed-to-feed distances. For these antennas, the feeds are at the centers of the antennas, and a spacing of zero in the simulation corresponds to a fully overlapping antennas. Shown is the peak cross-correlation coefficient averaged over 500 simulated or measured events in a ±6.0 ns time window, which is the causal window for the largest feed-to-feed spacing for which we made measurements (~ 2 m). We maintain a consistent time window in analysis and simulation at each distance to keep the trials factor the same across all distances shown. The error bars represent the standard deviation of the peak cross-correlation coefficient values across the 500 events.

At very small hypothetical feed-to-feed distances, the simulation approaches a maximum correlation coefficient that corresponds to the fraction of total noise in each channel due to the 300 K thermal noise compared to the total noise (the sum of the thermal noise and the 75 K system temperature). The thermal noise is filtered by both the antenna and the in-line filters, whereas the 75 K system temperature filtered by the in-line filters only, which are broader band than the Telewave antennas. The 75 K system temperature is independent between channels. At large spacings, the simulated data has a peak correlation coefficient of 0.05 for all three antenna types, which would change with different allowed time windows. True physical noise correlation, beyond the correlation level expected from the noise statistics alone (in our case ~ 5%), is not seen in simulation until the antennas are closer together than physically possible.

At physically allowed spacings where measurements are possible, (e.g., > 0.73 m for the ARA bicone antennas), the measured and simulated noise correlation for all antenna types agrees to within < 50% of the measured and simulated standard deviation. The difference between the measurements and the simulation for the ARA Bicone antennas is shown in Figure 5. We attribute these small differences to imperfect assumptions in the simulation, such as ignoring differences in antenna phase response as a function of angle, which would serve to further decorrelate channels.

3. Validation of Beamforming Technique

We also performed a simple validation measurement of the beamforming technique in the anechoic chamber. We used a system configuration shown in the schematic in Figure 1. The configuration was identical to the system described in Section 2 except for the following difference: after the second bias tee, we split the signal from each antenna channel and combined one branch of the signal from each channel to form a single beam that corresponds to zero time delay between the channels. This is shown with the dashed line in Figure 1. This beam is broadside to the antennas, at the highest-gain angle of each antenna.
Figure 4: The peak cross-correlation coefficient averaged over 500 simulated or measured events in a ±6.0 ns time window, which is the causal window for the largest feed-to-feed spacing for which we made measurements (~2 m). The error bars represent the standard deviation of the peak cross-correlation coefficient values across the 500 events. The data for each antenna goes to the smallest physically-allowed spacing. Predictions from the simulation are shown in blue and results from the measurements are shown in green. Top: ARA bicone antennas. Middle: Telewave ANT275D antennas. Bottom: Telewave ANT400D antennas.

For this measurement, we used the broadband dipole antennas that we developed (see Section 2.1.2).

We sent broadband, impulsive signals to the two receiving antennas from an identical transmitting antenna that was 4 m away inside the anechoic chamber, and was positioned broadside to the receivers for maximum transmission strength in the direction of the formed beam. A layout of the antennas inside the chamber for this transmission measurement is shown in Figure 6. The signals are generated using an Avtech AVP-AV-1S-C-P pulse generator, and are filtered before transmission with a Mini-Circuits NHP-200 and an NLP-450 filter.

Figure 5 shows the results of the measurement. The left-hand panel shows the impulsive signal received in the two independent antenna channels, averaged over 500 events recorded on the oscilloscope. Each channel had a slightly different impulse response, dominated by differences between individual antennas. Each channel also had a slightly different gain and noise temperature, dominated by differences in the individual front-end low-noise amplifiers. The right-hand panel shows the beam that we formed in hardware, compared to the ideal beam that should be formed, calculated by summing the waveforms shown in the left-hand panel. Some difference is evident between the beam formed in hardware and the ideal version formed in analysis; the peak-to-peak voltages agree to within 15%, and the difference is consistent with the additional loss expected from the splitters and combiners added to the system to create the hardware-formed beam.

Before averaging together many waveforms to produce the high signal-to-noise ratio (SNR) waveform shown in Figure 7, we calculate the SNR of the signal that was received in each channel, including the hardware-formed beam, compared to the noise level in the system. We define SNR as half of the signal’s peak-to-peak voltage divided by the RMS of the noise ($\frac{V_{pk2pk}}{2\sigma}$). The results are shown in Table 1. We then calculate the ideal beam that should be formed and the noise level corresponding to superimposed noise from the individual antenna channels. Note that because of the differences between the two signal chains, we do not expect to see the $\sqrt{2}$ improvement in
We model the digital phasing and event triggering of a linear antenna array. The antenna channels are formed into beams between the antenna phase centers and the ground mast. The antennas are spaced at a pitch of 55 cm.

A more efficient algorithm for the dispersive pulses recorded in the anechoic chamber calculates the power every eight samples, thereby including the majority of the power from a single transient pulse.
Figure 8: Trigger rate vs. normalized power threshold, $PZ_i/\sigma^2$, for noise traces taken in the anechoic chamber using the three Telewave antennas (data points) compared to simulations of thermal noise (solid lines). Two trigger configurations are shown: the blue data points indicate the trigger rate when the average power is taken over a 9.6 ns window and incremented every eight samples (4.8 ns). The red data points show the singles rate when the power is calculated at every sample point. We use the simulation to predict the threshold for rates lower than several kHz due to the limited amount of data taken in the anechoic chamber.

To detect transient events, a time-windowed power calculation is performed on each coherently summed beam, given by

$$P_{\text{window}} = \frac{1}{N_i Z_L} \left( \sum_{j=1}^{N_i} \sum_{i=1}^{N_{\text{ant}}} V_{ij} \right)^2,$$

where $N_i$ is the number of digitized samples in the time window, $Z_L$ is the load impedance, $N_{\text{ant}}$ is the number of antennas used in the beam, and $V_{ij}$ is the digitized voltage at sample $j$ within the time window for antenna $i$.

The relationship between the per-beam singles rate and trigger threshold is determined by $N_i$, as shown in Figure 8 where the power threshold, $P$, is normalized by the square of the noise RMS ($\sigma^2$) divided by $Z_L$. For these measurements, the data are down-sampled from 5 GSa/sec to 1.67 GSa/sec to reflect a Nyquist sampling rate for a system with a bandwidth of ~800 MHz.

Two power calculations are shown in Figure 8, one in which the average power is calculated in a window of $N_i=16$ samples (9.6 ns) and sampled every $N_i/2=8$ samples (4.8 ns), and a second in which the power in each sample is recalculated at every sample point. With a power calculated from an 8-sample window, we find voltage thresholds, $\sqrt{PZ_L}$, of 2.34$\sigma$, 2.21$\sigma$, and 2.07$\sigma$, for noise singles rates of 10, 100, and 1000 Hz, respectively, which corresponds to the range of achieved rates in radio-detection experiments.

To measure the trigger efficiency, event rates were measured from the 3-antenna array in the anechoic chamber while sending impulsive signals from the transmitting antenna at several attenuation levels. For each attenuation setting, we recorded 500 events. The SNR is defined as $V_{\text{peak}}/2\sigma$, for a single antenna. We choose 100 Hz as a baseline per-beam trigger rate, comparable to achieved trigger rates by currently-deployed radio experiments, such as ANITA. We measure the efficiency for a single antenna, the 0° beam formed by using 2 antennas, and the full 3-antenna 0° beam by comparing the power, calculated within the time window corresponding to the time when the pulse was transmitted using Equation 4 to the appropriate threshold level for the chosen trigger rate. The measured trigger efficiency at a trigger rate of 100 Hz, specified by Figure 8 using the 8-sample interval, is shown in the left plot in Figure 9.

These measurements compare well with simulation results shown by the solid lines in the left-hand plot of Figure 9. The simulated curves include 5000 events in which the average impulse response of each antenna is added to the appropriate level of uncorrelated system noise (75 K for our system plus 300 K of room temperature thermal noise). We chose to simulate 5000 events to achieve standard errors that are <1%.

The simulation is extrapolated to larger phased arrays as shown on the right-hand plot in Figure 9 and curves are shown for each size array at 10, 100, and 1000 Hz per-beam trigger.
rates, corresponding to the range of achieved rates in radio-detection experiments. The efficiency curves for the 8- and 16-antenna arrays assume equal impulse response for each antenna channel. A 16-antenna linear phased array that is set to trigger on impulsive events in a single beam at 100 Hz achieves a 50% efficiency at a SNR of about one. This is an improvement of a factor of four in SNR over single-antenna trigger thresholds, which reach 50% efficiency at an SNR of about four at the same trigger rate.

5. An In-Ice Phased Array at Summit Station

We have also studied thermal noise using an analog interferometric phased array in the ice at Summit Station in Greenland. In this Section, we describe the site, the analog phased array deployed there, and the noise environment observed with the phased array.

5.1. Summit Station in Greenland

Summit Station is a year-round NSF-operated site, located at N 72° 37’ W 38° 28’, near the highest point on the Greenland ice sheet. Summit Station sits atop 3 km of glacial ice, making it an ideal candidate site for radio detection of high energy neutrinos. At Summit Station, the density of the firn has reached 95% that of glacial ice by a depth of 100 m [16]. At the South Pole, the density has reached 95% that of glacial ice by a depth of 140 m [17]. Therefore, for a detector that is designed to sit below the bulk of the firn rather than at or near the surface, Summit Station would require shallower drilling compared to the South Pole.

The radio clarity of the ice at a site sets the effective volume of ice in which neutrino interactions are observable for a given radio detector configuration, directly related to the sensitivity of the experiment. The depth-averaged field attenuation length at Summit Station has been measured to be \( L_e = 947 \pm 35 \) m at 75 MHz [13]. To directly compare this measurement with radio attenuation length measurements that have been made previously at other sites of developing and proposed neutrino detectors, such as the South Pole (the site of ARA) and Moore’s Bay on the Ross Ice Shelf (the site of ARIANNA), this measurement is extrapolated to 300 MHz and averaged over only the upper 1500 m of ice, which is where the interaction vertex would be for most neutrino events that are detectable by a surface or subsurface detector. Assuming the measured temperature profile of ice at Summit Station and measured dependence of attenuation length on frequency, this indicates an average field attenuation length of 1022 ± 230 m over the upper 1500 m [13], compared to 1660 ± 255 m over the top 1500 m at 300 MHz at the South Pole [14] and 411 m with an experimental uncertainty of about 40 m averaged over all depths for the 578 m thick Moore’s Bay location [19, 20].

We can compare the electric field loss as a function of distance traveled through ice for the three candidate sites, which is the metric that is directly related to neutrino effective volume for a given detector. Figure 10 shows the electric field loss as a function of radio propagation distance through ice at candidate sites for neutrino detectors (Moore’s Bay, the South Pole, and Summit Station), including both the \( 1/r \) geometric factor and the measured attenuation length at each site. For neutrino events, which typically occur hundreds of meters from the detector, the loss seen through the ice at Summit Station is comparable to the loss seen through the ice at South Pole, and is much less than at Moore’s Bay.

5.2. An In-Ice Phased Array at Summit Station

An instrument was deployed at Summit Station in June 2015 to characterize the site and validate the phased array technique with an array deployed in the ice, as discussed in Reference [21]. The system used analog beamforming to combine signals from multiple antennas, as shown in the schematic of the RF signal chain in Figure 11. The system used the same front-end amplifier system described in Section 2.1.1. Each front-end amplifier was preceded by a 200 MHz high pass filter to protect the first stage amplifier from the 8 MHz transmitter at Summit Station. Coaxial Times Microwave LMR-240 transmitted the antenna signal to the surface over 115 m of cable. Variations in the cable lengths led to sub-ns variation in arrival times between antenna channels.

The signal from each antenna was split into two signal chain branches using 3 dB splitters. The first branch of the chain carried signals from individual antennas, while the second branch formed beams in the beamformer by splitting signals from each antenna eight ways, propagating signals from each antenna through fixed delay lines of Times Microwave LMR-200, and combining signals into eight beams at fixed angles from the horizontal. The LMR-200 delay lines ranged from 1.0 ns to 14 ns, corresponding to 0.25 m to 5.0 m and the signals were split and combined into beams using 8-way Mini-Circuits ZCS8-13-S+ power splitters. The system architecture allowed simultaneous digitization of both the antenna channels and the beams.

The instrument included up to eight broadband dipole antennas, described in Section 2.1.2. The number of antennas
Figure 11: A schematic of the system deployed in Greenland. Only four signal chains and beam channels are shown for simplicity.

Figure 12: Pictures of the system deployment in Greenland. Upper left: laying out the antennas on the surface, before lowering the front-end system down the borehole. Upper right: lowering the antennas, amplifiers, and cabling down the borehole. Lower left: the system installed down the borehole. Lower right: the deployment camp, including deployment gantry and data-taking tent.
included in the array during the 2015 deployment season was tunable.

Waveforms from both branches of the signal chain (antenna channels and beam channels) were sampled at 2 GSa/s with record lengths of 1024 points with four DRS4 evaluation boards\(^4\). A Tektronix MSO5204B oscilloscope generated a global trigger for the digitizers using either automatic (unbiased) triggers or a threshold crossing on either an antenna or beam channel.

The eight antennas and front-end amplifiers were lowered down the DISC borehole\(^5\) using the gantry and winch system shown in Figure 12. The DISC borehole is located approximately 0.5 km from the main activities of the station. A fixed feed-to-feed antenna spacing of 76 cm was achieved using plastic spacers. Eight 115 m cables were bundled together at the surface of the ice and fed through the center of the topmost antennas and spacers such that signals from each individual antenna could be recorded. The bottom of the array was lowered to a depth of 96 m.

During the June 2015 deployment, Summit Station was relatively radio quiet, with two notable exceptions. A balloon-borne radiosonde launched daily at Summit Station in support of the ICECAPS atmospheric monitoring program appears in our instrument at 402.8 MHz. The signal remains above thermal noise for several minutes, and the power falls off as the balloon drifts away. Intermittent, transient signals at 150 MHz and 433 MHz also appear in the downhole antennas, due to station communications at those frequencies.

5.3. Noise Correlations at Summit Station

Figure 13 shows the power spectrum measured by a single downhole antenna. The power spectrum shown is the mean of 200 individual power spectra of 500-sample waveforms recorded on the oscilloscope and is corrected for the overall gain in the signal chain. Uncertainties in the temperatures of the in-ice amplifiers and cables lead to a ±3 dB uncertainty in the spectral power. As shown in the figure, noise observed on the downhole antenna is consistent with the expected thermal noise power in the 160-440 MHz band, defined by the 3 dB point of the filters used in the system, at 241 K, the temperature of the ice at 100 m depth [22].

For uncorrelated noise, the RMS voltage in the beamformed channel, \( V_{\text{RMS,beam}} \), is the quadrature sum of the RMS voltages, \( V_{\text{RMS},i,j} \), in the individual antennas after accounting for the relative loss in the beamformer, \( L \), which is -19.9 dB in power for the system deployed in Greenland. The loss in the beamformer is dominated by the 8-way splitter and 8-way combiner in each channel. Although digitizer noise is small (< 2% for beam channels and < 0.5% for antenna channels) compared to the system noise (thermal noise plus amplifier noise) level, we account for the RMS voltage from digitizer noise in both the antenna channels, \( V_{\text{RMS},i,j} \), and the beam channel, \( V_{\text{RMS,beam}} \). The expected \( V_{\text{RMS,beam}} \) is given by

\[
V_{\text{RMS,beam}}^2 = 10^{L/10} \left( \sum_{i=1}^{N_{\text{antennas}}} (V_{\text{RMS,i}}^2 - V_{\text{RMS,0}}^2) \right) + V_{\text{RMS,beam}}^2. \tag{5}
\]

Figure 14 compares the expected to the measured \( V_{\text{RMS,beam}} \) for five antennas combined using the analog beamformer. This data set consists of events recorded at a constant rate (unbiased) over the course of one night. A small fraction (< 0.5%) of events that have high power in the 160-440 MHz band, indicative of man-made noise, are removed from the data set, leaving events dominated by thermal noise. The blue dashed line shows the expectation for an incoherent signal, such as thermal noise, while the red dashed line shows the expectation for a coherent signal, such as a true plane wave signal incident on the detector. The < 10% difference between the expected and measured \( V_{\text{RMS,beam}} \) shows that the noise observed by the downhole antennas adds incoherently when forming a beam, indicating that noise from adjacent in-ice antennas is uncorrelated. This is consistent with our results from anechoic chamber measurements (see Section 2.1).

6. Conclusions

The in-ice phased array for detection of high-energy neutrinos is a promising technique. We have performed studies that demonstrate that thermal noise is uncorrelated between tightly-packed neighboring antennas in each other’s nulls both in an anechoic chamber and with an in-ice phased array at Summit Station. In the anechoic chamber, we have also validated the beamforming technique through simulations and measurements, achieving the expected improvement in SNR when beamforming using an experimental system. Measurements at Summit Station of the noise environment and ice characteristics indicate that the site is suitable for an in-ice radio neutrino telescope.

\( ^4\)https://www.psi.ch/ds/evaluation-board
\( ^5\)http://www.icedrill.org/equipment/disc.shtml
A simulation including realistic parameters for an FPGA-based correlation trigger indicates that phasing signals from multiple low-gain antennas yields significant improvement in achieved trigger threshold, consistent with idealized expectations and anechoic chamber measurements. We are designing and constructing such a trigger to be implemented first at the South Pole on the ARA experiment. Pending successful demonstration of the technique, a larger array with hundreds of antennas per station could be proposed either at the South Pole or in Greenland to achieve a low energy threshold capable of providing significant overlap in energy with IceCube in the PeV energy range, and extending the measurement of high-energy neutrons through the higher-energy cosmogenic neutrino range.

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