Results from the Askaryan Radio Array Testbed Station

THE ARA COLLABORATION

Abstract: The Askaryan Radio Array (ARA) is an ultra-high energy neutrino telescope under development consisting of radio antennas to be deployed in the ice 200 m deep near the geographic South Pole. During the 2010-2011 Austral summer, an ARA testbed station was deployed, consisting of antennas, trigger and readout electronics, and high voltage pulsers, with most components at approximately 20 m depth. The first ARA stations will be deployed in the following two Austral summer seasons. We will present the results from data taken by the testbed this season, including characterizations of the in-ice noise environment, trigger performance, angular resolution, and measurements of the index of refraction and attenuation of radio pulses in the ice. We will conclude with implications of the testbed results for ARA design.

Keywords: neutrino antarctic radio cerenkov

1 Introduction

Neutrinos are unique cosmic messengers as they travel cosmological distances unattenuated and also do not undergo deflections in magnetic fields. Thus they would carry valuable information complementary to that from charged cosmic rays and gamma rays. Apart from solar neutrinos and a small sample of neutrinos from a singular event, SN1987a, neutrinos from beyond the earth’s atmosphere remain elusive. However, there is a nearly infallible argument for the existence of a cosmic neutrino flux in the ultra-high energy (UHE) regime (above $10^{18}$ eV) due to the interaction of UHE cosmic rays with cosmic microwave background photons through what is known as the GZK process [1, 2]. Berezinsky and Zatsepin first noted that this process would produce an observable neutrino flux [3, 4]. Since the expected UHE neutrino flux is rare (of order 10/km$^2$/year), detection volumes of order 100’s of cubic kilometers are necessary. IceCube and Antares are searching for cosmic neutrinos using the visible Cerenkov technique in South Pole ice and Mediterranean sea water respectively [5, 6, 7]. The length over which visible light is scattered or absorbed in these media is on the order of 50 meters. This sets the scale for the sensor spacings, and so detector scales beyond 1 km$^2$ for that technique are prohibitively expensive. The radio Cerenkov technique allows for much larger detection volumes due to attenuation lengths of approximately 1 km in ice [8]. This technique has been well established over the past two decades [9, 10, 11, 12] and the ANITA experiment, which searches for radio Cerenkov pulses from above the Antarctic ice sheet, places the strongest constraints on the cosmic neutrino flux above $10^{18.5}$ eV [13].

The Askaryan Radio Array (ARA) will use the radio Cerenkov technique to search for UHE neutrinos using antennas deployed in the South Pole ice [14, 15]. It aims to measure a sample of order 100 neutrinos in the UHE regime so that their properties, of interest to both particle physics and astrophysics, can be studied. The proposed first phase of the detector will consist of an array of 37 stations, with 16 antennas each, at a depth of approximately 200 m. The stations will be arranged on a hexagonal grid with a 2 km spacing. The antennas will consist of both vertically polarized, V-pol (bicone, 150 MHz) and horizontally polarized, H-pol (quad-slotted-cylinder, 200-850 MHz) antennas.

2 The Testbed

In January 2011, a first prototype “testbed” station for ARA was deployed 1.8 km grid East of the IceCube detector, at approximately 30 m depth. It included 10 antennas deployed in the ice and an additional six antennas deployed at the surface. Four V-pol antennas (bicone, 150-850 MHz) and four H-pol antennas (bowtie-slotted-cylinder, 250-850 MHz) and two quad-slotted-cylinders (200-850 MHz) were deployed at approximately 25 m depth. There are also two near-surface discones (150-850 MHz) and two near-surface “batwing” antennas (250-850 MHz). At the surface sit two “fat dipole” (30-300 MHz) antennas. These 16 antennas total were deployed in six boreholes with an approximate trapezoidal geometry and spacing at about 10 m.
The hardware and electronics draws from the strong RICE and ANITA heritage in the collaboration. A low-noise preamplifier is inserted close to the antennas to reduce insertion loss and thermal noise. Along with a second stage amplifier, the total gain is approximately 75 dB. The signals are split into trigger and waveform paths. Each time an event passes the trigger requirements, the RF waveforms for that event are recorded along with associated data such as temperatures, threshold settings, single antenna trigger rates, etc. to a single board computer, then transmitted to a computer at South Pole station over twisted wire pairs via ethernet modem. The data is then transmitted to the northern hemisphere computer archives via satellite link.

A calibration pulser was deployed near the testbed receivers. It pulses at a rate of 1 Hz during all data taking periods and is slaved to a high-precision Rubidium clock to permit signal averaging over multi-km distance scales with picosecond-scale resolution. This allows us to continuously monitor the functionality of the trigger while providing a reference for timing and signal amplitudes.

Three 4 kV, ns-scale pulsers manufactured by FID, Inc. were deployed in deep ice in two of the final holes drilled for IceCube. The furthest pulser from the testbed was at 2.01 km distance along the surface and at approximately 2.45 km depth, for a total distance of 3.16 km through the ice. We took several dedicated runs in mid-January where all three of the deep pulsers were easily observed in the testbed data.

An RF trigger requires that 3 waveforms of the 8 bi-cone and bowtie-slotted-cylinder antennas at depth exceed a threshold of approximately 3.5 times the RMS thermal noise voltage. This gives a thermal noise trigger rate of typically 0.5-1.0 Hz. In addition, the calibration pulser triggered the system once per GPS second.

3 Results

3.1 Thermal Noise

Figure 1 shows the testbed trigger rate as compared with three different environmental variables which were monitored continuously during take taking. We monitored the wind speed at the South Pole to check for any correlation of the noise rates with blowing snow and no such correlation was observed. There is, however, a clear correlation with the temperature of the testbed electronics. Some correlation is expected due to the temperature dependence of the thresholds. The software has the capability to adjust the thresholds in real time so as to maintain nearly constant trigger rates, but this feature has not yet been enabled.

Figure 2 shows the average Fourier power spectra measured by one of the borehole antennas from a run during a period in late April 2011. For pure thermal noise, the noise level is given by $kT\Delta f$ which is -175dBm/MHz for the electronics temperature $T = 290$ K. The average measured thermal noise levels imply a thermal+system noise temperatures of approximately 325 K.

3.2 Galactic Noise

The two surface antennas (one shown in Figure 3), show an increase in thermal noise at frequencies below 150 MHz. This is consistent with being galactic radio noise, whose sky temperature follows a power law given by $T_{\text{sky}} = 800 \text{ K}(f/100 \text{ MHz})^{-2.5}$ where $f$ is the frequency. The surface antenna temperatures are an average of the galactic noise temperatures as seen above and that of the ice below. Since the two surface antennas are low frequency dipoles with axis lying parallel to the surface, their nulls sweep the galactic plane over a period of a day. The galactic plane is at approximately 63° declination at the South Pole. Therefore, if the low frequency noise increase is galactic in origin, we should observe a sidereal variation in total noise power, and this is what is observed in Figure 4 for frequencies below 70 MHz. The phase difference in the sin waves...
from the two antennas is due to an approximately $22^\circ$ offset in orientation between them.

Figure 4: Noise voltage $V_{\text{RMS}}$ below 70 MHz as a function of time of day, showing a clear sidereal variation due to the dominance of galactic noise at these frequencies.

3.3 Radio Interference

An important motivation for the testbed was to assess the potential impact of anthropogenic radio noise on ARA data taking. Figure 5 shows the hourly trigger rates during a three month period of ARA testbed data taking. The high rates that occur twice daily until approximately day 65 and once per day after that are due to weather balloon launches, which utilize a $\sim$400 MHz transponder for data telemetry. These launches result in about 1/2 hour each of event rate saturation, for a total loss of livetime of approximately 5% when the launches occur twice a day. Additionally, incoming and departing aircraft each contribute approximately 20-30 minutes of deadtime. During busy periods with several flights per day, this will contribute an additional 5% or so of deadtime. Other sporadic sources of radio interference have minimal effect on the livetime. The reduction is trigger rates later in the year is due to a migration of trigger thresholds due to decreased temperatures.

Figure 5: Trigger rates in the ARA testbed by the hour. Top: rates each hour of each day during a three month period in 2011. The regions of white space are times when data transfer from the South Pole was not possible due to bandwidth restrictions.

3.4 Timing and Event Reconstruction

The local calibration pulsers allow for a continuous monitoring of the trigger functionality as well as a stable reference for timing and signal amplitudes. One of their important functions is to provide a means to determining the relative locations of the antennas in situ via the relative delays between waveforms at the receivers. Figure 6 shows the relative delay of a pulse between two in-ice V-pol antennas, showing a standard deviation of 136 ps and a standard error of 4.5 ps obtained from a fit to a Gaussian in the peak region. The delays between waveforms were determined by finding the peak of their cross-correlation function. For baselines typically 15 m or more, the angular resolution is of order $0.1^\circ$ for 136 ps timing error, which is more than adequate for ARA.

For Figure 7, for all of the events on January 29th 2011 we attempted to reconstruct source locations from measured waveforms. Not all timing calibration corrections have yet been implemented. On this day the winds were observed to be high and the South Pole station was open. When a thermal noise fluctuation causes a trigger, the event does not reconstruct to any location because the delays are not causal. RF triggers from the pulsers or any RF backgrounds do reconstruct to a particular direction. Figure 6 shows the reconstructed direction of origin relative to the known pulser location for all events that reconstruct on that day. No events were reconstructed beyond the limits shown. Fitting the peak to a Gaussian gives pointing-to-vertex resolutions of $0.27^\circ$ in $\phi$ and $0.60^\circ$ in $\theta$, quite acceptable keeping in mind that the timing calibrations are still in progress and the testbed sits at a shallow depth where there is a light velocity gradient due a depth dependent index of refraction.
3.5 Attenuation Lengths

Due to the distance of deep pulsers from the testbed, they provide an opportunity to measure RF loss due to attenuation in the South Pole ice over \( \sim 3 \) km. A previous measurement of RF pulses transmitted from the surface and reflected from the bedrock below gave attenuation lengths of order 1 km in the colder ice near the surface [8]. Two of the deep pulsers at intermediate depths \( \sim 1 \) km completely saturated the amplifiers at the receivers. We therefore used the deepest pulser at 2450 m depth for this measurement.

The Friis formula relates the power transmitted \( P_t \) and power received \( P_r \) between two antennas (both frequency dependent): \( P_r(f) = P_t(f) \cdot G_t^2 \cdot A_{\text{eff}}^2 / (4\pi r^2) \cdot e^{-2L/r} \), where \( G_t \) is the gain of the transmitter, \( A_{\text{eff}} \) is the effective area of the receiver (both absorb antenna coupling efficiencies), \( r = 3.14 \) km is the distance between the antennas, and \( L \) is the field attenuation length.

Due to unexpected difficulties with the high-voltage coupling into the deep pulser transmitters, the received pulse was spread in time over a \( \sim 20 \) ns window. However, using lab measurements, we are able to estimate the integrated power in transmission and reception using the observed waveforms in the testbed. Accounting for the antenna responses and beam patterns of the transmitter and receiver, we find an average attenuation length over the transmission distance of \( 670 \pm 180 - 66 \) m. Figure 8 shows the attenuation lengths and systematic uncertainty band as a function of depth, using the models in [16]. In the top 1 km, we find field attenuation lengths that exceed 1 km.

4 Summary

The ARA 2010-2011 testbed station has undergone several months of stable data taking with thermal noise triggers at a rate of a few Hz and deadtime due to RF interference from known sources at approximately 5-10%. The surface antenna see galactic noise at low frequencies, reconstruction has been achieved at the fraction of a degree, and we observe RF field attenuation lengths in the ice of over 1 km in the top km of the ice.

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References