33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

The Askaryan Radio Array (ARA) neutrino detector: Current status

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Abstract: The Askaryan Radio Array is a new >100 gigaton scale ultra high energy neutrino detector envisioned for installation in the deep radio transparent ice near the South Pole. The first three ARA stations (out of 37 planned) have been deployed and are operational. The primary science goals of the experiment are a discovery and measurement of a cosmogenic neutrino flux, and an exploration of the neutrino spectrum above current measured energies with good sensitivity to model predictions. We report on the science, design, and preliminary results from this experimental effort along with prospects for the completion of the detector construction.

Keywords: neutrino, UHECR, GZK, instrumentation

1 Introduction

One of the most tantalizing questions in astronomy and astrophysics, namely the origin and the evolution of the cosmic accelerators that produce the highest energy (UHE) cosmic rays, may be best addressed through the observation of UHE cosmogenic neutrinos. Astrophysical proton acceleration sites must also be neutrino emitters, since protons must undergo pion-photo production in order to escape the magnetic field of their source [6]. The decay chain of the daughter pions will contain gamma rays and neutrinos. Unlike the parent proton, neutrinos travel from their source undeflected by magnetic fields and largely unimpeded by interactions with intervening material. At high energies (above 10^{16} eV), neutrinos could be most efficiently detected in dense, radio frequency (RF) transparent media via the Askaryan [8] Effect. The abundant cold ice covering the geographic South Pole, with its exceptional RF clarity, has been the target volume for several pioneering efforts to develop this approach, including the englacial RICE [16] and balloon-borne ANITA [12].

Building on the expertise gained in these efforts, and the infrastructure developed in the construction of the IceCube optical Cherenkov observatory, we have deployed the first three stations of a RF-based neutrino detector, known as ARA (The Askaryan Radio Array), in the deep ice near the geographic South Pole. Above $\approx 10^{15}$ eV the power emitted in radio excedes that in optical wavelengths, and the attenuation length of RF in cold ice is long-on the order of a kilometer-allowing coverage with a larger, sparse array at low cost. South Polar ice is perhaps the most extensively studied on Earth. The combination of ice thickness and favorable radio frequency dielectric characteristics (see Figure 3), as well as the excellent scientific infrastructure, makes the site unparalleled for the location of this array.

With an instrumented area of an unprecedented ≈ 100 km^2, ARA's size was chosen to ensure the detection of the flux of neutrinos implied by the observation of a steep drop in the cosmic ray spectrum at $\approx 10^{19.5}$ eV [14, 21] by HiRes [1] and the Pierre Auger Observatory [3]. Greisen, Zatsepin, and Kuzmin (GZK) predicted the existence of this cutoff, which they attribute to the scattering of cosmic ray protons on the cosmic microwave background (CMB) photons via the delta-resonance process:

$$\begin{aligned} p+\gamma_{2.7K} \rightarrow \Delta^{+} \rightarrow n+ \quad & \pi^{+} \\ \hookrightarrow \quad & \mu \nu_{\mu} \\ & \hookrightarrow e \nu_{e} \nu_{\mu}. \end{aligned}$$

The presence of neutrinos in the decay of the resulting Δ resonance and the fact that ultra-high energy cosmic rays (UHECR) have been observed, and almost certainly include a significant proton fraction, implies the existence of neutrinos at $10^{17}-10^{19}$ eV, unless, coincidentally, this energy corresponds to a limit in the energy that can be attained by cosmogenic accelerators. The observation of ultra high energy cosmogenic neutrinos is needed to confirm that the observed dip is the result of the GZK process. The spectrum of astrophysical neutrinos is expected to follow the spectrum of cosmic rays, whose rates fall exponentially as a function of energy. However, if the drop in flux is attributable to the GZK process, the precise magnitude of the resultant neutrino flux will depend on the proton/iron composition of the cosmic rays, as well as the distribution of their sources in space. Thus, a measurement of ultra high energy neutrinos would also give an indirect measurement of the cosmic ray species.

Within 3 years of commencing operation, the full ARA will exceed the sensitivity of IceCube in the 0.1–10 EeV energy range by an order of magnitude. Because the antennas will be deployed in boreholes extending below the firn layer to 200 m depth, it will have the ability to distinguish surface noise from sources originating in the ice cap, otherwise not possible in the ballon-borne approach employed by ANITA [11]. Even under the extreme assumption that UHE cosmic rays are pure iron, ARA will have sufficient sensitivity to establish the presence or absence of the secondary UHE neutrinos produced in the GZK interaction. Such an observatory would also provide an unique probe of long-baseline high energy neutrino interactions unattainable with any person-made neutrino beam.

2 Array Baseline Design

The baseline design of ARA consists of 37 antenna clusters or "stations" arranged 2 km apart on a triangular grid, as

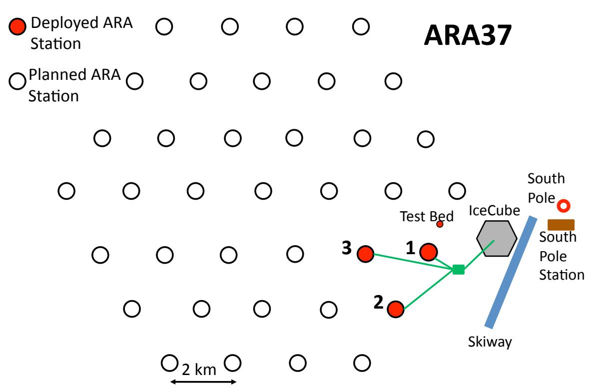

Figure 1: Planned layout of the 37 ARA stations with respect to the South Pole Station and associated sectors. The footprint of IceCube, which covers a square kilometer, is shown by the blue hexagon. The geographic South Pole is the magenta square in the South Pole operation zone.

shown in Figure 1. The primary goal of the ARA array is to establish the absolute cosmogenic neutrino flux through a modest number of gold plated events. We have therefore adopted a geometry in which a single localized cluster may act as a standalone array, which trades precise angular resolution for increased coverage. Because each local cluster has the ability self-trigger, this also avoids the complications of long trigger windows and deep buffers that would otherwise arise in triggering a sparse, large scale array.

The configuration of the ARA clusters is shown in Figure 2. Each cluster consists of four strings of receiver antennas and associated amplifiers installed in boreholes of approximately 6 inches (15 cm) in diameter and about 200 m deep into the icecap. The depth was chosen to allow the instrumentation to be placed below the first 100 m of the icecap, known as the "firn" layer, which has a varying index of refraction due to the gradual compactification of snow into ice. The firn layer would reflect away much of the power and complicate the ray tracing used in event reconstruction. The drilling technology and fuel constraints limit the depth and diameter of the borehole.

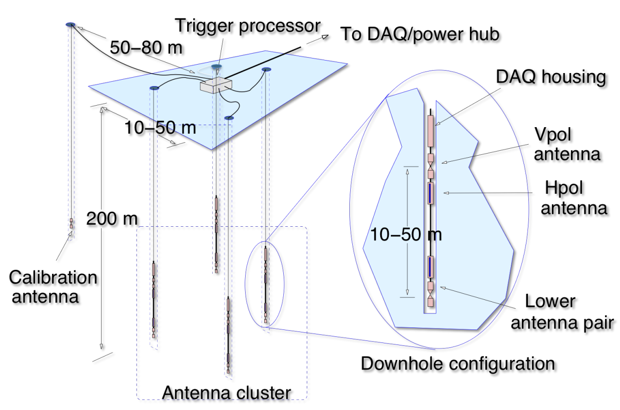

Figure 2: ARA Station layout and antenna string and cluster geometry.

Each string contains 2 pairs of antennas, each pair consisting of a horizontally polarized antenna and a vertically polarized antenna. The antenna pairs are separated by a distance of 15m for depth discrimination. By combining information from the two antenna polarizations, the entire Cherenkov cone may be reconstructed in the data analysis, allowing for more precise vertex reconstruction and additional background rejection. Each antenna is coupled to a low noise amplifier with low and high pass filters that select the sensitive frequency range, which extends from 100 MHz to 900 MHz. The digitization electronics are a descendent of those developed for ANITA [11, 19]. The cluster of four strings, along with the surface trigger and digitization logic, communications setup, and two additional antenna pairs in boreholes to transmit calibration pulses, form a station.

3 Prototype Construction and Performance

One of the goals of the first season of ARA construction was to test prototypes of the hardware. This prototype hardware can, in turn, be used to probe the noise environment at a distance of one kilometer from the IceCube array. Toward this goal, a "test bed" of shallow antennas was installed during the austral summer of 2010–2011. It consists of pairs of antennas, a "batwing" for horizontal polarization and a discone for vertical polarization, installed in trenches 3 m below the surface of the snow, as well as two low frequency antennas installed near the surface. An additional four pairs of antennas were installed in 6 inch boreholes drilled 40 m into the ice. Further deployments in 2011–2012 saw the installation of the ARA1 station at a depth near 100m, but otherwise as per the nominal station layout. In 2012–2013, with a reworked and enhanced drill for better heat delivery to the deep hole, the ARA2 and ARA3 stations were built with antennas below 200m, fully implementing the station plan. Future stations of the full ARA-37 array will differ only to enact minor performance improvements or cost savings.

Another goal of the first season of ARA was to measure the RF properties of ice to a sufficient degree to understand the performance of the array. The RF attenuation length decreases as a function of temperature, and the temperature of the ice at the South Pole has been precisely surveyed and has been found to vary from -50° C at the surface to -10° C at 2800 m depth[18]. In addition, the refractive index varies as a function of density, resulting in a lensing effect near near the top of the polar ice cap, where the snow is gradually compacting into ice. The RF propagation could also conceivably be effected by layering in the ice that could act as a waveguide. This "birefringence", if it is present, could also complicate the analysis of data. To investigate the RF properties of the ice, the ARA collaboration took advantage of the drilling of deep holes for the installation of the final IceCube strings to parasitically install three 5 kV broadband pulser and transmitter antenna assemblies at depths of 1450 and 2450 meters. The antenna was designed to wrap around the IceCube cable to eliminate uncertainty in the transmission pattern from cable shadowing effects. The siting of these transmitters allows the RF properties of the deep ice

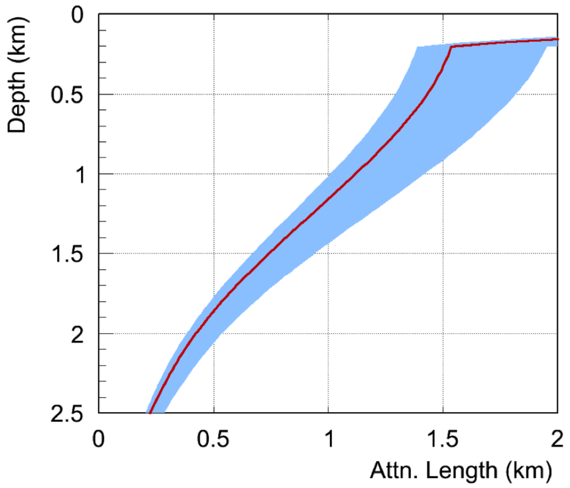

Figure 3: Ice Attenuation measurements made at the South Pole in 2011 measured from direct transmission from a source 2500m in depth along a 3.2 km slant depth.

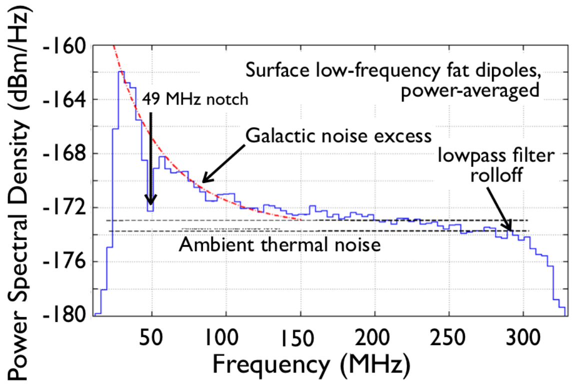

Figure 4: Spectrum of the noise density for surface dipoles measured at the ARA testbed.

to be probed without the uncertainties associated with the bottom reflection, and the high voltage of these pulsers allows them to be detected from many attenuation lengths away—well beyond the extent of IceCube, at the testbed, and within range of a large fraction of the planned ARA stations. The deepest transmitter is located at a slant depth of 3.2 km from the testbed, allowing a direct measurement of ice attenuation length over an unprecedented distance. The resulting measurement in shown in Figure 3. This will serve as a valuable calibration tool for ARA.

The testbed and high voltage transmitters have been operating for nearly two years, and the full results have been published [7]. The noise environment has been found to be very favorable, with the spectral noise density plotted for the low frequency surface antennas shown in Figure 4. The measurement agrees with the ambient thermal noise above 150 MHz. Below 150 MHz, it is dominated by the galactic thermal noise. A modulation of the galactic noise is seen as the horizontally oriented antenna aligns and anti-aligns with the plane of the Galaxy, which is inclined at $\approx 63°$ with respect to the South Pole, over a period of a sidereal day. Sources of manmade interference include weather ballon launches that employ a 400 MHz transponder for data telemetry, and a 129.3 MHz communication channel used for incoming and departing aircraft. The amount of interference decreases significantly over the winter. Overall, we expect to loose $\approx 3\%$ lifetime due to interference.

Local calibration pulsers installed within the testbed have been used to determine the geometry of the array *in situ*. By cross correlating the transmitted reference signal in the Vpol antennas, the timing of the transmissions for an ensemble of pulses can be measured to 4.5 ps, with a standard deviation of 136 ps. This corresponds to a 1 mm survey error in the position of the antennas.

4 Performance of the Proposed Array

4.1 Angular resolution

Because the goal of the ARA array is to make the first detections of neutrinos via the Askaryan effect, and establish the neutrino flux, angular resolution was not emphasized in the design. However, good up-down discrimination is essential in vetoing surface anthropogenic noise. The simulated angular resolution of the ARA baseline array is shown in Figure 5, with a median angular resolution of 5.96°. This resolution is for a single station detection, and is dominated by the azimuthal error. The error in the zenith angle reconstruction is about one degree.

4.2 Sensitivity to the neutrino flux

The limit on the cosmogenic neutrino flux from ARA after 3 years of operation of the full 37 station array is shown by the blue stars in Figure 6. Also shown are the expected flux upper limits from several competing experiments including RICE ([17], pentagons) , ANITA ([13], circles), Auger ([4], stars) and IceCube ([2], squares). The reason that the sensitive energy range of ARA was chosen to be lower than ANITA's was to optimize the instrument so that its peak sensitivity lie in the region where the cosmogenic neutrino flux is greatest, thereby maximizing the probability of detection. Also shown are several theoretical flux calculations based on different assumptions about the cosmic ray composition and the source evolution, including strong source evolution models [10, 20], mixed iron composition models [15, 9], and models incorporating constraints from the Fermi diffuse gamma ray flux [5]. ARA has the greatest sensitivity of any neutrino telescope in the energy interval from $10^{17} - 10^{19.5}$ eV. ARA can either detect or exclude a cosmogenic neutrino flux even in the more pessimistic scenario of an all iron cosmic ray spectrum [9]. ARA is intended as a discovery instrument for the ultra-high energy cosmogenic neutrinos.

The prototyping phase for ARA is now completed. After funding to build the balance of is secured, the array could be completed in five years. Once the flux of cosmogenic neutrinos is measured, this could inform the design of an observatory class array with precise angular resolution to study the origin and evolution of the highest energy cosmic ray accelerators.

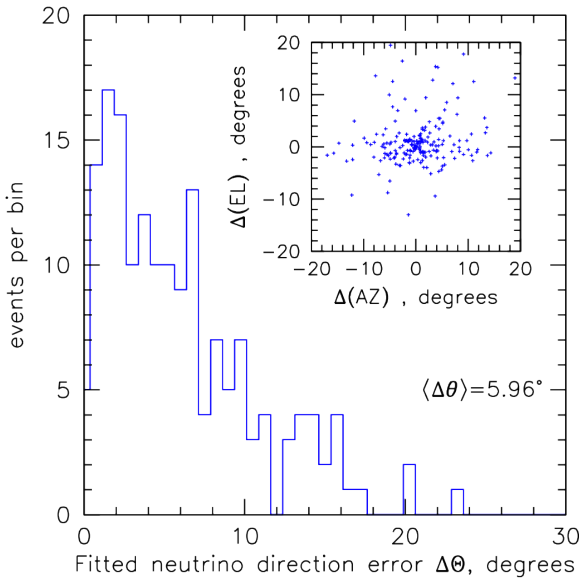

Figure 5: Distribution of fractional range errors in single-antenna-cluster reconstructions of the neutrino interaction vertex. Distribution of polar angle errors for full reconstruction of the incoming neutrino direction, using vertex reconstruction, amplitude, and polarization information. Inset: the 2-D distribution of reconstructed directions relative to true neutrino direction. [7]

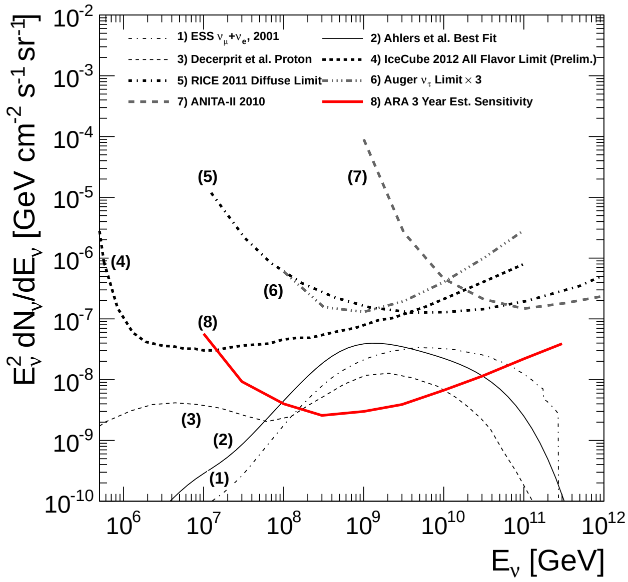

Figure 6: Compilation of sensitivity estimates from existing instruments, published limits, and a range of GZK neutrino models, along with the expected 3 year ARA sensitivity.

5 Acknowledgements

We thank the National Science Foundation for their generous support through Grant NSF ANT-1002483. We are very grateful to the National Science Foundation Office of Polar Programs, Raytheon Polar Services Corporation, and the Lockheed Martin Antarctic Support Contractor for their excellent field and logistics support at Amundsen-Scott South Pole Station, and the ARA and IceCube hot-water drillers who helped with our installation. See Figure 7.

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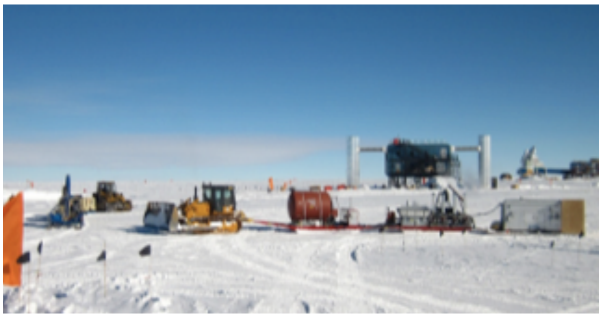

Figure 7: ARA hot water drill convoy in front of the IceCube Laboratory, heading out to the field to drill 200m deep, dry instrumentation holes.