

Performance of the ARIANNA Prototype Array

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Abstract: We describe the physics goals and detector capabilities of the the ARIANNA High Energy Neutrino Telescope, utilizing the unique geophysical features of the Ross Ice Shelf in Antarctica. ARIANNA relies on the radio Cherenkov technique and designed to improved the sensitivity to neutrinos with energies in excess of 10^{17} eV by at least a factor of 10 relative to current limits. The primary goal is focused on a measurement of the cosmological neutrino flux, whose existence is relatively secure but also expected to be quite small even under the best of circumstances. We report on recent results from the construction and operation of the first three stations of the Hexagonal Radio Array, a pilot program for the ARIANNA project, that was approved by the US National Science Foundation in 2011.

Keywords: icrc2013, ARIANNA, neutrino, GZK, cosmological.

1 Introduction

In 2011, NSF approved a pilot program for the ARIANNA project, called the Hexagonal Radio Array (HRA), to develop the technology and assess reliability of the concept to detect and measure the flux of cosmogenic neutrinos produced by the interaction of high energy cosmic rays with the cosmic microwave background. The measurements should provide important insight on the locations of the largest particle accelerators in the universe and allow physicists to probe for novel physics beyond the standard model used in the field.

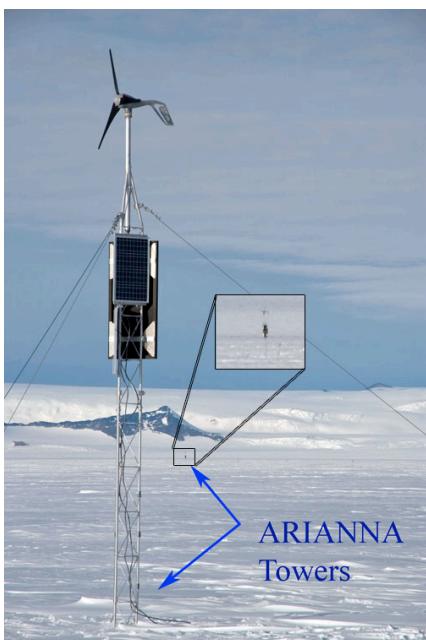


Figure 1: ARIANNA tower deployed in 2012 consisting of solar panels and a wind generator. Another is seen in the distance. Photo: C. Reed 2012

The seven-station HRA is the first step in a plan to completely understand the appropriate technology required

to measure the neutrino flux at the relevant energy and flux, and thus, it mostly serves as a technology development platform. The HRA pilot program[1] concentrated on three primary technological developments[2]:

1. Design and fabricate a high speed data acquisition system that could run autonomously on 10 watts of power that can trigger on events at rates up to 50 Hz. The main features: a) Digitization at 1.92 Gigasamples per second using an advanced integrated circuit b) consume less than 1.5W per channel with continuous sampling, c) use programmable trigger patterns to more efficiently select on neutrino signals in real time, d) generate pulses with a few ns width for heartbeat system, e) integrate housekeeping and health maintenance functionality, f) control station operation with low power microprocessor, and g) next season, deploy a more robust and less costly design.
2. Develop a power system that can supply 10 watts of power for six months of the Austral summer, with exploratory work to investigate continued operation during a portion of the Austral winter. We chose to focus on green technologies such as solar and wind rather than fossil fuel generators. The combination of wind and solar power systems have kept the 3 new stations fully operational through sunset. Battery levels have remained full or nearly full since commissioning in early December, 2012. We have previously reported that the prototype station has automatically restarted in the Austral spring when sufficient sunlight was available and expect the new stations to do the same. Figure 1 shows one of the towers with power systems.
3. Develop robust communications for monitoring, commanding, and data transfer. The ARIANNA collaboration has written special-purpose software for the microprocessor to command the data acquisition electronics, transfer digitized waveforms to local storage, and initiate data transfer over wireless internet (primary channel during the summer months) and Iridium satellites with the Short Burst Data protocol

(only communication channel during winter). Data transfer between HRA stations and the data archiving server at UC Irvine has worked as planned.

2 Scientific Motivation and Capabilities

When ultra-high energy neutrinos interact in a dense medium, such as the ice in the Ross Ice Shelf, the enormous cascade of secondary particles emit an intense sub-nanosecond pulse of coherent Cherenkov radiation at radio wavelengths. This emission mechanism, known as the Askaryan effect [3], was experimentally confirmed in ice and other media less than a decade ago [6, 7]. The effect arises from the excess of negative charge that builds up as electrons are swept out by the development of the cascade. The longer wavelengths of the broadband emission from the collective motion of the net charge will add coherently, producing a short duration, intense radio pulse. The shower dimensions determine the wavelengths of coherent emission, typically less than 5 GHz, but absorption in the media tend to limit the upper frequencies to 1 GHz. The balloon-borne ANITA payload [9] and the South Pole based RICE array [10] have exploited this effect to produce important constraints on the extraterrestrial neutrino flux.

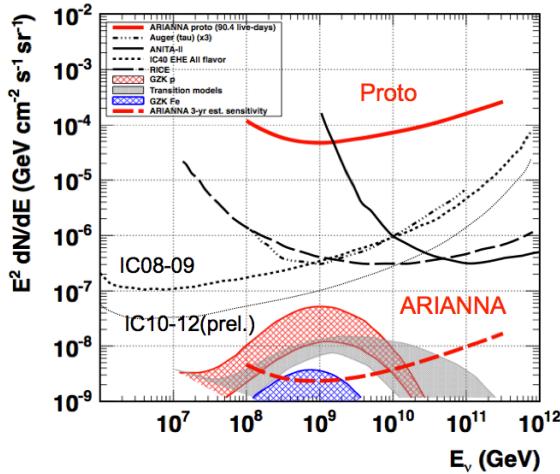


Figure 2: Representative survey of all-flavor neutrino flux limits, assuming 1:1:1 flavor ratio where needed, and widely-discussed theoretical predictions for cosmogenic neutrinos (colored and gray bands). ARIANNA sensitivity[16] is shown for 3 years of operation, assuming 2.3 events per decade of energy. See [14] for details of experimental limits, including those from ARIANNA Proto-station, which operated from 2009-2012 before decommissioning (figure from [14], adapted from [18]).

The idea of using a surface array of radio receivers to search for astrophysical sources has a long history. The ARIANNA (Antarctic Ross Iceshelf ANtenna Neutrino Array) concept [1] utilizes the enormous Ross Ice Shelf near the coast of Antarctica to increase the sensitivity to ultrahigh energy cosmogenic neutrinos by roughly an order of magnitude when compared to the sensitivity of existing detectors (Fig. 2). ARIANNA exploits a fortuitous natural phenomenon: the water-ice interface at the bottom of the Ice Shelf reflects radio signals with remarkable fidelity and attenuation lengths range between 350-500m [13].

Consequently, the reflected conical Cherenkov pulses can be detected from neutrinos traveling in any downward direction that interact in the ice. The reflected (and direct) radio pulses are detected by autonomous antenna stations located near the top of the ice surface, which greatly simplifies deployment of a large array. Shadowing effects from the gradient in the index of refraction are mitigated by the mostly vertical paths taken by the reflected pulses. Moreover, ARIANNA capitalizes on several additional useful properties of the site: it is geographically close to McMurdo, the major US base in Antarctica, and it exhibits low levels of anthropogenic radio noise due to shielding from Minna Bluff and the Transantarctic Mountains[8]. The baseline design of ARIANNA consists of 960 stations separated from each other by 1km on a 30km x 30km grid. The high sensitivity of ARIANNA results from nearly six months (and perhaps more based on recent experience) of continuous operation, low energy threshold ($\sim 3 \times 10^{17}$ eV), and a view of more than half the sky (declination +20 to -90 degrees).

Model and Reference	Model Class	Predicted N_ν
ESS Fig. 4 ($\nu_e + \nu_\mu$) [71]	No source evo.	30.8
Kotera (2010) Fig. 1 [33]	SFR1, Pure Proton	37.1
ESS Fig. 9 [71]	Strong evo.	104.9
Kalashev Fig. 2 [69]	High E_{max} , $z \leq 2$	96.1
Barger Fig. 2 [42]	Strong evo.	114.9
Yuksel, Kistler (2007) [53]	SFR evo.	45.4
Yuksel, Kistler (2007) [53]	QSO evo.	55.5
Yuksel, Kistler (2007) [53]	GRB evo.	156.1
Ave et al. (2005) [24]	Pure Fe comp.	11.3
Todor Stanev [80]	Fe, CMB+IRB	2.40
Kotera Fig. 7 upper [33]	Mixed comp.	21.7
Kotera Fig. 7 lower [33]	Pure Fe	7.50
Fermi-LAT [22]	$E_{cross} = 10^{17.5}$ eV	15.5
Fermi-LAT [22]	$E_{cross} = 10^{18.0}$ eV	21.1
Fermi-LAT [22]	$E_{cross} = 10^{18.5}$ eV	32.9
Fermi-LAT [22]	$E_{cross} = 10^{19.0}$ eV	42.8
WB (1999) [17]	No source evo.	22.4
WB (1999) [17]	QSO evo.	67.1
Olinto review (2011) [23]	Fe, $E_{max} = 100$ EeV	0.14
Olinto review (2011)	Mixed, $E_{max} = 10$ EeV	0.068
Olinto review (2011)	Proton, $E_{max} = 3$ ZeV	101.3
Olinto review (2011)	Various protonic, SFR	37.1

Figure 3: ARIANNA event rates for 3 years of operation for cosmogenic flux models that span a broad range of flux predictions. Representative all- proton models (p) and mixed composition (mixed) are shown. Computed for 1:1:1 flavor ratio. See [14] for details on models and references.

Greisen, Zatsepin, and Kuzmin (GZK)[4] first recognized that cosmic rays with energies in excess of 3×10^{19} eV readily interact with cosmic microwave photons and lose energy quickly, thereby limiting their propagation distance to the local supercluster. Recent measurements of the energy spectrum shows a clear suppression feature, likely due to the GZK mechanism[11, 12].

Neutrinos spanning the energy interval 10^{17-20} eV are produced as a direct by-product the GZK mechanism through charged pion decay, and therefore known as GZK or cosmogenic neutrinos. Neutrinos are uncharged and only interact weakly. Consequently neutrinos can travel unimpeded from the most distant sources and point back to their origin. In particular, GZK neutrinos are produced within a few tens of Mpc of the cosmic ray source, so it is expected that GZK neutrinos will point back with sub-degree accuracy. In addition, the neutrino energy spectrum helps to break model degeneracy between source distribution and

evolution[5] , complementing the studies of cosmic ray detectors.

Despite the recent exciting developments, there remains significant theoretical imprecision in the estimating the energy spectrum of cosmogenic neutrinos due to uncertainty associated with the elemental composition and injection spectra of the cosmic rays, source evolution, and cosmology. This uncertainty is schematically illustrated in Fig. 2 by three colored bands correspond to different classes of models: (red) all proton dip models, (gray) transition models that span a large range of assumptions associated with mixed composition, maximum acceleration energy and evolution of sources, and (blue) are Fe dominant models. The integrated event rates are shown in Fig. 3. ARIANNA is capable of probing all but the very lowest flux predictions, typically from models that rely on interesting and nontraditional astrophysics. On the other hand, it is also apparent from Fig. 2 that current experimental efforts will only probe the most optimistic of recent predictions. Given the current level of uncertainty, it is plausible that cosmogenic neutrino flux is too low for currently operating instruments. The next generation of UHE neutrino telescopes must be flexible and powerful enough to observe potentially very small fluxes.

Although we have focused on cosmogenic neutrino production, it is not the only potential source of neutrino messengers at ARIANNA energies. The sources of cosmic rays may also produce neutrinos directly. ARIANNA can survey the southern half of the sky for point sources of high-energy neutrinos from AGN or GRB with unprecedented sensitivity for energies between $10^{17} - 10^{19}$ eV. It would also be sensitive to novel, if somewhat unlikely, new components of cosmology such as topological defects produced in the Big Bang. Of course, we recognize that the study of ultra-high energy neutrinos with a uniquely sensitive instrument could reveal completely unexpected phenomena.

3 Hexagonal Radio Array - HRA

Fig. 4 shows the current and planned locations of the HRA stations at the ARIANNA site about 120km south of McMurdo station. Also shown is the proposed expansion of the array, the next step to eventual construction of a 960 station facility.

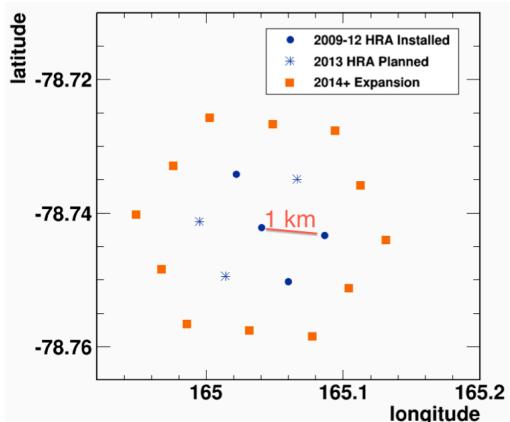


Figure 4: Layout of HRA and proposed expansion.

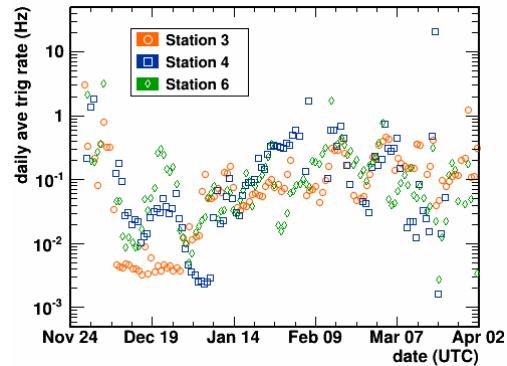


Figure 5: Trigger rates, averaged over a 24 hour period.

3.1 Data Quality

Fig. 5 shows the average daily trigger rates (in Hz) for all 3 stations deployed in late November 2012 through April 2013. The rates stay well below the maximum trigger rate of the DAQ electronics (50 Hz), which implies that dead time is minimal. The distributions of time differences between consecutive events are completely consistent with random processes, and the vast majority of events are due to thermal fluctuations due to non-zero absolute temperature in the ice and amplifier. After an initial period of rate decline, the thresholds were adjusted to produce ~ 0.1 Hz. The rate fluctuations are still under investigation, but much of it is due to subsequent threshold adjustments to investigate station response and variation of ambient temperature. The general trend to lower rates in late December anti-correlates with warmer weather. On rare occasions, the rates are affected by high winds (for example, on March 17, 2013). Thermal effects will diminish with time as the snow overburden increases, mitigating the ambient temperature fluctuations.

3.2 Angular Resolution and Reconstruction

The angular resolution of an ARIANNA station was obtained in situ by a set of studies performed by transmitting a short duration (~ 1 ns FWHM) pulse downward from a Seavey horn antenna and using the station electronics to record the upward traveling pulse that was reflected from the water-ice boundary at the bottom of the Ross Ice Shelf. The measured pulses shown are strong, with very little influence from ambient RF noise from the ice and amp (about 20 mV rms). For the case when the transmitter is co-located with the ARIANNA station (located at (0,0) in Fig. 6), the nearly identical waveforms are cross-correlated to determine the fixed time delays in each channel due to differences in cables and electronics.

As seen in Fig. 6 the Seavey horn transmitter is shifted to different positions on the snow surface and the arrival angle of the events are reconstructed subject to the constraint that all independent time delays are compatible with a plane wave. The reconstructed angle is then corrected for propagation through the firn layer with a simple model of ice density as function of depth to produce a predicted location on the surface. The blue stars indicate the actual positions, but are not known to better than 10m along a radial arc from the origin, which also is the center of the station. The median value for the precision of the angular measurements ranges between 0.14 to 0.17 degrees and

should improve once systematic effects such as the relative spatial positions of each receiver are determined.

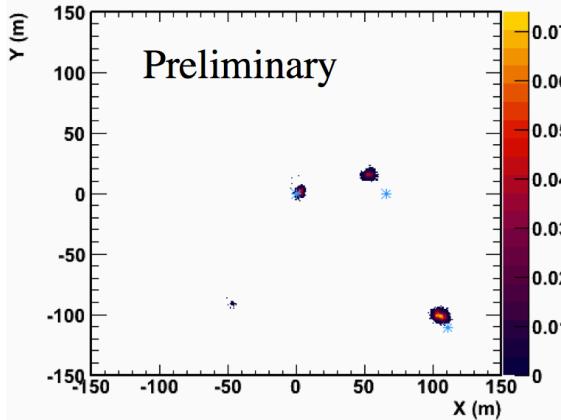


Figure 6: Reconstructed surface locations of test signals from a transmitter which bounce off the water-ice interface beneath the ARIANNA station.

3.3 Data Analysis

Fig. 7 shows the preliminary analysis of the data collected from station 3 during the month of January, 2013. The trigger logic required that any 2 of the four channels had to exceed a threshold of $\sim 5V_{rms}$, where V_{rms} is the root mean square of the time averaged voltage fluctuations that were monitored continuously by events acquired by forcing a trigger at a random time. The data were cleaned by removing forced trigger and heartbeat events from the event stream. Then the frequency dependent power spectrum was computed from the time dependent waveforms. Events were rejected if anomalous power was detected at frequencies below the high pass filter or exhibit strong narrow peaks in the frequency spectrum.

Finally, the power from parallel antenna channels are plotted (P_{ant1} and P_{ant2} , in arbitrary units) with the expectation that similar power should be measured for plane wave signals from neutrino events (defined by the black lines and labeled "Signal Region"). The reflected events from the Bounce tests mentioned in the previous subsection were used as reasonable proxies for signal waveforms to establish the boundaries of the signal region. The neutrino signal region contains 1 event. We note almost complete rejection of background based solely on characteristics of the power spectrum of each channel. Even without incorporating timing into event reconstruction, background rejection is straightforward due to the low level of nonthermal noise noise contributions. Moreover, the nonthermal events do not mimic the properties of neutrino signal.

4 Conclusions

In December 2012, three of seven ARIANNA stations were deployed and commissioned. We report that the stations operated reliably throughout the Austral summer and beyond, consuming 10W of power on average, and transmitting data in real time over the wireless internet link. Commanding was performed over both the wireless and Iridium satellite networks. The RF backgrounds are consistent with thermal emission from the ice with occasional contributions from

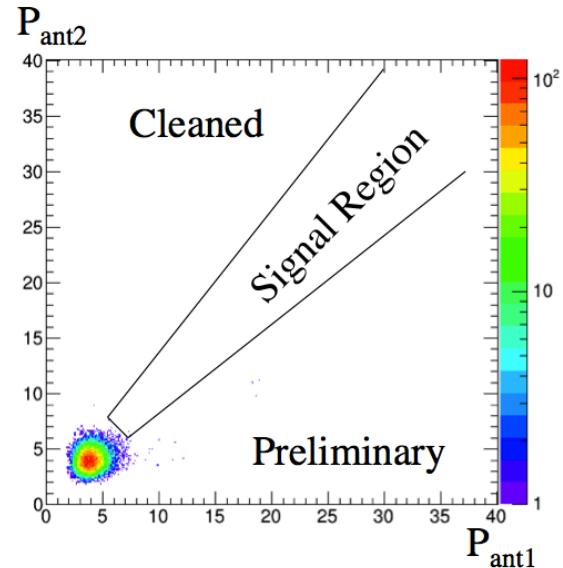


Figure 7: Preliminary analysis of events from station 3 collected in January 2013. The total integrated power is plotted for the pair of parallel antennas with the largest fractional difference in power.

non-routine aircraft activities, such as search and rescue missions, and from the wind generator when winds speed exceed 35mph. Neither of these backgrounds present significant losses in live-time nor confusion with expected signal.

A prototype station deployed several years earlier shut down safely at the start of Austral winter and restarted automatically during the following spring[8]. Data acquired from then prototype station was analyzed to produce the first limit on the neutrino flux using a detector based the ARIANNA concept[14]. The remaining ARIANNA HRA stations are planned for installation in December 2013, with emphasis on reducing deployment time and station costs.

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