PROCEEDINGS OF SCIENCE

Optimization of ARIANNA Station Configuration

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Recent measurements of the horizontal propagation properties of radio pulses through stratified polar firn indicate that surface detectors can observe signals from neutrino interactions throughout a much larger volume than previously considered. The evidence for horizontal propagation will be briefly summarized. Motivated by this new opportunity, the ARIANNA simulation tool to assess performance was upgraded to investigate traditional antenna receivers such as LPDA and fat dipoles in any orientation, pointing direction and geometrical position. The antenna response was computed for expected depth beneath the firn-air boundary and the separation between stations was also re-optimized to maximize sensitivity at 10^{18} eV. In addition, the investigations consider locations at the ARIANNA site at Moore's Bay on the Ross Ice Shelf and at the South Pole. We conclude with a discussion of the ramifications of these studies.

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

[1]Speaker

PoS(ICRC2017)1042

1.Introduction

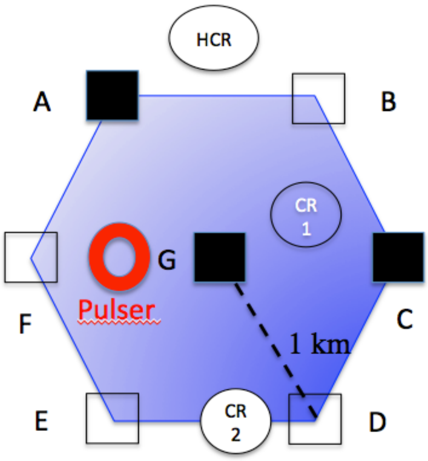
The planned ARIANNA high energy neutrino detector uses radio techniques to search for astrophysical sources of neutrinos with energies above 10^{16} eV [1]. The baseline architecture of ARIANNA, located on the Ross Ice Shelf about 110 km south of McMurdo station in Antarctica, is based on an rectangular grid of autonomous stations that send data back in real time through Iridium satellites or a long distance wireless network. The baseline design of each station consists of 8 log periodic antennas (LPDA) with a bandwidth 100-1000 MHz; half of which point vertically downward into the ice and the other half point upward, though still buried at least a meter beneath the snow surface. The upward LPDA are required to tag cosmic rays that interact in the atmosphere, producing a signal that acts as a calibration sources. Except for direction, the radio pulses produced by cosmic rays are quite similar to those expected from neutrino interactions in the ice [2][3]. After encouraging results from a prototype station deployed in 2009, the US NSF approved an ARIANNA pilot program in 2011, and construction of a 7 station array was completed in December 2014. All stations have operated continuously during the austral summer since that time [4][5][6]. Since the stations are located on the surface, as opposed to the deployment in drilled deep holes, construction costs are controlled and station repair is possible if needed. In addition, the search for high energy neutrinos is remarkably efficient due, in part, to the low ambient RF backgrounds [6].

The science mission of ARIANNA focuses on three energy ranges: 10^{16}-10^{18} eV, 10^{18}-10^{19} eV and >10^{20} eV. One of the primary goals is to measure the flux of cosmogenic neutrinos from the interaction of cosmic rays with the microwave backgrounds. The bulk of these neutrinos will be observed with E ~ 10^{18}-10^{19} eV. The target sensitivity of the first Generation ARIANNA is sufficient to observe a flux or rule out the hypothesis that all cosmic rays at extreme energies are protons and extragalactic, independent of many of the astrophysical details such as source evolution, cosmology, and injection spectra at the source [7]. A nearly equally important goal of ARIANNA will be to extend the energy spectrum of the isotropic diffuse flux IceCube events [8] to energies above 10^{16} eV. The final goal of ARIANNA Gen I centers on improving the search for neutrinos near 10^{20}eV by a factor 10 when compared to current limits. The observation of neutrinos at 10^{20} eV would have profound implications on the existence of cosmic rays with energies and order of magnitude higher, and potential acceleration mechanisms.

2. Horizontal Propagation and Detector Performance

The computer simulation of performance and other characteristics of the ARIANNA detector [1] relies on an important assumption related to ray propagation of the RF pulse from interaction to surface detector. First, the real part of the index of refraction smoothly and continuously increases from ~1.3 at the surface to ~1.8 at a depth of ~75m, corresponding to the transition from low density snow at the surface to ice. In this model, upward propagating rays may refract to horizontal direction parallel to the surface and then start to travel downward again. For a wide range of geometrical locations, there is no solution connecting an emitter to a detector, which is termed the "shadow region". The limitations of the shadow region reduces the visible solid angle by approximately half. Because ARIANNA is located on the Ross Ice

Shelf, shadowing losses are mitigated because additional signals are observed when reflecting from the ice-ocean interface at the bottom. The radio signals from reflected paths tend to propagate more vertically (to reduce attenuation) where shadowing is not relevant.



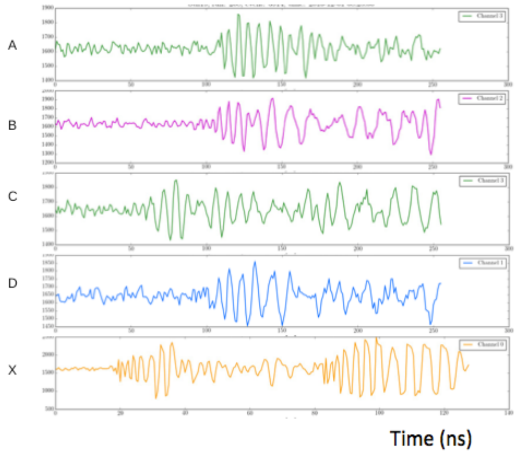


Figure 1: *Schematic of pulser studies at ARIANNA site with station identification letters.*

Figure 2*: Time dependent waveforms captured by ARIANNA stations from pulser shown in fig. 1.*

In the absence of scattering, a smooth gradient in the index of refraction implies that no signals can propagate horizontally between a transmitter and receiver just below the ice surface. Contrary to the expectation, horizontally propagating signals were reported [9]. Inspired by this report, the ARIANNA team investigated horizontal propagation at the Moore's Bay site in December 2016. They found that a central transmitter located at a depth of 20m, as shown schematically in Figure 1, was able to broadcast to all ARIANNA stations out to a distance of 1400m (see Figure 2). Figure 3 shows that the distance dependence of the integrated power of the electric field is compatible with a model $|\mathbf{E}(r)| \sim [1/r]e^{-r/L}$, where L is the field attenuation L=501±168 m. Remarkably, horizontal propagation was recently uncovered from archival data taken at the South Pole from a transmitter at a depth of ~100m (within the firn at the South Pole) to RICE receivers located at a distance of ~3.3 km and depths ranging from 100 m to 300 m. Figure 4 shows that the measured amplitude is compatible with a field attenuation length of 482±114 m [10], in agreement with the data from the ARIANNA site. The observation of horizontal propagation at two independent sites at different elevations with different temperature and density profiles suggests that this phenomena is universal on the continent of Antarctica, and perhaps elsewhere on the planet.

Though the phenomena of horizontal propagation has only recently been detected, and much remains to be understood, toy simulations of the Antarctic firn which incorporate measured density profiles replicate some aspects of horizontal propagation.

Though the depth dependence of the index of refraction was assumed to vary smoothly, the measured density of the firn ice fluctuates by ~1% for 0.5 m vertical steps. The variation in density is due to seasonal variation in snow accumulation and subsequent melting, creating stratified layers [15]. Horizontal propagation is possible between transmitters and receivers at the same depth if realistic density fluctuations as a function of depth are include in the signal transport model. A modest amount of non-specular scattering may be responsible for horizontal propagation between sources and receivers at dissimilar depths, but this is still under study.

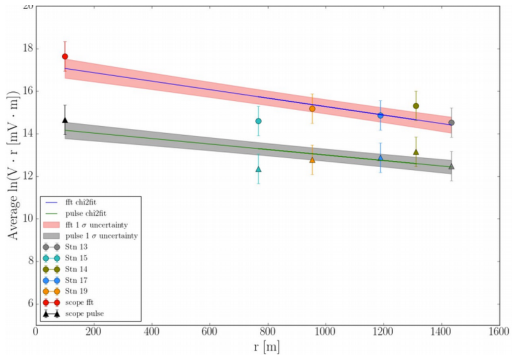


***Figure 3**: Distance dependence of amplitude of electric field (triangles) and integrated power (circles) at ARIANNA site. Errors shown are derived from linear fit.*

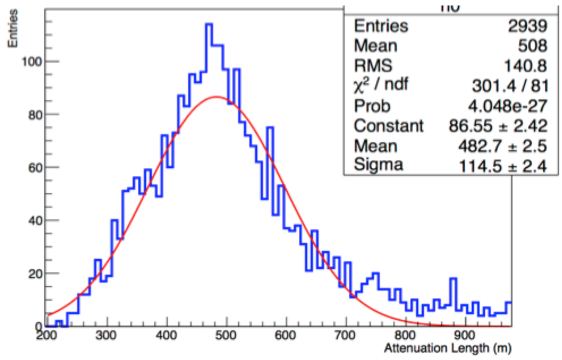


***Figure 4:** Distribution of field attenuation lengths derived from calibration pulses at the South Pole[10].*

3. Modifications to ARIANNA simulation

As mentioned, geometrical ray tracing in continuously and monotonically changing index produces shadow zones where two points cannot be connected by an allowed path. In addition to this situation, we have modified the ARIANNA simulation tool to include horizontal propagation. We model the physical path as follows: ordinary refraction occurs until the ray propagates parallel to the firn surface (assumed flat). Once the direction is parallel to the surface plane, the ray propagates horizontally. Additional losses may be included due to attenution, nominally set to L=500m to be consistent with data in Section 2.

Also we have improved the model of the LPDA gain as a function of frequency, phase, and angle by incorporating the results from WIPL-D antenna modeling software [11]. The antenna response has been extended to include both the front and backlobe.

4. Description of Configurations

The evidence for horizontal propagation is sufficiently suggestive to warrant further investigation of detector configurations. In this study, we broaden the site location to include both Moore's Bay and South Pole. We model the following stations configurations: (1) ARIANNA station with 8 downward pointing LPDA, (2) ARIANNA combo station with 4 LPDA and 4 vertically oriented ARA-style dipoles, shown schematically in Figure 5, (3) 4 ARA-style vertically oriented dipoles. The advantages of configuration 2: (1) polarization measurement in 3 orthogonal axis, which is expected to improve the angular resolution of the neutrino, (2) improved sensitivity to neutrino interaction vertices at small angles with respect to the horizon, which is important for a surface detector in the case of horizontal propagation.

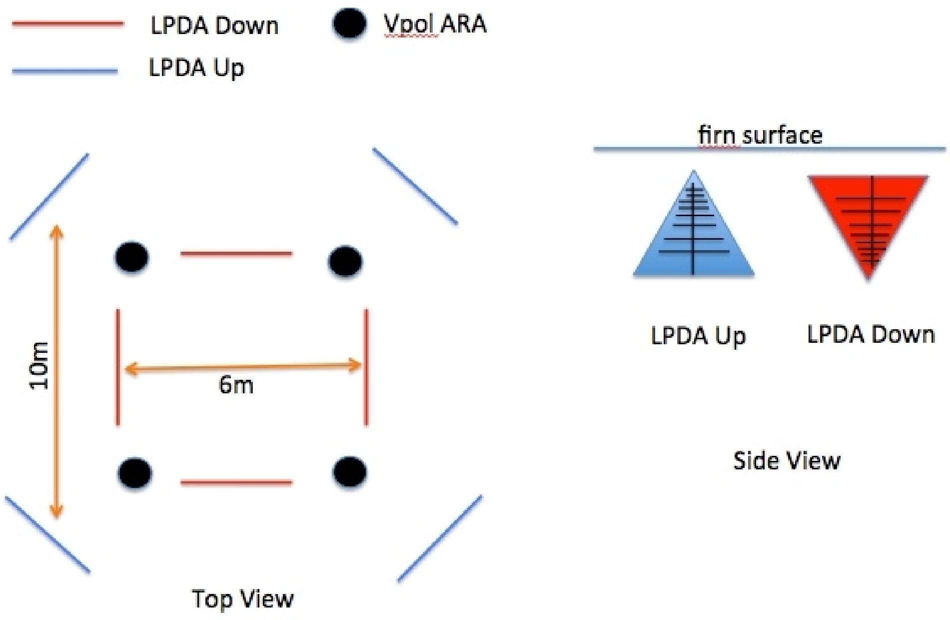


Figure 5: *Schematic of combination station (combo). It consists of four downward facing LPDA (red), four upward facing LPDA (blue) for cosmic ray tagging, and 4 dipole antennas currently installed by the ARA collaboration.*

We model two sites: (1) ARIANNA site with and without horizontal propagation included, (2) South Pole with and without horizontal propagation (the ARIANNA site without horizontal propagation was previously reported [1][6]).

South Pole ice model substitutes the measured thickness and depth dependent attenuation properties [12]. It also modifies the depth dependence of the density of the firn, which affects the geometry of the shadow zone. Finally, the bottom ice-water interface at Moore's Bay is replaced by a non-reflecting boundary at a depth of 2850m.

5. Results and Discussion

Figures 6 and 7 show the effective volumes (VeffAve) per station as a function of neutrino energy, averaged over neutrino flavor for a variety of conditions indicated by the figure caption.

Several conclusions can be extracted from Figure 6: (1) Due to the deeper and more transparent ice in the frequency range of interest, a surface array at the South Pole is a factor 2 larger than a similar station at Moore's Bay for energies at 10^{18}eV; (2) The combo detector is better than previous ARIANNA station architecture if horizontal propagation is included. The dipoles augment the effective volume due to the superior gain for horizontally propagating RF pulses from relatively shallow neutrino vertices, and because horizontally propagating RF pulses tend to be polarized vertically; (3) Ignoring the possibility of horizontal propagation, the effective volume of a detector buried at 200m is of order few larger than a surface detector at the South Pole. The advantage of a deeper station may be offset by lower cost and simpler installation of a surface array; (4) With horizontal propagation, there are no geometrically precluded regions for a surface detector. Therefore, the effective volume for the ARA station buried at 200m is comparable to the combination surface array at the South Pole. The relative advantages in gain and bandwidth for LPDA receivers are mitigated by the strong effects due to ice attenuation.

Figure 7 shows the relative improvement in effective volume for a combination station at the South Pole if horizontal propagation is included in the simulation. While the differences the three cases are signficant for neutrino energies of 10^{18} eV, there is far less variation at lower energies. For energies at 10^{18} eV, there is a factor 2.5 increase between horizontal propagation with 500 m attenuation length and the usual assumption of no horizontal propagation (which leads to a shadow region).

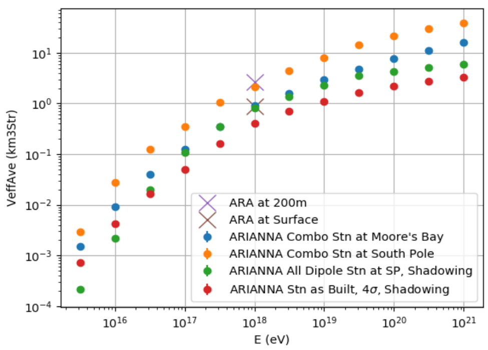


Figure 6: *Comparison of effective volume as a function of energy for ARIANNA combination station at ARIANNA site (blue circle) and South Pole (Orange circle) assuming horizontal propagation with 500m attenuation. The effective volume is also shown for an ARA station located near the surface and at a depth of 200m (colored X) and the ARIANNA baseline design(red circle).*

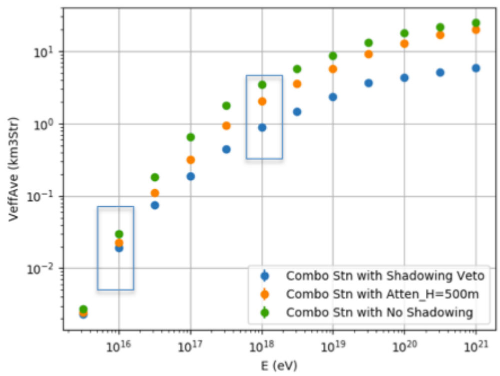


Figure 7: *Comparison of effective volume as function of energy for combination station at South Pole for the (1) standard shadowing physics with no horizontal propagation (blue circle), (2) horizontal propagation with no attenuation (green circle) and (3) horizontal propagation with attenuation length of 500m (orange circle).*

Figure 8 shows that 169 stations are required to reach the challenging physics goal of observing several events, integrated over energy in 5 years of continuous operation, for cosmogenic models based on pure proton composition of cosmic rays with no source evolution [7]. The goal of these models is to generate a robust minimum flux for all-proton composition. As indicated by Figure 6, it requires the same number of deep ARA stations or surface combination stations (with horizontal propagation) at the South Pole. For comparison, a detector configured with a standard ARIANNA station located at Moore's Bay without horizontal propagation requires 10 years for an array of 1296 stations powered by solar panels only to reach the same sensitivity.

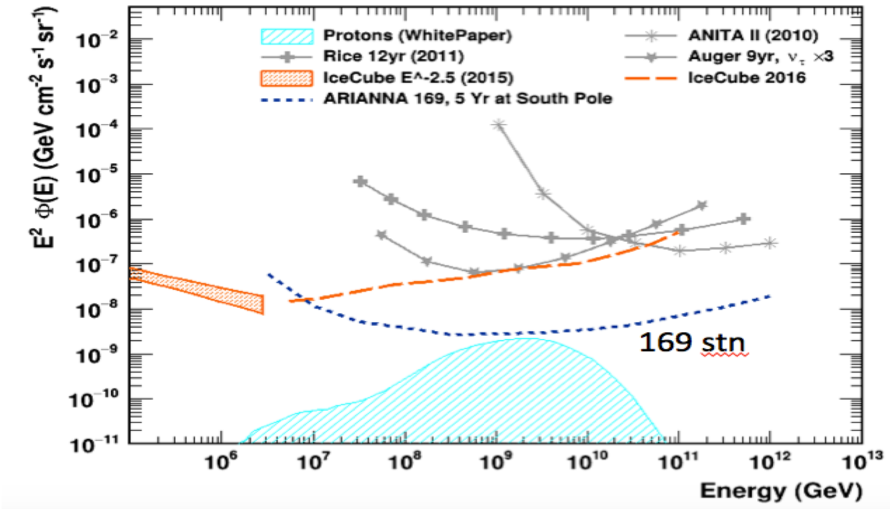


Figure 8: Projected flux sensitivity of combo detector at South Pole for 169 station array (blue dash). Also shown are current experimental measurements and flux limits. The upper edge of the blue band gives a minimum flux prediction for proton only models. The sensitivity calculation assumes 5 years of live time and horizontal propagation with 500m attenuation length as described in section 2.

The South Pole site has another potential advantage over Moore's Bay besides the deeper and more transparent ice: access to power the entire year supplied by Amundsen-Scott station. At Moore's Bay, the ARIANNA stations operate robustly on solar power during the Austral summer, but no established reliable technology provides power during the winter (though testing of a new wind gen design is expected the next Austral polar campaign [6]). However, the RF backgrounds are expected to be worse at the South Pole due to nearby human activities and aviation traffic. The impulsive noise sources due to human activities must be characterized in the context of a surface station, especially at frequencies below 150MHz.

To investigate operational reliability of the ARIANNA technology and RF backgrounds for a surface station, the ARIANNA collaboration has requested that an ARIANNA station be deployed at the South Pole during the 2017/2018 Austral campaign. The ARA collaboration has agreed to provide access to the ARA power grid for an ARIANNA station.

The ARIANNA and ARA pilot programs have developed technologies to relatively mature status, with known strengths and deficiencies. The discovery of horizontal propagation offers the opportunity to re-evaluate and re-optimize the site location and detector configuration, with the goal of selecting the best of both approaches to reduce cost and increase capabilities. Due to the potential growth of sensitivity due to horizontal propagation, cooperative efforts are planned for deep RF pulser studies to both buried and surface stations to study propagation properties in polar ice. These studies include the evaluation of pulse characteristics and their suitability for event reconstruction.

6. Acknowledgements

We wish to thank the US National Science Foundation for its support of the ARIANNA project under grant PHY-1607719. We also acknowledge support from National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) and from the German Research

Foundation (DFG, grant NE 2031/1-1). We are grateful for the outstanding cooperation in field planning and operations by the Antarctic Support Contractor.

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