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Simulation of ARIANNA Capabilities

F. WU[1], J. NAM[1] FOR THE ARIANNA COLLABORATION
[1]*Dept. of Physics and Astronomy, University of California-Irvine CA 92697*
fenfangw@uci.edu

Abstract: Antarctic Ross Ice Shelf ANtenna Neutrino Array (ARIANNA) is a new concept of a large radio telescope which consists of 10,000 broadband antenna stations located on the surface of the Ross Ice Shelf in Antarctica. Primary goals of ARIANNA are to test the GZK (Greisen-Zatsepin-Kuzmin) neutrino production and to measure the neutrino cross-section near 100 TeV. We present here a Monte Carlo simulation of the ARIANNA system that studies the sensitivity of the detector under various experimental configurations and event reconstruction techniques.

Introduction

ARIANNA is designed to detect neutrinos with energies between 10^{17}-10^{20}eV and it bridges the gap in sensitivity left by the first-generation neutrino telescopes such as AMANDA-II and ANITA. As high energy neutrinos interact with the nuclei in the ice, Cherenkov radiation is produced. At radio frequencies the Cherenkov radiation is coherent, which makes it promising to detect these distinctive short duration pulses, called Askaryan pulses [1].

ARIANNA will be located in the Ross Ice Shelf near the coast of Antarctica where the shelf ice is nearly transparent to electromagnetic radiation at radio frequencies and the smooth underneath behaves like an excellent mirror for reflecting the downward radio signals. Therefore, ARIANNA can detect radio signals from interactions from both up-coming and down-going neutrinos, providing more than 2π of sky coverage. ARIANNA is expected to have nearly six months of continuous operation. Benefiting from all the aforementioned advantages, ARIANNA increases the sensitivity to cosmogenic neutrinos by roughly an order of magnitude when compared to the sensitivity of existing detectors and those under construction.

It has been pointed out that the total interaction cross-section of extremely high energy neutrinos can provide a powerful probe of new physics at energies beyond the reach of terrestrial accelerators. Several ideas exist in the literature to measure the neutrino cross-section at extremely high energy, but suffer from limited statistical precision. ARIANNA has sufficient collecting power to ensure adequate statistics to determine the cross-section at center of momentum energies near 100 TeV from the zenith angle dependence of the measured flux.

Simulations

There are two ARIANNA simulation tools developed by the ARIANNA collaboration. This paper is based on the simulation done by UCI group. First, 100×100 moderately high gain antenna stations are arranged on a square grid with lattice separation of $\sim$300 meters. The complete array occupies an area of 30 km by 30 km, and is located on the surface of the Ross Ice Shelf where the ice thickness is about 500 meters. The upper 100 meters of ice is treated as firn with refraction index 1.3. Each station consists of a small group of cross-polarized antennas residing just beneath the snow surface and facing downwards. They communicate with a central control hub by wireless links to generate global triggers.

As a neutrino gets to the ice block where the stations are located, the direction of the neutrino and the interaction point are randomly picked within the ice volume. The direction of the neutrino, combined with the neutrino-nuclei cross-section [2], determines the possibility for the neutrino to interact at the interaction point. Then Cherenkov radio emission is estimated via standard parameterizations [3] that were validated at accelerators [4]. Refracted emission from the ice-firn interface is propagated geometrically to the surface. The stations within the Cherenkov cone, where the signal is still detectable, will be the candidates for triggering. Next, the signal strength at each of the these stations is calculated by taking the depth-dependent attenuation into account. The shelf ice has been measured to be nearly transparent to electromagnetic radiation at radio frequencies [5]. Averaged over the vertical temperature profile, the average effective field attenuation length for one-way radio propagation through the ice-shelf is about 450 m.

Each antenna station consists of two dual-polarization antennas with gain and angular sensitivity identical to the measured properties of the Seavey antenna employed by ANITA. A local trigger is formed at a given antenna station when the detected power exceeds a specified threshold. Typically, we require that the signal in 2 of the 4 polarization channels exceed $2.3V_{rms}$, where V_{rms} is the rms noise generated by thermal fluctuations of ice with a vertically averaged temperature of $-10°$C. A master trigger is generated when a minimum of 3 stations report a local trigger within a 20 microsecond time window. The arrival time is determined at each station by local GPS clocks with a precision of 10 ns.

To simulate the reflected signal case, the mirror-stations and mirror-ice are obtained by taking the ice bottom as a mirror and getting the images of the real stations and ice. Then there are two station arrays in the simulation, one is on the surface of the firn facing downward and the other one is 1000 meters below the surface with antennas facing upward. As Cherenkov radiation propagates in the ice, we assume the signals in the lower half of the Cherenkov cone would penetrate the bottom of the ice, propagate through the mirror-ice and directly get to the mirror-stations. This process is equivalent to the case that the signals get to the bottom of the ice and reflect back to the surface stations. Then we can repeat the modeling process for direct signals. Both triggered real stations and mirror-stations are accounted for in the final trigger.

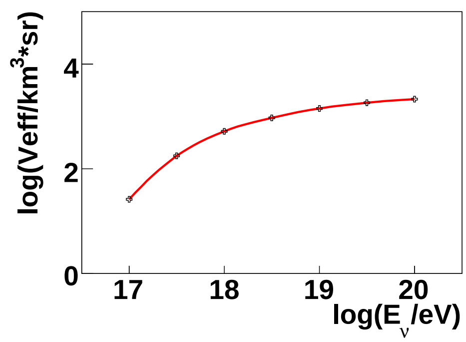

Figure 1: Effective aperture of ARIANNA.

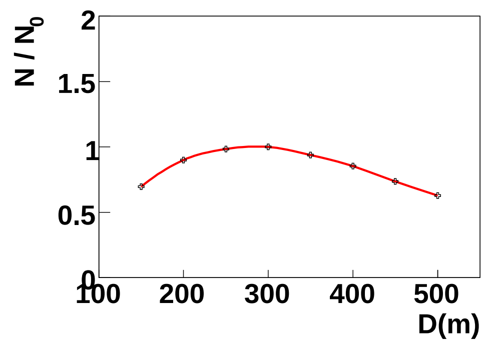

Figure 2: N_0 is the events rate while using the standard parameters mentioned in the simulation section. N is the events rate corresponding to the varied lattice separation of stations. The curve gives the optimized separation for ARIANNA at about 300 m.

The previous paragraphs describe the standard configurations of ARIANNA. The corresponding effective aperture is shown in figure 1. To get a more systematic check for ARIANNA, some of the standard parameters are varied to see how the events ratio (N/N_0) changes. Figure 2 shows the events ratio per as a function of the lattice sparation of stations. 300 m is chosen for the nominal separation.

Figure 3 shows how the events ratio depends on the attenuation length, which indicates that the effective aperture is very sensitive to the field attenu-

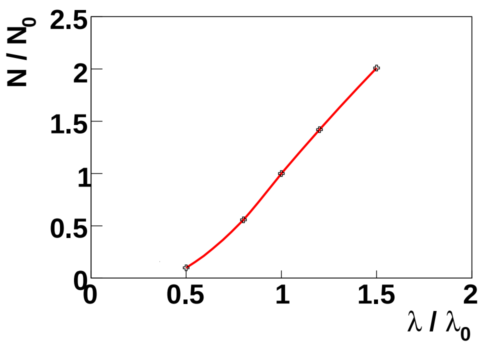

Figure 3: Events ratio as a function of field attenuation length. λ_0 is the nominal attenuation length.

ation length. The most recently measurements for the ice properties in the Ross Iceshelf were done by S. Barwick et al. in November, 2006 [5]. They found that the ice at the site (Moore's Bay) is thick (624 m), the water-ice bottom of the shelf behaves like an excellent mirror, and signal attenuation is small for all frequencies of interest. In addition, radio backgrounds are negligible.

Reconstruction

The measurement of the neutrino direction is important for the neutrino cross-section measurement by fitting the number of events distribution as a function of zenith angle near the horizon [6]. In order to estimate the capability of ARIANNA for measurements of neutrino direction and its energy, we implemented event reconstruction software using timing and amplitude information from each station.

A shower position is found by χ^2 fit which minimizes

$$\chi_t^2 = \sum_i^{N_{hit}} \left(\frac{t_{obs}^i - t_{exp}^i(x,y,z)}{\sigma}\right)^2. \qquad (1)$$

Here, the N_{hit} is number of triggered stations, the t_{obs}^i is arrival time of the signal recorded at the station i, the $t_{exp}^i(x,y,z)$ is expected arrival time for a trajectory of the radio Cherenkov signal from a given hypothesis of shower position (x,y,z) to the station, and the σ is time resolution of the system which we assume by 10 ns. Since the radio Cherenkov signal could propagate either directly to the receiver antenna or reflected from the bottom, both signal paths are considered for each station. The incorrect path assumptions are effectively reduced by requiring boundary conditions; shower position (x,y) to be associated the receiver antenna position of the maximum voltage within 1 km and depth (z) to be within the ice thickness. Further studies are on going to reduce the path ambiguity using the polarization information as well. We perform 10 iterations of fits to reduce misreconstructions caused by local minima. In each iterations, initial fit parameters of x,y,z are uniformly varied within the boundary conditions.

Once the shower position is found, a vertex position of the Cherenkov cone is constrained by it. For the angle measurement, we perform two steps of fits. The first angle fit is to find a rough angle by using a geometric hit pattern of the triggered stations. It is used for an initial input for the next step. Then, in the second step, amplitude information allow a precise measurement of angle by minimizing

$$\chi_V^2 = \sum_i^{N_{hit}} \left(\frac{V_{obs}^i - V_{exp}^i(\theta,\phi)}{V_{rms}}\right)^2. \qquad (2)$$

Here, the V_{obs} is recorded voltage of the signal, the V_{rms} is the thermal fluctuation of voltage, and the $V_{exp}^i(\theta,\phi)$ is expected signal voltage for a given hypothesis of neutrino direction (θ,ϕ) after taking into account $1/R^2$ power loss, attenuation, and angular distance from the center of the Cherenkov cone;

$$V_{exp} = V_0 \frac{e^{-R/\lambda}}{R} e^{(-\delta\Phi^2/2\sigma_\Phi^2)}, \qquad (3)$$

where the V_0 is generated voltage at the shower origin, λ is effective attenuation length along the path of the radio signal, $\delta\Phi$ is angular distance from the Cherenkov cone, and the σ_Φ is the width of the Cherenkov cone. We perform 10 iterations in which initial input parameters of (θ,ϕ) are randomly varied within 10 degrees of the output from the first angle fit. The V_0 can be converted to the shower energy. Figure 4 shows a good linearity between the reconstructed energy (E_{recon}) and the neutrino shower energy (E_{shower}). A Gaussian fit to the $(E_{recon}-E_{shower})/E_{shower}$ distribution estimates 10% of the shower energy resolution. Fig-

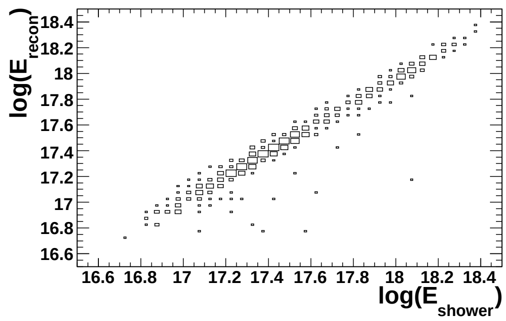

Figure 4: Correlation between the reconstructed energy and the neutrino shower. Unit is in eV.

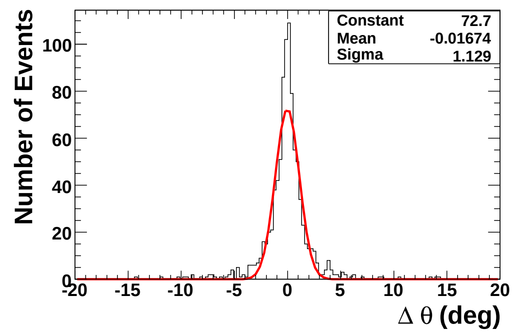

Figure 5: Estimation of resolution of the zenith angle.

ure 5 shows a distribution of the zenith angle difference ($d\theta = \theta_{recon} - \theta_{gen}$). It estimates 1.1 degrees of resolution which is sufficient for the neutrino cross-section measurement [7].

For a more realistic estimation of the angular resolution, we are planning to take into account an angular dependence of the antenna response. This causes an additional error on the amplitude measurement and consequently effects to the angle measurement. In contrast, we have a room to improve the amplitude measurement by combining all amplitude information from all channels in triggered stations. We assume that the time resolution is only limited by the GPS clock in the current simulation. On the other hand, the angle resolution can be improved by taking advantage of an excellent time resolution (100-200 ps) between channels in a station.

Conclusions

We discussed the different systematic configurations for ARIANNA and assess the corresponding sensitivities of ARIANNA. We presented the reconstruction technique and showed some of the results as well. Simulations indicate that ARIANNA can detect ∼40 events in six months of operation based on the neutrino flux predicted by Engel, Seckel and Stanev [8]. Preliminary reconstruction studies show that ARIANNA can achieve angular resolution of 1.1 degrees.

Acknowledgements

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