

Ross Ice Shelf Thickness, Radio-frequency Attenuation and Reflectivity: Implications for the ARIANNA UHE Neutrino Detector

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Abstract: The ARIANNA high energy neutrino detector is planned to be deployed on the surface of the Ross Ice Shelf to search for astrophysical neutrinos. Collisions with nuclei in the ice generate showers of particles that emit short pulses of radiation, created by the Askaryan mechanism, in the frequency range of 100 MHz to 1 GHz. The ARIANNA site is located about 65 miles from McMurdo Station, the main hub of US Antarctic operations, and is protected from ambient RF interference by a geologic formation known as Minna Bluff. In this work, we report preliminary results for the frequency interval 90-180 MHz from site studies of the field attenuation length (averaged over depth), and reflection and polarization properties of the saltwater-ice boundary.

Keywords: ARIANNA, Antarctica, GZK, neutrino astronomy, Ross Ice Shelf, attenuation length

1 Introduction

The Antarctic Ross Ice Shelf Antenna Neutrino Array (ARIANNA) is designed to detect ultra-high energy (UHE) cosmogenic neutrinos, via the Askaryan effect [1, 2, 3, 4, 5]. When a neutrino interacts in bulk matter with an index of refraction, the resulting hadronic and electromagnetic cascades can produce coherent GHz radiofrequency (RF) pulses. High energy scattering processes and positron annihilation cause a negative charge excess to build up in the cascades, creating an effective radiating dipole moment. This radiation is coherent, since the coherent radiated power from Cherenkov radiation scales quadratically with the charge of the emitter [6], and the wavelengths are set by the lateral size of the shower initiated by the original neutrino interaction. Simulation studies show that the signal pulses from high energy neutrinos usually arrive at ARIANNA surface receivers by first reflecting from the ice-water interface at the bottom of the Ross Ice Shelf (RIS), and then propagating through the bulk ice [7]. Relatively few neutrino signals propagate directly from the interaction vertex to the surface receivers. Therefore, the sensitivity and capabilities of ARIANNA depends on the ice properties such as the attenuation length and reflection efficiency. In this work, we report on several key properties of the ARIANNA site.

The ARIANNA detector consists of an array of autonomous stations deployed on the surface of the RIS, viewing 513 km³ of glacial ice centered at (77° 44' 523" S, 165° 02' 414" E) in western Antarctica. Prior studies of the electromagnetic properties of the ARIANNA site have

measured the electric field attenuation length by using vertically reflected pulses and assumed a value for the reflection coefficient from the ice-water boundary at the bottom [11]. In this work, we examine reflected pulses over several baselines to determine both the field attenuation length and reflection coefficient. We also show that the reflected pulse preserves its polarization orientation. Measurements of the reflection coefficient have been made independently [8, 9], revealing strongly reflected RF pulses in regions free of sub-glacial flow lines and sea-ice freezing zones. ARIANNA is in Moore's Bay, which is far from glacial irregularities [8] and in good RF isolation. For a similar study of attenuation lengths performed in ice located in a different region of Antarctica, see Besson (2008) [10].

We quantify absorptive losses experienced by an electromagnetic wave by adding an imaginary component to the dielectric constant, parameterized by

$$\alpha = -8.686(\pi\nu/c)(\sqrt{\epsilon'}\tan\delta) \text{ (dB/m)} \quad (1)$$

Here, the vacuum speed of light is c , ν is the frequency in Hz, ϵ' is the real part of the dielectric and the loss tangent $\tan\delta$ is the imaginary part of the dielectric over the real part ϵ''/ϵ' . The electric field attenuation length is then defined as [11]

$$L_\alpha = 1/\ln\sqrt{10^{\alpha/10}} \quad (2)$$

which is the distance the electromagnetic wave travels before decreasing in amplitude by a factor e^{-1} .

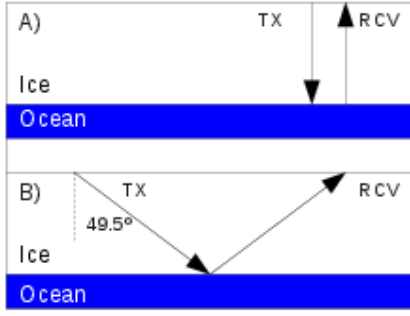


Figure 1: A) A schematic of the direct bounce experimental geometry. B) The angled bounce experimental geometry.

2 Experimental Methods

To create broad band RF pulses for propagation through the ice shelf, a short duration (1 ns wide), kilovolt pulse is delivered from the HYPs Pockel Cell Driver to a log-periodic dipole array (LPDA) transmitter (105 MHz-1300 MHz), supplied by Creative Design Corp (CLP5130-2). These antennas are directional, with a gain of 6-7 dBi. An identical LPDA serves as a receiver. Along with a precise measurement of the ice-shelf depth at the ARIANNA site, we have the S11 and voltage standing wave ratio (VSWR) parameters for the antennas as they couple to the dielectric properties of the snow around them [5]. The lowest frequency measurable by the LPDA in snow decreases to approximately 80 MHz because the wave speed slows down in the snow, while the antenna response remains constant. The VSWR is close to one for all relevant frequencies in this work. The signal from the receiver is filtered with both a NHP-50+ highpass filter and a NLP-1200+ lowpass filter, and amplified by a 1 GHz Miteq AM-1660 low-noise amp before being recorded on a Tektronix oscilloscope with 1 GHz bandwidth. We also attenuate by 20 dB where appropriate to obtain manageable signal amplitudes.

Figure 1 shows two distinct reflection geometries employed in these studies for the antennas, both of which are buried in the low density firm snow and pointed down. The direct bounce configuration (1a) is indicated by the vertical path between the transmitter and receiver antennas, which are separated by 18.7 m. The radio pulse travels 576 m to the water-ice interface and reflected back to the surface for a total path length of 1152 m. The angled bounce configuration (1b) is similar to the direct bounce, where the antennas are oriented vertically downward, but the separation between the two antennas is increased to 977 m, which increases the total path length to 1510 m (see Table 1). The unattenuated signal amplitude is determined by rotating the LPDA antennas to point toward each other through the surface snow while separated by 18.7 m. The path length for this test is the shortest of the three configurations. In practice, R , G , and the exponential factor are set to 1 in eqn. (4).

Since the signal in this test is relatively strong, the amplifier is removed for this measurement.

The analysis presented here focuses on the frequency range between 90 MHz and 180 MHz, where the measured power was well above thermal noise for the three configurations. It assumes that losses due to RF scattering in the ice medium are negligible for the frequencies of interest, and that the field reflection coefficient does not depend significantly on incidence angle of the two reflection configurations. We verified with a noise source that cable losses are negligible at these frequencies.

The Friis equation relates the power received (P_r) to the transmitted power (P_t) in a lossless medium at a given wavelength. For two identical antennas, separated by a distance d , it becomes

$$P_r = \frac{G_a^2 \lambda^2}{(4\pi)^2 d^2} = \frac{P_0}{d^2} \quad (3)$$

where G_a is the intrinsic gain of the antenna and λ is the electromagnetic wavelength. The factor P_0 can be treated as a constant at each frequency for all configurations since the variation in LPDA intrinsic gain is small for the frequency interval of this study. P_0 was determined from the short distance configuration with the antennas rotated to point toward each other. To account for absorption losses and possible losses upon reflection, the Friis equation is modified to

$$P_r = \frac{P_0 R G^2}{d^2} \exp\left(-2 \frac{d}{\langle L_\alpha \rangle}\right) \quad (4)$$

The factor R is the reflection coefficient, defined for power. The factor of 2 is required in the exponential if $\langle L_\alpha \rangle$ is the electric field attenuation length, rather than a quantity associated with the power. The brackets around $\langle L_\alpha \rangle$ indicate that the attenuation length is averaged over the full depth of the ice, and thereby integrated over the temperature dependence of the path¹. Following convention, the reflection coefficient for the electric field is then $R^{1/2}$. The factor G^2 accounts for the difference in relative antenna gain for each antenna. G is 1 for the direct bounce, where the returned signal is aligned along the receiver boresight. The orientation of the antennas remained vertical for the angled bounce configuration, so the signal pulses were emitted and received at an angle of 49.5°. At this angle in the H-plane of the antennas, $G = 0.80$.

1. This temperature dependence arises from the modest temperature dependence of the imaginary part of the dielectric constant of bulk ice, which is roughly one part in a thousand.

Year/site	Delay (ns)	Depth (m)
2006 [11]	6783 ± 10	577.5 ± 10
2009 [12]	6745 ± 15	572 ± 6
2010 [this work]	6772 ± 15	576 ± 10

Table 1: The result from this work was produced using the same $n(z)$ model as the result in the first row. The larger final uncertainties come from using slightly larger uncertainties on the index of refraction of bulk ice.

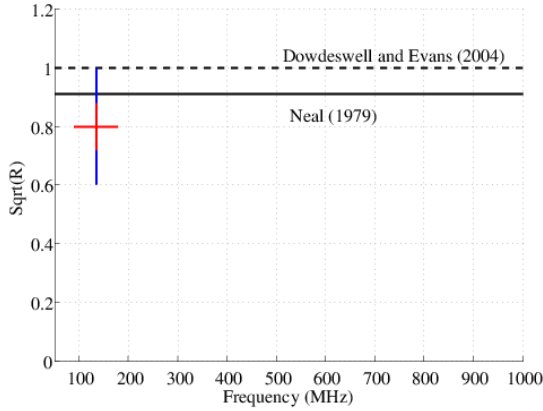


Figure 2: Expected field reflection coefficient $R^{1/2}$ vs. frequency, for an ideal flat surface. The longest vertical error bar indicates 95% confidence. The horizontal error bar indicates the range of frequencies used in this analysis.

3 Data and Analysis

3.1 Depth of the Ice Shelf

The thickness of the ice at the ARIANNA site can be determined by the round-trip travel time and knowledge of the index of refraction, $n(z)$, as a function of depth. For depths greater than 65-75 m, the ice is uniform with $n = 1.78$. At shallower depths, the mass density of the firm is characterized with an exponential dependence [11]. Along with the linear dependence between index of refraction and mass density, we have a complete description of $n(z)$ in the firm ice. Table 1 summarizes the calculations of ice thickness at the ARIANNA site. The 2009 and 2010 measurements were performed at the same geographical location on the ice shelf, whereas the 2006 measurement was performed at a location about 1 km from the 2009 and 2010 tests. The round trip travel times agree to within two standard deviations. The uncertainties in the depth measurements include statistical errors in the round trip travel time and index of refraction in the uniform ice, and systematic errors due to the functional variation of $n(z)$. The larger errors associated with the 2006 and 2010 depths are due to slightly larger uncertainties for the index of refraction in the bulk ice.

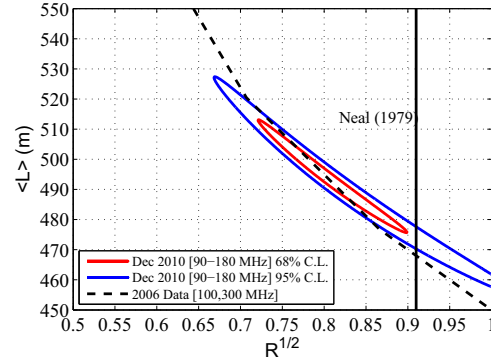


Figure 3: Contour plot of the depth averaged attenuation length $\langle L_\alpha \rangle$ in (m) vs. $R^{1/2}$ showing 1 and 2- σ errors. Dashed curve was obtained from [11], as explained in the text. Vertical line indicates theoretical expectation of $R^{1/2} = 0.91$ from [9].

3.2 Attenuation Length, Reflectivity and Signal Polarization

After correcting for the geometrical effects of path length for the three different configurations and relative antenna gain, the field reflection coefficient $R^{1/2}$ and $\langle L_\alpha \rangle$ are treated as free parameters in eqn. (4). The statistical errors in P_r were obtained from the rms fluctuation over the entire frequency band. The 1 and 2- σ contours in figure 3 were obtained from a reduced chi-squared fit. The contours match the dashed curve, which was derived by varying the reflection coefficient $R^{1/2}$ assumed in [11] for the quoted attenuation lengths at 100 and 300 MHz. The attenuation length is determined to be 495 ± 15 m at 68 % C.L., in agreement with previous values from 2006 [11], and the field reflection coefficient $R^{1/2} = 0.80 \pm 0.08$ at 68% C.L., in agreement with a theoretical expectation ($R^{1/2} = 0.91$) for an ideal ice-saltwater interface [9].

Our measurements indicate that the field reflection coefficient at the ARIANNA site is compatible with an ideal flat surface, although values as small as 0.7 are also permitted. The reflection coefficient is not expected to vary significantly with frequency for specular reflection, as shown in figure 2. If the permittivity of sea-water is assumed to be very large for 100-1000 MHz, then the field reflection coefficient is 1 with no frequency dependence (the upper horizontal line in figure 2) [12]. In addition, multi-path effects are safely ignored in this analysis because the maximum duration of our signal pulses (100 ns) is small compared to the total propagation time.

The radio pulse from the neutrino interaction is perfectly linearly polarized, with the orientation perpendicular to the direction of the propagation of the pulse. It lies in the plane defined by the neutrino direction vector and propagation vector. Therefore, the polarization information helps to determine the direction of the neutrino, and reflected signals must retain a known correlation with the initial polarization.

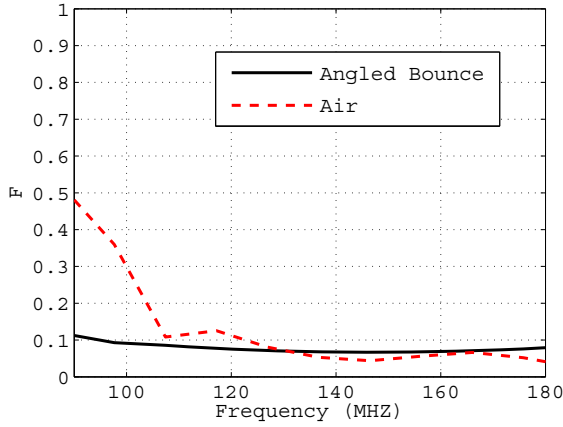


Figure 4: Polarization fraction, F , is shown as a function of frequency for transmission through air (dashed line) and for the angled bounce configuration at the ARIANNA site (solid line).

We investigate this by comparing the co-polarized power, $P_{||}$, to the cross-polarized power, P_{\perp} for the angled bounce configuration. The fraction of cross-polarized power to total power is

$$F = \frac{P_{\perp}}{P_{||} + P_{\perp}} \quad (5)$$

Figure 4 compares F for the angled bounce configuration (solid curve) to a study performed in air (dashed curve). Due to imperfections in the LPDA antennas, some power will leak into the cross-polarized configuration, representing a lower limit to F . This is estimated by air measurements with the LPDA antennas oriented to point toward each other, and separated by 10 m to avoid near-field effects. The sudden rise to a value of 0.5 (the value of F for unpolarized noise) at frequencies below 105 MHz is due to the antenna response. In air, the VSWR of the LPDA increases dramatically below 105 MHz, whereas the VSWR for LPDAs buried in snow remains low down to 80 MHz [5]. The good agreement between the angled bounce configuration and the air studies suggests that little power is transferred from the co-polarized direction to the cross polarized direction after reflection from the water-ice boundary.

4 Conclusion

Preliminary studies of the site properties in the frequency band 90-180 MHz confirm large field attenuation lengths (495 ± 15 m), and show that the reflection coefficient is compatible with theoretical expectations for a smooth saltwater-ice interface ($R^{1/2} = 0.80 \pm 0.08$), and signal polarization is preserved. Further work is required over multiple baselines to distinguish the smooth water-ice hypothesis from potential small losses due to surface roughness

at the ARIANNA site. We note that Neal [9] reported very small levels of surface roughness at sites in the RIS characterized by large reflection coefficients at 60 MHz. Such small effects will have little, if any, impact on signal attenuation and time profiles if similar values for vertical rms fluctuations from flatness and horizontal correlation lengths are found at higher frequencies.

5 Acknowledgements

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