Radar absorption, basal reflection, thickness and polarization measurements from the Ross Ice Shelf, Antarctica

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ABSTRACT. Radio-glaciological parameters from the Moore’s Bay region of the Ross Ice Shelf, Antarctica, have been measured. The thickness of the ice shelf in Moore’s Bay was measured from reflection times of radio-frequency pulses propagating vertically through the shelf and reflecting from the ocean, and is found to be 576 ± 8 m. Introducing a baseline of 543 ± 7 m between radio transmitter and receiver allowed the computation of the basal reflection coefficient, R, separately from englacial loss. The depth-averaged attenuation length of the ice column, (L) is shown to depend linearly on frequency. The best fit (95% confidence level) is \(L(\nu) = (460\pm20) – (180\pm40)\nu\) m (20 dB km\(^{-1}\)), for the frequencies \(\nu = [0.100-0.850] \) GHz, assuming no reflection loss. The mean electric-field reflection coefficient is \(\sqrt{R} = 0.82 \pm 0.07\) (1.7 dB reflection loss) across \([0.100-0.850]\) GHz, and is used to correct the attenuation length. Finally, the reflected power rotated into the orthogonal antenna polarization is <5% below 0.400 GHz, compatible with air propagation. The results imply that Moore’s Bay serves as an appropriate medium for the ARIANNA high-energy neutrino detector.

KEYWORDS: ice/ocean interactions

INTRODUCTION

The vast Antarctic ice sheet has become important to high-energy neutrino physics in recent years (Barwick, 2007; ANITA Collaboration, 2010; Klein, 2012; Kravchenko and others, 2012; IceCube Collaboration, 2013), motivated by the convenient properties of glacial ice, including optical and radio-frequency (RF) dielectric properties. High-energy cascades induced by neutrinos emit Cherenkov photons; photons with 350-500 nm wavelengths can propagate 10–100 m in Antarctic ice before being detected by photomultiplier tubes (AMANDA Collaboration, 2006). Similarly, at energies 0.1 EeV, neutrinos begin to produce measurable Askaryan pulses (Askaryan, 1962), a form of coherent radio-frequency (RF) dielectric properties. High-energy neutrino physics in recent years (Barwick, 2007; Besson and others, 2008; Allison and others, 2012; Fretwell and others, 2013).

Baseline reflection in Moore’s Bay has been studied previously. Neal (1979, 1982) reported on the RIS, using a 60 ns wide, 60 MHz pulse, recording the returned power vs location. Flights 1 km above the RIS were performed, including several points over Moore’s Bay. Basal reflection coefficients were derived in 10 dB increments, assuming no losses from dust or other impurities, for contours across the shelf. Moore’s Bay produces reflection coefficients near the Fresnel limit (–0.82 dB, or –0.91 for the electric field), and two explanations were offered. First, Moore’s Bay is far from brine percolation zones that are traced from the grounding line to the shelf front, which are correlated with ice velocity. Second, the melt rate near the grounding line for basal ice prevents the formation of an abrupt basal layer of saline ice, and instead replaces glacial ice with saline ice over time. The freeze-on of saline ice at the shelf bottom does occur; however, these regions are far from the location of the Antarctic Ross Ice-Shelf Antenna Neutrino Array (ARIANNA), and the average accumulation rate of bottom saline ice is only 0.3 ± 0.1 m a\(^{-1}\) in the east RIS (Rignot and others, 2013).

Neal (1982) showed that two parameters besides peak power can be extracted from the data. First, the width of the peak power distribution for a specific location pertains to vertical roughness at the oceanic interface. Second, the spatial correlation of power measurements reveals horizontal correlation lengths for roughness. These measurements must

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be compared to theoretical distributions of the same parameters, from the theory of rough-surface scattering (Dookayka, 2011). The most general statistical surface, with the fewest parameters, was chosen: a Gaussian roughness described by normal fluctuations about a mean depth, and a specified horizontal correlation length. Neal reports vertical root-mean-square (rms) of 3 cm at the ocean/depth, and a specified horizontal correlation length. Neal and others (Ross Ice Shelf radio properties (USGS, 2012). The main ice flowlines are illustrated with dashed lines. Fahnstock (2000) provides further analysis and discussion.

RF attenuation length

The amplitude of an electric field decreases by 1/e after propagating one attenuation length. For an electromagnetic plane wave travelling through a dielectric medium with a complex index of refraction \( n = n' - i n'' \), the electric field is

\[
E = E_0 \exp \left( -i (n' k x - \omega t) \right) = E'_0 \exp \left( -n'' k x \right)
\]

The electric field attenuation length is then \( (n'' k)^{-1} = \ell \) (\( \omega \) is the angular frequency). When measured over a volume of material with varying dielectric absorption, the attenuation length is averaged over the effect of depth on the dielectric constant \( \epsilon = \epsilon' - i \epsilon'' \), and in turn the loss tangent, \( \tan \delta = \epsilon'' / \epsilon' \). If \( \tan \delta \ll 1 \), it can be shown that

\[
\left( \ell \right)^{-1} = \left( \pi \nu / c \right) \sqrt{\epsilon' \tan \delta \left( m^{-1} \right)}
\]

\[
N_r \left( \text{dB km}^{-1} \right) = 8686.0 \left( \left| \nu \right| \right)^{-1}
\]

Equation (3) is the conversion from attenuation length to absorption loss, \( N_r \). The Debye model shows that \( \nu \tan \delta \) is approximately constant, provided the frequency is far from any molecular resonances (this is true for 0.1–1 GHz). Additionally, \( \epsilon' \) (in ice) is constant for the bandwidth 0.1–2 GHz. Thus, frequency dependence in \( \ell \) is attributed to other effects, such as acids and sea-salt impurities (Bogodsky and others, 1985; Matsuoka and others, 2012).

Reflection coefficient

Under the Debye model, with a single relaxation time, the ice conductivity \( \sigma = 2 \pi \nu \epsilon' e' \tan \delta \approx 10 \mu \text{S m}^{-1} \) at 100 MHz (Dowdeswell and Evans, 2004). By comparison, sea water has a conductivity of a few 5 m⁻¹, with a skin depth of 30 mm, at 60 MHz (Dowdeswell and Evans, 2004; Somaraju and others, 2006). The reflection coefficient for the electric fields (\( \sqrt{R} \), where \( R \) refers to power) is given by

\[
(1 - n_1 - n_2) / (n_1 + n_2)
\]

where the ice and \( n_2 \) refers to the ocean, given the limits \( n_2 \gg 1 \), and \( n_1 \approx 0 \), and \( \alpha = \epsilon'' / \epsilon' \). In Eqn (4), the fact that \( n_2 \rightarrow \pi/2 \) has been used. Equation (4) is completely general as long as the limit is satisfied. The left-hand side has a global minimum at \( \alpha = 1 \), or \( \epsilon'' / \epsilon' \), corresponding to a minimum electric field reflection coefficient of \( \sqrt{R_{\text{min}}} \approx 0.41 \). Realistic values for both ice and sea water indicate \( \alpha \) ranges from 20 to 30, depending on the salinity and temperature of the sea water (Dowdeswell and Evans, 2004; Somaraju and others, 2006). Neal (1979) suggested that the reflection coefficient in Moore’s Bay is approximately –0.82 dB, or \( \sqrt{R} \approx 0.91 \), based on the properties of the sea water beneath the RIS. These upper and lower bounds form an allowed range of \( \sqrt{R} = 0.41–0.91 \).

In addition to vertical radio echoes, measurements were taken with a baseline distance between transmitter and receiver, introducing a new overall path length. In this work, these measurements are named angled bounce studies. For the angled bounce studies reported here, Eqn (5) shows that the reflected power limits to the expression for normal incidence (for \( s \)-polarized waves). Also, the initial transmission angle from normal is reduced, because the upper firm layer bends the transmitted pulse downward (to \( \theta \geq 30^\circ \)), given the initial antenna orientation of 45°. Ignoring the cosine dependence in Eqn (5) amounts to a 1–5% correction, depending on \( n_2 \):

\[
\sqrt{R} \approx \frac{n_1(1 - \theta^2 / 2) - n_2(1 - 1 / (\theta^2))}{n_1(1 - \theta^2 / 2) + n_2(1 - 1 / (\theta^2))} \approx \frac{n_1 - n_2}{n_1 + n_2}
\]

Ice thickness calculation

The upper 60–70 m of the ice shelf is firm with density \( \approx 0.4 \text{ g cm}^{-3} \) near the surface (Gerhardt and others, 2010). This result is in agreement with the value 0.36 g cm⁻³ from Dowdeswell and Evans (2004). Looyenga’s equation, \( n_{\text{ice}} \) and the firm surface density predict the firm index to be \( n_{\text{term}} \approx 1.3 \). This value was confirmed with pulse propagation timing at the surface, over a distance of 543 ± 7 m (see Fig. 1. The site studied in this work is marked with the black circle. Moore’s Bay is the area south of Ross Island, enclosed by Minna Bluff. The satellite data are made available by the US Geological Survey (USGS, 2012). The main ice flowlines are illustrated with dashed lines. Fahnstock (2000) provides further analysis and discussion.)
below for detail). From the pulse arrival time, the implied wave speed indicated an index of $n_{surf} = 1.29 \pm 0.02$ (Hanson, 2013).

The density and thus the index of refraction has an exponential depth dependence, according to the Schytt model:

$$n(z) = n(z \geq 67m) = 1.78 = n(z \gtrsim 67m)$$

$$n(z) = n_0 + p \exp(-z/q) \quad (z < 67m)$$

In Eqn (7), $n_0 = 1.86$, $p = -0.55$ and $q = 35.4$ m, with the upper layer density $\rho \approx 0.4$ g cm$^{-3}$, and $z > 0$ for increasing depth. A different model with a constant firn correction (to sounding propagation times) and no exponential density profile yields shelf depths consistent within errors (Gerhardt and others, 2010). Equations (6) and (7) are based on measurements taken at Williams Field near McMurdo station (Schytt, 1958; Barrella and others, 2011). Given the measured physical delay between pulse and reflection, $\Delta t$, the shelf depth can be obtained from integrating over the total path length $d$ (Eqns (8) and (9)). Error propagation yields Eqn (10), where $D_l = 67 \pm 10$ m is the firn depth (Dowdeswell and Evans, 2004). A density profile for the RIS in figure 2 of the latter reference is consistent with this model.

$$\frac{c\Delta t}{2} = \int_0^{d_{\text{ref}}} n(z) \, dz$$

$$d_{\text{ice}} = \frac{c\Delta t}{2n} - D_l(n_0 - n) + \frac{q}{n}(e^{-D_l/q} - 1)$$

$$\sigma_{d, \text{ice}} = \sqrt{\left(\frac{\sigma_q^2}{2n^2}\right)^2 + \left(\frac{\sigma_{\Delta t}^2}{2n^2}\right)^2 + k\sigma_{\text{firn}}^2}$$

The fractional difference between $n_0$ and $n$ is small, and $\exp(-D_l/q)$ is small, so $k$ turns out to be of order $10^{-2}$. The term in Eqn (10) involving $k$ is a factor of 10 below the others so it may be dropped. For similar reasons, cross-terms involving firn properties and $\sigma_q$ have been neglected.

### EXPERIMENTAL TECHNIQUE

The experimental set-up is shown in Figure 2, with additional detail in Table 1. Figure 3 shows the vertical and angled bounces. To create broadband RF pulses, a 1 ns wide, 1–2.5 kV pulse was delivered from the HYPS Pockels Cell Driver (PCD) to a transmitting antenna, and the reflection is received by a second antenna. The PCD and oscilloscope enabled the introduction of a long baseline between the antennas.

Voltage standing wave ratio (VSWR) measurements were performed to study antenna transmission in snow. In all cases, the VSWR of the transmitting and receiving antennas demonstrates good transmission and reception when buried in the surface snow (Gerhardt and others, 2010; Barrella and others, 2011). Noise above and below the receiver bandwidth was filtered with MiniCircuits NHP and NLP filters, and amplified by a 62.4 dB Miteq AM-1660 low-noise amplifier (typical noise figure of 1.5 dB). Signals were attenuated by 3–20 dB where appropriate, to remain in the linear regime of the amplifier.

For the 2006 season (Barrella and others, 2011), the transmitter and receiver were Seavey radio horns used in the ANITA (ANtarctic Impulsive Transient Antenna) experiment (ANITA Collaboration, 2009), with a bandwidth of [200–1300] MHz. In the data from the 2010 season, the receiver and transmitter were log-periodic dipole arrays (LPDAs;
Create Corp. CLP5130-2N) with a bandwidth of [100–1300] MHz. The Seavey is a dual polarization quad-ridge horn antenna that has higher gain above 200 MHz than the LPDA. The LPDA antennas have a wider bandwidth, but stretch the signal in time with respect to the horn (Barwick and others, 2015). In the 2011 season, the data were recorded with a Seavey transmitter and an LPDA receiver. The 2010 data have been published (Hanson, 2011, 2013). In this work, the thickness results from 2010 are compared to three new measurements, and a new reflection coefficient and attenuation length analysis are presented.

In the surface test, we measured the pulse propagation time over the 543 ± 7 m baseline, and extracted the surface index of refraction from the speed. The result was \( n_{\text{surf}} = 1.29 \pm 0.02 \), and is needed for the boundary conditions in the shelf-thickness model. In the vertical bounce measurements, where the transmitter and receiver are co-located, the separation in 2006 was typically 9 m. In 2010 and 2011 the separation was 19 and 23 m, respectively. This ensures that the receiver is in the far field of the transmitter during calibration. Comparing vertical bounce soundings to calibration measurements allows derivation of \( \delta \) assuming a value for \( \sqrt{R} \).

The angled-bounce measurements are also compared to calibration measurements and vertical bounce cases to measure both \( \delta \) and \( \sqrt{R} \). Angled signals were captured without having to account for complex ray tracing near the surface. During angled bounce tests, the transmitter and receiver were angled 45° downward from horizontal. For the angled bounce measurements, the 2010 baseline was 977 ± 7 m, and the 2011 baseline was 543 ± 7 m. The angled bounce measurements in 2010 and 2011 had signal path lengths of 1517 ± 8 m and 1272 ± 7 m, respectively. The incident angle with respect to normal refracts closer to 30° when the pulse reaches the ocean, because the firm index \( n_{\text{firm}} = 1.3 \) is smaller than the bulk ice index \( n_{\text{ice}} = 1.78 \).

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 in air, it may be written

\[
P_r = \frac{P_t (G)G_s}{(4\pi d)^2} = \frac{P_0}{d^2} \tag{11}
\]

Here \( G_s \) is the intrinsic gain of the antennas and \( \nu \) is the frequency. \( P_t \) and \( P_r \) are the received and transmitted power, respectively. To account for absorption losses and possible losses upon reflection, the Friis equation is modified to

\[
P_r = \frac{P_0 RG_1G_2}{d^2} \exp\left(-\frac{2d}{L}\right) \tag{12}
\]

By convention, the factor of 2 in the exponential means \( L \) refers to electric field, and the reflection coefficient for the power is \( R \). The factor \( G_1G_2 \) accounts for the relative power radiation pattern of the transmitter and receiver (Table 1). \( G_1 \) and \( G_2 \) are for the vertical bounce measurements, in which the signal is transmitted and received in the forward direction of the antennas. As the angle at which the signal interacts with the antenna increases, \( G_1G_2 \) decreases from 1 according to the antenna radiation patterns. The radiation patterns have been both simulated and measured (ANITA Collaboration, 2009; Barwick and others, 2015). Manipulating Eqn (12) gives Eqn (13), the left-hand side of which may be plotted vs path length \( d \) to obtain a line with a slope \( -1/(L) \), and a constant y-intercept. The reflection coefficient is treated as a free parameter in the fit. The error in the

<table>
<thead>
<tr>
<th>Year</th>
<th>( \Delta t_{\text{meas}} )</th>
<th>( \Delta t_{\text{phys}} )</th>
<th>( \sigma_{\text{stat}} )</th>
<th>( \sigma_{\text{sys}} )</th>
<th>( \sigma_{\text{pulse}} )</th>
<th>( \sigma_{\text{lat}} )</th>
<th>( d_{\text{ice}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>– 6783</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10</td>
<td>577.5 ± 10</td>
</tr>
<tr>
<td>2009</td>
<td>– 6745</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15</td>
<td>572 ± 6</td>
</tr>
<tr>
<td>2010</td>
<td>7060</td>
<td>6772</td>
<td>5.0</td>
<td>8.0</td>
<td>10</td>
<td>14</td>
<td>576 ± 6</td>
</tr>
<tr>
<td>2011</td>
<td>6964</td>
<td>6816</td>
<td>4.0</td>
<td>5.0</td>
<td>10</td>
<td>12</td>
<td>580 ± 6</td>
</tr>
</tbody>
</table>

The reflected pulse from the 2009 set-up was only several mV above noise backgrounds, so the entire pulse width was included as systematic error (Gerhardt and others, 2010). For the 2011 data, the location and uncertainty in peak voltage oscillations in the reflections were used instead, because the signal was well above backgrounds. The low-frequency ringing in the reflected data originates from group delay in the LPDA, which is 10 ns at 0.2 GHz (the lowest frequency emitted by the transmitter). When folded into the timing uncertainties, smaller but comparable errors to 2006 are obtained for the thickness. Timing uncertainties are lowest in 2006 because both transmitter and receiver were Seavey horns, which have lower group delay than the LPDA.

In general, statistical errors come from Eqn (10), with \( n = 1.78 \pm 0.02 \), and total timing error from Table 2. The magnitude of \( \sigma_n \) comes from measurements made at the surface \( n_{\text{surf}} = 1.29 \pm 0.02 \) (Hanson, 2013). Fluctuations in \( n \) are largest at the surface, making this a conservative estimate for the bulk ice, and it is similar to previous work (Gerhardt and others, 2010; Barrella and others, 2011). The total error from 2006 is higher because a larger error on the dielectric constant was used. The mean thickness over all seasons is \( d_{\text{ice}} = 576 ± 8 \) m (statistical and systematic added in quadrature). Errors in Table 2 other than from the index of refraction are treated as systematic. A linear fit to the four
As long as the first few Fresnel zones of the transmitted pulse are not significantly larger than the horizontal correlation length of roughness features along the shelf base, then the effect of the vertical roughness scales on the reflection coefficient is avoided (Peters and others, 2005). Prior data collected at two locations on the Ross Ice Shelf, near Moore’s Bay, indicate horizontal correlation lengths $L_C = 12.5$ m and $L_C = 27.5$ m at the two sites (Neal, 1982). The glaciological Fresnel zone equation, for an observation point a distance $h$ above the snow surface, with a shelf thickness of $z$, shelf index of refraction $n$, Fresnel zone number $m$, and an in-air wavelength $\lambda$ is

$$D_m \approx \sqrt{2m\lambda\left(h + \frac{z}{n}\right)}$$

(15)

The approximation arises from the small angle approximation, and is sound because the Fresnel zones are small compared to $z$. The measurements take place at the surface, so $h = 0$. Using $n = 1.78$, $\lambda = 3$ m and the measured shelf thickness, Eqn (15), gives $D_1 = 10$–40 m, for the bandwidth. Vertical rms fluctuations at the ocean/ice surface were reported to be be 3 cm and 10 cm for two sites, spread out over a typical length scale of $L_C$. Vertical height fluctuations of 10 cm and 3 cm spread out over 12.5 m and 27.5 m, respectively, mean that specular reflection is a good approximation for this bandwidth (Neal, 1982). The attenuation lengths derived assuming constant $\sqrt{R}$ are revised in the next section, to account for reflection loss ($\sqrt{R} < 1.0$).

Consider the calibration pulse, $V_C$, the vertical bounce pulse, $V_{\text{ice}}$, and the depth-averaged attenuation length vs frequency, $\langle \ell(\nu) \rangle$, at all a frequency $\nu$:

$$V_C(\nu) = \frac{V_0}{d_C}$$

(16)

$$V_{\text{ice}}(\nu) = \frac{V_0}{d_{\text{ice}}} \exp\left(-\frac{d_{\text{ice}}}{\langle \ell(\nu) \rangle}\right)$$

(17)

$$\langle \ell(\nu) \rangle = \frac{d_{\text{ice}}}{\ln\left(\frac{V_C(\nu)d_C}{V_{\text{ice}}(\nu)d_{\text{ice}}}\right)}$$

(18)

Because the surface of the firm is snow, with a density of 0.4 g cm$^{-3}$ and an index of refraction $n = 1.3$, the reflection coefficient (for power) between air and snow is $\sim 0.02$, so potential interference from surface reflections is not expected to modify Eqn (16). The antennas were placed at the maximum height allowed by the cables and other equipment (1.5 m), and this calibration was compared to the case with the antennas buried in snow slots. Because of the low snow density, dielectric absorption is negligible over the calibration distances (23 m). The antenna calibrations produced similar waveforms with the antennas lowered in snow. The waveform amplitude increases when LPDAs are in the snow, due to the shift in the lower cut-off frequency by the index of refraction. This effect is confirmed in Numerical Electromagnetic Code (NEC) antenna simulations, and VSWR data (Barwick and others, 2015).

The 2011 data are shown in Figure 4a. In Eqns (16–18), the voltages are defined $V \propto \sqrt{P(\nu)}$, where $P$ is the measured power at the frequency $\nu$. The antenna impedance is the same for the calibration and bounce studies, making it irrelevant in the ratio in Eqn (18) (Barwick and others, 2015). The 2011 power spectra begin at the low-frequency cut-offs of the transmitter type (200 MHz for the Seavey, and 100 MHz for the LPDA). The englacial loss (dB km$^{-1}$) is also shown (Eqn (3)).

The 2011 data extend to 0.850 GHz, where the signal-to-noise ratio is close to 1.0, and the error bars are the standard deviation from error propagation in Eqn (18). About 10 m of the error is due to uncertainty in the shelf thickness, and 10 m is due to uncertainty in the power spectrum. Data above 0.850 GHz appear to be rising due to noise floor contributions. Also, systematic fluctuations in the vertical bounce power spectra lead to systematic fluctuations in $\langle \ell(\nu) \rangle$. Systematic errors arise from differences in system frequency response after changing the transmitter location and type, and reflections within the system. The angled bounce data at 0.240 and 0.315 GHz, in particular, are
systematically high. The Seavey transmitter was placed in a snow cavity rather than fully buried for the angled test, which can lead to cavity resonance effects.

The frequency resolution is maximized in Figure 4a, with no window function. A higher resolution extends the upper frequency limit by avoiding folding noise into the highest-frequency bins. The correction for potential angular dependence of the reflection coefficient only applies to the angled bounce data (~4 m). In Figure 4a, the data are averaged into 0.075 GHz bins, with a linear fit. The best-fit slope is \(-180 \pm 40 \text{ m GHz}^{-1}\), and the best-fit offset is \(460 \pm 20 \text{ m}\) (95% confidence level, \(\chi^2/\text{dof} = 1.2\)). Data above 0.850 GHz are neglected in the average and fit shown in Figure 4; however, the \(\chi^2/\text{dof}\) only increases to 1.8 if it is included. As in Figure 4a, the averaged attenuation length is converted to dB km\(^{-1}\) on the right-hand \(\gamma\)-axis using Eqn (3).

Despite the systematic fluctuations, the fit to the data in Figure 4 is in close agreement with the quadratic fit to the data from 2006 (Barrella and others, 2011). In the publication of the 2006 data, the reflection loss was assumed to be 0 dB. If a lower value is assumed (see below), the attenuation length increases, because the returned voltage per unit frequency in Eqn (18) must remain constant. The level of systematic variation in \(\sqrt{R}\) shown below will also generate \(\sim 5\%\) systematic uncertainty in \((L)\), but only to increase it. The 2006 and 2011 data agree, even though the measurements were made 1 km apart. The area of Moore’s Bay near Minna Bluff is far from any zones of high glacial velocity that could cause depth or basal reflection variations, and crevasses have not been observed in the area, so the ice is expected to be relatively uniform.

**BASEL REFLECTION COEFFICIENT**

The 2006 season \((L)\) results were derived from vertical bounce measurements assuming \(\sqrt{R} = 1.0\). Using the path lengths derived from shell thickness, and the measured power spectra of the calibration, vertical bounce and angled bounce reflections, \(\sqrt{R}\) can be derived separately from the attenuation length. The errors in \(\sqrt{R}\) arise from propagating errors in path length (from thickness, and geometry) and returned power through Eqn (13).

The three tests (calibration, vertical and angled bounce) serve as three measurements of \(f(d)\) for different values of the path length \(d\), given the free parameter \(\sqrt{R}\). The measurements are compared to the linear model \(f_{\text{model}} = -d/(L + f_0)\), which is scanned through \((\sqrt{R}, (L))\) parameter space. The \(y\)-intercept is irrelevant to the physics, coming from the linear fit upon each iteration. (The overall power at a given frequency is relative to the calibration pulse power.) Each iteration produces a \(\chi^2\) value, and \((\sqrt{R}, (L))\) were scanned until a global minimum was reached at each frequency.

The averaged power spectra of the time-dependent waveforms are shown in Figure 5a. The spectra are constructed from averaging the modulus-squared of the fast Fourier transform of the time-dependent signals, and plotted relative to the maximum calibration power. The error bars are the error in the mean for each bin. Examples of waveforms from which these power spectra are derived are shown separately in Figure 6. For all recorded waveforms, a sampling rate of 5 GHz was used on the 1 GHz bandwidth oscilloscope. The spectra in Figure 5 have a frequency resolution of 0.025 GHz.

The 2010 data for \(\sqrt{R}\) vs \((L)\) have been analysed by Hanson (2011, 2013). The basic results were 480 m ≤ \((L)\) ≤ 510 m (17–18 dB km\(^{-1}\)), and 0.72 ≤ \(\sqrt{R}\) ≤ 0.88 (1.1–2.8 dB loss), for the average attenuation length and reflection coefficient (68% confidence level). The set-up (Fig. 2) demonstrated good transmission through surface snow for frequencies below 0.180 GHz that season, and the LPDA lower limit in the snow is 0.080 MHz. The index of refraction of snow extends the LPDA response to 0.080 GHz. The index of refraction of snow extends the LDPA response to 0.080 GHz. The index of refraction of snow extends the LDPA response to 0.080 GHz. The index of refraction of snow extends the LPDA response to 0.080 GHz.

A shorter angled bounce baseline (543 ± 7 m) was chosen for the 2011 season, relative to the prior year, to boost signal at higher frequencies; however, the snow absorption effect was not observed in 2011.

Figure 5b shows the \(\sqrt{R}\) results from the 2011 season. The baseline sets the path length difference between the
angled and vertical cases, introducing a trade-off. A shorter baseline causes the attenuation length to become large compared to the difference in path length between the angled and vertical bounce tests (∼130 m in 2011). At low frequencies, the difference in power loss between vertical and angled cases becomes smaller than the errors in the frequencies, the difference in power loss between vertical compared to the difference in path length between the baseline causes the attenuation length to become large.

Table 3 (Dookayka, 2011). The origin of the roughness in the reflected spectra is likely noise interference, since the signal-to-noise ratio is lower than in the calibration study.

Finally, knowledge of the basal reflection coefficient allows the correction of the attenuation length numbers in Figure 4 to more realistic values. If $L_0$ is the measured attenuation length, assuming $\sqrt{R} = 1.0$, then the actual attenuation length ($L$) can be expressed as

$$\frac{L}{L_0} = \left(1 + \frac{L_0}{2d_{ice}} \ln R \right)^{-1}$$

Using the $L_0$ values from Figure 4, Table 3 shows the $L$ results for the mean value of $\sqrt{R} = 0.82 \pm 0.07$, vs frequency. Table 3 also shows the imaginary part of the dielectric constant, derived from $\eta''$, via $(L)^{-1} = n''k$, where $k$ is the free-space wavenumber. Assuming $\tan \delta \ll 1$, the expression $\epsilon'' = 2n'' \sqrt{\epsilon}$, with $\epsilon'' = 1.78$, relates the two quantities.

The $\epsilon''$ results are in agreement with an earlier low-frequency projection for typical ice-shelf temperatures (Matsuoka and others, 1996). The Debye model predicts $\epsilon'' \propto \nu^{-1}$ for frequencies below 2 GHz, and the $\epsilon''$ data follow this trend. The quantity $\nu \tan \delta$ is expected to be small and constant for a simple dielectric material, and Table 3 also displays this quantity in the final column, which agrees with an estimate from analysis of the 2006 data (Barrella and others, 2011). Although $\nu \tan \delta$ varies with frequency, this variation is such that no measurement is more than one standard deviation ($0.2 \times 10^{-4}$) from the mean ($1.37 \pm 0.06$).

### Table 3. Summary of dielectric parameters. The first column is the frequency, $\nu$, followed by the attenuation lengths, which are uncorrected ($\langle L_0 \rangle$) and corrected ($\langle L \rangle$) for $\sqrt{R} = 0.82 \pm 0.07$. The fourth column is $\langle L \rangle$ expressed in dB km$^{-1}$. The imaginary part of the dielectric constant, $\epsilon''$, is shown in the fifth column. The final column shows $\nu \tan \delta$ (GHz). The typical error on the quantity $\nu \tan \delta$ is $0.2 \times 10^{-4}$.

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<thead>
<tr>
<th>$\nu$ (GHz)</th>
<th>$\langle L_0 \rangle$ (m)</th>
<th>$\langle L \rangle$ (m)</th>
<th>$\epsilon'' \times 10^3$</th>
<th>$\nu \tan \delta \times 10^4$</th>
</tr>
</thead>
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<tr>
<td>0.100</td>
<td>432</td>
<td>449</td>
<td>19.3</td>
<td>3.8</td>
</tr>
<tr>
<td>0.175</td>
<td>467</td>
<td>487</td>
<td>17.8</td>
<td>2.0</td>
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<td>457</td>
<td>476</td>
<td>18.2</td>
<td>1.4</td>
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<tr>
<td>0.325</td>
<td>422</td>
<td>438</td>
<td>19.8</td>
<td>1.2</td>
</tr>
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<td>408</td>
<td>423</td>
<td>20.5</td>
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<td>378</td>
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<td>360</td>
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<td>341</td>
<td>25.5</td>
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<tr>
<td>0.775</td>
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<td>319</td>
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<tr>
<td>0.850</td>
<td>320</td>
<td>329</td>
<td>26.4</td>
<td>0.61</td>
</tr>
<tr>
<td>Ave.</td>
<td>380 ± 16</td>
<td>400 ± 18</td>
<td>22 ± 1</td>
<td>1.3 ± 0.3</td>
</tr>
</tbody>
</table>

**Polarization Measurements**

The $\sqrt{R}$ result shows that little power is lost from the basal reflection. In this section, we assess potential losses by scattering or rotation of the linearly polarized signal. For any non-ideal linearly polarized antenna system, a small amount of power can leak into the cross-polarized channel. Significant transfer of power into the cross-polarized direction would indicate polarization rotation in the ice, and bias the attenuation length results. Birefringence and surface roughness effects at the water–ice interface at the bottom of the ice shelf are expected to generate power in the cross-polarized direction.

To quantify the polarization rotation, the cross-polarization fraction, $F_{ice}$, was measured in the vertical bounce configuration, and compared to $F_{air}$. $F$ is defined in Eqn (20), where $P_\perp$ and $P_\parallel$ refer to the measured power in the cross-polarized and co-polarized direction with respect to the linear polarization of the transmitter at a given frequency:

$$F = \frac{P_\perp}{P_\perp + P_\parallel}$$

The leakage between co-polarized and cross-polarized channels is expected to be low across the bandwidth, but difficult to observe at high frequencies. Cross-polarized signals are weaker than co-polarized, and the vertical bounce data in the cross-polarized state are subject to noise interference above 0.4 GHz. The intrinsic transfer into the cross-polarized direction of a specified antenna pair was estimated by facing the transmitter toward the receiver in air. $F_{air}$ is computed from the power observed between co-polarized and cross-polarized orientation of the receiver. The results of this study are shown in the third column of
Table 4. It was verified that the snow surface 1.5 m below the antennas scatters back a negligible amount of power. 

\( F_{\text{ice}} \) was obtained from the vertical bounce set-up, with a Seavey transmitter and LPDA receiver. The Seavey antenna transmits very little power below 0.175 GHz, and the cross-polarized signal is weaker than the co-polarized signal, limiting \( F_{\text{ice}} \) results to frequencies below 0.4 GHz. These measurements are shown in column 4 of Table 4. These data can be compared to measurements taken in 2010, in which \( F_{\text{ice}} \) and \( F_{\text{air}} \) were shown to agree at 0.1 GHz with a LPDA transmitter and LPDA receiver at the same location as the 2011 measurements (Hanson, 2011). A comparison of \( F_{\text{air}} \) with \( F_{\text{ice}} \) reveals no excess power in the cross-polarization direction, with the possible exception of data at 0.400 GHz, which show a 2\( \sigma \) deviation from intrinsic antenna effects. These data do not confirm the \( F_{\text{ice}} \) analysis of the 2006 data, which showed \( F_{\text{ice}} = 0.7 \) at 0.4 GHz.

DISCUSSION

The data are in agreement with independent analyses and models. A study from Greenland found the total transfer function of the Greenland ice sheet, and models the different contributions from basal reflection and attenuation (Paden and others, 2005). A reflection coefficient (for power) of \(-37 \text{ dB}\) is reported for the North Greenland Ice Core 2 (NGRIP2) location, and ice absorption of \(-56 \text{ dB} \). Given the depth of 3.1 km, a loss rate of \(-9.0 \text{ dB km}^{-1} \) is obtained. (The Greenland study was limited to 0.11–0.5 GHz.) The upper half of the Greenland ice sheet is colder than Moore’s Bay, lowering the attenuation rate through temperature dependence of \( e^\alpha \). The reflection coefficient from that study \((-37 \text{ dB})\) is much smaller than that of Moore’s Bay. However, other authors have estimated it to be higher (Bamber and others, 2001; Avva and others, 2014), with an absorption rate of 9.2 dB km\(^{-1}\), conservatively assuming no reflection loss (attributing all loss to absorption). The Greenland site also exhibits a frequency dependence that produces a change of 8.5 dB km\(^{-1}\) over the bandwidth (0.11–0.5 GHz). The slope of the loss rate vs frequency is therefore 8.5/(0.55 – 0.11) \( \approx 22 \text{ dB km}^{-1} \) GHz\(^{-1}\). The corresponding value for the ARIANNA site is 9.3 dB km\(^{-1}\) GHz\(^{-1}\), from Table 3.

Another study presents models for ice absorption across the entire Antarctic continent, given an array of inputs, such as temperature and chemistry data (Matsuoka and others, 2012). That expansive study presents results for shelf and sheet depth across the continent, and the portion depicting the Ross Ice Shelf, near the ARIANNA site, is in agreement with our thickness measurements. The RIS depth is peaked at 500 m in that model, and we find 576 ± 8 m. The inputs to this model indicate that the Ronne Ice Shelf has smaller absorption rates (dB km\(^{-1}\)) than the Ross Ice Shelf, which leads to a double-peaked distribution of loss rates, with one peak near 12.5 dB km\(^{-1}\), and the other near 22.5 dB km\(^{-1}\). The ARIANNA site average absorption rate is within one standard deviation of the mean for the entire distribution (15.1 ± 6.2 dB km\(^{-1}\)), and is in agreement with the second peak in the distribution of loss rates, corresponding to the Ross Ice Shelf.

Finally, a study of the Ross Ice Shelf at 2 MHz reveals large-scale thickness uniformity in the shelf, up to 40 km from the grounding line of the glaciers flowing into the shelf (MacGregor, 2011). The measurements are obtained from basal echoes with travelling transmitters and receivers at the surface. In some cases, multiple echoes are observed, corresponding to multiple round trips made by the signal, from surface to base. This technique provides excellent constraints on the thickness and absorption rate. Specifically, this study shows that our depth measurement is typical for large expanses of ice, a key requirement for large-scale ground arrays in neutrino detectors.

CONCLUSION

During the 2011/12 Antarctic season, radio-echo sounding measurements were performed in Moore’s Bay with high-voltage broadband RF pulses in the 0.1–0.850 GHz bandwidth, to understand the dielectric properties of the ice shelf. The shelf thickness determined from the total propagation time was 576 ± 8 m. The echo soundings revealed depth-averaged attenuation lengths well fit by the linear function \( L(\nu) = (460 \pm 20) - (180 \pm 40) \times \nu \) m (19.3–26.4 dB km\(^{-1}\)), where \( \nu \) is the frequency (GHz). The \( \chi^2/\text{dof} \) of this linear fit to the combination of multiple datasets was 1.2, with 9 degrees of freedom. The fit is consistent with prior measurements (Barrella and others, 2011), and the functional dependence is compatible with theoretical expectations (Matsuoka and others, 1996; Somaraju and others, 2006).

Vertical echo soundings were compared to echo soundings with a 543 ± 7 m baseline between transmitter and receiver, which allowed independent measurement of the basal reflection coefficient, found to be \( \sqrt{R} = 0.82 \pm 0.07 \) (1.7 dB). The slope of \( \sqrt{R} \) vs frequency is consistent with a flat-mirror approximation. The average value of \( \sqrt{R} \) is consistent with earlier studies performed at lower frequencies (Neal, 1979). The short duration of the observed pulses (90% of the power contained within 100 ns) precludes significant multi-path effects. The Fresnel zones of the pulses at the shelf base are not significantly larger than measured horizontal correlation lengths. After correcting attenuation lengths for the effect of \( \sqrt{R} \) on returned power, dielectric quantities like \( e^\alpha \) and \( \nu \tan \alpha \) were derived. The results for \( e^\alpha \) and \( \nu \tan \alpha \) agree with theoretical expectations (Matsuoka and others, 1996). Finally, the fraction of scattered power by the ice into the cross-polarized direction, \( F_{\text{ice,c}} \), is <10% (0.100–0.400 GHz), compatible with the fraction of power
due to intrinsic limitations of the transmitting and receiving antennas. Both the large value of $\sqrt{R}$ and the small value of $F_{\text{ice}}$ suggest that the bottom surface of the Ross Ice Shelf at Moore’s Bay is smooth. The measurements of $F_{\text{ice}}$ do not demonstrate any significant features below 0.400 GHz, where cross-polarized power is noise-limited. This result, combined with the measured field attenuation length at frequencies between 0.100 and 0.850 GHz, suggests that the Moore’s Bay region of the Ross Ice Shelf will be an excellent medium for the ARIANNA high-energy neutrino project.

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