Measurement of the radiofrequency properties of Antarctic ice with the RICE detector

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Abstract

Using the RICE detector at the South Pole, we have estimated the variation in the index of refraction, as a function of depth into the firn (z), to z=–160 m. Measurements were made in Dec. 2002 by lowering a dipole transmitter into a 12 cm caliber borehole, originally drilled for the RICE experiment in 1998. Signal arrival times (and corresponding propagation velocities), as a function of transmitter depth, in the RICE receiver array underice are determined as the transmitter broadcasts short-duration pulses. Our measurements are in agreement with previous laboratory characterizations of the dielectric properties of ice cores. These are the first such *in situ* measurements to be performed at the South Pole.

Introduction

The Antarctic icecap has provided an extraordinary laboratory for a variety of scientific purposes. The AMANDA[1], IceCube[2], ANITA[3], and RICE[5,6] collaborations seek to use the dense, solid, large-volume, and extraordinarily transparent (for $\lambda > 100\,nm$) icecap as a neutrino target; the pioneering AMANDA experiment has sucessfully demonstrated the viability of in-ice optical detection of atmospheric neutrinos, through the reconstruction of hundreds of muon neutrinos. Similarly, the RICE and ANITA experiments also seek to detect neutrinos interacting in the Antarctic icecap; whereas AMANDA's sensitivity is maximal for ν_μ, the RICE and ANITA experiments focus on ν_e detection, by measuring the Cherenkov radiation produced by neutrino interactions in polar ice, albeit at lower frequencies (100 MHz−1 GHz) than AMANDA/IceCube. The RICE experiment consists of an array of 20 in-ice dipole receivers, deployed at depths of $100 - 400$ m, and read out into digital oscilloscopes. Calibration techniques and event reconstruction[5], as well as results on the neutrino flux at earth[6], are presented elsewhere. Whereas neutrinos are expected to interact below the array, RF backgrounds due to air showers, or above-surface anthropogenic sources, require recontruction of sources viewed upwards through the firn. This necessitates ray tracing the trajectories of radio waves through a region of variable ice density and

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dielectric constant, resulting in shorter signal propagation times and reduced signal amplitudes (at non-zero incident angles) compared to the case where sources are entirely below the firn. Reconstruction of under-ice neutrino interactions by the balloon-borne ANITA experiment also requires ray tracing through the firn. In order to accurately estimate both the neutrino's energy and direction, it is therefore important to have an accurate characterization of the variation of the dielectric constant with depth in polar ice.

Methods

Each RICE receiver consists of a half-wave dipole antenna, offering good reception over the range 0.2–1 GHz, plus a 36 dB low-noise amplifier. The peak response of the antenna is measured to be ∼500 MHz in air (∼300 MHz in ice), with a bandwidth $\frac{\Delta f}{f}$ ∼0.2. An identical dipole antenna, without the amplifier, is used as the transmitter for this measurement. As the transmitter was slowly lowered into a RICE borehole, a pulser signal was broadcast from the transmitter (at 5-10 meter depth increments) to the RICE receiver array, and signal arrival times in the receivers recorded (Figure 1a). This afforded two measurements of the index of refraction: 1) the index of refraction as a function of depth ($n(z)$) could be inferred by determining the transit time difference to a particular receiver between successive transmitter locations ($n = c(t_{i+1} - t_i)/(|\vec{r}_{Tx,i+1} - \vec{r}_{Rx}| - |\vec{r}_{Tx,i} - \vec{r}_{Rx}|)$, and 2) the "mean" index of refraction ($< n(\Delta z) >$), averaged over the distance from the transmitter to any receiver could be inferred by subtracting cable delays from the measured full circuit (pulse generator→transmitter→receiver→DAQ) time. At each transmitter location, the t_0 of the transmitter signal, as well as an 8.192 microsecond waveform (sampled at 2 GSa/s) was recorded in an HP5452 digital oscilloscope, for each receiver. The hit time is determined from the first 6σ excursion in each waveform; the variation in receiver hit time with transmitter depth is shown in Figure 1b). As the transmitter approaches the (deeper) receiver, the hit time migrates to smaller values; also evident in the Figure are the "afterpules" corresponding to signals which reflect off of the surface firn-air boundary, and back down to the buried receiver.

The local electromagnetic wave propagation velocity is directly obtained from successive hit times in Figure 1b), and can therefore be translated into an index-of-refraction profile, $n(z)$. Figure 2a) shows the locus of hit times for several receiver channels; the local value of n(z) can be obtained from slopes to these data points. We have attempted to obtain an "aggregate" estimate of n(z) by: a) adding the raising-transmitter plus lowering-transmitter datasets, b) adding all "good" data from all possible channels, where the contribution to the final average from each channel was weighted by geometry (favoring nearly-vertical channels), c) averaging over possible transmitter location uncertainties by rebinning data and re-obtaining averages using 20 m distance differences (rather than

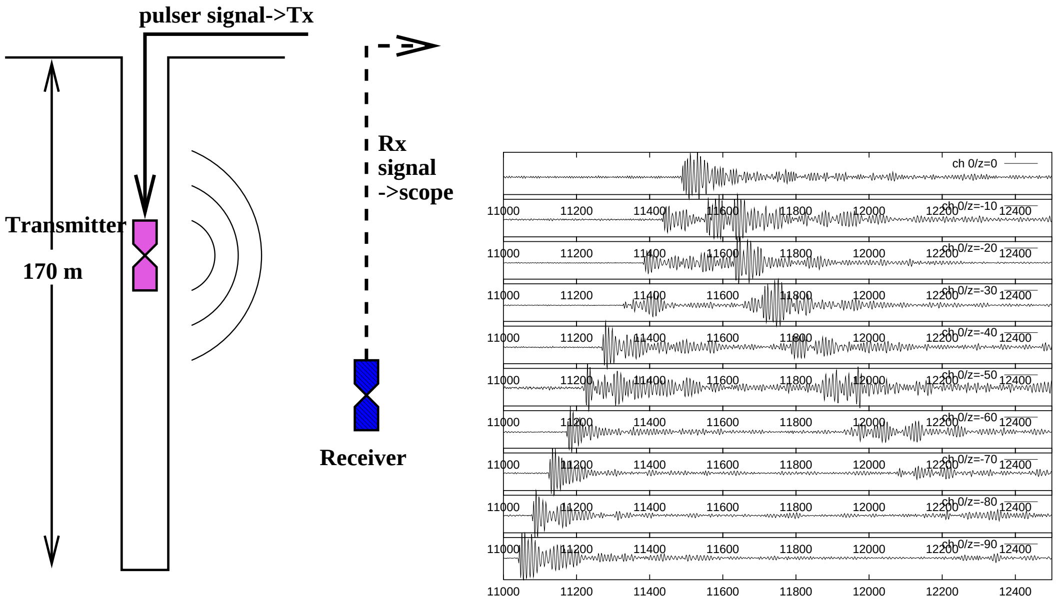

Fig. 1. Left (a): Geometry of measurements. The transmitter (Tx) is connected, via coaxial cable, to a pulse generator or in the Martin A. Pomerantz Observatory. The transmitter broadcasts to one of the RICE dipole receivers (located in-ice). Right: Successive signals recorded (at 10m depth increments) in one receiver channel, as the transmitter is lowered into the ice. Horizontal units are 0.5 ns.

10 m) between successive Tx broadcasts. In all cases, we assumed a transmitter location uncertainty of 0.5 m for all measurements, as well as a hit-time uncertainty of 1 ns. Fig. 2b) shows the result of this procedure, and also includes data obtained by broadcasting horizontally between a transmitter-receiver pair being lowered simultaneously into two neighboring boreholes. Also included are measurements derived from the "average" n(z) values obtained using absolute t_0 measurements, as well as comparisons with the predictions of the Schytt model[7], which relates index of refraction directly to firn density $\rho(z)$, assuming that the ice-firn transition occurs at either z=-115 m or z=-130 m.

The RICE data points are fit to a 2nd-order polynomial, with the constraint that the value of index of refraction at large depths approach a constant asymptotic value. We obtained an estimate of that asymptotic value by broadcasting from the deepest buried RICE transmitter down to the deepest buried RICE receiver over a distance of 233.4 m; both of these antennas are presumably well below the firn-ice transition. The measured propagation time is 1369±8 ns, corresponding to $n = 1.764 \pm 0.021$. This value is in fair agreement with the accepted value of 1.78, as obtained by several measurements[4]. The overall error (statistical + systematic) of each data point is estimated at 4%.

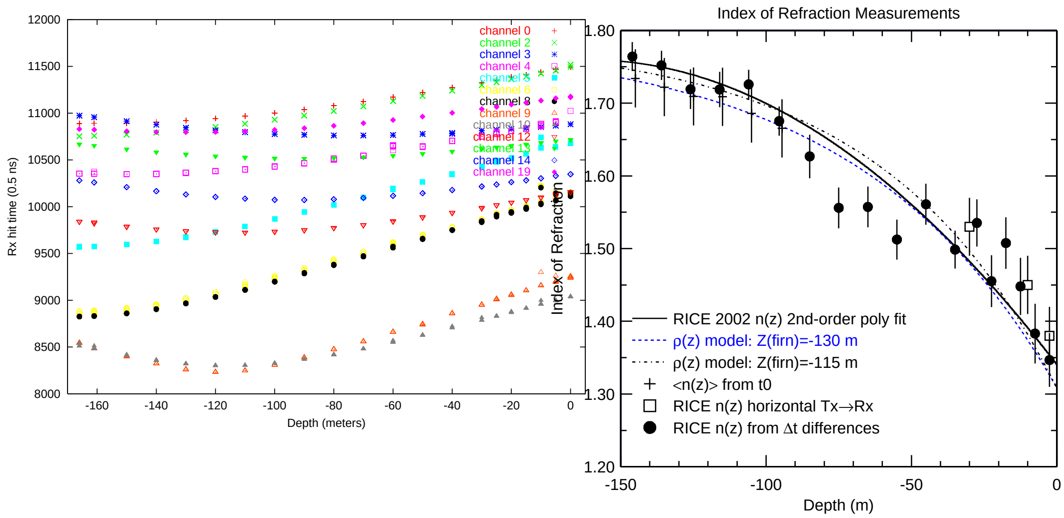

Fig. 2. Left (a): Recorded hit times, for several channels, as a function of transmitter depth. Right (b): Final fit to index-of-refraction data, as described in the text.

Summary

Using the RICE detector, we have made the first *in situ* measurements of the index-of-refraction through the South Polar firn. In 2003-04, we hope to use a distant transmitter, broadcasting horizontally, to measure the attenuation length at RF frequencies.

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