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Energy Resolution and Calibration of the ANITA Detector

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Abstract: The balloon-borne ANITA neutrino telescope successfully launched from McMurdo Station, Antarctica during the 2006-2007 austral summer. In this paper we present ongoing studies of the energy resolution and system response of the ANITA detector, which provide an excellent test bed for validating the ANITA Monte Carlo and will be of great interest if ANITA discovers signal events. While in view of the launch site ANITA received calibration pulses from two antennas, located on the surface and in a borehole in the Ross Ice Shelf, which facilitate these studies.

Introduction

In the 1960's Askaryan predicted that coherent radio Cherenkov radiation would result from the charge asymmetry developed in an electromagnetic shower in a dielectric medium [1]. Experiments at the Stanford Linear Accelerator Center in 1999-2000 [2], 2002 [3], and 2006 [4], have now verified these predictions in sand, salt, and ice. Askaryan also noted that these radio pulses could be exploited for the detection of ultra-high energy (UHE) neutrinos ($E_\nu > 10^{18}$ eV) interacting in large target volumes, such as the lunar regolith and the Antarctic ice sheets. The primary goal of the ANITA experiment is to observe UHE neutrinos, for the first time, by detecting Askaryan pulses resulting from their interaction with atomic nuclei in Antarctic ice. Since the expected flux of UHE neutrinos is small, ANITA is designed as a long-duration high-altitude balloon (LDB) payload [1] which can observe large volumes of ice simultaneously.

1. During its inaugural flight, the ANITA instrument was aloft for $\sim$ 35 days (the second longest LDB mission in history), at an approximate altitude of 36 km.

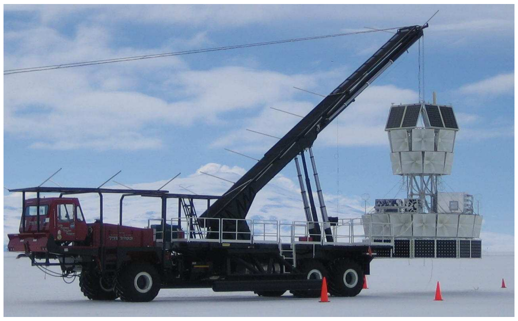

Figure 1: The ANITA payload, prior to launch from Williams Field, Antarctica (December 15, 2006).

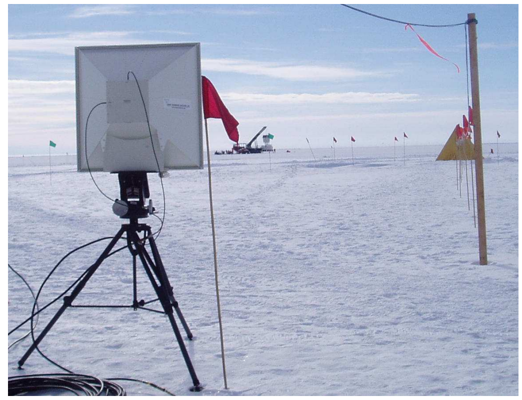

Figure 2: The ANITA ground pulser system. The surface horn antenna is in the foreground; the borehole discone antenna is $\sim$ 20 m below the surface (under the yellow Scott tent). The ANITA payload is visible in the background, on the launch vehicle.

We model the predicted sensitivity of the ANITA experiment with two independent Monte Carlo simulations, the accuracy of which is of crucial importance in interpreting the results of ongoing data analysis efforts within the collaboration. To verify the health of the instrument during flight we operated ground-based pulser systems from two sites, one adjacent to the balloon launch area outside of McMurdo Station, and one at a remote camp near Taylor Dome; the results presented in this paper concentrate solely on the system near McMurdo. We use received radio pulses from the ground system to estimate the total Fresnel factor as a function of refracted angle at the snow surface. This measurement validates the treatment of RF propagation through the firn-air interface in our Monte Carlo, and tests the absolute energy resolution of the ANITA detector.

ANITA Ground Pulser System

When the payload was above the horizon from McMurdo Station, we operated a calibration system which transmitted radio pulses from two antennas on the ground to the ANITA instrument in flight. The first antenna was a discone, located in a borehole 26 meters below the surface of the ice. The discone transmitted a $\sim$ 1.2 kV pulse of a few ns duration three times per second for most of the time that the payload was in range. The second antenna was a quad-ridged horn antenna, identical to those flown on the ANITA instrument. From the surface-based quad-ridged horn, we transmitted a $\sim$ 400 V pulse of a few ns duration once per second. The borehole antenna provided us with a signal of constant amplitude and polarization which originated from inside the ice, and which approximated the radio Cherenkov signal from a neutrino interaction. The surface antenna could be seen from a greater distance due to its high gain and the absence of Fresnel losses. It also provided us with the capability to alter the amplitude or polarization of the signal in order to test the instrument more thoroughly.

During flight, we used frequent updates of the payload position to calculate the distance from each antenna to the instrument. We used these distances to calculate the time-of-flight for a radio pulse to reach the balloon, and continually adjusted the transmission time of each pulse so that it would arrive in a preset time window at the instrument. Defining a preset trigger time allowed us to detect the calibration pulses even in the presence of heavy anthropogenic RF noise from McMurdo.

Event Selection & Corrections

We select events containing impulses from the ground system by enforcing requirements on signal amplitude, polarization, background noise level, timing of the peak sampled voltages within the recorded waveforms, and relative timing offsets between waveforms in neighboring antennas. These selection criteria reject noise-triggered events with $\sim$ 99 % efficiency. Those remaining are removed by hand, resulting in a pure sample of $\sim$ 4000 ground-system impulses.

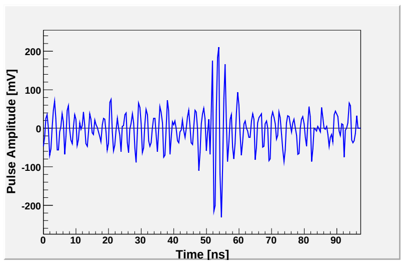

Figure 3: Typical waveform of a received impulse from the borehole antenna.

The RF environment near McMurdo Station contains many strong sources of anthropogenic noise which can affect measurements taken up to several hundred km away. To account for this noise we calculate the rms voltage away from the impulse in each signal waveform and correct the peak amplitude of the impulses by subtracting off this value. Prior to launch we measured the gain of each channel of each antenna in the assembly hangar, using a noise figure meter. We calculate $gain_{\rm ch} - gain_{\rm avg}$ for each channel, and apply these factors to correct the response of each channel to $gain_{\rm avg}$.

Measurement of Fresnel Factor

To measure the overall Fresnel factor we first calculate the predicted magnitude of the electric field broadcast by the borehole discone antenna and extrapolate this signal (forward) to just under the snow surface. We then calculate the magnitude of the electric field incident at the payload in flight, and extrapolate this signal (backward) to just above the snow surface. The ratio of these two amplitudes, $backward/forward$, is the measured overall Fresnel factor. In these calculations, antenna effective height is determined from in situ measurements near the launch area, and effective bandwidth is determined from averaged power spectra of successfully transmitted/received pulses.

The ANITA simulation code assigns a constant index of refraction for ice below the average firn depth (approximately 150 m). In the firn layer, the index of refraction is depth dependent. The code performs ray tracing to determine the path of the RF signal from the interaction point through to the surface, and from there out to the payload. Radiation from an Askaryan pulse or our borehole pulser is not accurately modeled by a pure plane wave at the firn-air transition. To account for the (small) divergence of the rays, propagation through the surface includes a modified treatment of the Fresnel equations and the magnification factors which enforce conservation of energy across the firn-air interface [5] [6]. The analytical form is given by:

$$t = \sqrt{\frac{\tan\theta_i}{\tan\theta_r}(1 - R^2_{\parallel,\perp})} \qquad (1)$$

where t is the Fresnel factor for the transmitted power, θ_i and θ_r are the incident and refracted angles, and R is the standard Fresnel reflection coefficient.

ANITA personnel measured the densities of ice cores drilled for the borehole discone antenna, yielding a parameterization of the local index of refraction vs. depth. Using this parameterization and equation 1, we obtain predicted Fresnel factors as a function of refracted angle from the simulation. Over the range of angles spanned during the pulsing period ($\sim 75°$ to $85°$) these factors are well fit by a second-order polynomial, which we will use to represent the predicted values as a function of distance between the pulser antenna and the ANITA payload. Finally, we use the predicted signal amplitude from the borehole discone antenna, projected to just above the snow surface, and define the constant, A_0. In Figure 4, we plot the corrected peak pulse amplitude vs. distance from the borehole discone antenna (points), and show three curves:

1. A fit to the data using the function a/r, where a is the fit parameter (dashed line). The agreement between this curve and the distribution is poor ($\chi^2/dof = 1810/11$).
2. The function A_0/r, where A_0 is the predicted signal amplitude.

3. The function $(A_0/r) \times (c_1 + c_2 \cdot r + c_3 \cdot r^2)$, where c_1, c_2, c_3 define the predicted Fresnel factor as a function of distance (derived from a polynomial fit to the predicted Fresnel factor vs. refracted angle, given by equation 1).

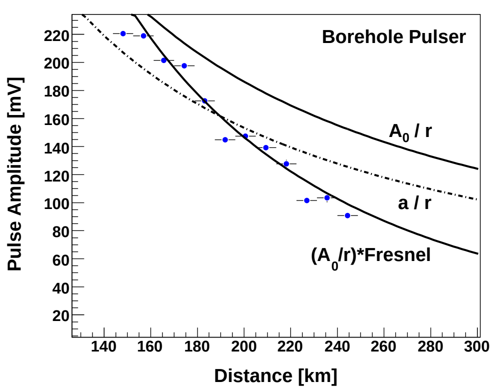

Figure 4: Corrected pulse amplitude vs. distance from the borehole discone antenna (points). The three curves are: a/r (dashed line, a is the fit parameter), A_0/r (A_0 is the predicted signal amplitude above the snow surface), and $(A_0/r) \times (c_1 + c_2 \cdot r + c_3 \cdot r^2)$, where c_1, c_2, c_3 define the predicted Fresnel factor as a function of distance.

In Figure 5, we plot the measured Fresnel factor vs. refracted angle (points), and overlay the predicted curve from the simulation (equation 1).

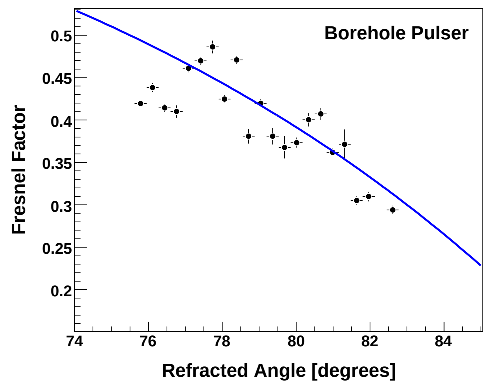

Figure 5: Measured Fresnel factor vs. refracted angle (points), and predicted curve from the simulation (equation 1).

Summary

Using impulses sent from the borehole antenna of the ANITA ground pulser system and received by the ANITA instrument during the first ~ 24 hours after launch, we have measured the Fresnel factor as a function of refracted angle, and compared the measured values to the predictions of the ANITA Monte Carlo simulation code. We observe good agreement in both shape and absolute normalization, indicating that the simulation is modeling well the propagation of an Askaryan pulse through the firn-air interface in Antarctica. Future work with these data will further improve our understanding of the absolute response of the ANITA instrument, and will hopefully lead to the creation of useful analysis variables for neutrino searches with the remainder of the ANITA flight data set.

Acknowledgements

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