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# Measuring the Askaryan Effect in Ice with the ANITA Instrument

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**Abstract:** Most ultra-high energy neutrino experiments using ice as a target medium rely on the Askaryan effect (coherent impulsive radio Cherenkov radiation from the charge asymmetry in an electromagnetic shower). This effect was measured with the Antarctic Impulsive Transient Antenna (ANITA) experiment at the Stanford Linear Accelerator Center (SLAC) in June 2006. The showers were produced by 28.5 GeV electrons with a number density of $10^9$ electrons per bunch impacting a 7.5 metric ton ice target (roughly 12.5 radiation lengths). In this paper we present the measured angular and frequency dependence of the radiation and compare the results with the predicted response.

## Introduction

It remains a challenge to unravel the mystery of the highest energy cosmic ray events. Since protons at such energies cannot travel very far from a cosmological standpoint before interacting with photons left from the Big Bang, we should see nearby point sources. To date, no local sources have been observed and a paradox has arisen.

In 1966, Greisen, Zatsepin, and Kuzmin [1, 2] predicted that the flux of these UHE protons would be reduced via the process:

$$p + \gamma \rightarrow \Delta^* \rightarrow n + \pi^{\pm} \qquad (1)$$

where the decay chain of the $\pi^{\pm}$ leads to the flux of high energy neutrinos ("GZK $\nu$ flux").

Large scale optical Cherenkov detectors such as the Antarctic Muon and Neutrino Detector Array (AMANDA) [3] and its successor, IceCube [4], have been successful in detection of neutrino interactions at $>$ TeV energies using Cherenkov radiation. While both use ice as their target medium, the need for larger detector volumes is evident when evolving into the $>$ 100 PeV energy regime.

## Radio Detection of UHE $\nu$'s

During the development of an electromagnetic particle cascade in normal matter, high-energy processes such as Compton scattering knock electrons from the material into the shower. In addition, other high-energy processes such as Bhabha and Moller scattering along with positron annihilation should lead to a 20%-30% negative charge excess for the compact bunch-like ensemble of particles which carry most of the shower energy. In 1962, Askaryan [5, 6] first hypothesized this effect and suggested that it should lead to strong coherent radio and microwave Cherenkov emission for showers propagating within the dielectric. Since the dimensions of the clump of charged particles are small compared to the wavelength of the radio waves, the shower radiates coherent radio Cherenkov radiation whose power is proportional to the square of the net charge in the shower. The net charge in the shower is proportional to the primary energy so the radiated power scales quadratically with the shower energy ($P_{RF} \propto E^2$). This effect is depicted in figure 1.

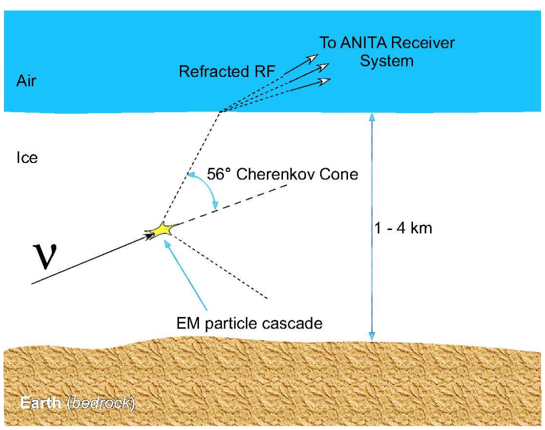


Figure 1: UHE $\nu$ interaction in Antarctic ice illustrating the generation of coherent radio Cherenkov emission.

Recently, this effect has been observed in silica sand [7] and in rock salt [8] after renewed interest came with experiments such as the Radio Ice Cherenkov Experiment (RICE) [9], and the Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE) [10], designed to test Askayan's prediction. Further developments of Askaryan's work have extended the detection regime to satellite spacecraft; the Fast On-orbit Recorder of Transient Events (FORTE) [11], and balloon-born payloads, ANITA [12], using large volumes of ice ($\sim 10^6$ km$^3$) from Greenland or Antarctica respectively as the dielectric media.

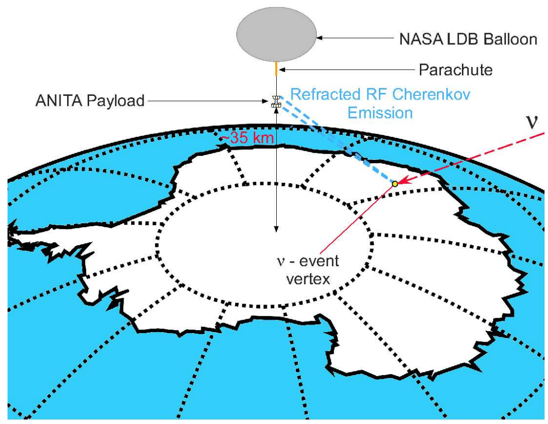


Figure 2: Conceptual view of ANITA at a $\sim$35 km altitude over the Antarctic continent. Not to scale.

Figure 2 illustrates ANITA's concept of utilizing the detection of coherent radio emission from refracted Cherenkov radiation at the Antarctic ice surface. The payload, flying on a NASA Long Duration Balloon (LDB), circles the continent at a $\sim$35 km altitude while simultaneously digitizing 72 RF channels from 32 dual-polarized quad-ridged horn antennas, sensitive over 200-1200 MHz, and eight additional vertical polarized broadband monitor antennas (4 bicones & 4 discones). The ANITA instrument samples at $\sim$2.6 GSa/s which is sufficient for capturing Askaryan pulses where most of the energy arrives in $\sim$0.1 ns [13]. An overview of the ANITA instrument is shown in figure 3.

## Measuring the Askaryan Effect in Ice

SLAC T486 was performed during the period from June 19-24, 2006. Figure 4 shows the overall experimental setup including the ice target which was constructed using $\sim$55 rectangular blocks of 136 kg ultra-pure carving ice closely packed to form a trapezoidal, $\sim$7.5 metric ton stack 5 m $\times$ 2 m $\times$ 1.5 m tall (at the beam entrance). The upper ice

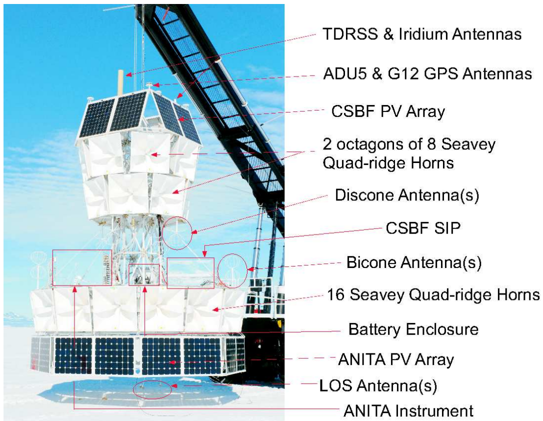


Figure 3: The ANITA payload.

surface was then carved to a slope of $\sim 8^\circ$ to prevent total internal reflection (TIR) produced from the Cherenkov emission near the surface. In addition, the bottom of the ice target was covered with a layer of 10 cm ferrite tiles to supress reflections while radio absorbing foam was in place on the front face of the ice to supress upstream RF signals from metal beam vacuum windows and air gaps. The entire ice volume was enclosed in a temperature regulated cooling enclosure with walls of 10 cm thick insulating foam and a 10 cm thick removable cover. Throughout the duration of the experiment, the ice was kept between -5°C and -20°C.

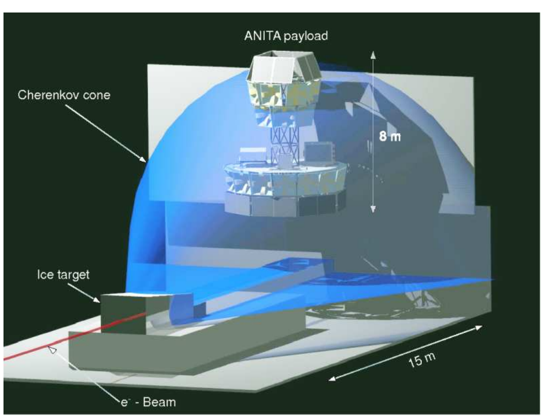


Figure 4: Rendered view of the experimental setup of SLAC T486 at SLAC's ESA. A cone of refracted optical Cherenkov radiation is shown illuminating the ANITA payload.

The 28.5 GeV electron beam entered the target $\sim$40 cm above the target floor producing the electromagnetic showers. Typically, the 28.5 GeV electrons were in 10 ps bunches composed of $\sim 10^9$ particles. Figure 5 (left) shows the electric field strength from the different antennas on the ANITA payload. The curve represents a parameterization of a shower in ice at this energy. Figure 5 (right) displays the Cherenkov power with shower energy. This relation indicates that Cherenkov emission is coherent over 200-1200 MHz frequency band which is consistent with Askaryan's prediction [14].

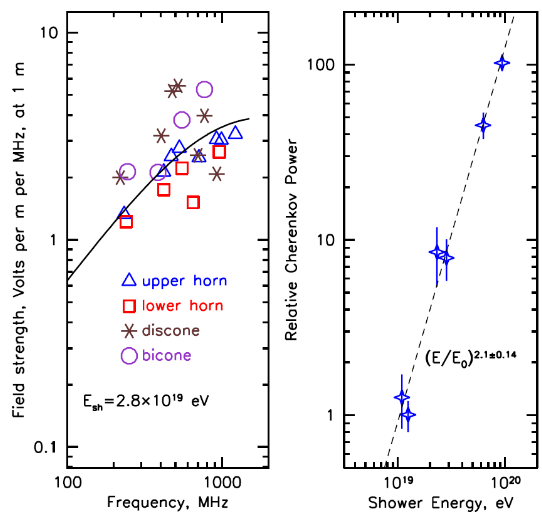


Figure 5: Left: Electric field strength vs. frequency of radio Cherenkov emission from T486 with a theoretical curve representing a shower profile in ice at this energy. Right: Cherenkov power vs. shower energy indicating the coherence of radio Cherenkov emission.

Figure 6 shows the measured and predicted angular dependence of the radiation detected at the payload. For the in-ice case the peak of the Cherenkov cone is at $\sim$54° while the refracted case yields a peak of $\sim$23°. In the case where the Cherenkov cone refracts into the foward direction, we see a direct correlation with the experimental data [14].

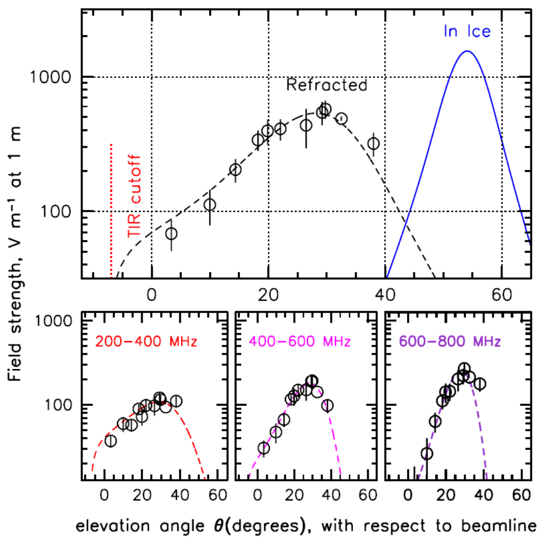


Figure 6: Top: Angular dependence of the radiation for the refacted and in-ice case for a frequency range of 200-800 MHz. Bottom: Same as top only for 3 different sub-frequency bands. The curve is a theoretical expectation for a shower in ice at a beam current of $10^9$ $e^-$ per bunch and 28.5 GeV electrons.

## Conclusions

We have validated the Askaryan hypothesis for dielectrics that are optimized for detecting coherent Cherenkov emission from electromagnetic particle cascades (ice [14], salt [8], & sand [7]). With this confirmation in place, large scale detectors like the ANITA experiment are a promising means of probing the low fluxes of ultra-high energy neutrinos.

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