Tuning into UHE Neutrinos in Antarctica - The ANITA Experiment

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The Antarctic Impulsive Transient Antenna (ANITA) experiment is being developed to search for ultra-high-energy (UHE) neutrino interactions ($> 3 \times 10^{18}$ eV) in the Antarctic ice cap. A neutrino interaction in the ice will produce a radio pulse by the means of the Askaryan effect. The large radio transparency of ice allows for such a pulse to be recorded by a cluster of balloon-borne antennas. The details of the ANITA instrument, now in a construction phase, and the science we hope to achieve is discussed. In order to prepare for the main mission, we have flown ANITA-lite during the 2003/04 austral season. ANITA-lite consisted of two quad-ridge horn antennas and a prototype RF (radio frequency) triggering and recording system. Here we present the results of an impulsive RF background survey of Antarctica, as well as proof-of-principle gain, tracking, and timing calibrations conducted by observing solar radio emissions and calibration radio-pulses. A preliminary UHE neutrino flux limit based on ANITA-lite data is also presented.

1. INTRODUCTION

High-energy neutrinos (>few tens of GeV) are currently an unexplored information channel available to particle astrophysicists. They are the third leg necessary to support current astrophysical theories, and combined with optical and cosmic-ray observations can provide a more clear view into the inner workings of the most energetic engines in the Universe. Due to their low interaction cross-sections, neutrinos are devilishly hard to work with, and only in the last decade experimental physics has been able to provide first definitive results based on large scale neutrino observations. At the same time, the power law nature of astrophysical accelerators means that a particle flux decreases rapidly as one looks at higher energies. These two facts imply that for high-energy neutrino observations one needs to instrument a very large target volume; for the expected fluxes at TeV energies observatories of ~ 1 km$^3 \cdot$sr are required, while at EeV energies one needs ~ 1000 km$^3 \cdot$sr. While neutrino observatories at 1 km^3 scale are currently being constructed [1], *in-situ* instrumentation of much larger volumes is impractical. However, substantial transparency of cold ice ($< -20°$C) to radio frequency radiation, combined with enhancement of radio emissions from high-energy neutrino-induced showers in ice due to the Askaryan effect, offers a promising way for reaching the required target volumes. A balloon-borne radio telescope at an altitude of 35-40 km above Antarctica would observe $\sim 10^6$ km^3 of radio-transparent ice. In this report, we describe plans for such an experiment, starting with a summary of Askaryan effect physics and the science goals of the mission. We also present results from the prototype flight and describe expected sensitivity to ultra-high-energy neutrino flux.

1.1. Askaryan effect

G. Askaryan proposed in 1962 [2] that a compact particle shower will produce a coherent radio Cherenkov emission. Subsequent theoretical work in the 80's [3, 4, 5] and the 90's [6] supported this prediction. The experimental verification came in 2001 [7], with follow up measurements confirming frequency and polarization properties of the emitted radiation [8].

The emission of coherent radio signal comes about from an appearance of the charge asymmetry as a particle shower develops in a dense medium. This asymmetry is due to combined effects of positron annihilation and Compton scattering of electrons at rest.

There is $\sim 20\%$ excess of electrons over positrons in such a particle cascade, which moves as a compact bunch a few cm wide and ~ 1 cm thick at the velocity above the speed of light in the medium. The frequency dependence of Cherenkov radiation emitted is $dP \propto \nu d\nu$. In addition, for radiation with wavelength $\lambda \gg l$, where l is the scale of the particle bunch, the radiated signal will add coherently and thus be proportional to the square of shower energy.

A radio signal emitted by a particle shower in a material such as ice is coherent up to few GHz, is linearly polarized, and lasts only about a nanosecond. A neutrino with energy of 10^{19} eV interacting in the ice produces a radio pulse with a peak strength of $\sim 10^{-3}$ V/m/MHz at a distance of 1 km.

Several experiments have already utilized Askaryan effect to search for high-energy neutrino interactions, RICE at the South Pole [9], FORTE in Greenland ice cap [10], and GLUE in the lunar regolith [11].

1.2. Science Goals

Unlike photons, high-energy astrophysical neutrinos propagate through the Universe unattenuated. They carry information from distances beyond the photon horizon which extends only to few hundred Mpc in 10-100 TeV range, and even less at PeV energies. Thus, they stand as a unique probe to acceleration processes associated with the sources of the highest energy cosmic-rays which extend to 10^8 TeV. Additionally, the GZK process [12, 13], interaction of high-energy cosmic-ray protons with the cosmic microwave background, produces high-energy neutrino flux. Observation or strict constraints on such a neutrino flux is crucial to resolution of GZK cutoff, which is currently one of the most controversial topics in cosmic ray physics.

Beyond the Standard Model, certain models of microscopic hidden dimensions predict that high-energy neutrino interactions in ice could produce highly unstable micro black holes (MBH) [14, 15]. The decay of these MBH via Hawking radiation would produce hadronic showers detectable through the Askaryan effect. The signature of this process would be an increase in the expected event rate with a strong energy dependency. Besides observation of extra dimensions, any top-down model of high-energy cosmic-ray production produces an associated neutrino flux [16], which would also be detectable.

2. ANITA

2.1. The Detection Concept

The ANtarctic Impulsive Transient Array (ANITA) has been designed to detect radio pulses emitted by
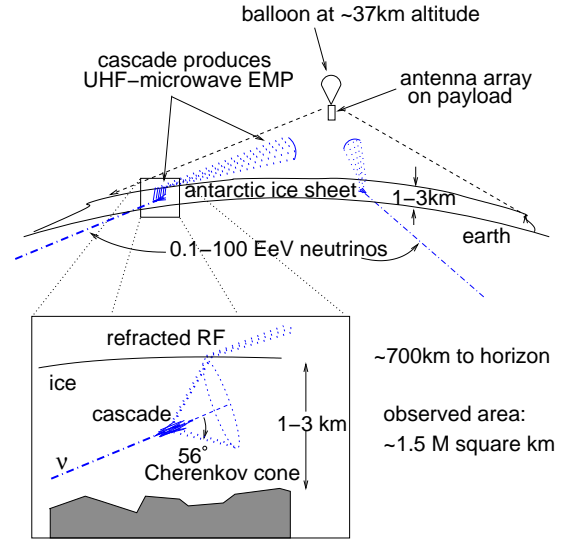

Figure 1: A schematic of ANITA detection concept.

neutrino interactions in Antarctic ice sheet. At energies above 10^{18} eV, the Earth is opaque to neutrinos, so ANITA would be sensitive only to neutrinos arriving at glancing angle with respect to the ice surface (Figure 1). Neutrinos interacting in the ice will produce a radio pulse emitted along a Cherenkov cone. This pulse will suffer very little attenuation before refracting at the surface and exiting the ice [17]. The interaction point and the direction of an incoming neutrino is determined by the time difference in radio pulse arrival between antennas and by the polarization of the pulse.

2.2. The Detector

The ANITA instrument (Figure 2) will consist of 40 dual polarization, quad-ridged horn antennas arranged in cylindrically symmetric upper and lower clusters. Each antenna records two linear polarizations of an incoming radio pulse and has a beam width of about $60°$. These antennas operate over 0.2 to 1.2 GHz, have approximately 10 dBi gain over the entire frequency range, and a very small phase dispersion, resulting in a sub-nanosecond impulse response. The separation between antenna clusters provides for a vertical timing baseline needed to determine the elevation angle of the arriving pulse. An overlap between adjacent antenna beam patterns provides a pulse gradiometry for determination of the azimuthal angle. The absolute azimuthal orientation will be measured by Sun sensor instruments, while the instrument tilt will be monitored by a differential GPS unit. The instrument will trigger on a coincident increase in RF power in several antenna channels. On trigger, all antennas will be readout and digitized at ~ 3GSa/s
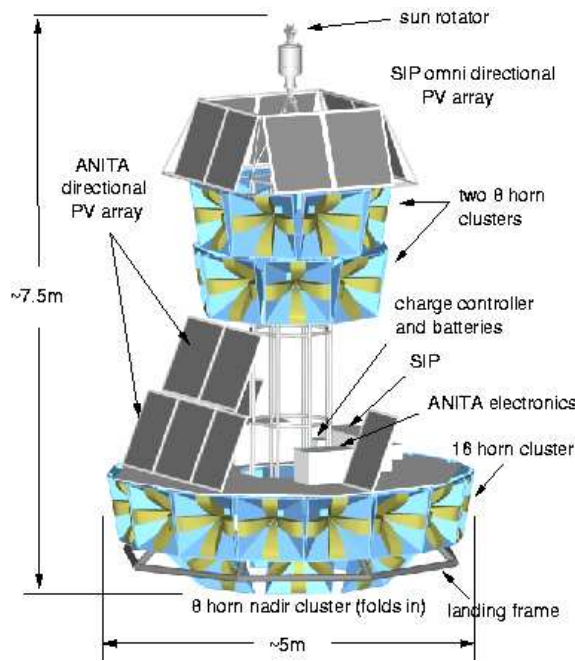
Figure 2: A mechanical model of the ANITA instrument.

sampling rate, allowing a capture of ~85 ns of data per trigger. The DAQ system will be able to record data rates up to 5 Hz.

3. ANITA-lite

ANITA-lite was a two antenna prototype of ANITA that was flown during the 2003/04 Antarctic season as a piggyback instrument on board Trans-Iron Galactic Element Recorder (TIGER) payload [18]. The goals of ANITA-lite were to conduct an RF background survey of Antarctica and to test prototype antennas and RF electronics which are to be used for ANITA. We have also performed the timing calibration of the system by sending RF pulses from the ground station to the instrument in flight.

The ANITA-lite instrument triggered on a coincident increase in RF power in both antennas. The data were digitized at 2 GSa/s, with 512 ns of data per trigger. We collected the total of 130,000 triggers (including the data taking and the calibration) over 18 days.

3.1. Timing calibration

Tone bursts at various frequencies and of various durations were sent with a ridged horn antenna from the ground to ANITA-lite at float. The signals were observed out to distances greater than 200 km, the main limitation being the loss of line-of-sight due to

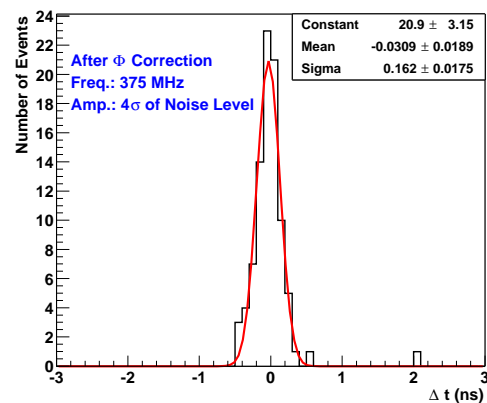Figure 3: The TIGER/ANITA-lite payload prior to launch.

Figure 4: Distribution of time differences between co-polarized channels.

the Trans-antarctic mountain range. Calibration signals were bandpass filtered around the calibration frequencies, and a time reference for each antenna was measured by interpolating the zero-crossing of a signal. Correcting for the separation between the two antennas, we measure the uncertainty in the signal arrival time between co-polarized channels of $\sigma_{\Delta t} = 0.16$ ns (Figure 4).

Based on this measurement, we estimate the time resolution between antenna clusters in ANITA to improve to $\sigma_{\Delta t} = 0.1$ ns due to the increase in number of channels receiving the signal and higher sampling speed. Since the error in the pulse arrival angle for antennas separated by the distance d is approximately given by

$$\sigma_\theta \approx \frac{180}{\pi} \frac{\sigma_{\Delta t} c}{d}, \qquad (1)$$

we estimate $0.5°$ and $1.5°$ uncertainty in determining the elevation and azimuth angles of arrival, respectively, for pulses originating near the horizon.
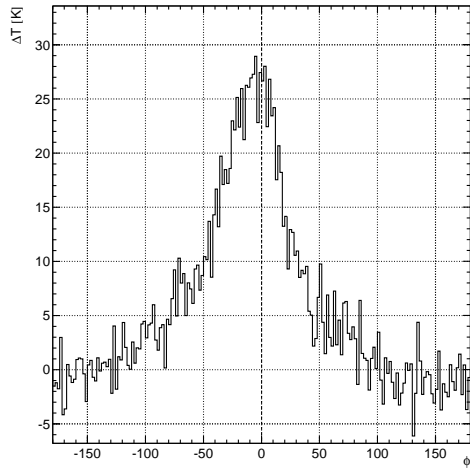
Figure 5: The excess effective antenna temperature as a function of azimuth between the direction of the Galactic Center and the ANITA-lite orientation. The asymmetry in the distribution is due to location of the Sun relative to the Galactic Center.
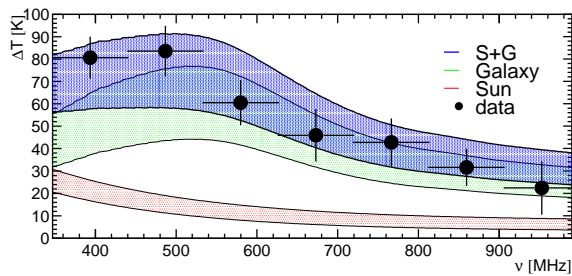

Figure 6: An average increase in the effective antenna temperature when pointing to the Sun and the Galactic Center. The top band is a model of the expected temperature increase, the width of which accounts for systematic uncertainties. The lower two bands give contributions due to galactic and solar emissions, respectively. The antenna frequency response is folded into the model.

3.2. Thermal background survey

In addition to observing the Antarctic ice sheet, ANITA-lite antennas have a significant portion of the sky in their field-of-view. As the instrument rotates, the two brightest radio sources in the sky, the Sun and the Galactic Center (GC), come into view (Figure 5).

During the ANITA-lite campaign, they were separated by 5-14 degrees, making it impossible to resolve them with our broad-beam antennas. Figure 6 compares an average increase in the observed background radiation, expressed in terms of an effective antenna temperature, as a function of frequency when pointed in the direction of the Sun and the GC with a model of the expected temperature increase. The model was based on the quiet Sun model [19] corrected for the observed solar activity during the ANITA-lite flight [20]
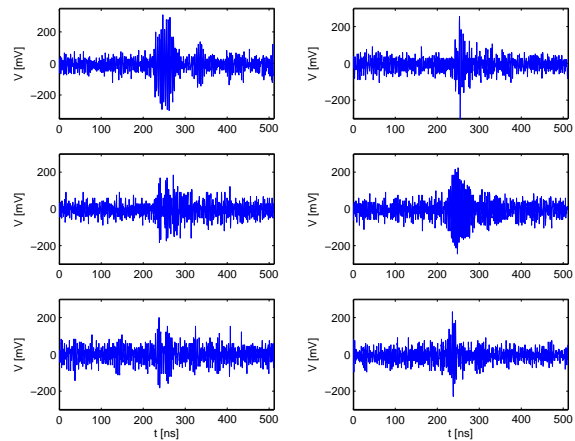

Figure 7: Examples of the six most common types of impulsive events recorded. Since they are repeatable and have no correlation with instrument location or orientation, we attribute them to locally generated RF noise.
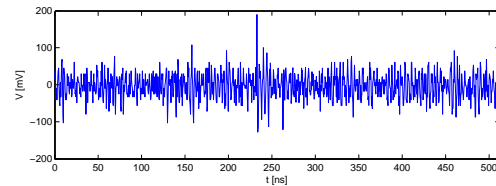

Figure 8: An example Askaryan pulse as would be seen by ANITA-lite.

and on the all-sky radio survey at 408 MHz [21] with an assumption of synchrotron-like frequency dependency of radio emissions from the galactic plane. The good agreement between measured and expected antenna temperature increase confirms that we have a good understanding of the antenna and RF system behavior, as well as of instrument orientation tracking.

3.3. Impulsive RF background survey

The impulsive RF background analysis is based on 87,475 events recorded during 16.2 days of data taking with 38% average livetime. By comparing the recorded waveforms with the expected shape of coherent Cherenkov radio pulses, we were able to reject all of the recorded events while retaining 62% of simulated signal pulses. Over 90% of all recorded events can be classified into six event categories (Figure 7), which we believe are all due to radio noise generated aboard the instrument[1]. Figure 8 shows an example of

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[1]As a piggyback instrument, we could not enforce as strict radio quiet conditions as would be required for this type of measurement. This will not be a problem with ANITA.
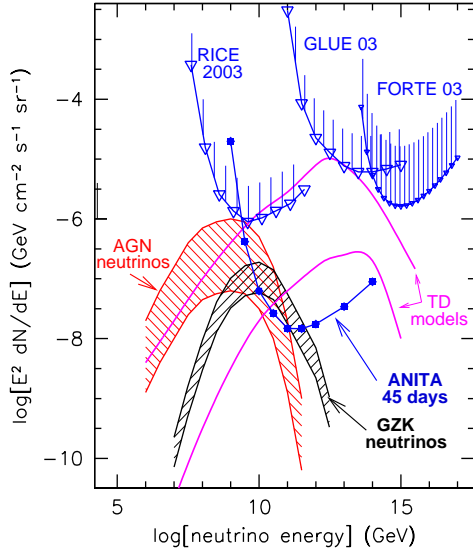
Figure 9: Published RICE, GLUE, and FORTE neutrino flux limits, and the expected sensitivity of ANITA. The models of neutrino sources are given as bands, spanning the range from optimistic to conservative ones.

the expected coherent Cherenkov radio pulse as would be recorded by ANITA-lite. Since we did not observe any radio pulses that could be associated with high-energy neutrino interactions in the ice, we can place a limit on the high-energy neutrino flux based on the ANITA-lite data. Currently, we are investigating the ANITA-lite trigger efficiency which is required to set the limit.

4. NEUTRINO FLUX SENSITIVITY

Simulating the performance of the full ANITA instrument and assuming an average flight trajectory over Antarctica, we can calculate an expected flux sensitivity and compare it with published high-energy neutrino flux limits and with models of neutrino flux (Figure 9). In the figure, the sensitivity is given for 45 days of flight. An average long duration balloon flight above Antarctica is 15 days, although in 2004/05 season CREAM instrument flew for 42 days [22].

ANITA will be sensitive to neutrinos arriving from low declinations (Figure 10). Instantaneous sky coverage is few degrees wide, but by circumnavigating Antarctica, the instrument will observe the region indicated in the figure.

5. CONCLUSIONS

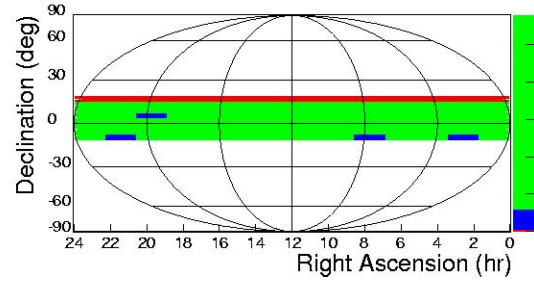The Askaryan effect opens the possibility for use of huge quantities of Antarctic ice as a neutrino detec-

Figure 10: Sensitivity of ANITA as function of neutrino arrival declination and right ascension. The green region indicates solid angle from which 90% of the detectable flux originates, blue and green region account for 99%, while blue, green and red account for 99.9%. Neutrinos of 10^{19} eV were simulated.

tion medium. ANITA will be the first experiment with sufficient sensitivity to test current models of neutrino production due to GZK process and to probe for other astrophysical sources of neutrinos in the energy range from 0.1 to 100 EeV. ANITA-lite was a successful test of almost all subsystems planned for the ANITA instrument. We have established that Antarctica is a very radio quiet environment, suitable for a search of neutrino-induced radio pulses. Also, we have demonstrated required timing precision and RF system gain calibration needed to perform accurate measurements of such radio pulses.

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