Possible Impulsive Radio Signals from Ultra-high Energy Extensive Air Showers Detected by the ANITA Experiment

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***Abstract*. The ANITA (ANtarctic Impulsive Transient Antenna) experiment is a balloon-borne neutrino telescope which consists of an array of 32 broad-band horn antennas. The primary goal of ANITA is to search for astrophysical neutrinos with energies $E > 3 \times 10^{18} eV$ by detecting radio Cherenkov signals from neutrino induced showers in the Antarctic ice. ANITA-I successfully completed a 35 day flight over Antarctica during the 2006-2007 austral summer. During the flight several horizontally polarized events were recorded that are consistent with impulsive radio signals from ultra-high energy extensive air showers. This data analysis is presented along with a discussion of the characteristics of those events.**

***Keywords*: UHECR Detection, Extensive Air Shower, Radio Frequency**

I. Introduction

Forty years after the first observation of radio emissions from Extensive Air Showers (EAS) [1] and Askaryan's prediction of coherent radio Cherenkov emissions [2][3], radio detection has now become a promising method for Ultra High Energy Cosmic Ray (UHECR) Physics with enormous development of Radio Frequency (RF) technology. Numerous experiments such as LOPES [4] and RICE [5][6] have exploited these areas, and also many new experiments have been proposed [7][8][9].

ANITA is a long duration balloon (LDB) experiment to detect radio Cherenkov signals from neutrino-induced showers in Antarctic ice. By simultaneously viewing a vast area of ice from a high altitude of 35 km, ANITA achieves a large target volume covering the energy $E > 3 \times 10^{18} eV$. Although ANITA is utilized for radio Chrenkov emission originated by neutrinos in Antarctic ice, it has the capability to detect radio signals emitted from UHE EAS as well. Figure 1. shows ANITA detection concepts.

Neutrino induced showers produce coherent Cherenkov radiation resulting from charge asymmetry which develops in a particle shower in a dielectric medium. When the radio signal propagates through ice and air to the ANITA instrument, transmission at the ice-air boundary suppresses horizontally polarized signals due to a low Fresnel coefficient for transverse electric waves, so that neutrino signals should be dominantly vertically polarized.

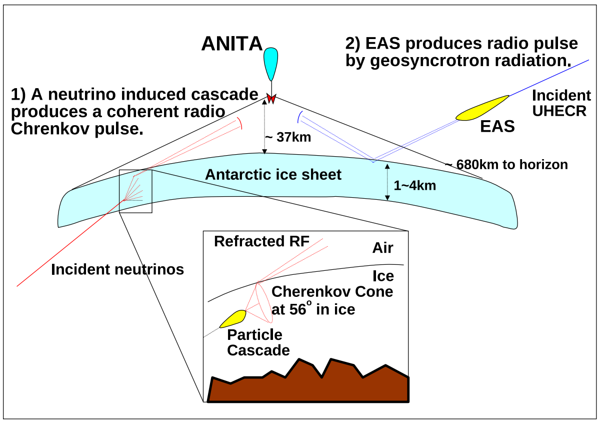

Fig. 1. ANITA Concept for Neutrino and EAS Detection

On the other hand, radio pulses from EAS are primarily produced by geosynchrotron radiation [10]. Because the direction of the geomagnetic field in Antarctica is almost vertical, the geosynchrotron pulses exhibit predominantly horizontal polarization (H-pol). Radio pulses from inclined showers can reach ANITA after reflection from the ice surface. The vertical polarization (V-pol) component of the signal is further suppressed in the reflection, thus detected EAS signals are mainly H-pol. The radio emission from EAS is a coherent emission below 100 MHz, but partially coherent emission above 200 MHz is also detectable [11][12][13].

II. ANITA Instrument

An overall view of the ANITA payload is shown in Fig. 2. There are 32 dual-polarized quad-ridged horn antennas with 9-11 dBi directional gain with about 45° beam width, arranged cylindrically to see all azimuthal directions simultaneously. Two groups of 16 antennas are separated by about 3 meters in the higher and lower tiers to provide a time baseline for RF incident angle measurement. The frequency range of the system is 0.2 - 1.2 GHz. RF signals are fed into high- and low-pass filters and 75 dB amplifiers in the front-end of the electronics, then split into the trigger path and the digitization path.

The trigger is formed in multiple frequency bands (270, 435, 650 and 990 MHz). The first level (L1) requires 3 out of 8 channels to be coincident within 12 ns. Trigger thresholds of individual channels are adjusted depending on the noise level to keep a constant trigger

Fig. 2. ANITA payload in a preparation of launch, Dec 15 2006.

rate. The second level (L2) requires two L1 triggers in adjacent antennas within 20 ns; the third level (L3) requires L2 triggers in the upper and lower tiers within 30 ns. The L3 trigger rate is 5-6 Hz on thermal noise with an efficiency of about 50% at 5.4 σ_V and $\sim$100% at 7 σ_V, where σ_V is the root-mean squared voltage of the thermal noise. The signal at the digitizer [14] is continuously sampled at a rate of 2.6 GHz. A differential GPS system is used to determine event timing, location and orientation of the instrument.

ANITA operated successfully during its 35 days flight making 3.5 orbits over Antarctica. About 8.2M events were recorded with 17.25 days of total cumulative live time. The ANITA instrument [15] has been calibrated using Askaryan signals from an ice target exposed to a 28.5 GeV electron beam at the Stanford Linear Accelerator Center (SLAC) [16]. The full instrument function and response to the Askaryan signal from ice were verified, and also system gains were absolutely calibrated with the beam energy. Another calibration was performed using ground based calibration systems during the flight. Impulsive radio pulses were sent by the pulser systems at Williams Field and Taylor Dome [17]. These pulser systems are used for various purposes such as validations of the ANITA system, timing calibrations, and tests of event reconstruction and RF propagation model.

III. Data Analysis

To minimize biases in data analysis, we followed blinding procedures until all analysis methods were established. We blinded 90% of data set while the remaining 10% data set was opened for background studies. For the 10% data, 100 consecutive events were randomly chosen within each 1000 event epoch in order to ensure a randomness of the sample and to keep short- and long- term time dependencies that are present in the full data set.

The main crux of the data analysis is the event reconstruction which selects events that originate from impulsive plane waves and determines their arrival direction. Using arrival timing information from 5 or 6 adjacent antennas, a χ^2-fit is performed to find the best fit direction. A cross-correlation technique is employed to determine the precise arrival time between recorded waveforms with a resolution of 47 ps - 66 ps. Angular resolutions are $0.2°$ and $0.8°$ for elevation and azimuth angle, respectively. The χ^2 from the fit is used as a fit quality parameter to reject incoherent thermal noise events which comprise $\sim$99% of the data set. The reconstructed direction is projected onto the Antarctic ice surface to find an RF source location. Events with an elevation angle above the horizon are rejected.

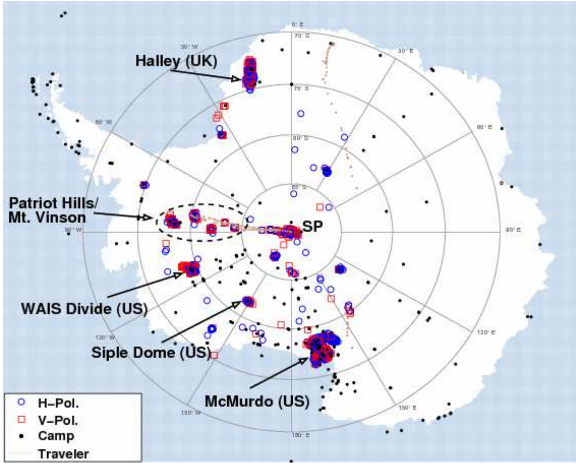

Fig. 3. Projected event map after application of suitable reconstruction. Red circles are for H-pol events and blue circles are for H-pol.

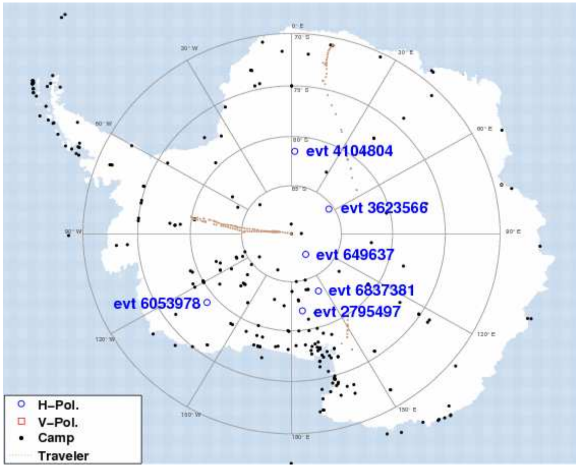

Fig. 4. Projected event map after application of appropriate reconstruction and rejection of anthropogenic background.

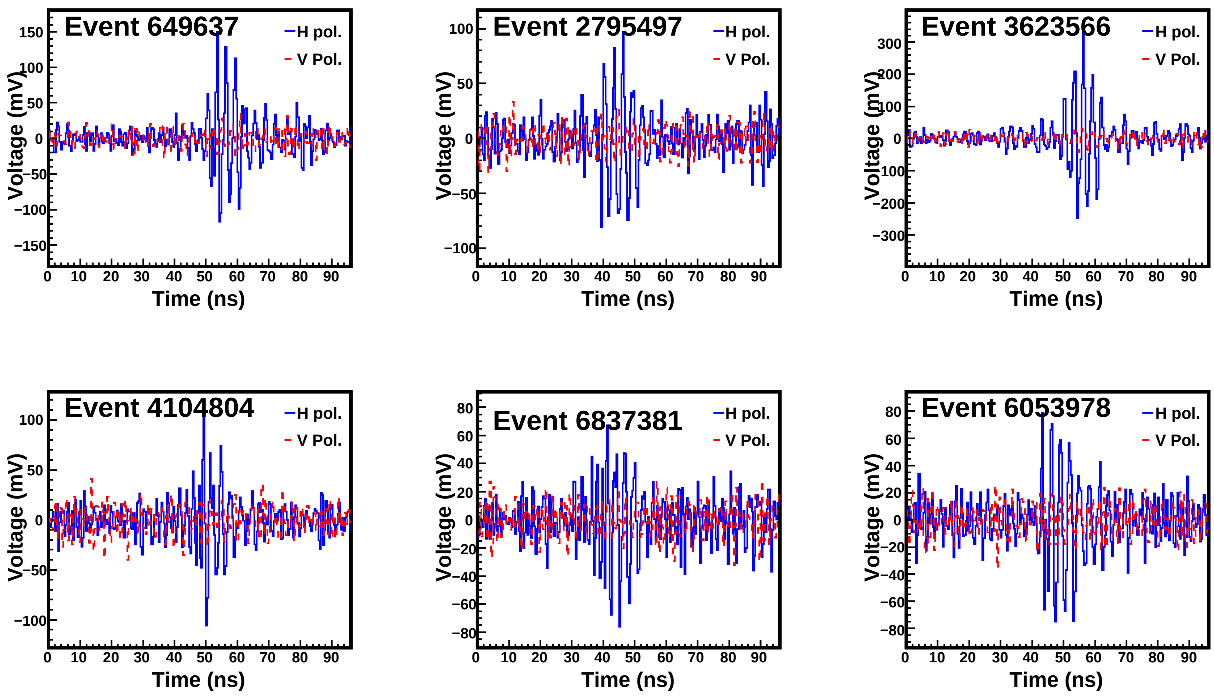

Fig. 5. Recorded waveforms of the 6 H-pol events. Red dashed lines are for V-pol and blue solid lines for H-pol. Displayed waveforms are only for maximum channels which have the maximum voltage in each event.Observed signal shape is due primarily to the effects of the ANITA system such as amplifiers and filters.

Figure 3 shows a map of projected RF source positions after selections on good angular reconstruction. Anthropogenic background events correlated with activities at existing bases, camps, automatic weather stations(AWS), and trajectories of travellers are rejected. An event is further required to be isolated from other events because repeated signals at the same location are likely to be of anthropogenic origin. Figure 4 shows an event map after anthropogenic background rejection. There are 6 H-pol events left, but no vertically polarized event is observed. The 6 H-pol signals are not considered to be neutrino signals due to the argument that Askaryan signals from ice should be V-pol dominant. New neutrino flux limits are reported from this result [19][20].

IV. Discussions

The 6 H-pol events are widely distributed across the continent. All 6 H-pol events have clear impulsive waveforms as shown in Fig 5. The possibility that impulsive radio signals from satellites could be a source of these events is ruled out because no differential group delay from ionospheric dispersion is observed.

In order to be sure that these events originated from EAS, further investigations are made with a full Monte Carlo simulation (MC). The MC is based on a simulation by Huege & Falcke [18] for geosynchrotron radio emission from EAS. A detailed description of simulation parametrizations is found in another paper [15]. Events are simulated over the entire ANITA field of view. A standard L1 trigger is used with proper Rician noise. The UHECR shower rates are normalized employing Auger 2007 normalization and the 2007 parametrization of the empirical GZK cut-off. The integral flux above $10^{19}eV$ is $J(E>) = 2.0\times10^{-18}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$.

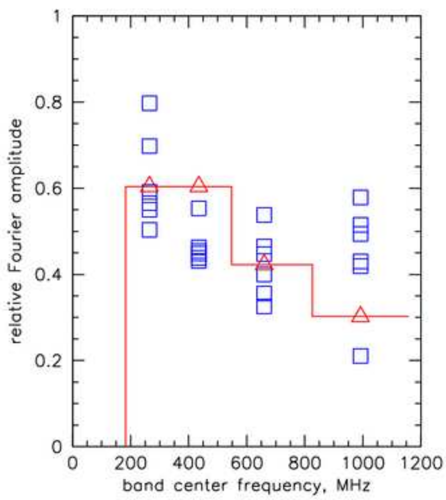

Fig. 6. Power Spectra of the 6 H-pol events (square dots) and geosynchrotron signal from EAS (line)

The simulation predicts a total of 4.5 ± 0.4(statistical) detected events for ANITA's cumulative instrument live time. The systematic error on this result is of order 100%

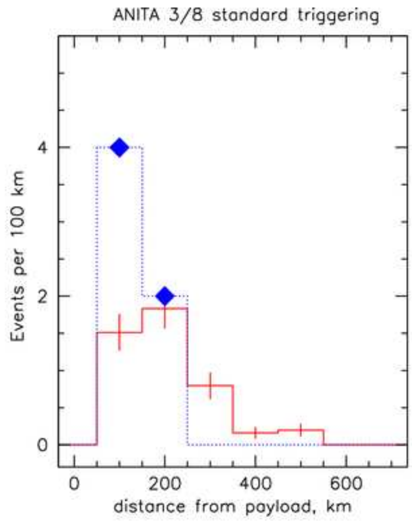

Fig. 7. Distribution of RF propagation distances from reflection points to ANITA. Dotted histogram marked with diamond dot is for the 6 H-pol events, solid histogram is MC prediction.

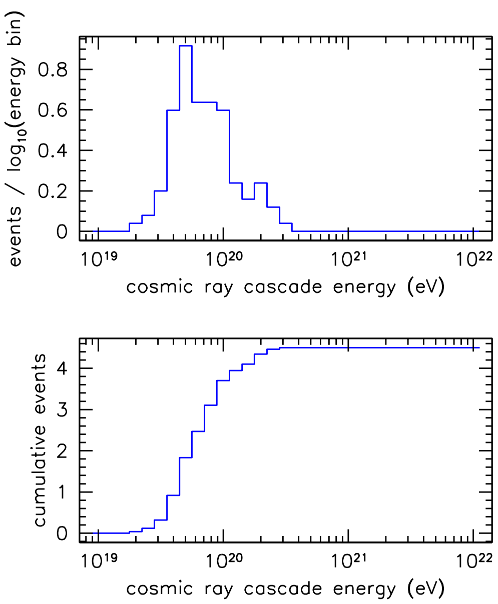

Fig. 8. Energy distribution of detected MC events. Top is differential distribution, bottom is cumulative distribution.

due to the high degree of uncertainty on the simulation of partially coherent signals from EAS in the ANITA band. Figure 6 shows power spectra of the 6 events with the expected spectrum from MC superimposed. The spectra of the 6 candidates are generally flat showing good agreement with the MC prediction.

Distributions of RF propagation distances (R_{RF}) from ANITA to the reflection points are shown in Fig.7. Here, the R_{RF} for the data is the distance from ANITA to the projected RF source position of the reconstructed plane wave. R_{RF} distributions from data and MC are reasonably consistent, although they are statistically limited.

Figure 8 shows the energy distribution of detected MC events. While the overall normalization is subject to a large systematic uncertainty, the relative fluxes are less sensitive to it. The low energy turn-on at about $4 \times 10^{19} eV$ is due to the energy threshold of the ANITA system, and the high energy edges are shaped by the GZK cutoff.

V. SUMMARY

During the successful ANITA-I flight, 6 horizontally polarized impulsive signals were detected. They can possibly be interpreted as geosynchrotron emissions from UHECR EAS. Detailed simulation studies show ANITA's sensitivity is adequate to detect these signals. Observable event characteristics such as number of events, power spectra, and RF propagation distances from reflection points to the instrument show distributions consistent with the simulated expectations, supporting the hypothesis.

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