

Observation of radio emissions from electron beams using an ice target

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Abstract. To observe high energy cosmogenic neutrinos above 50 PeV, the large neutrino telescope ARA is being built at the South Pole. The ARA telescope detects neutrinos by observing radio signals by the Askaryan effect. We performed an experiment using 40 MeV electron beams of the Telescope Array Electron Light Source to verify the understanding of the Askaryan emission as well as the detector responses used in the ARA experiment. Clear coherent polarized radio signals were observed with and without an ice target. We found that the observed radio signals are consistent with simulation, showing that our understanding of the radio emissions and the detector responses are within the systematic uncertainties of the ARAcATa experiment which is at the level of 30%.

1 Introduction

The Askaryan Radio Array (ARA) telescope [1] is being built at the South Pole aiming for observing high energy cosmogenic neutrinos above 50 PeV. The ARA detector identifies the amplified radio emissions from the excess charge in a particle shower induced by a neutrino interaction. Such a radio emission was first predicted by Askaryan in 1962 [2] and experimentally confirmed by Saltzberg et al. using the SLAC accelerator in 2001 [3]. To verify the understanding of the Askaryan emission and the detector responses used in the ARA experiment, we also performed a similar experiment using 40 MeV electron beams.

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2 The ARAcITA experiment

The Telescope Array (TA) experiment is the largest ultra-high energy cosmic-ray detector in the northern hemisphere. To calibrate their fluorescence telescopes, they have a linear accelerator which accelerates electrons up to 40 MeV. Typical electron number per bunch train is 2×10^8 . The total track length corresponds to a 30 PeV EM shower, though the shower length is limited to 20 cm in this experiment because 40 MeV electrons easily lose the energy by ionizing losses. We optimized the bunch train width to 1.5 ns, changing the value from the TA default of $1\mu\text{s}$, to extend the coherent signals up to a high frequency of several hundred MHz where the ARA antenna has a sensitivity (150-850 MHz). We also employed a wall current monitor (WCM) which allows us to estimate the number of electrons in a beam with an uncertainty of 3.3%.

The beams are shot upward to mimic air showers. We deployed an ice block with a size of $1\text{ m} \times 0.3\text{ m} \times 0.3\text{ m}$ on the way to stop the electron beams, and observed radio signals from the beams. We used two ARA birdcage antennas to measure the polarization of the radio signals. The signals were amplified by an amplifier, filtered by a band-pass filter to select 230-430 MHz to cut ambient radio noises and measured by a fast 20 GHz sampling oscilloscope. We deployed an antenna tower to change the antenna height up to 12 m to measure the angular dependence of the radio signals. To cover a wider angles, we also changed the inclination angle of the ice block utilizing a refraction of the radio signals at the top surface of the ice block. We measured the coherence of the signals using the electron number measured by WCM. We characterized observed radio signals by those measured information.

3 Simulation

To understand the observed signals, we developed a detailed simulation. We employed the Geant4 [4] simulation for the electron beam tracking in air and ice. E-fields from beams are calculated with Liénard-Wiechert potentials based on the classical electro-magnetic theory. We employed two methods: one is the ZHS method [5] and the other is the endpoints method [6]. We thank Anne Zilles for her kindness to share her codes for the implementation. We confirmed both methods give the same E-fields. It turned out that the ray tracing of the radio signals is very important to reproduce the observed signals because there are multiple paths allowed to reach to the antenna due to refractions and reflections at the ice surface. The detector response of the ARA antenna as well as an amplifier and a band-pass filter used for this experiment is applied to obtain waveforms. We analyzed the simulated data in the same way as we performed for observed data.

4 Results

Clear coherent polarized radio signals were observed even without the ice block when beams exited from the accelerator container. Three other radio experiments performed at the TA site also observed the sudden appearance signals at different frequency ranges, covering from 50 MHz to 12.5 GHz. We compared the observed energy spectrum densities with simulation, and found good agreements for all the experiments. The angular dependence of the sudden appearance signals is also consistent with the simulation as shown in Fig. (1), showing the angular response of the ARA antenna is confirmed within the uncertainty of this experiment of $\sim 30\%$.

Clear coherent polarized radio signals were also observed with an ice block. The observed radio energies depending on the observation elevation angles are shown in Fig. (1) for each ice inclination angle. The observed radio signals with the ice block is higher than that without the ice, agreeing

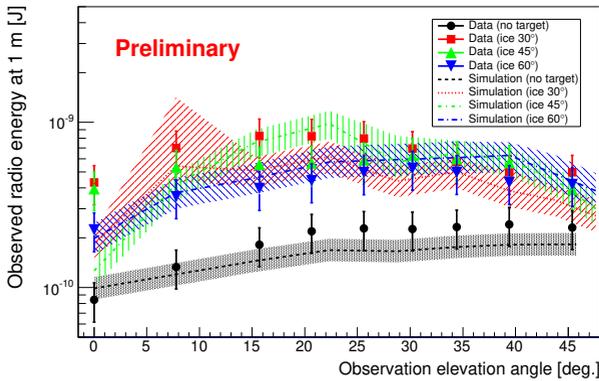


Figure 1. Observed radio energy scaled to 1 m distance assuming quadratic distance dependence, depending on the observation elevation angle corresponding to each antenna height. Data were taken with several configurations without the ice target (circle), and with the ice target (square: 30°, triangle: 45°, inverted triangle: 60°). The lines represent the simulation for each configuration, showing the 1 σ uncertainty with the shade.

with the simulation with ice block. We identified three contributions in simulation. One is the sudden appearance signals when beams appear as described above, another is the transition radiation emitted at the boundary at the bottom of the ice block and the other one is the Askaryan like signals emitted inside ice. The detail study to quantify each contribution is in progress.

The statistical uncertainty is relatively as high as 8% because we observed signals with many different conditions with different ice inclination angles with different antenna heights, therefore, the statistics for each condition is limited. The largest systematic uncertainty for data is the stability of the antenna position because the distance between the beam and the antenna was changing due to relatively strong winds at the site. The uncertainty for the radio energy is estimated as $\pm 19\%$. The largest systematic uncertainty for the simulation comes from the uncertainty of the beam bunch shape measured by our oscilloscope. The uncertainty due to the bunch shape was estimated as -17% and $+20\%$.

5 Summary

We performed an experiment using 40 MeV electron beams at the TA site to verify the understanding of radio signals in ice as well as the ARA antenna. Clearly polarized coherent radio signals were observed with and without an ice target. We also developed a detailed simulation which takes reflections and refractions at the ice boundaries into account. Observed signals are consistent with the simulation within the uncertainty of 30% for both cases with and without the ice target, verifying our understanding of the radio emissions and the ARA antenna within the uncertainty.

References

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