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AURA—A radio frequency extension to IceCube

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ABSTRACT

The excellent radio frequency (RF) transparency of cold polar ice, combined with the coherent Cherenkov emission produced by neutrino-induced showers when viewed at wavelengths longer than a few centimeters, has spurred considerable interest in a large-scale radio-wave neutrino detector array. The AURA (Askaryan Under-ice Radio Array) experimental effort, within the IceCube collaboration, seeks to take advantage of the opportunity presented by IceCube [A. Karle, Nucl. Instr. and Meth. A (2009), this issue, doi:10.1016/j.nima.2009.03.180. [1]; A. Achtenberg et al., The IceCube Collaboration, Astropart. Phys. 26 (2006) 155 [2]] drilling through 2010 to establish the RF technology needed to achieve 100–1000 km^3 effective volumes. In the 2006–2007 Austral summer, three deep in-ice RF clusters were deployed at depths of $\sim$1300 and $\sim$300 m on top of the IceCube strings. Additional three clusters will be deployed in the Austral summer of 2008–2009. Verification and calibration results from the current deployed clusters are presented, and the detector design and performances are discussed. Augmentation of IceCube with large-scale (1000 km^3 sr) radio and acoustic arrays would extend the physics reach of IceCube into the EeV–ZeV regime and offer substantial technological redundancy.

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1. Introduction

Astrophysical high energy neutrinos might carry valuable information about their sources, possibly point sources like GRBs, AGNs, or SGRs, or high energy cosmic rays (through the GZK process). They might also offer the chance to investigate particle physics in an energy range unreachable by Earthbound accelerators.

Recent measurements from cosmic ray detectors indicate a change in the CR spectrum as predicted by the GZK process [3]. The expected flux for GZK neutrinos is so low that IceCube is expected to measure no more than a few events a year [4] and the suggested heavier composition of the cosmic rays will further lower this flux. Measuring GZK neutrinos will help to explain the generation mechanism of the CRs, their flux and composition.

Current neutrino detectors like IceCube, AMANDA, and Antares incorporate hundreds of photo-multiplier tubes, sensitive to photons in the optical wavelength range. They are designed to detect neutrinos with energies between 10^2–10^{10} GeV. In order to survey the extreme high energy (EHE) regime of above 10^{10} GeV, larger detectors will be needed.

In 1963, Askaryan [5] suggested that cascades generated by high energy charged particles moving through a dielectric at relativistic speeds, build up an excess of negative charge, giving rise to strong coherent radio and microwave Cherenkov emission. Coherence obtains when the wavelength of the emitted radiation is longer than the transverse dimensions of the cascade. It is expected that neutrinos with energy of $\sim 10^{18}$ eV or more will produce cascades with transverse dimensions of order $\sim$0.1 m, thus emitting coherent radio frequency (RF) radiation. This effect was demonstrated in an accelerator measurement where coherent linearly polarized RF radiation was measured from the interaction of a beam dumped into RF transparent matter (sand, salt and ice) [6].

As the limits on possible fluxes of extraterrestrial neutrinos measured by current experiments become more stringent, it becomes evident that even larger detectors are needed for gathering enough statistics on human time scales.

The cost of hardware, deployment and drilling in the ice limit the size of IceCube and alternatives to optical detection are needed to cover larger volumes. The simpler installation of radio detectors, the long attenuation length of RF in shallow ice and the sensitivity to EHE events, together with lower cost as compared to optical detectors, makes the RF region interesting for EHE neutrino detection.

The concept of a GZK RF detector, deployed at shallow depths or as a surface array had been suggested more than 20 years ago

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[7]. Several experiments are already using the Askaryan effect for neutrino detection in Antarctica: the RICE [8] array was deployed with the AMANDA neutrino telescope near the South Pole at depths of 100–300 m. The array consists of 20 dipole antennas covering a volume of $200 \times 200 \times 200\,m^3$, and is sensitive between 200 and 500 MHz. RICE not only established the feasibility of a radio array and measured the RF properties of South Pole ice, but also published limits on neutrino fluxes between 10^{16} and 10^{18} eV and on exotic models. The ANITA [9] experiment, balloon borne at 40 km, observes the Antarctic ice searching for RF emission. The high altitude allows ANITA to cover a large volume (1.5 million km^3), but the short flight time limits its exposure. Askaryan Under-ice Radio Array (AURA) builds on the experience of the RICE experiment with its electronic design based on the RF specific electronic applications developed by ANITA [10]. We use the communication and time calibration systems developed for IceCube and rely on the experience within the IceCube collaboration to develop hardware and procedures for building and deploying highly sensitive equipment in the extreme environment of the South Pole.

2. South Pole ice

The RF ice properties determine the feasibility and design of a future GZK detector. Specifically the attenuation length will influence the spacing between channels, and the index of refraction will determine the reconstruction capabilities and simulation quality. The latest index of refraction measurement is reported in Ref. [12] using the RICE array down to 150 m and ice cores down to 240 m. The index of refraction changes rapidly in the soft ice layers on top of the glacier (firn) and decreases the angular acceptance of shallow deployed detectors by causing total reflection of rays propagating between the layers. This is illustrated in Fig. 1.

On the other hand, the attenuation of RF decreases with temperature, making colder ice more RF transparent. Thus shallow deployment in colder ice, is more favorable for RF detection. This measurement is summarized in Ref. [13] where a surface transmitter was used to send signals down into the ice. A receiver recorded the signals after bouncing back from the bedrock. This measurement was performed at frequencies of 200–700 MHz and provided an average RF attenuation for the round-trip down and back. The attenuation as a function of depth is then calculated using temperature models. The IceCube detector provides an accurate temperature measurement down to 2.5 km. The average attenuation length is 1.5 km, with longer lengths for lower frequencies, and for shallower (colder) ice.

In the coming season, using a powerful in-ice transmitter unit we will try to perform point-to-point direct measurement of attenuation length.

3. The detector design

3.1. AURA I: 2006–2007 design

Each AURA unit, called a "cluster", consists of four receiver antennas, equally spaced along 40 m, a transmitting antenna for calibration and a sphere containing the electronics, called a DRM—Digital Radio Module. Six cables are connected to the DRM: one for power and communication going to the surface and to a computer handling data acquisition and control; an additional cable holds the Array Calibration Unit (ACU); and four cables connected to receiver antennas. A schematic of the AURA cluster is shown in Fig. 2. A set of front-end electronics, including a chain of amplifiers and filters is mounted before each of the four receivers, between the antennas and the DRM.

The DRM, within a 36 cm diameter glass sphere, contains the triggering, digitization and communication electronics as well as a

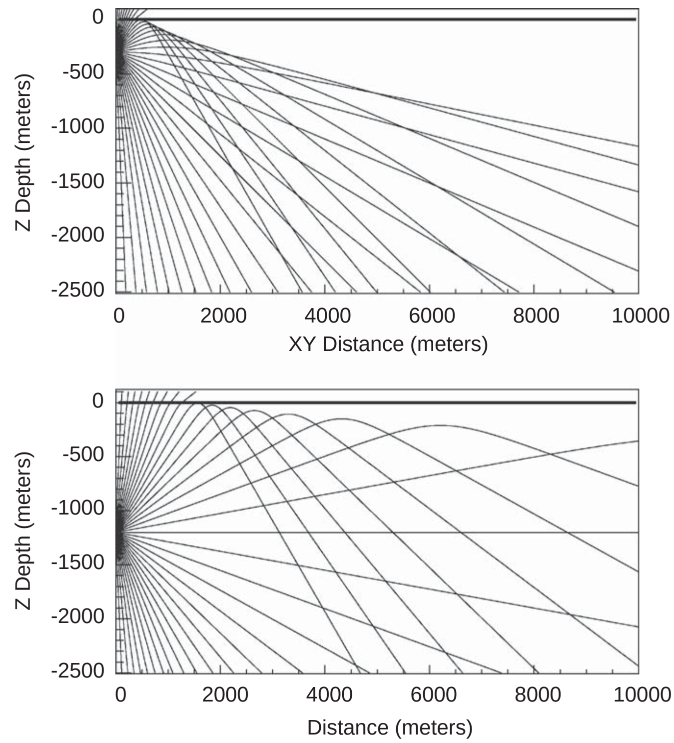

Fig. 1. Ray trace modeled for detectors deployed at −300 m (top) and −1200 m (bottom). Only waves propagating at certain angles will emerge to the surface.

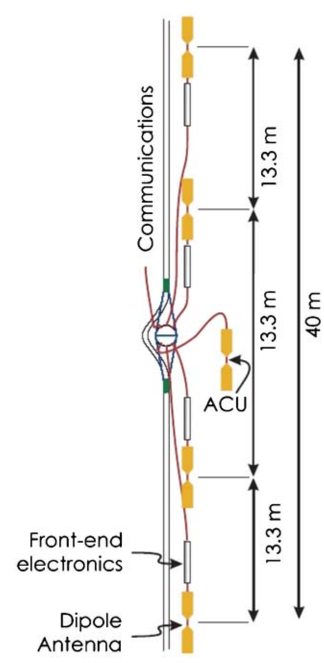

Fig. 2. The radio cluster, made of a DRM (Digital Radio Module), and five antennas (four receivers and a transmitter).