AURA: The Askaryan Underice Radio Array

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Abstract. The abundant cold ice covering the Antarctic provides a tantalizing medium for Askaryan signatures of ultra high energy (UHE) neutrinos due to it's excellent rf transparency. RICE, a first generation radio array buried between 100 and 300 m near the geographic South Pole, took advantage of this natural resource and made great advances toward the realization of a GZK scale neutrino detector, establishing techniques for radio detection, and studying the properties of South Pole ice. However, an array large enough to be sensitive to the low flux of neutrinos at UHE would have to overcome the technical challenges associated with designing and operating a sparse array in a hostile environment, including power distribution, time calibration, triggering and readout over a scale of kilometers in temperatures of -50°C. Two other astrophysical neutrino experiments, ANITA and IceCube, have developed technologies and infrastructure that could be applied to making a large scale, englacial array a reality on a short time scale. In the coming austral summer, the AURA collaboration will begin deploying prototype antenna clusters parasitically on IceCube strings, using technologies adapted from ANITA and IceCube, as well as RICE, in order to establish the feasibility of a 100 square kilometer scale array.

1. Introduction
The demonstrated rf transparency of cold ice [1] makes it an excellent medium for the detection of ultra high energy neutrinos via the Askaryan effect, and nowhere is cold, mechanically stable ice more abundant than Antarctica. Several current and proposed experiments exploit this natural resource in the search for astrophysical neutrinos. Perhaps the most ambitious to date is ANITA [2], a balloon borne experiment which, for a few weeks in the austral summer of 06-07, will survey the entire continent for radio frequency emissions emanating from horizontal neutrino induced showers that are refracted at the surface of the ice. From its vantage point, ANITA will have a clear line of sight over a vast 1.5 million square kilometers of the Antarctic ice cap, however, the length of the observation time is limited to the duration of the balloon flight. There is therefore a clear motivation for the development of a more permanent antenna array to monitor the ice for signals of GZK neutrinos.

One such array has been built by the RICE Collaboration [3] and installed permanently within a 200m x 200m x 200m cube at depths from 100-300m in the Antarctic ice cap near the geographic South Pole, where the ice is in excess of 2.5 kilometers thick. Although the small flux at ultra high energies convoluted with the small neutrino cross section make it unlikely that a small array such as RICE will ever detect a high energy neutrino, it has been invaluable in establishing the feasibility of a radio array as well as the rf properties of South Pole ice. Ultimately one would require an array covering an area of about 100 square kilometers to study GZK energy neutrinos. The challenges associated with building, synchronizing, triggering and reading out an array over such a vast area are
formidable, and the technology used to build RICE would be too costly and impractical to scale up to such a large array. However, many of these challenges have been addressed by the IceCube Collaboration [4], which is presently installing a kilometer cubed optical Cerenkov array in the deep ice near the South Pole. By combining the rf specific electronics developed by ANITA and RICE, with the infrastructure and instrumentation developed for the building and operation of large scale englacial arrays developed by IceCube, the realization of a technologically feasible design for a large scale radio array may be achieved at low cost, in a relatively short time.

A new collaboration, AURA, has been formed by collaborators from IceCube, RICE, and ANITA to develop and test the technology needed to construct a large scale englacial radio array. Many of the innovations developed for those projects are being implemented in the AURA array. It is hoped that the AURA array will begin deployment of prototype antenna clusters in the austral summer of 06-07, using much of IceCube’s infrastructure.

2. From RICE to AURA

The RICE array is based on a simple, low cost design, using commercially available technologies when available. It is comprised of 20 single dipole receivers as well as several under ice transmitters that broadcast short duration pulses for calibration and verification of vertex reconstruction capabilities. Signals are boosted at the antenna by 36 dB and routed to the surface by high quality coaxial cable, where it is filtered and reamplified with an additional 52-60 dB gain. The signal is then split, with one copy fed to a CAMAC crate for triggering, and the other sent to a digital oscilloscope for readout. Hardware and software algorithms reject anthropogenic noise. A full event readout incurs about 10s of deadtime, and the trigger threshold is set to allow approximately 90% livetime. A number of modifications to RICE’s design will be required to maximally exploit the physics potential of any future large scale array.

First, high quality coaxial cable is too expensive to run over a distance of kilometers and the signal degradation too severe. Tests during the austral summer of 05-06 on the mechanical resilience of optical fiber under the high pressures experienced during freeze-in were not encouraging. Second, the high cost of digital oscilloscopes makes them impractical for a large, multi channel array. The only practical solution is to develop an application specific chip to digitize the signal in the ice. Due to the harsh conditions and the high cost of transporting fuel to the Pole, the chip must be operable at low temperatures, and must consume very little power. These requirements are similar to those of the ANITA experiment, and a digitizer chip, the LABRADOR, has been developed for their purposes. The LABRADOR can sample at speeds of up to 3.5 GHz with little deadtime and can read out eight channels with a power consumption that is less than 0.05 W per channel.

The challenges of accurately time stamping and triggering many channels over a large area is also formidable. IceCube has developed an ingenious method of synchronizing the on board clocks in each of its optical modules. A CPU on the surface generates a waveform that is sent over the connecting cable to each of the optical modules. The optical modules each contain an exact hardware copy of the circuit that generated the waveform, and after a preset delay, an identical waveform is generated and sent back over the cable to the initiating CPU. By comparing the peaks of the two waveforms, the effect of signal distortion over the cable can be eliminated and the exact length of the roundtrip can be computed, thereby calibrating the respective clocks with nanosecond precision. This process is called RAPCAL (reciprocal active pulsing). In addition, onboard field programmable gate arrays (FPGAs) allow local trigger conditions to be changed remotely via firmware.

Realistically, in order to have a chance of observing GZK neutrinos, every effort must be made to discriminate noise from signal. ANITA exploits the broadband frequency profile characteristic of Askaryan pulses to reject background by dividing signals into several frequency bands and requiring hits in multiple bands. In addition, installing antennas together in clusters separated by a large enough vertical distance to give a discernable difference in the hit time profiles of surface generated noise versus signals originating in ice could be a powerful discriminator.
3. AURA first generation clusters

Figure 1: Components of an AURA cluster. The left shows an antenna immediately followed by a pressure vessel containing front end electronics for filtering and amplification. On the right is a digital radio module for power distribution, triggering, timing and digitization. One digital radio module will control four receivers and one transmitter.

In order to expedite the development, the first generation of AURA clusters has been designed by retrofitting IceCube’s digital optical modules (DOMs) for radio. IceCube’s DOMs consist of a 10” phototube and printed circuit boards enclosed in a glass pressure sphere. A single quad cable provides the interface between the module and IceCube’s main cable. By reusing the same form factor, the digital radio modules (DRM) that control AURA’s clusters may be installed parasitically on IceCube cables suing the same mechanical mounts and quad cable for communication.

In the digital radio module, pictured in Figure 1, the phototube has been removed, and five additional holes have been drilled in the pressure sphere for coaxial cables that connect the antennas-four receivers and one transmitter per cluster. The DOM motherboard has been kept to provide time stamping using the RAPCAL technique, but the power distribution has been moved off the DOM motherboard onto the PIFL board so that it may be shielded from noise sensitive components of the electronics by an aluminum plate. The antenna signals are received and digitized on the ROBUST board, which has been developed specifically for radio and employs ANITA’s LABRADOR chip for digitization. Copies of the signal are simultaneously sent to the SHORT board, another implementation from ANITA, which filters the signal into separate frequency bands for triggering. The TRACR board controls the triggering and communications. Further details of the triggering and electronics contained within the DRM can be found in [6].

Each receiver assembly (Figure 1) contains an antenna immediately followed by a pressure vessel containing front end electronics for filtering and amplification. The simple RICE-style dipole antennas have been reused, since the high cost of fuel may make it cost prohibitive to drill holes large enough to accommodate horn antennas in a large englacial array, and ultimately, all hardware developed by
AURA should be adaptable to such an array. The signal from the dipole is put through a filter chain to avoid saturating the amplifiers downstream. The frequency band from 200MHz-1GHz is kept, and a surgical notch filter removes an emergency communications band at 450-452 MHz. To provide noise rejection using up-down discrimination, the antennas are mounted at vertically on the IceCube cable at intervals of 13m as shown in Figure 2 (left). A low noise amplifier followed by a single stage amplifier boost the signal as much as 80 dB to counter attenuation en route to the DRM.

![Figure 2: Deployment configurations of the digital radio module. Antennas are connected to the digital radio module with coaxial cables (left). Deep deployments (middle) make use of an extra connector to the IceCube cable for power and communication. Shallower deployments will require a dedicated cable (right).](image)

Although it is convenient to employ unused connectors on IceCube cables for the DRM, the shallowest of these connectors is located 1500m beneath the surface of the ice. It is desirable to leave the option of a shallower deployment open for several reasons. First, it would be informative to install at least one cluster near the existing RICE antennas, which are deployed between 100 and 300 meters depth. Second, colder ice has been found to be more rf transparent, and a larger effective volume may be achieved through shallow deployments.

Tests performed during IceCube’s 05-06 drilling season demonstrated that a separate cable may be strapped to the IceCube main cable as it is being lowered into the hole with minimal impact on IceCube’s deployment. A schematic illustration of a shallow deployment is shown in Figure 2 (right). Both the shallow and deep deployment options will be available during the 06-07 austral season, and installations are planned for each of the two depths.

4. Outlook
The development of antenna clusters for deployment during the 06-07 austral season has progressed at a frenetic pace using a combination of recycled and application specific components, and prospects are good for getting the first clusters in the ice. For the following austral summer, many modifications are foreseen based on the experience in the first season. Also, some of the retrofitted components will be
phased out in favor of components more easily adaptable for a GZK scale detector. For example, if the form factor of the electronics boards could be modified to fit in a smaller pressure vessel, it could greatly reduce the cost of drilling dedicated holes for a large array. In addition to the four clusters being built for deployment the first year, an additional eight next generation clusters are planned for the following year. Our hope is that by the time IceCube’s construction is complete, we will have working prototypes on which to base the proposal of a larger array.

![Comparison of the effective volume of RICE (solid) and the four AURA clusters planned for the first year's deployment (dashed) and a total of 8 planned AURA clusters (dotted).](image)

**Figure 3:** Comparison of the effective volume of RICE (solid) and the four AURA clusters planned for the first year's deployment (dashed) and a total of 8 planned AURA clusters (dotted).

In the meantime, AURA will occupy a unique niche in the study of the rf properties of South Pole ice, as well as a number of high energy phenomena. RICE currently holds the most stringent published limits on neutrinos from $10^{16}$ to $10^{18}$ GeV, as well as limits on magnetic monopoles, low scale gravity, and other exotica. AURA will achieve a significantly improved effective volume over RICE as shown in Figure 3, with greater livetime and improved noise discrimination. In conclusion, AURA will not only provide a platform for instrumentation development, but a prolific source of physics results as well.

**References**

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