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Radio Detection of GZK Neutrinos - AURA status and plans

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Abstract: The excellent radiofrequency 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 an ultimate, large-scale radiowave neutrino detector array. A statistically compelling GZK signal will require at least an order of magnitude improvement in the product of (livetime)x(Effective volume) over existing (RICE, ANITA, e.g.) neutrino detection experiments. Correspondingly, the AURA (Askaryan Underice Radio Array) experimental effort seeks to take advantage of the opportunity presented by IceCube drilling through 2010 to establish the radiofrequency technology needed to achieve $100 - 1000km^3$ effective volumes. We discuss three test strings co-deployed with IceCube in 2006-07 which combine fast in-ice digitization with an efficient, multi-tiered trigger scheme. Ultimately, augmentation of IceCube with large-scale $(1000km^3 sr)$ radio and acoustic arrays would extend the physics reach of IceCube into the EeV-ZeV regime and offer substantial technological redundancy.

Introduction and Detection Principle

The Astrophysical high energy neutrinos hold valuable information about their sources, either a point source like GRBs, AGNs, and SGRs, or high energy cosmic rays (through the GZK process). Consequently they can also teach us EHE particle physics in energies unreachable by earthbound accelerators.

As the energy of the neutrino increases the atmospheric neutrino background flux decreases and the interaction cross section of the neutrino increases, which favors the detection of HE neutrinos over low energy ones. On the other hand, the estimated fluxes of those high energy neutrinos exhibit an overall decrease with energy. The combination of a small flux, low neutrino interaction cross section, and limited life span of humans require the construction of large scale detectors to improve the detection probability.

The km^3 scale detectors like IceCube, AMANDA, NEMO and Antares are (will be) made of thousands of photo-multiplier tubes, sensitive to optical photons. They are sensitive to neutrinos with energies between $10^2GeV - 10^{10}GeV$. In order to survey the extreme high energy regime of more than $10^{10}GeV$, larger detectors are needed.

In 1968, G.A.Askaryan [1] suggested that cascades generated by high energy charged leptons moving through matter, produce an excess of negative charge moving at relativistic speed, thus emitting Cherenkov radiation. For radiation with shorter wavelength, like optical photons, the phase is random and the electric field is proportional to the square root of the net negative charge developed in the cascade. But for photons with wavelengths longer than the transverse dimensions of the cascade, like RF photons, the radiation is coherent and the electric field is proportional to the negative charge in the cascade. It is expected that neutrinos with energy of$\sim 10^{18}eV$ or more will produce cascades with transverse dimensions of order ~ 0.1 meters, thus emitting coherent RF radiation. Radio-frequency neutrino detectors are therefore more sensitive to such high energy events than optical detectors .

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)[2]. The simpler installation of radio detectors, the long attenuation length of RF in ice and the sensitivity to EHE events makes the RF region a useful probe for EHE neutrino detection.

Several experiments are already using the Askaryan effect for neutrino detection in Antarctica: The RICE 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 to 500 MHz. RICE established limits on high energy neutrino fluxes as well as investigated the radio-glacial properties of the deep ice [3]. The ANITA experiment, air borne at 40km, observed the Antarctic ice searching for RF emission. The high altitude makes the volume that ANITA covers large (1.5 million km^3), but the short flight time and the refraction of RF photons in the transition from ice to air limits the exposure time and the angular coverage of this experiment [4].

Detector design and 2006/2007 Deployment

In the austral summer of 2006-2007, three Radio Clusters were co-deployed with the IceCube optical array as part of the AURA (Askaryan Under-ice Radio Array) experimental effort. Each cluster consists of up to four broadband dipole antennas, centered at 400MHz, and four metal tubes holding the front-end electronics including filters and amplifiers supporting these antennas: specifically, a 450 MHz notch filter to reject constant noise from the South Pole communication channel, a 200 MHz high pass filter and a $\sim 45dB$ amplifier. An additional $\sim 20dB$ amplification is done at later stage, for a total of $\sim 65dB$ amplification. An additional antenna is used as a transmitter for calibration.

The DRM (Digital Radio Module) within a 13 inch diameter glass sphere contains the triggering, digitization and communication electronics as well as a power converter. It holds the TRACR board(Trigger Reduction And Communication for RICE) that controls the calibration signal and the high triggering level, the SHORT board (SURF High Occupancy RF Trigger) that provides frequency banding of the trigger source, the ROBUST card (Read Out Board UHF Sampling and Trigger) that provides band trigger development, high speed digitization and second level trigger discrimination, the LABRADOR (Large Analog Bandwidth Recorder And Digitizer with Ordered Readout)[5] digitization chip, and a Motherboard that controls the power, communication and timing.

A 260-capacitor Switched Capacitor Array (SCA) continuously observes the input RF channels (two channels per antenna) and an additional timing channel. To reduce power consumption and dead times, the information is held and digitized only when a trigger is received. The sampling speed is two Giga-Samples Per Second, with a 256 ns buffer depth. A 300 MHz on-board Advanced Transient Waveform Digitizer is used for precise trigger timing. A Wilkinson type ADC converts the measured voltage into a count value with a 12-bit dynamic range.

Six cables are connected to the DRM. One for power and communication with the surface and five for the transmitter and receiver antennas. The spacing between the antennas is 13.3 meters, and the total length of the cluster is 40 meters. The AURA cluster is shown in figure 1.

The fast and broadband nature of the Askaryan RF signal is exploited for background reduction. Once the voltage measured on an antenna crosses an adjustable threshold, the digitization is triggered and the signal is split into four frequency bands (200-400 MHz, 400-650 MHz, 650-880 MHz and 880-1200 MHz). If enough frequency bands are present in the signal, the channel associated with this antenna will trigger. In the current settings, at least two out of four bands are needed for triggering to happen. The cluster will trigger if enough channels trigger (current setting requires at least three out of four antennas).

The digitized data is sent to the surface using the IceCube in-ice and surface cables.

IceCube on-going construction activity made it possible to deploy clusters down to 1400 meters deep, a depth that is usually less favored by RF de-

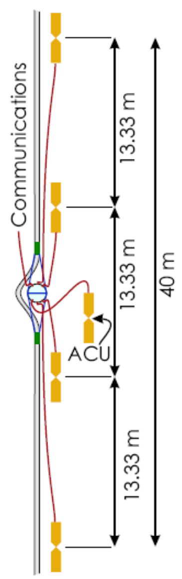

Figure 1: The radio cluster, made of a DRM (Digital Radio Module), and 5 antennas (4 receivers and a transmitter).

tectors due to warmer ice and high drilling cost. The clusters were deployed on the top of IceCube strings, at depths of 1400 or 400 meters.

Table 1 summarizes the depth and location of the three units. Out of the 8 receivers deployed, 7 receivers are operational. One channel was tested fine before deployment, and most likely damaged during the freeze-in of the water surrounding the cluster after deployment. The data being taken consists of ambient and transient background studies, calibration runs using the AURA transmitter and the in-ice RICE transmitters.

The proximity of the South Pole station and especially the IceCube and AMANDA detectors may cause significant RF noise in the AURA sensitive band of $200-1200$ MHz. This noise pattern is being carefully studied and the amplified background noise frequency has a clear enhancement between $200-400$ MHz, with an amplitude of about $50mV$ corresponding to 7 ADC bits depth. The noise spectrum and intensity depends on the location of the antenna relative to the DRM and the type of front-end amplifier used. Background studies were also performed with the IceCube and AMANDA detectors turned off. Figure 2 shows sample waveforms taken for background studies with and without the transmitter antenna on for a single antenna.

2008 Deployment and beyond

The concept of a GZK radio frequency detector, deployed in shallow depths or in a surface array had been suggested more than 20 years ago [6]. A future large scale GZK $100km^2$ scale detector will be a hybrid of different Cherenkov radiation detection techniques, allowing composite trigger and coincidence and can be built around IceCube. The long attenuation length of the ice (hundreds of meters), makes the South Pole ice a natural choice for deploying a RF detector.

In the next season (2007-2008) we plan to continue our efforts to design and build a shallow GZK neutrino detector. We will continue to use the IceCube deep holes and existing deployment and DAQ infrastructure for deploying additional clusters. We will investigate different depths ($1400, 200, < 100$ meter and surface) and study the noise in lower frequencies (< 200MHz) since the acceptance is expected to increase with wavelength, albeit at the expense of timing resolution.

A cluster will also be deployed $\sim 1km$ away from the IceCube array to study the ice and environment away from the IceCube array, and investigate possible solutions to communication and power distribution challenges that a large scale array presents. A surface array of radio detectors is relatively easy to deploy, but the refractive index difference between the ice, firn (soft ice layers on top of the glacier) and air decreases the angular acceptance of a surface detector due to total reflection of rays propagating between the layers. On the other hand, deeper deployments in depths of tens to hundreds of meters increases the technical difficulties and cost of such an array.

The design of the cluster will be similar to last year's clusters with possible minor changes to the antennas and electronics. By deploying at different depths and locations the RF properties of the ice, the suitability of ice for such of detector and studies of different cluster designs will be checked,

Cluster	num. Transmitters	num. Receivers	Location (x,y,z) in m	Front end amplifier brand
1	1	4	$(50, 500, -1400)$	Miteq
2	1	4	$(220, 210, -250)$	LNA-SSA
3	1	0	$(195, 120, -1400)$	None

Table 1: Locations of the deployed clusters. Coordinates are relative to IceCube center array at surface.

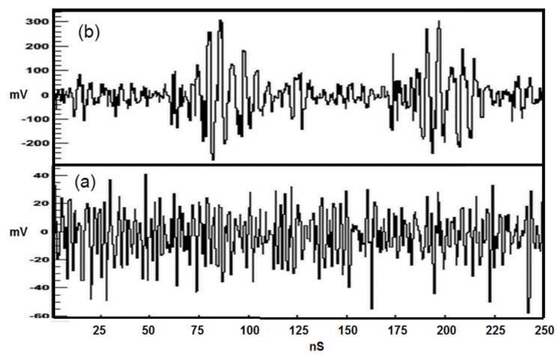

Figure 2: Wave form signals for a single antenna for background and calibration runs. (a) Background only (b) In ice transmitter pulse.

while building a sub-GZK detector that will be able to detect HE events, reconstruct vertices, and look for events coincident with IceCube.

Once completed, IceCube is expected to measure about 1 GZK event per year. A sucessful GZK detector deployed on surface or in shallow depth will have to measure at least $\sim 10GZK$ events a year. A hybrid of the RF array and IceCube will give sub-samples of coincidences events with cross-calibration capabilities and unique signal signatures.

Summary

Three radio clusters were deployed at the South Pole as an extension to the IceCube array. In the next year, we plan to deploy additional clusters to have a sufficient 3D array for vertices reconstruction, make radio-glaciological measurement at different depths and distances from the IceCube array, and check the suitability of the IceCube environment for RF detection. These are the first steps toward building a $100km^2$ GZK detector built around IceCube. Such a detector will be a powerful tool in investigating the EHE neutrino world.

Acknowledgements

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