Phase-II: Towards an IceCube-centered Radio-Cherenkov Cosmogenic Neutrino Detector

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I. SUMMARY OF SCIENCE GOALS

We propose a study towards the phased development of a radio-Cherenkov telescope addition to the IceCube detector which will pursue the following scientific goals:

1. Extend IceCube energy sensitivity to ExaVolt energies, to yield substantial rates of cosmogenic neutrinos–the so-called GZK or "guaranteed" neutrinos.
2. Determine the energy and source directions for each neutrino to degree-scale precision, to identifying directly the sources of the highest energy cosmic rays, which produce the cosmogenic ultra-high energy neutrinos.
3. In some cases to co-detect hybrid events with the main IceCube detector, yielding both primary vertex energy via radio-Cherenkov and secondary lepton energy via optical techniques, for complete event calorimetry on a subset of the total neutrino events.

Any proposed system should have the potential to significantly enhance the scientific reach of IceCube with regard to total ultra-high energy neutrino event calorimetry, an important and compelling scientific challenge. As we will argue here, a wide-scale radio-Cherenkov [1] detector is a natural and highly complementary addition to IceCube. To assure an adequate discovery potential, such a detector system would eventually have to reach instrumented areas of 300-1000 km^2, with an intermediate detector in the 50-100 km^2 region being the intermediate step. As will be noted this would represent the 3nd and 4th phases of the detector development. Recent improvements in the understanding of the radio Cherenkov method [2–5], and its advancing technological maturity have greatly reduced both the risk of such systems and their costs. This fact, and the near pristine electromagnetic noise environment offered by the South Pole are the main drivers behind this proposal.

II. SCIENTIFIC MOTIVATION

The typical charged-current neutrino-nucleon deep-inelastic scattering event that leads to a detectable secondary muon (or potentially a tau lepton for tau neutrino primaries) in IceCube is $\nu + N \rightarrow \ell^{\pm} + X$ where the lepton $\ell^{\pm}$ may then propagate for 20-30 km or more before it is detected in the optical Cherenkov array [22]. This potentially long propagation distance leads to an unknown amount of lost energy, and the measurement of lepton energy in an array such as IceCube can thus only provide a lower limit on the energy of the original neutrino. The kinematics of the event is such that the lepton typically carries 75-80% of the primary neutrino energy, with the remainder being deposited into a local hadronic cascade initiated by the hadronic debris X above. This cascade, while initiated by hadrons, rapidly develops into a characteristic $e^+e^-\gamma$ shower in ice.

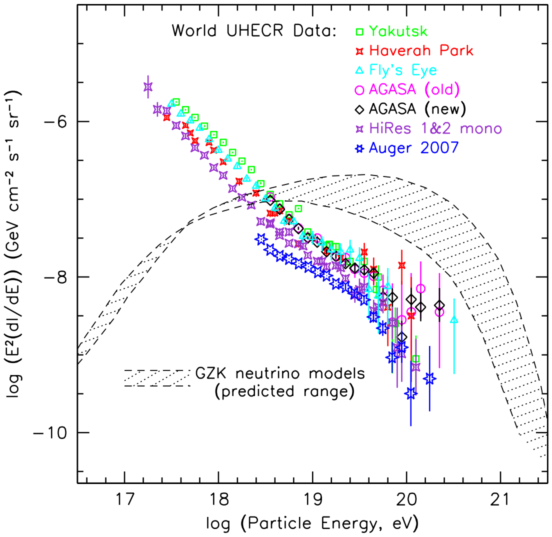


FIG. 1: *World ultra-high energy cosmic ray and predicted cosmogenic neutrino spectrum as of early 2007, including data from the Yakutsk [11], Haverah Park [12] the Fly's Eye [16], AGASA [13], HiRes [14], and Auger [15], collaborations. Data points represent differential flux $dI(E)/dE$, multiplied by E^2. Error bars are statistical only. GZK neutrino models are from Protheroe & Johnson [18] and Kalashev et al. [19].*

A series of experiments at SLAC [10], has shown such cascades produce a strong coherent Cherenkov radio pulse,as postulated by Askaryan (1960), and this pulse is detectable at great distances in a radio-transparent medium such as Antarctic ice. Thus a suitably stationed array of antennas in a configuration surrounding IceCube on the scale of several km to several tens of km could observe the Cherenkov emission from the primary vertex of the same events that may produce detectable leptons in IceCube. Such a radio array is insensitive to the secondary lepton, but even a relatively coarse array with km-scale spacing between small-number antenna clusters, can coherently detect the strong radio impulses from the cascade vertex. The two methods are thus truly complementary in their physics reach.

There is a been renewed interest in a particular set of neutrino models sometimes called the “guaranteed neutrinos”– those that arise from the interactions of the highest energy cosmic rays with the microwave background radiation throughout the universe [8, 9]. Such cosmogenic neutrinos, as they are also known, are required by all standard model physics that we know of, and their fluxes are tied closely to the parent fluxes of the ultra-high energy cosmic rays which engender them.

In addition, we expect that radio technology, greatly enhanced in the last two decades by the explosion in wireless, microwave, and satellite television device development, will lead to an array that will be affordable given the size and scale of the proposed detector.

The Highest Energy Neutrinos. Figure 1 shows the ultra-high energy cosmic ray flux as of late 2007, with a shaded band indicating the cosmogenic neutrino flux range that results from the interactions of these cosmic rays in intergalactic space. While current uncertainty in the observations of the Greisen-Zatsepin-Kuzmin (GZK) [6, 7] cutoff continue to allow for a relatively wide range of cosmogenic neutrino fluxes, the ongoing measurements of the UHECR fluxes by the Auger Observatory [15], as well as experiments such as ANITA [36], will soon lead to much better constraints on, or possibly even initial detections of these “guaranteed” neutrino models. Thus we expect a significant narrowing of the allowed range of fluxes in the next several years.

It is important to note that UHE cosmogenic neutrinos peak at energies of order 10^{18} eV, well above the canonical range of IceCube, and in fact even well above the ~ 10 PeV threshold at which radio detection for an embedded or surface ice array becomes practical. Thus, as we will discuss below, it is possible to design arrays that are much coarser-grained than would be required at the threshold energy for the technique, and to make use of far fewer detectors overall in reaching a given level of sensitivity for the cosmogenic neutrino fluxes. This has important implications for the economics of our studied detectors.

Radio Detection History. Figure 2 shows the original figure from the paper by Gusev and Zheleznykh [24] in which a surface radio array with a ~ 10 km^2 footprint is proposed to detect the Askaryan radiation of from 10 PeV neutrinos via antennas with grid spacing of several hundred meters. Later, in a landmark paper published in 1992 E. Zas, F. Halzen, and T. Stanev [27] presented detailed shower simulations which included the electrodynamic calculations in a compelling and comprehensive way. This paper gave high credibility to Askaryan’s predictions and made the first quantitative parameterization of the radio emission, both in its frequency dependence, and angular spectrum.

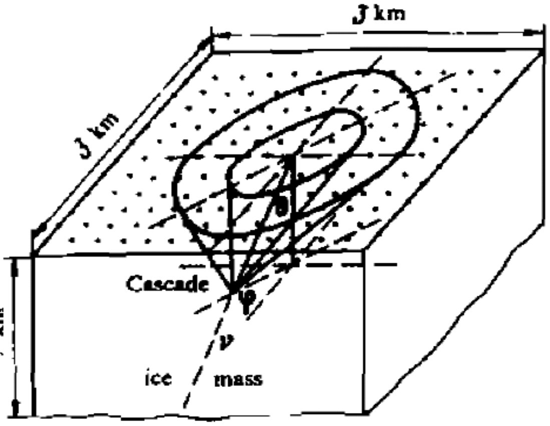


FIG. 2: Original figure from reference [24] in which a surface radio antenna array is used to detect high energy neutrino cascades.

Since those results in the early 1990’s, the field has grown steadily with the recognition that the relatively high neutrino energy threshold, 10 PeV or more in a reasonably scaled embedded detector in ice, and even higher for other geometries, is well-matched to a number of emerging models for high energy neutrino sources and production mechanisms such as the GZK process. Notable efforts are the RICE [29] array, which continues to pilot the study of embedded detector arrays with a small grid of submerged antennas above the AMANDA detector, the GLUE [30] and FORTE [23] experiments, which set the first limits at extremely high energies above 10^{20} eV, and more recently, the ANITA balloon payload [36], which completed a prototype flight in 2004 [32], and its first full-payload flight in early 2007.

Future Science Radio Detection May Enable . The discovery of extremely-high-energy (EHE) Greisen-Zatsepin-Kuzmin (GZK) neutrinos would verify the conventional wisdom in a fundamental way. With flux estimates of 5 to 10 events per 100 km^2 per year, IceCube is too small at 1 km^2 to make a significant statement. Present thinking suggests any detection scheme should initially cover 50 to 100 km^2 at a minimum, and the planning should be consistent with an eventual expansion to

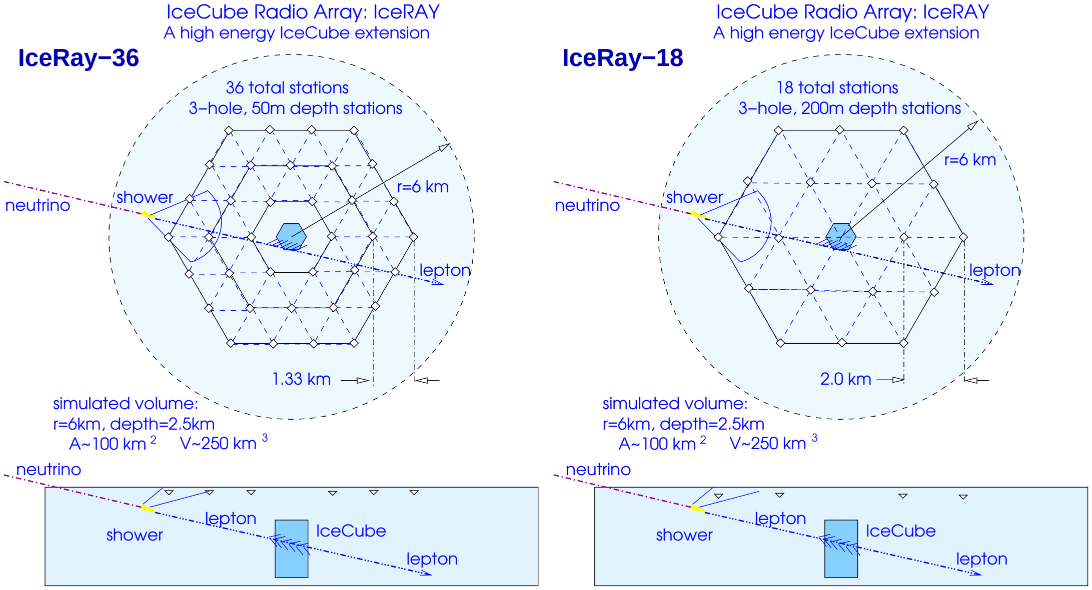


FIG. 3: Left: Baseline 36 station, 50-m depth array, in a plan view (top) and side view (bottom) showing the simulated interaction region around the detector. Right: Alternative 200 m depth, 18 station array.

detector sizes of 300 to 1000 km^2. These radio-detection processes have recently been demonstrated to be a viable technique by the ANITA group's experiments at SLAC and by subsequent ANITA balloon flights over Antarctica. Such techniques can add significant detection and analysis power in the EHE region to a parent detector-like IceCube. These GZK detection prospects, coupled with the South Pole's intrinsic low-noise electromagnetic (EM) environment, would further allow the study of lower-energy or ultra-high-energy (UHE) $10^{17} eV$ neutrino interactions The UHE/EHE neutrino detection capabilities of detectors such as IceCube and IceTop could be stretched by partnering with sub-surface radio-arrays, such as the proposed IceRay system, or by a similar radio- detector system that measures radio signals produced by neutrino interactions occurring in the distant ice surrounding the IceCube detector. Given the steeply-falling cosmic-ray and neutrino energy spectra, each factor-of-ten increase in detection sensitivity as the result of lower EM noise can result in gain factors of hundreds in increased data production. The importance of low noise thresholds in the detector's immediate neighborhood is thus of paramount importance.

III. ICERAY: A PROJECT OVERVIEW

We propose a phased design study, which will include the development and deployment of prototype hardware, that will enable the construction GZK neutrino detector array covering a physical area of ~ 50 km^2 (Fig.3), working in concert with the IceCube detector at the South Pole.

We envision four distinct phases to develop the IceRay detector. We briefly discuss them here, and they will be discussed in further detail in the subsequent sections devoted to each phase.

Phase-I, the initial radio-detection effort, called AURA, was started in 2006 by a small number of members from within the IceCube and RICE collaborations. AURA stands for Askaryan Underice Radio Array. Two detectors were installed in IceCube boreholes in Jan 2007 (AURA-I), and three additional detectors are planned for Jan 2009 (AURA-II). AURA has built on the RICE experience, and much of the AURA technology was adapted from RICE and ANITA technology. RICE has been a source of continuous support for the AURA effort, specifically providing AURA with both calibration signals and analysis expertise.

Phase-II, what this current proposal specifically addresses, proposes that members of the ANITA team join the AURA-IceCube effort, thereby being able to contribute the experience and resources that the ANITA effort has to offer. Specifically, the ANITA team-members would like to install the IceRay-0 Testbed, a surface detection station at the pole during the 2009-2010 season. This would allow for the first long-term program for measuring RFI backgrounds at the South Pole. This instrument has already be built and tested with funds from the University of Hawaii, and only requires to be installed at South Pole. The testbed could provide the South Pole scientific community and NSF management with a comprehensive temporal display of the detected power spectrum in the 30-to-1000-MHz range down to power levels of -110 dBm/MHz for both continuous and episodic events. The ANITA team-members could contribute to the AURA data-analysis and simulations as well as provide hardware experience, and testing facilities, such as Hawaii's anechoic chambers to the program. The ANITA members have recently contributed a number of potential (strawman) detector designs to AURA, and have run a number of simulations on these designs to determine their effectiveness as GZK neutrino detectors.

Phase-III presently calls for the IceCube team to submit a proposal for developing a 50-100 km^2 detector in June of 2010, since this could allow deployment to start at south pole during the 2011-12 season. We note that a number of straw-man designs and simulations for such a size detector have already been proposed in IceRay-36 and are presented, along with Monte Carlo simulations of their characteristics as part of the this proposal. The phase-III 50 km^2 detectors all have radii of about 4-5 kilometers which provide challenges for delivering power and harvesting data and trigger information. The communications challenges lend themselves well to wireless technology, and specifically to how the Auger detector addressed these issues, but the power is a major concern. Since the individual power-draws is small, power cables could prove to be the most economical way to power the closer in stations. The outer stations will probably require some combination of solar and battery power. that has to be extremely efficient and reliable if we hope to approach running the experiment throughout the austral winters. This will be the major challenge of the really large detector.

Phase-IV The current wisdom holds that an eventual GZK detector with sufficient analysis capabilities will probably have to encompass 300-1000 km^2. Given the radii of 300 to 1000 km^2 arrays is 10 to 18 km, one will certain have to design for efficient individual power sources like AUGER. This will be the real challenge. Realistically, we are probably looking at a Phase-IV start in 2015 or later, and the planning will require a continuous and sustained effort probably out to 2015.

The full Phase-III IceRay would be a discovery-class instrument designed to detect at least 3-5 GZK neutrinos per year based on current models, and would serve as the core for expanding to larger precision-measurement arrays of 300 to 1000 km^2, capable of detecting at least 20-50 GZK neutrinos per year. The present challenge is to determine the number of individual detectors, their spacing and the depth at which these detectors should be placed in the Antarctic Ice. This depth question is paramount, since deeper detectors sample a greater volume of ice more efficiently and thus reduce the number of detectors needed to achieve a desired GZK sensitivity. But deeper detectors also require the drilling of deeper boreholes, which can be expensive and time-consuming. The question of detector depth and spacing is also driven by ice temperature. Since cold Antarctic ice has an attenuation length greater than 1 km for radio emissions in the 60-1000 MHz range it means that shallow ice nearer the surface is more transparent and it is then possible to detect neutrino signals from interactions that are kilometers away. The quest is thus to find the optimum detector spacing-depth ratio that maximizes GZK sensitivity while minimizing the cost

Initial IceRay prototype stations will focus on a wide-scale, detector scheme designed to investigate the radio detection properties from the ice surface down to about 200-250 meter depths, or possibly greater using the smaller and more efficient firn-drill techniques, and to establish background levels several km out from the central part of the South Pole station. The Phase-I,and II AURA mission will complement investigations instrumenting IceCube boreholes as part of an ongoing efforts. The AURA efforts have allowed some of the current team to already begin investigation of deeper ice through deployments of radio detectors as elements of IceCube strings over the last several seasons, and these detectors and further ongoing efforts for AURA now already provide a first-order testbed for studies of a deep-ice detector. Although not a direct part of the activities proposed and costed here, we discuss AURA in some detail in a later section, since it provides an important facet of the investigation into the utility of deep antenna deployments, without requiring separate high-cost deep boreholes.

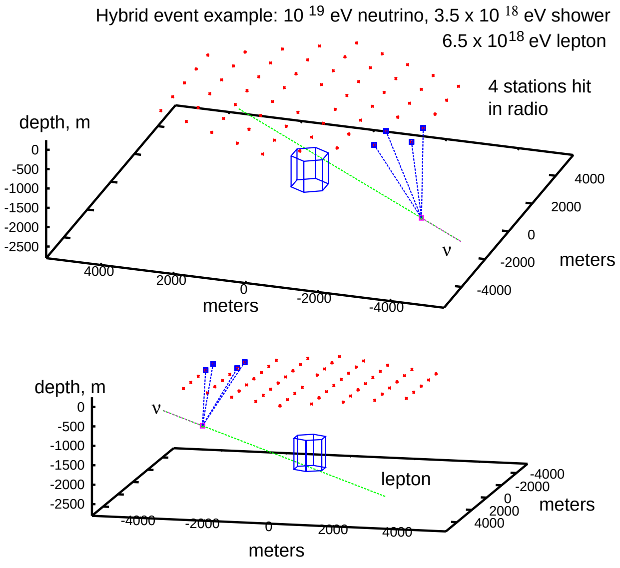


FIG. 4: Example of a hybrid event where the vertex is seen by 4 surface radio detectors and the resulting lepton passes near enough to IceCube to make a detection

The basic geometry is initially assumed to be like IceCube, that is, individual detectors are located at the corners of equilateral triangles, which then are formed up into series of expanding hexagons as is shown in Fig. 3. An example of the overall event geometry for one example is shown in Figure 4. Here we show an event detected by the surface array in which an incident 10^{19} eV neutrino put 35% of its energy into a shower which was seen by 4 of the surface radio detectors, and the secondary lepton passed just outside the IceCube array with initial energy of 6.5×10^{18} eV. At this energy either a muon or tau lepton is losing of order 0.1 EeV per km of track–this level of emission would produce a huge signal at IceCube, even with an impact parameter several hundred meters distance outside the array.

For the standard IceCube geometry, the total hybrid event fraction of is of order 10% in these two regions. Recent studies of "guard-ring" extensions to IceCube [17] have shown the utility of one or more outer rings of strings 500-1000m outside the standard array. If we assume a single ring at a radius of 1 km from the center of IceCube, with itself an additional 500 m of reach for secondary lepton detection, the hybrid fraction extends to 15% of all neutrino events, and a 1.5 km guard ring could yield a hybrid fraction reaching 20%.

Ice Drilling and Detector Deployment. Each station requires three holes 50-80 meter deep, and 60 cm in diameter to accommodate the antennas. Present plans are to use the IceCube "firn" drill, a "hotpoint" style drill that specializes in drilling through the firn: that porous ice that makes up the first 50-70 meters of low-density ice just below the surface. We also will investigate what is needed to extend the reach of the firn drill to depths of 100-200 meters. The present IceCube firn-drill uses about 150 kW and can drill at a rate of about 4 m/hour. The whole setup is about 24 ft long by 8 ft wide. It circulates about 15-20 gpm of hot fluid (60-40 mix of propylene glycol and water) to the head at about 75 deg. C. (returning 15 to 30 C cooler depending on drill rate). The heaters come on and off as needed to maintain the fluid tank at 75C. The total available power is 150 kW but we rarely used it all. We usually had about 3 or 4 heaters on (@ 30kW) at a time so we probably averaged about 100 kW for most of the hole. We drilled about 6 meters/minute near the top of the hole and at about 3 meters/minute at the bottom (around 38-40 m deep). The system would start to slow down somewhat below where we start to get in to pooling water. This could slow down drill progress. That remains to be seen but we did find we were drilling with all 5 heaters running more of the time.

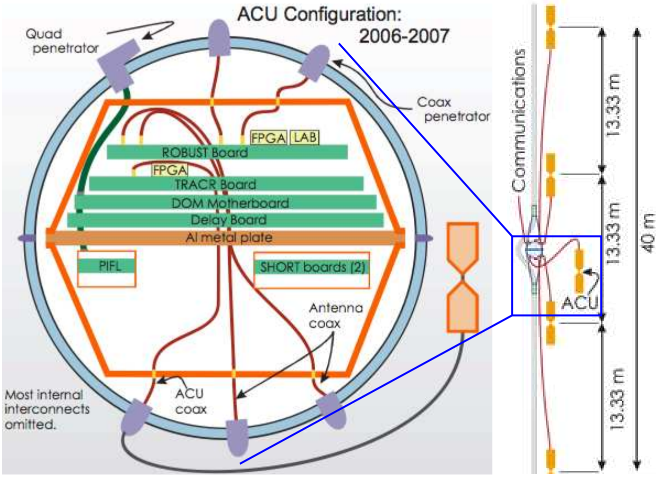


FIG. 5: Left: A schematic of the DRM. Right: Showing location of Antenna structure, and DRM along the IceCube string.

IV. ICERAY DEVELOPMENT PHASES

Phase-I: RICE and AURA . RICE (the Radio Ice Cerenkov Experiment) was the first array in the Antarctic to use the Askaryan effect to search for neutrinos and other high energy phenomena. Since it began operations, RICE has made initial studies of the South Pole RF noise environment, studied the RF properties of the South-Polar ice, and developed techniques for radio analysis of high-energy phenomena, eventually setting limits on many high-energy phenomena. Following on the progress of RICE, the AURA working group was formed to further study the unique opportunity created by IceCube operations to deploy radio antennas over a larger footprint and at greater depths. Further, the electronics and infrastructure developed by IceCube to provide power, time synchronization, and data readout across large distances, along with radio specific hardware developed for ANITA, have been used as a spring board to develop radio instrumentation that could be scaled up to a large in-ice array for GZK neutrino studies.

At this time(August 2008) AURA consists of two radio detector clusters at ice-depths of 250, and 1400 meters. In Jan 2007 the first two AURA radio clusters were installed: each clusters consisting of four receivers and one transmitter Additionally a transmitter only unit was installed. A schematic of a cluster is shown in Figure 5. The electronics which provide the power, data acquisition, trigger logic and communications are located inside of an IceCube pressure vessel, so that the mechanical mounting and connection of the digital radio module (DRM) could proceed exactly as it does for IceCube digital optical modules, with zero impact on IceCube operations. Present plans call for installing two additional shallow detectors (250 m depth), and one additional deep detector (1400 m) in January 2009.

Phase-I includes the work done by the AURA group in collaboration with the RICE effort. Specifically Aura-I was installed into IceCube holes 47, 57, and 78. Full 4-channel receiver clusters were installed at a depth of 1400 meters in hole-78, and a depth of 250 meters in hole-57. These clusters are referred to as ”deep” and ”shallow.” A third partial cluster consisting only a pinger radio transmitter was installed in hole-47 at a depth of 1400 meters. The 4 antenna-receiver units in a cluster cover the frequency range of 200-1000 MHz. The amplifiers provide power gains of about 70 dB so that the system has a floor sensitivity of about -110 dBm, or very close to the kT or blackbody noise floor. The cluster trigger relies on the fast and broadband nature of the Askaryan Cherenkov signal. The cluster triggers when three out of four receivers report sizable signal power in three of the four frequency intervals between 200-400, 400-600, 600-800, and 800-1000 MHz

These clusters perform in-situ a 12-bit digitization of the received signal amplitude at the 0.5 ns time scale. The sampling speed is 2 GSPS, with a 1.3 GHz bandwidth and 256 ns buffer depth. The simple RICE-style broadband dipole antennas have been used. Located near each antenna are pressure vessels containing front end electronics for amplification and filtering. These digital signals are then transmitted back to the counting house using the standard IceCube data handling mechanisms. These clusters have been taking data since their installation. The fully digitized waveforms allow for zenith angle reconstruction. Reconstruction verifies that most of the signals come from the South Pole area. Figure 6 shows the trigger time distributions folded over a 24 day for a period of 38 days. During the austral summer, the pole is 13 hours ahead of UTC, so we certainly see a diurnal effect. Most of the events look like the down-going event shown in Figure 7, and the zenith angles calculated by phase alignment point back to the South Pole base.

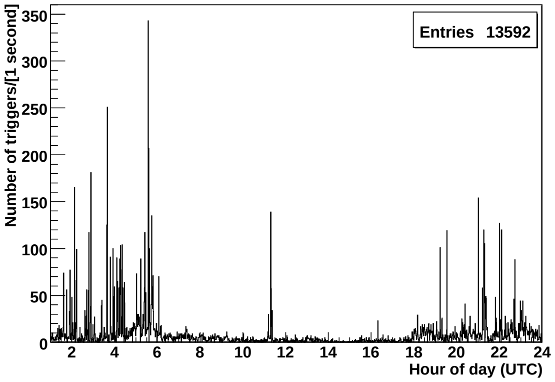


FIG. 6: Time distribution of triggers in 24 hour period during a 38 day period.

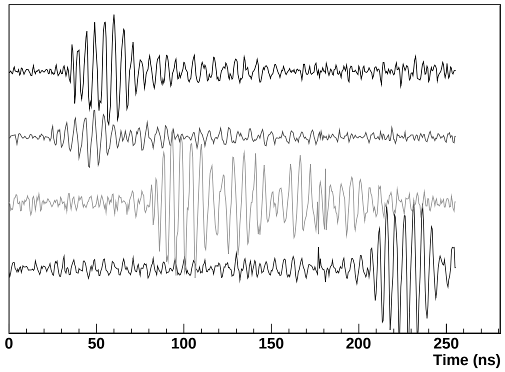


FIG. 7: waveforms for the 4 channels, top antenna to bottom

Clusters were installed 500m apart at a depth of 1450 m to allows a survey of the noise environment in the deep ice, as well as studies of the effects of the proximity of the IceCube DOMs. The remaining receiver-transmitter cluster was installed at a depth of 250m in a hole near the existing RICE array to allow cross calibration of the two instruments. Since February 2007 the clusters have been operated in both self trigger and forced trigger mode, and to date, a large quantity of data has been transmitted north for analysis. The data being taken consists of ambient and transient background studies, calibration runs using the AURA transmitter and the in-ice RICE transmitters. The first unambiguous confirmation of our ability to receive and digitize radio signals was achieved shortly after deployment with a series of special calibration runs using the RICE continuous waveform transmitter. The effect of IceCube electronics has been studied using the deep transmitter cluster by taking special runs with IceCube turned on and off.

Current plans (Sept-2008) call for three additional clusters (AURA-II) to be installed in Jan 2009 in IceCube holes 3, 6, and 36. Hole 3 will accommodate a deep cluster(1450 meters), while holes 6, and 36 will accommodate shallow clusters(250 meters depth). Two of these AURA-II clusters have an extended frequency range, down to 100 MHz to take advantage of the wider Cherenkov-cone at the lower frequencies. Plans also call for the installation of stronger RF pingers, which provide both narrow-band and wide-band pulsed signals to further aid the sensitivity calibrations, and determine the ice frequency-attenuation characteristics. This will allow us to continue the vertex studies and to pinpoint man-made noise sources, and to investigate the Pole’s EMI noise environment in general. It is hoped that that we can make analysis of these data part of the proposed Phase-II effort.

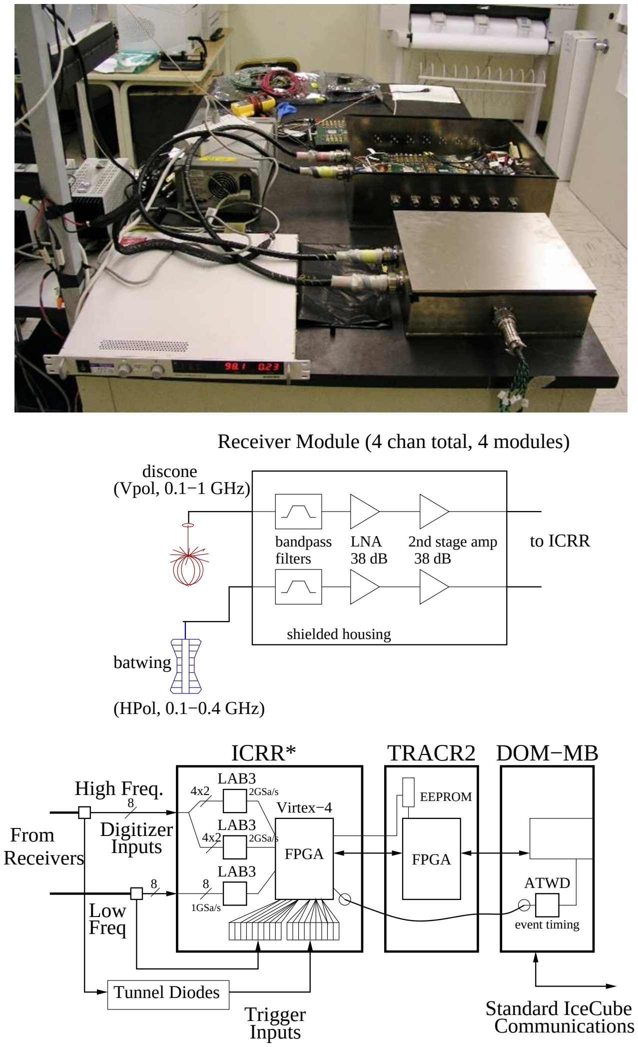
This Phase-I AURA work will continue to be complementary to the Phase-II efforts to learn just how deep in the ice we have to locate the detectors in order to develop a credible GZK neutrino array. Deep access is provided as a result of the IceCube string deployments, and from the point-of-view of the current IceRay proposal, the utilization of these resources with minimal impact on IceCube provides important added-value to the decision process for a wide-scale radio array.

This phase-I effort will continue within IceCube, but it will be limited because of the limited amount of people resources that can be allotted to AURA given the demands of bringing on-line the IceCube Detector As noted above, however, the AURA program despite its limited scale, has produced a useful body of in-ice data as well as allowing for the refinement of the construction requirements of placing receivers in the ice. Finally, we mentioned that a more extensive AURA effort was proposed to the NSF, but was declined because of its support requirements, so that the resulting AURA-I and AURA-II efforts reported on represent the installation of the prototype devices, and a much smaller effort than originally envisioned.

Phase-II: Testbed and Array Design . Intrinsically, the South Pole is one of the most radio-quiet places on earth, once one leaves the immediate vicinity of the station environment. The absolute EM noise-floor is set by the ambient blackbody power spectrum, where total noise power is proportional only to absolute temperature and to the bandwidth sampled. Determining the South Pole's suitability for effectively supporting experiments employing radio-detection techniques would require careful study of anthropogenic sources of EM noise.

This listening station, called the "Testbed" would allow for continuous monitoring of the electromagnetic spectrum from 60 MHz - 1000 MHz with sensitivities to power-levels of -110 dBm/MHz, or just above the thermal noise-floor. It would provide the scientific community with valuable data as to the suitability of the South Pole Station to support very sensitive radio-detection experiments. IceRay-0 was built to support the possibility of IceRay-36 going forward. It is already built and tested and only requires the support of the NSF for installation at the pole.

RFI surveys conducted primarily by the SPAWAR group in support of activities related to aeronautical navigation and logistics, have centered on spectrum analyzer-based measurements of the above-ice, near-station levels of RF power in discrete spectral lines arising from narrow-band transmitters. While such transmitters make a significant contribution to the overall RFI profile, these studies presently do not cover five important aspects of this potential interference. The Testbed can fill these gaps by providing: Estimates of any broad-band interference that may be present; Estimate of time-variation of the sources, except over the several-day period of the survey; Estimate of impulsive interference that may be present; Provide absolute overall calibration of their results with respect to ambient thermal noise, or in standard field-strength reference units such as micro-volts/meter/MHz; and Estimate of what degree of interference may be coupled into the regions under the ice. This last aspect is compounded by ice being virtually transparent to all electromagnetic radiation in the range from a few tens of kHz up through a few GHz. Scientific activity at the station now involves under-ice transmission and reception of radio signals. Thus, armed with this spectral information from the Testbed, the South Pole scientists and managers could plan better, and the NSF could better manage this remarkable radio-quiet resource.



*ICRR=IceCube Radio Readout

FIG. 8: Top: Testbed Hardware: DAQ and power control systems. Bottom: Schematic diagram of the Testbed system.

The Testbed hardware is shown in Figure 8(top), and a schematic is displayed in Figure 8(bottom). The testbed initially was intended to be an instrument for a program involving radio Cherenkov detection of neutrinos, as a complement to the IceCube detector (IceRay-36). The testbed could certainly allow the SP station to apply corrective action to reduce its EM footprint in significant ways without compromising the efficiency or the mission of the Station. The testbed has the capability to measure separately both the EM power spectrum in deep ice (for neutrino detection) and the atmospheric (above-ice) EM levels to assist any future atmospheric radio- detection or other aeronomy programs.

Plans call for testbed operations to be conducted in the IceCube laboratory (ICL) at the South Pole. Its power, data bandwidth, and computing support requirements are modest: the actual remote station would only require about 100 watts of power and about 1 MHz of bandwidth. A single computer at the ICL would control the operation. There should be no direct impacts on Station personnel; the small power and bandwidth impacts could be easily and willingly absorbed by IceCube. Real-time monitoring and data analysis would normally be done remotely (off-Station) as satellite coverage would allow, along with direct interaction with Station personnel when needed. The testbed should not require any increase in Station population, and should make only minimal and discretionary impacts on IceCube personnel. Signals from the remote site will then be sent over the testbed cable to IceCube junction box, where they would be integrated into the standard IceCube data flow.

At the remote test site, 7 antennas will perform the in-ice survey, each about 6 feet in height and buried between 6 and 12 feet below the snow surface. To guarantee that these are only picking up in-ice noise and not atmospheric or ice-surface noise, the antenna complex will be covered with a 50X50-foot copper ground screen. The screen itself will also be located about 6 feet below the nominal snow surface. In the 2nd Phase-II pole season (FY-11) we plan to use the firn-drill to position a number of the antennas at depths of 200 to 250 meters, or as deep as we can drill while still operating the firn-drill in an efficient manner. In addition to these under-screen antennas, we will include several above-screen antennas to monitor noise in the unshielded zone as well.

The antennas deployed include both vertically polarized very broadband discone-type wire-frame antennas with excellent impulse response characteristic of such antennas, along with horizontally-polarized batwing antennas. The latter antennas were much more difficult to design given the constraints of the borehole geometry, but in the end the design has been found very satisfactory in testing, as shown in Fig. 9.

The entire antenna complex installation is shown Figure 10, and the size of one of the ”batwing” antennas is shown in Figure 11.

To pursue these efforts the Hawaii and Ohio State ANITA-members of the AURA-IceCube effort would require some modest increase in our personnel, and well as some funds for testing and shipping equipment to the south pole staging areas. We are looking at support for a post-doc and a couple of students, principally to run the IceRay-0 experiment, and to continue work on refining the ice-characteristics for radio work, and to further the antenna design work, and analyzing the data being harvested by the AURA and IceRay-0 detectors. Presently we are looking at a two-year proposal with support from April-2009 to April-2011. Specifics will be developed in the budget sections. We hope to obtain NSF support for two years from April 2009 to April 2011. By involving some of the ANITA team-members with the IceCube AURA efforts, we plan to augment the current analysis of the Phase-I AURA data, as well as contribute to the analysis of the new clusters coming on-line in Jan 2009.

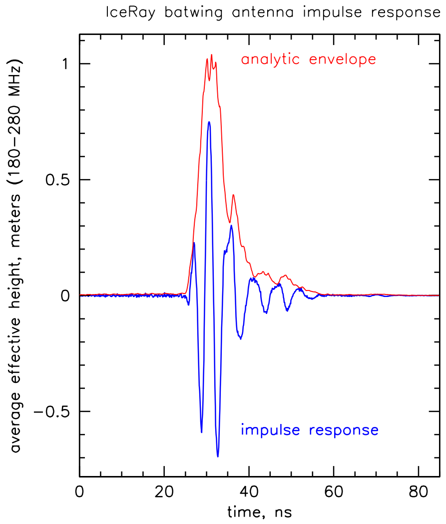


FIG. 9: An example of the surprisingly good impulse response of the batwing horizontally polarized antenna and its power analytic envelope function. The FWHM of the power arrives in about 5 ns.

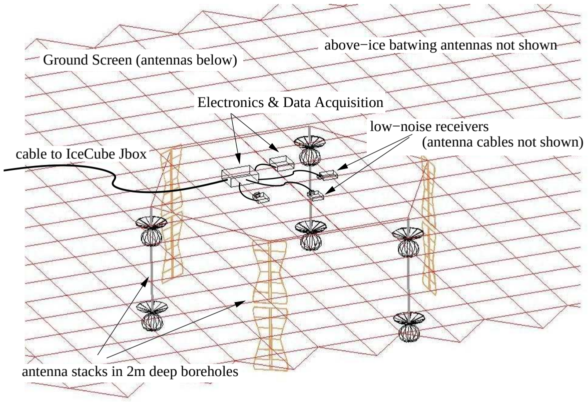


FIG. 10: Testbed Antenna complex. This version shows both discone and batwing antennas at separate vertices; in recent tests we have found that the two antennas can be alternated together at the same vertices.

FIG. 11: Christian Miki holds an example of a fully tested production model of current configuration of hybrid testbed vertices, combining both batwing and discone antennas that fit together into the 2m deep by 24” diameter auger-bored borehole. 6 sets of these antenna pairs have been already constructed and tested.

IceRay Design Drivers The field attenuation length for South Polar ice in the upper 1000 meters is of order 1.5 km [33] at frequencies of 0.1 to 1.0 GHz. In finding the maximum spacing at which a Cherenkov array still has good sensitivity without regard for angular resolution, it is reasonable to adopt distances of order the attenuation length in the medium. If the expected signal is large compared to the threshold of the technique, as is the case for the cosmogenic neutrinos, then even larger spacings can be considered, giving up signal strength for physics reach at the expense of some resolution.

Our approach is driven by the desire to combine with IceCube on the detection of the “guaranteed” cosmogenic neutrino fluxes, the radio array is designed only to maximize such detection as early as possible, at the lowest cost, and with the highest cross-section possible for hybrid detection with IceCube. With such design choices defined, and based on the physics of the interactions as outlined above, the layout of the necessary array must extend out radially from IceCube far enough to begin covering a significant fraction of the range where neutrino vertices are located. At high energies, this favors lepton events coming from near the horizon for IceCube, since that is the direction with the largest probability for neutrino interactions within the 20-30 km range of the resulting muons. For purposes of these initial studies, we have chosen to adopt spacings of 1 to 2 km, and grid which occupies an initial 4 km radius around IceCube.

Figure 3 shows the two example full-scale IceRay arrays studied in the most detail here. On the left is a 36-station, 50 m deep version with 1.33 km spacing; and on the right, an array with 2 km spacing, 200 m depth, with 18 total stations. In each case a “station” is required to be able to produce stand alone measurements of an event, including location of the vertex and a rough calibration of detected energy. The use of polarization information is also presumed to allow for first-order single-station measures of the event momentum vector. The antennas are assumed to have low directivity gain, equivalent to a dipole, with a dipole-like beam pattern. Directionality is attained by providing local, several-meter baselines within each station’s array, either through a local-grid-positioning of antennas at the surface, or through use of multiple boreholes (of order 3 with 8-10 m spacing) at each submerged station.

Signal Nature–Askaryan Pulses. In the fully-coherent regime, Cherenkov radiation arising from the Askaryan effect has an frequency spectrum for which the incident electric field strength $\mathbf{E}(f)$ within the Cherenkov cone rises linearly with frequency, thus [23]

$$|R\mathbf{E}(f)| = \sqrt{2\pi}\mu\mu_0\, Q\, L\, f \sin\theta\, e^{-(kL)^2(\cos\theta - 1/n)^2/2} \quad (1)$$

where R is the distance to the shower from the observation point, Q is the excess charge in the shower (typically about 20% of the total shower charge), L is a characteristic length of the shower in the medium, θ is the emission angle with respect to the shower axis, and $k = 2\pi n/\lambda$ is the wavenumber in the dielectric medium of index of refraction n. For typical dielectrics $\mu = 1$, $\mu_0 = 4\pi \times 10^{-7}$ is the permeability of free space. Equation 1 provides an analytic form for evaluating emission from this process, and gives insight into the angular spectrum as well as the frequency spectrum. For ice, loss of coherence rolls off the linear f dependence above ~ 1 GHz.

Figure 12 shows a comparison of the expected signal at a distance of 1.5 km for ice with characteristics of the South Pole. Two parameterizations for the radio emission used for comparison: Zas, Halzen, and Stanev [27] and that given by Lehtinen et al. [23]. There are two important considerations here: first, the strength of the signal on the peak of the Cherenkov cone, which grows with frequency; and second, the width of the Cherenkov cone at the detection threshold, here given as 6σ above the thermal noise. The former consideration determines the minimum detectable neutrino energy, while the latter determines the total acceptance by the angular width of the cone where it exceeds detection threshold.

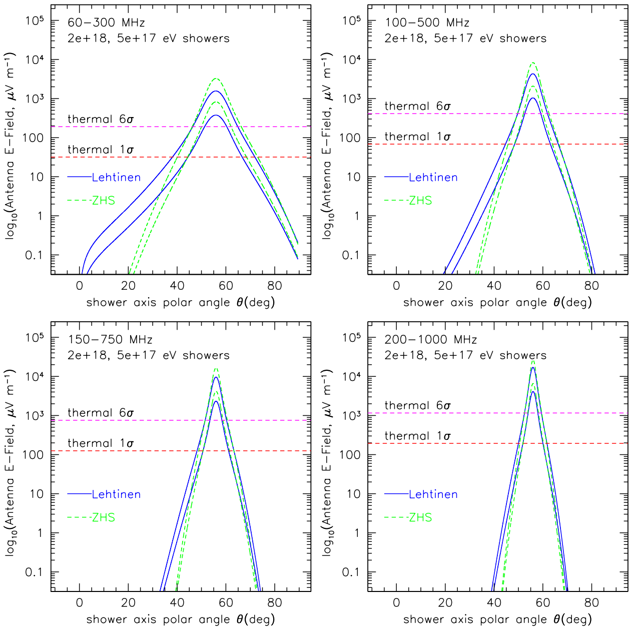


FIG. 12: Angular widths for various frequency ranges and two cascade energies in the heart of the cosmogenic neutrino spectrum. See text for details.

Note in equation 1 that the full-frequency bandwidth contributes to the power radiated at the Cherenkov angle, as the exponential is unity there. Off the Cherenkov angle the higher frequencies are suppressed in the radiated power by the factor $\exp -(kL)^2$. Thus while lower frequencies have generally less power because of the leading factor of f, they provide more angular acceptance, and this can favor a detector centered at frequencies as low as 30-60 MHz if the signal power is otherwise adequate for detection. The solid-angle for acceptance for any isotropic source, as the cosmogenic neutrinos are expected to be, scales linearly with the solid angle of emission for the Cherenkov cone, and thus the frequency range for optimal detection is an important parameter to investigate.

In Fig. 13 we show data reprinted from the ANITA experiment's measurements of radio Cherenkov impulses at SLAC during mid-2006, using a 7.5 ton block of pure ice as a target for electron-showers with composite energies of up to several times 10^{19} eV. The data show excellent agreement with all predictions for this process in ice, including the overall radio power, its coherence, and the angular spectrum as well as its frequency dependence.

In Figure 14(top) we show the deconvolved time-dependent electric field strength at the antenna as measured from other beamtests at SLAC [26]. However, for the tests run at SLAC, the actual signal voltage that appears at one of the receiving antenna's terminals (in this case a dispersive log-periodic dipole array) is shown in Figure 14(bottom). The GZK identification challenge thus is two-fold: first we must design antennas systems that minimize ringing, and thus minimize the group-delay distortions, and second, we must develop good signal deconvolution algorithms to handle the waveform distortion.

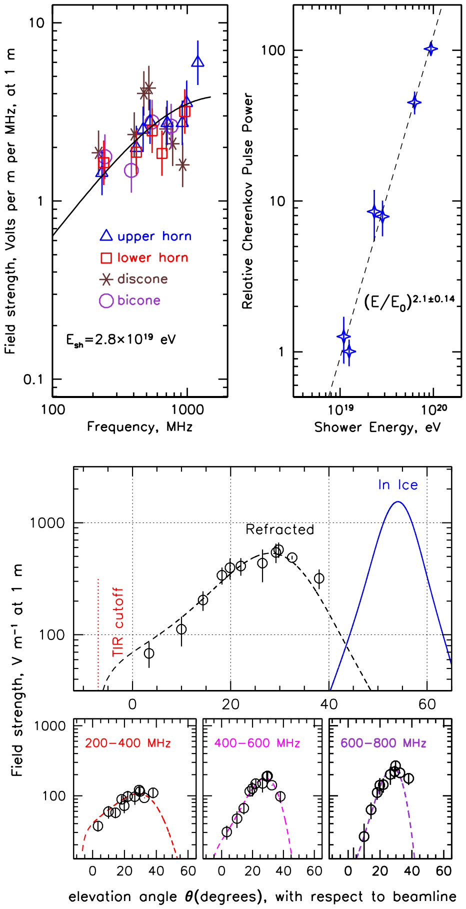


FIG. 13: Top Left: Absolute power spectrum of Askaryan events in ice as measured at SLAC by ANITA in mid-2006. The curve is based on the ZHS parameterization. Top right: radio coherence measurements from the same data. Bottom: Full-spectrum and frequency-dependent radio Cherenkov cone measurements from the same data. Reprinted from reference [10].

In choosing a frequency range over which such an array will operate, we begin with the range of frequencies over which ice is transparent: from a practical lower limit of several MHz, where time resolution will already be an issue, and backgrounds potentially prohibitive, to of order 1 GHz, where the attenuation length of ice becomes a problem, especially in the warm deeper ice. Antenna designs will generally limit usable fractional bandwidths to no more than 5:1 for extreme broadband designs, and we therefore assume this as the working bandwidth ratio (5:1 indicates the ratio of the upper frequency to the lower frequency).

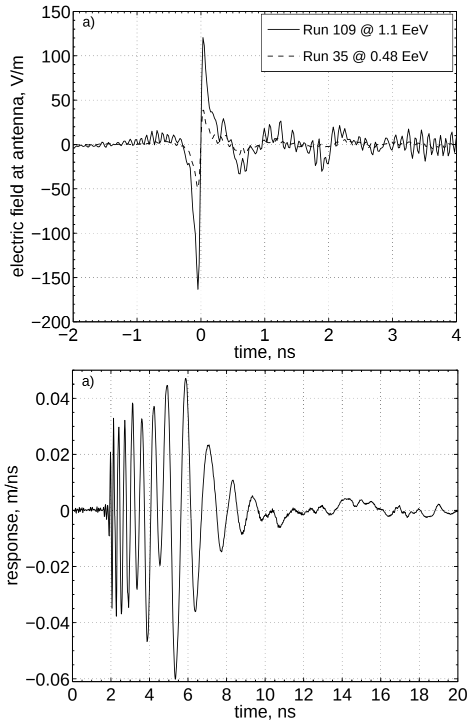


FIG. 14: Top: The deconvolved time-domain electric fields at the antenna in two SLAC test runs. Bottom: raw antenna voltages before deconvolution. Reprinted from reference [26].

Finally, the system noise is also a consideration, and for a receiver which sees a total system noise, the RMS induced voltage noise referenced to the input of the receiver is $V_n = \sqrt{kT_{sys}\, Z\, \Delta f}$ where k is Boltzmann's constant, Z the receiver impedance, and Δf the bandwidth. However, this is not the whole story. Since a neutrino detector depends not only on threshold energy for detection, but also on the total acceptance for events at that energy, we must also consider the dependence of acceptance on radio frequency. There are two terms that contribute to acceptance, one dependent on observable volume of ice, and another on the effective solid angle over which events can arrive and still produce detectable emission. Since the cosmogenic ultra-high energy neutrino spectrum peaks above several times 10^{17} eV, we conclude from this comparison that lower frequencies gain more acceptance and still retain adequate signal-to-noise ratios for detection, as compared to higher frequencies. To put it another way, lowering the energy threshold below the peak of the cosmogenic neutrino flux gains no increase in event rate unless one can preserve the solid angle for acceptance; in this case that does not occur, and a lower frequency array is preferable.

Ice Refraction and Absorption. Through the efforts of of the AMANDA and IceCube collaborations there now exists an excellent ice-temperature vs ice-depth profile from the surface to the bedrock at 2800 meters. Many properties of the ice, including its radio refractive-index and frequency dependent absorption depend in a significant way upon the ice temperature, and thus upon its depth.

The density approaches an asymptotic value of about 0.92 at an ice-depth of about 200 meters. The density at deeper depths stays pretty constant with only slight variation due to the ice warming deeper depths. The index-of-refraction n(z) as measured by Besson et. al. and fit by Gorham is shown in Figure 15. This index of refraction behavior must be accounted for in any simulation, and we show some typical results giving the ray-trace behavior for detectors located at 50 meters and 200 meters below the surface. This is of particular concern for a relatively shallow subsurface array, and Figure 18 shows a series of rays traced from deep source directions to the near-surface, illustrating the tendency for a near-surface array to see an inverted horizon below the ice, precluding detection of source above a conical region below the detector. Such concerns limit both the effective volume for a near-surface detector, and the solid angle above the horizon over which events can be seen, and the effect, while significantly less for more deeply submerged 200 meter arrays, cannot be neglected in the 50 m array depths studied here.

The effective volume depends on the attenuation length of the surrounding ice. Figure 16 shows measurements [33] of ice attenuation at the South Pole, based on bottom reflection data. It is evident that there are frequency dependent increase in losses over the range 200-800 MHz, of order 25-30%. Since the reduction in volume is to first order cubic in the attenuation length, this implies a loss of as much as a factor of 2 in available volume this important frequency range. Estimates of the radio signal attenuation-length as a function of frequency and ice-depth(temperature) are shown in Figure 16. This attenuation has both a significant temperature and frequency dependence, which means that much care has to be given to the placement of receivers in the ice as their bandwidth and their locations and depths. These frequency-depth considerations coupled with the ray-optics conditions set by the index makes the determination of the index and attenuation a very important consideration in setting up a large-scale detection array. Currently on simulated ray-tracing studies do show a steady improvement fiducial volume in with increasing depth up to about 400 meters, however drilling cost certainly do increase. One can compensate for the reduced volume sampled by shallow depth detectors by employing more of them. This is one of our current challenges.

Phases-III: Testing and Building IceRay-50 Two Straw-man detector designs are presented. There function is just to provide a platform on which to refine present ideas and to develop new ideas. IceRay-36 consists of 36 stations buried 50-80 meters deep in the ice, based on

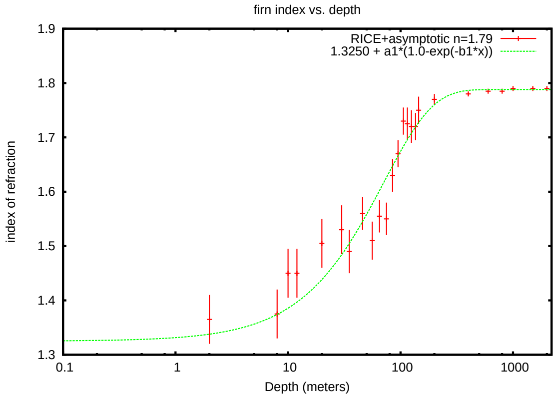


FIG. 15: *Index of refraction in firn at South Pole station, based on data from the RICE experiment [29].*

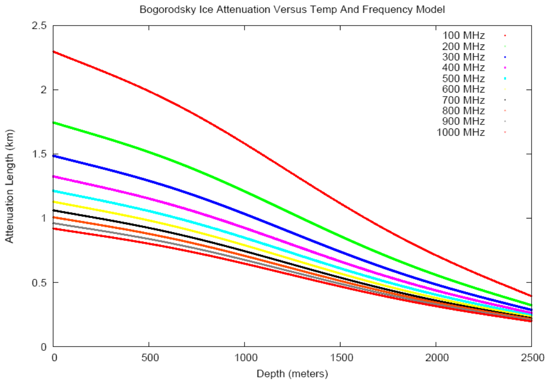


FIG. 16: South pole ice frequency-attenuation.

current or projected firn-drill capability. The basic geometry consists of 1.3 km equilateral triangles which form a series of three concentric hexagons with IceCube in their center. While we have adopted the 50 m depth version of IceRay as the baseline, we propose to study the cost-benefit of deeper detectors. The present IceRay schemes also calls for three boreholes per detector station, most probably arranged on the corners of an 8-10 meter equilateral triangle. Such an arrangement will provide not only multi-fold coincidence information, but timing-phase information will allow directions to be determine to 1-2 degrees or better depending on signal power.

Considerable effort has already gone into antenna design and optimization and this topic will certainly be further addressed as part of our study, although for brevity we do not detail these here. The amplified RF signal is transmitted via coaxial cable to trigger and digitization electronics located on the surface. Amplification of approximately 76 dB is needed to boost the signal from thermal noise levels to an amplitude large enough for direct triggering and digitization. The trigger scheme [35]will probably evolve from a combination of AURA and Auger techniques and the scheme that has been successfully flown on the ANITA payload [36]. Each detector station is connected via fiber optic and a number of station inter-trigger and readout topologies have been considered, one such study has been published [37]. The first year prototype IceRay-0 or the Testbed has been based upon the LABRADOR3 ASIC [38], used by both ANITA and AURA. However, to be able to store data for an entire array-transit-time for sub-threshold event reconstruction will require a future generation of storage chips.

Antennas will be designed, constructed, and tested at both Kansas and Hawaii. Both institutions have had extensive experience in this area with their pursuits of RICE, AURA, and ANITA. Both institutions have Anechoic Chambers and equipment required to completely characterize antennas, such as measuring complex impedance and VSWR in both the frequency and time-domain. For short-pulse work, the time-domain is the proper domain in which to characterize the antennas. Since the antennas are physically small protecting them is not a major problem. The antenna arrangement will be back-filled with snow, so that in time, the antennas will see an almost uniform environment of snow and a constant index of refraction.

Each detector station will consume of order 50 watts of power. The present plan is to run both the power and the signals over copper lines, at least to the inner-most detectors! This design will require an optimization scheme that depends on the total number of detectors planned. For example, the designs as to wire-sizes and wire paths that might be quite adequate for IceRay-18 would be impossible for an IceRay-300 detector. For the immediate future we mention that the present cable design has been supplied by Ericsson, who also makes the IceCube cables. The signal transmission over 2 km is not that challenging at the expected data bandwidths required. This is quite similar to the IceCube data transfer requirements from 2.4 km depths, using the same type of cables.

In truth, the formation of triggers, the routing of data and the supplying of power to and from these remote stations is a considerable challenge, whose solutions probably lie in the near-future developments of wireless industries, and power industries. We certainly can expect significant developments in battery technology from the automobile industry. In the meantime we have just floated our current ideas on how we have chosen to solve the problem of supplying power and communicating with the inner-most detectors.

V. MONTE CARLO RESULTS

Figure 17 shows results for some standard distributions for both arrays over a range of energies important to cosmogenic neutrino detection. Detections up to 2 km beyond the outer perimeter of the arrays are considered, and this additional volume is important at higher energies, as seen in the upper left panes of each plot. Distributions of detected events (upper right in each set) with depth show the distinct behavior for the 50 m deep array due to the effective “exclusion zone,” or horizon, caused by the firn shadowing of events, whereas the deeper 200 m array shows more uniform range for detection. On the lower right a plot of the angular distribution of events shows the cutoffs imposed by firn shadowing for both arrays, although much less restrictive for the submerged array. Finally, on the lower left the multi-station hit distributions are shown– the denser array has a clear advantage here, and will as a result give a larger fraction of events with high-precision measurements of the event geometry and kinematics.

Figure 19 shows the volumetric acceptance of several of the arrays studied, including a surface-array with 60 stations, 1 km spacing, and 3 m depth, which was found to be constrained by the losses in the firn refraction, and helps to indicate the importance of getting at least part-way below the firn. Each curve shows the volumetric acceptance, in water-equivalent km^3 times steradians plotted as a function of energy over the range of interest for cosmogenic neutrinos. IceRay-18 generally gives somewhat higher acceptance than IceRay-36 at the highest energies, but at the cost of slower turn-on at the lowest energies of interest, where it is has a smaller net acceptance, attributable to the coarser spacing of this array.

Table I shows the results for the IceRay-36 and IceRay-18 arrays in tabular form, and also approximately factors out the solid angle, to give some additional insight into the differences: the 18-station version gains considerably in solid angle because of its 200 m depth, which reduces the horizon losses under the ice, while the 36 station array makes up for this in the better sampling of the volume that the higher-number-density array affords. The most important results come after the acceptance has been integrated over various current cosmogenic neutrino models, and the results of such an integration are shown in table II.

TABLE I: *Acceptance and its factors as a function of energy for the two primary example arrays considered here.*

$\log_{10}$(Neutrino Energy)	17	17.5	18	18.5	19	19.5
Interaction Length, kmwe	2650	1744	1148	756	498	328
Iceray-36 $V_{eff}\Omega$ (km^3 sr)	13	26	60	94	137	149
Iceray-36 Ω (sr)	2.4	2.4	2.1	1.8	1.7	1.6
IceRay-18 $V_{eff}\Omega$ (km^3 sr)	11.6	38	63	115	137	185
IceRay-18 Ω (sr)	3	4.4	4.2	4.1	3.8	3.8

The three “standard model” cosmogenic fluxes give 4-9 events per year. Such events would be dramatic in general, and we expect no irreducible physics background, so detection of even a few events is statistically plausible here. If stronger source evolution obtains, or cosmogenic neutrinos experience other enhancements still allowed by the current limits, these arrays would go beyond detection in a single year, and would begin to provide statistics adequate to develop differential energy spectra on single-year timescales.

TABLE II: *Event rates per year for several classes of UHE cosmogenic neutrino models. The lowest two models are in direct conflict with observations, which do not favor a strong iron content for the UHECR; and the next model assumes no evolution of the cosmic ray sources, which is also a scenario that is improbable for known UHECR source candidates.*

Cosmogenic neutrino model	36sta/50m events/yr	18sta/200m events/yr
ESS 2001,$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$	3.5	4.4
Waxman-Bahcall-based GZK-ν flux	4.2	4.8
Protheroe and other standard models	4.2-7.8	5.5-9.1
Strong-source evolution (ESS,others)	12-21	13.8-28
Maximal, saturate all bounds	24-40	32-47

Hybrid Events. Not all three neutrino flavors, nor all neutrino-initiated showers can yield hybrid IceCube detections. Neutral current events produce no secondary charged lepton, and will comprise about 20% of all events. In the remaining 80% of charged-current interactions, electron neutrinos undergoing yield a secondary high energy electron which interacts very quickly to produce a secondary electromagnetic shower. Muon and tau neutrinos do produce secondary penetrating leptons which can be detectable at IceCube.

At EeV energies in the heart of the cosmogenic neutrino spectrum, the secondary leptons deposit large amounts on energy quasi-continuously along their tracks, and are detectable optically from several hundred meters distance. Secondary EeV muons yield strong electromagnetic subshowers primarily through hard bremsstrahlung and pair production. Secondary tau neutrinos at these energies give their largest secondary showers through photohadronic interactions, and may also produce a strong shower upon their decay, although they typically must fall below 0.1 EeV through energy loss prior to this. In our simulation we have assumed that all three neutrino flavors are equally mixed, and thus the hybrid event fractions reported here apply to 2/3 of the total events, except at the lowest energies where electron-neutrino events comprise a larger fraction than $1/3$ of the total.

Table III gives the resulting total hybrid events expected for the IceRay-36 detector, for two different IceCube configurations, the baseline design, and one that includes a 1.5 km guard ring, known as IceCube-plus. The totals are for ten years of operation, and although they are relatively small totals, they will represent the first set of UHE neutrino events where the complete event topology can

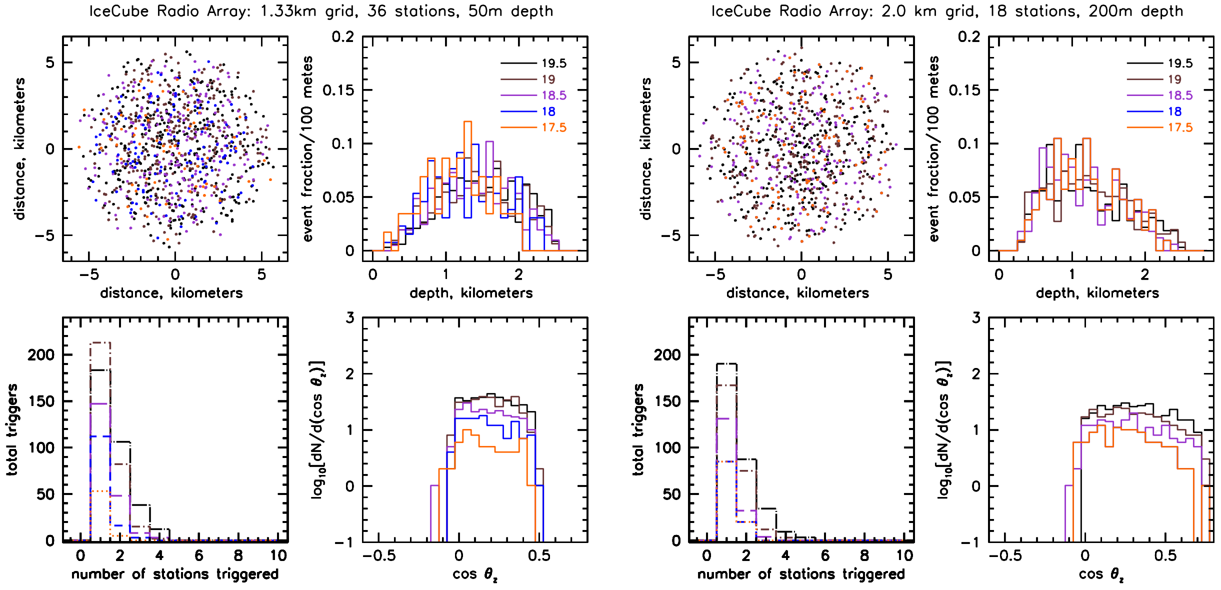


FIG. 17: *Histograms of various distributions from the Monte Carlo results for the two configurations studied. Left: distributions for the 36 station array at 50 m depth with 1.33 km spacing; clockwise from upper left: a) the vertex locations in plan view (color coded by energy according to the legend in the next pane to the right); b) the depth distributions of events with energy, with shape governed in part by the refractive horizon; c) the angular distribution of detected neutrino interactions, most events from above the physical horizon, but cut off by the underice refraction at low zenith angles; d) the multi-station hit distribution with energy. Right: similar distributions for the 18-station array with 200 m depth and 2 km spacing with effects of the less restrictive under-ice refraction horizon evident in the shift of the peaks of the depth distribution, and the wider angular acceptance. However, the coarser station spacing yields fewer multi-station hits.*

TABLE III: *Hybrid event rates for the baseline IceCube, and IceCube-plus (1.5 km guard ring), per 10 years of operation, for several classes of UHE cosmogenic neutrino models, assuming the IceRay-36, 50m-deep radio array.*

Cosmogenic neutrino model	IceCube 10 yrs	IceCube+ 10 yrs
ESS 2001$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$	3.2	6.4
Waxman-Bahcall-based GZK-ν flux	3.8	7.6
Protheroe and other standard models	3.8-7.1	5.0-8.2
Strong-source evolution (ESS,others)	10-19	13-25
Maximal fluxes, saturate all bounds	22-36	30-44

be constrained, and calorimetric information can be extracted. In addition, these events should be free of any known physics backgrounds.

VI. PRIOR/ONGOING NSF SUPPORT

The proposal members have contributed to a variety of successful NSF supported research programs, including AMANDA, Auger, IceCube, and RICE.

AMANDA (Antarctic Muon And Neutrino Detector Array). UW (including R. Morse, AMANDA Principal Investigator, now at UH) has been the lead US institution in the AMANDA collaboration. AMANDA pioneered the use of an array of photo-multiplier tubes in deep clear polar ice to gather Cerenkov light from neutrino generated muons. AMANDA served as a testbed for deployment, DAQ, calibration and analysis techniques that have been vital for development of the IceCube detector. Late in life AMANDA is operating as a high density low threshold component of IceCube.

Auger. J. Beatty (OSU) is a leading member of the Auger collaboration, and serves as Task Leader for the Auger Surface Detector Electronics. The OSU group is involved in work on data acquisition, calibration, and data analysis focusing on the surface detector.

IceCube. Members of this IceRay/AURA proposal from UW, UMd, UD, and KU are all collaborating members of the IceCube collaboration. This includes NSF support for the construction of IceCube. Using data from the first year of physics operation ($\sim$ 12% of full array), the collaboration has already produced its first scientific paper on the atmospheric neutrino flux.

ANITA (Antarctic Impulsive Transient Antenna). While ANITA does not receive direct NSF support, it does receive substantial indirect support through NSF's strong support for the NASA Long Duration Balloon (LDB)

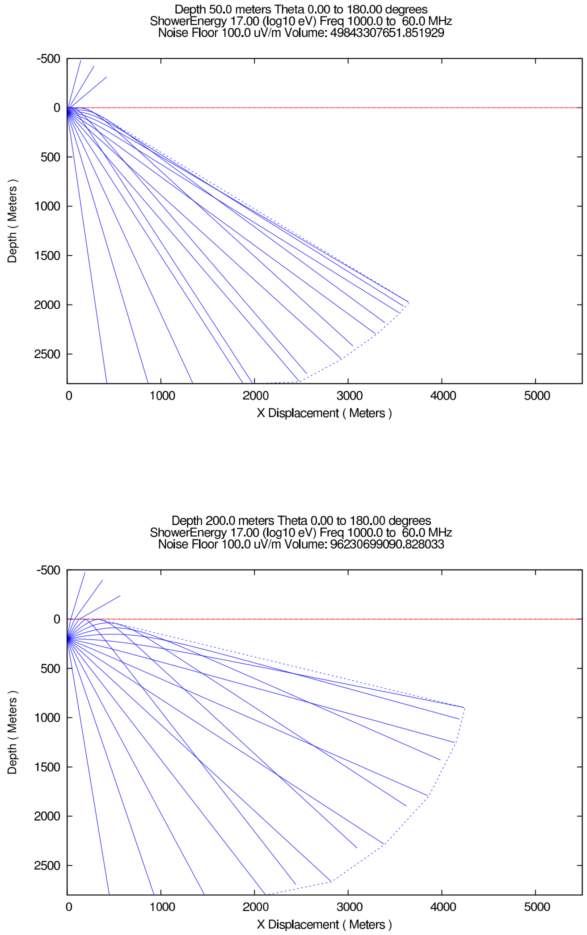


FIG. 18: *Example of refraction effects for shallower antenna locations. Both 50 m (upper) and 200 m (lower) deep antenna locations are shown. On the left are the wide-scale ray geometries, showing the terminal horizon angle in each case, and on the right the details of the ray bending in the near zone are shown.*

Program. Collaborators P. Gorham (PI for ANITA), G. Varner, P. Allison, J. Learned, P. Chen, R. Nichol, and A. Connolly have all played important roles in bringing ANITA to the forefront of current UHE neutrino detectors. Without NSF support for LDB and the infrastructure necessary to sustain it, ANITA and similar projects would not be possible.

VII. BROADER IMPACTS

As Phase-II is intended as an augmentation to IceCube capabilities, we propose to augment IceCube's Education and Public Outreach (EPO) programs with material and activities that will widen the understanding that Cherenkov radiation, the electromagnetic analog to the more familiar acoustic shock-wave, can have effects across the whole electromagnetic spectrum, including radio.

The IceCube EPO program at the UW Madison has focused on three main areas: providing quality K - 12

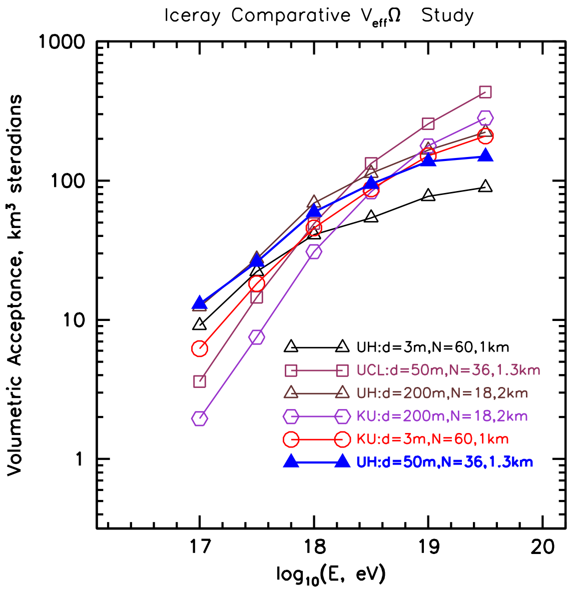


FIG. 19: *Volumetric acceptance, in km^3 steradians, of several arrays studied here, including results from the three independent Monte Carlos within our collaboration: UH indicates Univ. of Hawaii, KU the Univ. of Kansas, and UCL the Univ. College London.*

teacher professional development, and producing new inquiry-based learning materials that showcase ongoing research; increasing the diversity of the science and technology work force by partnering with minority institutions and programs that serve under represented groups; and enhancing the general public appreciation and understanding of science through informal learning opportunities, including broadcast media and museums.

In addition to IceCube's formal EPO program, many efforts to share the excitement of science with students and the public at-large take place at the institutional level as well. Several of our institutions also have formal partnerships with local high school teachers as well.

The University of Hawaii are heavily involved in the QuarkNet program. Through UH's QuarkNet program, established in 2003, Gorham, Varner, and Learned have been actively involved in developing cosmic ray detectors for classroom use. Morse will take on a contributing role for the UH Quarknet efforts, providing seminar and mentoring contributions to the local Quarknet curriculum. The UH Quarknet program involves both teachers and students from under-served outer-island districts, and a radio-based augmentation to this will have accordingly greater impact.