An IceCube-centered Radio Array for Ultra-High Energy Neutrino Event Cross-calibration

R. Morse, P. Allison, M. DuVernois, P. Gorham, J. Learned, & G. Varner, *Dept. of Physics and Astronomy, Univ. of Hawaii, Manoa, HI 96822*; D. Besson, *Dept. of Physics, University of Kansas, Lawrence, KS 66045*; A. Karle, F. Halzen, & H. Landsman, *Dept. of Physics, University of Wisconsin, Madison, WI 53703*; J. Beatty, *Dept. of Physics, The Ohio State University, Columbus, OH 43210*; K. Hoffman, *Dept. of Physics, Univ. of Maryland, College Park, MD 20742*; D. Seckel, *Dept. of Physics and Astronomy, Univ. of Delaware, Newark, DE 19716*; D. Cowen, & D. Williams, *Dept. of Physics, Penn State Univ., University Park, PA 16802*; I. Kravchenko, *LNS, Massachusetts Institute of Technology, Cambridge, MA 02139*; P. Chen, *Dept. of Physics, National Taiwan Univ., Taipei 106, Taiwan.*; R. Nichol & A. Connolly, *Dept. Physics & Astronomy,Univ. College London, LONDON WC1E 6BT.*

I. SCIENCE SUMMARY

We propose here to begin phased development of a low-cost, high-value radio-Cherenkov augmentation to the Ice-Cube detector which will seek the following scientific goals:

1. Extend IceCube energy sensitivity to ExaVolt energies, to yield substantial rates of cosmogenic neutrinos–the so-called "guaranteed" neutrinos

2. Determine source directions for each neutrino to degree-scale precision, thus identifying directly the sources of the highest energy cosmic rays, which produce the cosmogenic ultra-high energy neutrinos

3. Detect and geolocate of initial interaction vertices for neutrino events, and make energy measurements of the primary cascade, yielding a new and complementary measure of neutrino interaction kinematics.

4. Co-detect hybrid events with the main IceCube detector, yielding both primary vertex energy via radio-Cherenkov and secondary lepton energy via optical Cherenkov, for complete event calorimetry on a subset of the total neutrino events.

Our proposed system has the potential to significantly enhance the scientific reach of IceCube with regard to total ultra-high energy neutrino event calorimetry, an imortant and compelling scientific challenge. As we will argue here, a wide-scale radio-Cherenkov detector is a natural and highly complementary addition to IceCube. Recent improvements in the understanding of the method and its technological maturity have greatly reduced both the risk of such systems and their costs. The time to consider such an augmentation is upon us: once IceCube construction nears completion and the infrastructure and human resources begin to dissipate, the costs for such a system will rise immeasurably.

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
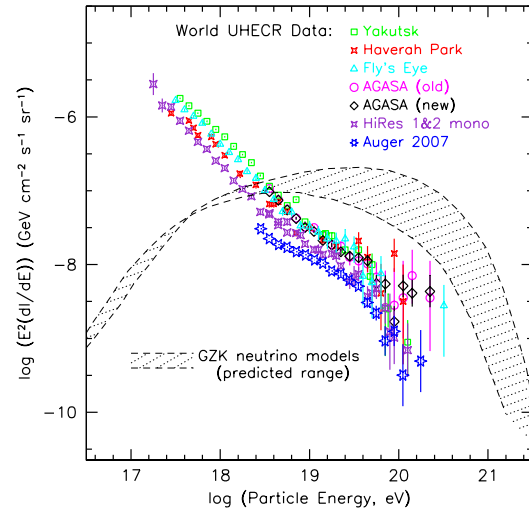

FIG. 1: *World ultra-high energy cosmic ray and predicted cosmogenic neutrino spectrum as of early 2007, including data from the Yakutsk [10], Haverah Park [11] the Fly's Eye [13], AGASA [4], HiRes [22], and Auger [30], collaborations. Data points represent differential flux $dI(E)/dE$, multiplied by E^2. Error bars are statistical only. GZK neutrino models are from Protheroe & Johnson [15] and Kalashev et al. [16].*

$\ell^{\pm}$ may then propagate for 20-30 km or more before it is detected in the optical Cherenkov array. 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 dumped 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. As has now been shown in a series of recent experiments at SLAC, such cascades produce a charge asymmetry as postulated by Askaryan in the early 1960's, and the net negative charge produces strong coherent Cherenkov radio emission, 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 will observe the Cherenkov emission from the primary vertex of the same events that may produce detectable leptons in IceCube. It is these hybrid detections, relying on both radio and optical detection, that we investigate in this report. Such a radio array is completely insensitive to the secondary lepton but even a relatively coarse array, as we will show, with km-scale spacing between small-number antenna clusters, can coherently detect the strong radio impulses from the cascade vertex. The two methods are this truly complementary in their physics reach.

One may ask why such a methodology was not adopted early in the design for IceCube. The answer is that the energy of the events that are detectable by a wide-scale radio array is well above the initial design scale for IceCube, intended to go to PeV scales but initially not above this scale. However, since construction of IceCube began, much work has been done on understanding the high-energy reach of the array beyond the original design scale, and it is now evident that IceCube does have significant reach [18] into the range where there is useful overlap between the techniques, and comparable acceptance. In addition, work on understanding the properties of the Askaryan effect and the radiation it produces has proceeded steadily, and we are now in a position to make confident predictions regarding the sensitivity of radio arrays.

This has been facilitated to a large degree by 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. 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. Thus our design approach has been to require that any radio array that would provide hybrid detection for IceCube cross-calibration must be able to detect such neutrinos with confidence in a single year of operation, even at their lowest plausible fluxes. In addition, we expect that the economy of scale for radio technology, which has been greatly enhanced within the last two decades by the explosion in wireless, microwave, and satellite television device development, will lead to an array that is highly affordable on the scale of a small fraction of the costs for IceCube, operating within the scope of a calibration enhancement to the original array. To this end, our choices for the study array have strongly leaned toward giving up spatial and angular resolution in favor of high sensitivity, to maximize the probability for hybrid radio/IceCube detections.

The Highest Energy Neutrinos.   A proper evaluation of our approach requires an understanding of the distinct nature of the cosmogenic neutrino flux which provides the basis for our design. Figure 1 shows the ultra-high energy cosmic ray flux as of 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) cutoff continue to allow for a relatively wide range of cosmogenic neutrino fluxes, the ongoing measurements of the UHECR fluxes by the Auger Observatory, as well as experiments such as ANITA, will lead to a much better calibration of these "guaranteed" neutrino models. Thus we expect a significant narrowing of the allowed range of fluxes in the next several years. The effective calibration of these neutrino fluxes which are closely tied to UHECR fluxes will result in a standard isotropic test beam of UHE neutrinos which we propose to utilize in the measurements we have studied here.

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 range at which radio detection for an embedded or surface ice array becomes practical. Thus, as we will discuss more 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 detectability for the cosmogenic neutrino fluxes. This has important implications for the final economics of our studied detectors.

Radio Detection History.   It is surprising to find that proposals for multi-cubic-km radio Cherenkov detectors in ice are concurrent or perhaps even predate the earliest suggestions that an optical Cherenkov array could engender neutrino astronomy, but that is in fact the case. In the early 1980's, several Russian investigators began to revisit Askaryan's suggestions regarding coherent radio detection of high energy particles in dense media such as ice, and in 1983, Gusev and Zheleznykh described an array that utilized this methodology.

Figure 2 shows the original figure from the paper by Gusev and Zheleznykh [36] in which a surface radio array with a ~ 10 km^2 footprint is proposed to detect of order 10 PeV neutrinos via antennas with grid spacing of several hundred m.

In the later 1980's and early 1990's further investigations were done on the feasibility of the technique, and a landmark paper was published in 1992 in which E. Zas, F. Halzen, and T. Stanev [38] first presented detailed shower simulations which included electrodynamics 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.

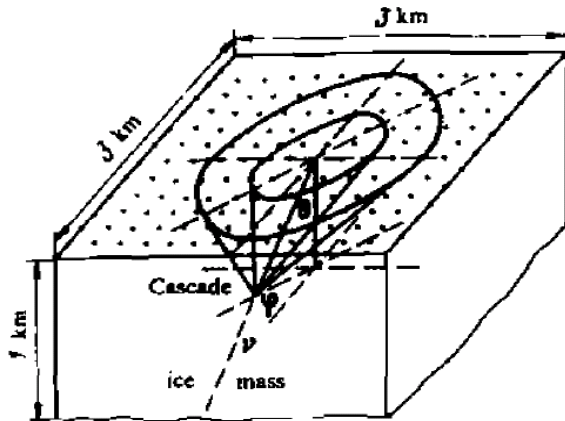Since those results in the early 1990's, the field has

FIG. 2: Original figure from reference [36] in which a surface radio antenna array is used to detect high energy neutrino cascades.

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 array, which continues to pilot the study of embedded detector arrays with a small grid of submerged antennas above the AMANDA detector, the GLUE and FORTE experiments, which set the first limits at extremely high energies above 10^{20} eV, and more recently, the ANITA balloon payload, which completed a prototype flight in 2004, and its first full-payload flight in early 2007.

III. THE AURA/ICERAY-36 PROJECT

IceRay/AURA-2007 proposes to perform a detailed design study, including development of prototype hardware, that will enable the construction GZK neutrino detector array covering a physical area of ~ 50 km^2, working in concert with the IceCube detector at the South Pole. Such a detector will be designed to detect at least 4-8 GZK neutrinos per year based on current conservative models, and would serve as a prototype for expanding to larger arrays of $300 to 1000 km^2$. These larger arrays could detect as many as 30-100 GZK neutrinos per year. The present challenge is to determine the number of individual detectors, their separation distance and the depth at which these detectors should be buried in the Antarctic Ice. This depth question is paramount, since deeper detectors sample a greater volume of ice, 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 an expensive and time-consuming matter. The quest is thus, to find the optimum detector spacing-depth ratio that maximizes GZK sensitiv-

ity while minimizing the cost

AURA is a array of radio detectors buried between 250-1400 meters in the Antarctic ice. These detectors are designed to measure the radio characteristics of the deep ice. Selected IceCube boreholes have radio receivers installed in them to measure the radio spectrum from about 200-1000 MHz. Three such detectors were installed during the 2006-07 polar field season, two at depths of about 1400 meters and the third unit was installed at about 250 meters. These three detector sites have been actively studied since their installation in January 2007. In the 2007-08 field-season, we would like to install four additional frequency extended (60-1000 MHz) AURA-II detectors. Present plans call for installing three shallow detectors (250 m depth), and one deep detector (1400 m) in January 2008.

This AURA work is crucial to our effort 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, so that it is very important that we avail ourselves of every opportunity to instrument these deep holes so that we might get sufficiently reliable data to understand the ice optics at these depths. This is a very important question to study for it tells us "how-much-or-how-little" we might gain in developing the techniques and equipment to deploy detectors into the deep ice.

By constrast IceRay is a shallow detector scheme designed to investigate the radio detection properties from the ice surface down to about 50-80 meter depths, or possibly greater using the much cheaper firn-drill techniques. No one disputes that deep detectors are more effective than shallow detectors, but now this is a quantitative question, how much more do we gain, and is it worth it, given that shallow detector deployments are easier and less costly than the deep deployments. Understanding these trade-offs is a fundamental question confronting the array designers. In that regard, IceRay-36, is a first-blush strawman radio-Cherenkov array with 36 detectors separated by 1.3 km, and buried 50-80 meters in the Antarctic ice. Simulations predict that it will have the capability of detecting 5-10 GZK neutrinos per year.

The Plan. The ice-depth of the detectors and the spacing between them is of paramount importance, and is one of the primary objectives of this study. The detectors are sensitive to the radio Cherenkov signal emitted when these very high energy GZK neutrinos interact and shower in the ice. Since cold Antarctic ice has an attenuations length greater than 1 km for radio emissions in the 60-1000 GHz range, it is possible to detect neutrino signals that are kilometers away. The basic geometry is initially assumed to be like IceCube, that is, individual detectors are located at the apices of equilateral triangles, which then are formed up into series of expanding hexagons as is shown in Fig. 3.
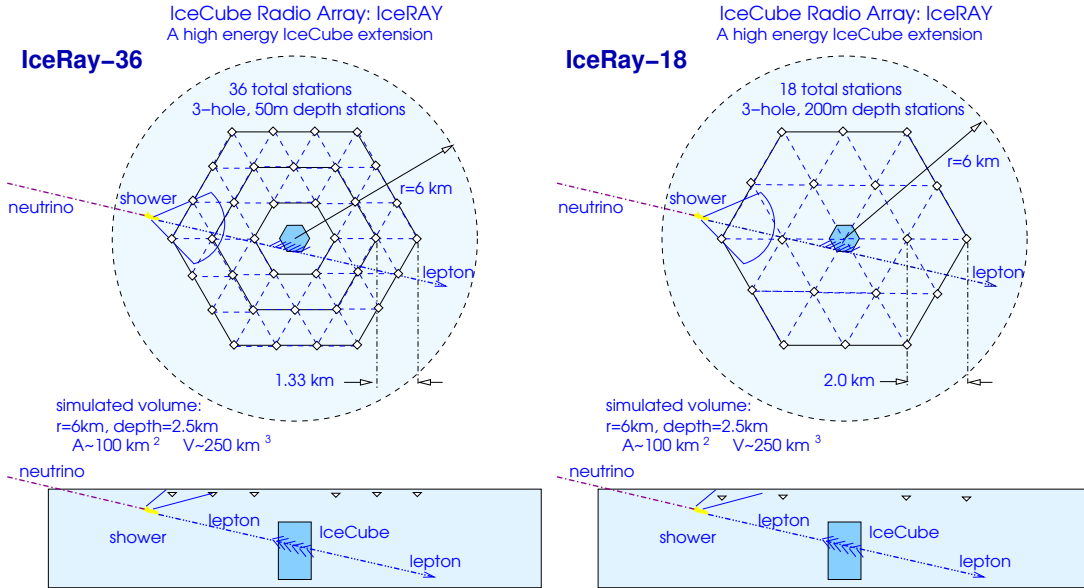
FIG. 3: Left: Baseline 36 station, 50-m depth array. Right: Alternative 200 m depth, 18 station array.

We request support for three years, or from March 2008 to March 2011. The characteristics of deep-ice detection will be studied using the current AURA technology. It is hoped that we can augment this technology by deploying additional AURA-II detectors with an enhanced low-frequency response (down to 60 MHz) in the 2007-08 field-season, and with the possibility of adding even more detectors in future seasons. Operating at these lower frequencies enhances the solid angle acceptance of the detector. Using the fact that the Cherenkov -angle cone broadens from being concentrated at a single angle as in the optical regime, to a wider Gaussian-shaped angular distribution centered around the optical Cherenkov angle at the lower radio frequencies.

The shallow-ice detections schemes will be studied by IceRay. The IceRay plan calls for collaborating with many of ANITA's experienced team members, that is we hope to capture as much of their expertise, knowledge-base, and technology as is possible. In the first season at pole we propose to install a surface listening post, IceRay-0, to determine the strength, and duration of radio emission in the 60-1000 MHz region. This surface listening-post also has SCOARA and the NSF interested in how it might be possible to get a continuous monitoring of the EMI situation at South Pole, that is providing not only frequency usage, but amplitude and duration measurements in a continuously logged fashion. Using the combination of ANITA and IceCube technology this installation of the IceRay surface listening-post should be a straight forward installation.

In the second season (FY-09) we propose installing IceRay-2, or two sub-surface stations at ice depths of between 50-80 meters, or possibly deeper if the firn-drill techniques allow.. These activities would serve as a prototyping of the IceRay-36 array, and give us experience of drilling the holes needed for detector installation. We would also consider installing a few more frequency-enhanced AURA-II detectors. In the third season (FY-10) we would propose installing IceRay-3, or 2-3 more sub-surface stations of ice depths of 50-100 meters, or deeper if developments in firn-drill technology will allow such extensions.

It is hoped that in that in the fourth season (FY-11) that work can start in a modest fashion on the full IceRay-36 array, whatever its form—deep or shallow. The assumption here would be that we have resolved the depth-of-detectors question. This, of course, would be the subject of an proposal submitted to continue the project to its planned full-size. In FY-11 the IceCube work should be ramping down so that a seamless transition from IceCube installation to IceRay installation might be achieved. Given that 5-6 stations might be installed in that fourth season it is estimated that the remaining 25 stations with a modest presence could be installed during the FY-12, and FY-13.

AURA/IceRay Relationship to IceCube. IceRay's relationship to IceCube is critical if we are to minimize the cost and manpower levels associated with the proposed installations of IceRay-2, and IceRay-3 during the FY-09 and FY-10 field-seasons. IceRay, working through the Wisconsin group, can be scheduled into the IceCube deployment plan with minimum impact. IceRay's use of the firn-drill, and the deployment winches is an example of making use of equipment that is already on site because of Ice-

Cube's needs. IceCube drillers and string-deployers are also available to provide advice and experience. In addition, there is a good possibility that the AURA-II detectors will continue to be installed. This AURA install is really pretty transparent to the IceCube operations, so that in general no major issues or conflicts present themselves. In FY-11, after the successful completions of the IceRay-2 and IceRay-3 phases, we could then , with approval, start the IceRay-36 work. FY-11 is also the season when the IceCube deployment will be ramping down, so the degree of coordination between IceCube and IceRay will be reduced.

IceCube presents this wonderful "window of opportunity" for mounting preliminary investigations into new neutrino detection techniques. AURA is thus able to locate radio-cherenkov antennas at depths of 1400 meters. These preliminary investigations would just have been prohibitively expensive, if not impossible, without the IceCube connection. Similarly, the locating of distant IceRay detection stations which requires the ability to place antennas at depths of 50-100 meters below the snow/ice surface would also be expensive without the use of IceCube's firn-drills, winches, and data retrieval systems.

AURA is a extension of the RICE scheme. AURA is a network of radio-Cherenkov detectors installed in IceCube boreholes. To date, three such detectors have been installed, two "deep" detectors at depths of 1400 meters, and one "shallow" detector located at about 250 meters depth. A tentative plan calls for installing about four detectors each year, or eventually instrumenting 20-25% of the IceCube strings.

Having these AURA radio detector's in close proximity to IceCube will certainly enhance IceCube's analysis power. GZK neutrinos are extremely rare, and present estimates are that IceCube may see of the order of one event per year. By incrementally adding a few AURA detectors per year we enhance IceCube's ability to detect and identify these GZK events. This increased "effective volume" is unique to the very high energies of the GZK process. Our ally here is the very cold ice surrounding IceCube. This ice is quite transparent over kilometer scales to radio emission in the 60-800 MHz region where we expect to detect most of the radio-Cherenkov emissions from these GZK events. In essence AURA allows us to look about 1-1.5 km in all directions around IceCube.

Having a few of these hybrid events detected both in radio and in IceCube will allow us to cross-calibrate between the purely optical GZK detection, and the purely radio detections. Establishing this cross-calibration may turn out to be crucial in moving to the IceRay-like purely radio-detection sector covering areas of hundreds of square kilometers, a sector eventually leading to dozens or more of GZK neutrinos detections per year.

Responsibilities and Oversight. It will be the primary responsibility of the IceRay effort not to slow down or in anyway impede the normal progress of the IceCube installation. A planning and oversight group consisting of members from both the IceCube and IceRay collaborations will be formed up to provide the necessary oversight. Of course, it is the primary mission of the IceRay effort to work as efficiently as possibly within the IceCube environment.

It will also be the responsibility of IceRay to propose the most effective and cost-efficient detector design. To guarantee that we are receiving and responding to responsible reviews we plan to form up an external review panel that can provide annual reviews of our designs and our progress. Such a committee would be formed up from the people that are in the radio-Cherenkov detection discipline

IV. DESCRIPTION OF ARRAYS STUDIED

The field attenuation length for South Polar ice in the upper km is of order 1.3 km [45] at frequencies in the several hundred MHz regime. 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.

In one previous study of a combined radio and acoustic detector coincident with IceCube, the Askaryan Under-ice Radio Array (AURA) [17], the goals were somewhat different, and the approach was to build the array initially as part of IceCube itself, making use of the upper portions of the IceCube boreholes and then extending it out to larger radii. Such an array preserved angular resolution and PeV-scale sensitivity while gradually extending its size up to the scale where it could begin to detect cosmogenic neutrinos. Our approach here is quite different; 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. This approach will yield the earliest possible coincident calibration with IceCube, and can thus "pay for itself" through the utility of providing input during the commissioning phase of the full detector, concurrent with its completion.

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 Ice-Cube 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 this study, we adopt spacings of 1 to 2 km, and grid which occupies an initial 4 km radius around IceCube. We treat two cases: a surface array based loosely on the ideas first outlined by Gusev and Zheleznykh, and an embedded array as suggested by the AURA/RICE approach.

Figure 3 shows the two initial arrays chosen for study, the first called *IceRay* for IceCube radio array, and the second *AURA-18*, as an extended version of the original AURA concept (although we have not attempted to make use of acoustic detection here). These initial designs are meant to be low-cost seed arrays for potentially much larger versions, but are designed with sensitivity to GZK cosmogenic neutrinos as their foremost characteristic. In each case a "station" is required to be able to produce standalone 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. To this end we assume each station to consist of 12 antennas 6 of each polarization, horizontal and vertical. 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 5-10 m spacing) at each submerged station.

Choice of frequency. 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. 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).

Antenna effective collecting area A_e is related to its directivity gain G (a measure of its beam shape) by the standard equation $A_e = G c^2/(4\pi f^2)$ where f is the mean frequency and c is the speed of light. Since the radiation that arrives at the antenna from an Askaryan radio impulse is often described in terms of it peak field strength $\vec{\mathcal{E}}_p$ in V/m, the resulting voltage induced at a matched-load receiver attached to an antenna is given by $V_{rcv} = \vec{\mathcal{E}}_p \cdot \vec{h}_e/2$ where the vector effective height $\vec{h}_e$ has a magnitude given by $h_e = 2\sqrt{ZA_e/Z_0}$ where Z is the antenna impedance, assumed matched to the receiver here and $Z_0 = 377\ \Omega$. The direction of the vector effective height is given by the direction of maximum response to an incident linearly-polarized electric field at a frequency where the antenna is responsive.
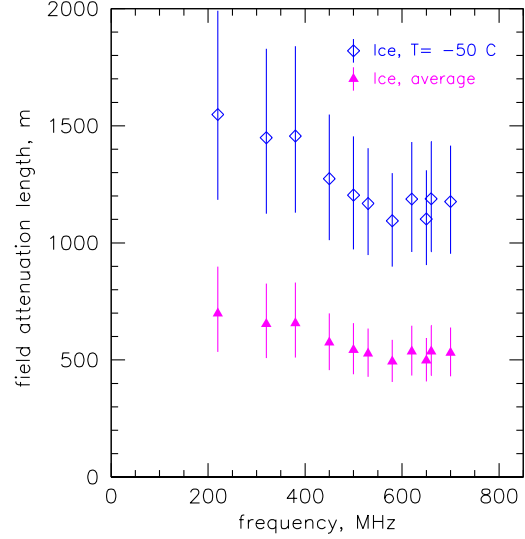

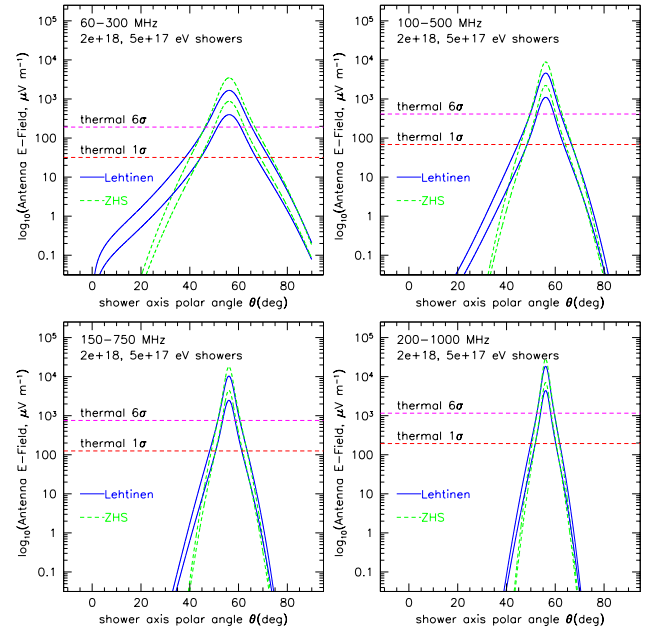FIG. 4: South pole ice attenuation measurements made in 2004.

FIG. 5: Angular widths for various frequency ranges and two cascade energies in the heart of the cosmogenic neutrino spectrum. See text for details.

Coherent Cherenkov radiation arising from the Askaryan effect has a frequency spectrum for which the incident field strength at the peak of the Cherenkov cone rises linearly

with frequency, thus

$$R\mathcal{E}_p \simeq A_0 \frac{E_{shower}}{E_0} f \quad \text{V/m/MHz} \qquad (1)$$

where R is the distance to the shower from the observation point, A_0 is a medium-dependent scale factor, E_{shower} is the shower energy, and E_0 a reference energy. This dependence will obtain up to frequencies where loss of coherence due to the size of the shower begins to set in, typically near 1 GHz for showers in ice. Thus, solving the equations above, we find the induced signal voltage at the receiver is given by

$$V_{rcv} = cA_0 \left(\frac{E_{shower}}{E_0} \right) \sqrt{\frac{ZG}{Z_0}} \, \Delta f \qquad (2)$$

which no longer contains any explicit dependence on *frequency*, though a bandwidth dependence remains in the term Δf. If there is also no implicit dependence of the gain G on frequency, which is often the case with many antennas, then the signal is proportional to bandwidth only, independent of the center frequency.

The system noise is also a consideration, and for a receiver which sees a total system noise (from both the antenna and any intrinsic receiver noise or cable noise) $T_{sys} = T_{ant} + TLNA + Tcable + ...$, 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. Thus the signal-to-noise ratio (SNR) is

$$SNR = \frac{V_{rcv}}{V_n} = cA_0 \left(\frac{E_{shower}}{E_0} \right) \sqrt{\frac{G\Delta f}{kT_{sys}Z_0}} \qquad (3)$$

showing that for Askaryan impulse detection, SNR grows with the square-root of bandwidth, but is independent of the center frequency over which this bandwidth is obtained. Since it is generally easier to observe larger total bandwidths around higher center frequencies, this appears to favor a higher center frequency for observations, all else being equal.

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 here, one dependent on observable volume of ice, and another on the effective solid angle over which events can arrive and still produce detectable emission. Effective volume depends generally on the attenuation length of the surrounding ice. Figure 4 shows recent measurements [45] at the South Pole, based on bottom reflection data (and thus subject to relatively large systematic error bars). It is evident that there is some frequency dependent increase in losses over the range 200-700 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 at the two extremes of frequencies here.

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. The polar angle θ of emission around the direction of the shower momentum peaks at the Cherenkov angle. The angular spectrum of radio Cherenkov emission can be approximated with [32]:

$$F(\theta; f) = \sin\theta \, e^{-(2\pi cL/f)^2(\cos\theta - 1/n)^2/2} \qquad (4)$$

where n is the index of refraction of the medium, and L is a parameter describing the characteristic shower length. The resulting solid angle is

$$\Omega(f) = \int_0^\pi F(\theta; f) \sin\theta \, d\theta \, d\phi \; .$$

Clearly, frequency plays an important role in the total solid angle, entering quadratically in the exponential: However, this integral is not analytic, and analysis of the solid angle as a function of frequency is best done numerically.

To understand the behavior of the solid angle terms, we thus refer to actual simulations of the expected signal, based on semianalytic parameterizations such as that given in equation 4. Figure 5 shows a comparison of the expected signal at a distance of 1.5 km for ice with characteristics of the South Pole. The parameterizations for the radio emission used are those of Zas, Halzen, and Stanev [38] and that given by Lehtinen et al. [32]. The same fractional bandwidth is used in each case, and the noise is scaled assuming an antenna the same directivity gain, constant with frequency, is used for each band considered. 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. 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 compred 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.

Refraction effects. The density of Antarctic deep ice is relatively constant at about 0.9 gm cm^{-3}, but near the

surface the density rapidly decreases, eventually terminating in the density of the hard-packed snow surface that is common to most of the ice sheet. This has a similar effect on the radio index of refraction and is thus important for relatively shallow embedded arrays such as we consider here. Figure 6 shows this behavior in the index of refraction, which is dependent primarily on the density.
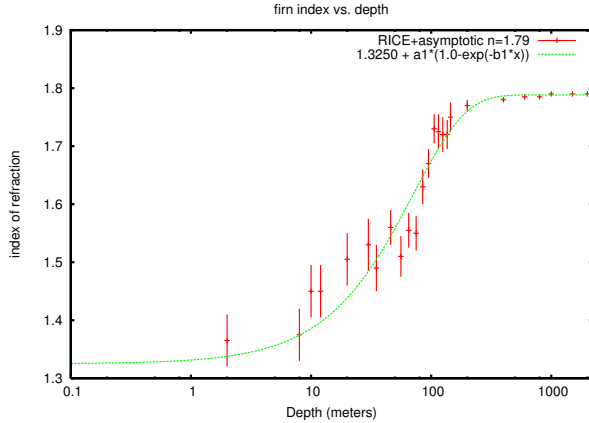

FIG. 6: Index of refraction in firn at South Pole station, based on data from the RICE experiment [40].
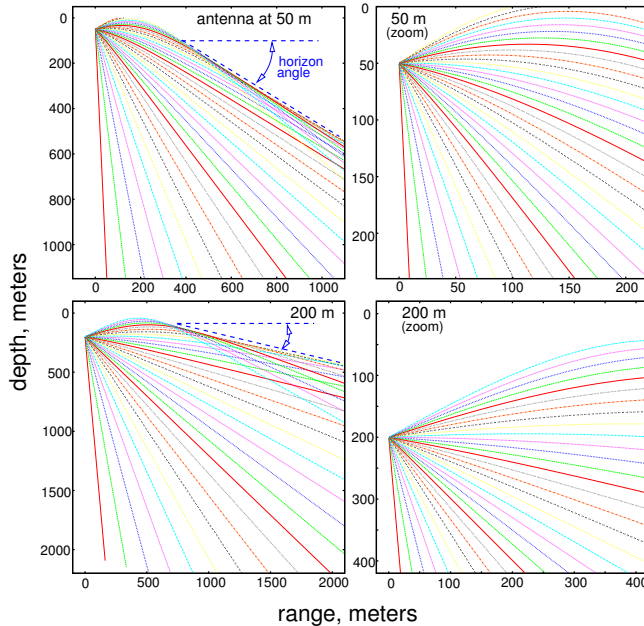

FIG. 7: Example of refraction effects for shallower antenna locations. Both 50 m (upper) and 200 m (lower) deep antenna locations are shown. On the left are the wide-scale ray geometries, showing the terminal hrizon angle in each case, and on the right the details of the ray bending in the near zone are shown.

This behavior in the index of refraction must be accounted for in any simulation, and we show here some representative results giving the ray-trace behavior near the surface. This is of particular concern for a relatively shallow subsurface array, and Figure 7 shows a series of rays traced from deep source directions to the 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 antennas, cannot be neglected in either the 50 m or 200 m array depths we studied here.

V. MONTE CARLO RESULTS

We have studied these arrays with three completely independent Monte Carlo codes (MCCs), and find good agreement with all of them. In addition, the Univ. of Delaware has done MCC studies of some of the specifics of the underice detection, and has independently validated several important aspects of the investigations. The most detailed studies to date were done with the UH Monte Carlo (developed for ANITA and SalSA) from which most of the plots here are derived, but IceRay-36 and -18 studies have also been done with both the Kansas MCC under the direction of D. Besson, modified from the RICE code, and from the UC London MCC under the direction of A. Connolly, which has been developed both for ANITA project and for studies of the ice-surface array ARIANNA. Thus we have considerable confidence that our basic approach has been validated to the highest degree currently possible in simulations, and the simulations themselves have been validated with a variety of experimental efforts.

Figure 8 shows results for some standard distributions for both of the studied arrays, as a function of neutrino energy, over a range of energies important to cosmogenic neutrino detection. Detections are allowed up to 2 km beyond the outer perimeter of the arrays in each case, and this additional volume is important in both cases 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. However, we note that at 10^{17} eV, very few events were detected by the 200 m deep array, due most likely to its sparser spacing. 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, in the lower left, we show the multiple-station hit distribution for the surface array, which has a much higher density by virtue of its economics. For the submerged array, multiple hits are relatively rare, and
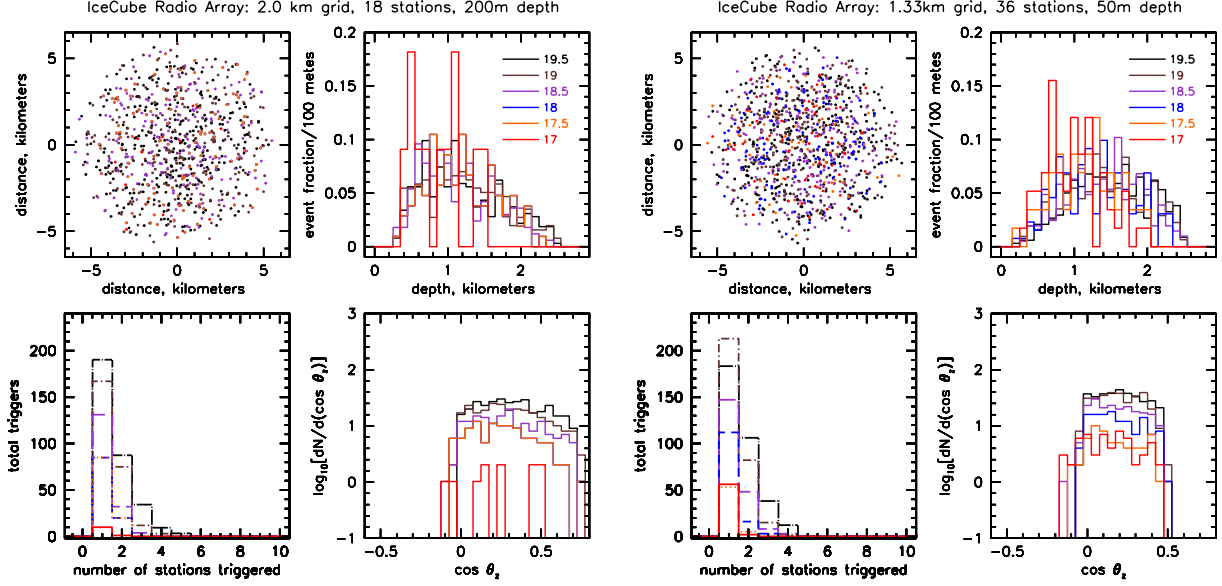
FIG. 8: Histograms of various distributions from the Monte Carlo results for the two configurations studied.

we do not show the distribution here. This is one compensating factor for a surface array– the higher station density will give improved vertex reconstruction on a significant fraction of events.
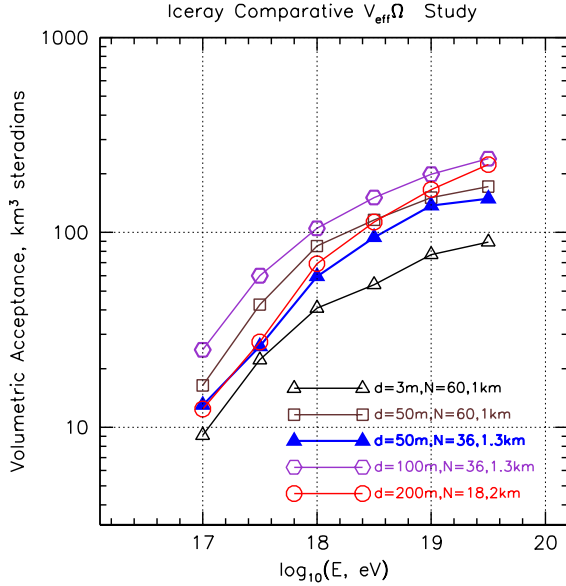

FIG. 9: Volumetric acceptance, in km^3 steradians, of the two arrays studied here.

Figure 9 shows the volumetric acceptance of the two arrays, plotted as a function of energy over the range of interest for cosmogenic neutrinos. The submerged array,

labeled AURA-18 gives about 80% higher acceptance at the highest energies, but at the cost of a somewhat slower turn-on at the lowest energies of interest, where it is has a smaller net acceptance, attributable to the coarser spacing of the submerged array. Table I shows these results in tabular form, and also factors out the solid angle, which is the major difference in the acceptance of the two methods. This arises largely from the fact that the 200 m deep array does not experience as large a degree of firn shadowing that the 50 m deep array does.

TABLE I: *Acceptance and its factors as a function of energy for the two 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
AURA-18 $V_{eff}\Omega$ (km^3 sr)	11.6	38	63	115	137	185
AURA-18 Ω (sr)	3	4.4	4.2	4.1	3.8	3.8

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. The lowest two models [42] are in direct conflict with observations [43], which do not favor a strong iron content for the UHECR since models cannot reproduce the observed UHECR spectral endpoint. Such models are detectable on a several-year timescale, but would yield very few hybrid events and are not considered further. The next three "standard model" cosmogenic fluxes give 4-9 events per year. Such events would be dramatic in

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	36st/50m events/yr	18st/200m events/yr
Fe UHECR, std. evolution	0.50	0.60
Fe UHECR strong src. evol.	1.6	1.8
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
Maximul, saturate all bounds	24-40	32-47

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 diffferential energy spectra on single-year timescales.

It appears plausible that the arrays we have developed for this study can both provide adequate sensitivity for detection of cosmogenic neutrinos on single-year timescales; it remains still to understand the fraction of such events that will provide hybrid detection with IceCube.

Hybrid Events.

Not all three neutrino flavors, nor all neutrino-initiated showers will 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
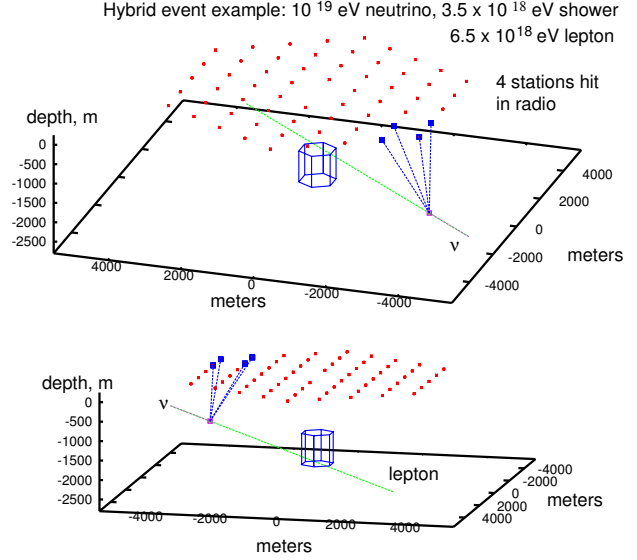

FIG. 10: Example of a hybrid event where the vertex is seen by 4 surface radio detectors and the resulting lepton passes near enough to IceCube to make a detection
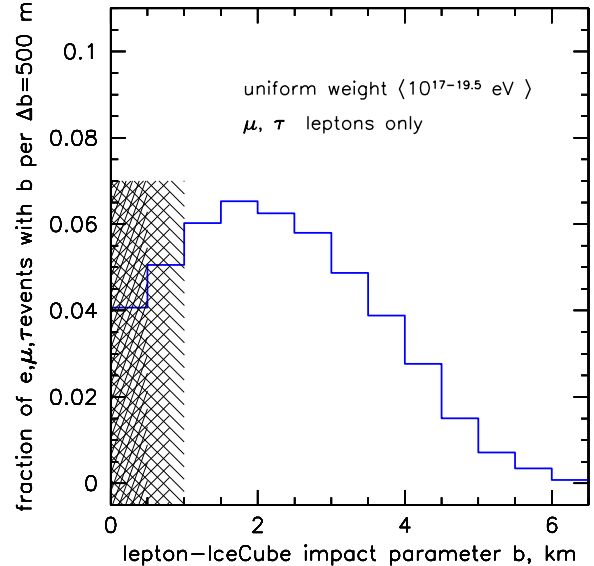

FIG. 11: The distribution of impact parameters relative to the center of IceCube for the outgoing leptons for both muon and tau neutrino events.

energies where electron-neutrino events comprise a larger

fraction than $1/3$ of the total.

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

An example of the overall event geometry for one example is shown in Figure 10. 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.

In Figure 11 we quantify the hybrid event detection fractions for the IceRay-36 array, indicating the distribution of all neutrino events vs. their impact parameter b for 500 m increments, using a graded hatching to denote the regions over which there is a direct detection within the fiducial volume of the IceCube detector, or a detection within a 500 m annular region around the array, as expected for these very high energy (and thus very bright) leptons. We have included electron neutrino events and neutral current events in the total count, even though they do not produce an outgoing long-range lepton, so that the hybrid fractions are with respect to total neutrino events, not just charged-current muon or tau neutrino events. For the standard Ice-Cube geometry, the total hybrid event fraction of is of order 10% in these two regions. Recent studies of "guard-ring" extensions to IceCube [18] 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%.

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

Further enhancement of the hybrid subsample can be achieved using sub-threshold cross-triggering techniques, whereby events detected in either IceCube or the radio array would provide a trigger to the other array, allowing the data stream to be searched for contemporaneous signals that might not have been otherwise detectable. For example, IceCube can only observe events arrive from above the horizon if their energies are very high, far above the atmospheric muon background. However, an apparent atmospheric muon event that was coincident with a radio event with the right geometry could be promoted into the hybrid event subsample. We propose here to quantify the detector requirements to take advantage of such possibilities.

VI. THE ICERAY DETECTOR

The IceRay-36 detector, which we have currently adopted in preference to the 18-station, 200 m deep detector, consists of 36 stations buried 50-80 meters deep in the ice, based on 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. Ray-tracing studies do show a steady improvement fiducial volume in with increasing depth up to about 400-500 meters, however drilling cost certainly do increase. One can compensate for the reduced volume sampled by shallow depth detectors by employing more of them. The present IceRay schemes also calls for three boreholes per detector station, most probably arranged on the apices 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.

Design. The detector system consists of antennas, filters, low-noise amplifiers (LNAs), signal splitters, triggering units, and time-amplitude digitizers which provide a time-stamped data stream that is sent over the data-link to a Central DAQ operating in the IceCube Laboratory (ICL). The detector is designed along the lines used by ANITA.

Antennas that can be deployed can be combinations of simple dipoles, discones (vertical polarization), or batwings (horizontal polarization). Fortunately, because of our frequencies of interest (60-1000 MHz) all these devices are physically small, being of the order of 0.3-1.0 meters in size. All of the devices will have to fit down a 60 cm borehole. All of these various antenna designs can be numerically studied as to gain and directional patterns with the NEC codes to provide performance vs frequency plots.

IceRay, like AURA, will use an "ANITA-like" trigger system, where basically the sensitive frequency region is broken up into four sub-regions of about 200 MHz bandwidth. The power in these various bands is measured by tunnel diodes functioning as square-law detectors. Four DC levels are thus presented to discriminators so that various combinations of trigger combinations can be formed up.

The time-amplitude information is captured by the BLAB chip. BLAB is a 2nd generation Labrador Chip developed for use in ANITA. We propose to use the BLAB2 ASIC, a custom 64k deep switched capacitor array "oscilloscope on a chip". These 65,536 samples may be partitioned among 16 input channels or ganged together to form a single sample record. In this latter configuration, at 1GSa/s, a maximum global trigger latency of 65us is possible, allowing communication of trigger conditions between stations. Measurements with the first generation BLAB1 indicate that sampling rates between 0.1 - 6 GSa/s are possible, as well as 300MHz of analog bandwidth. BLAB2 should extend this analog bandwidth to at least 500MHz. The die is just over $10mm^2$, fabricated in the TSMC 0.2um CMOS process, and we plan to package it in a 100-pin PQFP leadframe, as has been used for both the LAB3 (ANITA and existing AURA prototypes) and BLAB1. Average measured noise for BLAB1 is approximately 1.4mV per sample, with a dynamic range of over 1.5V, corresponding to 10 true bits of single-shot resolution. Conversion speed depends upon sample window size. Digitization speed is 33ns/sample or just over 2ms for all samples. A key feature of this architecture is low power. Typical power draw during sampling is less than 50mW per channel, with increase to approximately 200mW during conversion.

Construction. 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 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.

The signals detected by the antennas are fed to the LNAs (50 dB gain) and then run to the surface via coaxial cables to a data collection box (DCBs) on the surface. In addition, this shielded DCB accepts the power to run all the devices from the station DC power supply and cable system. The DCBs also provides additional amplification of each of the antenna channels. The various antenna signals are then routed to discriminators to determine that we have a signal of interest, and if they trigger, the signals are then run to the BLAB digitizers, where their full time-amplitude development is digitized, and the data is routed via the power-signal cable to the Central DAQ in the ICL. We are also going to investigate possibly sending the data over a fiber-optic line.

Ice Drilling and Deployments. 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.

Power and Signal Transport. .... 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, though we will be looking into a combo-cable that carries both power and fiber optics. 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 might be quite different for IceRay-36 as opposed to an IceRay-300 design. The present cable design has been supplied by Ericsson, who also makes the IceCube cables. It consists of three twisted-quads or 12 0.9mm wires (#19 AWG). Two of the quads carry 100 watts of 120 VDC power, while the third quad carries the signals from the detector location approximately 2 km to the ICL. The voltage drop is about 25 volts over 2 km, so it represent about a 25% power-loss in the cables. It is expected that we will supply about 125 VDC at the ICL to obtain about 100 volts and 1 amp at the detector to supply power to the various DC to DC converters. 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.

Control & Data Handling. The IceCube infrastructure is used for communication, control, timing, data handling and data transfer to the northern hemisphere. Once a multiple bands and antenna triggers occurs, the digitized waveforms are read from all the antennas, packed and sent to a special designated host machine located in the IceCube Counting house on a special crate. The station is connected to the counting house through a surface junction box, using the additional special connector for special devices when not used for IceCube instrumentation. A surface cable from the surface junction box runs to the central counting house. The South Pole host machines (hubs) are standard industrial Single Board Computers. The communication is done through a customed PCI cards developed for IceCube (DOm Readout card). The hub is also equiped with a special service board distributing the GPS time string to all PCI cards. Each hub is costumized with +48 Volt and -48 Volt switiching regulated AC-DC single output power supplies, to supply 96 Volts to the main boards. Each DOR card can connect to two power and communication wire pairs. For IceCube, they were used to connect two adjacent DOMs on a string. We will use one of the wires to connect to the main board, and the other to supply additional power to the RF amplifiers using an external power supply. Timing with an accuracy of a few ns is achieved by using the RAPCAL method as used by IceCube. Offline processing looking for time coincidenced between several stations and with IceCube, will further filter the data.

VII. THE AURA DETECTOR.

RICE (the Radio Ice Cerenkov Experiment) was the first array in the Antarctic to employ the Askaryan effect in the search for neutrinos and other high energy phenomena. Since it began operations, RICE has mapped out the South Pole RF noise environment, studied the RF properties of the cold South Polar ice, and developed techniques for radio analysis, eventually setting limits on low scale gravity and other high-energy phenomena. Following on the success of RICE, which was largely deployed parasitically to the AMANDA installation, the AURA collaboration was formed to exploit 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 quickly develop radio instrumentation that could be scaled up to a large englacial array for GZK neutrino studies.

Regardless of whether a future GZK scale neutrino detector takes the form of a surface array or an in-ice array, studies of the RF properties of deep ice made accessible by IceCube drilling may prove to be invaluable. Be-
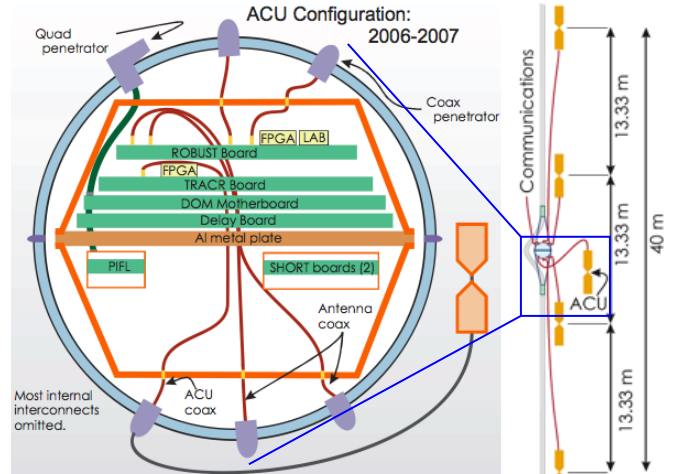

FIG. 12: Left: A schematic of the DRM. Right: its location along an IceCube string.

cause the shallowest IceCube istrumentation is installed at 1500m, the AURA collaboration has the ability to study ice properties in situ down to depths of 1.5 km. This information could provide crucial inputs into ray tracing programs which must track RF response over large volumes of ice. Further, the trade off's between shallow deployments, which are cheaper and provide more RF transparency since the ice near the surface is colder, and deeper deployments, which have a larger aperture for events at or above the horizon, and suffer less from the ray tracing difficulties created by the variable refractive index of the firn, can be fully studied. Finally, monitoring some portion of the ice with both radio and optical sensors may provide a small but indispensable sample of events that are seen by both instruments, which could be used for cross calibration.

In the austral summer of 2006-2007, the first AURA instrumentation was deployed: two clusters consisting of four receivers and one transmitter, and one cluster with a transmitter only. A schematic of a cluster is shown in Figure 12. 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.

A schematic of the DRM is shown on the right in Figure 12. 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) digitization chip, the PIFL supplies the power, and a Motherboard that controls the communication and timing. The sampling speed is 2 GSPS, with a 1.3 GHz bandwidth and 256 ns buffer depth. The simple RICE-style dipole antennas have been used. Located near each antenna are pressure vessels containing front end electronics for amplification and filtering. The digitized data is sent to the surface using the IceCube in-ice and surface cables where it is being processed and analyzed.

The DRM with the single transmitter and one of the transmitter-receiver clusters were deployed in holes drilled 500m apart at a depth of 1450 m with unused connectors in the IceCube cable. This 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, when the clusters were first frozen in, they 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 Ice-Cube electronics has been studied using the deep transmitter cluster by taking special runs with IceCube turned on and off.

For the austral summer of 2007-2008, AURA plans to install an additional four DRMs. Although they will be similar to the modules installed last year, some tweaks have been made based on the experiences with the clusters currently operating. First, they will have the ability to transmit much stronger signals. The existing DRMs can detect their own transmitter, but it is hard to see unambiguous transient signals over long distances. With stronger signal, we will be better able to perform vertexing studies. Some changes have been made to the antenna design as well. The design of the currently deployed receivers, which have a peak response around 400 MHz, has been tweaked for a more uniform response over a wider range of frequencies. Since monte carlo studies have shown a much higher hit multiplicity in lower frequencies, presumably due to the diffractive widening of the Cerenkov cone, a few channels will be dedicated to studying the low frequency noise environment and will be left out of the trigger. For these channels, some changes have been made to the electronics, including changing the frequency threshold on a high pass filter in the front end, and new larger dipole antennas with lower frequency sensitivity will be used. A few alternative antenna designs, such as a bicone, will also be installed on select channels for study. A few optimizations to the DRM electronics have been made as well. Three of these DRMs will be deployed at depths of 250m in IceCube interior holes, and one DRM will be deployed at 1450m. The deep cluster is scheduled to be installed on an exterior IceCube to place it on the Cerenkov cone for IceRay transmissions, providing a synergistic cross sudy between the two instruments.

We will continue to pursue options for an array to study GZK neutrinos. Whether we conclude that surface antennas, in ice deployments, or some hybrid approach provides the best option, our goal is to have working prototypes by the time IceCube construction is complete, so that plans for a larger array can commence in a timely fashion. 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.

VIII.   PRIOR NSF SUPPORT RESULTS

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 Morse, 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. Data from earlier years is producing a steady output of scientific papers on virtually all subjects of high energy neutrino Astronomy, from atmospheric neutrinos to constraints on AGN models with neutrino enegies above a PeV.

Auger.   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. The southern Auger detector is nearly complete, and results concerning the spectrum, anisotropy, and composition of the highest energy cosmic rays are being released.

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 managed through UW and disbursed to US collaborators, as well as 'Physics analysis' grants to the individual institutions. The main component of IceCube is a 1 km^3 neutrino detector, deployed at a mean depth of 2 km at South Pole. The detector consists of an array of PMTs for detecting optical Cerenkov signals - ultimately due to neutrino interactions in deep ice, or in

bedrock below the detector. The detector is approximately 1/4 finished. It has an operational live time of better than 95%, and is transmitting ~ 30 GB of filtered data per day to the northern hemisphere. 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. The experiment also includes Ice-Top, an array of frozen water tanks, reminiscent of Auger tanks, for detecting cosmic ray induced air showers. In coincidence with the in-ice detector, such events are useful for cosmic ray science, calibration, and vetoing a background of large cosmic ray events which may masquerade as UHE neutrino events in and near the deep detector.

RICE (Radio Ice Cerenkov Experiment). Besson (KU) is the PI of the RICE experiment. Seckel (UD) and Kravchenko (MIT) have been collaboration members since its inception in 1995. RICE is a prototype for an englacial neutrino detector utilizing the Askaryan radio technique. RICE has deployed over 20 receivers in the Antarctic ice at South Pole and has collected physics quality data since 2000. RICE data is responsible for the strongest limit on UHE neutrino fluxes in the energy range of $10^{17} - 10^{18}$ eV. RICE data has been used to place limits on neutrino nucleon cross-sections in low scale gravity models, the flux of ultra relativistic magnetic monopoles, and the flux of UHE neutrinos from gamma ray bursts.

IX. BROADER IMPACTS

The opportunity to explore a new technique to monitor the universe provides a wonderful platform for illustrating how new approaches to science are developed. The challenges of carrying out his work in the extreme Antarctic environment makes for a compelling story that will interest students, teachers and the general public.

In particular, the connection of IceRay/AURA to the IceCube project opens up many avenues already in place for Education and Outreach. The IceCube E & O program at the UW Madison has focused on three main areas: providing quality K - 12 teacher professional development, and producing new inquiry-based learning materials that showcase ongoing research; increasing the diversity of the science and technology workforce by partnering with minority institutions and programs that serve underrepresented groups; and enhancing the general public appreciation and understanding of science through informal learning opportunities, including broadcast media and museums. These efforts have been supported by the University of Wisconsin since 2001.

In addition to IceCube's formal E & O program, many efforts to share the excitement of science with students and the public at-large take place at the institutional level as well. Kara Hoffman frequently visits local high schools to talk to students about her life as a scientist and Polar traveler. Within the last year, Dave Besson at the University of Kansas has been giving classes to senior citizens on the subject of astrophysics, with a particular emphasis on his own experience with RICE and AURA. These classes are typically attended by $\sim$50 persons from the Lawrence-Topeka-Kansas City area.

The primary science mission of this proposal lends itself to active undergraduate involvement. RICE has benefited from the efforts of previous physics majors – seven KU undergrads, including Adrienne Juett (Goldwater Scholar, 1998, and MIT, Ph.D., 2005), Dave Schmitz (Goldwater Scholar, 2001, now finishing his Ph.D. at Columbia), Josh Meyers (Goldwater Scholar, 2003, now a grad student with the Perlmutter group at LBL), and Hannah Swift (Goldwater Scholar, 2005, also a grad student with the Perlmutter group at LBL) performed initial work on data analysis and both the attenuation length and index-of-refraction measurements at the South Pole. Current undergrad, and Rhodes Scholar nominee Daniel Hogan is currently finishing an analysis of the sensitivity of RICE to monopoles. The University of Maryland has also involved three undergraduate physics majors to produce simulations to determine the optimal placement of the AURA hardware. We expect to continue this heavy reliance on undergraduates as the radio effort moves forward in the future.

Several of our institutions also have formal partnerships with local high school teachers as well. The OSU group is working with teacher Doug Forrest at Pickerington North High School in suburban Columbus to incorporate simple cosmic ray experiments into the honors physics high school curriculum. They helped him secure $11,000 form a local educational foundation for laboratory equipment, and are working with him to design appropriate experiments and educational materials and conduct classroom visits from time to time. Both the University of Maryland and 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. UM's QuarkNet chapter was established in 2002, and since her arrival at UM in 2004, Hoffman has been the main organizer and mentor for this group. In the past summer, she ran her third summer teacher institute, and she has been instrumental in increasing participation from ethnically diverse communities. She has also helped secure cosmic ray detectors for several of the teachers she mentors.