

# Toward Hybrid Optical/Radio/Acoustic Detection of EeV Neutrinos

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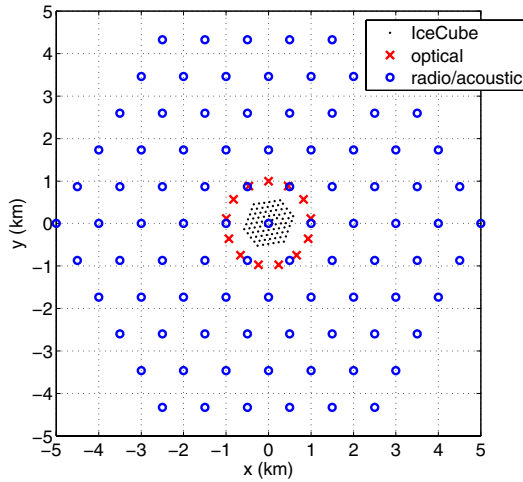
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**Abstract.** Astrophysical neutrinos at EeV energies promise to be an interesting source for astrophysics and particle physics. Detecting the predicted cosmogenic (Greisen-Zatsepin-Kusmin, “GZK”) neutrinos at  $10^{16}$  -  $10^{20}$  eV would test models of cosmic ray production at these energies and probe particle physics at  $\sim 100$  TeV center-of-mass energy. IceCube may be able to detect  $\sim 10$  GZK events per year with an extension including optical, radio, and acoustic receivers sparsely arrayed surrounding the optical core. Such a detector would feature cross-calibration with coincident events and would allow superior background rejection capability, energy and direction resolution, and confidence in discovered signals compared to single-method detectors. We present estimates of the neutrino effective volume for such a hybrid array both with the single-method sub-arrays independently and requiring combinations of sub-arrays to detect the same events. We also present ideas on hybrid event reconstruction and results from a proof-of-principle Monte Carlo test of a hybrid reconstruction algorithm.

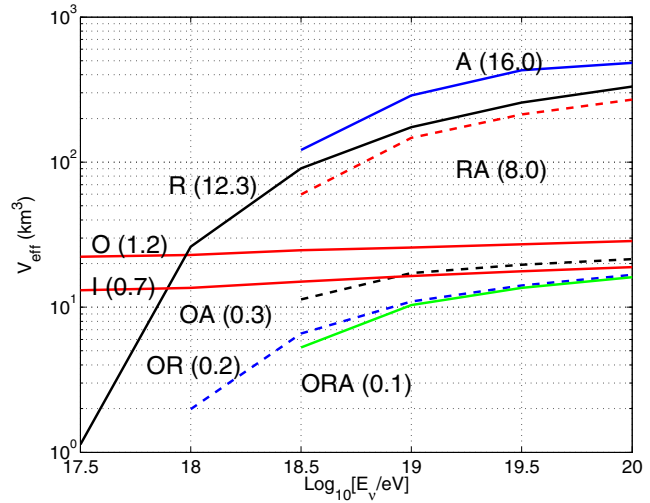
## 1. Sub-Array and Coincident Effective Volumes

Less than one GZK event per year is expected to be detected by  $\text{km}^3$  optical neutrino telescopes. To increase this rate to greater than 10 per year in order to do physics and astronomy with angular, temporal, and spectral distributions, alternative techniques such as radio and acoustic are necessary. However, while both methods have been verified with proton bunches in accelerator tests, neither has detected a neutrino. Although both the optical and radio methods may be near the threshold of discovering GZK neutrinos, either method will require careful separation from backgrounds and may require verification with an independent method. It may be possible to build a hybrid detector that can detect a large number of radio and acoustic events, a large fraction of which are in coincidence with one another and a small fraction of which are also detected by an optical detector. A signal seen in coincidence between two of the three methods would uniquely confirm the signal and constrain its parameters better than any single method alone.

A large hybrid detector could be realized by expanding the IceCube observatory currently under construction at the South Pole. We estimated the sensitivity of such a detector by exposing all three components to a common Monte Carlo event set and identifying events detected by each method alone and by each combination of multiple methods. We used a configuration consisting of a “small” optical array overlapped by a “large” acoustic/radio array with a similar number of



**Figure 1.** Geometry of the simulated hybrid array.



**Figure 2.** Effective volume for each of the seven combinations of detector components, as well as for IceCube alone (“I”). GZK event rates per year are given in parenthesis.

strings but larger horizontal spacing (Fig. 1). We take the optical array to be IceCube augmented by a ring of 13 optical strings with a 1 km radius [1]. Encompassing this is a hexagonal array of 91 radio/acoustic strings with 1 km spacing. The optical strings are instrumented in depth from 1.5 to 2.5 km, and the radio/acoustic strings from 0 to 1.5 km.

To obtain event rate estimates, we assume all upgoing neutrinos in this energy range are absorbed in the Earth before reaching the fiducial volume, and no downgoing neutrinos are. Vertices are generated uniformly in a fiducial cylinder of radius 10 km, extending from the surface to 3 km depth. The Bjorken parameter  $y = E_{had}/E_\nu$  varies with energy and from event to event, but we choose the mean value,  $y = 0.2$ , for simplicity. We assume electromagnetic showers are undetectable by the radio and acoustic methods due to the LPM effect; we only include hadronic showers. AMANDA, RICE, and SAUND software was used to determine the response of the individual optical, radio, and acoustic arrays. More details can be found in [2].

Ten-thousand events were generated at each half-decade in neutrino energy and the common event set was processed by each detector simulation. For each method and combination of methods, the number of detected events was used to calculate effective volume as a function of neutrino energy (Fig. 2). This was folded with a standard GZK flux model and standard cross-section parametrizations to estimate detectable event rates (Fig. 2). We use the Engel-Seckel-Stanev (ESS) flux model that assumes GZK source evolution tracking the star formation rate (SFR) according to  $\Omega_\Lambda = 0.7$  [3]. For radio, acoustic, and their combination, all flavors and both CC and NC interactions were included. For those combinations including the optical method, only the muon channel has been simulated thus far. The cascade channel is expected to contribute a comparable event rate.

## 2. Hybrid Event Reconstruction

Once GZK neutrinos are discovered, it will be desirable to improve the accuracy of the energy and direction reconstruction of the events to do physics and astronomy. For charged-current  $\nu_\mu$  events, it would be possible to detect the outgoing muon with the optical array, and the hadronic shower with one or more of the optical, radio, and acoustic arrays. For both charged-current

and neutral-current events of all neutrino flavors, a hadronic cascade is produced that could be detected by any combination of sub-arrays. To do physics with reconstructed neutrino energy and direction using cascades, most approaches depend on first determining the cascade location precisely.

There are two possible strategies to combine the information from sub-arrays: (1) operate the sub-arrays independently with high threshold and quality cuts, allowing high confidence in events detected by any sub-array individually and even higher confidence in coincident events; or (2) operate the sub-arrays with lower threshold such that each array alone has a high event rate but sufficient confidence in the events is only achieved when information from the sub-arrays is combined. This second possibility could be achieved either with online triggers initiated of one sub-array by another, or with offline analysis.

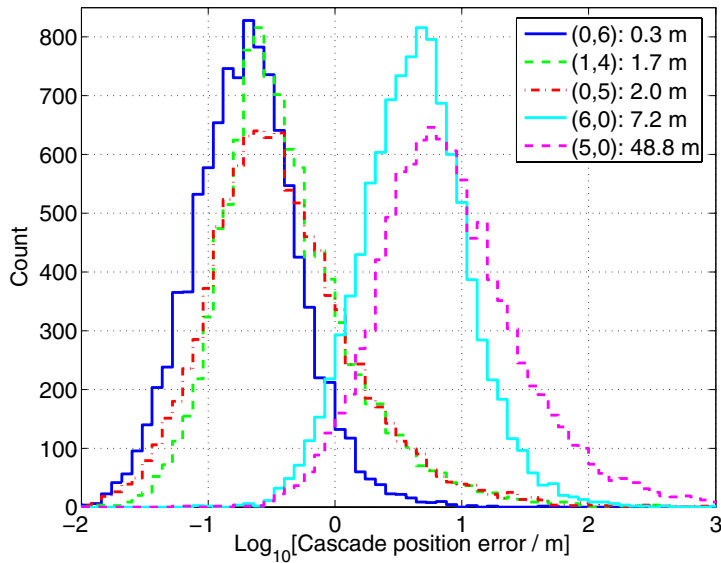
Photons in AMANDA and IceCube typically scatter multiple times between emission and detection, scrambling the propagation direction and smearing and delaying the arrival time by an amount comparable to the direct travel time. Optical reconstruction algorithms therefore require many hits in order to determine the width of the arrival time distribution or to record enough counts to pick out the first ones corresponding to unscattered photons. Radio and acoustic signals, on the other hand, propagate largely unscattered. The signal time of flight is directly related to the source-receiver distance. Moreover, the radiation pattern is preserved: while optical Cherenkov cones are significantly distorted by scattering, the radio Cherenkov cone and the acoustic radiation disk geometries are preserved in the configuration of detector modules that are hit.

Timing algorithms can be used both to reject noise hits and to reconstruct the cascade location: source reconstruction with one or more noise hits with random arrival time typically results in equations with no solution or gives a nonphysical source position. Analytical equations exist to reconstruct the source position and time from a set of hits, where a hit is a trigger at a particular position and time. An event can include any number of optical, radio, and acoustic hits, and we wish to determine the cascade location that produced the hits. For a set of pure radio or pure acoustic hits, algorithms exist to linearize the equations (each independent pair of hits constrains the source location to a hyperboloid) and analytically determine the least-squares solution to the system of equations in the presence of measurement error.

This can also be done when two different signal types traveling at two different speeds are combined. Over km-scale distances, optical and radio signals travel for  $\sim 10^{-6}$  s while acoustic signals travel for  $\sim 10^{-1}$  s; optical and radio propagation are instantaneous with respect to acoustic. This is even true in the presence of optical scattering, which introduces a time delay significant compared to optical unscattered travel time but insignificant compared to acoustic travel time.

Under this approximation, the radio or optical signal arrival time is *equal to* the acoustic signal cascade emission time with respect to the acoustic hits. If multiple radio or optical hits are present, the first hit can be chosen to improve the approximation. Each acoustic hit now constrains the source to a sphere. These equations can be linearized to give an analytical solution similar to that for hit sets of a single signal type. Most combinations of  $(N_O, N_R, N_A)$  (where  $N_i$  denotes the number of hits of signal type  $i$ ) with at least 4 total hits permit an analytical solution.

A simple Monte Carlo program was written to investigate this algorithm. We do not choose a particular array geometry or simulate neutrino-induced signals. Instead we simply generate a set of module locations and a source location, all chosen uniformly in a fiducial volume (a cylinder of height 1.5 km and radius 5 km), independently for every event. We then determine the hit time for each module and include a finite time resolution. Including a particular array geometry and simulating the actual configuration of hits produced by neutrino interactions can be expected to modify the results from this study, but this constitutes a basic proof of principle



**Figure 3.** Cascade vertex reconstruction resolution for various combinations of (radio, acoustic) hit multiplicities. For each combination, the mean vertex reconstruction error is given in the legend. Note that the hybrid configuration gives a similar result to that expected from a set of acoustic hits with the time resolution of one hit replaced by the (smaller) radio array crossing time.

for the algorithm.

Fig. 3 shows cascade location reconstruction results for various  $(N_R, N_A)$  combinations. We include time resolution by smearing signal arrival time by  $\pm 5$  ns for radio hits and  $\pm 10$   $\mu$ s for acoustic hits. For single-method configurations, the resolution scales as expected with time resolution and signal speed:

$$\frac{\sigma_r(R, 6)}{\sigma_r(A, 6)} = \frac{\sigma_r(R, 5)}{\sigma_r(A, 5)} = \frac{\sigma_t(R)c(R)}{\sigma_t(A)c(A)}, \quad (1)$$

where  $\sigma_r(i, N)$  is the cascade position resolution for  $N$  hits of signal type  $i$  (using the mean error given in Fig. 3),  $\sigma_t(i)$  is the time resolution for hits of signal type  $i$ , and  $c(i)$  is the propagation speed of signal type  $i$  ( $c(R) = \frac{3}{1.8}10^8$  m/s,  $c(A) = 3900$  m/s). The resolution also improves by the same factor for radio compared to acoustic hits in increasing the hit multiplicity from 5 to 6.

In addition to signal time of flight, the radio and acoustic radiation patterns could also be used for event reconstruction. Comparing the geometrical arrangement of hit modules with the known radiation pattern (conical for radio, disk-like for acoustic) could be a valuable method to reject individual noise hits, reject background events, and fit for the cascade location and orientation. In the case of acoustic hits, the radiation pattern is flat enough that simply fitting a plane to the hit modules yields an upward normal that is within  $\sim 1^\circ$  of the incident neutrino direction (determined by the width of the radiation pattern compared to its radius). Hit amplitudes could also be used. Finally, radio Cherenkov cones have a known polarization orientation which could further enable background rejection and signal reconstruction.

It may be possible to build an extension like that considered here for a relatively small cost. Holes for radio antennas and acoustic transducers can be narrow and shallow. Acoustic signals are slow moving and low-frequency, making data acquisition and processing requirements inexpensive. Extending IceCube with radio and acoustic strings could produce a neutrino detector competitive with other projects optimized for high-statistics physics and astronomy with GZK neutrinos but with the unique advantages of coincident optical-radio, optical-acoustic, and radio-acoustic events.

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