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# Optimizing Deep Underwater Neutrino Detectors*

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ABSTRACT

Procedures for the determination of the best parameters for an underwater neutrino detector are discussed. These parameters will depend on the choice of physics to be emphasized: through-going muons or contained events, low energy or high energy. The DUMAND II array currently being readied for deployment is discussed as a concrete example.

## 1. Introduction

Several large deep underwater neutrino detectors are now planned or under construction: AMANDA, BAIKAL, DUMAND and NESTOR. The first two will operate at about one km depth, the second two at 4 km or greater. AMANDA will actually be in polar ice, but it will operate on the same principle as others, namely the detection of Cherenkov light from the muons and electrons produced by the interaction of neutrinos in the water.

While the Cherenkov technique has been applied with great success in the underground experiments IMB and KAMIOKANDE, these instruments were designed primarily to search for proton decay. Neutrino astronomy was a minor consideration in the original planning of these experiments, their sizes being regarded as too small to see extraterrestrial neutrino events unless these phenomena defied reasonable expectation. Nevertheless, the power of the Cherenkov technique for neutrino telescopes was demonstrated with the observation of neutrinos from SN1987a by both groups, and by the confirmation of the solar neutrino deficit by KAMIOKANDE. The technique also has proved useful in the search for neutrino oscillations, with both groups finding a $\nu_\mu/\nu_e$ deficit that might be a sign of oscillations.

Deep underwater detectors represent the next generation of

* To appear in the Proceedings of the 2nd NESTOR International Workshop, 19–22 October, 1992, Pylos, Greece, L. Resvanis, ed.

Cherenkov neutrino experiments, after IMB and KAMIOKANDE. Unlike the latter, they are being built with neutrinos in mind as a signal rather than as an annoying background to proton decay. However, the optimum configuration of these experiments still depends on the physics emphasis that the experimenters choose to make. A detector designed for through-going events will be different from one for contained events. We want maximum detection area for the first, maximum detection volume for the second. Similarly, the energy range to be explored dictates certain geometrical parameters, such as the spacing of Cherenkov light sensors.

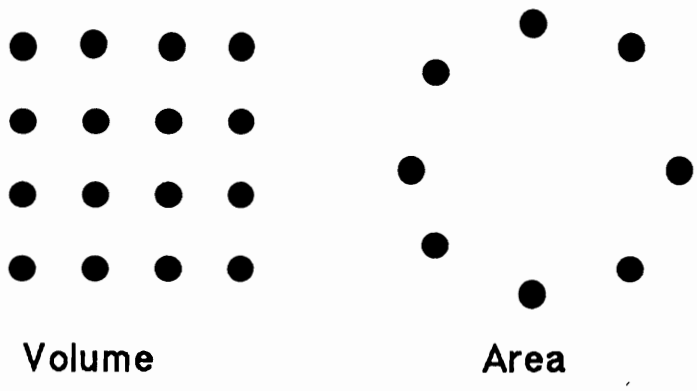


Figure 1 . A volume array compared to an area array of vertical strings of optical sensors, as viewed from the top.

In this note, the procedures that led to the determination of the configuration and parameters of DUMAND II are described.[1] In this case, the choice was made to optimize for the very high energy ($\gtrsim$ 100 GeV) through-going muons. This made it possible to distribute the optical modules far from one another and maximize the effective area. It was further decided to make the array approximately isotropically sensitive to muons for zenith angles in the range $80^\circ - 180^\circ$ where any observed events would almost certainly be the result of neutrino interactions. Finally, pointing accuracy in the reconstruction of muon directions of at least $1^\circ$ was required, dictating as long a lever arm as possible.

The design of the DUMAND II array meets these specifications. Like the underground experiments mentioned above, DUMAND II has other capabilities than those specifically emphasized in its design. Not only muons but electromagnetic and hadronic cascades can be detected with excellent efficiency.

And while the array is very efficient for high energy events, it still has appreciable effective volume at low energies resulting simply from its great size. However, here I will focus on muons.

In the following, I will assume that we wish to build a deep underwater detector that maximizes the effective area for very high energy through-going muons. Further, I will assume that the basic detection units are optical sensors that are deployed in vertical strings. While this is not what is planned for NESTOR, it is the scheme used by the other experiments and most of the conclusions drawn can be applied to NESTOR as well.

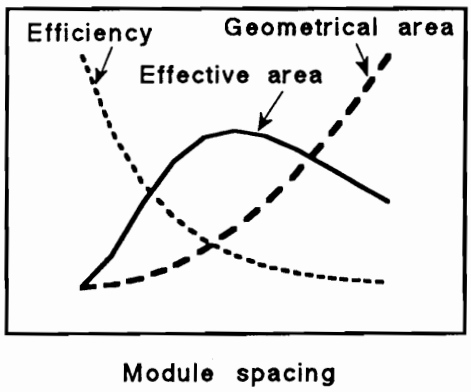


Figure 2 Sketch showing how geometrical area increases with sensor module spacing while efficiency decreases, giving a maximum effective detection area that i neither maximum efficiency nor maximum size.

## 2. Volume vs. Area

Suppose we have the funding to build an array containing N optical modules. We want to arrange them in $N_s$ vertical strings. The first decision we must make is the general configuration of the array: Is it to be a *volume* array or an *area* array? See Fig. 1. Rather obviously, the area array shown with eight strings (viewed from above) has about the same cross sectional area for through-going muons as the volume array on the left with twice as many strings. It also has about the same enclosed volume. One would be foolish to build an array like the one on the left unless the events are of such low energy that light cannot reach the wall of optical modules, or one needed the *spatial* detail provided by a volume array for contained events. Note

that the *temporal* information is better on the right because of the larger average distance between strings.

Both IMB and KAMIOKANDE recognized the advantage of area arrays, even for the search for proton decays – contained events for which volume is maximized. Clearly the area configuration is optimum for energies that are high enough so that light from the same event is able to cross a diameter. This will occur when either the muon has a range greater than a diameter, or when there is sufficient light from a shower to reach across the array.

In DUMAND II, a central string was added for redundancy, better detection of vertical muons, improved low energy efficiency, and calibration purposes. However the basic concept that was adopted was one of a vertical cylinder with strings of optical sensors on the surface.

## 4. Effective Area

Given the cylindrical configuration, we next need to determine the best way to arrange the N optical sensors. For this purpose, a Monte Carlo program is used to determine the maximum value of the effective area for through–going muons,

$$A_{eff} = \epsilon \, A_{geom} \tag{1}$$

where $A_{geom}$ is the geometrical area and $\epsilon$ is a kind of efficiency. In practice, muons are generated in an area $A_{gen}$ which is much larger than $A_{geom}$, and $A_{eff}$ computed from

$$A_{eff} = f \, A_{gen} \tag{2}$$

where f is the fraction of events which successfully trigger and reconstruct. This takes into account events that occur outside the array.

While it is not a bad approximation to optimize for horizontal muons, a more accurate procedure is to generate muons with a zenith angle distribution that is uniform in the region that one will be looking for a signal. In the case of DUMAND or NESTOR, this is $-1 \leq \cos\theta_Z \leq 0.2$. Shallower detectors cannot look above the horizon for neutrinos. For the analysis presented here, minimum ionizing muons were used

since many Monte Carlo runs had to be made and this greatly speeded up the process. Thus the absolute effective areas given represent lower limit estimates, although the conclusions on best parameters should still be valid. The precise sensitivity of any given array is finally determined by Monte Carlos in which the muons are generated with an energy spectrum that approximates the spectrum expected from the primary signal being sought. If the signal is neutrinos with an $E_\nu^{-2}$ differential spectrum, then the muons will have a spectrum of approximately $E_\mu^{-1}$.

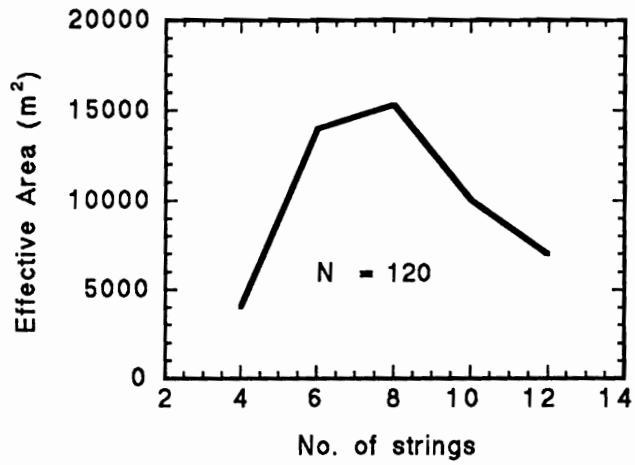


Figure 3 . Effective area as a function of $N_s$, the number of strings, for an array with N = 120 sensors. The other parameters of the array have been optimized in each case.

An important point to be made is one that is not widely recognized: Most experiments, including those underground, are designed for the maximum possible efficiency within their detection volumes. However underwater detectors are almost unique in utilizing the medium outside the instrumented volume as well as that inside. (Air shower experiments are another). Thus, maximum $A_{eff}$, which gives maximum signal, may not necessarily correspond to maximum efficiency. This is illustrated in Fig, 2. The optimum array may be one that is "leaky," missing some muons that pass through while catching others that pass by completely outside the instrumented volume.

It also should be noted that any optimization procedure

must not only consider the signal but also the background. Trigger conditions, software filters and cuts, and event reconstruction algorithms must all be developed, not just with an eye toward the events one is seeking to observe, but also to the reduction of background to sufficient levels so that the expected signal can be seen. The Monte Carlos used here contained event analysis procedures that reduced the background from all known sources to less than 2 events per year in a $1^{\circ}$ circle ($\pi$ sq. degrees solid angle) on the sky.

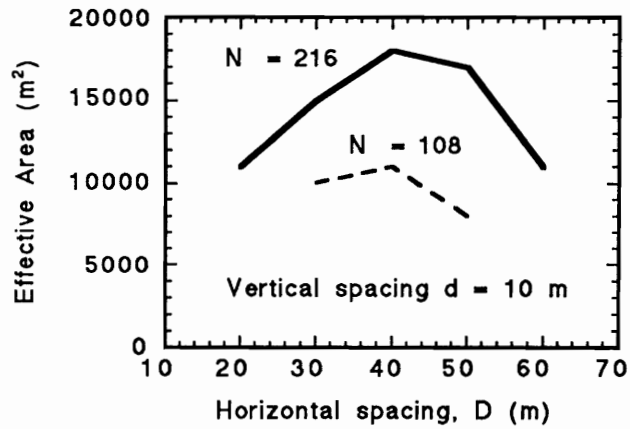


Figure 4 . Effective area for minimum ionizing muons in an 9 string array as a function of horizontal spacing D, for a vertical spacing of 10 m, for N = 216 and 108.

## 4. Optimum Parameters of Cylindrical Area Arrays

Let us now determine what the optimum parameters are for a cylindrical array of N optical sensors and $N_s$ strings. Let the distance between strings be D and the vertical distance between sensors be d. I will assume, for simplicity, that each string has the same number of sensors and the sensors are equally spaced, though Monte Carlos have been run where this is not the case. Also, several experiments deploy their sensors in clusters of up to four. What is done here would apply to N such clusters if the sensors within a cluster are close together.

With these parameters, the geometry of the array is determined: The number of sensors per string is $N/N_s$; the height of the cylinder is $N_d/N_s$; the diameter of the cylinder is,

approximately, $N_s D/\pi$.

For several values of N, the configuration of the other parameters which gave the greatest effective area was determined. Except for small values of N, the optimum number of strings $N_s$ was found to be eight, as illustrated in Fig. 3 for the case N = 120. That is, the octagon configuration is best, and was duly adopted for DUMAND II, with a ninth, central string added for reasons mentioned above.

The optimum value of the horizontal spacing between strings D for nine string arrays is given in Fig. 4, for N = 108 and 216 optical sensors, i.e., 12 or 24 modules per string. In both cases we see that 40 m represents the best choice for the sides of the octagon.

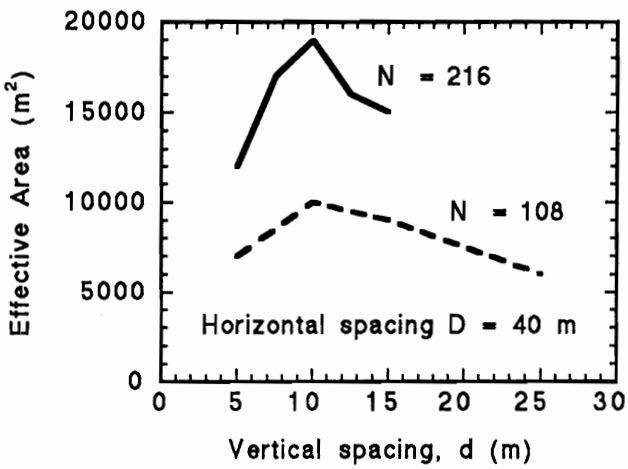


Figure 5 . Effective area for minimum ionizing muons in a 9 string array with horizontal string spacing D = 40 m, as a function of the vertical spacing of sensors along a string, d, for N = 216 and 108.

The optimum value for the spacing of optical sensors vertically along a string is given in Fig. 5, for the nine string octagon with 40 m sides. The best value is d = 10 m.

It must be emphasized that these Monte Carlos were done for the ocean water conditions that exist at the DUMAND site in the mid–Pacific. The key physical parameter is the clarity of the water at the site. I have used a somewhat conservative optical spectral transmission curve that gives 30 m attenuation length (1/e) at 450 nm, within the error bars of measurements at the site.

All the other sites being considered have poorer clarity, and so the optimum parameters will be correspondingly less. A rule of thumb is to scale by the attenuation length: Thus if you have 20 m water, multiply my best values of d and D by 2/3 (or do you own Monte Carlos).

Finally, is interesting to see how the effective area varies as a function of total number of sensors N, since this is the primary parameter in the determination of the cost of an array. As seen in Fig. 6, a simple linear relation can be used to roughly estimate about the best that can be achieved with a given number of light sensors:

$$A_{eff} = 100\ N\ m^2 \tag{3}$$

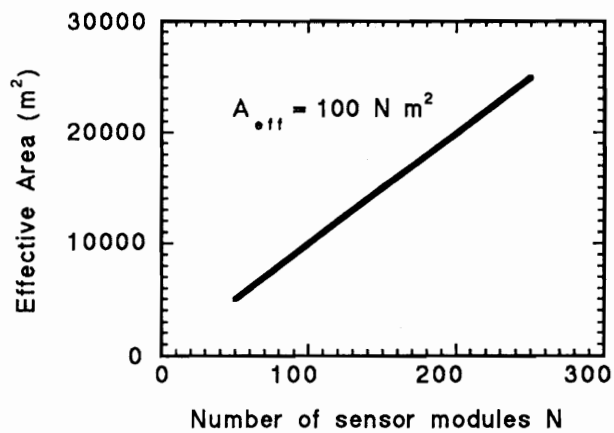


Figure 6 . Effective area as a function of number of sensor modules N, for optimized cylindrical arrays.

## 5. Conclusions

The optimum configuration of an underwater Cherenkov array is one in which the sensors are arranged as far apart as light from the same event can reach. Given that vertical strings of sensors represent a practical deployment unit, these are best arranged on the surface of a cylinder to maximize effective area. A central string adds redundancy and improved detection isotropy. If one optimizes for very high energy through-going muons, $E_\mu \gtrsim 100$ GeV, an octagon configuration with a central string, with the horizontal distances between strings of 40 m and

vertical spacing of sensors along a string of 10 m gives the largest effective area. This was the configuration chosen for DUMAND II; it applies for 30 m water and a depth of at least 4 km. A simple rule for estimating the best one can achieve with a given number of modules N under these conditions is $A_{eff} = 100\ N\ m^2$. Lesser effective areas will result if compromises are made to include other physics, such as low energy events, or if backgrounds are so high that clusters of sensors acting in coincidence, or other means, must be applied to reduce the background.

## 6. References

1.For more details, see V.J. Stenger, 1988, "The DUMAND Octagon Array," Hawaii DUMAND Center report HDC–1–88.