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DUMAND - Deep Underwater Muon and Neutrino Detector

THE TRIAD: A PROPOSED SECOND STAGE FOR DUMAND

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ABSTRACT

It is proposed that the second stage of DUMAND be an array composed of three vertical strings on the corners of a 25-30 m equilateral triangle. Each string would have 7 optical modules 12-15 m apart. We refer to this array as the TRIAD. Only slightly modified versions of the current Short Prototype String are required for each string. The array would be placed on the ocean bottom and connected to shore by a single electro-optic cable. It is shown here that this array would have an effective area for fully reconstructed muon tracks of ~3000 m². The solid angle resolution will be about 10 msr. The minimum muon energy will be about 25 GeV.

INTRODUCTION

When it was first proposed[1] that DUMAND (Deep Undersea Muon and Neutrino Detector) should give its first priority to the search for extraterrestrial point sources of very high energy (~ 1 TeV) muon neutrinos there was little observational evidence on which to base the case that such sources exist. Astrophysicists had shown great imagination in thinking up ways that neutrinos might be produced in astronomical bodies[2], but atmospheric Cerenkov γ-ray observations on a handful of objects were all that was available at TeV energies. Very high energy γ-rays had been reported from Cygnus X-3[3] and, less convincingly, from perhaps two or three other sources.[4] Unfortunately the existence of TeV γ-rays from a source does not automatically guarantee a corresponding flux of neutrinos; they can be purely of electromagnetic origin. A neutrino flux requires that the source be accelerated protons or other nuclei.

The 250x250x500 m^3 DUMAND array proposed in 1982, consisting of 36 vertical strings and a total of 756 photomultiplier detector modules, was the minimum size which could detect neutrinos from sources such as Cygnus X-3, provided these neutrinos are produced at the same flux level as γ-rays. It was recognized that such a large array would have to be built in stages over a period of several years.

Since that proposal there have been several observational and theoretical developments which now permit greater optimism that a smaller area muon detector, in the sea or underground, will be able to detect high energy neutral particles from a number of promising objects. On the observational front there are the reports of 1000 TeV airshowers from the direction of Cygnus X-3 by Kiel[5] and Leeds[6], more recently confirmed by Akeno[7], Vela X-1 and LMC X-4 by Adelaide,[8] and Her X-1 by the Fly's Eye.[9] These results cannot be explained by electromagnetic processes, since electrons cannot be accelerated to 10^{15} eV in the magnetic fields likely to be present, and thus represent the first evidence for a localized source of cosmic ray proton acceleration. A corollary is that neutrinos can now be expected, at least at the same flux level as the γ-rays and possibly even higher.[10]

More recently, two experiments (Soudan[11] and NUSEX[12]) have claimed the detection of underground secondary muons, produced by some unknown neutral particles from Cyg X-3. These results have not yet been confirmed in other experiments but, if true, imply very high event rates in larger underground or undersea instruments.

On the theoretical front, models for the powerhouse of sources such as Cyg X-3 have been developed which can account for the observed γ-rays.[13] Further, a number of recent papers predict that an instrument with an area on the order of $1000 m^2$ will have a good chance of observing neutrinos from these sources.[14] One particularly attractive model, in which the energy source is accretion onto a neutron star and protons are accelerated in the accretion disk, suggests that the neutrino flux can be 100-1000 times the measured TeV γ-ray flux[15]. This high ratio results from a line-of-sight column density of 100-300 gcm^{-3} which attenuates the γ-rays while allowing for maximal neutrino production.[10]

The 1982 DUMAND proposal[1] envisaged a staged development toward the 756 PMT array. The first stage, the Short Prototype String (SPS) deployed from a ship, was designed just to demonstrate muon detection and track reconstruction in the ocean. The SPS is now built and under test, and this experiment should be complete by early 1986. The new developments discussed above have lead the DUMAND Collaboration to propose to build upon what we have learned from the SPS and deploy for long-term observations, by 1987, a small 3-string array with the ability to detect and reconstruct the directions of muons, with an effective area higher than any existing or planned underground experiment.

We propose that the second stage of DUMAND, after the SPS, be a bottom-moored array of three identical strings attached to shore by a single electro-optic cable. A sketch is shown in Fig. 1. Each string would be essentially a duplicate of the SPS, with the 7 optical modules, two calibration modules and one environmental module already developed and under test. Monte Carlo studies, described in more detail below, suggest that the vertical spacing should be approximately 12-15 m, compared with the current 5 m spacing for the SPS, but otherwise there should be little change. The three strings would be arranged in an equilateral triangle, about 25-30m on a side. All three strings can be handled by a single String Bottom Controller (SBC), identical to the one currently under development at UC Irvine for the SPS, with some additional input circuitry. An effective detection area for muons passing through or near the TRIAD of ~3000 m^2 appears possible.

Event rates for a 3000m^2 detection area are indicated in Table I for three assumed sources: (1) muons from the unknown particles from Cyg X-3 at the flux reported by the NUSEX experiment[12]; (2) muons from neutrinos from Cyg X-3 if their flux level is 100x that observed for γ-rays;[15] (3) muons from neutrinos from LMC X-4, as predicted by Cocconi.[16]

Table I. Event rates for a $3000m^2$ detection area underground or undersea muon detector, for three source fluxes.

Source	Events per year per $3000m^2$
Muons from unknown particles from Cyg X-3 at NUSEX obs. flux: $F_\mu = 2.5X10^{-12}cm^{-2}s^{-1}$ [at 5 kmwe]	2500
Muons from neutrinos from Cyg X-3 if ν flux level is 100x that observed for γ-rays, $F_\mu = 7x10^{-14}cm^{-2}s^{-1}$	70
Muons from neutrinos from LMC X-4 as predicted by Cocconi, $F_\mu = 5x10^{-14}cm^{-2}s^{-1}$	50

PROPERTIES OF THE TRIAD

The basic TRIAD array, as shown in Fig. 1, has three strings of seven optical modules each. This configuration was chosen so that we can simply triplicate the SPS, without any substantial redesign the the modules and String Bottom Controller. The major expense is then the acquisition of the shore cable, and the deployment. The latter is difficult, but should not require the development of a deployment canister as would a full 24 module string.

The strings are assumed to be arranged on the corners of an equilateral triangle of horizontal side D_H, hanging vertically upward from anchors on the bottom.[1] The modules have a vertical spacing of d_V, for a

1/ Other configurations, such as a pyramid in which the ends of the strings are brought together, at the top or bottom, have been briefly explored and found to be less efficient than the parallel TRIAD.

total height of $D_V = 6d_V$, exclusive of tare height and other elements at either end of the string. The PMTs all point down, to optimize for neutrinos or other penetrating particles; the anisotropy of the PMT module, including the effect of shadowing by the module electronics around the stem of the tube, has been measured and can be represented as $0.55+0.45\cos\alpha$, where α is the PMT entry angle. The poor backward sensitivity (10%) turns out to be an advantage for the TRIAD, reducing the cosmic ray muon background.

Monte Carlo Analysis

The DUMAND Monte Carlo program[17] has been used to find the effective area for a variety of array parameters and trigger conditions. The procedure is as follows. Minimum ionizing muons are generated in a cylinder of area $A = \pi\rho^2$ where the radius ρ is larger than the overall dimensions of the array plus the attenuation length of light in water. The tracks are uniformly populated within the cylinder and parallel to its axis, which passes through the center of the array at an angle θ with the vertical. No changes were made to the long-standing routines in the DUMAND Monte Carlo which generate the Cerenkov light, propagate it to the array and simulate the measured data from the optical modules. The photoelectrons are given Poisson statistical fluctuations, and the arrival times are given a Gaussian fluctuation with a standard deviation of 10 ns, higher than assumed in past analyses but probably more realistic with the existing PMT and associated circuitry.

The program has the capability of simultaneously testing a wide variety of triggering conditions. Two levels of PMT discrimination are possible, and coincidence combinations for adjacent or non-adjacent tubes tested. The false trigger rates which result for a particular trigger combination are computed analytically in a separate program. Consideration of false triggers is an important part of the optimization process, as will be described below.

After the data are simulated, the rest of the Monte Carlo program acts as if it were analyzing actual data from the array. No information is used which would not be available in the experiment, except at the end to compare the reconstructed parameters with those for the true events.

First the trigger tests are applied. For events passing these tests, attempts are made to reconstruct the muon's direction. An analytical space fit is made, serving as the initial guess for a χ^2-minimizing fit which uses the pulse arrival times and charge, as well as the PMT locations. In the χ^2-fit, the track is reconstructed by finding the direction which minimizes the differences between the predicted and measured arrival times and phototube charges. Five parameters describing the muon track are determined: the two direction angles and the three space coordinates of the point on the track passed by the muon at $t = 0$. A minimum of 6 PMT hits at the >1 photoelectron level are required in the current triggering scheme, described in detail below, and the absence of hits on some tubes is included in the χ^2; so there are at least 40 [= 4x6+21-5] degrees of freedom, although the 21 PMT charge degrees of freedom are rather loose, when one operates at the 1 photoelectron level, and have only a marginal effect on the fits.

The effective area is defined as $A_{eff} = \varepsilon A$, where ε is the fraction of tracks which pass the trigger and any other cuts which one expects to apply to the real data. Note that A is not the physical cross section of the instrument, so the trigger efficiency ε is itself a meaningless quantity, depending on how far away from the array tracks are generated. As the arbitrary area $A=\pi\rho^2$ increases, ε decreases. A_{eff} is the physically interesting quantity anyway.

Optimum Array Parameters

In principle, the optimization procedure simply seeks those array parameters which maximize effective area, while giving acceptable angular resolution for the reconstructed muons. In practice, this is complicated by the large number of variables and the presence of backgrounds. Although the basic configuration has been restricted in this study to 21 optical modules on three vertical strings, other variables include not only the spacings d_V and D_H but a matrix of triggering conditions and threshold levels. These triggering conditions must be set in such a way to reduce the number of fake events resulting from backgrounds to an acceptable level.

Previous analyses for both the SPS and full array[18] have shown that the most effective way to reduce false triggers is by the use of adjacent coincidences along a string, the old Roos pair idea[19] generalized to include more than two tubes. By demanding that the coincidences be adjacent, the coincidence time window can be made as small as possible. If n is the number of adjacent tubes in coincidence, the time window then is $\tau_n = 1.35[n-1]d_V/c$, where 1.35 is the index of refraction of sea water at 500 atm.

These studies also showed that raising the PMT discriminator level beyond 1 photoelectron is a very poor strategy, in the absence of a PMT with extraordinary photoelectron resolution, greatly reducing effective area with only moderate gain in false trigger rejection. Adding another level of coincidence when the false rates are too high is generally a superior way to reduce background.

In what follows let us assume that the PMTs are operated at about the 1 photoelectron level. Measurements on the Hamamatsu PMTs currently in use indicate that, when the discriminator is set at the peak of the 1 photoelectron charge distribution, random low-level light will trigger the tube about 77% of the time.

I will not attempt to reconstruct all the iterations which have led to the currently proposed set of TRIAD array parameters. A large number of triggering schemes and array dimensions were tried, backgrounds calculated and found to be too large, and new schemes tried. These studies have converged on a triggering method which demands at least 6 PMTs be hit, in a large number of ways which are best summarized by patterns shown in Table II.

Table II. The proposed triggering scheme for the TRIAD. The first three columns show the **minimum** number of PMTs adjacent on each of the three strings which must contain a hit at the one photoelectron level. The number of combinations are shown in parentheses. The last column shows the relative fraction of triggers for each combination a typical TRIAD geometry.

Trigger	Combin.	Fraction
6 - 0 - 0	(x3)	0.014
5 - 1 - 0	(x6)	0.087
4 - 2 - 0	(x6)	0.185
4 - 1 - 1	(x3)	0.126
3 - 2 - 1	(x6)	0.392
3 - 3 - 0	(x3)	0.118
2 - 2 - 2	(x1)	0.077

The first row in Table II says that if there is only one string hit we demand a 6-fold adjacent coincidence. The last row allows 2-folds, but only if there is a set on each string. In between are all the other combinations which add up to six tubes. Note that almost 40% of the triggers are 3-2-1, which can occur in six different ways. Only 14% are single-string triggers, and many of these will have hits on other strings.

We will see later that this triggering scheme should give an acceptably low fake event rate with the backgrounds suggested by our current knowledge. Schemes with fewer than 6 PMTs in the trigger will give higher effective areas, but also generally give fake event rates which will make it impossible to exploit these higher areas - unless we discover some radically new algorithms.

An astronomical point source will trace a path across the celestial sphere and basically be visible to the TRIAD, in neutrino-generated muons, whenever it has a zenith greater than 70°. Cosmic ray muons will dominate at zenith angles less than 70°. In order to obtain average array properties over the range in zenith angles for a signal, muons are generated in the Monte Carlo with a uniform distribution in cosθ in the range $-1 \leq \cos\theta < .34$. In Fig. 2 the resulting effective area for triggers is shown as a function of d_V and D_H; it is 3000-3500 m^2 for a wide range of array parameters. The optimum vertical spacing d_V is 12-18 m and the optimum string spacing D_H is 20-30 m. The dashed curve in Fig. 2(b) actually indicates that very close string spacing gives the highest effective area, but this is not the whole story. We need to reconstruct muon directions to have some idea of the source location and to remove downward cosmic rays. We will see below that close string spacing does not do this effectively, since the azimuthal angle then becomes poorly known.

Typically 90% of the triggers give some kind of track reconstruction. A rather sophisticated algorithm to maximize the number of fitted events has been developed. If an event has hits on only one string, or the χ^2-fit fails, the analysis program switches to a separate single-string algorithm, that used for the SPS. This reconstructs the muon's zenith angle (more precisely, the angle with respect to the string), but is necessarily ambiguous in azimuth. Single string fits are considerably less desirable than multiple string fits, but should still be useful and so events are saved in this way. There is also a two-fold ambiguity in those fits with hits on only two strings, resulting from the reflection symmetry of the plane of the strings. However these are typically only about 4% of the total.

In Fig. 2(b) the top solid curve shows the effective area for triggers as a function of D_H for d_V=15 m. The bottom solid curve shows that for fully reconstructed events for the same parameters. The peak of 3300 m^2 occurs at D_H=20 m. About 70% of this, or 2300 m^2, is for multiple string fits, which provide azimuth as well as zenith information on muon direction.

Angular Resolution

Track reconstruction works best when the detectors are as far as apart as possible, consistent with an adequate number of hits, so the lever arm is maximized. In the full DUMAND array a muon angular resolution of about 0.5^{0} is achieved by the fact that a throughgoing track will have PMT hits at least 250 m apart.[1] The TRIAD cannot hope to match this with the string spacing basically governed by the light attenuation length in water, ~30 m.

In Fig. 3 the muon directional resolution of the TRIAD with the current reconstruction algorithms is indicated, as a function of D_H for d_V = 15 m. Shown are the average and median errors in zenith, azimuth and solid angle on the celestial sphere. The last is the most important, since it measures our ability to locate an astronomical source. The big differences between average and median in all three cases show that the errors are non-Gaussian, with long tails on the distribution. Tighter cuts on χ^2 reduce the tail, but also reduce the effective area. We anticipate that further improvements can be made in the reconstruction algorithms to reduce the undesirable tails.

Azimuth is more poorly determined than zenith since there are only three strings and thus basically only three data points to give the orientation in the horizontal plane. A fourth string might help, but this is yet another variable and has not been considered. The height of the string (90 m for 15 m vertical spacing) plus 7 PMTs per string make the determination zenith better, but still not as good as in the 500 m high full array, with PMT modules 25 m apart.

The need for maximal string spacing is best illustrated by the median solid angle error $\delta\Omega$, which goes from 40 msr at D_H = 20 m to 10 msr at D_H = 40 m. Thus we find that we have a tradeoff to make between effective area, which is maximized at about D_H = 25 m, and angular resolution which gets better as the string spacing increases.

The fundamental question is: how well will we be able to locate a source on the celestial sphere? In our search for neutrinos sources we might divide the sky up into $4\pi/\delta\Omega \approx 1000$ boxes of these dimensions. This is not quite the angular resolution of the Space Telescope, but it is hard to see how we can do much better. It should be adequate for this first glimpse at neutrino astronomy. If, for example, a statistically significant signal were found in a box including the LMC, and it had the period of LMCX-4, there would be a good case that neutrinos had been observed from that source.

Energy Resolution

The TRIAD will not have enough detector sampling to hope to determine the energy of a muon by dE/dx. However, muons will need at least 25 GeV to traverse the array. I have elsewhere shown that virtually all the muons from neutrinos with the fairly flat (E^{-2}) spectra expected from astronomical sources will have energies above 100 GeV.[22] On the other hand, about half the muons from atmospheric neutrinos, with their steeper spectra, will be below 25 GeV. Cosmic ray muons below 25 GeV will also be rejected. Thus the TRIAD will filter out some of the background from cosmic rays, while not losing any significant portion of the expected signal.

EFFECT OF BACKGROUNDS

As has already been mentioned, the triggering conditions of the TRIAD are determined by backgrounds. These will be generally of two types: (1) cosmic ray muons triggering the system and being falsely reconstructed to have the large zenith angle associated with neutrinos or even more exotic extraterrestrial events; (2) incoherent triggering of individual PMTs by low levels of light in the ocean, either radioactivity (K^{40}) in the sea water or bioluminescence. Let us discuss each in turn.

Cosmic Rays

Monte Carlo runs simulating the expected cosmic ray muon angular distribution at a depth of 4.5 km indicate that the effective area of the TRIAD for downward cosmic ray muons is typically 1000 m^2, 30% lower than for muons in the signal range (zenith angles $>70^0$). This results from the lower sensitivity of the PMTs in the backward hemisphere.

Some of these downward cosmic rays may be expected to fake neutrino events. What fake rate would be acceptable? Let $\Delta\Omega$ be the solid angle on the celestial sphere being tested for a signal. The rate of cosmic ray muons faking a neutrino event in the angular region $\Delta\Omega$ will then be given by

$$C = \frac{\Delta\Omega}{4\pi} \varepsilon_c F_\mu A_{eff} \qquad [1]$$

where ε_c is the fraction of cosmic ray muons which are incorrectly reconstructed as signal and F_μ is the cosmic ray muon flux. At 4.5 km, $F_\mu = 2.5\times10^{-5}m^{-2}s^{-1}$, giving a total muon event rate of 0.025 s^{-1} for A_{eff} = 1000 m^2.

An acceptable false signal rate would be C = 1 event per year; in that case, a true signal of 10 events per year would be detectable. Larger backgrounds would be acceptable for larger signals, such as would be expected from the Soudan-Nusex events [see Table I]. As we found in the previous section, we should be able to divide the celestial sphere into about 1000 angular bins. In this case we need $\varepsilon_c \approx 10^{-3}$. So, less than one cosmic ray muon in 1000 can be falsely fit with a direction beyond 70^o of zenith. Running the Monte Carlo program for cosmic ray muons having the angular distribution expected at 4.5 km, none out of 276 single string fits but three out of 683 multiple string fits were reconstructed to be below the horizon, not quite the 10^{-3} rejection required. Thus it appears that the cosmic ray background may be a problem if the reconstruction algorithm cannot be improved to remove the error tail mentioned above. Also, multiple muons will be present at the level of a few percent. Some of these may be interpreted as upward single tracks. This background still needs to be looked at in detail, but is not expected to be worse than single muons.

<u>K40 and Biolight</u>

Incoherent background light has always been a major concern in DUMAND. Consider a single string of M PMTs, each randomly triggering at a rate R_o. The false trigger rate for an N-fold adjacent coincidence [i.e., >N adjacent tubes in coincidence] is

$$R_N = R_o \sum_{n=N}^{M} (M+1-n)(R_o \tau_n)^{n-1} \qquad (2)$$

where $\tau_n = 1.35(n-1)d/c$ $(R_o\tau \ll 1)$.

From experiments at the actual DUMAND site we believe that the background singles rate for a bottom-moored instrument will be essentially that for K^{40}, viz., 100 KHz for the 15" PMT now in use and the discriminator threshold set just above phototube noise.[21] Laboratory measurements indicate that if we set the discriminator at the peak of the 1 photoelectron distribution, 77% of low light level pulses will trigger. In what follows, I will assume this setting and take R_o = 77 KHz. In practice we will be able to fine-tune this level from shore.

I am also assuming that we will be able to transmit all PMT data at the 1 photoelectron level to shore. At 77 KHz per tube and 32 bits per word (actually only 28 are used in the SPS but we may want more in the TRIAD), we have a total data rate of $(21)(32)(7.7\times10^4)$ = 51.7 MBd for the cable and electronics to handle. If this is impossible, or the background rates should prove to be higher than K^{40}, some of the triggers shown in Table II will have to be eliminated, with corresponding loss in effective area.

In Fig. 4 the coincidence trigger rates which will occur in a single string for a singles rate of 77 KHz are shown, as a function of coincidence level N and vertical spacing d_V. We see that these trigger rates rise with PMT vertical spacing; the smaller the spacing the smaller we can make the coincidence window. A 15 m vertical spacing results in a single string adjacent 2-fold trigger rate of 4 KHz. Requiring 6-folds reduces the rate to less than 0.01 Hz.

An array with 15 m vertical spacing is 90 m high. If the strings are 25 m apart, then a T = 420 ns time window is needed for cross string coincidences. In Table III we illustrate the calculation of false trigger rates for the 6-fold coincidence patterns described earlier.

Table III. False trigger rates for the proposed TRIAD triggering scheme when the singles rate is 77 KHz, as expected from K^{40}.

Pattern	False Trigger Rate	
6-0-0	R_6	= 0.0057 Hz
5-1-0	$3R_5R_1T$	= 0.062
4-2-0	$6R_4R_2T$	= 0.0075
4-1-1	$3R_4R_1^2T$	= 0.188
3-2-1	$6R_3R_2R_1T^2$	= 0.060
3-3-0	$3R_3^2T$	= 0:0023
2-2-2	$R_2^3T^2$	= 0.0026
TOTAL FALSE TRIGGER RATE		= 0.33 Hz

where the values of R_N are calculated from (2) for d_V = 15 m (see Fig. 4) The coincidence pattern with the highest rate is the one which allows two singles. This could be removed from the trigger, but it would be shame to give up any three-string events.

In Fig. 5 the total false trigger rate is shown as a function of d_V, for D_H = 25 m. Larger values of the array coincidence time window T are needed for larger D_H, however this is not a big effect, only slightly raising the rates for greater horizontal spacings. More important is the effect of the vertical spacing d_V. For example, by going from 15 m to 10 m we can lower the total false trigger rate from 0.33 Hz to 0.04 Hz. This again shows the tradeoffs we must consider in our final decision on array geometry.

What rates can we withstand? Following a procedure similar to what was done for cosmic ray muons, the background rate in the solid angle $\Delta\Omega$ which results from incoherent single tube triggers will be

$$B = \frac{\Delta\Omega}{4\pi} \varepsilon_B R_F \qquad (3)$$

where ε_B is the fraction of these false triggers which pass the muon track reconstruction algorithm. An acceptable background of B = 1 event per year in each of 1000 solid angle bins implies that $\varepsilon_B R_F$, the rate of fake reconstructed muons in all directions, must be less than $3\times10^{-5}s^{-1}$. For a false trigger rate of 0.3 Hz, as determined above, the rejection factor must be $\varepsilon_B \sim 10^{-4}$, about 10% of that for cosmic rays. That is, of the background events which pass the trigger, less than one in 10,000 can be allowed to fake a muon. For 0.04 Hz we only need to reject about one in 1000. Taking 4691 Monte Carlo events which pass the trigger requirements and scrambling the times within 420 ns, we find no cases where randoms give a fake fit with χ^2/NDF < 1, so this cut can be applied with only a slight loss in signal effective area. It appears that we will be able to handle this background.

Clearly there are strategies which will be employed in the actual experiment to maximize signal and S/N. We will be able to move the discriminator level slightly up and down about the 1 photoelectron peak. We can take high false rate patterns out of the trigger, or add another tube in the coincidence. It is impossible and unnecessary to decide now on exactly what will be done since considerable flexibility and shore control will be built into the system. The examples considered above demonstrate a triggering scheme with acceptable background, while giving a respectable effective area. Further work on reconstruction algorithms should lead to better rejection of unwanted events, given the large number of degrees of freedom available with 6 or more PMT hits. An effective area of approximately 3000 m^2 is a reasonable estimate at this stage.

CONCLUSION

The TRIAD is proposed as the second stage of DUMAND. It should have an effective area of about 3000 m^2, making it capable of detecting neutrinos or other sources of undersea muons if the muon flux level at 4.5 km depth is at least $10^{-14}cm^{-2}s^{-1}$ above 25 GeV, about an order of magnitude better than the largest existing underground detector, the IMB proton decay experiment in Cleveland. The position of such a source on the celestial sphere will be determined to about one part in a thousand.

This array is a natural extension of the DUMAND Stage I Short Prototype String now built and under test. It is composed of three similar vertical strings, each with seven photomultipler modules spaced about 15 m apart. The strings are at the base of an equilateral triangle of side 25-30 m and are moored 4.5 km deep in the ocean off the island of Hawaii. They attach to a String Bottom Controller which multiplexes their outputs onto a single electro-optic cable which then carries the signals to shore 30 km away. Power and control for the array is provided from shore back along the same cable.

The photomultipliers will be operated at or near the one photoelectron level. The precise triggering conditions and array parameters will be refined by further analysis, but it appears that a six-fold coincidence scheme, in which coincident tubes along a string must be adjacent, will have adequate rejection of the two major backgrounds: downward cosmic ray muons and K^{40} decay in the ocean. These must be rejected in reconstruction at about the 10^{-3} and 10^{-4} levels respectively.

The major cost of the experiment will not be in the instruments in the sea or on shore, but in the electro-optic cable and deployment. All components, including the cable, either already exist or utilize current proven technology. The deployment scheme has yet to be worked out in detail, but appears feasible. If this experiment is approved by the spring of 1986, it is possible that it can be built and deployed by 1987.

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REFERENCES

1. DUMAND Proposal, Hawaii DUMAND Center, 1982 (unpublished).

2. Berezinsky, V.S. and Volynsky, V.V., Proc. 16th Int. Cosmic Ray Conference (Kyoto), 10,326(1979); Eichler, D. and Schramm, D., Proc. 1978 DUMAND Workshop (Honolulu),2,135(1978); Kafatos, M., Shapiro, M. and Silberberg, R., Comments on Astrophys. 9,179(1981); Margolis, S.H., Schramm, D.N., and Silberberg, R., Ap.J. 221,990(1978); Protheroe R.J. and Kasanas, D., Ap.J. 265,620(1983); Stecker F.W.,Ap.J., 228,919(1979)

3. Fomin, V.P. et al.,Izv. Krym. Astro. Ob. 53,59(1975); Stepanian, A.A., Adv. Space Res. 3, 123-130 (1984) and references therein. For a recent review and other references, see Weekes, T.C., Center for Astrophysics preprint 2175, to be published in Proc. New Particles Conf., Madison (1985).

4. For a review and references, see Grindlay, J.E., Proc. Int. Workshop on Very High Energy Gamma ray Astronomy, Ootacamund, India, 257(1982).

5. Samorski, M. and Stamm, W., Ap.J. Lett. 268,L17(1983).

6. J. LLoyd-Evans et al., Nature 305, 784-787 (1983).

7. Kifune, T., et al., Ap. J., in press.

8. Protheroe, R.J., Clay R.W., and Gerhardy, P.R., Ap.J.Lett. 280, L47(1984); Protheroe R.J.,and Clay, R.W.,Nature 315, 205 (1985).

9. Baltrusaitis, R.M., et al., Proc. 19the Int. Cosmic Ray Conf. (La Jolla), 1, 111(1985).

10. Stenger, V.J.,Atrophys. J. 284, 810-826 (1984

11. Marshak, M.L., et al., Phys. Rev Lett. 54, 2079 (1985).

12. Battistoni G., et al., Phys. Lett. 155B, 465 (1985).

13. Eichler D.,and Vestrand, W., Nature 307, 613-614 (1984); Hillas, A.M., Nature 312, 50-51 (1984); Chanmugam, G. and Brecher, K., Nature 313, 767-768 (1985)

14. Stecker, F.,Harding, A., and Barnard, J.,Nature 316, 418 (1985); Kolb, E., Turner, M., Walker, T.,submitted to Phys. Rev. (1985); Berezinski, V., Castagnoli C.,and Galeotti, P., unpublished (1985); Barnhill, M.V., Gaisser, T.K., Stanev, T., and Halzen, F., Univ. Wisconsin report MAD/PH/243, to be published (1985).

15. Chanmugam, G. and Brecher, K., Proc. 19th Int. Cosmic Ray Conf. (La Jolla),1, 103,(1985).

16. Cocconi, G., submitted to Physics Letters (1985).

17. Stenger, V.J., Proc. 1980 DUMAND Signal Processing Workshop, 187 (1980).

18. Stenger, V.J., Hawaii DUMAND Center Report HDC-4-84 (1984).

19. Roos, C. Proc. 1982 DUMAND Signal Processing Workshop, 91 (1982); Roberts, A., ibid., 102.

20. Stenger, V.J., Hawaii DUMAND Center Report HDC-4-85 (1985).

FIGURE CAPTIONS

1. A sketch of the TRIAD array. Seven optical modules are shown on each of three vertical strings moored at the ocean bottom. They are attached to a controller at the bottom which multiplexes their signals onto an electro-optic cable which carries them to shore. Power and control are provided by the same cable. The array will be located in a depth of 4.5km a distance 30km west of the island of Hawaii. There will be two calibration modules and an environmental module per string, which are not shown.

2. The effective area of the TRIAD using the 6-fold scheme described in the text, as a function of the vertical spacing d_V between optical modules and D_H, the horizontal distance between strings. All the curves except for the lower solid curve on the right figure correspond to triggers only. That curve shows the effective area for fully reconstructed muons when d_V = 15 m.

3. The angular resolution of the TRIAD, for d_V = 15 m, as a function of D_H. The top figure is for the zenith angle θ, the middle for azimuthal angle ϕ, and the bottom figure for solid angle on the celestial sphere. The dashed curves are the average errors, the solid curves are the median errors.

4. The trigger rate for a <u>single</u> string, as a function of vertical spacing d_V and coincidence level N, when the singles rate is 77KHz, as is expected from K^{40} when the PMT discriminators are set a the peak of the 1 photoelectron charge distribution.

5. The false trigger rate for the TRIAD array with the 6-fold scheme described in the text, as a function of d_V for D_H = 25 m. Larger values of D_H will give slightly higher rates as the time window must be increased somewhat as the array is made bigger.

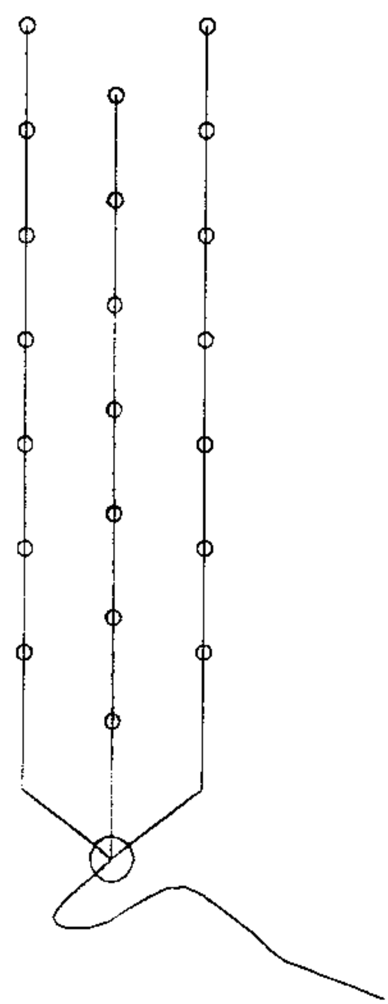
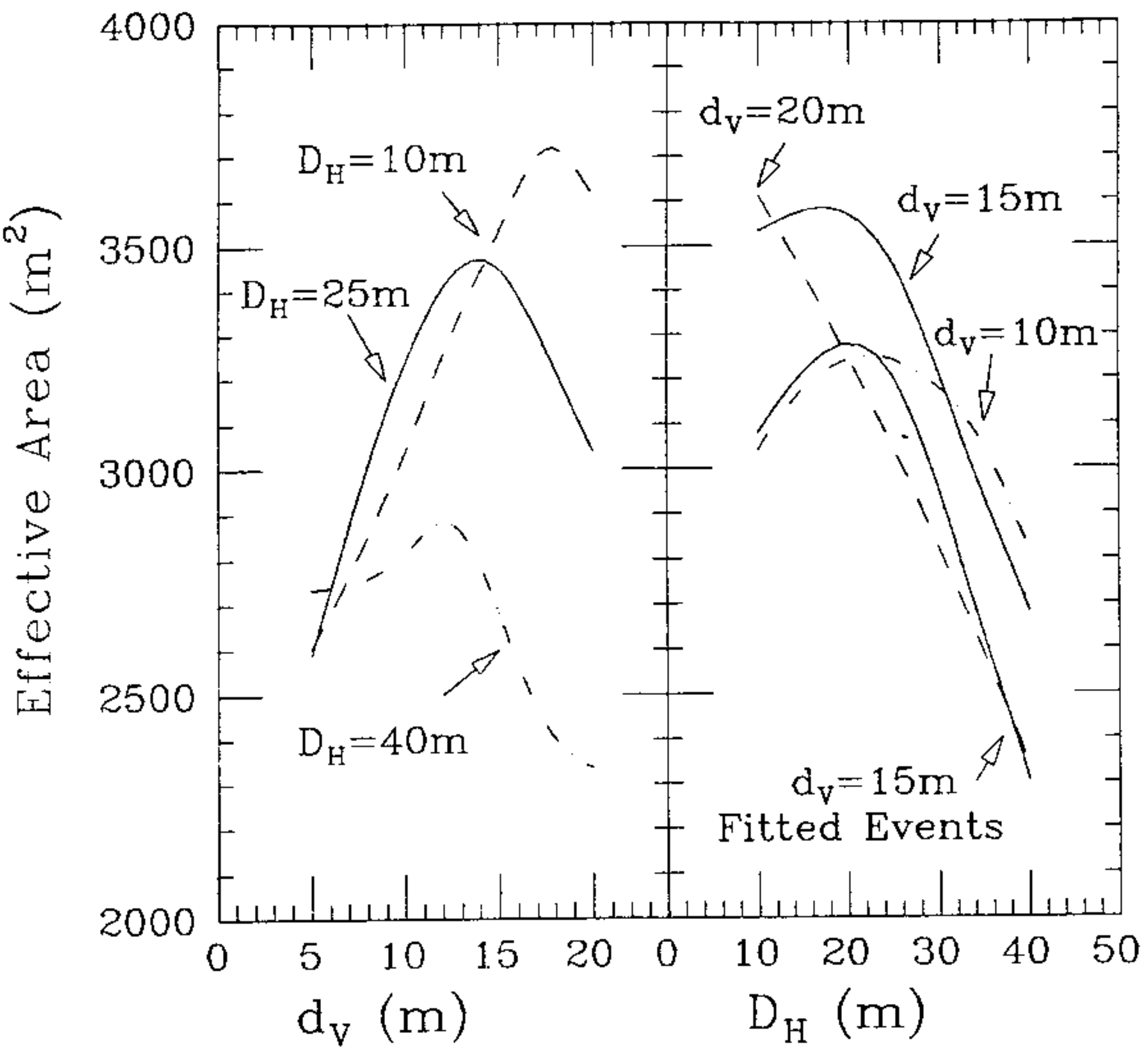


FIG. 1



4000
3500
3000
2500
2000
Effective Area (m2)
D_H=10m
D_H=25m
D_H=40m
0
5
10
15
20
d_V (m)
d_V=20m
d_V=15m
d_V=10m
d_V=15m
Fitted Events
0
10
20
30
40
50
D_H (m)

FIG. 2

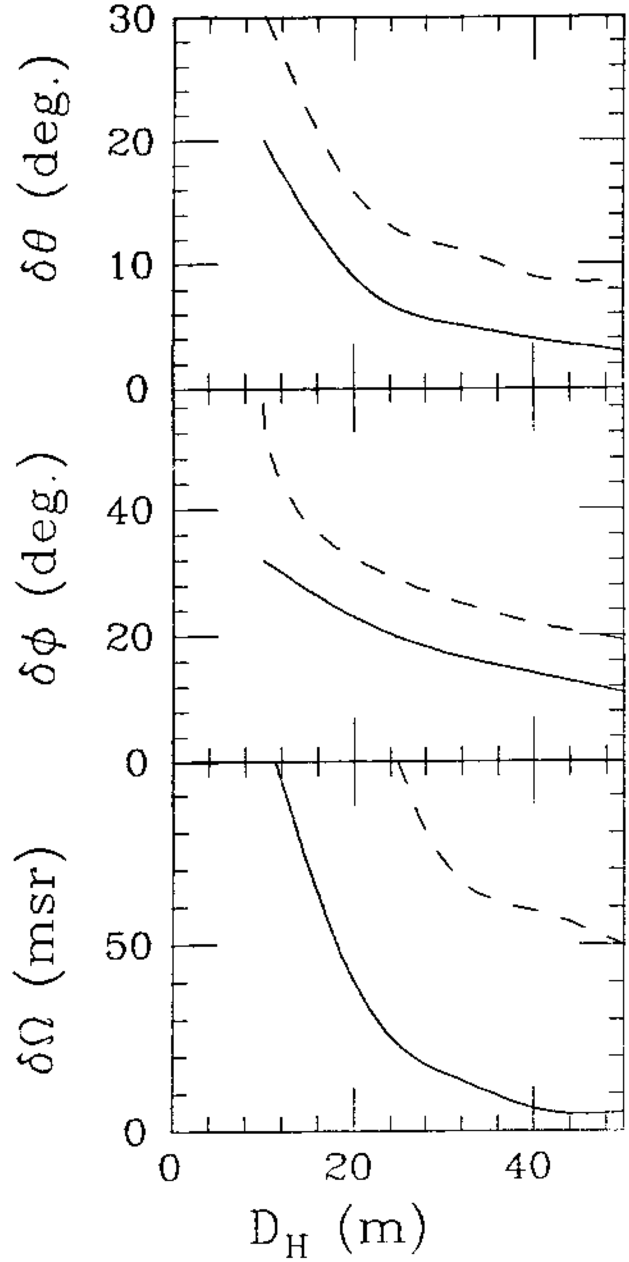


FIG. 3

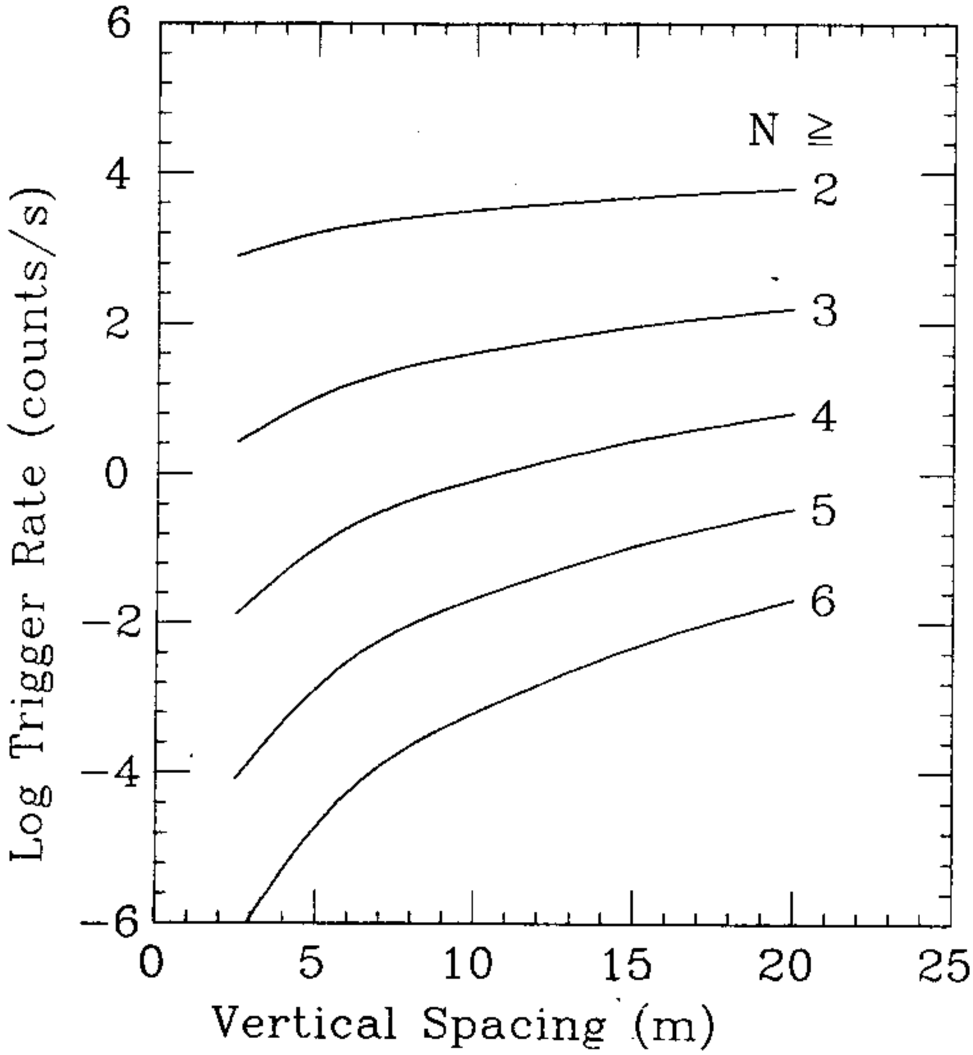
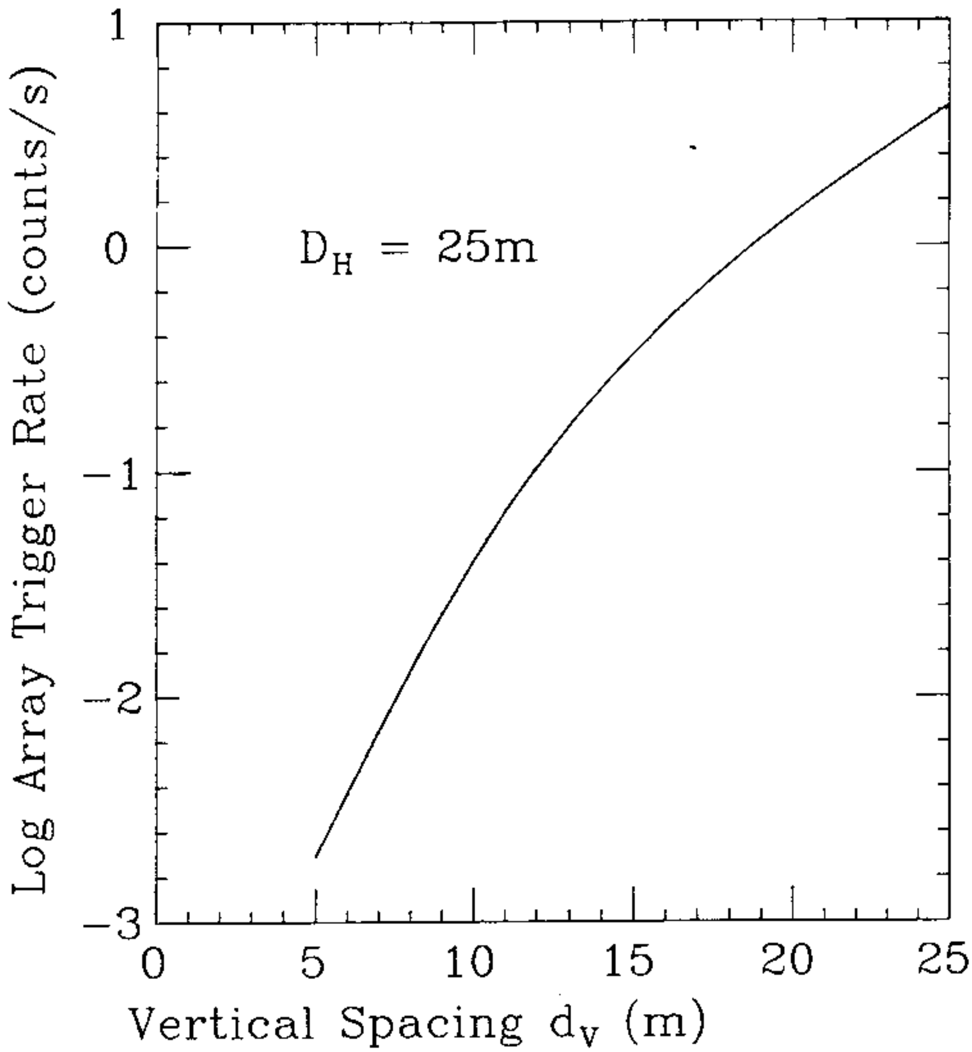

Log Trigger Rate (counts/s)
Vertical Spacing (m)
N ≥
2
3
4
5
6
6
4
2
0
−2
−4
−6
0
5
10
15
20
25

FIG. 4



Log Array Trigger Rate (counts/s)
1
0
−1
−2
−3
0
5
10
15
20
25
Vertical Spacing d_V (m)
D_H = 25m

FIG. 5