NESTOR
A NEUTRINO PARTICLE ASTROPHYSICS UNDERWATER LABORATORY FOR THE MEDITERRANEAN

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ABSTRACT

A new program for an underwater neutrino astrophysics laboratory to be located in die international waters off the Southwest of Greece, near the town of Pylos has now been funded for the initial stage. In the last 2 years a group of physicists from Greece and Russia have carried out two demonstration experiments in 4km deep water, counting muons and verifying the adequacy of the deep sea site. Plans are presented for a 100,000 m^2 high energy neutrino detector composed of a hexagon of hexagonal towers, with 1176 optical detector units. A progress report is given and the physics potential of a single tower with 168 phototubes (currently under construction) is described.

I would like to welcome all the participants to the 2nd International Nestor workshop. The aim of this workshop is a) to announce to the international physics community the existence of project NESTOR and the funding approval for the initial phase, b) to review the measured environmental parameters of the proposed NESTOR site, c) to review the physics aims of project NESTOR, d) to review the design parameters of the first NESTOR tower and e) to briefly review the physics interest of the field of high energy neutrino astrophysics. Our hope is to hold another workshop, in a year from now, in order to review in much more detail the "final" (hopefully) NESTOR parameters. It turns out that the scheduling of oceanographic cruises is not much more reliable than accelerator scheduling. Our Russian colleagues were a few weeks late in starting their trip from Kaliningrad in the Baltic to Pylos due to the sudden manyfold increase of diesel prices in Russia. They are on their way to Pylos now and they should arrive here in ten days. Once they get here we will proceed with our plans and take more measurements of the water transmissivity, the underwater currents and the sedimentology of the NESTOR location, further we do hope to deploy a few phototubes at depths of 4000m to measure again the flux of cosmic ray muons. For completeness we will include the results of these measurements ex post facto in these proceedings

I hope that everyone here is a believer that neutrino astrophysics will soon become an important part of both Elementary Particle Physics and Astrophysics. Clearly the field was born with the detection of neutrinos from supernova 1987A by IMB and Kamiokande. Very soon, with the deployment of DUMAND off the coast of Hawaii the detection of high energy neutrinos will become a reality also. The laboratory of Gran Sasso is a real proof of the importance that the European Physics community gives to extraterrestrial neutrino physics, but $1000m^2$ is the maximum sensitive area that an underground detector can have. Most of us believe that in order to get into the point astronomy with neutrinos a sensitive area of $100{,}000m^2$ or more is needed, the only way that one can get to these huge areas is to go deep into the water. One has to go deep (usually around 4000m deep) in order to reduce the huge cosmic ray background (noise to signal on the earth's surface of $\sim 10^{11}$) to a level that is both manageable by fast electronics and efficient reconstruction. The water is a beautiful Cerenkov medium, with a Cerenkov angle of $\sim 43°$ and a water transmission length that can be as good as 60 meters. So the sea water, acts as I) an absorber that filters out cosmic rays, II) a target with which the neutrinos interact and III) an active detector medium which with the Cerenkov effect illuminates large areas quite a distance away from the passage of the particles (mainly the muon) that are produced in neutrino interactions.

We believe that Europe needs its own dedicated underwater neutrino laboratory that will extend the sensitive reach of Gran Sasso to more than a million square meters. The Baltic Sea, the Black Sea and the North Sea are relatively shallow and the required depths of 4000m are found only in the

Mediterranean and the Atlantic. The deep Atlantic sites are far away from shores and good harbours, a fact that gives nightmares to many of us especially when we worry about deployment and is compounded by the high waves and the big swells that are always present, to contrast this, the placid (most of the time) waters of the Mediterranean offer a haven. In fact there are two underwater plateaus in the Mediterranean with depths of 4000m or more, one off the South East coast of Rhodes and the other 7.5 miles South West of Sapienza near Pylos (fig.l), where a little further away one finds the deepest part of the Mediterranean 5200m. This is the location we have chosen to deploy our neutrino telescope. Further, the Bay of Navarino (Pylos) is a perfect testing station for underwater hardware and a good assembling area before going out a few miles away to deploy the telescope towers.

We call our project[1] NESTOR because we want to honour the most famous man of the land of Pylos, Nestor was the wise king of Pylos who counselled the Greeks during the Trojan war. To us now the name underlines the scientific goals of our laboratory to engage in the detection of both low energy and high energy neutrinos, so it is an acronym, NEutrinos from Supernovae and Tevsources Ocean Range. Although our finances right now are such that we cannot afford to built an extragalactic supernova detector we have designed a high energy neutrino detector that is also an efficient low energy neutrino detector (in order to do atmospheric neutrino oscillations) and still is a competitive galactic supernova detector.

Site

As you can see from the chart of isobaths (fig.2) we have located at a depth of 3,750m a rectangular plateau with sides of 8km • 9km (at a distance of 7.5 nautical miles from the lighthouse of Sapienza (where our counting room will be located), then the processed data will be transferred from Sapienza to Pylos by either microwave link or optical fiber. It is worth emphasise that the slope of the plateau is indeed fiat and horizontal, its depth changes only by 100m over 9 kilometers, it is also interesting to note that on a two dimensional projection our site lies on the extrapolation of a straight line from CERN to Gran Sasso.

Water Transmissivity

The water transmissivity at the depth of 3800m is the most important environmental parameter. This is why we have spent a lot of effort to measure it. Basically there are three ways of measuring it.

1) taking a large number of samples (47 in our case) from different depths at various locations in the vicinity of the deployment site and

measuring the attenuation coefficient aboard the oceanographic ship with a highly collimated monochromator spectrophotometer[2]. This technique yielded an attenuation coefficient ranging from .025 to .045 (fig.3) at 4600 Angstroms. But the scattering of the light does not take light away from a water Cerenkov experiment[3], we therefore have to correct the attenuation coefficient for scattering. Oceanographers differ in this correction[2],[3] and their estimates range from 20% to 50%. If you believe the first number, then the absorption length (i.e. the inverse of the attenuation coefficient corrected for scattering) is somewhere between 28m and 50m. If you believe the 50% correction then the transmission length is between 35m and 60m. In either case the water transparency is very good.

2) Taking an autonomous module[2], e.g. a photometer and deploying it in situ. Three such deployments were made down to depths of 4000m. Since there was no reference cell one gets relative numbers only. The shape we get is consistent with the results of method 1, which means that we understand the systematics. For more details see reference 2.

3) A high energy physicist's way of doing the measurements i.e. measuring in situ the light detected as a function of the distance between the light source and the detector. Indeed such a device was designed and built by Hugh Bradner was used for the DUMAND measurements. The advantage of this technique is that the light beam is not highly collimated so one does not have to correct for the scattered light. The same device[4] was deployed four times in the NESTOR location and measurements gave a transmission length of 54±10m (fig.4). This result is clearly consistent with the one described in 1 above. If one considers that the cost of the detector drops inversely with the third power of the transmission length, I can only say that we are very fortunate to have such great water transmission length.

Underwater Currents

The underwater currents in the proposed NESTOR site were measured in October 1989, July/August 1991 and October/November 92. Their values are a few cm/sec, truly minimal. There is a detailed presentation in a paper by Demidova[5]. We will soon embark on a long term program of continuous measurement of the underwater currents in order to accumulate long term statistics.

Sedimentology

A large number of photographs of the sea bottom around the proposed site were taken. Nine core samples (almost 2 meters long) and 3 core grabs were taken also and careful sedimentology studies were made. The result is nice firm clay, good anchoring ground. The detailed sedimentology study is presented in a paper by Trimonis et. al.[6].

Deep Water Cosmic Ray Measurements In The Nestor Site

During July 1991, a collaboration of the Institute for Nuclear Research and the Institute of Oceanology of the Russian Academy of Sciences and the University of Athens carried out a successful cruise using the R/V VITYAZ off the coast of Pylos. We deployed[1] a Russian built hexagonal structure fig. 5a,5b,5c,5d (7m radius) built out of titanium using 10 phototubes (15 inch photocathodes) facing upwards, down to a depth of 4100m. Six of the phototubes were located at the corners of the hexagon and four 3.5 meters below the center. We successfully measured the vertical muon intensity and the angular distribution of downcoming muons. As one can see from figures 6-7 our results at 3300m, 3700m, and 4100m agree very well with DUMAND I, the deep mine measurements, and Miyake's formula.

In November 1992 we deployed[7] a linear string of five 15 inch phototubes (again the photocathodes were facing upwards). This time the deployment was made from the Russian research vessel "Ac. Mstislav Keldysh". The string was deployed in depths from 3700m to 3900m, the vertical intensity of cosmic ray muons and their dependence of the muon flux as a function of the zenith angle was obtained. The results are in good agreement with the previous measurements and calculations.

To summarise, at depths between 3700m and 3900m the vertical flux $(9.8 \pm 4.0) \cdot 10^{-9} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. The background due to radioactive K^{40} and water bioluminescence is 597±150 photons/cm^{2}s. We note that this is an upper limit because since the phototubes were suspended from the ship the vertical motion excites the various organisms giving very high values for the bioluminescence compared to anchored phototubes

Basic Detector Element: Omni Directional Module

Instead of using one 15 inch phototube facing down (like DUMAND), we will use two 15 inch phototubes (each in its own protective glass 17 inch Benthosphere), tested to 600 Atmospheres of pressure one looking up and the other looking down (fig.8, detail). This way we get a detector element with an isotropic (4π) response.

Two Dimensional Array Element: A 16m Hexagon

Six Omni-Directional Modules will be placed at the corners of a horizontal hexagon and a seventh one in its center. The radius of the hexagon is planned for 16m, and the arms made out of titanium piping. This design is a straightforward extension of the hexagonal autonomous module we used during the tests off Pylos in the summer of 91, and the increase of the hexagon radius from 7m to 16m may easily be achieved. We are investigating the feasibility of constructing titanium hexagons with 20m radius, in order to increase the active detection area.

Three Dimensional Element: 330m Tower

By stacking hexagons we can built "towers", figure 8. The vertical distance between these hexagonal floors will be around 30m, this spacing matches well the light transmission length of 55m±10m (at 460nm) we have measured in these waters. With 30m inter-hexagonal floor spacing and 7 phototubes from a lower hexagon looking up and 7 phototubes from a higher hexagon looking down, the active volume between hexagonal floors will be monitored efficiently. A total of 12 such hexagonal floors is planned for one tower. At this moment, the number of floors is constrained to 12 by the number of optical fibers in currently commercially available electro-optical cables for the data transmission to the shore and for the supply of electrical power to the tower. Each floor will be electrically and electronically independent from the other floors and will have its own optical fiber for data transmission. We are studying the possibility of multiplexing the analogue phototube outputs and modulating a laser output in order to pipe it out to shore via the optical fiber. This way there will be no fast electronics in the sea and the shore station will function as a traditional counting room where all the triggering and data aquisition electronics will be located.

Single Tower Sensitivity

The beauty of the water Cerenkov technique is that the detector sensitive area reaches out quite a bit further away than the actual geometrical area of the detector. Clearly the effective area is a function of the energy of the muon. In fig.9 we see that for 10° reconstruction accuracy of the direction of a 10 TeV muon the effective area is 20,000m^2 and 50,000m^2 for 10^3TeV muons and 40° reconstruction accuracy(compare this to 400m^2 for IMB and 1000m^2 for MACRO). The angular resolution along the horizontal for a single tower is, of course, not as good as needed for point source astronomy simply due to the restricted lever arm. Note however that the predictions for the flux of UHE neutrinos for Active Galactic Nuclei is for a diffuse background of neutrinos with energies up to 10^{16} eV, so very good pointing is not needed in order to get started.

Full Detector Array: e.g. A Hexagon Of Hexagonal Towers

The need for a full $10^5 m^2$ array can be satisfied with a hexagonal configuration of another six towers deployed on the apexes of an 100m or 150m radius hexagon centered around the original tower fig. 10. Such an arrangement would provide an overall angular resolution of better than 1°, excellent for point astronomy, and sensitive area bigger than $10^5 m^2$ for neutrinos of 1 TeV. The total cost of such an array is less than 15M$. Such a detector would have a sensitive area of > 100,000m^2, angular resolution of < 1°, enclosed mass > 20 Megatons and would almost certainly be able to begin the field of high energy neutrino point source astronomy.

Of course the possibilities do not stop at $10^5 m^2$. The beauty of the deep sea approach is the potential for following the physics as one gains experience and first looks at the data. A bigger detector is obviously possible, as are configurations that maximise low energy sensitivity, or tune on any particular facet of the science that may prove worth pursuing.

The Physics Potential Of Nestor With Only One Tower

There is a multitude of exiting physics that we can do with one NESTOR tower, while waiting for the events of extraterrestrial origin to come in. These include atmospheric neutrino oscillations, long baseline oscillations with CERN, (perhaps in conjunction with a detector at Gran Sasso). Stavros Katsanevas will present a detailed description of the physics.

References

1. L.K.Resvanis et. al., *NESTOR: A Neutrino Particle Astrophysics Underwater Laboratory for the Mediterranean,* High Energy Neutrino Astrophysics Workshop, Hawaii March 1992, V.J.Stenger
2. S.A.Khanaev and A.F.Kuleshov, *Measurements of water transparency South-West of Greece,* these proceedings.
3. H.Bradner, *Attenuation of light in clear deep ocean water,* these proceedings.
4. E.G.Anassontzis et. al., *Measurement of light transmissivity in clear and deep sea water,* these proceedings.
5. T.A.Demidova and I.A.Repin, *Investigation of near bottom currents in Inouse pit in the vicinity of NESTOR area,* these proceedings.
6. E.Trimonis, *Geomorphology and bottom sediments of the Pylos area,* these proceedings.

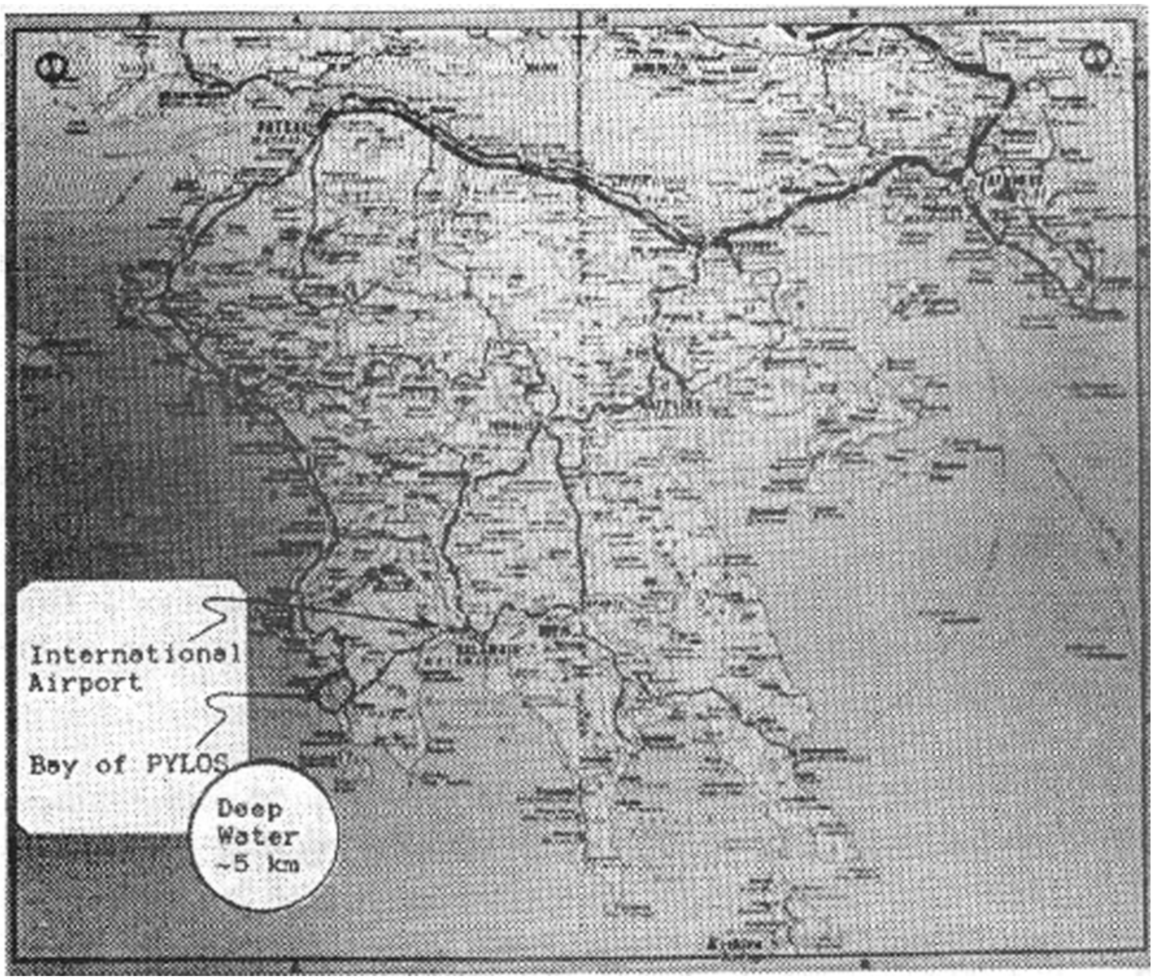


Figure 1

ISOBATHS
CONTOURS OF EQUAL DEPTH

The lighthouse of Sapientza will be the counting room. Then the data will be transmitted to PYLOS by cable or microwave link.

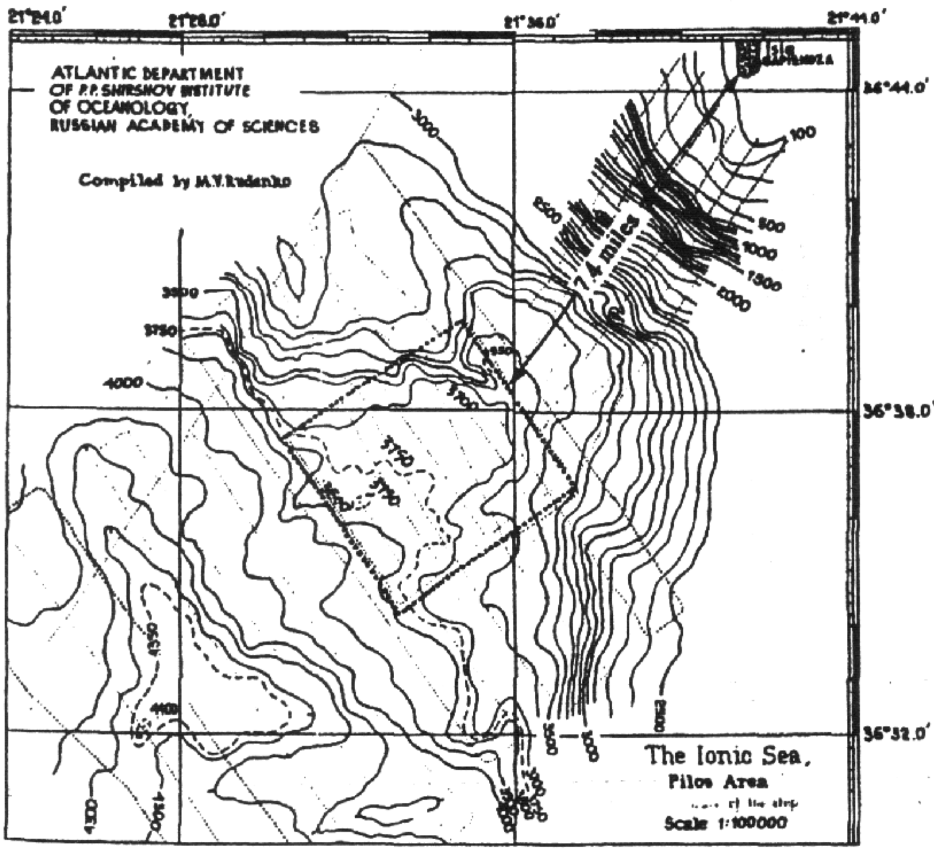
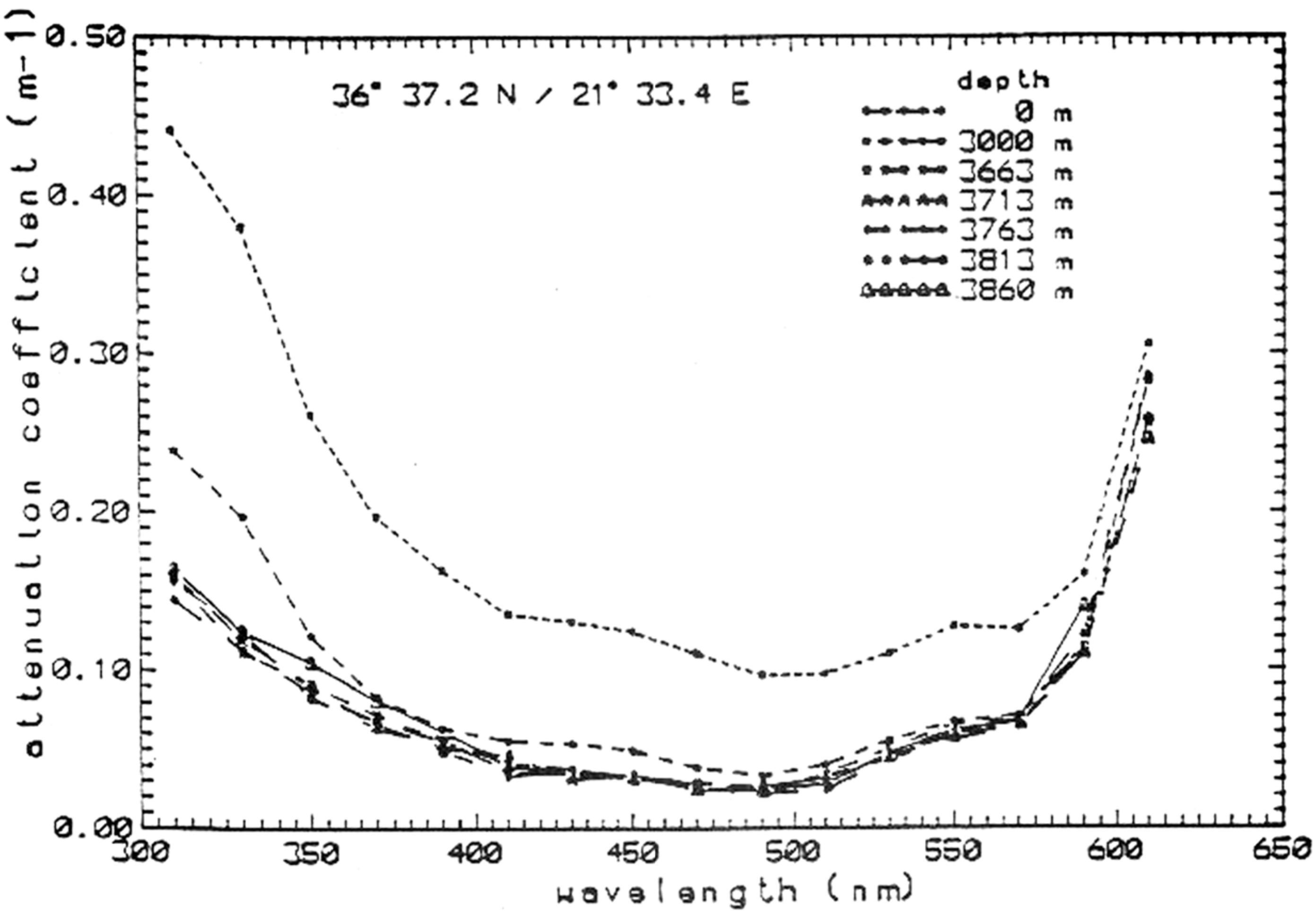


Figure 2

Figure 3


36° 37.2 N / 21° 33.4 E
depth
0 m
3000 m
3663 m
3713 m
3763 m
3813 m
3860 m
attenuation coefficient (m-1)
0.00
0.10
0.20
0.30
0.40
0.50
300
350
400
450
500
550
600
650
wavelength (nm)

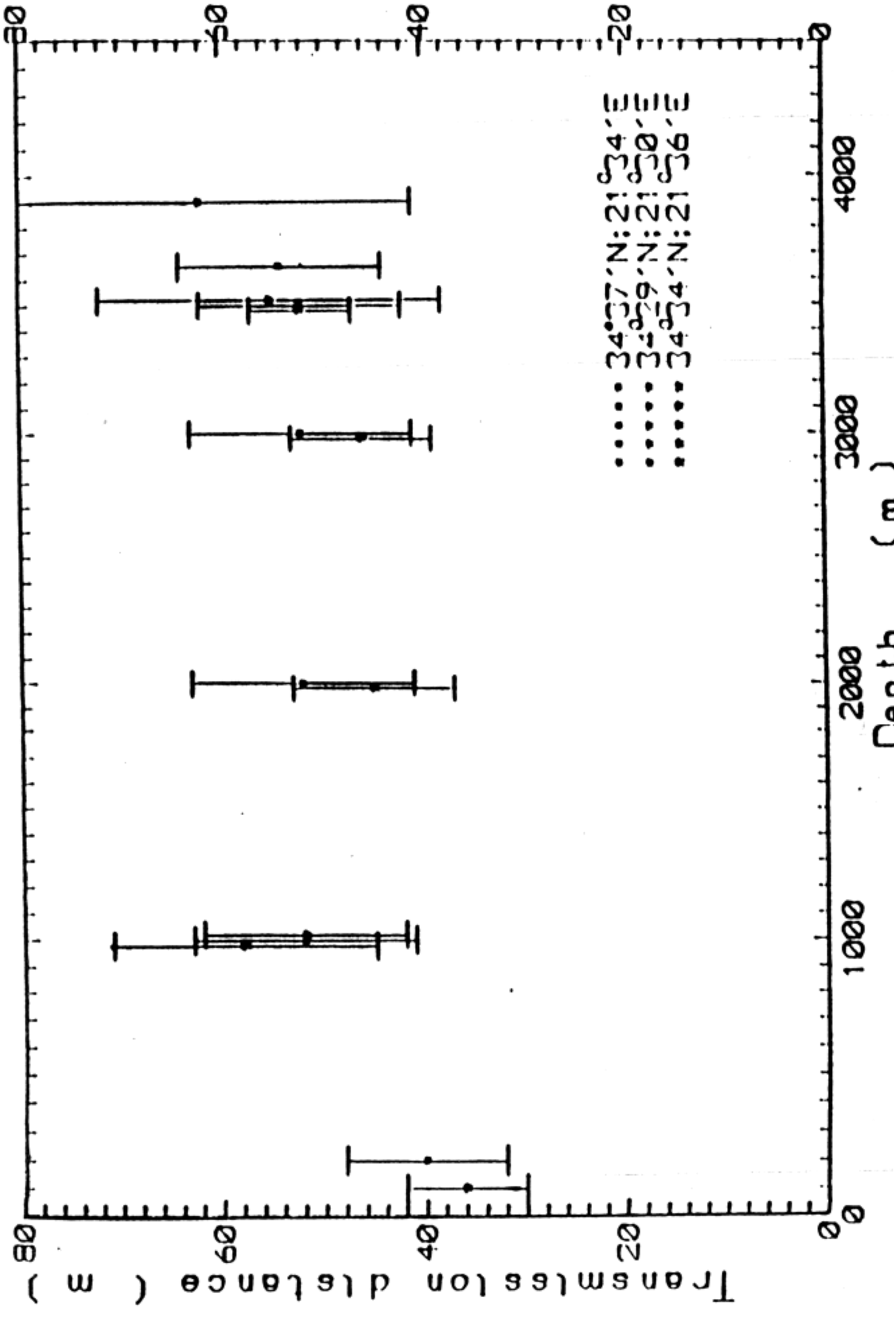


Figure 4. Transmission distance vs depth at three locations near the future NESTOR site.

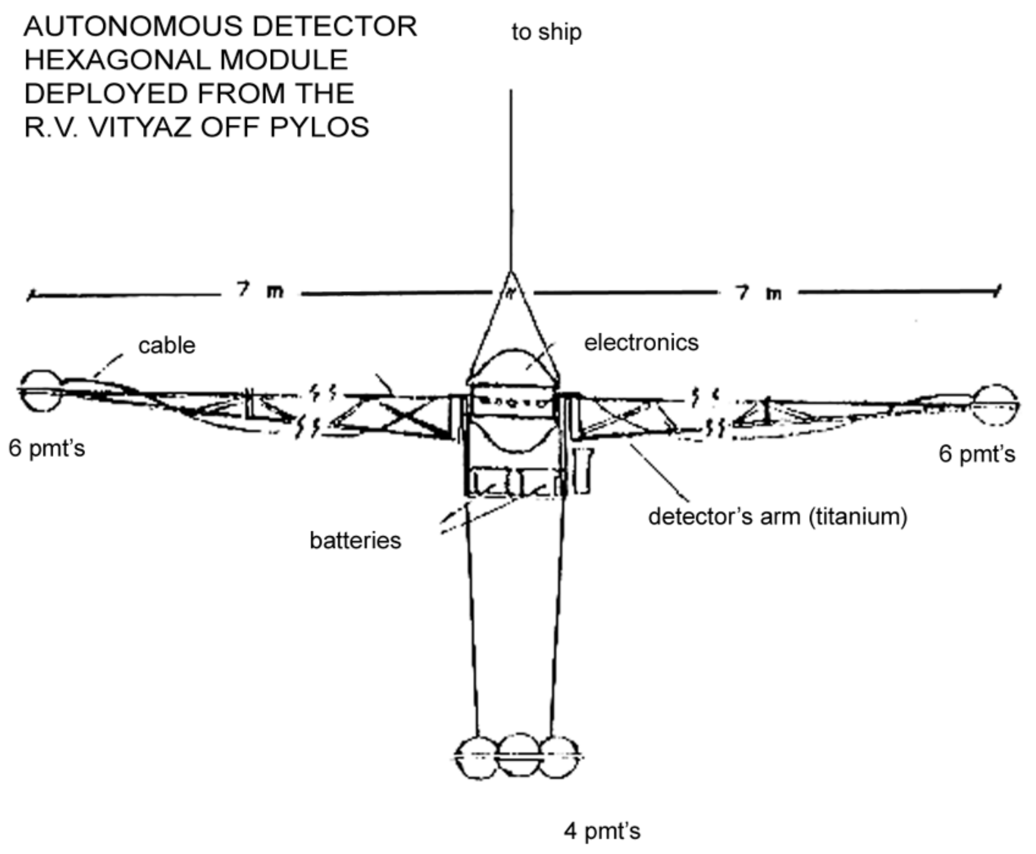

AUTONOMOUS DETECTOR
HEXAGONAL MODULE
DEPLOYED FROM THE
R.V. VITYAZ OFF PYLOS
to ship
7 m
7 m
cable
electronics
6 pmt's
6 pmt's
detector's arm (titanium)
batteries
4 pmt's

Figure 5a

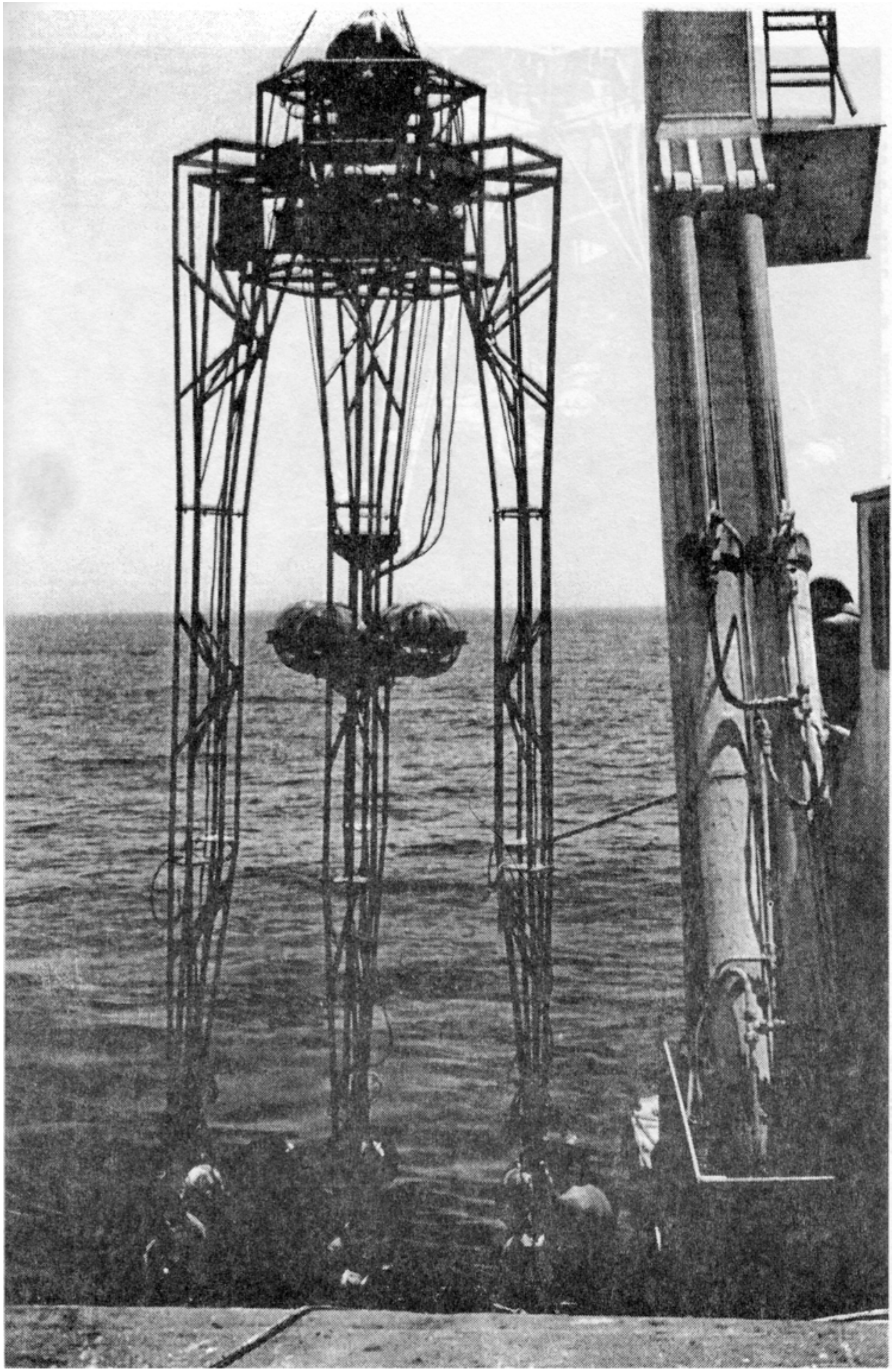


Figure 5b

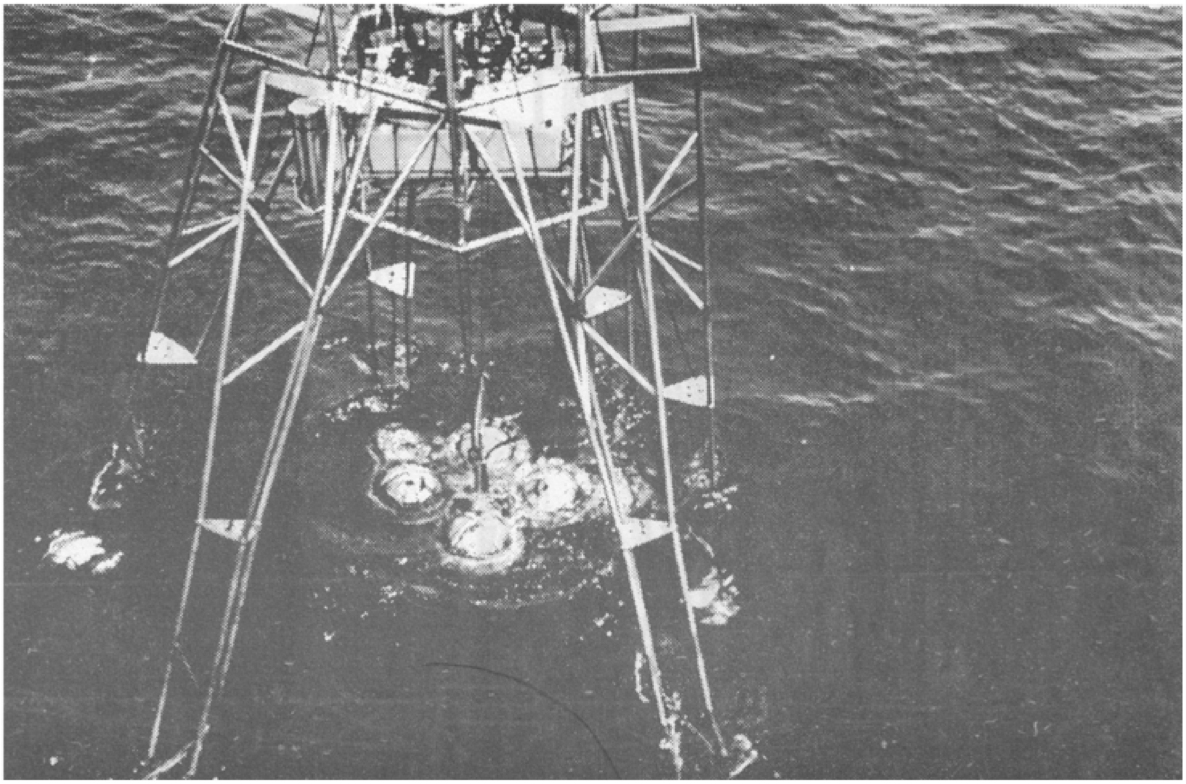


Figure 5c

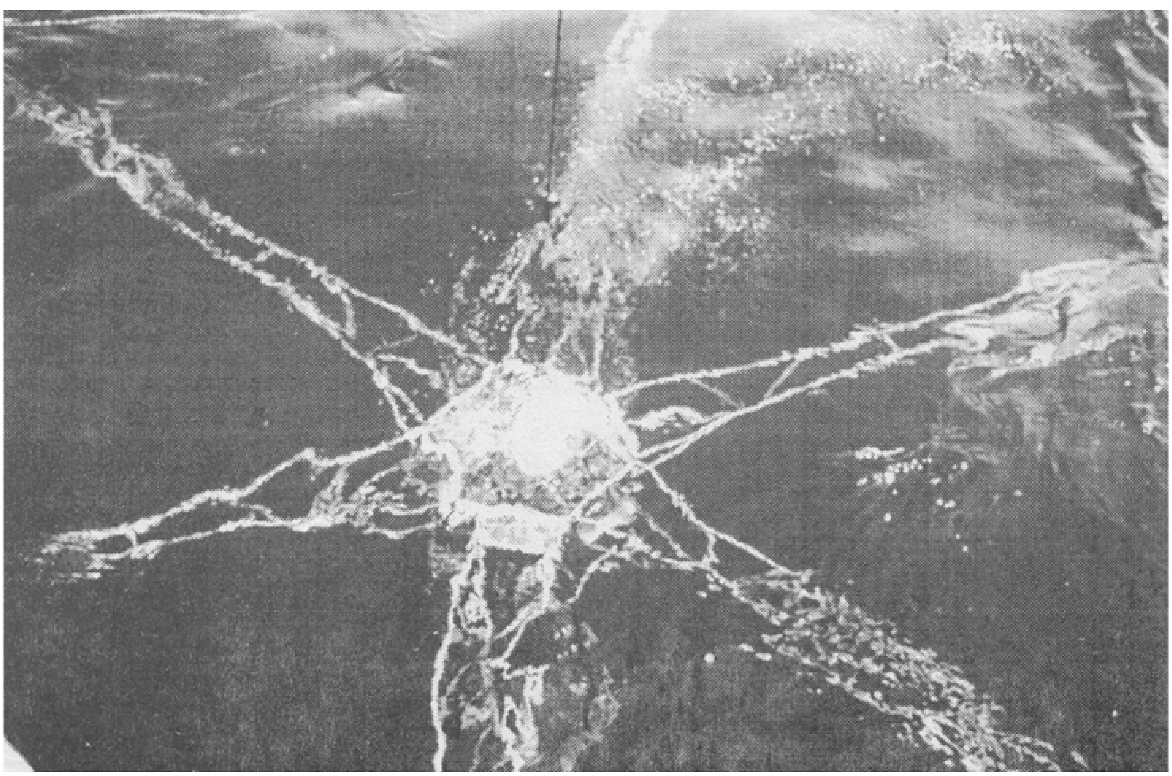


Figure 5d

Figure 6

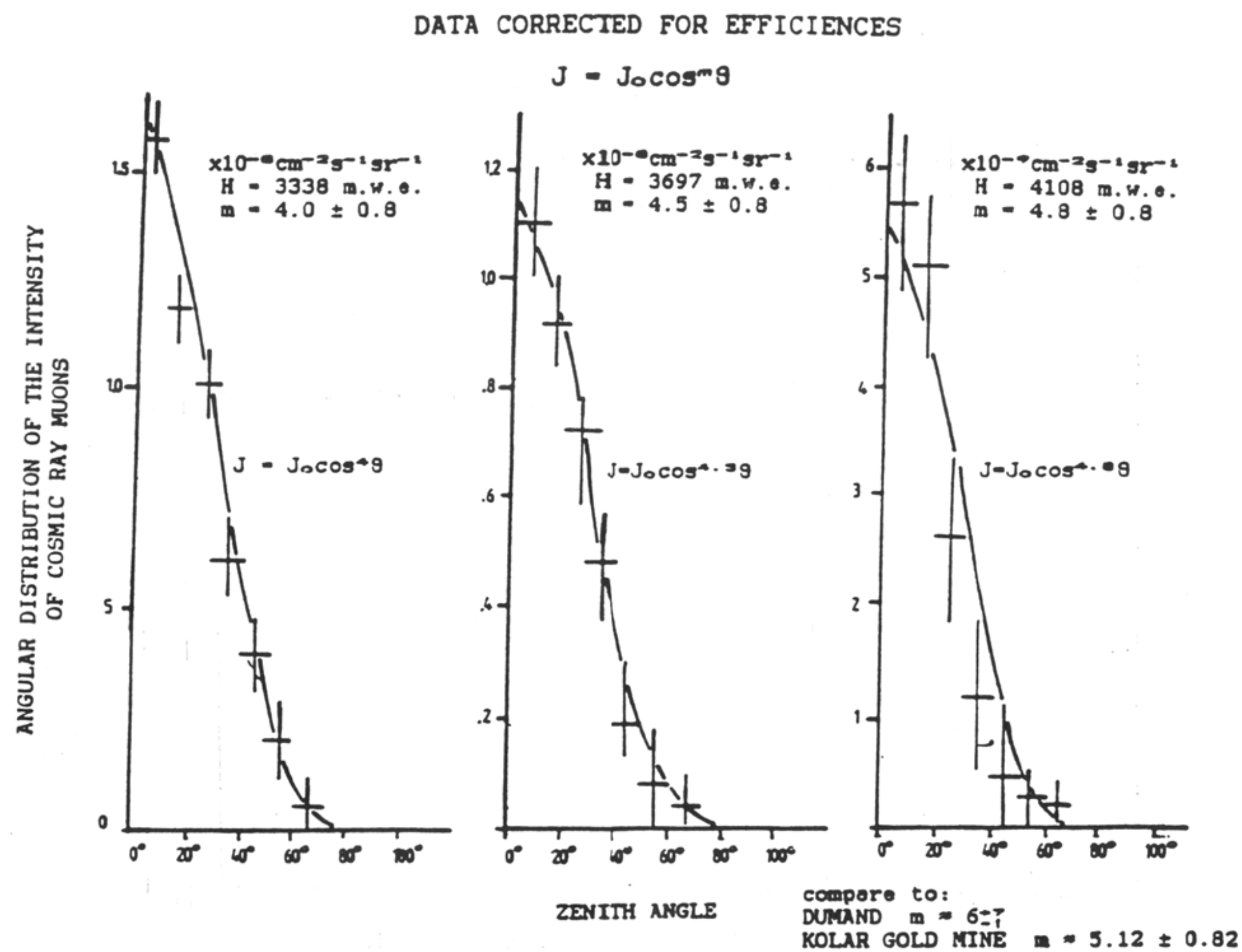
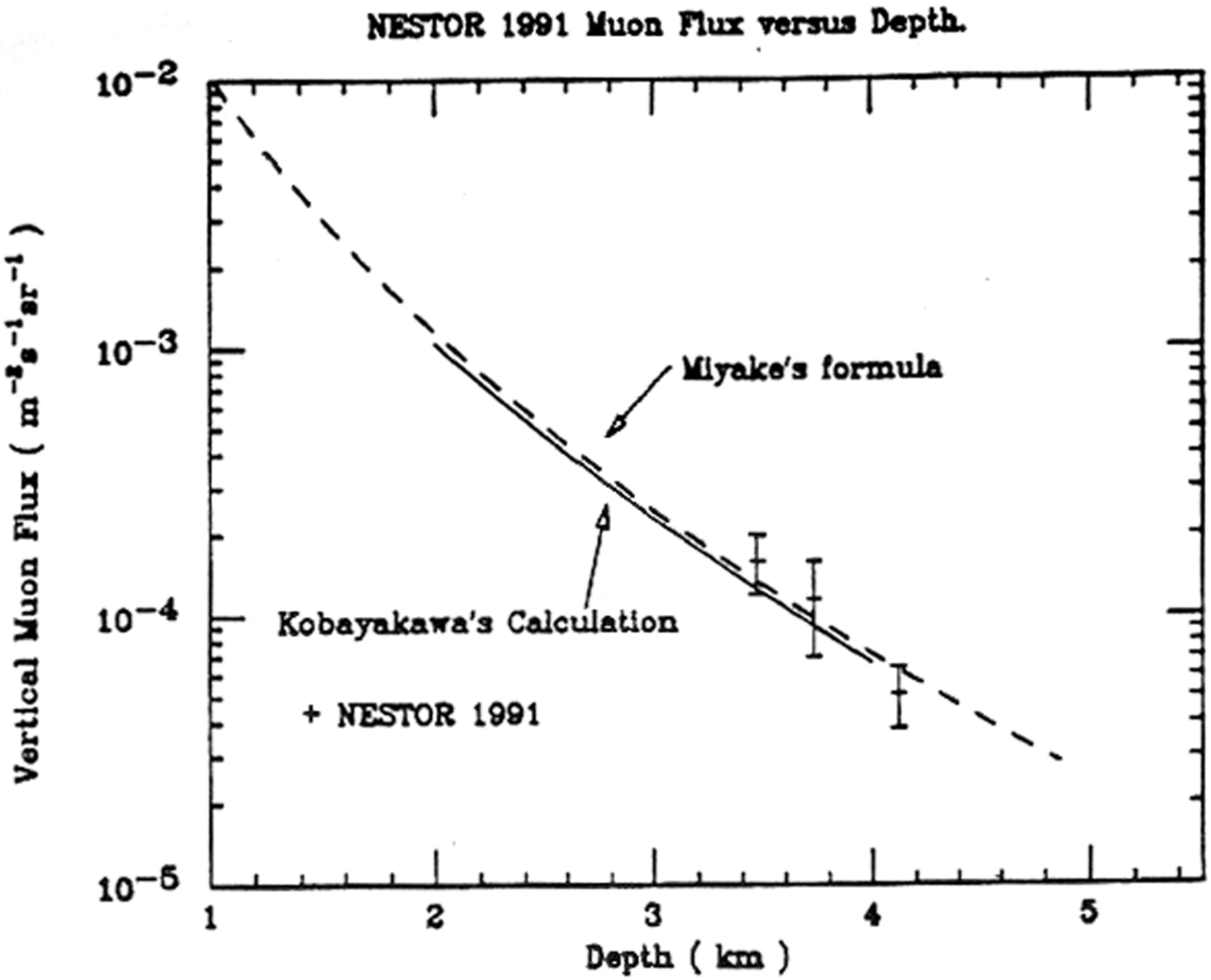

DATA CORRECTED FOR EFFICIENCES
J = J₀cosᵐθ
ANGULAR DISTRIBUTION OF THE INTENSITY
OF COSMIC RAY MUONS
x10⁻⁸cm⁻²s⁻¹sr⁻¹
H = 3338 m.w.e.
m = 4.0 ± 0.8
J = J₀cos⁴θ
x10⁻⁸cm⁻²s⁻¹sr⁻¹
H = 3697 m.w.e.
m = 4.5 ± 0.8
J=J₀cos⁴·³θ
x10⁻⁹cm⁻²s⁻¹sr⁻¹
H = 4108 m.w.e.
m = 4.8 ± 0.8
J=J₀cos⁴·⁸θ
ZENITH ANGLE
compare to:
DUMAND m = 6
KOLAR GOLD MINE m = 5.12 ± 0.82

Figure 7



NESTOR 1991 Muon Flux versus Depth.
Vertical Muon Flux (m^{-2}s^{-1}sr^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
2
3
4
5
Depth (km)
Miyake's formula
Kobayakawa's Calculation
+ NESTOR 1991

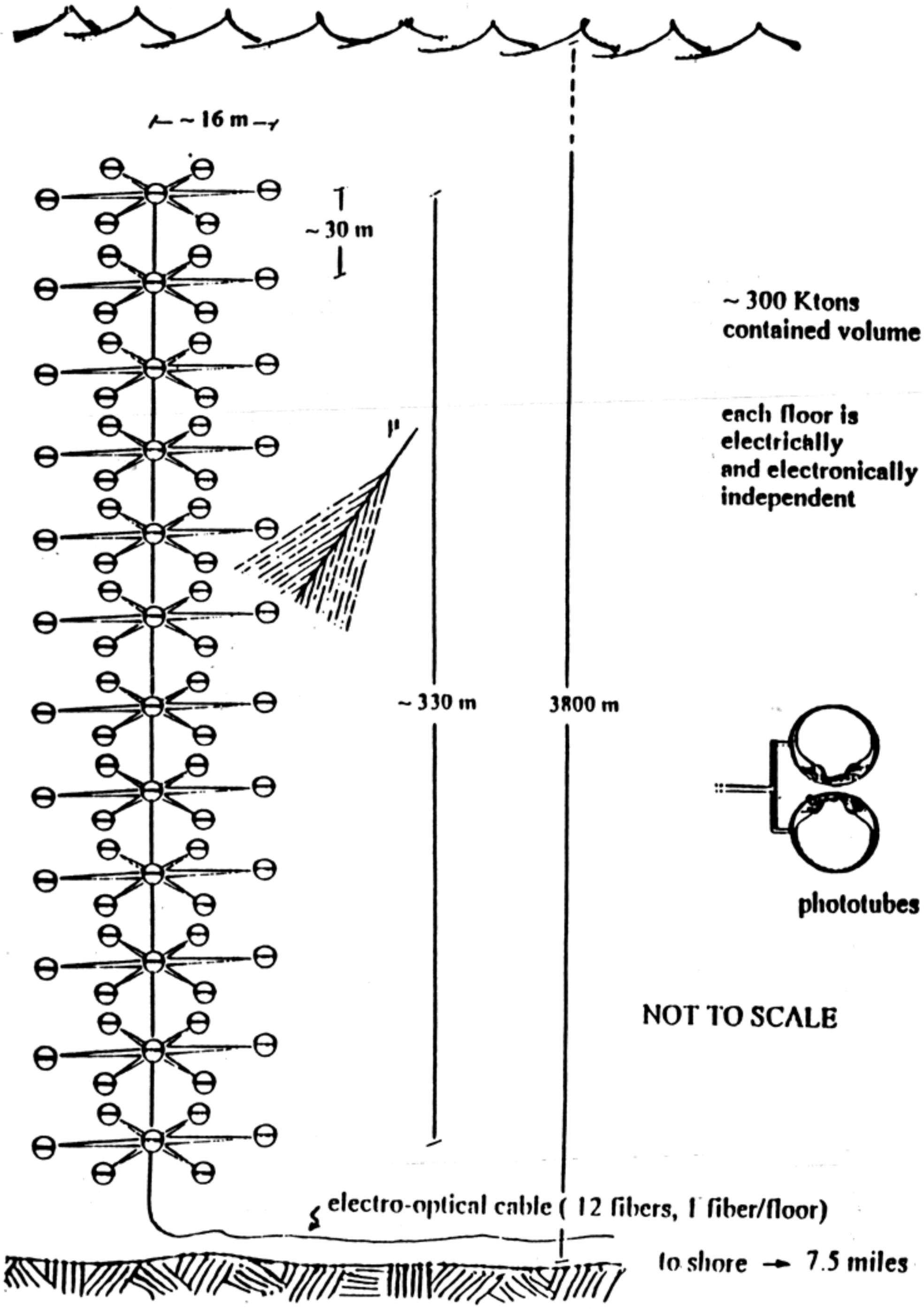
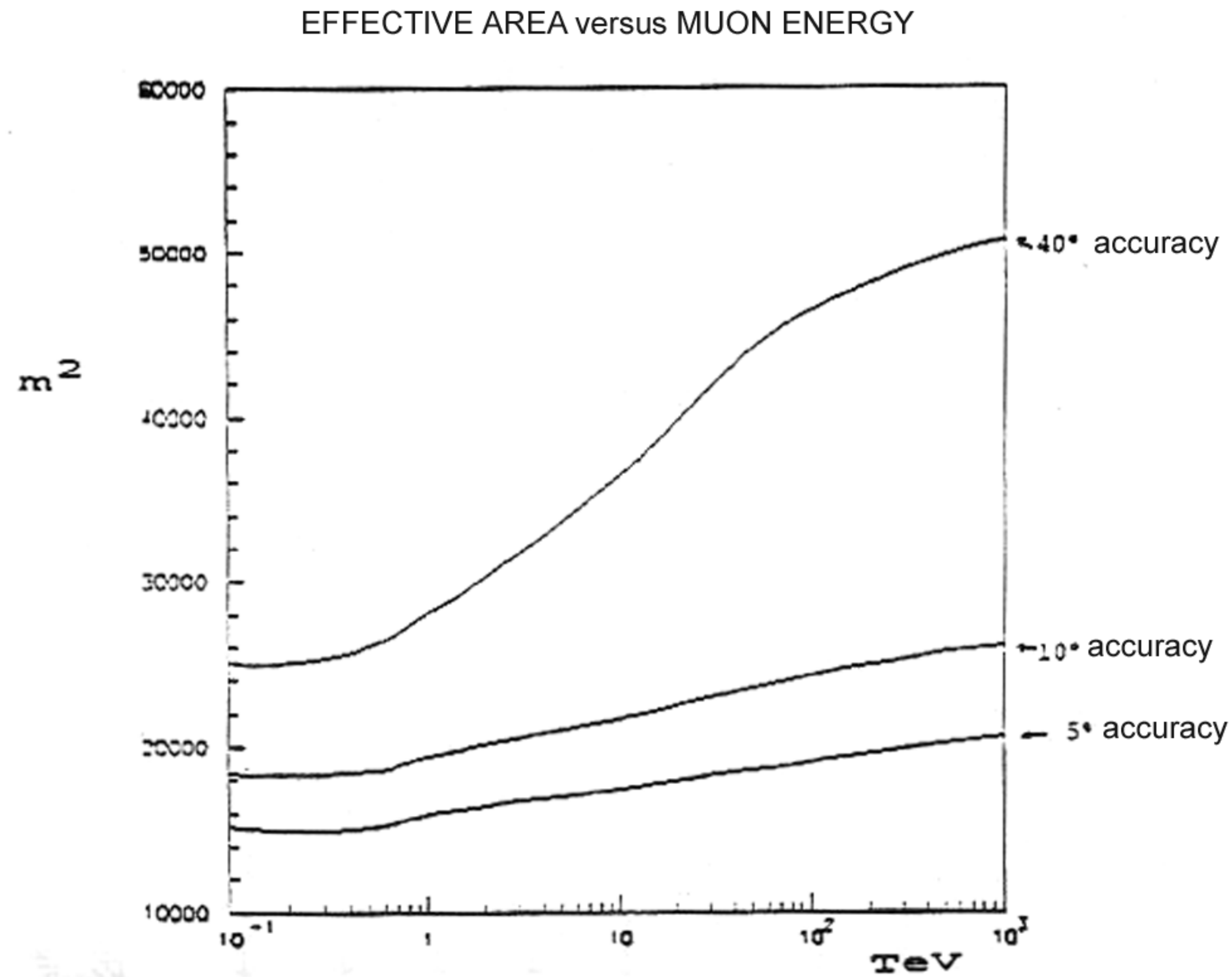

~ 16 m
~ 30 m
μ
~ 330 m
3800 m
~ 300 Ktons
contained volume
each floor is
electrically
and electronically
independent
phototubes
NOT TO SCALE
electro-optical cable (12 fibers, 1 fiber/floor)
to shore → 7.5 miles

Figure 8

Figure 9

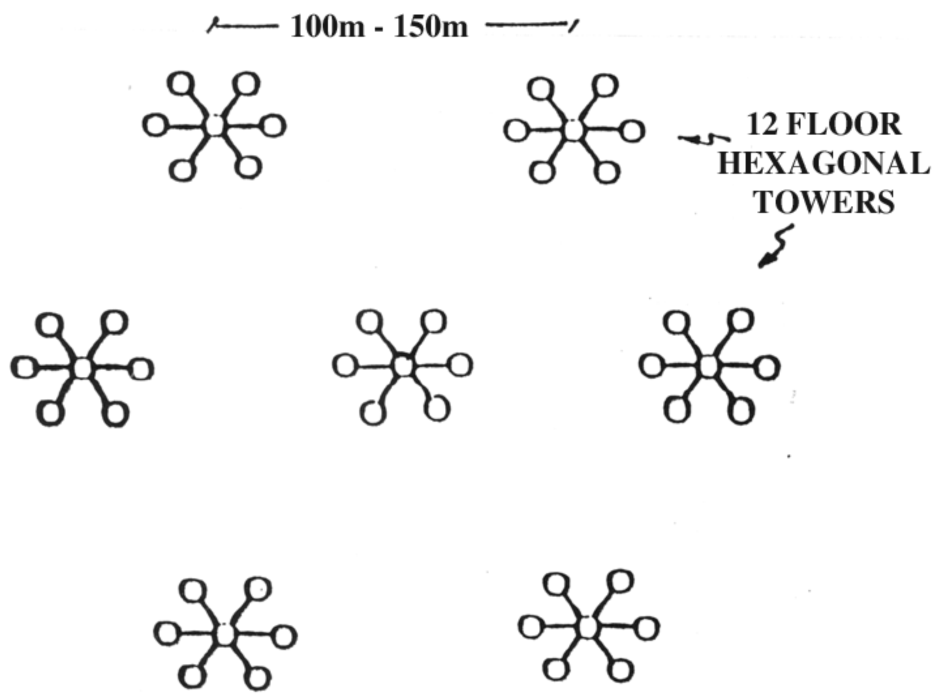


EFFECTIVE AREA versus MUON ENERGY
m2
60000
50000
40000
30000
20000
10000
10-1
1
10
102
103
TeV
40° accuracy
10° accuracy
5° accuracy

FULL NESTOR ARRAY

A HEXAGONAL ASSEMBLY OF 7 TOWERS
VIEW FROM ABOVE

each tower has 12 floors
the towers are mechanically and electrically independent



sensitive area > 100,000m^2
angular resolution ~ 1°
enclosed volume > 20 megatons
total number of phototudes 1176

THIS CONFIGURATION SHOULD BE BIG ENOUGH TO BEGIN THE FIELD OF HIGH ENERGY NEUTRINO POINT SOURCE ASTRONOMY

Figure 10