1. INTRODUCTION

The Roman naturalist Gaius Plinius Secundus, in his treatise “Naturalis Historia” in the first century AD, states that ...There are some crazy people who go inside mines to study the stars... I will talk about the efforts of such people who are trying now to detect interactions from Extraterrestrial High Energy Neutrinos. The cosmic ray spectrum shows clearly that there exist cosmic rays with energies of up to $10^{21}$ eV. These highest energy particles must be extragalactic because they are too energetic to be trapped in our galaxy by the galactic magnetic field. So neutrinos and gamma rays at high energies must reach the Earth because they are the ultimate decay products of interacting cosmic rays in the Cosmos. Astronomy requires ”pointing back” to the source, i.e. the origin of production. So, the detected particle must:

1. either be neutral or very highly energetic, so it is not bent significantly by the magnetic fields,
2. it must live long enough to reach our planet, and
3. it should not interact during its long voyage in the Cosmos.

It is therefore natural for an elementary particle physicist to ask himself the question. Which Elementary Particles satisfy the above criteria and therefore we can use in order to start a New Astronomy? From the charged cosmic rays only those of the highest energies (probably protons) travel rectilinearly i.e., they are not bent significantly by the galactic and intergalactic magnetic fields. Therefore, only very few of the cosmic ray protons are useful in ”pointing back” to their origin. Neutrons are not very useful either, because only those with energies bigger than $10^{18}$ eV live long enough to cross our Galaxy. Unfortunately there are very few of those too. So they can not be used if their origin is outside our Galaxy. In any case, the physics is understood and one can calculate that protons (or heavier nuclei) with energies above $4 \times 10^{19}$ eV interact significantly with the primordial 2.7 K microwave background. Their energy is rapidly degraded and eventually these events of the highest energies (originally) get buried in the background of lower energies. Thus, charged protons cannot provide us with information for distances further away than 20–30 Mpc. So, the only elementary particles available for Astronomy are the photons and the neutrinos. Traditional Astronomy is the oldest science of the Homo Sapiens. Last century it was demonstrated that not only the optical part of the electromagnetic spectrum is useful but the whole spectrum contains a thesaurus of information. It is not therefore surprising that some of us are eager to see the birth of Neutrino Astronomy. The “delivery” started at the end of last century with the observation of solar neutrinos and with the neutrinos from Supernova 1987A.

EGRET observations of gamma rays with energies up to the tens of GeVs and the observations of AGNs [1] by the Mount Hopkins Atmospheric Cherenkov Telescope, around 1 TeV have stimulated calculations on the interactions of very high energy gamma rays with the ambient intergalactic photons [2]. The calculations can be interpreted to show that the mean free path of gamma rays with energies above some hundreds of GeV is around 100 Mpc due to scattering with the intergalactic ambient infrared and ultraviolet starlight. This conclusion combined with well known calculations that show that gamma ray
attenuation due to scattering with the 2.7 K background is very serious for gamma rays of hundreds of TeV energies, leaves the neutrinos as the only promising particles for TeV or higher energies Astronomy. The neutrinos not only go through interstellar space without suffering any attenuation but they also escape their progenitor’s acceleration and target sites without suffering any absorption. Therefore the only way to measure the emission/production spectrum at the source is to measure the spectrum of the neutrinos arriving on Earth. The inescapable conclusion is that with neutrinos one can see “further” into the past or “deeper” in the Cosmos than with any other known to date particle. The difficult question is “what is the neutrino flux” [3,4]? Or conversely, how big a detector do we need in order to start the field of "High Energy Neutrino Astronomy”? The only reasonable way to answer this question is to use the experience gained over the last 20 years or so by the construction and operation of the second generation neutrino telescopes and scale up by a few orders of magnitude in well defined steps. Each step should have the potential to contribute significantly to Astrophysics or Particle Physics [3,4]:

1. Relic neutrinos from the Big-Bang fill the Universe but no one has yet proposed a practical way to detect them.

2. Low energy neutrinos of keV to ≈ 1 MeV are emitted continuously from the interior of stars like our Sun. At this moment there are at least half a dozen solar neutrino telescopes in operation, but there is no proposal to detect neutrinos produced in the interior of other stars.

3. Slightly higher energy neutrinos (≈ 14 MeV) are produced during the explosions of supernovae and one can argue that the birth of Neutrino Astronomy happened with the detection of supernova 1987A by KAMIOKANDE and IMB, although no one has yet proposed a practical way to detect supernova neutrinos further away than the immediate neighborhood of our galaxy.

4. Neutrinos in the higher energies are produced from decays of particles produced from cosmic rays interacting and the subsequent cascades in the Earth’s atmosphere The shape of their spectrum is caused by the competing processes of meson production and decay in a target medium (the atmosphere) of continuously changing density.

5. Neutrinos with energies in the range of one to a few hundred GeV for example may also come from the annihilation of WIMPs (Weakly Interacting Massive Particles) in the Galactic center (s), the stars like our Sun or the central core of the Earth.

6. Neutrinos from point sources are decay products of particles produced in hadronic interactions, in potential cosmic accelerators such as neutron stars, black holes and young supernova remnants. Our own galaxy is full of such candidates. Further the Cosmos is full with Active Galactic Nuclei (AGN) and they are very promising sources of Ultra High Energy neutrinos. Detection of neutrinos from point sources would unambiguously establish the existence of high energy hadronic interactions e.g.

\[ p + \text{target} \rightarrow \pi^0, \pi^\pm + \ldots \]

\[ \downarrow \]

\[ \gamma \gamma, \mu^\pm \nu_\mu \]

\[ \downarrow \]

\[ e^\pm \nu_e \nu_\mu \nu_\tau \]

The observation on Earth of \( \gamma \)s from \( \pi^0 \) decay can only be a rare event, because the target must be thick enough in order to produce \( \pi^0 \) s and at the same time thin enough (≈ 5–100 g/cm²) [5] so as not to absorb the \( \pi^0 \) decay \( \gamma \)s and then these \( \gamma \)s should not interact with interstellar matter or the ambient starlight ultraviolet and infrared photons or the primordial 2.7 K microwave photons during their very long trip to the Earth. On the other hand high energy photons (up to a few TeV) can be produced not only in hadronic processes via \( \pi^0 \) decay but also by purely electromagnetic processes e.g. inverse Compton scattering or synchrotron radiation of energetic electrons and then they must escape the general environment of the target before they get absorbed.
2. PHYSICS SCOPE

The physics aim of neutrino telescopes covers one or more of the following topics (in order of descending neutrino energy):

1. Neutrino Astronomy (galactic and extragalactic) and the search for cosmic accelerators [2,3,6].
2. Particle Physics beyond the Standard Model (a few examples follow):
   - Search for dark matter particles. Their annihilation or decay will eventually give neutrinos e.g. neutralinos trapped in the Galactic center, the Sun or the Earth [7].
   - Ultra High Energy neutrinos have energies beyond $10^7$ GeV in the Laboratory. No terrestrial accelerator can produce these energies. If the neutrino telescope is large enough the limitation of low flux can be, in part, overcome and this might be the only way for High Energy Physics to reach these Ultra High Energies. In any case we can start right away, the experimental problems of neutrino telescopes are well understood. Multiple W/Z production [8]. Search for possible substructure of the elementary particles i.e. compositeness of quarks and leptons [9,10].
3. Neutrino oscillations (and thereby contributing to the question of "dark matter" in the Universe) using neutrinos produced in the atmosphere. The large range of the available oscillation length (15 km to 13000 km) gives an extremely good sensitivity of $\Delta m^2 \geq 10^{-4}$ eV$^2$ [11–15].
4. Long baseline neutrino oscillations using one of the high energy physics accelerators [13–16].
5. Proton decay (in the sense that the ultimate background to proton decay experiment is atmospheric neutrino interactions and therefore a low threshold neutrino telescope can also be a proton decay detector).
6. Supernovae detection.
7. Magnetic monopoles.
8. The unexpected. A new observational window will open up with these neutrino telescopes. No one has ever viewed sites in the Universe shielded by more than a few hundred grams of matter. One should keep in mind that each time a new brand of astronomy opened up, a new class of phenomena was discovered.

The experimental requirements for the study of the above physics topics look incompatible at first glance e.g. low vs high energy threshold, good angular accuracy vs coarse, high fractional coverage with sensitive photocathode area vs maximizing the detector’s sensitive area etc. After a couple of decades of operating small prototypes and R+D, the High Energy Physics community seems to have the right tools to build a detector to study all the above. The approach must be stepwise and modular. The detector of today’s measurements will be the prototype for tomorrow’s experiment. The background of today’s measurement is the signal of tomorrow’s experiment.

3. PRODUCTION OF ASTROPHYSICAL HIGH-ENERGY NEUTRINOS

There exist some excellent review articles of the subject and the reader is referred to [3,4,6,17,18]. The point one should stress here, is that according to Stenger’s calculations [5] the optimal condition for high energy neutrino production in a cosmic beam dump (e.g., in an X-ray binary system) is a column density $z \geq 100$ g cm$^{-2}$, target density $< 10^{-8}$ g cm$^{-3}$ and a primary proton spectral index $\alpha \leq 2$. Then, a beam of 1 TeV neutrinos would be produced at a rate of 10% of the protons that strike the source. Under these conditions the neutrino flux emitted is at least 3 times bigger than the corresponding gamma ray flux produced by the same hadronic interactions. The photon interaction cross section is many orders of magnitude larger than the neutrino cross section, therefore high energy gamma rays can be destroyed much easier than neutrinos either near the source of their production by interacting with matter or during their vast flight distance to Earth by interacting with the 2.7 K background or the intergalactic infrared
and ultraviolet starlight \([2]\). The inescapable conclusion is that we should expect more and more copious neutrino sources than gamma ray sources (assuming that the gamma rays come from decaying hadrons). Another class of sources which has become rather popular in the last ten years is neutrinos produced in the vicinity of Active Galactic Nuclei. In this mechanism, neutrinos originate from the decay of mesons which in turn are the decay products of photoproduced \(\Delta\) resonances.

\[
P\gamma \rightarrow \Delta^+ \rightarrow \pi^+ n \quad \text{or} \quad \Delta^+ \rightarrow \pi^0 p
\]

Calculations show that although signals from individual AGNs will not be detectable with the neutrino detectors presently under construction, the sum of all AGNs \([19]\) should be detectable by the neutrino telescopes under construction. Finally, we should mention that high energy neutrinos may also originate from heavy (hundreds of GeV) dark matter particles e.g., WIMPs which are trapped in the Sun or the Earth and which eventually annihilate with their antiparticles producing neutrinos among other particles.

4. CHOOSING THE NEUTRINO ENERGY

In order to detect neutrinos from the previously mentioned sources it is advantageous to focus on high energy neutrino detection. The reason is simple. The mere word astronomy implies that one ought to be able to point back to the source with high angular accuracy. In neutrino detection we cannot achieve the angular accuracy of traditional astronomy. Neutrinos are detected by observing mainly the muon which is produced from the charged current neutrino interactions with matter, in the vicinity of the detector. In high energy neutrino astronomy usually, one is NOT required to detect the vertex of the neutrino interaction, this way one maximizes the available detection volume. The physics of the interaction is such that, the angle between the detected muon and the parent neutrino direction \([20]\) for 63% of the charged current events is \(1.5\sqrt{E_{\nu}}(\text{TeV})\). So, if a source is observed with a dozen events or so, one can greatly improve the directional determination by determining the centroid of the distribution and reach accuracies of a fraction of a degree. The pointing improves also with increasing energy not only because the muon goes further forward but also because the statistics improve due to the increase of the cross section \((E_\nu\) until 10 TeV and then \(\log E_\nu\)). Another parameter which improves with energy is the range of the muon \((E_\mu\) until 1 TeV and then \(\log E_\mu\)) and thus the effective detection volume of the detector is increased proportionately. Further, the signal to noise improves with energy for the following reason. The inherent background comes from atmospheric neutrinos, which are the result of cosmic ray interactions in the atmosphere. The spectral index \(\gamma\) of the flux of atmospheric neutrinos \([21]\) follows that of the cosmic ray spectrum and is \(\approx 2.7\) up to 100 GeV or so, but then at higher energies it becomes \(\approx 3.7\), while neutrinos produced extra terrestrially follow the hard core \((\gamma \approx 2.0-2.2)\) cosmic ray spectrum. So, for neutrino energies larger than 100 GeV the signal to noise improves with energy. For all the above reasons it is advantageous to optimize the telescope for detection of high energy neutrinos. One should keep in mind though, that the design of neutrino telescopes in the water with phototubes directed toward the Earth (in order to minimize background from downcoming cosmic rays that reach the detector or because of sedimentation problems \([22]\)) can be disadvantageous when one aims to detect very high energy neutrinos (e.g., from AGNs) because then the Earth is no longer transparent to neutrinos (e.g., the mean free path for a 500 TeV neutrinos is about one Earth diameter). Therefore the upward coming neutrinos of energy larger than a few hundred TeV will be severely attenuated.
5. BACKGROUNDS IN NEUTRINO TELESCOPES

The first large neutrino telescopes, were designed for proton decay experiments e.g., IMB [23], KAMIOKANDE, but yesterday’s background is today’s signal. The neutrino interactions in or around the big proton-decay experiments were considered to be a source of background. In the quest for neutrino astronomy, part of it becomes the signal. But, on the Earth’s surface the background due to the downcoming cosmic ray muons is overwhelming, the signal (for calculational purposes now we consider the atmospheric neutrinos as the signal) to noise (called up to down ratio) is of the order of $10^{-12}$. Therefore, for shielding purposes, neutrino telescopes are located in deep mines inside mountains or in deep water. For instance, 4000 mwe (meters water equivalent) of shield reduces the up to down ratio to about $10^{-6}$. So, it is essentially impossible in the energy regime below 10 TeV to do neutrino astronomy by looking for downcoming muons, because neutrino induced muons are indistinguishable from downcoming cosmic ray muons. This is the reason that for those muons which originate outside the detector (and therefore no vertex determination is possible) only muons coming up from the lower hemisphere are useful. Then the only remaining background is due to the omnipresent atmospheric neutrinos because the earth is transparent to most of them. In general, well shielded detectors can “look” up at about 20° above the horizon, while shallow detectors (1000 mwe) can look up only 20° below the horizon. The kinematics of neutrino production and the multiple scattering is such that the best overall angular resolution is 1°. So in order to find point sources of neutrinos one would at best divide the sky into 1° square pixels and plot the detected muon direction in a Declination versus Right Ascension plot. A source would manifest itself as standing above the background caused by the atmospheric neutrino interactions, which constitute a flat background (with a slight zenith dependence visible over tens of degrees).

6. PLINY WAS RIGHT, DEEPER IS BETTER

Gaius Plinius Secundus understood well that in a field which is signal limited and therefore there is nothing one can do to enhance the signal, one must work very hard on the background. This is why the ancient people he refers to, went into deep vertical mine shafts, in order to reduce the background caused by the Sun and observe the culminating stars at day time. The ultimate background to neutrino telescopes comes from the atmospheric neutrinos and one must design the detector sensitivity to come as close to this limit as possible. In detectors in clear water it is possible to achieve angular resolution of about one degree. This is the optimal pixel dimension ($\sim 1° \times 1°$) in order to minimize the effects of the omnipresent atmospheric neutrino background. The background due to the radioactive decay of K40 in seawater is depth independent (seawater salinity changes only by a few percent). The bioluminescence is reduced as one goes deeper with an 1/e length of 800 m. The big gain however with depth comes from the drastic reduction of downcoming muons produced by cosmic rays interacting in the atmosphere. V. Stenger [5] has done a very instructive calculation for a generic neutrino telescope like DUMAND (Table 1).

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Rate (year/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^40\text{K}$ and other random noise</td>
<td>$0.40 \pm 0.08$</td>
</tr>
<tr>
<td>Single cosmic ray muons*</td>
<td>$0.63 \pm 0.36$</td>
</tr>
<tr>
<td>Multiple cosmic ray muons*</td>
<td>$0.15 \pm 0.07$</td>
</tr>
<tr>
<td>Atmospheric neutrinos</td>
<td>$0.13 \pm 0.01$</td>
</tr>
<tr>
<td>Total</td>
<td>$1.31 \pm 0.38$</td>
</tr>
</tbody>
</table>

*Note, that even at a depth of 4800 m the cosmic rays are the greatest background i.e., downcoming muons which are reconstructed as upcoming.

Therefore, in order to make a 5σ discovery the source must have a flux of 6 muons/pixel/year. If one simply scales up the cosmic ray backgrounds listed above by the approximate factor of 500 that the
cosmic ray flux at 1 km exceeds that at 4.8 km, we get almost 400 fake events per year per pixel for a detector equivalent to DUMAND located at 1 km depth. In order to detect a signal at the $5\sigma$ level in the presence of this background, some 100 events would then be required. That is, if DUMAND were deployed at 1km, it would be inherently one order of magnitude less sensitive than the same instrument deployed at 4.8 km.

7. **HOW BIG A DETECTOR?**

Detectors like KAMIOKANDE and MACRO have a sensitive area of about 1000 $m^2$, as one can see from their skyplots Fig. 1.

![Skyplot of reconstructed events at SuperKamiokande from [24] (left figure). Skyplot of reconstructed events at MACRO from [25] (right figure)](image)

There is no concentration of points, this means that they are have not detected point sources but are looking at atmospheric neutrinos. AMANDA, with a sensitive area of 10 000 $m^2$ [26], has recently published similar results (Fig. 2). It is therefore obvious that the next detector should be at least two orders of magnitude larger in sensitive area. Conventional particle detectors e.g., scintillators, drift tubes, resistive plate chambers etc. cost about 10,000 to 20,000 Swiss francs per square meter. This means that a $10^5$ $m^2$ detector will cost $\approx 2000$ million Swiss francs which is twice the CERN budget for one year. The conclusion is that the cost must be reduced to 100–200 Swiss francs per square meter. This is where the water Cherenkov technique comes in, some of us call it, the technique of the "poor physicist".

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8. LARGE-VOLUME WATER CHERENKOV DETECTORS

The idea to use the sea as a neutrino Cherenkov detector was first proposed by M. Markov [27,28]. For neutrino energies of a GeV and above, up to the many PeV (10^{16} eV) the water Cherenkov technique seems to be the preferred technique, i.e., one detects the Cherenkov light emitted by the muon of CC neutrino interactions (Fig. 3). If one selects muons which come upward (i.e., they come from the other side of the Earth) then these muons must be products of neutrino interactions which have traversed the Earth and interact in the general vicinity of the detector. Using the muon events, pointing accuracies of the parent neutrino can be achieved which are better than one degree. Given the long range of muons in water, one can instrument a large sensitive volume with a minimal number of phototubes as was demonstrated by the DUMAND studies many years ago [20]. Nobody has demonstrated yet that we can even get coarse directional information using the cascade events (i.e. neutrino interactions without a muon). For energies greater than a few GeV, the neutrino fluxes become very low and in order to increase the sensitive area one has to leave the relative benign environment of a mine and either go to the deep sea or Antarctica. The solid platform of ice eases the deployment of neutrino telescopes and so, BAIKAL and AMANDA have made significant progress and have already produced skyplots and can calculate lower sensitivity limits thereby putting the first constraints for some optimistic very high energy neutrino production models, but both experiments are relatively shallow (1000–2000 mwe overburden) and are therefore inundated by downcoming muons. Further, the optical properties of the Antarctic ice do not permit the angular resolution which is required in order to improve the signal to noise ratio by restricting the angular bin size to one square degree pixels.

The index of refraction of sea water is 1.35, this gives a Cherenkov angle of 43°. In other words, relativistic particles will “illuminate” the sea water with a 43 degree cone, emitting about 250 Cherenkov photons/cm (between 3000–5000 Å) a range where most photomultipliers have a reasonable quantum efficiency([13,15]). Then, depending on the water transmissivity (ranging from 20 m in clear lakes to 50–60 m in clean deep ocean waters), one can instrument large areas of water fairly cheaply, at a cost of about 100 Swiss francs per square meter. The long range of muons in water helps tremendously, a 1 TeV muon has a range of about 2.5 km in water! A variance to this technique is using the Antarctic ice as a Cherenkov radiator. The high energy physics community has accumulated considerable experience with the water Cherenkov technique mainly from the three big proton decay experiments IMB, HPW and KAMIOKANDE and the various test-deployments down to 4.000 m as done with the DUMAND I and the NESTOR tests, lake BAIKAL at 1.000 m and AMANDA in the ice. The deep water large Cherenkov neutrino experiments will also deploy hydrophones in the hope of determining very high energy neutrino interactions acoustically. The threshold of this technique is in the PeV range. The acoustic pulse is produced by the thermal expansion of the water when heat is deposited by the interaction. The energy transfer is very inefficient, about 10^{-9} [4], but the advantage is that the attenuation length, in the frequency range of 10–20 kHz, is of the order of a few kilometers. So, one could instrument literally, many

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Fig. 3: Track reconstruction using the Cherenkov light from muons and cascades (neutrino interactions without a muon). The reconstruction of the direction of the muon track uses the time profiles of the Cherenkov photon flight times.
cubic kilometers at low cost. However we should point out that in the clear ocean one can reconstruct
muons which have not crossed the instrumented volume but have traversed tens of meters outside the
detector. Figure 4 shows the reconstruction efficiency as a function of the distance from the central axis

![Graph showing reconstruction efficiency for vertical muons achieved with one NESTOR Tower](image)

Fig. 4: Reconstruction efficiency for vertical muons achieved with one NESTOR Tower

of the NESTOR detector for vertical muons of energy 1 TeV, 10 TeV and 100 TeV. One should note that
a reconstruction efficiency of 90% is achieved with vertical muons that cross 50 to 100 m outside the
detector. Even if a $10^5$ m$^2$ detector finds neutrino sources, the physics of this field will not be harvested
until square kilometer detectors come into operation. For this reason the quest for neutrino astronomy
has three benchmarks.

1. The reliable operation over a few years of a detector of 10 000 to 20 000 m$^2$.
2. The quick growth of this detector to cover a sensitive area of 100 000 m$^2$.
3. The subsequent expansion of the detector in order to instrument an 1 km$^2$ in a timely and
   affordable fashion.

9. NESTOR
The NESTOR Collaboration (see at the end of this paper) has located near the S.W. of Greece a 8 km
by 9 km horizontal plateau at a depth of 4000 m [13,14]. The depth is constant to within ± 50 m over
the entire plateau. The plateau is at a mere distance of 7.5 miles from the shore. Extensive studies of the
water transmissivity were made employing

1. spectrophotometric analysis of a very large number of samples,
2. deployment of photometers in situ (i.e. down to 4000 m) and
3. large acceptance photometric measurements in situ.

These measurements show that the water transmission length in the blue part of the spectrum
is about 55 m [29,30]. The underwater currents have been measured over many years and they have
been found to be minimal [31] i.e. a few centimeters per sec. Last, the sedimentology analysis is com-
pleted [32]. The NESTOR design differs from that of original DUMAND design and AMANDA in that
it deploys half the phototubes looking upwards, thus having a $4\pi$ sensitivity and at the same time will be
shielded by 4000 mwe. They employ a total of 144 large 15 inch phototubes like DUMAND but they are
clustered closer so that they have a much lower energy threshold. They have been making tests in situ
of a half scale model of their basic detector element by suspending it from a ship and providing power
with regular car batteries. They measured the downcoming muon flux and angular distribution a number
of times and at various depths down to 4200 m [13–15]. The basic detector element is a horizontal rigid hexagon made out of titanium (or aluminum) with a diagonal of 34 m radius (Fig. 5). At each one of the comers and at its center there is a pair of two 15 inch phototubes (one looking up and the other one down). By stacking 12 of these hexagons in the vertical, with a distance between hexagons of 30 m, they create a tower (Fig. 6). The whole tower will be deployed in a single operation, its sensitive area for TeV muons will be 20 000 m². Soon after the first tower is deployed, the three strings from the DUMAND experiment will be deployed at a distance of 80 m around the tower. The sensitive area of this telescope as a function of energy is shown in Fig 7. Then the collaboration hopes to find quickly additional funds to build another six towers in order to deploy them in a hexagonal fashion around the first tower and at a distance of about 150 meters from it (Fig 8). This array would have, for 10 TeV, a sensitive area larger than 150 000 m² (since it would also reconstruct neutrinos interacting in the volume between the towers), it would provide an overall angular resolution better than 1°, with a uniform response in the zenith angle (Fig 9). It would have an enclosed mass of 20 Megatons. Within each one of the 7 towers the energy threshold is a few GeV, i.e. a low threshold active target of 1.5 Megaton mass. The combination of the seven tower system is a good approximation to a spherical detector.

The umbilical cable for NESTOR was laid by the MAERSK FIGHTER cable ship of ALCATEL, in June 2000 and was damaged during the lay. The damage was caused by mishandling of the cable by the ship. In January 2002 the cable ship TENO of TYCOM recovered the end of the cable, repaired it and redeployed it. The end of the cable was deployed at 4100 m with an electrooptical junction box and a number of associated instruments such as underwater current meter, Ocean Bottom Seismometer, nephelometer, thermometers, compass, pressure gauges et.c.. For the first time ever data were transmitted from the deep sea in real time (Fig. 10). The onset of bad weather did not allow the deployment of one floor (however see the Note Added to Proof at the end of this section). In order to reach independence from cable ships and accelerate the rate of progress, the NESTOR Institute is building a highly specialized deployment platform the DELTA-BERENIKE. She is a central well, ballasted, self propelled, equilateral triangle platform (51 m side) which can keep its position in the high seas to a few meters, using dynamic control GPS systems Fig. 11. With the DELTA-BERENIKE one can deploy stars of almost 100 m in diameter.
Fig. 6: NESTOR Tower
Fig. 7: NESTOR Expected Performance: Effective Area: (a) 1 Tower & 3 DUMAND strings, 80 m from center of Tower (144+72 PMTs); (b) 1 Tower (144 PMTs); (c) same as (a) for resolution better than 5 degrees; (d) same as (b) for resolution better than 5 degrees

Fig. 8: Schematic of 7 NESTOR Towers and a muon crossing them emitting Cherenkov radiation
Fig. 9: Effective Area of 7 NESTOR Towers versus zenith angle of incident muons

Fig. 10: Typical data from the Ocean Bottom Seismograph (left figure). Typical data from the Underwater Currentmeter (right figure)
10. AN AFFORDABLE 1 km² DETECTOR

Assuming operational success of the 7 tower hexagon of hexagonal NESTOR towers the next step is obvious. Employ another six towers in a hexagonal fashion 150 meters around the first hexagon and fill in the gaps between them in the perimeter with six strings. Each string has 24 phototubes, clustered in pairs and spaced with the same spacing between floors of the towers. This array will have a sensitive area of 430 000 m². For the following step it suffices to use strings only with 24 phototubes each. Employing 18 strings ≈ 150 meters outside the last perimeter will only cost 5 million dollars and the total sensitive area will be 850 000 m². The enclosed mass will be about 300 Megatons, of which 4 or 5 will be contained within each tower with local energy threshold of a few GeV, (Fig 12).
11. NOTE ADDED IN PROOF

In March 2003, while the text of this lecture was getting typed the NESTOR Collaboration, using the cable ship, RAYMOND CROZE, of France Telecom (Fig 13), deployed one hexagonal floor, with twelve 15 inch phototubes and associated environmental sensors to a depth of 4000m. The floor is connected to the shore with an umbilical cable with 18 monomode fibers for data transfer and one electrical conductor (power returns done electrolytically via the sea water). This first neutrino telescope to operate in the sea is a major milestone in the field of Deep Sea Neutrino Telescopes. Figure 14 shows a reconstructed muon which comes along the horizon. Since NESTOR is at a depth of 4000 m, there is no background of horizontal cosmic ray muons. This event is a good neutrino candidate for further study.

![Fig. 13: The RAYMOND CROZE cable ship of France Telecom](image1.jpg)

Fig. 13: The RAYMOND CROZE cable ship of France Telecom

![Fig. 14: The PMT pulses of a successfully reconstructed event as a horizontal muon. The direction of the muon is reconstructed with a zenith angle $\theta = 101^\circ \pm 18^\circ$ and an azimuth angle $\varphi = 116^\circ \pm 19^\circ$ with respect to North. The fit gave a $\chi^2$ per degree of freedom equal to 1.2 and an impact parameter of 8 $\pm$ 6 meters.](image2.jpg)

Fig. 14: The PMT pulses of a successfully reconstructed event as a horizontal muon. The direction of the muon is reconstructed with a zenith angle $\theta = 101^\circ \pm 18^\circ$ and an azimuth angle $\varphi = 116^\circ \pm 19^\circ$ with respect to North. The fit gave a $\chi^2$ per degree of freedom equal to 1.2 and an impact parameter of 8 $\pm$ 6 meters.
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