

Neutrinos Out of the (Deep) Blue-The Status of Underwater Neutrino Telescopes

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Abstract. The status and future plans of the ongoing underwater neutrino telescopes projects ANTARES, BAIKAL, NEMO, NESTOR and KM3NeT are presented.

1. Introduction

The neutrino is a unique probe in which to study our universe and provides complementary information to more conventional probes such as photons and charged particles. Being neutral it is not deviated by magnetic fields thereby in principle allowing a precise astronomy to be achieved. Further, as the neutrino is only sensitive to the weak interaction, it is essentially unaffected during its journey from the source to the detector. Unfortunately, the very properties which make the neutrino such an interesting ‘messenger’ also mean that it is notoriously difficult to detect experimentally; the weakness of its interaction imply that exceptionally large detector volumes, of the order of a km³, are required.

The scientific goal of underwater neutrino telescopes is the detection of high energy neutrinos expected to be produced within many energetic astrophysical bodies. The detection of such neutrinos will yield crucial information on the acceleration mechanisms operating in these objects. Over the last two decades many projects have been pursued; located deep, either in ice (AMANDA/ICECUBE), freshwater lakes (BAIKAL) or under the sea (DUMAND, NESTOR, ANTARES, NEMO), such hostile environments provide many technical challenges to overcome.

2. Physics Motivation

The observed flux of high energy cosmic rays impinging on the earth, implies the existence of cosmic accelerators somewhere in the universe. Since their initial discovery more than a 100 year ago, the origin of these cosmic rays remains unclear. Although many candidate acceleration sites have been suggested, the deflection of the cosmic rays by the interstellar magnetic fields means that only at the highest energies is it possible to point back the cosmic rays to their origin. Fortunately, such hadronic accelerators inevitably also produce charged pions, via interaction of the cosmic rays in the matter or photon fields surrounding the source. Their decay will lead to a correlated flux of high-energy neutrinos, which if detected would allow the unambiguous location of the source.

Recently gamma ray telescopes such as HESS and MAGIC have observed a number of galactic and extra galactic high-energy gamma ray sources. Two mechanisms for the production of these gamma rays are proposed; *leptonic*-inverse Compton scattering on energetic electrons or *hadronic*- the decay of neutral pions. Currently it is not possible to unambiguously identify the process involved, the

detection of high-energy neutrinos from these sources would be a smoking gun signature for the hadronic process.

Another important physics topic for neutrino telescopes is the search for dark matter. In many theoretical models a weakly interacting massive particle (WIMP) is suggested to explain the formation of structure in the universe and the discrepancy observed between the measured rotation curves of stars and the associated visible matter distribution in galaxies. A generic property of such WIMPs (relics from the big bang) is that they accumulate at the centre of massive bodies, such as the sun, the centre of the galaxy, where they can self annihilate into normal matter, which subsequently decays to produce neutrinos.

3. Detection Principles Of high Energy Neutrinos

As shown in Figure 1, the detection principle adopted by all large volume neutrino telescopes is the observation of Cherenkov light generated by an energetic upward-going muon produced by the interaction of a neutrino in the rock or water close to the detector.

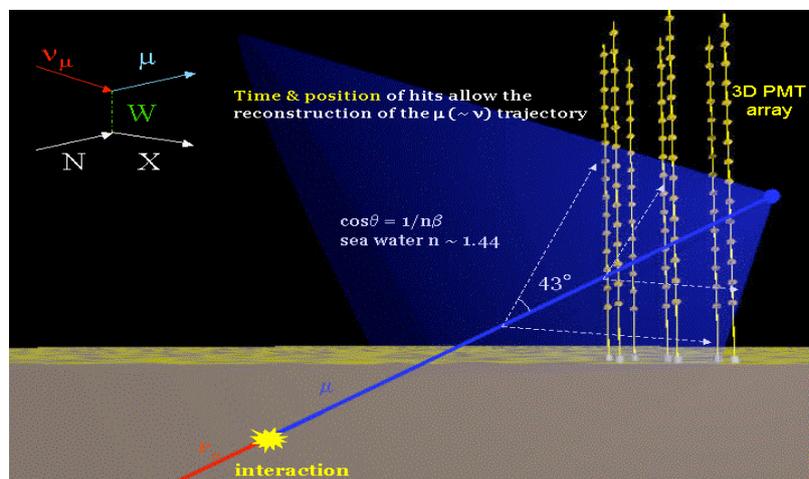


Figure 1: Principle of detection of high energy neutrinos in underwater neutrino telescope.

A three dimensional grid of photomultiplier tubes (PMTs) is used to measure the arrival time and position of the detected Cherenkov photons. The reconstruction algorithm relies on the characteristic emission angle of the light (about 43 degrees) to determine the direction of the muon. The precision on the corresponding neutrino direction is limited at low energies by the physics of the neutrino decay. For incident neutrino energies above 10 TeV the angular resolution can be less than 0.3 degrees and is limited by the detector resolution; typically nanosecond timing resolution and centimetre positions resolutions are necessary.

The detectors rely on the accuracy of the direction information to distinguish upward going muons from the overwhelming background from downward-going muons, produced by cosmic ray interaction in the atmosphere above the detector. Installing the detector at great depths serves to attenuate this background and also allows to operate the PMTs in a completely dark environment.

At high energies the large range of the muon allows the sensitive volume of the detector to be significantly greater than the instrumented volume, for example at 10 TeV the muon range is more than a km. Although optimised for muon neutrino detection, the detectors are also sensitive to the electron and tau neutrinos albeit it with reduced efficiency except at the highest energies.

Compared to detectors based in ice, such as Amanda/Icecube, the water based telescopes have better angular resolution, due to the absence of light scattering on dust and/or bubbles trapped in the ice. On the other hand, they suffer from additional background light produced by beta decay of ^{40}K salt present in the seawater as well as bioluminescent activity.

4. The Ongoing projects

Over the years a number of projects have attempted the construction of a deep underwater neutrino detector. Such an undertaking presents many technical challenges; pressure resistant structures, leak integrity, corrosion, deployment scheme, detector movement, large bandwidth data acquisition etc. The various projects have adopted a variety of different solutions.

The DUMAND project [1] (1980-1995), pioneered the field, and was located at a very deep site (6000 m) off the Hawaii coast. Although a prototype line was successfully operated for a short period, the funding for this project lapsed in 1993. The BAIKAL project [2] is located at the bottom (1100 m depth) of a Siberian freshwater lake. The locations of the three Mediterranean Sea projects are shown in Figure 2. The NESTOR project [3] is located 15 km from the Greek coast at a depth of 4100m. NEMO [4], an Italian R&D and site evaluation project for a km³-scale detector, have selected a 3450 m deep site, 100 km from the Sicilian coast. The ANTARES experiment [5] is deployed at a depth of 2475 m, 42 km from the French coast. The members of the three Mediterranean projects are collaborating within KM3NeT, an European Union funded design study for a km³-scale detector in the Mediterranean.

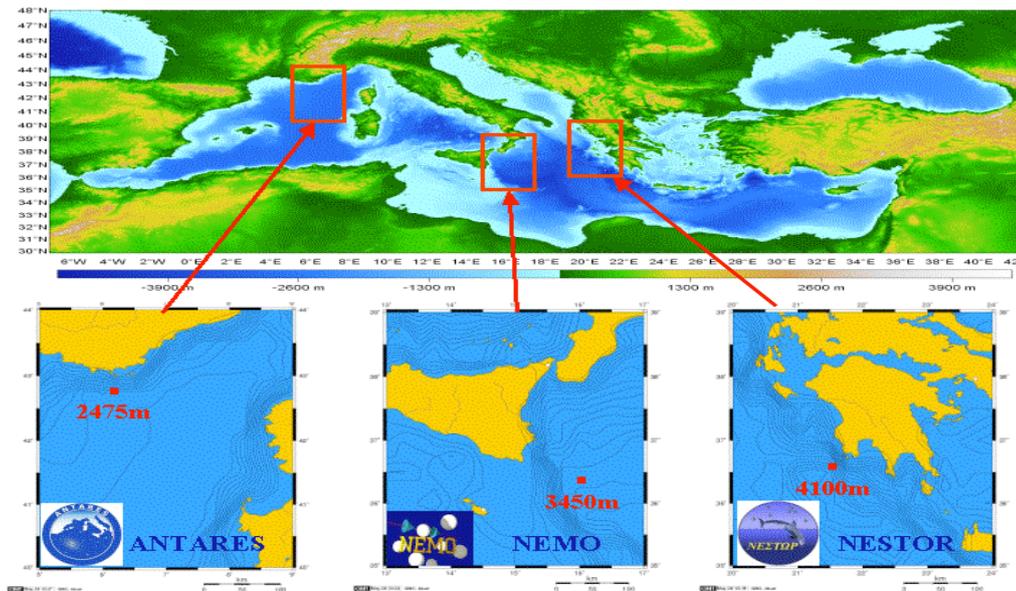


Figure 2: Location of the Mediterranean based neutrino telescope projects.

4.1 BAIKAL

The first stage telescope configuration NT200 (Figure 3 (left)) started permanent operation in April 1998. An umbrella like frame supports 8 cables each with 24 pair-wise arranged optical modules (192 in total). The optical modules are based around the 37 cm diameter QUASAR phototubes. Four underwater electrical cables connect the detector to the shore station. The freezing of the lake surface in the winter season facilitates the deployment of the array. The upgraded telescope NT200+ started operation in April 2005. This configuration comprises the old NT200 supplemented by three new external strings placed 100 m from the NT200 core.

BAIKAL has published a number of physics results; searches for WIMPs, relativistic and non-relativistic magnetic monopoles, point sources and diffuse fluxes. The NT200 all-flavour limit for a steady diffuse neutrino flux with an E^{-2} shape $E^2\Phi=8.1*10^{-7}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}$ ($20\text{ TeV}<E<50\text{ PeV}$), is among the most sensitive limit published so far by neutrino telescopes.

For NT200, the detection strategy for high energy neutrino events is based on a search for Cherenkov light from point-like cascades in the Mton-scale sensitive volume below the detector. With the upgrade to NT200+ the long outer strings will allow the shower energy to be measured improving the rejection against the downgoing muon background. It is expected the limit for an E^{-2} diffuse all flavour neutrino flux will be improved to $E^2\Phi=2*10^{-7}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}$ ($E<100\text{TeV}$, 3 years).

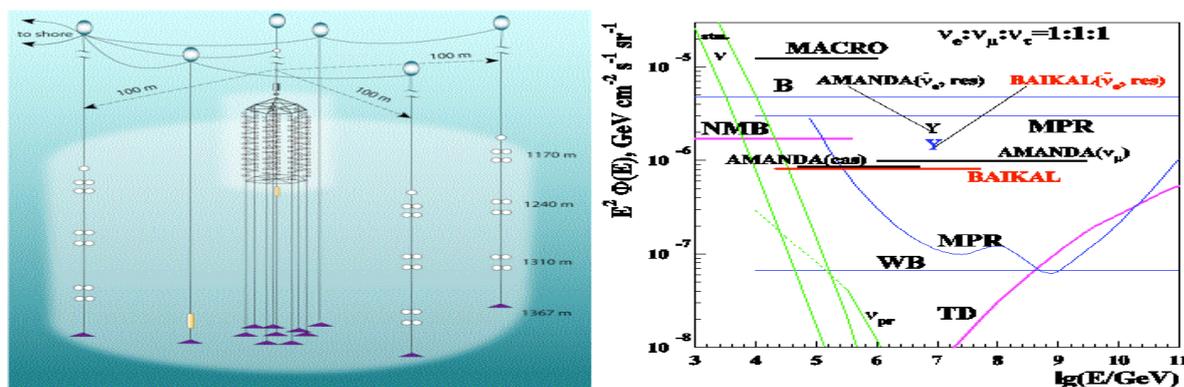


Figure 3: BAIKAL: (left) The configuration of NT200 and NT200+. (right) Diffuse flux limit.

The BAIKAL collaboration have funding for R&D towards a km^3 -scale detector, with a TDR planned for 2008 and deployment starting in 2010. Initial studies indicate that the geometry of 1300 OMs on 91 strings will yield a 0.7-0.9 Gton detection volume for neutrino induced high energy cascades.

4.2 NESTOR

The concept of the NESTOR tower, illustrated in Figure 4 (left), consists of 12 mechanically rigid titanium 6-pointed 'stars' separated by distances of 30 m. At the point of each arm of the star are located a pair of optical modules, one pointing up and one pointing down. A tower therefore comprises a total of 144 PMTs. A key difference in approach compared to NEMO and ANTARES is that all connections are performed using a floating platform (Delta Berenike) on the sea surface, thus eliminating the need for expensive submarines.

In January 2002 an electro-optical junction box with a variety of environmental measurement instruments was connected to a previously deployed underwater cable. The first prototype detector floor was subsequently connected in March 2003. This floor operated continuously for about one month until a problem in the underwater cable prevented further operation. Nevertheless, the reconstruction of atmospheric muons was demonstrated and their flux measured (Figure 4 (right)).

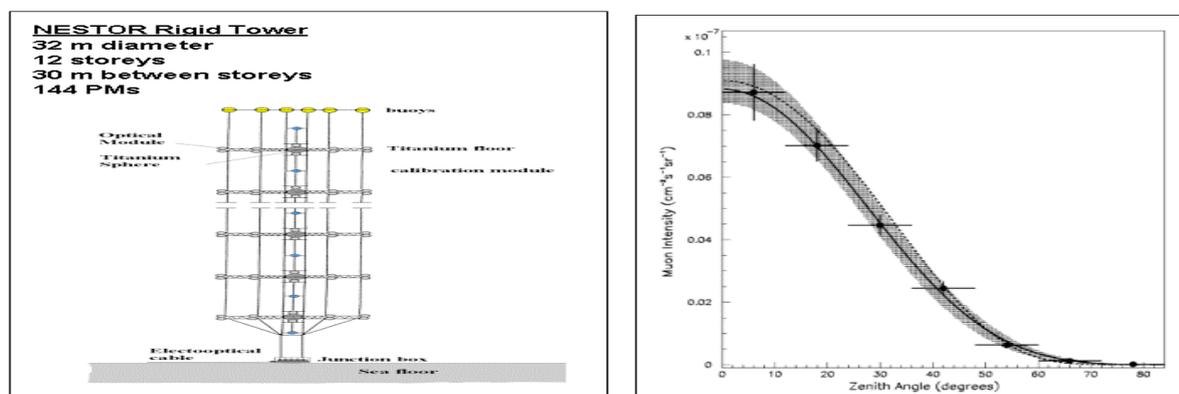


Figure 4: NESTOR: (Left) Configuration of the NESTOR tower. (right) Measured flux of downward going muons.

Future plans for the NESTOR collaboration include repair of the underwater cable and deployment of a four-floor prototype tower.

4.3 NEMO

The NEMO concept is a km³-scale array with ~5000 optical modules installed on 64 ‘flexible’ towers, distributed in a square grid geometry with 200 m spacing. Each tower, illustrated in Figure 5, is 750 m high and comprises 16 floors spaced by 40 m. Each floor has a pair of optical modules (one pointing downward, one pointing horizontal) at each end of the arm. A set of mechanical cables ensure that the arms deploy orthogonally to each other once the tower is deployed. Unlike NESTOR, a submarine is needed to connect together the undersea infrastructure.

Although the preferred site is at a depth of 3800 m off the coast near Capo Passero, NEMO have also developed a shallower ‘test’ site (2031 m) closer to shore. At the ‘test’ site an underwater cable has already been deployed and a seismic monitoring station (Geostar) is operational. It is planned that a novel equi-pressure junction box and a prototype four-storey tower will be deployed before the end of 2006. In parallel, the deployment of a 100 km electro-optical cable is foreseen in 2007 at the Capo Passero site.

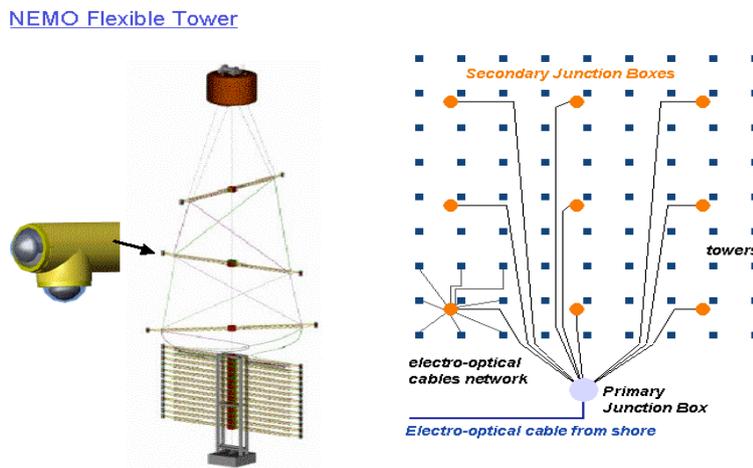


Figure 5: NEMO: (left) The NEMO tower design. (right) A possible seabed layout.

4.5 ANTARES

The layout of the ANTARES detector is illustrated in Figure 6. It comprises a total of 900 optical modules distributed over 12 flexible lines, each comprising 25 storeys. Three Hamamatsu 10-inch photomultipliers, orientated at 45 degrees, are located at each storey. The lines are maintained vertical by a syntactic floater at the top of the 450 m line. An acoustic system provides real-time positioning of the detector elements to a precision of a few cms. A system of optical beacons allows in-situ time calibration. A submarine is required to connect the lines to the infrastructure.

The main electro-optical cable and the junction box have been operating in situ since their installation in 2002. A series of prototype lines have allowed verification of the technological choices. A Mini-Instrumentation Line with Optical Modules (MILOM) connected in March 2005 has provided

continuous real-time monitoring of environmental parameters such as sea current speed and direction, optical module counting rates and seismological activity. The first two full-size production lines were successfully connected in March and September 2006 respectively. The remaining 10 lines will be deployed during 2007. Figure 7 shows an example of a downward-going muon reconstructed with the first ANTARES line.

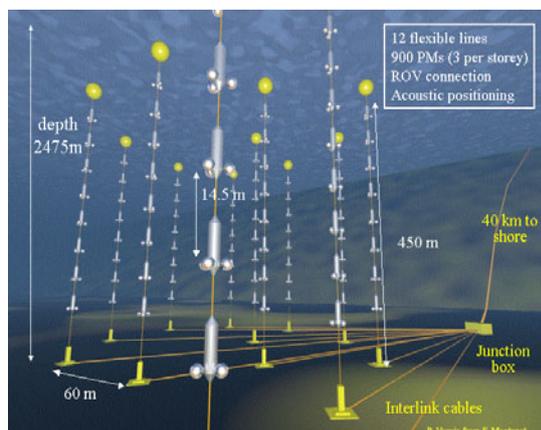


Figure 6: Layout of the ANTARES detector

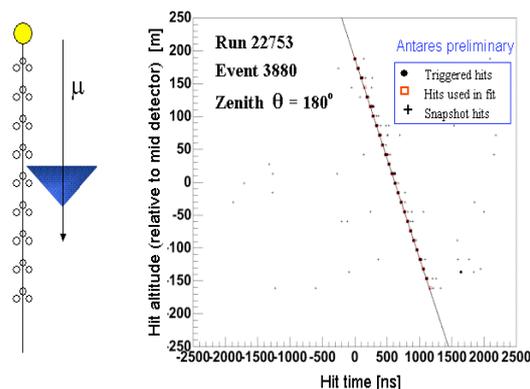


Figure 7: Downward-going muon observed in the first ANTARES detection line.

4.6 KM3NeT

KM3NeT is a three-year design study supported by the research infrastructure portion of the 6th framework program of the European Community. Started in February 2006, the design study will culminate in the delivery of a technical design report for a future km³-scale neutrino telescope in the Mediterranean Sea. The infrastructure will also provide an undersea platform for associated sciences such as marine oceanography, seismology etc. The major challenge of the design study is to find cost effective solutions to efficiently instrument such a large detector volume. The KM3NeT consortium includes all institutes involved in the three ongoing Mediterranean projects as well as a number of marine research institutes.

The km³-scale infrastructure in the Mediterranean Sea will be complementary to the ICECUBE detector. Being located in the northern hemisphere it will study the region of the galaxy not observed by ICECUBE, including the important region of the galactic centre. Being water based it will allow a significantly improved angular resolution; preliminary studies indicate that an angular resolution better than 0.1 degrees should be achievable for energies above 10 TeV (c.f. 0.6 degrees obtained by ICECUBE).

5. Conclusion

The field of high-energy neutrino astronomy is coming of age. First generation projects such as AMANDA, ANTARES, BAIKAL and NESTOR have demonstrated that the construction of large-scale detectors deep in the sea and ice is technically feasible. The construction of the second-generation km³-scale projects ICECUBE and KM3NeT will provide full sky coverage of the universe in the second decade of this century.

6. References

- [1] DUMAND Collaboration, Nucl. Phys. Proc. Suppl. 48, 466-468, 1996.
- [2] BAIKAL Collaboration, Astro-ph/0609743.
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- [6] KM3NeT Consortium: <http://km3net.org>