

# KM3NeT: A Next Generation Neutrino Telescope in the Mediterranean Sea

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**Abstract**— To complement the IceCube neutrino telescope currently under construction at the South Pole, the three Mediterranean neutrino telescope projects ANTARES, NEMO and NESTOR have joined forces to develop, construct and operate a  $\text{km}^3$ -scale neutrino telescope in the Mediterranean Sea. Since February 2006, the technical specifications and performance of such a detector are studied in the framework of a 3-year EU-funded Design Study. In 2009 a technical design report will be released laying the foundations for the construction of the detector. In the following, the current status of the Design Study is presented and examples of solutions for the technical challenges are discussed.

## I. INTRODUCTION

The detection of high energy neutrinos from astrophysical sources would be a major breakthrough in our understanding of origin and production mechanisms of cosmic rays. Unfortunately, despite intense search for these neutrinos during recent years no such neutrino has been identified up to now. Recent calculations [1], [2] indicate that detectors with at least a  $\text{km}^3$  of instrumented volume are required for this task where detectors of the first generation like AMANDA or ANTARES have typical volumes of  $0.01 \text{ km}^3$ .

At the South Pole the IceCube detector with an instrumented volume of  $1 \text{ km}^3$  is currently being built as the successor to the AMANDA neutrino telescope. However, due to the large atmospheric muon background for upward observations with neutrino telescopes, the sensitivity of the detector to sources in the southern sky which includes most of the Galactic Plane and the Galactic Centre is greatly reduced. These regions harbour many potential high energy neutrino sources like supernova remnants, pulsar wind nebulae, microquasars and other binary systems, but also unidentified sites of high energy gamma-ray emissions. In order to be able to observe these sources, a  $\text{km}^3$ -scale neutrino telescope in the Northern Hemisphere is required.

Building on the experience gained in the pilot projects ANTARES, NEMO and NESTOR, the three collaborations have joined forces to develop, construct and operate such a  $\text{km}^3$ -scale neutrino telescope, KM3NeT, in the Mediterranean Sea at the beginning of the next decade. At the time of this article the consortium consists of 37 institutes from 10 European countries (Cyprus, France, Germany, Greece, Ireland,

Italy, Netherlands, Romania, Spain, UK). Further, also non-European institutions are welcome to join the collaboration. KM3NeT is envisioned as a multidisciplinary research infrastructure with a permanent deep-sea access for marine sciences (such as oceanology, marine biology, environmental sciences, geology and geophysics) through an *associated science node*.

## II. STATUS OF THE KM3NeT PROJECT

Evaluating the experience gained with the pilot projects it became clear that a simple scale-up of these detectors to  $\text{km}^3$  size is technically not feasible and/or too expensive. Therefore, a research and development phase was initiated which is conducted within the framework of a Design Study funded by the EU in FP6 with 9 MEuro (total volume ca. 20 MEuro). It started in February 2006 and will end in 2009. The main goal of the Design Study is the compilation of a technical design report (TDR) that subsequently allows for a timely construction of the detector and its concurrent operation with IceCube. The overall cost for the KM3NeT infrastructure is estimated to lie between 220 and 250 MEuro.

KM3NeT is recognised by ESFRI (European Strategy Forum on Research Infrastructures) as a *research infrastructure of pan-European interest* and is listed on the ESFRI roadmap [3] for future large scale infrastructures. This entitled the consortium to be funded in the framework of a *Preparatory Phase* in the EU FP7 program which will address the political, financial, governance, strategic and remaining technical issues. This process will also lead to a decision concerning the choice of the site for the construction of KM3NeT. Apart from environmental parameters relevant to the physics performance of the detector this also involves socio-political and regional considerations.

## III. DETECTOR PERFORMANCE STUDIES

The aim of the Design Study is to deliver the design specifications for a detector which yields the best physics performance for a given budget. Therefore, in the first phase of the Design Study a large number of basic detector configurations have been simulated and their performance with respect to astrophysical benchmark fluxes has been evaluated. The minimal performance objectives are an effective volume

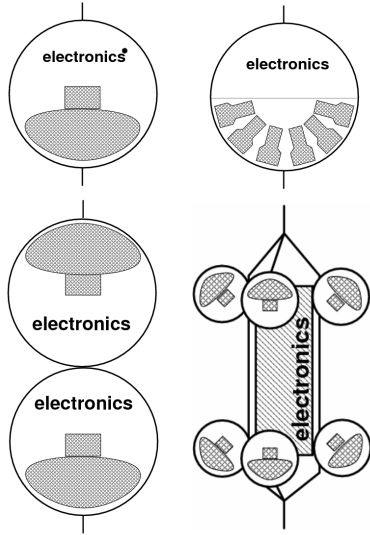


Fig. 1. Examples of optical module designs that were evaluated in different detector layouts with respect to their performance. The two OMs on the left side and the one in the lower right corner contain 10" PMT(s) whereas the one in the upper right corner is build up of 21 3" PMTs (taken from [4]).

of at least  $1 \text{ km}^3$  with an angular resolution of  $0.1^\circ$  for muons with energies above 10 TeV. The detector has to be sensitive to all neutrino flavors and the lower energy threshold should be at a few 100 GeV (about 100 GeV for selected targets).

The basic building block of a detector is the optical module (OM) which contains the photomultiplier(s) (PMTs) for the detection of the Cherenkov light from charged particles. Up to now, neutrino telescopes have been using a single (typically 10") PMT mounted in a pressure resistant glass sphere. In the case of ANTARES three of these optical modules are mounted on one frame, looking downward at an angle of  $45^\circ$ . AMANDA and IceCube are using a single large PMT per OM, facing downward.

In the course of a detailed simulation [4], a large variety of possible OM configurations was studied (examples can be seen in Fig. 1), among others a configuration that uses several small 3" PMTs either arranged in a half sphere (Fig. 1 upper right) or in a full sphere (not shown). Small PMTs have a higher quantum efficiency, a better single photon resolution and a smaller transit time spread. Also, the usage of several PMTs in an OM further improves the single photon counting capability and yields directional sensitivity which helps in suppressing the optical background from bioluminescence.

The OM configurations were then evaluated in different spatial arrangements (detector layouts) [4]. The OMs are positioned with equal spacing in a vertical structure (detector unit). Several of these units are then combined in different seafloor layouts. Examples can be seen in Fig. 2. In order to compare the intrinsic sensitivity of different detector designs, the instrumented volume of all detectors was fixed to  $1 \text{ km}^3$  and the total cathode area was kept approximately constant.

It turns out that a configuration of 225 detector units arranged in a cuboid grid with an inter-line spacing of 95 m,

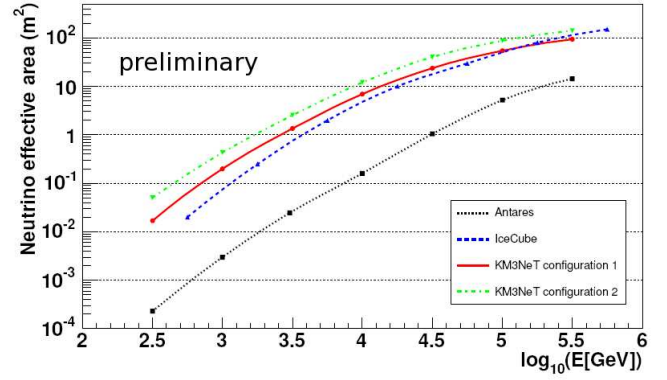


Fig. 3. Muon effective area as a function of energy for two different KM3NeT configurations (see main text for a description) and ANTARES and IceCube (taken from [4]).

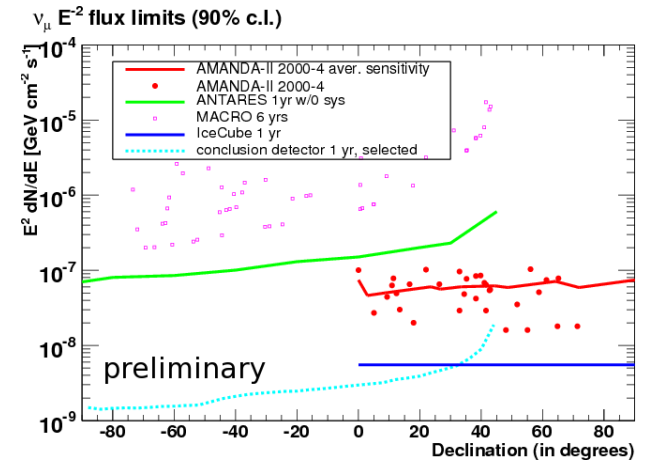


Fig. 4. Sensitivity of a possible KM3NeT configuration (blue dashed line labelled *conclusion detector*; equivalent to configuration 1 in Fig. 3) to point-like sources as a function of declination. Also shown are the sensitivity of IceCube and other experiments (taken from [4]).

a vertical OM distance of 16.5 m and 21 3" PMTs per OM (upper right configuration in Fig. 1) yields a very good performance. The resulting muon effective area as function of neutrino energy is displayed in Fig. 3 (configuration 2) where it is compared to an alternative configuration 1 (127 detector units with 100 m horizontal spacing; 25 OMs per unit with 15 m separation; lower right OM configuration in Fig. 1) as well as IceCube and ANTARES. Its determination is based on a full simulation of the neutrino reaction, muon propagation in water and photon detection. Optical noise equivalent to 40 kHz in a 10" PMT (corresponding to results from measurements at potential detector sites [5], [6]) was also simulated. Event selection and muon-track reconstruction algorithms were applied.

The detector configuration 1 was also used to determine the sensitivity of KM3NeT to point sources. In Fig. 4 this is compared to the sensitivity of several other experiments. The improved sensitivity as compared to IceCube can be largely explained by the three times larger photo-cathode area

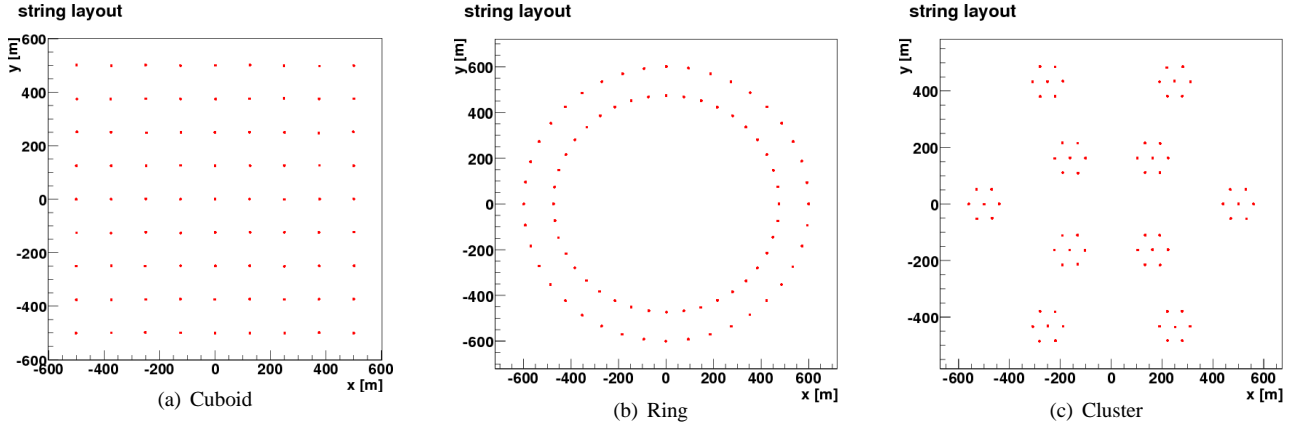


Fig. 2. Examples of different seafloor layouts. Each dot represents a vertical structure (detector unit) with several OMs (taken from [4]).

and to lesser extent by the better angular resolution and the non-consideration of background from miss-reconstructed atmospheric muons. In this configuration KM3NeT will be able to search the southern sky with a sensitivity more than 10 times higher than current experiments.

#### IV. R&D OF DETECTOR COMPONENTS

In overcoming the technical challenges of constructing a neutrino telescope in the deep sea, the collaboration can build on the long-lasting experience from a series of neutrino telescopes experiments both in water (DUMAND, Baikal, ANTARES, NEMO, NESTOR) and in ice (AMANDA, Ice-Cube). Each of these experiments has created valuable knowledge on which the design of a large detector in a highly hostile environment is now based. In the following, examples of technical challenges and ideas for their solutions are discussed.

A crucial parameter for the successful operation of the detector is the reliability of all off-shore components. Although, in contrast to detectors frozen into the ice, it is possible to recover and repair deep-sea parts of the detector, this requires a large amount of time and resources. Also, due to the large number of components (more than 200 detector units with roughly 10000 OMs), even a moderate failure rate is unacceptable. Therefore, the reliability of all deep-sea components has been one of the prime guide lines in the design of the hardware from the begin of the Design Study.

One strategy to improve the reliability is to simplify the hardware as much as possible. For example, in ANTARES each OM is connected to an electronics container that—apart of communicating with the OM—also contains electronics for the optical and acoustic calibration. Currently, it is investigated whether the calibration devices can be completely separated from the photon detection units and mounted on separate lines communicating with the detection units by light only. A further reduction of complexity currently under investigation affects the readout scheme of the PMTs. For KM3NeT the feasibility of an “all-data-to-shore” concept is discussed which would require the usage of optical fibres. Therefore, in order to reduce the needed electronics as much as possible, a photonics-

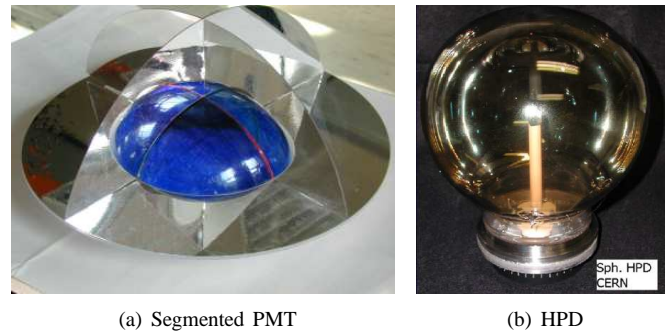


Fig. 6. (a) Prototype of a four-anode 10” PMT developed by Hamamatsu. (b) Crystal hybrid photon detector.

based network is under consideration [7]. The electrical signal coming from the OM is “imprinted” with an optical modulator on an optical signal coming from shore. The modulated signals are then transferred back to shore where they are timestamped. In this scheme no off-shore laser and no digitisation or timing electronics are required.

As shown in Fig. 3 and discussed in the previous section OMs equipped with several small PMTs show a very good performance and several further advantages. A prototype of such an OM is currently being built and tested at Nikhef [8]. Pictures can be seen in Fig. 5. As an individual readout is probably not feasible due to the required bandwidth, the idea would be to reduce the signal from the individual OMs to a digital pulse with a length equal to the time-over-threshold of the signal. The rectangular pulses of all PMTs inside an OM are then superimposed with their proper timing and sent to shore. In this way sufficient information can be retained afterwards.

Instead of using several small PMTs, another way of obtaining directional sensitivity currently investigated is the combination of a segmented with a large multi-anode PMT. A prototype four-anode PMT developed by Hamamatsu is shown in Fig. 6(a). The reflecting walls and the floor visible in the picture act like Winston cones and reflect the photons into the



Fig. 5. Technical drawing (left) and first prototype (middle and right) of an OM with several small PMTs (taken from [8]).

respective quadrant.

Another option being investigated is the usage of crystal hybrid photon detectors (X-HPDs) (Fig. 6(b)). These are large (up to 15") tubes of almost spherical geometry in which photoelectrons emitted from a standard bi-alkali photocathode are accelerated in a  $\sim 25$  kV field to bombard a crystal scintillator viewed by a small PMT. Crystal HPDs have been in operation at the Lake Baikal detector since 1996. Spherical geometry X-HPDs show a larger overall efficiency and have a much greater solid angle coverage than standard large PMTs. Hence, they would allow a larger volume to be instrumented at approximately the same costs.

Up to now a large cost factor for a deep sea neutrino telescope is the titanium used for the structures and pressure-resistant components that get in contact with the sea water. Titanium is the only material that can withstand both the large pressure and the aggressive salt water in the deep sea. However, a separation of the pressure and corrosion resistant elements would allow the usage of much cheaper materials. This idea was realised by the NEMO collaboration in the design of a junction box [9] which consists of four cylindrical steel vessels hosted in a large, oil-filled fibreglass container. This avoids the direct contact between steel and sea water. As the KM3NeT infrastructure will probably require several junction boxes, this may lead to a significant cost reduction.

In contrast to other (astroparticle) experiments there exists currently no neutrino source that can be used to independently check the direction calibration of the neutrino telescope. Though the direction of a reconstructed track is completely determined by the position and timing of the photon signals in the PMTs it is highly desirable to have an independent check for this crucial parameter. Therefore, the requirements for and feasibility of a floating surface array somewhat similar to IceTop at the South Pole are currently investigated. Its position can be determined very precisely with GPS receivers and it would use atmospheric muons to calibrate the deep sea detector. According to preliminary results from these studies three stations at distances of 20 m, each consisting of  $16 \text{ m}^2$  of scintillating hodoscopes are sufficient. Apart from the direction calibration, such a surface array would also allow to verify the efficiency and angular resolution of the detector.

## V. PRODUCTION MODEL AND SEA OPERATIONS

Not only the design of the components but also the production model poses a major challenge. A realistic detector configuration consists of 10000 OMs on 250 detector units. For calibration purposes about 25 further dedicated lines are required. The construction should not take longer than about 3 years in order to take data concurrently with IceCube over a long time period. This results in the requirement to produce 15 OMs per day and integrate and test 10 detector and 1 calibration units per month. The latter will probably need 5 assembly sites and an elaborate logistics to deliver all required components from the different locations in time.

The large number of detector units also implies that new ways of detector deployment have to be developed. For example, in the case of ANTARES (12 lines) each line is deployed separately which takes typically 6 hours. Afterwards, in a separate campaign the lines are connected to a junction box with a submersible which again takes several hours. This scheme is clearly impractical for a telescope with 250 detector units. A possible solution is the deployment of "compacted" detector units similar to the NEMO scheme [9]. An example is displayed in Fig. 7. Here, the rolled-up detector unit resides in a container together with the buoy and a release mechanism. After deployment of the container on the sea floor the release mechanism is triggered by an acoustic signal and the buoyancy of the buoy unfolds the detector unit. The deployment of several containers already interconnected at the surface reduces the underwater operations and further speeds up the deployment process. That this is a viable option was demonstrated by the NESTOR collaboration which deployed their tower module without any underwater operation [10]. Apart from the time saved by interconnecting the detector units already at the surface this also reduces the number of wet-mateable connectors which are a considerable cost factor (each costs several thousand Euro) and are potential points of failure.

## VI. ASSOCIATED SCIENCES

Already the continuous measurements of the deep-sea bioluminescence rate with the ANTARES detector off the coast of Toulon has triggered much interest in the marine biology community. Permanent deep-sea installations are rare and most

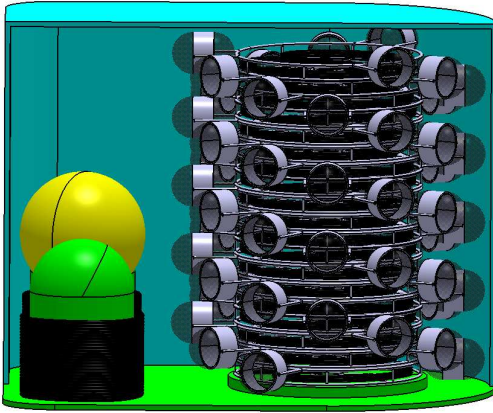


Fig. 7. Technical drawing of a possible packaging scheme for a detector unit prior to deployment. The rolled up detector unit is located on the right side and the buoy (yellow) and release mechanism (black+green) are depicted on the left side.

measurements are performed with battery-powered devices that are deployed for rather short periods of time. Therefore, the possibility to connect dedicated instruments to a node with a permanent data and power link to shore is highly welcome. The importance of this part of the KM3NeT infrastructure is reflected by a dedicated working group consisting of marine scientists within the framework of the Design Study.

This so called *Associated Science Node* [11] will directly branch off the shore cable and will consist of several junction boxes widely distributed over the sea floor. Each junction box serves several test sites connected with tethers which can be moved with remotely operated vehicles (ROVs). Well defined hard- and software interfaces allow for the connection of arbitrary observatories.

## VII. CONCLUSIONS AND OUTLOOK

The next generation neutrino telescope in the Mediterranean Sea, KM3NeT, is well on its way. With the expertise from the construction of the first generation of deep sea neutrino telescopes an EU funded Design Study is currently conducted that will provide a TDR by 2009. This TDR will contain the technical specifications for the future KM3NeT infrastructure consisting of the neutrino telescope and an associated science node. Subject to the convergence of the accompanying political process, construction is planned to begin shortly afterwards and to be finished within 3 years.

The first half of the Design Study has been dedicated to the exploration of different detector layouts, their physics sensitivity and technical concepts for their realisation. In preparation of the TDR a conceptual design report (CDR) will be compiled at the end of this year containing the results from this first phase. Based on this information the final detector concept will be elaborated in detail in the second phase of the Design Study and published in the TDR.

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