The KM3NeT Project[☆]

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Abstract

The KM3NeT research infrastructure in the deep Mediterranean Sea will host a multi-cubic-kilometre neutrino telescope and provide connectivity for continuous, long-term earth and sea science measurements. The KM3NeT neutrino telescope will complement the IceCube telescope at the South Pole in its field of view and surpass it substantially in sensitivity. In this document the major aspects of the KM3NeT technical design are described and the expected physics sensitivity is discussed. Finally, the expected time line towards construction is presented.

Keywords: Neutrino astronomy, KM3NeT, design study, Cherenkov detector

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1. Introduction

Observing high-energy cosmic neutrinos opens fascinating opportunities to complement the information gained through electromagnetic radiation. Neutrinos are not absorbed nor deflected on the way from their source to the Earth, they can escape dense environments, and they are inevitably produced in regions where nuclei are accelerated to the energies typical for cosmic rays.

Neutrino telescopes are designed to observe the Cherenkov light emitted by secondary particles produced in neutrino reactions in transparent target media, such as water or ice. The first generation of such detectors, AMANDA at the South Pole [1], ANTARES in the Mediterranean Sea [2] and Baikal [3] in the homonymous Siberian lake, have proven the feasibility of this concept, albeit with instrumented volumes “only” of the order of a percent of a cubic kilometre.

Over the last decade, it has become obvious that km^3-sized detectors are necessary to exploit the scientific potential of neutrino astronomy. A first detector of this size, IceCube [4], is currently being installed at the South Pole. The KM3NeT neutrino telescope [5] is to surpass IceCube in sensitivity by a substantial factor and complement it in its field of view. In particular, it will cover the Galactic Centre and a large fraction of the Galactic plane that are hardly visible to IceCube and that contain prime candidates for neutrino emission in the high-energy regime [6].

Technical solutions for the KM3NeT neutrino telescope that are cost-effective, reliable, can be constructed in a reasonably short period and provide the targeted sensitivity have recently been presented in a Technical Design Report (TDR) [7]. For selecting and optimising these solutions, physics priorities had to be defined. For KM3NeT, the prime science objective is the detection and investigation of point-like sources of neutrino emission in the energy range 1–100 TeV, i.e. “classical” neutrino astronomy.

In the following, the KM3NeT technical design will be described (Sect. 2), physics sensitivity and cost discussed (Sect. 3) and the envisaged project time-lines presented (Sect. 4). This article is an update of [8]; further details can be found there and in [7, 9].

2. Technical Solutions

The neutrino telescope will be an array of optical modules, i.e. photomultiplier tubes (PMTs) in pressure-resistant glass spheres, attached to vertical structures (detection units, DUs). The DUs are anchored on the sea floor and kept vertical by subtended buoys. They are connected to shore via a sea-bottom network of electro-optical cables and junction boxes.

Experience from the first-generation Mediterranean projects, ANTARES, NEMO [10] and NESTOR [11],

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shows that local clusters of PMTs are essential for event selection and reconstruction due to the presence of optical background from K40 decays and bioluminescence. Such clusters, mounted on mechanical frames called storeys, can either comprise several optical modules with one large PMT each, or one optical module with multiple smaller PMTs (see Sect. 2.1).

For the DU structure, three design options are currently investigated (see Sect. 2.2). They have in common that the DUs can be folded into compact structures for deployment and unfurl under water once they have been placed on the sea floor. The main difference is the horizontal distance between PMTs on the same DU.

The PMT signals will be processed by dedicated front-end electronics recording time-over-threshold information for each signal (see Sect. 2.3).

2.1. Optical Modules

The classical optical module [12, 13] consists of a pressure-resistant glass sphere (17 inch diameter) housing a large hemispherical PMT (10 inch) including its high-voltage base, a mu-metal magnetic shielding, a valve for pressure regulation during assembly and a feed-through for a bulkhead connector.

In addition to simplified variants of this setup, featuring 8-inch PMTs with increased quantum efficiencies in 13-inch spheres, a multi-PMT approach is being studied. In this multi-PMT module, 31 PMTs with 3 inch diameter are fit into one 17-inch glass sphere, which also contains the front-end electronics (see Fig. 1). High-voltage bases with a power consumption as low as 140 mW for a complete optical module have been designed for this application. The PMTs cover the directions of view from vertically downwards to about 45° upwards. They are supported by a foam structure and fixed to the glass sphere by optical gel. The overall photocathode area in one such optical module exceeds that of a single-PMT one by more than a factor of three; a further increase is possible by extending the light collection area using reflective rings. The multi-PMT design provides very good separation between single- and multiple-photon hits and some information on the photon direction.

2.2. Detection Unit

Three different approaches are currently being pursued for the mechanical design of the DUs.

The *flexible tower* consists of an anchor unit and 20 horizontal bars of about 6 m length at vertical distances of 40 m. Adjacent bars are connected by a tetrahedral set of ropes, so that they are oriented orthogonally to each other. Each bar can carry three pairs of single-PMT optical modules, one at each end and one in the middle. Alternatively the bars could also be equipped with 2 multi-PMT optical modules, one at each end. In Fig. 2 the basic elements of the flexible tower in the configuration with single-PMT optical modules are shown.

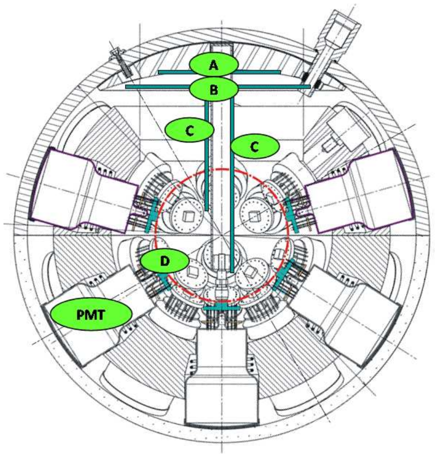


Figure 1: Schematic drawing of a multi-PMT optical module. In addition to the PMTs including their bases (D), an aluminium cooling structure (A) and the front-end electronic components (B,C) are indicated. A single penetrator is used to provide connectivity to the backbone cable.

A full-size mechanical prototype similar to the setup in Fig. 2 has been successfully deployed and unfurled in February 2010.

Alternative to the flexible tower, *slender strings* are considered. They are equipped with 20 multi-PMT optical modules at vertical distances of 30 m, fixed to two parallel Dyneema® ropes. For deployment, the strings are rolled onto spherical structures with a diameter of about two metres. After lowering them to the sea bed, they unroll under their buoyancy, thereby releasing the string. This procedure has been successfully tested in situ with a full-size prototype at the end of 2009.

A further alternative are *strings with extended storeys*, each carrying three pairs of single-PMT OMs, arranged in a triangular way on a circular mechanical frame. The use of three multi-PMT optical modules per storey would also be possible. One string carries 21 storeys with vertical distances of 40 m. The general design principle in this approach is based on the ANTARES experience and reduces the number of new components and required tests. The storeys are interconnected by a mechanical-electro-optical cable providing both electrical power and fibre-optic data connectivity and mechanical support.

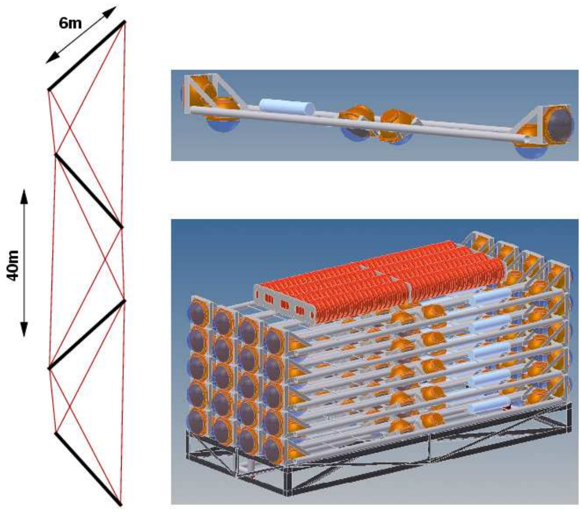


Figure 2: Left: Schematic view of four storeys (thick black lines) and the ropes holding them in place (thin red lines); top right: Design of one of the storeys, with three pairs of optical modules; bottom right: Compactified tower ready for deployment, with the buoy on top.

Various considerations are common amongst different design options:

A *backbone cable* along the DUs has been designed for power and data transport, with the target to reduce the numbers of penetrators and connectors (which are expensive and failure-prone) and to implement a topology without major single-point failures. This cable consists of a oil-filled hose with copper conductors and optical fibres inside, operated at equi-pressure with the ambient sea water. At each storey, a break-out unit provides connectivity to one fibre and two copper conductors. The optical network is set up in a star-like topology branching off an optical multiplexer located roughly in the middle of a DU. A prototype of this backbone design has been successfully tested; further verification steps are under way. If successful, this concept is usable both for the flexible towers and the slender strings. If not, fall-back solutions using classical cables are available.

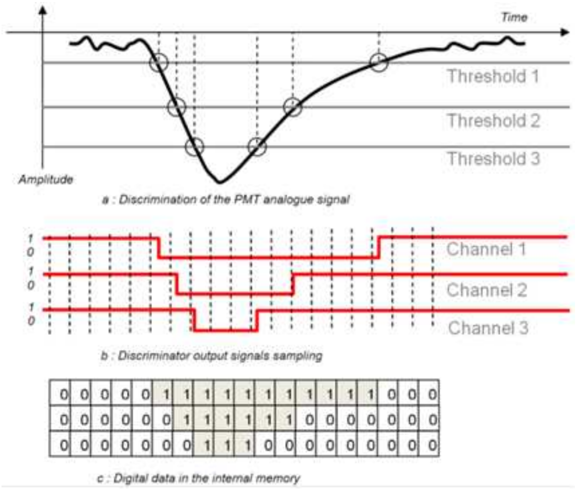
Regular position and orientation *calibration* is necessary to account for the movement of the DUs in the sea current. As in ANTARES, acoustic triangulation methods will be applied, together with orientation measurements by compasses and tilt-meters. The option to glue the acoustic sensors to the inner surface of the optical modules is under study. For time calibration, pulsed light signals from LED or laser beacons will be used.

2.3. *Readout Scheme*

A dedicated ASIC, the Scott chip, will be the central front-end component of the readout. It converts the analogue PMT signal into digital time-over-threshold information, where one or several adjustable thresholds can be assigned to each PMT. See Fig. 3 for a schematic presentation of this functionality.

For use with single-PMT optical modules, the signal shape can be reconstructed from the time-over-threshold data for several thresholds per PMT. For the multi-PMT configuration, one threshold will be assigned to each PMT. At low rates, this allows for photon counting by determining the number of PMTs hit in a certain coincidence window. At large rates, the time-over-threshold information provides a logarithmic measure for the number of photo-electrons per PMT.

All digitised data corresponding to PMT hits above a noise threshold of typically 0.3 photo-electrons are sent to shore and subjected to an online filter running on a computer farm (about 1000 nodes) in the shore station. Selected data are stored and distributed for analysis.



0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0

Figure 3: Functionality of the readout scheme. Top: A given PMT analogue signal is compared to a number of adjustable thresholds; middle: The comparator provides one on/off voltage signal per threshold; bottom: These signals are sampled at fixed time steps and and the times over thresholds recorded in digital format.

2.4. *Deep-Sea Infrastructure*

The deep-sea cable network consists of one or few main electro-optical cables from shore to primary junction boxes, from where it branches via secondary junction boxes to the DUs. Since the footprint of the detector is not yet decided, the exact configuration of the network is still open. Both star-like topologies and a ring topology of the main cable with branches to a series of primary junction boxes are considered. The functionalities of cables, connectors and junction boxes in terms of electrical power distribution and data transmission have been studied in detail and are well defined. They will be implemented based on the existing experience from ANTARES, NEMO and other deep-sea research projects such as NEPTUNE [14]. The overall power consumption will be about 125 kW, the overall data rate sent to shore will be of the order 25 GByte/s.

3. Physics Sensitivity and Cost

Detailed Monte Carlo simulations have been performed for the design options discussed above, taking into account signal, atmospheric neutrino and atmospheric muon events. It turns out that optimal solutions for event and hit selection, reconstruction and definition of quality cuts strongly depend on the PMT arrangement; in particular, single- and multi-PMT optical modules require significantly different approaches. The corresponding optimisation process has not yet fully concluded, so that the results reported here have remaining uncertainties and, at the same time, are conservative.

Simulation studies have been central in optimising design parameters, in particular with regard to the detector geometry. Based on these studies, detector configurations using the DU design options described in Sect. 2.2 have been defined for further simulation and for cost estimation purposes. For the flexible towers and the extended strings, these are equilateral hexagons of 127 DUs arranged on a regular triangular grid, with an inter-DU distance of 180 m (flexible towers) or 150 m (extended strings), respectively. For the slender strings, a homogeneous configuration of 310 DUs at distances of 130 m was chosen. A driving objective behind these choices was to define units of approximately equal sensitivity that could be implemented using one main cable to shore. The simulations indicate that these configurations are very similar in sensitivity, in particular when applying strict quality cuts.

The investment cost for the three detector configurations discussed above has been estimated based on commercial quotations, experience from existing installations, price lists and input from marine science and technology projects. The results, including costs for the deep-sea network and the deployment but not for the shore infrastructure or personnel, are 88, 107 and 99 M€ for the flexible towers, slender strings and extended strings, respectively. Please note that these numbers carry an uncertainty of at least 20% and thus do not provide a basis for a quick technology decision.

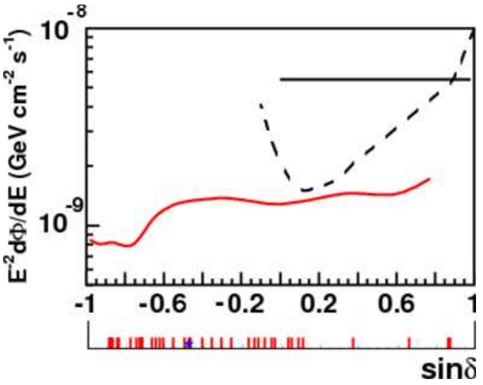


Figure 4: Sensitivity of the full KM3NeT neutrino telescope to point-like sources of neutrino emission with fluxes proportional to E_ν^{-2} as a function of declination δ (red line extending to $\delta = -90°$). The sensitivity is inferred from a binned analysis of simulation data. The vertical axis indicates the expected exclusion limit at 90% C.L for 1 year of livetime. Also shown is the corresponding IceCube sensitivity (black dashed line at positive declinations, taken from [15]). The tick marks in the lower panel indicate the positions of TeV gamma sources in the Galactic plane, the blue star marks the Galactic Centre.

The configurations investigated fall short to reach the objective of surpassing IceCube by a substantial factor in sensitivity (see below). The full KM3NeT neutrino telescope is therefore envisaged to comprise approximately two of the configurations (“building blocks”) discussed above, so as to be compatible with a projected overall capital investment budget of 220 M€ [16, 17]. The operation costs for this set-up have been estimated to be between 4 and 6 M€, depending on the number of maintenance operations required. This corresponds to 2–3% of the capital investment and thus is significantly lower than for other projects of comparable complexity.

The full KM3NeT neutrino telescope will instrument a water volume of 4 to 5 cubic kilometres and thus by far outperforms the initial target of the KM3NeT Design Study, i.e. a price tag of 200 M€ per instrumented km^3 of water. The sensitivity of the full KM3NeT detector to point sources emitting a neutrino flux proportional to E_ν^{-2} is shown in Fig. 4 as a function of the declination of the source. The shape of the sensitivity curve reflects declination dependences of the visibility, the effective area and the Earth’s transparency to neutrinos. Also indicated are the corresponding IceCube sensitivity and the declinations of the TeV gamma sources in the Galactic plane, which are prime candidates for high-energy neutrino emission. The KM3NeT sensitivity is better than that of IceCube over a large fraction of the full sky (about 3.5π steradians), by more than half an order of magnitude on average. There is room for further improvement by optimising the event selection and reconstruction procedures or using unbinned analysis methods.

4. Project Development

The projected KM3NeT time lines towards construction and operation are indicated in Fig. 5.

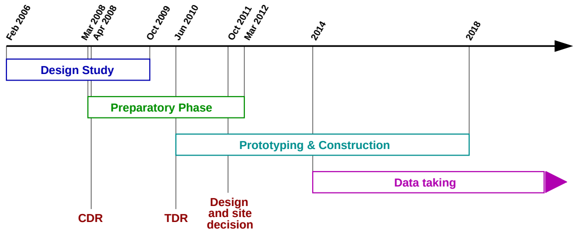


Figure 5: Time line of the KM3NeT project development towards construction and operation.

The further work will be organised inside the FP7-funded KM3NeT Preparatory Phase project running until February 2012. The decisions for specific technical solutions require further prototyping and field tests. A period of 18 months after TDR publication (June 2010) is foreseen for these activities, as well as for verifying those component designs which are new and have been developed specifically for the KM3NeT neutrino telescope (such as the equi-pressure backbone, the front-end electronics or the multi-PMT optical modules). Concurrently, simulation studies will be pursued to react to technical developments and to assess the detector footprint.

At the same time scale, a site decision has to be taken. Currently, three sites (near Toulon, at the east coast of Sicily and at the west coast of the Peloponnesus) have been proposed. They differ in depth (2.5 km to 5 km), in distance to shore (between about 15 km and 100 km) and in their environmental properties.

Once these decisions have been taken, the final technical design of the KM3NeT Research Infrastructure will be laid down in a detailed proposal. Assuming that funding, legal and administrative issues are sorted out by then, it will be possible to launch production at that point.

Data taking will start as soon as the first DUs are operational. From a very early stage of its construction on, the data from the KM3NeT neutrino telescope will exceed data from first-generation Northern-hemisphere neutrino telescopes in quality and statistics and thus provide an exciting discovery potential.

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References

[1] Ch. Spiering, Phys. Scripta **T121**, 112 (2005).
[2] J. Brunner, ANTARES Coll., *The ANTARES neutrino telescope: Status and first results*, to appear in Proc. VLVnT09, Athens, 2009.
[3] V. Aynudtinov, Baikal Coll., *The Baikal neutrino experiment*, to appear in Proc. VLVnT09, Athens, 2009.
[4] K. Hultqvist, IceCube Coll., *IceCube: Physics, status and future*, to appear in Proc. VLVnT09, Athens, 2009.
[5] KM3NeT homepage, available on `http://km3net.org`.
[6] A. Kappes, J. Hinton, C. Stegmann, F.Aharonian, Astrophys. J **656**, 870 (2007).
[7] KM3NeT Consortium, *Technical Design Report*, available on `http://www.km3net.org`.
[8] U.F. Katz, for the KM3NeT Consortium, *The KM3NeT project*, Nucl. Inst. Meth A, DOI 10.1016/j.nima.2010.06.207, 2010, available on `http://dx.doi.org/10.1016/j.nima.2010.06.207`.
[9] *Proceedings of the VLVnT09 Workshop, Athens, 2009*, to appear in Nucl. Inst. Meth. A.
[10] M. Taiuti, NEMO Coll., *The NEMO project: A status report*, to appear in Proc. VLVnT09, Athens, 2009.
[11] P. Rapidis, NESTOR Coll., Proc. VLVnT08, Toulon.
[12] ANTARES Coll., P. Amran et al., Nucl. Inst. Meth. **A 484**, 369 (2002).
[13] R.I. Bagduev et al., Nucl. Inst. Meth. **A 420**, 138 (1999).
[14] NEPTUNE Coll., available on `http://www.neptunecanada.ca/`.
[15] R. Abbasi et al., IceCube Coll., Astrophys. J. **701** (2009).
[16] ESFRI, *European Roadmap for Research Infrastructures, Report 2006*, 2006, available on `http://ftp://ftp.cordis.europa.eu/pub/esfri/docs/esfri-roadmap-report-26092006_en.pdf`.
[17] ESFRI, *European Roadmap for Research Infrastructures, Update 2008*, 2008, available on `http://ftp://ftp.cordis.europa.eu/pub/esfri/docs/esfri_roadmap_update_2008.pdf`.