Status and progress of 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.

1 Introduction

Cosmic 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. Observing high-energy neutrinos of extraterrestrial origin thus opens fascinating opportunities to complement the information gained through electromagnetic radiation.

The neutrinos are detected by observing 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 neutrino telescopes, 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 with instrumented volumes of the order of a percent of a cubic kilometre. At neutrino energies below about 10^{15} eV, the Earth serves as a shield against any other types of particles; neutrino telescopes are thus effectively sensitive to the downward hemisphere.

Over the last decade, it has become obvious that km^3-sized detectors are necessary to exploit the scientific potential of neutrino astronomy. The first detector of this size, IceCube [4], has been constructed in the deep ice of the South Pole; it has been completed in December 2010. 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].

The prime science objective for KM3NeT is the detection and investigation of point-like astrophysical sources of neutrino emission in the energy range 1–100 TeV, i.e. "classical" neutrino astronomy. The detector design is being optimised for this priority. 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].

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, 9]; further details can be found there and in [7, 10].

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.

The neutrino telescope will be installed at a water depth of at least 2500 m and thus be completely shielded from day light. Remaining background light comes from K40 decays and bioluminescence. Experience from the first-generation Mediterranean projects, ANTARES, NEMO [11] and NESTOR [12], shows that local clusters of PMTs are essential to reliably identify neutrino events in the presence of this background. 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 described in the TDR (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 [13, 14] 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. It is important noting that this setup requires additional equipment, in particular external containers for electronic components for data digitisation and transport, which increase cost and reduce reliability.

Therefore, in addition to simplified variants of single-PMT setups with 8-inch PMTs in 13-inch spheres, a multi-PMT approach with integrated electronics components is being pursued. In this multi-PMT module, 31 PMTs with 3 inch diameter plus the front-end electronics components are fit into one 17-inch glass sphere (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 are oriented 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 [15]. 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 have been studied in detail for the mechanical design of the DUs. Meanwhile, priority is assigned to the flexible tower option:

The *flexible tower* consists of an anchor unit and 20 horizontal bars of

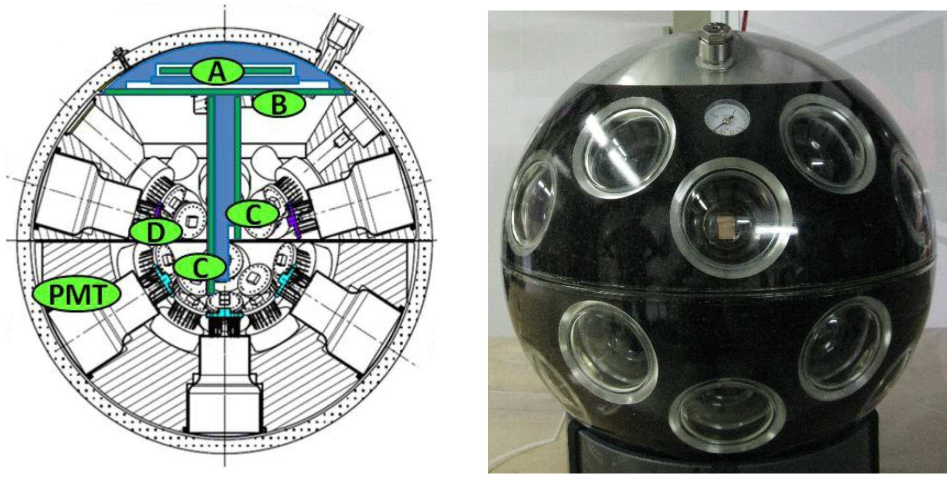

Figure 1: Left: Schematic drawing of a multi-PMT optical module. In addition to the PMTs including their bases (D), an aluminium cooling structure (A) and the front-end electronic components (B,C) are indicated. A single penetrator is used to provide connectivity to the backbone cable. Right: Photograph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

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 will carry two multi-PMT optical modules, one at each end. Alternatively, the bars could also be equipped each with three pairs of single-PMT optical modules, one at each end and one in the middle; this configuration was assumed when the design of the basic elements of the flexible tower shown in Fig. 2 was devised. One advantage of this structure is that the bars' horizontal extent allows for locally reconstructing the azimuthal angle of muon tracks, thereby improving the detection efficiency for low and intermediate neutrino energies.

A full-size mechanical prototype similar to the setup in Fig. 2 has been successfully deployed and unfurled in February 2010. Meanwhile, a decision has been taken in the KM3NeT Consortium that the prime option for further testing and development will be flexible towers with two multi-PMT optical modules per horizontal structure.

Alternative to the flexible tower, *slender strings* were considered, equipped with 20 multi-PMT optical modules at vertical distances of 30 m. For deployment, the strings are wound onto spherical structures with a diameter of about two metres which are lowered to the sea bed and then unroll

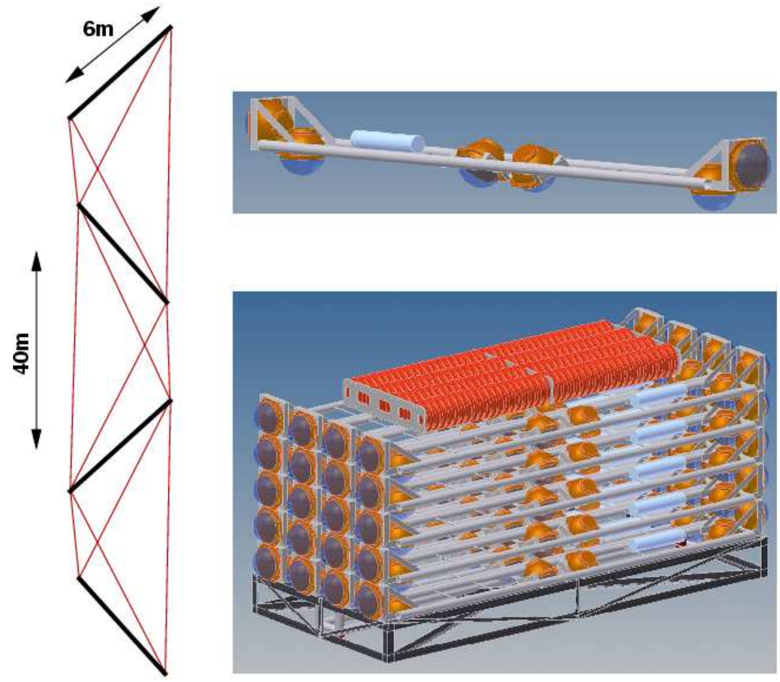

Figure 2: Left: Schematic view of four storeys (thick lines) and the ropes holding them in place (thin lines); top right: Design of one of the storeys, with three pairs of optical modules; bottom right: Compactified tower ready for deployment, with the buoy on top.

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 storeys are interconnected by a mechanical-electro-optical cable providing both electrical power and fibre-optic data connectivity and mechanical support.

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 unsuccessful, 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 piezo ceramic elements used as acoustic sensors to the inner surface of the optical modules is under study. Such a setup might also provide a cost-effective solution for instrumenting several cubic kilometres of water for acoustic detection tests (see [16] and references therein) and studies in marine biology. 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 the multi-PMT optical modules, it is planned to assign one threshold 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. For use with single-PMT optical modules, the signal shape can be reconstructed from the time-over-threshold data for several thresholds per PMT.

All digitised data corresponding to PMT hits above a noise threshold typically corresponding to 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.

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

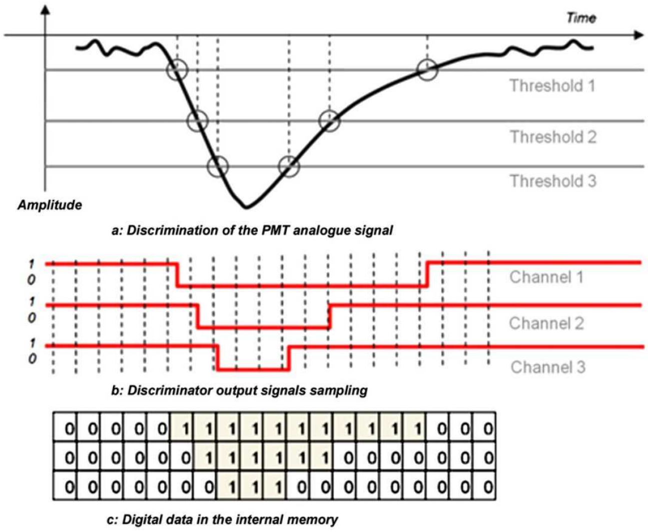

Figure 3: Functionality of the readout scheme. Top: A given PMT analogue signal is compared to a number of adjustable thresholds; middle: The comparator provides one on/off voltage signal per threshold; bottom: These signals are sampled at fixed time steps and and the times over thresholds recorded in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

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 [17]. 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 software optimisation process for the multi-PMT solution is therefore still ongoing, 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. As an example, the sensitivity as a function of the horizontal bar length is shown in Fig. 4. Based on this and further 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, these are equilateral hexagons of 127 DUs arranged on a regular triangular grid, with an inter-DU distance of 180 m. 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.

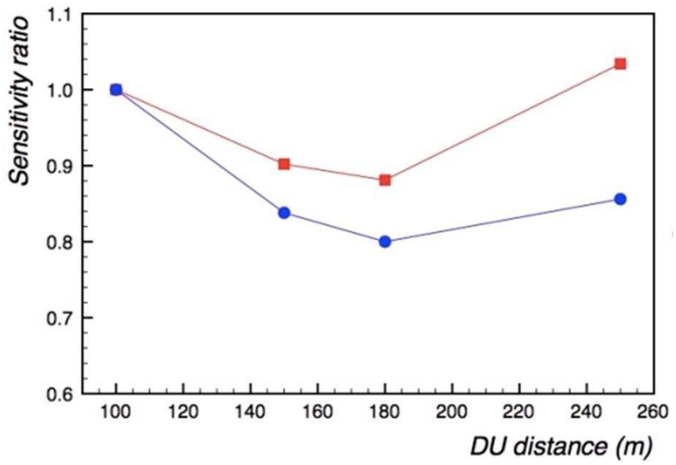

Figure 4: Relative sensitivity of detector configurations with 127 flexible towers as a function of the inter-DU distance, for point source searches with assumed unbroken power-law neutrino energy spectra with spectral indices $\alpha = 2.0$ (circles) and $\alpha = 2.2$ (squares), respectively. The sensitivities are normalised to the results for a distance of 100 m. Note that sensitivities are given in terms of the upper neutrino flux limits achievable, so lower values indicate higher sensitivities.

The investment cost for the three detector configurations discussed above has been estimated based on commercial quotations, experience from exist-

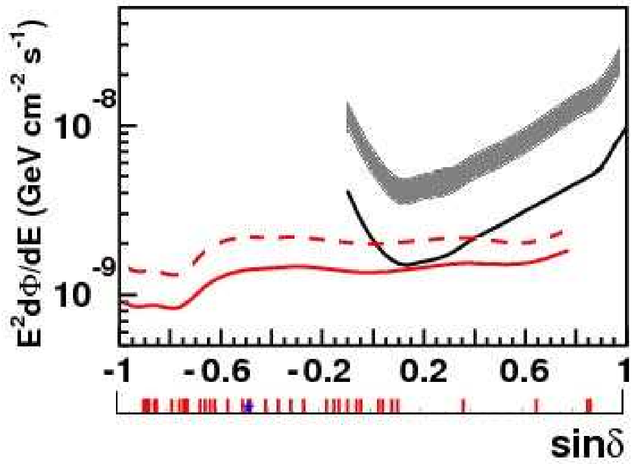

Figure 5: Sensitivity of the full KM3NeT neutrino telescope to point-like sources of neutrino emission with fluxes proportional to E_ν^{-2} as a function of declination δ. The lines extending to $\delta = -90°$ indicate the expected exclusion limits at 90% C.L (full line) and the 5σ discovery level (gray band), for 1 year of data taking. Also shown are the corresponding IceCube sensitivities (lines at positive declinations, taken from [20]). The tick marks in the lower panel indicate the positions of TeV gamma sources in the Galactic plane, the star marks the Galactic Centre.

ing 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 about 95 M€ per set-up described above, with design-dependent variations that are substantially smaller than the uncertainty of at least 20% of this price tag. Cost alone therefore does not provide a sound basis for a quick technology decision.

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 and will thus be compatible with a projected overall capital investment budget of 220 M€ [18, 19]. The operation costs for this set-up, including maintenance, electrical power, computing, shore station crew and management, 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 outperform 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. 5 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. 6.

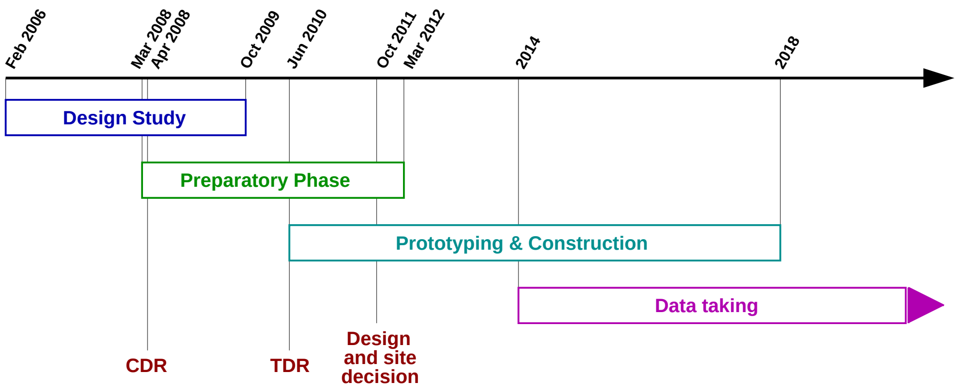

Figure 6: Time line of the KM3NeT project development towards construction and operation.

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. This work will be organised inside the FP7-funded KM3NeT Preparatory Phase project running until February 2012.

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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