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 measurements of earth and sea sciences, such as geology, marine biology and oceanography. The KM3NeT neutrino telescope will complement the IceCube telescope currently being installed at the South Pole in its field of view and surpass its sensitivity by a substantial factor. 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

1. Introduction

Using neutrinos as messengers for investigating the non-thermal, high-energy processes in the Universe is a fascinating idea, driving since long intense efforts towards suitable detectors. The approach commonly pursued is to instrument large volumes of natural transparent media with photo-sensors to register the Cherenkov light emitted by charged secondary particles produced in neutrino interactions. 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 both in water and ice.

Over the last decade, it has become obvious that the target volumes of these installations, typically of the order of a percent of a cubic kilometre, are insufficient to exploit the scientific potential of neutrino astronomy. For this reason, a first km^3-sized detector, 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. Observations of TeV gamma rays from astrophysical sources in this region indicate that various of them are prime candidates for neutrino emission in the high-energy regime [6].

The main challenge in designing the KM3NeT neutrino telescope is to identify and validate technical solutions that are cost-effective, reliable, can be constructed in a reasonably short period and provide the targeted sensitivity. An initial set of design concepts is summarised in the *KM3NeT Conceptual Design Report (CDR)* [7]. For selecting and optimising the solutions under consideration, physics priorities have to be defined. For KM3NeT, the prime science objective is the detection and investigation of point-like sources of neutrino emission, i.e. "classical" neutrino astronomy. Further physics topics, such as the indirect search for Dark Matter, the identification and measurement of a cosmogenic diffuse neutrino flux or exotica such as magnetic monopoles are taken into consideration but do not drive the design effort.

In Sect. 2 some prime features of the KM3NeT technical design will be described. In a few cases, different options are still being investigated since final decisions need extended prototyping and fields tests to be performed over the next 1.5 years. This in particular applies to the choice of the optical modules, the mechanical structures and the sea-floor layout of the detector ("footprint"). Assuming certain configurations, the cost of the neutrino telescope has been estimated and its physics sensitivity evaluated and optimised; these results are presented in Sect. 3. Finally, the envisaged further development of the project is discussed in Sect. 4.

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 [8] and NESTOR [9], shows that local clusters of PMTs are essential for event selection and reconstruction due to the presence of optical background from K40 decays and

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bioluminescence. These clusters can either be implemented using several optical modules with one large PMT each or one optical module with multiple smaller PMTs. Each cluster is mounted on a mechanical frame called storey. Both single- and multi-PMT approaches are currently pursued (see Sect. 2.1).

For the DU structure, three design options are currently investigated. 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 extent of the structures, i.e. the horizontal distances between PMTs on the same DU. These designs will be discussed in Sect. 2.2.

The PMT signals will be processed by dedicated front-end electronics recording the time-over-threshold for each signal (see Sect. 2.3). One or several thresholds can be assigned to each PMT. For all PMT signals above a certain noise level (typically 0.3 photo-electrons), the corresponding timing information is sent to shore (all-data-to-shore concept).

2.1. *Optical Modules*

The classical arrangement of an optical module [10, 11] 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.

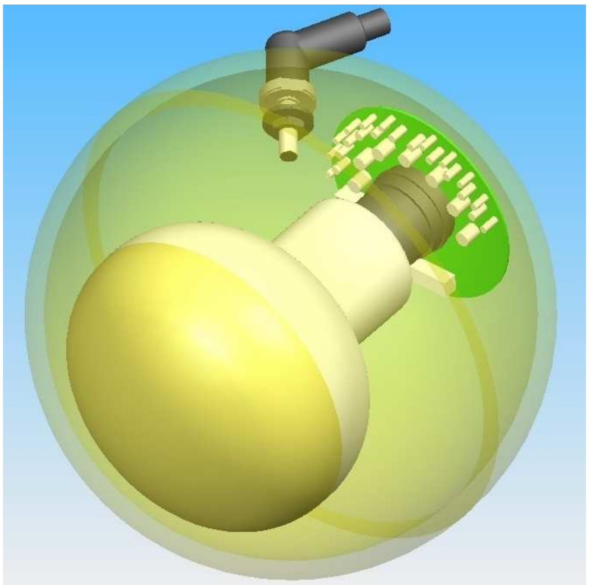

Figure 1: Design of an optical module consisting of a 13-inch glass sphere and an 8-inch hemispherical PMT. The PMT is connected to the inside of the sphere using optical gel. No mu-metal shielding or valve are planned to be implemented. The bulkhead connector for voltage supply and signal lead is situated at the top of the sphere.

Due to the recent progress on the quantum efficiency of bi-alkali photocathodes (see e.g. [12–14] and references therein), 8-inch PMTs nowadays provide the same sensitivity as 10-inch PMTs previously, thus allowing for a reduction of the PMT cost and the sphere size. Further simplification by omitting the mu-metal shielding and the valve (which is obsolete if the the optical module is assembled under reduced pressure) is being investigated. A drawing of such a simplified single-PMT optical module is shown in Fig. 1. The use of common readout electronic modules for local clusters of such optical modules requires an additional container, most likely another glass sphere to be attached to each storey.

An alternative also under investigation is to use glass vessels consisting of two cylindrical pieces closed by half spheres ("capsule). One such capsule could contain two 8-inch PMTs and the associated readout electronics.

In the multi-PMT approach [15], 31 PMTs with 3 inch diameter are fit into one 17-inch glass sphere, which also contains the front-end electronics (see Fig. 2) and forms a full storey. High-voltage bases with particularly low power consumption (about 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 [16]. The multi-PMT design provides very good separation between single- and multiple-photon hits and some information on the photon direction.

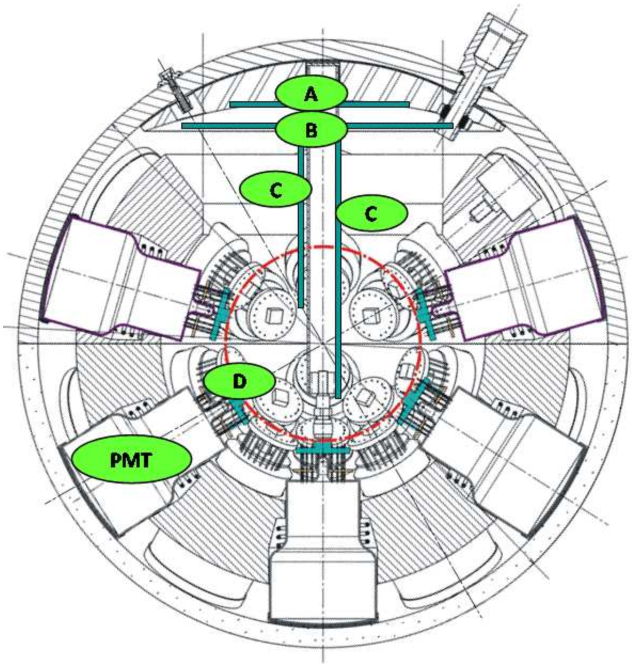

Figure 2: Schematic drawing of a multi-PMT optical module. In addition to the PMTs including their bases (D), an aluminium cooling structure (A) and the front-end electronic components (B,C) are indicated. A single penetrator is used to provide connectivity to the backbone cable.

The final choice of optical modules will be driven by cost and reliability considerations, performance and the timely availability of the PMTs. These issues are currently under study.

2.2. Detection Unit

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

- A flexible tower, consisting of an anchor unit and 20 horizontal bars of about 6 m length at vertical distances of 40 m [17]. The first storey is located 100 m above the seabed. Adjacent bars are connected by a tetrahedral set of ropes, so that they are oriented orthogonally to each other. Each bar carries three pairs of single-PMT optical modules, one at each end (looking downward and horizontally outward) and one in the middle (looking downwards at an angle of 45° with respect to the vertical). In Fig. 3 the basic elements of the flexible tower are shown.

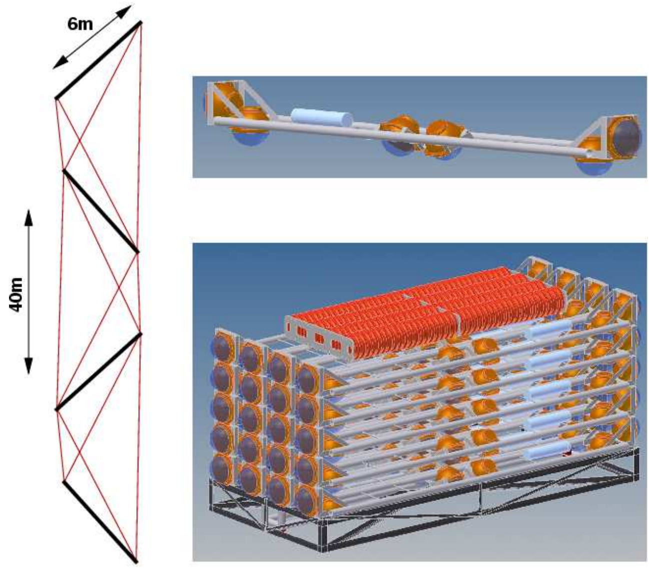

Figure 3: Left: Schematic view of four storeys (thick black lines) and the ropes holding them in place (thin red lines); top right: Design of one of the storeys, with three pairs of optical modules and an electronics container (to be replaced by a glass sphere); bottom right: Compactified tower ready for deployment, with the buoy on top.

One advantage of the tower structure is the fact that its horizontal extent breaks its azimuthal symmetry and therefore allows for reconstructing the azimuth of muon tracks from charged-current ν_μ reactions, even if they are detected only by one DU. This increases the detector sensitivity, in particular at lower and intermediate neutrino energies.

Alternatively to the single-PMT optical modules, the flexible towers could also be equipped with 2-3 multi-PMT optical modules per storey.

- A slender string, equipped with 20 multi-PMT optical modules at vertical distances of 30 m to each other, starting 100 m above the seabed [18]. Additional empty spheres provide the required buoyancy. Spring-loaded titanium collars holding the glass spheres are attached to a pair of parallel Dyneema® ropes. In order to provide torsional stability, composite-material braces will be inserted between the ropes, alternating with the optical modules.

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. The empty structures finally rise to the sea surface from where they are recovered for reuse. This deployment scheme has been successfully tested in situ with a full-size prototype at the end of 2009.

The mechanical structure of the string and the deployment device are presented in Fig. 4.

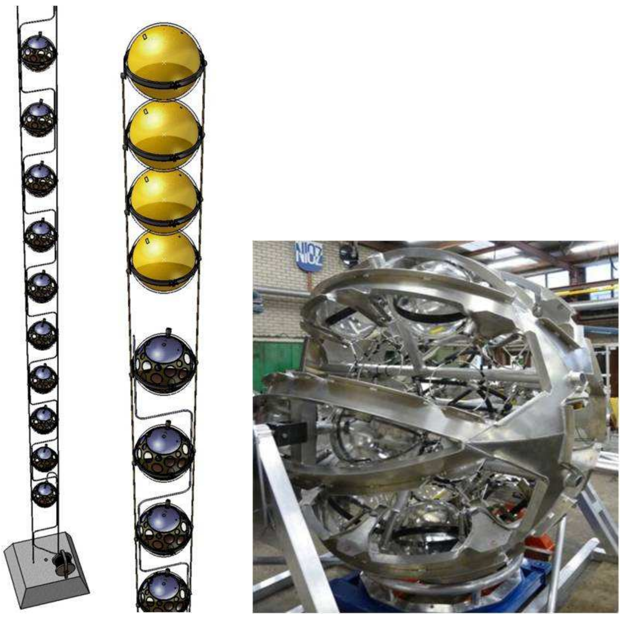

Figure 4: Left: Drawings of the anchor and top parts of a slender string. In addition to the multi-PMT optical modules and the vertical ropes, the backbone cable (see text) is indicated; it forms a meander along the string to minimise torque effects in the sea current. The anchor carries the cable for connection to a junction box. Right: Empty deployment structure for rolling up the string.

- A string with extended storeys, each carrying three pairs of single-PMT OMs per storey, arranged in a triangular way on a circular mechanical frame. Of each pair of optical modules, one is oriented vertically downward and the other horizontally outward. The use of three multi-PMT optical modules per storey would also be possible. One string carries 21 storeys with a vertical distance of 40 m, starting 100 m above sea bed.

The general design principle in this approach is based on the ANTARES experience and represents a conservative solution, reducing the number of new components and required tests. As in ANTARES, the storeys are interconnected by a mechanical-electro-optical cable providing both electrical power and fibre-optic data connectivity and mechanical support.

In contrast to ANTARES, the DUs are stacked on top of each other for deployment. Together with a bell-shaped cover they form a compact structure, which is positioned on the seabed and subsequently unfurled by pulling up the cover (with the top buoy attached to it) from the sea surface.

Details of this design and the stacked structure are shown in Fig. 5.

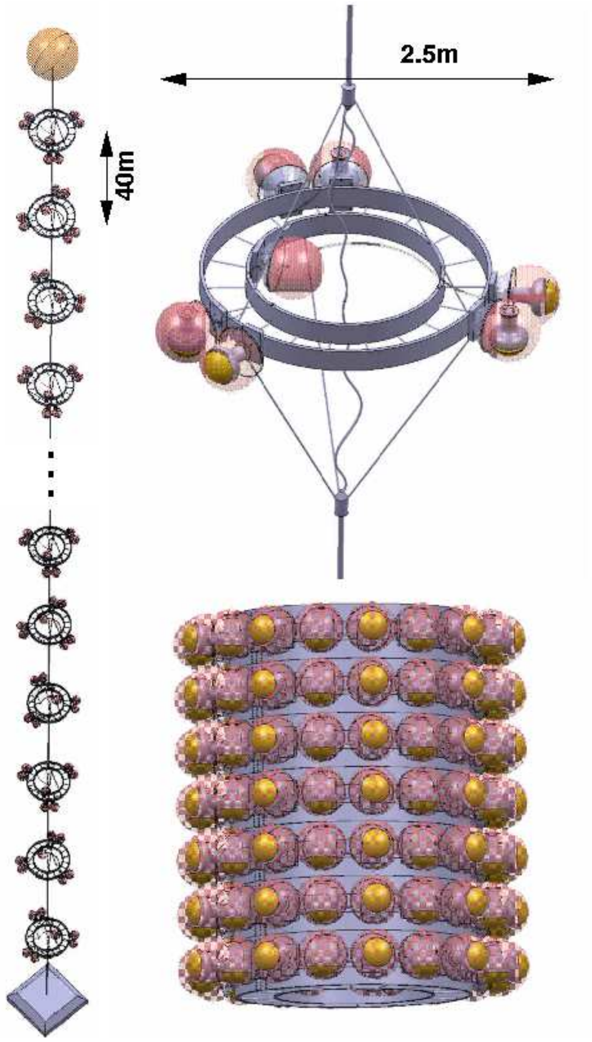

Figure 5: Left: Drawings of the anchor and top parts of the extended string. Top right: enlarged view of one storey, with three pairs of single-PMT optical modules and a glass sphere used as electronics container attached to the inner part of the ring. Bottom right: Stack of 21 storeys, arranged in 7 planes with 3 storeys each.

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) to a minimum 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 between an optical multiplexer located roughly in the middle of a DU and each storey. A prototype of this backbone design has been successfully tested; further verification steps are planned. 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.

The deformation of the DUs under drag forces in sea currents has been studied. Generally, the deviation of the DU top from a vertical configuration increases with the square of the current velocity and can be adjusted by a suitable choice of the top buoyancy. For all three configurations, a maximum deviation between 80 m and 90 m is expected for a sea current of 30 cm/s, which corresponds to the largest values recorded at any of the Mediterranean neutrino telescope sites to date. Given an expected inter-DU distance of at least 130 m and the fact that the current is expected to be mostly homogeneous in the detector volume, these deformations are fully acceptable.

Regular position and orientation calibration is necessary to account for the movement of the optical modules in the sea current. As in ANTARES, acoustic triangulation methods will be applied [19, 20], together with orientation measurements by compasses and tilt-meters if required. A system with the acoustic sensors glued to the inner surface of the optical modules is under study. For time calibration, pulsed light signals from LED or laser beacons will be employed [21].

2.3. Readout Scheme

A dedicated ASIC, the Scott chip, is being developed as the central front-end component of the readout. It converts the analogue PMT signal into time-over-threshold information, where one or several adjustable thresholds can be assigned to each PMT. The times of threshold crossing are recorded digitally; see Fig. 6 for a schematic presentation of this functionality.

For use with single-PMT optical modules, several thresholds will be used for each PMT. In this case, the signal shape can be reconstructed from the time-over-threshold data. 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 signal amplitude, i.e. the number of photo-electrons per PMT.

All digitised data corresponding to PMT hits above a noise threshold are sent to shore and subjected to an online filter running on a computer farm in the shore station. Selected data are sent to mass storage and distributed for analysis.

2.4. Deep-Sea and Shore 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

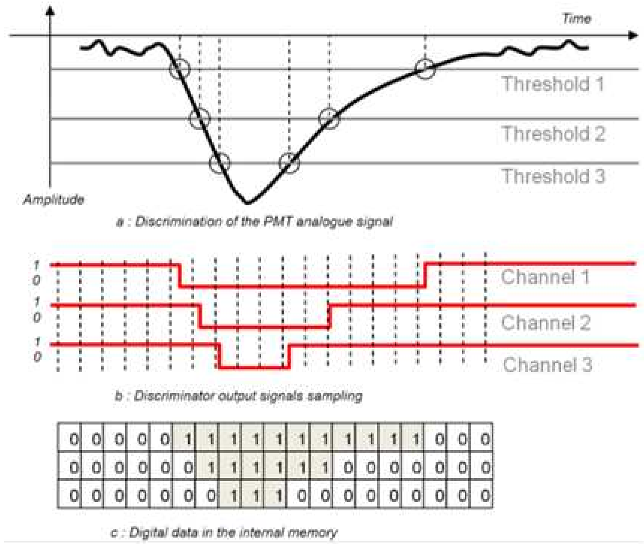

Figure 6: Functionality of the readout scheme using the Scott chip for time-over-threshold processing. Top: A given PMT analogue signal is compared to a number of adjustable thresholds; middle: The comparator provides one on/off voltage signal per threshold; bottom: These signals are sampled at fixed time steps and and the times over thresholds recorded in digital format.

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 [22]. The overall power consumption will be about 125 kW, the overall data rate sent to shore will be of the order 25 GByte/s.

A shore station will house a computer farm with approximately 1000 nodes required for running the online filter (see Sect. 2.3). Furthermore, it will contain the on-shore components for the readout (lasers, power supplies, etc.), the electrical power feeds and the control system for operating KM3NeT.

Plans are being investigated to provide a green power plant (wind or sun) for covering the power consumption of KM3NeT [7]. Such a scenario requires cooperation with local electricity companies to guarantee steady provision of the electrical power needed and the feed-in of temporal power overproduction.

2.5. The Earth and Sea Science Node

The earth and sea science instrumentation of the KM3NeT Research Infrastructure will be connected to an output of the primary junction box, or to a dedicated primary junction box if several of these will be employed.

Examples of such instrumentation are lines of autonomous sensors such as seismographs; moorings containing suites of devices for monitoring surface water, water column, sea-bed and the sub-seafloor volume in a coordinated manner; fixed structures with removable modules containing instruments such as cameras or acoustic sensors. These devices are expected to be deployed at a safety radius of at least a kilometre from the neutrino telescope in order to avoid adverse interference during operation of both components. In addition, synergetic use of instruments inside the neutrino telescope volume (including the PMTs) in conjunction with the peripheral devices is foreseen.

3. Physics Sensitivity and Cost

Detailed Monte Carlo simulations have been performed for the design options discussed above, taking into account the full process chain for signal, atmospheric neutrino and atmospheric muon events (primary interaction, propagation of secondary particles, secondary interactions, Cherenkov light emission, propagation of the light through the sea water, detector response, online filter and reconstruction). 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 (since algorithmic improvements will increase rather than decrease the resulting sensitivities).

Sensitivities have been investigated in terms of neutrino effective areas, i.e. the fictitious areas in which all neutrinos of a given energy would be detected, and in terms of the discovery or exclusion potential for neutrino fluxes of a given type. In particular, neutrino fluxes $\Phi(E_\nu) = \Phi_0 \cdot (E_\nu/(1\,\text{TeV})^{-\alpha}$ ("unbroken power law") from point sources have been assumed and the expected upper limit on Φ_0 determined. Note that lower numbers correspond to stricter limits.

Simulations have been a central instrument in optimising design parameters, in particular with regard to the detector geometry. As an example, Fig. 7 shows the relative sensitivity of a search for point sources as a function of the inter-DU distance for the flexible towers, for two different values of α. A distance of 180 m appears to be favourable.

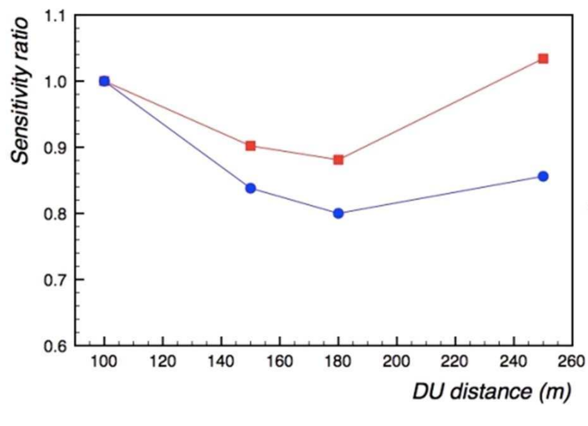

Figure 7: Relative sensitivity of detector configurations with 127 flexible towers as a function of the inter-DU distance, for point source searches with assumed unbroken power-law neutrino energy spectra with spectral indices $\alpha = 2.0$ (blue circles) and $\alpha = 2.2$ (red squares), respectively. The sensitivities are normalised to the results for a distance of 100 m.

Based on such 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 configuration of 310 DUs at distances of 130 m was chosen, also in an hexagonal homogeneous arrangement. A driving objective behind these choices was to define units of approximately equal sensitivity that could be implemented using one main cable to shore.

In Fig. 8, the effective areas for two out of these three configurations are shown. It can be easily inferred that the differences between the two design options is small, in particular when applying strict quality cuts. This result has also been confirmed for the extended strings (not shown). Note that that the optimisation of the quality cuts has a strong impact on the sensitivity achievable and is still subject to ongoing studies.

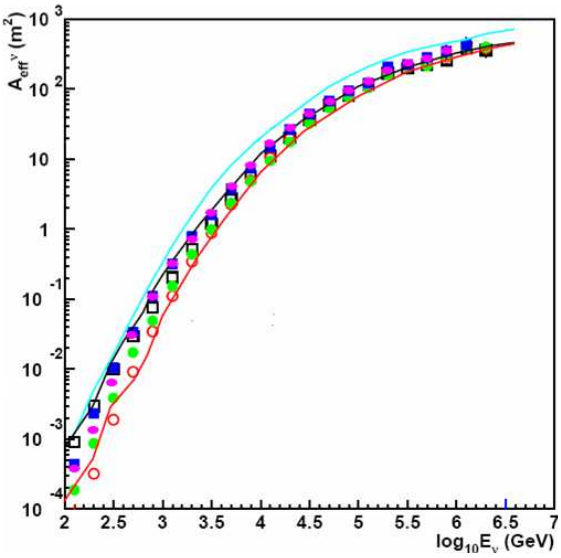

Figure 8: Neutrino effective areas for the configurations of flexible towers (symbols) and slender strings (lines) described in the text. In each case, results corresponding to different levels of quality cuts are shown (lowest effective areas correspond to hardest cuts).

The investment cost for the three detector configurations discussed above has been estimated based on commercial quotations, experience from ANTARES, NEMO and NESTOR, 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, 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%.

The following two conclusions are drawn from these results:

1. It is too early to make a decision on the technical design based on cost and performance considerations. Further studies, refinement of cost estimates, prototype and field tests as well as studies of site dependencies have to be performed before final decisions can be taken.
2. 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€ [23, 24]. 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 thus includes approximately 250 DUs of the flexible tower or extended string type, or more than 600 slender strings. The instrumented water volume is between 4 and 5 cubic kilometres for all configuration options. Note that this result by far outperforms the initial target of the KM3NeT Design Study, i.e. a price tag of 200 M€ per instrumented cubic kilometre of water. The sensitivity of the full KM3NeT detector to point sources with an unbroken power law energy spectrum (index $\alpha = 2$) is very similar for all design options and is shown in Fig. 9 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.

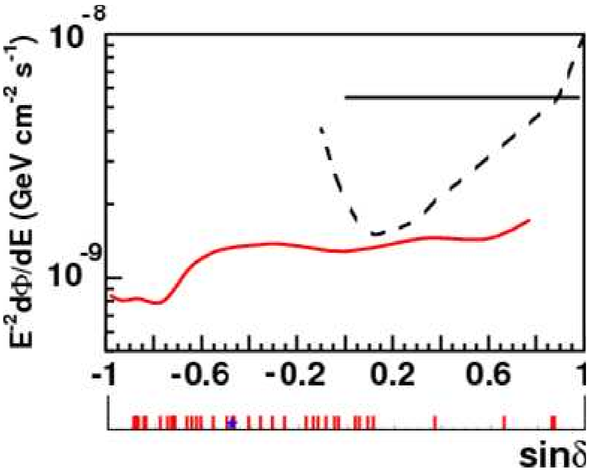

Figure 9: Sensitivity of the full KM3NeT neutrino telescope to point-like sources of neutrino emission with fluxes proportional to E_ν^{-2} as a function of declination δ (red line extending to $\delta = -90°$). The sensitivity is inferred from a binned analysis of simulation data. The vertical axis 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 [25]). 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.

In conclusion, the KM3NeT sensitivity to point-like sources with unbroken E_ν^{-2} flux is better than that of IceCube over a large fraction of the full sky (altogether about 3.5π steradians), by more than half an order of magnitude on average. This result would not be achievable with only one of the "building blocks", for which the effective areas are shown in Fig. 8. There is room for further improvement by optimising the event selection and reconstruction procedures or using unbinned analysis methods.

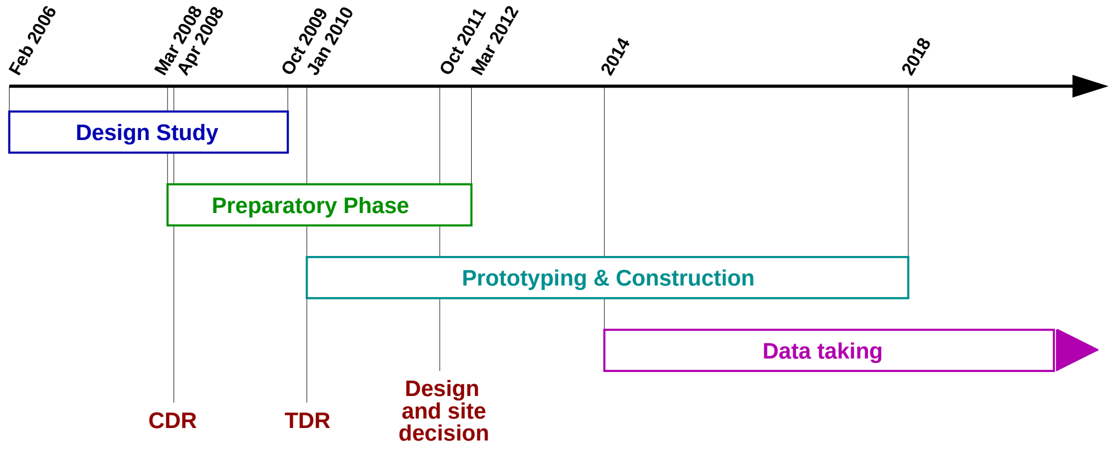

Figure 10: Time line of the KM3NeT project development towards construction and operation.

4. Project Development

The technical solutions described in this document, the results from the physics sensitivity studies and aspects of assembly, quality control and risk assessment will be published in the KM3NeT *Technical Design Report (TDR)* in the first months of 2010. The further work will be organised inside the FP7-funded KM3NeT Preparatory Phase project which will continue until February 2012.

As stated above, the decisions for specific technical solutions require further prototyping and field tests. A period of 18 months after TDR publication 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 to host the project. 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. The exact knowledge of these parameters is a prerequisite for devising the final technical design.

Once these decisions have been taken, the final technical design of the KM3NeT Research Infrastructure will be laid down in a detailed proposal which will become available versus the end of the Preparatory Phase. 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 deployed and connected to shore. 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.

The projected KM3NeT time lines towards construction and operation are indicated in Fig. 10.

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