Status of the KM3NeT Project ⋆

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Abstract

KM3NeT is a future research infrastructure in the Mediterranean Sea, hosting a cubic-kilometre scale neutrino telescope and nodes for associated sciences such as marine biology, oceanology and geophysics. The status of the KM3NeT project and the progress made in the EU-funded Design Study is reviewed. Some physics studies indicating the sensitivity of the KM3NeT neutrino telescope are highlighted and selected major technical design options to be further pursued are described. Finally, the remaining steps towards construction of KM3NeT will be discussed. This document reflects the status of the KM3NeT *Conceptual Design Report (CDR)*, which has been presented to the public for the first time at the VLVnT08 Workshop.

Key words: neutrino telescopes, neutrino astronomy, astroparticle physics, light detection, deep-sea technology, research infrastructures, marine sciences
PACS: 07.05.-t, 07.07.Df, 13.15.+g, 91.50.-r, 95.35.+d, 95.55.Vj, 95.85.Ry, 98.70.Sa

1. Introduction

The objective to detect high-energy neutrinos from astrophysical sources and thus to open a completely new window to understanding the most violent processes in the Universe has long driven the development of neutrino telescopes, i.e. arrays of photo multiplier tubes (PMTs) buried deeply in transparent media such as ice or water to detect the Cherenkov light emitted by secondary particles produced in neutrino reactions.

Currently, three such installations are taking data: The Baikal experiment [1] in the homonymous lake in Siberia, ANTARES [2] in the Mediterranean Sea and IceCube [3] at the South Pole. Whereas the first two are first-generation projects with typical instrumented volumes of the order $0.01\,\mathrm{km}^3$, IceCube will comprise roughly $1\,\mathrm{km}^3$ after its completion in 2011. There are many good reasons to assume that this is the minimum size required to exploit the scientific potential of neutrino astronomy. The KM3NeT neutrino telescope targets to exceed IceCube in sensitivity by a substantial factor, exploiting the superior optical properties of sea water as compared to the Antarctic ice and an increased overall photocathode area. Its technical design is subject of the ongoing KM3NeT Design Study; the resulting Conceptual Design Report (CDR) [4] forms the basis for this write-up.

A deep-sea neutrino telescope with its infrastructure also provides scientific opportunities to a wide range of earth and marine sciences, in particular for performing long-term real-time deep-sea measurements. The KM3NeT research infrastructure will therefore also contain nodes for instruments of these *associated sciences* and will become a major element in a wide network of deep-sea observatories.

⋆ Supported by the EU under contracts no. 011937 (FP6 Design Study) and 212525 (FP7 Preparatory Phase).

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2. Sensitivity of the KM3NeT neutrino telescope

In this section the physics sensitivity of the KM3NeT neutrino telescope will be discussed. Since there is still a variety of viable design options, the corresponding simulation studies are rather generic, both concerning the assumed neutrino fluxes and the detector properties. Nevertheless, investigations of various detector geometries and designs indicate that the results presented below are "stable" in the sense that they depend mostly on global parameters, such as overall photocathode area times quantum efficiency, and less on design details.

2.1. *Target neutrino sources*

The central physics goal of a neutrino telescope is to detect neutrinos of extraterrestric origin with energies above about 100 GeV. The experimentally accessible quantities to be measured are the neutrino direction, energy and flavour and its time of arrival. These measurements target different types of astrophysical neutrino sources, which can be generically classified as follows:

- Steady point sources yield a time-invariant (or very slowly varying) flux of neutrinos, typically assumed to have a power law energy spectrum with a cutoff in the 10 TeV to 1 PeV region. Such fluxes are expected to originate both from galactic (e.g. supernova remnants) and extragalactic (e.g. active galactic nuclei) sources. Their detection requires a precise direction measurement (target resolution: 0.1° at neutrino energies above 30 TeV) to suppress the background from neutrinos produced by cosmic-ray interactions in the atmosphere (*atmospheric neutrinos*) and a moderate energy measurement to apply energy cuts in the event selection procedure. The "golden channel" for point sources are reactions of the type [2] $\nu_\mu N \rightarrow \mu X$, where the muon traverses up to several kilometres of water and can be precisely measured.

  Note that some candidate point sources in fact exceed the expected point spread function in angular size. This applies e.g. to Galactic shell-type supernova remnants, but also to possible neutrino emissions [5] from extended regions near the Galactic Centre and the Crab region, from which Milagro has observed high-energy gamma rays [6].
- Transient point sources are coupled to flares of high-energy radiation, in particular from gamma ray bursts (GRBs). The detection of such sources again requires a decent direction measurement, and in addition relies on coincidences in time with observations by other detectors, such as satellite-borne gamma ray instruments. A corresponding global alert system (GRB Coordination Network, GCN [7]) is in place. A twofold coincidence in time and direction would reduce the background expectation to almost zero and thus also allow for applying source-stacking methods.
- The diffuse neutrino flux is formed by neutrinos from sources that are not individually resolvable, plus those coming from cosmic-ray interactions with the radiation fields in the Universe (most notably the so-called GZK neutrinos from proton reactions with photons of the cosmic microwave background). Since the diffuse flux is assumed to be isotropic, it has to be identified by its energy spectrum which is expected to be much harder than that of the atmospheric neutrino background. For these measurements, a decent energy resolution (target: 0.3 in $\log(E_\nu)$) is therefore mandatory, whereas directional information is less important. Also neutrino interactions without a final-state muon, i.e. $\nu_e N \rightarrow eX$, $\nu_\tau N \rightarrow \tau X$ or $\nu_x N \rightarrow \nu_x X$, will thus yield important information, provided a good energy reconstruction of the resulting hadronic and/or electromagnetic showers can be achieved.

The neutrino energy range of central interest is roughly $1-100$ TeV, which is the relevant interval for point source searches. Of course any neutrino telescope optimised for this energy range will also yield substantial sensitivity to lower energies. For higher energies, one has to take into account the shielding of the neutrinos by the Earth; beyond about 100 TeV, sensitivity to horizontal and downward-going neutrinos is required. It is a KM3NeT design goal that in this energy domain the directional sensitivity is only limited by neutrino absorption in the Earth.

Several further physics questions to be addressed by the KM3NeT neutrino telescope, such as investigations of neutrino properties, flavour composition and cross sections, searches for exotica like magnetic monopoles, nuclearites or strangelets, or tomography of the Earth will not be discussed in this document.

[2] No distinction is made in the following between neutrinos and antineutrinos, unless explicitly stated otherwise.

2.2. *Configuration studies and the reference detector*

Assuming generic isotropic neutrino fluxes with energy spectrum $\propto E^{-2}$, the sensitivity of various detector configurations has been investigated in simulation studies [8] by assessing the effective neutrino area and the achievable angular resolution. Both the geometry of the array of *optical modules (OMs)* and the assumed OM design have been varied; more details can be found in [9]. Overall, it was concluded that there is no configuration that is superior over the full energy range. Geometries with separated clusters of high OM density have advantages at low energies, while e.g. ring-like geometries are better suited for higher energies. Homogeneous configurations offer a compromise between these options. Clearly, the final configuration will have to result from an optimisation process taking into account the physics priorities.

In order to achieve consistent and directly comparable results, simulation studies for KM3NeT have been performed using the following homogeneous *reference detector configuration*: A rectangular grid of 15×15 vertical detection units, each carrying 37 OMs with 21 3″ PMTs each (see also Sect. 3.2). In an OM, the PMTs are arranged such that they roughly cover the downward-looking hemisphere. The horizontal distances between adjacent detection units is 95 m, the vertical distance between adjacent OMs is 15.5 m. Note that this selection of a reference configuration does not imply any design decision.

2.3. *Sensitivity estimates*

The simulated sensitivity of the reference detector to point sources and to a diffuse neutrino flux, both assumed to have E^{-2} neutrino energy spectra, is shown in Fig. 1 and Fig. 2, respectively. For details on the simulation study see [9]. Note that the sensitivity estimates depend strongly on the assumptions made for the event selection. In the studies presented here, events were required to pass standard trigger conditions and to be successfully reconstructed with modified ANTARES software, with a muon direction error below 5°.

The significant difference between the estimated KM3NeT sensitivities and those of IceCube has two major components: First, the product of overall photocathode area and quantum efficiency assumed for KM3NeT exceeds that of IceCube by more than a factor of 2; second, the muon angular resolution in sea water is much better than in the polar ice, where light scattering is stronger. For point source searches both effects accumulate, whereas angular resolution is of minor impact for diffuse flux measurements.

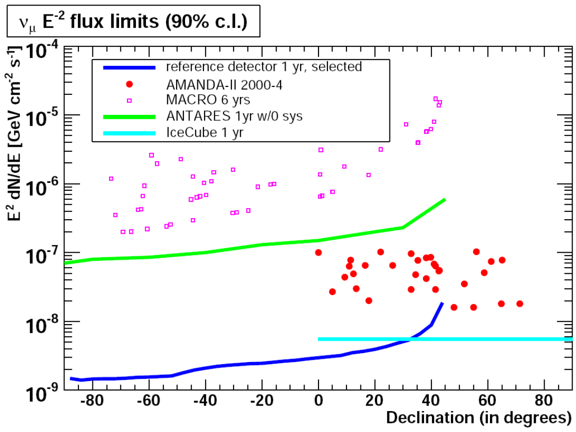

Figure 1. Average flux limit for point sources vs. declination achievable with the KM3NeT reference detector within one year of operation, calculated for ν_μ events (lower solid line). For comparison, the experimental results from AMANDA (filled dots) and MACRO (open squares) for searches for signals from specific source candidates are plotted together with expected limits from the ANTARES (upper solid line) and IceCube (solid line at positive declinations) neutrino telescopes.

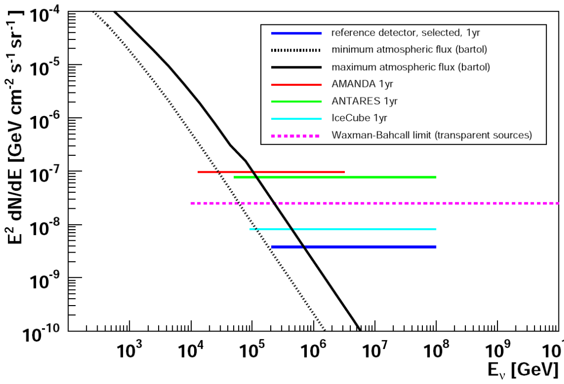

Figure 2. Average diffuse flux limit achievable with the KM3NeT reference detector within one year of operation, calculated from ν_μ events (lowest horizontal line). Also plotted are the experimental upper limits from the IceCube, ANTARES and AMANDA detectors, all scaled to one year of data taking (other horizontal lines, from bottom to top). The horizontal dashed line shows the theoretical Waxman-Bahcall limit, the curves falling with E indicate the band of atmospheric neutrino flux expectations.

Further studies have been performed to assess e.g. the potential signals from Galactic sources with TeV gamma ray emission [10], from blazars and from gamma ray bursters (see [4] and references therein). The general conclusion is that the KM3NeT neutrino telescope in the reference configuration will have good chances to detect signals from these source classes, albeit with limited statistics.

It may be interesting to note that KM3NeT, in spite of the random light background from K40 decays and bioluminescence, may have a significant sensitivity to SN1987a-type supernova neutrino bursts in our Galaxy, i.e. for distances below about 10 kpc [11].

3. Technical design options

Four sources contribute significantly to the design options under consideration for the KM3NeT research infrastructure: (i) the solutions used in the pilot projects (ANTARES, NEMO, NESTOR) and, where applicable, in the Baikal, AMANDA and IceCube experiments; (ii) new or enhanced approaches developed in the KM3NeT Design Study; (iii) deep-sea technology from the field of marine sciences (e.g. junction boxes); (iv) industrial solutions. Based on this pool of options, a set of preferred solutions expected to be suited for a cost-effective design is described in the CDR [4]. In the following, some selected aspects are described in some detail, whereas other issues are presented summarily.

3.1. *Design goals*

KM3NeT is foreseen to be a long-term observatory, with at least 10 years of operation without major maintenance operations; the construction should take no longer than 4 years. The objective is to achieve optimal sensitivity in the neutrino energy range of about 1 TeV to 1 PeV, and full acceptance for neutrinos originating from directions up to at least 10° above the horizontal.

The neutrino telescope design will be physics-driven, i.e. the technical requirements must match the physics objectives. In order to set viable "boundary conditions", a set of such physics-based design goals is defined, as given in Tab. 1.

The requirements on timing and position resolution ensure that the neutrino direction resolution is only limited by the irreducible contributions coming from the average neutrino-muon scattering angle and light dispersion in the sea water. The charge dynamic range is particularly important for reconstructing showers (see Sect. 2.1). The two-hit time separation is required to improve background separation, whereas the coincidence and dark noise demands aim at optimising trigger efficiencies and reducing background contaminations.

Table 1
Design goals for the KM3NeT neutrino telescope. Resolutions are given as RMS values.

Overall single-photon time resolution	< 2 ns
Position resolution of OMs	< 40 cm
Charge dynamic range	≈ 100 photo-electrons/25 ns
Two-hit time separation	< 25 ns
Two-photon coincidences	efficiency $> 50\%$; purity dominated by random coincidences of marine background light
Dark noise rate	$< 20\%$ of K40 rate
OM failure rate	$< 10\%$ over 10 years without major maintenance

3.2. *Photo-sensors and optical modules*

The detection of the Cherenkov light requires the use of PMTs, enclosed in glass spheres that withstand the static pressure of several hundred bar. Whereas most of the current neutrino telescope projects use OMs composed of a single large (typically 10″) standard PMT per sphere, alternative solutions are also under investigation for KM3NeT. The four main options are:

(i) The "classical" solution described above.
(ii) Several smaller (3″ or 3.5″) PMTs per sphere (see Fig. 3). This approach increases significantly the overall photocathode area per OM and gives a very good separation between one- and multi-photon hits.
(iii) Large PMTs with segmented anode and a mirror system between glass sphere and PMT to achieve directional sensitivity. It has been demonstrated that the use of this directional information in the reconstruction increases the efficiency significantly at neutrino energies of the order of a TeV and below.
(iv) Large spherical hybrid PMTs (X-HPDs) operated at typically 20 kV, where the photoelectrons are accelerated to a scintillator anode that is read out by a standard photomultiplier (see Fig. 4). A similar device is used in the Baikal experiment [12]. The advantages are

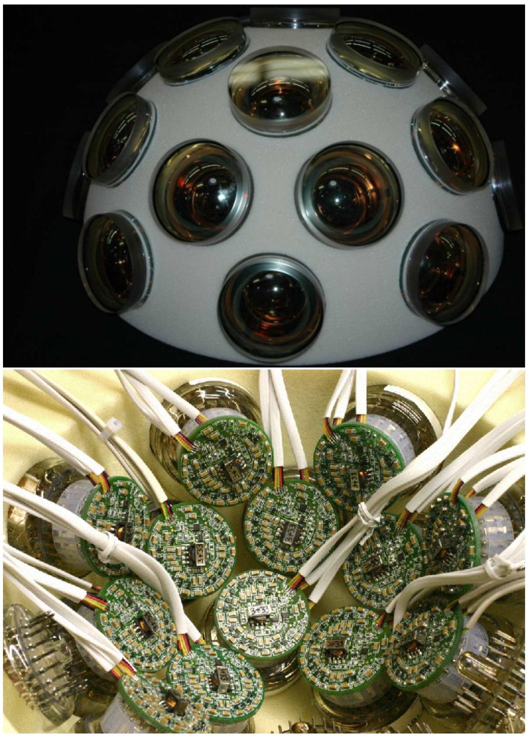

Figure 3. Prototype of a multi-PMT OM with 20 3″ PMTs. The upper picture shows the PMTs in their Styrofoam support, the bottom one the high-voltage supplies and cables for testing purposes.

increased quantum efficiency (since a photon crossing the spherical bulb has two chances to interact with the photocathode) and a superb charge resolution. However, it is not clear whether the R&D time-line for X-HPDs matches the KM3NeT schedule.

Note that trigger conditions – applied online on shore – are usually based on local coincidences, i.e. the recognition of two or more photon hits in the typical readout time window of 25 ns. In case of standard large PMTs, this requires local clusters of at least two OMs since the limited charge resolution does not allow for a clean separation between signals of one or two photo-electrons in one PMT. The multi-PMT and the X-HPD solutions avoid this constraint.

Recently, two major manufacturers of PMTs, Hamamatsu and Photonis, have announced the development of new photocathodes with strongly increased quantum efficiency. Figure 5 shows the improvement over the current standard; the Photonis results are at least as promising. The use of PMTs with this new technique could increase the KM3NeT sensitivity per Euro by a substantial factor. However, issues like operation stability and availability of large numbers of PMTs remain to be investigated. It is e.g. unclear whether large PMTs with the new photocathode will be mass-produced in time for KM3NeT construction.

Figure 4. 8″ prototype of a spherical X-HPD tube. The development of tubes with diameters up to 15″ is planned.

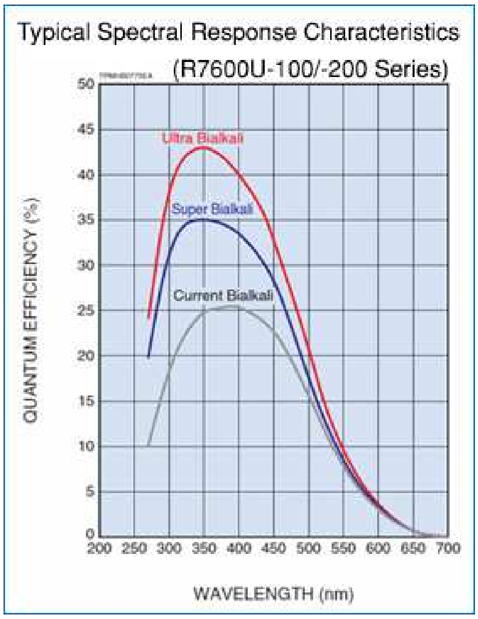

Figure 5. Spectral quantum efficiency of different types of bi-alkali photocathodes provided by Hamamatsu. The lower line shows the current standard, the upper lines are for two improved photocathode types. Figure taken from `http://www.hamamatsu.com`.

3.3. *Data acquisition and information technology*

The basic tasks of the data acquisition is to collect the analogue signals of the photomultipliers and store them on shore in a format suited for data analysis. The central strategic approach in this is to reduce the required off-shore equipment to the necessary minimum, so as to avoid frequent difficult and expensive maintenance operations. As an immediate consequence, no off-shore triggering or filtering involving signals from more than one OM is foreseen, i.e. all OM signals passing certain OM-internal criteria (e.g. a charge threshold) are sent to shore (*all-data-to-shore* concept).

Different options exist for the front-end interface (including digitisation) between the PMTs and the signal transport, and for the transport itself. Whereas overall data rates and distance to shore make the use of optical fibres obligatory for the transport along the sea bed, both optical and electrical solutions may be viable for the vertical transport along the detection units and in substructures thereof.

The overall data rate sent to shore will be of the order 100 Gb/s. On shore, a computer farm will perform the online filtering to reduce this rate by about 5 orders of magnitude. Provision will be made to store the full data temporarily for a sufficiently long period to apply specialised selection algorithms retroactively after external or internal alerts, e.g. on GRBs or supernovae.

3.4. *Mechanical structures and deployment*

Two major questions are: (i) How to support the OMs mechanically; (ii) How to deploy the resulting objects to the sea bed and connect them to shore. Both questions are intimately interrelated and must be addressed in conjunction. Major design criteria are cost, reliability and transportability. Three different strategies, evolving from the pilot project solutions, are under consideration:

(i) Extended, rigid horizontal structures (e.g. NESTOR-like “floors” [13] with diameter up to 120 m) forming towers. The floors are assembled at sea surface and subsequently lowered into the water. Specialised vessels are required for this operation (see below). The advantage of this solution is the reduction of wet-matable connections which are expensive and failure-prone.

(ii) Flexible structures with horizontal extent, e.g. 15 m-long bars as in NEMO [14]. These detection units are foreseen to be deployed in a compact configuration and to unfurl under the buoyancy of a buoy at their top after reaching the sea bed. The advantage is to deploy a three-dimensional array of OMs in one operation – thus also reducing the number of wet connections – and to avoid constraints imposed by sea-surface assembly work.

(iii) “Strings”, i.e. vertical cables carrying storeys of one or several OMs. Also here, deployment in a compact configuration and subsequent unfurling either using buoyancy or operation from surface is foreseen. One approach under study is based on a cable consisting of an oil-filled hose in equipressure with the sea water, with optical fibres and power leads inside. The mechanical and power/data transmission functionalities are thus separated.

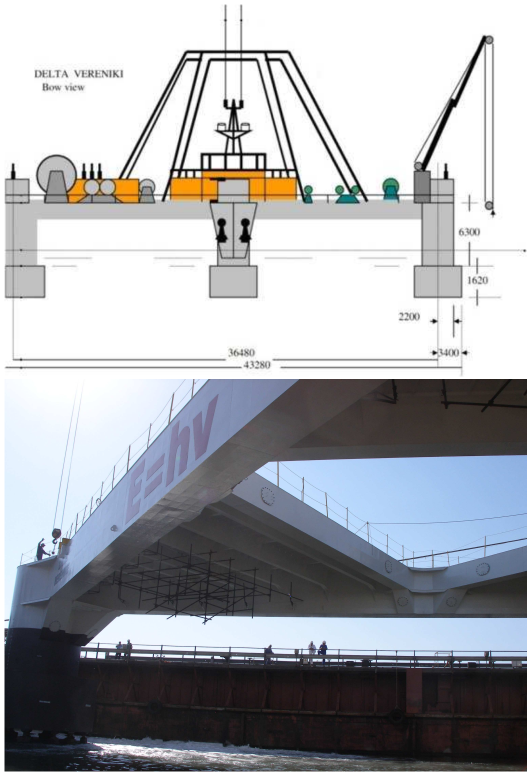

Figure 6. Schematic bow view of the Delta-Berenike platform (top) and photograph from the final stage of construction work (bottom).

For the deployment, either ships or specialised platforms can be used, depending on the character of the work to be performed at the deployment site.

For the flexible, compactified mechanical solutions deployment operations with ships of opportunity might be envisaged. Heave-compensated platforms such as the custom-designed Greek Delta-Berenike (see Fig. 6) are an alternative option in these cases and a necessity for deploying large rigid structures.

3.5. *Deep-sea and shore infrastructure*

The deep-sea infrastructure consists of one or several main electro-optical cables connecting the shore station to the deep-sea detector site, junction boxes serving as fan-outs to secondary cables (possibly in a hierarchy of several levels), connectors between these elements and the detection units, and the deep-sea equipment required for operation and maintenance.

The cable network must be able to provide about 50 kW of electrical power to the detector and to sustain the data rate of altogether 100 Gb/s (see Sect. 3.3). Options under investigation are AC or DC power transmission, with return lead or sea return. Suitable cables and connectors are available from industry, where they are mass-produced mainly for telecommunication and off-shore oil production purposes. However, compliance with industrial standards may impose stringent constraints on design parameters such as the number of optical fibres or copper leads per cable.

Junction boxes, typically also equipped with transformers and data network elements, are expected to be custom-designed for KM3NeT, possibly building on the experience of the marine science communities (see e.g. [15]). An approach developed in the NEMO project is to separate the corrosion and mechanical protection functionalities by using a pressure-resistant steel vessel immersed in an oil-filled fibreglass container in equipressure with the sea water (see Fig. 7).

The construction of the neutrino telescope will require deep-sea operations to construct the cable network and to connect the detection units to the junction boxes. Such operations can be performed with submersibles, *remotely operated vehicles (ROVs)* and/or *autonomous undersea vehicles (AUVs)*. Suitable ROVs are commercially available for all depths under consideration. Combined AUV/ROV systems are being developed in other projects and will be considered for KM3NeT.

On-shore, infrastructure is required for housing the computing equipment (in particular for the on-line filter), for data transport to mass storage sites, for storing detector elements, for preparing sea operations and for servicing the corresponding equipment. An option under consideration is to exploit the favourable Mediterranean wind/sun conditions for power production for KM3NeT.

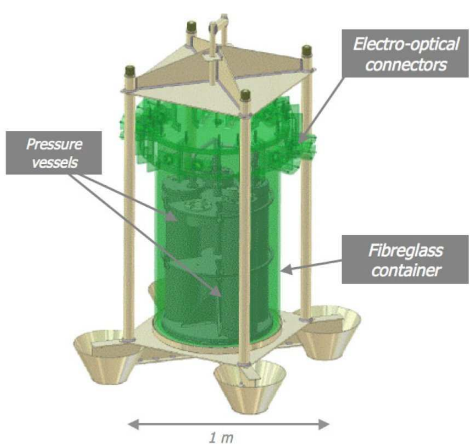

Figure 7. Junction box as used in the NEMO project.

3.6. *Calibration*

It is required to constantly survey the positions of the OMs to guarantee precise event reconstruction results. Precise measurements of the travel times of acoustic signals between transponders on the sea floor and receivers at the detection units will be used to infer the OM positions by triangulation. This method has been proven by ANTARES to work within the required specifications.

For the absolute pointing calibration, both a procedure based on depth and position measurement of the detection unit sockets (via pressure sensors and acoustic positioning coupled to GPS on the sea surface) and the use of auxiliary detectors for coincident measurements of cosmic-ray induced atmospheric showers on surface and in the deep sea are being considered. A corresponding surface detector could be operated temporarily on one or several ships or platforms.

Finally, the PMTs have to be synchronised to nanosecond precision. This will require the survey of delays in the electronics components and the data transmission by sending suitable calibration pulses from the coast to the photosensors and measuring their travel times. In addition, depending on the choice of the PMTs, transit time monitoring by optical light flashes (LEDs, lasers) may be required.

3.7. *Marine science infrastructure*

The KM3NeT infrastructure will also provide interfaces for associated science instrumentation. It is foreseen that such devices are installed both in the neutrino telescope volume, where they are symbiotically used both for monitoring the environment and for marine sciences (e.g. measurements of sea currents or of bioluminescence activity using the PMTs), and in dedicated marine science nodes at some distance to the neutrino telescope to avoid adverse interferences due to light or sound emissions. A schematic view of the associated science infrastructure is shown in Fig. 8.

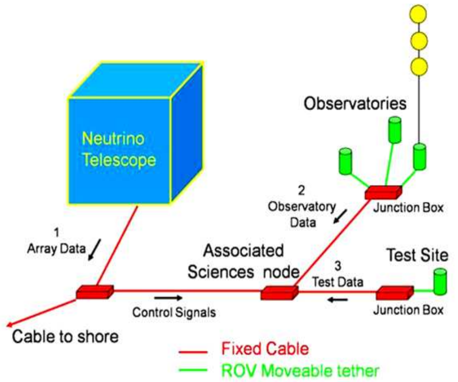

Figure 8. Schematic view of the associated science infrastructure in KM3NeT.

4. Towards KM3NeT construction

In the ongoing Design Study (EU FP6), the design of the KM3NeT research infrastructure will be worked out and described in the *Technical Design Report (TDR)* by the end of 2009. In parallel, since March 2008, a 3-year KM3NeT *Preparatory Phase* project (KM3NeT-PP, EU FP7) addresses the political, funding, governance and strategic issues that need to be settled before the start of construction. Also included in KM3NeT-PP is technical work to continue from the TDR with prototyping and system test activities.

It is envisaged that by the end of the Preparatory Phase funding for KM3NeT will be established. The current budget estimate is 220–250 M€. Already now there are substantial commitments, e.g. from Greece and Italy, even though these are subject to mutually exclusive site conditions. Three suitable candidate sites for KM3NeT have been extensively explored by the pilot projects: off the French Mediterranean coast near Toulon (depth 2500 m), off the Sicilian east coast near Capo Passero (3500 m) and off the west cost of the Peloponnesus near Pylos (different locations at 4500 – 5200 m). The site decision will require scientific (e.g. water quality, bioluminescence background), technological (implications of depth and distance to shore) and political considerations.

The timeline for KM3NeT is presented in Fig. 9.

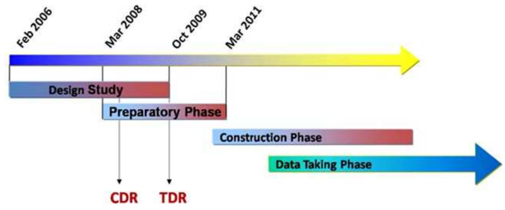

Figure 9. Timelines for KM3NeT. The final full-scale prototyping is included in the construction phase.

Acknowledgements

The KM3NeT project is supported by the EU in FP6 under contract no. 011937 and in FP7 under contract no. 212525. The author wishes to thank the VLVnT08 organisers for their hospitality and a very inspiring workshop.

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