The Neutrino Telescope of the KM3NeT Deep-Sea Research Infrastructure

R. Lahmann* 

Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

Abstract

KM3NeT is a future deep-sea research infrastructure in the Mediterranean Sea that will hold a multi-cubic-kilometre neutrino telescope. Located in the northern hemisphere, KM3NeT will be able to observe point-like sources of cosmic neutrinos in a region of the sky that includes the Galactic Centre. The KM3NeT neutrino telescope will employ a number of innovative technologies that are the main subject of this article. It is planned to install optical modules of 17 inch diameter that will contain 31 photomultiplier tubes each. Triggered data will be digitised off-shore. The optical modules will be installed on horizontal bar structures of about 6 m length. Twenty of these structures will be stacked to form a vertical tower, interconnected by ropes at 40 m distances. Fundamental to achieving the required pointing position for neutrino astronomy is the knowledge of the relative positions of the photomultiplier within 20 cm. Accordingly, a time synchronisation on the nanosecond level is required to reconstruct the Cherenkov cones of charged particles produced in neutrino interactions. To calibrate the complete timing in situ, LED beacons, integrated into the optical modules, and laser beacons installed on the sea floor will be used. To calibrate the positions of the optical modules on the towers, a system of acoustic transceivers at fixed positions on the sea floor and receivers along the towers will be used. Data transmission is done over a fibre optic network employing multiplexing of up to 80 wavelength over individual fibres.

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1. Introduction

High-energy neutrino astronomy is dedicated to the search for neutrinos from outside the Solar System. The established technology for the detection of neutrinos is the measurement of Cherenkov light emitted along the tracks of relativistic secondary particles generated in neutrino interactions in ice or water. Cherenkov neutrino telescopes are optimised to reconstruct the tracks of muons produced in the interaction of muon neutrinos; their detection threshold of several tens of GeV is a convenient definition of the energy threshold for “high-energy” neutrinos. High-energy neutrinos detected on Earth are of two different origins: First, atmospheric neutrinos that are mainly produced in the decay of pions and kaons emerging from reactions of cosmic rays or gamma-rays in the upper atmosphere; second, astrophysical neutrinos that originate

*for the KM3NeT Consortium

Email address: lahmann@physik.uni-erlangen.de (R. Lahmann)
from either galactic or extra-galactic processes. Existing neutrino telescopes (NT200+ in Lake Baikal [1], ANTARES [2] in the Mediterranean Sea and IceCube [3] at the South Pole) are routinely reconstructing muon tracks from the interactions of atmospheric muon neutrinos. Cosmic rays and gamma-rays, which have been observed over wide energy ranges on Earth, are thought to be accompanied by the production of neutrinos at their sources. However, no experimental evidence for the existence of such high-energy neutrinos originating from outside of the Solar System has yet been found.

Besides neutrinos, atmospheric muons are produced in the interactions of cosmic rays and gamma-rays in the atmosphere. These muons are abundant and pose a substantial background in the search for muons from neutrino interactions. In order to remove this background, neutrino telescopes are using the Earth as a shield, looking for “upgoing” tracks from interactions of neutrinos having traversed the Earth. The Galactic Centre, which contains many sources of high energy photons, is within the field of view of a neutrino telescope in the Mediterranean Sea during a large portion of the day. Observations of this region are a prime objective for the KM3NeT detector, the future cubic-kilometre scale neutrino telescope network to be built as a part of a deep-sea research infrastructure at the bottom of the Mediterranean Sea. Its central physics goal is the investigation of neutrino point sources in the energy regime of $1 - 100$ TeV. The neutrino telescope will complement the field of view of the IceCube detector and will be big enough to substantially exceed its sensitivity. In addition to supporting the neutrino telescope, the infrastructure will provide a node for Earth and marine sciences, allowing for continuous deep-sea measurements.

2. Design Criteria and Implementation

The KM3NeT project started with a design study that lasted from February 2006 until October 2009, in which the proposed deep-sea research infrastructure was described first in a conceptual design report [4] and then in a technical design report [5]. The prime objective of the preparatory phase, which started in March 2008, is to find solutions to remaining open political and scientific points and to prepare rapid and efficient construction of the KM3NeT infrastructure once approved. With the preparatory phase lasting until March 2012, the project has by now entered the prototyping and construction phase.

From an engineering point of view, the objective of the KM3NeT project is the installation and support of a three-dimensional array of photomultiplier tubes (PMTs) and their connection to shore in a cost-efficient and reliable fashion. The communication between the off-shore detector and the shore station comprises the transfer of data, power supply, and a slow control system. The mechanical structures involved must be easy to deploy with the construction time for the complete infrastructure not exceeding five years. As construction is ongoing, a sea floor and shore infrastructure will be installed to accommodate operation with the partially completed detector—a concept that has been employed successfully for previous experiments such as ANTARES and IceCube. Once completed, the operation of the infrastructure shall proceed over a period of at least ten years without major maintenance.

The installation and operation of the array will take place in one of the most adverse places for a technical installation. The environment imposes the following conditions and technical challenges:

- High pressure (~200 bar at 2 km depth) and salt water as a highly corrosive environment;
- Long distance from shore for communication;
- Forces on structures due to sea currents;
- Relative position of PMTs has to be known with 20 cm precision at any time to achieve the required pointing precision for neutrino astronomy;
- Wet-mateable connectors required for the installation.

Further difficulties for the goal of reconstructing muon tracks are posed by background due to the natural processes of $^{40}$K decay, Cherenkov radiation from downgoing muons and bioluminescence. Given the scale and the technical challenges of the project, all decisions needed careful evaluation and consideration. Meanwhile for most design criteria, unique or preferred solutions have been agreed upon, several of which will be presented in this article.
One of the most crucial decisions is the choice of the site for the installations. Long-term site characterisation measurements have been performed as part of the design study at three different locations: Offshore of Toulon (ANTARES site), Capo Passero (NEMO [6] site) and the Pylos area (NESTOR [7] site). The currently preferred solution is an infrastructure of networked KM3NeT nodes at different sites. This solution is supported by the finding that the efficiency of the detector beyond a given volume is optimised by increasing the surface area. While a track length of about 1 km within the instrumented volume is required to optimise the resolution of the track reconstruction, the resolution does not improve anymore for tracks exceeding that length [8]. On the other hand, for high energy neutrinos the detection rate is proportional to the product of the muon track length and the surface area of the telescope projected into the plane orthogonal to the track. Hence the most efficient design is to construct the KM3NeT neutrino telescope of a number of physically separated “building blocks”. These will be discussed in the next section.

3. Detector Layout

Each KM3NeT building block, together with its shore infrastructure, is a fully functional neutrino detector on its own. A minimum of two building blocks are foreseen, each comprising a primary junction box (PJB), from which a main electro-optical cable establishes the connection to shore. From the PJB, through a number of secondary junction boxes (SJBs), the signal and power lines are fanned out to the “Detection Units” (DUs). The DUs are vertical structures supporting PMTs, anchored to the sea floor and held taut by submerged buoys. During the preparatory phase, DUs with a design as shown in Fig. 1, denoted as towers, have been chosen as the optimal solution. Each tower consists of 20 “storeys”, see Fig. 1(b), where each storey is a bar structure of about 6 m length, with an optical module attached to each end. The optical modules will be described in Sec. 4. Bars are rotated in the horizontal plane by 90° for alternating storeys, adjacent storeys are held in place by four 5 mm Dyneema® ropes at an inter-storey distance of 40 m. With 100 m distance of the lowermost storey from the sea floor, the topmost storey of each tower is at a height of 860 m. Two electro-optical cables run the entire unfurled height of the structure.

For the deployment, a full tower is brought as a single package to the sea floor. The buoy is released and the storeys are drawn from the package one-by-one. During the process, the ropes are held taut by unwinding them from braked synchronised drums. The readout cables are stored, spiralled around two of the ropes. An unfurling tower is shown in Fig. 1(a).

The currently considered option for a building block comprises 154 towers and has the footprint of a “randomised hexagonal grid” in which distances between neighbouring towers are on average 180 m, varying at a level of 20 m. The random variations of the inter-tower distances reduce symmetries and therefore help to resolve tracking ambiguities. Such a building block has an instrumented volume of about 3 km³ and a surface area of about 4.2 km². Recently, smaller building blocks have been considered [8] of which a larger number could be installed.
4. Optical Modules

Each optical module contains a total of 31 PMTs with 3 inch (76 mm) diameter (19 in the lower and 12 in the upper hemisphere), mounted inside a standard deep-sea glass sphere of 17 inch (432 mm) outer diameter. The PMTs are held in place by a foam support and an optical gel fills the space between the glass sphere and the photocathode of each PMT. All electronics is housed within the sphere and data are digitised before transmission to shore, a feature which has established the expression “digital optical module” (DOM) for these modules. A custom-designed low power (< 45mW) Cockroft-Walton base [9] provides an adjustable high voltage from 800 to 1400 V. A single penetrator provides access to the DOM for optical fibres and electric wires. A photograph of a DOM is shown in Fig. 2(a). The advantage of the multi-PMT design is a good single- vs. multi-photon hit separation, where single hits are most likely the result of $^{40}$K background while multi-photon hits most likely stem from muon tracks.

An additional advantage of the design is the large photocathode area per optical module. The photon collection area of the 3 inch PMTs is further extended by the use of a bevelled reflective aluminium collar, the “expansion cone”. It consists of an aluminium ring filled with optical gel. Measurements of reflectivity under various angles of incidence indicate an increase in collection efficiency by 30% on average for angles of incidence from $-50^\circ$ to $+45^\circ$ w.r.t. a line parallel to the PMT axis. The maximum of 35% gain in efficiency is reached for perpendicular incidence [10]. Ray-tracing simulations allow for an estimate of the increase in the overall sensitivity, integrated over all angles of incidence, by 27% [10]. A PMT with and without expansion cone is shown in Fig. 2(b). The effect of the expansion cone on the collection efficiency is shown in Fig. 3.

Specifications for the PMTs result from the specific conditions present in the Mediterranean Sea. The Cherenkov photon spectrum in the Mediterranean Sea is most intense between $\sim 400$ nm and $\sim 500$ nm [11]; hence the requirements for the quantum efficiency (QE) of the PMTs is specified at 404 nm and 470 nm, where it has to exceed 32% and 20%, respectively. Over a distance of 50 m, travelled in the Mediterranean Sea by photons with a spectrum of Cherenkov light, chromatic dispersion introduces a time spread with $\sigma \approx 2$ ns [5]. From this, the relatively loose requirements for the transit time spread (TTS) of $\sigma \lesssim 2$ ns is derived.

Hit triggering is done by the time-over-threshold method, i.e. by defining a threshold for the analogue signal from the PMT and measuring the time for which the signal is above that threshold. For this purpose, the PMT base is equipped with an ASIC [12] comprising a comparator whose level can be set through an I²C control line. A preamplifier stage in the ASIC allows for the operation of the PMT at a low gain, which is specified at $5 \times 10^6$.

To digitise the time the signal is above the threshold, two options are investigated. In the most straight
forward case, the signal is digitised by a TDC whose digital output is fed into an FPGA\(^1\). The FPGA is used to handle the readout of the data from the DOM, but it is not yet clear if it can provide the “time stamping” of the signals with the required precision of about a nanosecond or better. If not, a dedicated ASIC, the so-called SCOTT\(^2\)-chip, will be used instead of the TDC. The SCOTT-chip will then digitise and time-stamp the analogue data before submitting them for further processing to the FPGA.

Furthermore, each DOM will be equipped with calibration devices: In addition to the components required for acoustic positioning (see Sec. 6) and time calibration (see Sec. 7), a tilt meter and a compass, measuring the orientation w.r.t. the Earth’s magnetic field, will be installed.

### 5. Fibre Optic Network

Data transmission and communication with the shore station will be done using optical fibres and a system of continuous wave lasers installed on-shore. The available bandwidth must allow for point-to-point transmission (i.e. each DOM has its dedicated channel to shore) and for the realisation of the “all data to shore” concept. The latter implies that all triggered data from the photomultipliers will be sent to shore where a dedicated computer farm will perform further triggering and hit selection.

In order to minimise the number of fibre connections required between the off-shore part of the detector and the shore station, the Dense Wavelength Division Multiplexing (DWDM) technique will be employed. With this technology, a number of wavelengths (colours) can be superimposed on the same fibre. In KM3NeT it is planned to multiplex 80 wavelengths per fibre according to the ITU\(^3\) grid specifications. According to these specifications\(^4\), KM3NeT will operate in the C (1530-1570 nm) and L (1570-1610 nm) bands with 25 GHz separation between colours. For the KM3NeT data rate and its data structure, a bit rate capacity of 1 Gbps per fibre will be sufficient.

A schematic diagram demonstrating the operating mode of the optical network is shown in Fig. 4. For the communication from the shore station to the DUs, an electric signal (denoted by ‘e’ in the figure) is modulated only upon one wavelength. In the primary junction box (PJB) all wavelengths transmitted in the fibre are modulated with this information (box ‘o\(\backslash\)e’ in the figure). Hence the system operates in a broadcast mode, where the timing information required for synchronisation is part of the information flow.

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\(^1\)Field Programmable Gate Array
\(^2\)Sampler of Comparator Outputs with Time Tagging
\(^3\)International Telecommunication Union, [http://www.itu.int](http://www.itu.int)
In the PJB, the multiplexed signals are fanned out to the SJBs, where they are split into four groups of 20 wavelengths each. Each group of wavelengths is then routed to an optical fanout module (OFM) at the foot of the DU where the wavelengths are demultiplexed and sent over individual fibres to the same number of DOMs.

To increase the efficiency and reduce costs, in the DU a single fibre with bidirectional communication is used. In each DOM a small portion of the wavelength is directed to an APD (Avalanche Photo Diode) for the incoming information and the other part to the REAM (Reflective Electro-Absorption Modulator) for the outgoing data. The 80 returning signals from 2 DUs are multiplexed onto one fibre in the SJB and routed via the PJB to shore.

In order to establish a relative timing calibration between DOMs on a nanosecond level, the latency of both the transmission path to and from each DOM needs to be measured separately in situ. For this purpose, a pulsed signal can be sent over either path and reflected in the DOM. This way the difference between the times of emission and reception can be measured with an accuracy of better than 50 ps.

6. Acoustic Position Calibration System

The towers of the KM3NeT detector are free to sway with twist in the undersea current with an expected displacement of up to 150 m at the top for sea currents reaching 30 cm per second [8]. In order to determine the relative positions of the storeys with a precision of not worse than 20 cm the detector will be equipped with an acoustic positioning system. The system employs acoustic transceivers at the sea floor and acoustic receivers (hydrophones) in each storey. By performing multiple time delay measurements and using these to triangulate the positions of the individual hydrophones, the hydrophone positions can be reconstructed relative to the positions of the emitters. With acoustic receivers installed at both ends of each storey, its orientation can be determined, providing redundancy for the measurements of the compass and tilt meter installed in each DOM. Reliable, low-power and cost-efficient emitters operating in the range 20 – 40 kHz are under development [13].

The KM3NeT positioning system is based on experience of the systems developed for ANTARES see [14, 15] and references therein. Sampling will be done at about 200 k samples per second and all data will be written to shore. This way, algorithms for the position calibration, running on an on-shore computer farm, can be adapted to in-situ conditions that may affect the shape of the received signal. Furthermore, the data can be used for additional analyses, such as acoustic detection of neutrinos, see e.g. [16] and references therein, or marine science investigations.
Two types of acoustic sensors, both based on the piezo-electric effect, are currently tested. First, standard hydrophones, i.e. a piezo ceramic and preamplifier coated with polyurethane for high pressure water tightness. Second, a compact unit of piezo ceramic and preamplifier, glued to the inside of the glass sphere of the DOM near its “South Pole”. This design has been tested in the AMADEUS [17] project within the ANTARES detector. The advantages w.r.t. to standard hydrophones are lower costs and a reduction of the number of failure points: No additional cables and junctions are required and the sensor is not exposed to the aggressive environmental conditions. Disadvantageous on the other hand is a reduced angular acceptance and the vulnerability of the system to electric interferences with the PMTs in the same sphere. A prototype Detection Unit planned to be deployed in 2012 will contain both types of sensors and will allow for a design decision for KM3NeT.

7. Optical Time Calibration System

Time calibration can be established on an absolute scale, w.r.t. UTC\textsuperscript{5}, with a precision of 110 ns, which is well below the time variability of any conceivable astrophysics process observed through a neutrino signal [5]. More challenging is the relative time calibration between hits in different DOMs of the detector. Given the uncertainties from the TTS ($\sigma \approx 2$ ns), chromatic dispersion ($\sigma \approx 2$ ns) and electronics ($\sigma \approx 0.5$ ns), the relative timing has to be established on the level of a nanosecond. Knowing latencies of signals travelling within the optical network (see Sec. 5) relative time calibration can be done by emitting a light signal at a known time for known positions of emitter and receiver (i.e. a DOM) and recording the arrival time.

The proposed optical calibration system for KM3NeT [18] builds upon the experience with the ANTARES system [19], employing LED beacons and laser beacons. The former are intended for calibration within a tower (intra-DU), whereas the latter will be used for inter-DU calibration. As LED beacons, so-called “nano-beacons” will be employed. These are single LEDs, one mounted inside each DOM at an angle of 30\degree from the vertical axis, where effects of bio-fouling should be small. Light is emitted into the upward direction. As each LED can illuminate the DOMs of several storeys above, the system provides a high redundancy. The LEDs are inexpensive using a simple, robust technology. Several LED models with wavelengths around 470 nm are currently investigated.

The inter-DU calibration will be done with Nd-YAG lasers operating at a frequency of 532 nm. The lasers will be installed at fixed positions, presumably at the anchor of some DUs or at the secondary junction boxes, and emit short (<1 ns), high intensity pulses of light. The intensity is tunable by a liquid crystal optical attenuator. A dedicated device has to be employed to diffuse the collimated laser beam for reception over a large solid angle. Laser beacons are expensive but only about 15 to 20 per building block are required. The inter-DU calibration allows for cross-checks with the positioning system and for a relative time calibration of DOMs in different DUs where time synchronisation of the emitted pulse is not crucial.

\textsuperscript{5}Coordinated Universal Time
8. Summary and Conclusions

The major technical design decisions for the KM3NeT neutrino telescope, such as the design of the Optical Modules and their arrangement in vertical structures, the Detection Units, have been taken. An optical fibre network has been designed for data transmission and timing on the nanosecond scale. Calibration systems are under development. The in-situ operation of a prototype Detection Unit is planned for 2012.

The footprint of the KM3NeT detector is being optimised for detection of Galactic sources; an infrastructure of networked KM3NeT nodes is the most likely scenario. Data taking could start as early as 2014.

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