Time calibration and positioning for KM3NeT

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Abstract

In this contribution we review the concepts put forward for the time calibration and positioning systems of the future KM3NeT neutrino telescope in the Mediterranean Sea. Even though the final layout of the detector, its mechanical structures and the light detection technologies to be used are not yet defined, much progress has been made in clarifying the possible technologies available for calibration and positioning. Concerning time calibration, we review the different concepts proposed, namely *Optical Beacons* (LED and Laser), fibres or copper cables, ^{40}K, and a pre-deployment calibration. For positioning, the use of acoustic signals with lower frequency components in combination with cheaper hydrophones than in ANTARES is being investigated. The need and use of compasses and tiltmeters is strongly correlated to the mechanical structure chosen. For absolute positioning several methods are being considered. In the following, the solutions proposed in the KM3NeT Conceptual Design Report (CDR)[1] are discussed.

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1. Introduction

Building on the experience gained on neutrino detection with the pilot projects ANTARES, NEMO and NESTOR, the three collaborations have joined efforts to develop, construct and operate a km^3-scale neutrino telescope, KM3NeT, in the Mediterranean Sea.

The neutrino detection is based on the measurement of the Čerenkov light induced by the muons produced by neutrino interactions with matter in or around the detector. The Čerenkov radiation emitted by the muons can be measured by using sensitive optical detectors like photomultiplier tubes (PMTs). The muon track, and therefore the neutrino direction ($E_\nu > 1$ TeV), can be reconstructed from the arrival time of the Čerenkov photons at the PMTs, knowing the optical sensor positions. The quality of the reconstruction thus depends on the timing and position resolutions.

Monte Carlo studies show that a total instrumental time resolution of 3 ns is enough to reach an angular resolution better than 0.1°. This corresponds to a PMT and electronics resolution better than 2

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ns and a positioning precision better than 40 cm.

2. The timing calibration systems

The experience gained in previous experiments shows that a relative timing calibration at the 1 ns level can be achieved. To determine the absolute and the relative time between the Optical Modules (OMs) that contain the optical sensors, several complementary time calibration systems are under study.

2.1. *Relative timing*

- *LED Beacons*. Commercial LEDs can be pulsed using a dedicated circuit to generate nanosecond-scale flashes which directly illuminate the PMTs. This technique is used in both *intra-line* (on same line) and *inter-line* (on different lines) calibration in ANTARES [2] via optical beacons made up of several LEDs (Fig.1). In order to ensure that the light pulses are coincident for all LEDs, a synchronization of the LEDs emission times ($\sim$ 20 ps) is required which constitutes the main drawback of this system. Alternatively, recent investigations focus on the identification of more powerful LEDs which will reduce the number of LEDs required in a single device, as well as on the development of different pulsing circuits.

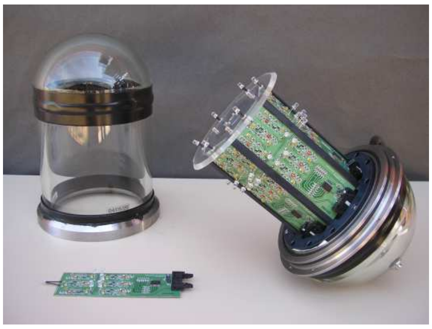

Fig. 1. The ANTARES LED Optical Beacons with its container. Six faces each containing six LEDs are arranged on a hexagonal cylinder.

To simplify and reduce the cost of the calibration system, the possibility of decoupling the intra-line and the inter-line calibration is currently under study. A very simple system, made of one only LED housed inside the OM and pointing upwards, could be used to make the relative timing between the OMs in the same line, while a more sophisticated system could be used to perform the calibration of a few "strategic" OMs needed for the relative timing between lines.
- *Laser Beacons*. Lasers, as those used in the ANTARES optical beacon system [2], produce high intensity pulses ($\sim 1\ \mu$J) of short duration (below 800 ps of FWHM). They emit a collimated beam with a not-tuneable intensity. In the final design of the ANTARES Laser Beacon a dispersion device and a voltage-controlled optical attenuator were included in order to control the intensity.
- *^{40}K coincidences*. Underwater neutrino telescopes are subject to an environmental background due to the β-decay of the ^{40}K isotope present in the oceanic salt. The Čerenkov light produced by the emitted electron usually reaches only one OM. However, as experienced in ANTARES, some detector configurations will enable the light to be observed by two different PMTs simultaneously. The coincidence rate of these desintegrations can be used to validate the time calibration results of a more sophisticated system.
- *Optical Fibres*. Optical fibres are used to lead the light coming from an optical pulser towards the OMs. The approach based on LED pulsers has been developed inside the NEMO collaboration, whereas the solution adopted in the IceCube detector uses lasers as the source emitters. An important issue is that this system requires to accurately determine the path length of the fibres.

Solutions that facilitate in-situ timing calibration are of paramount importance for the continuous monitoring of timing calibration constants. Prior to the deployment of the detector, however, a *pre-deployment* calibration in a dedicated *dark-room* is foreseen after the integration of the structure, in order to measure the initial timing calibration constants. This will require calibration test benches to be built at the sites where final construction and assembly will take place.

2.2. *Absolute timing*

Whilst the primary requirement for timing calibration hardware for KM3NeT is to determine the relative timing between PMTs, it is also necessary to accurately determine the *absolute* timing of the events. In particular, this is crucial when requiring the observation of a high-energy neutrino to be synchronized with, for instance, a transient astrophysical source. Time-stamping at the milli-second accuracy is enough to study any conceivable transient astrophysical object and this is easily achievable with commercially available GPS units.

3. The position calibration systems

Since the optical sensors of the neutrino telescope are attached to non-rigid structures, they are subject to undersea currents that can displace them by up to several metres. For an accurate muon reconstruction, a real-time measurement of the PMT positions is needed with an accuracy better than 40 cm (equivalent to 2 ns).

3.1. *Acoustic and tilt-meter/compass system*

The requirements of the positioning system strongly depend on the given mechanical structure that will hold the PMTs. Two possible systems can be envisaged to provide the necessary information.

- *A Long BaseLine acoustic system* (LBL) gives the 3D position of hydrophones placed along the structure. It is done by triangulation from the measurements of the travel times of acoustic pulses between the emitters, fixed on the sea bed, and the receiving hydrophones. Based on the experience of the ANTARES acoustic positioning system [3], a precision on acoustic distance measurements of ~ 2 cm and an accuracy on the 3D hydrophones spatial positions better than 5 cm can be achieved.
- *A Tilt-meter/compass system* gives the local tilt angles of each detection unit with respect to the horizontal plane (pitch and roll) as well as its orientation with respect to the Earth Magnetic North (heading). Complementary to the acoustic positioning system, tiltmeters and compasses are necessary for the shape reconstruction of the structure as well as for measuring the optical module orientations.

Using this information as input for a 3D mechanical model, the detection unit shape is reconstructed taking into account the weight and drag coefficients of all the elements in the unit. This kind of system has been successfully used both in ANTARES and NEMO.

A possibility to reduce the cost of the acoustic positioning system with respect to the ANTARES one would be to substantially reduce the number of acoustic emitters-receivers, i.e. triangulating over longer distances. This would imply the use of lower sound frequencies, and, therefore, a worsening in the time and positioning resolutions would be expected. Pulse compression signals are being studied in order to compensate this effect and improve the resolution [4].

An alternative approach to reduce the unit cost of the system has been proposed consisting in attaching ceramic piezoelectric transducers inside to the OM containing the optical sensor [5].

Additional measurements of the water currents and the sound velocity in sea water are needed in order to apply the aforementioned methods. The design of calibration lines equipped with dedicated instrumentation (Acoustic Doppler Current Profiler, Conductivity-Temperature-Depth sensors, Sound Velocimeter) is foreseen to this end.

4. Absolute orientation system

In order to observe celestial objects and compare the results with other experiments an absolute positioning and pointing calibration are required. Three different systems have been proposed to provide such calibrations.

4.1. *Acoustic method*

The position determination is based on the precise measurements of the geographical coordinates (x,y, in the UTM grid system) and the depth z of the acoustic transducers fixed on the anchors of the detection units. To measure the geographical coordinates, a surface boat, equipped with an acoustic transducer, determines its own position with a GPS/Galileo receiver and the distance to a given deep-sea transducer by sound transit time. This measurement gives the absolute azimuth of the detector with an accuracy of $\sim 0.02°$.

On the other hand, the depth is measured by a pressure sensor located in the anchor of the detection unit which can be verified by the measurement from a *Remote Operated Vehicle* (ROV) equipped with an accurate pressure sensor. Furthermore, the temperature and salinity profiles are performed on the same day to get the pressure-depth relationship. The measurement gives the tilt of the detector with

an accuracy of ∼ 0.01°.
A combination of these measurements gives an absolute pointing accuracy for the neutrino telescope better than ∼ 0.03°.

4.2. *Sea Surface Detector*

The method based on the HELYCON design [6] employs cosmic ray induced showers that contain muons of sufficient energy (E_μ >2 TeV) to reach the undersea detector. A Monte Carlo study has been performed to quantify the calibration capabilities of three autonomous detector arrays on floating platforms (4000 m above the telescope) at distances of 150 m from each other. The direction of the shower axis (reconstructed for the surface detector) is compared with the direction of the muon reconstructed in the underwater telescope (Fig.2). An absolute pointing accuracy of ∼ 0.05° is reachable with this method in ten days of data taking.

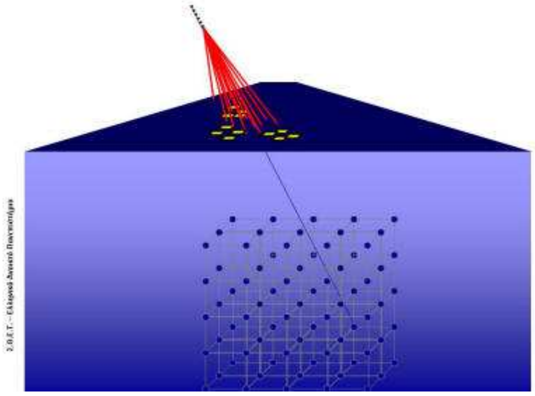

Fig. 2. Artistic view of the HELYCON stations. The floating array has been proposed as a calibration infrastructure for the KM3NeT neutrino telescope

The absolute position of the detector can be estimated by measuring the distance between the impact points of the reconstructed muon track and the shower axis. The accuracy is better than 1 m within a ten day data taking period.

4.3. *Moon shadow*

A verification of the detector angular resolution and its absolute position can be performed by looking at the "Moon Shadow" in the reconstructed downgoing muon tracks [7]. Since the Moon absorbs cosmic rays, a lack of atmospheric muons from the direction of the Moon disk (angular radius $R_{Moon} = 0.26°$) is expected.
NEMO simulation studies indicate that a 3σ effect can be observed in less than one year of data taking with a km^3 apparatus [8].

5. Conclusions

Following the success of the first generation neutrino experiments the three collaborations ANTARES, NEMO and NESTOR have formed the KM3NeT consortium to study the construction of a cubic kilometre-scale neutrino telescope in the Mediterranean Sea.
In order to achieve an angular resolution of 0.1° at $E > 10$ TeV several calibration systems have been proposed inside the collaboration, and the experiences based on the pilot projects have been evaluated to implement new ideas and to study the feasibility for KM3NeT. All these systems are within the guidelines of the KM3NeT CDR, recently presented by the collaboration. The culmination of the current studies on these systems will provide the basis for the design of the final calibration system in the Technical Design Report, containing the technical specifications for the future KM3NeT infrastructure.

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