TIPP 2011 - Technology and Instrumentation for Particle Physics 2011

Time Calibration of the KM3NeT Neutrino Telescope

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Abstract
KM3NeT is a future deep-sea Research Infrastructure hosting a cubic kilometer-scale neutrino telescope and facilities for marine and earth sciences in the Mediterranean Sea. The consortium is made up of 40 institutes from 10 European countries, and includes all the groups that have developed the pilot projects, ANTARES, NEMO and NESTOR. The KM3NeT telescope will consist of a three-dimensional array of optical modules arranged on vertical detection units (DUs), anchored to the sea floor and held in tension by submerged buoys. The time resolution of this detector has to be known with great accuracy since the angular resolution of the track reconstruction depends on the accurate measurement of the relative arrival times of Cherenkov photons reaching the photon sensors. The intrinsic, unavoidable limitation in time resolution (chromatic dispersion and PMT transit time spread) imply that the calibration system of a water-based neutrino telescope must provide a precision at the nanosecond level. The experience with the ANTARES deep sea neutrino telescope has shown that a distributed system of external light sources illuminating the photon detectors with short (∼5ns FWHM) time-referenced light flashes is very useful to ensure the time calibration of the detector and to measure water optical properties. Whilst the basic timing calibration concept applied in ANTARES will be retained, the larger spacing between photo-detectors required in a cubic-kilometer-scale detector results in modified requirements for the KM3NeT system. A three-dimensional system of optical emitters has been studied: several LED models have been tested, and four models preselected as suitable for use in KM3NeT were incorporated into ANTARES for in-situ testing. Based on the resulting data, several LED beacons will be integrated in the forthcoming deployment of a pre-production KM3NeT detection unit planned for autumn 2011. The design, optimization and construction of the KM3NeT optical time calibration devices are described.

Keywords: Time calibration, Neutrino Telescopes, KM3NeT

1. Introduction

Time calibration is a key element in the performance of very large volume neutrino telescopes. The angular resolution of the reconstructed tracks depends on the accurate measurement of the arrival time of Cherenkov photons reaching the photon sensors. Water-based neutrino telescopes have intrinsic and unavoidable limitations in the time
precision as the chromatic dispersion and scattering of light in water (\(\sigma \sim 2\) ns for a traveling distance of 50 m), and the combined effect of the photomultiplier (PMT) transit time spread and electronics (\(\sigma \sim 1.5\) ns). Taking into account these intrinsic limitations, the required precision of a time calibration system to measure the relative time between photo-sensors should be \(\sigma \leq 1\) ns. Experience has shown that a system of external sources is very useful to ensure the time calibration of the detector and to measure water optical properties. Pulse light emitters (beacons) have been successfully used in ANTARES to measure in situ relative time offsets between Optical Modules (OMs). LEDs and lasers located throughout the detector produce short duration and powerful light pulses which are detected by the photo-sensors, allowing the measurement of the time delay between the arrival of the photon to the photocathode and the time stamping in the front-end electronics. Whilst the basic timing calibration concept applied in ANTARES remains applicable, the larger spacing between Detection Units (DUs) of photo detectors required in a cubic kilometer scale detector results in different requirements for a KM3NeT system.

2. The KM3NeT neutrino telescope

The KM3NeT Consortium aims to construct a deep sea research facility at the bottom of the Mediterranean Sea, which will house a neutrino detector of cubic kilometer scale (in Fig 1 a conceptual view is shown).

![Figure 1: The KM3NeT detector concept - the MultiPMT optical module sphere and Detection Unit mechanics.](image)

The detector will consist of a three-dimensional array of several thousand PMTs, enabling the detection of muons induced by high energy cosmic neutrinos. In order to reach an angular resolution better than 0.1° for energies above 100 TeV, high quality positioning and timing calibration are required.

The mechanical structure of the detection unit is a semi-rigid system composed of a sequence of horizontal elements (storeys) interlinked by a system of tensioning ropes arranged to force each storey to a position perpendicular to its vertical neighbours. The DU is anchored on the seabed. A buoy located on each storey to provide the unfurling force and to help keep the structure under tension in the deep sea currents.

Actually the pre-production model of the multi-PMT Digital Optical Module (DOM) is in progress (Figure 2): the objective of the DOM is to measure photons at a single photon level. The DOM is designed to reduce the number of connectors in the telescope as much as possible. The equivalent of the DOM consists of a 17 inch diameter pressure resistant glass sphere with in total 31 photomultipliers (PMTs) of 3 inch diameter. The PMTs are suspended in a foam support structure: 19 in the lower hemisphere and 12 in the upper hemisphere. The photon collection area of the PMTs are extended by the use of a bevelled reflective aluminum collar, the expansion cone.

3. The calibration system

The angular resolution of the track reconstruction of a neutrino telescope depends on the accurate measurement of the arrival time of the Cherenkov photons reaching the photon sensors. For this reason an optimized optical calibration system for KM3NeT is proposed. In order to simplify the system and at the same time to reduce the costs,
an optical system decoupling the intra/inter DU calibration and based on pulsed light sources, LEDs and lasers has been designed (see in Figure 3 the optical calibration devices). Devices performing intra-DU time calibration allow determination of the time offsets between the optical modules of the same DU: based on the idea of the ANTARES LED optical beacons, a system made of nanobeacons, devices containing a small number of LEDs pointing upwards, will be mounted in the inner surface of the optical modules (see details in Figure 2).

Conversely, global time offsets between DUs can be determined by means of powerful lasers located at the bottom of several DUs or in a different position (between DUs) on the sea floor: in this way these laser beacons will permit relative calibration between several OMs of different DUs. In fact, lasers anchored to the seabed provide a common reference with a fixed position, representing a useful monitor for possible DU movements and allowing for cross-checks within the positioning system [3].

3.1. The Laser beacons

The laser is housed in a cylindrical titanium container. The bottom end-cap holds the penetrator of the power supply and the cable connectors. Inside the container, the laser and the associated electronics are held by an aluminum inner frame. The laser beam leaves the container through an opening in the top end-cap.

This opening is equipped with an anti-biofouling system consisting of a flat disk diffuser that spreads the light beam out following a Lambertian distribution and a quartz rod cylinder bonded to the upper surface of the diffuser. The light leaves the cylinder through its vertical wall where biofouling is negligible. A voltage-controlled optical attenuator consisting of a liquid crystal retarder and a linear polarizing beam-splitter cube allows the change of the light intensity emitted by the laser. The use of only one linear polarizer is possible due to the fact that the laser light is already linearly polarized. (The schematic view is shown in Fig. 4) The retarder is a Liquid Crystal Head (model LVR-100-532) [4] from Meadowlark Optics and the polarizer is a Broadband Beamsplitting Cube (model BB-050-VIS-B7669) [5]. Fig. 3 a) shows the final configuration of the optical variable attenuator, composed of a liquid crystal variable retarder and a single linear polarizer.

3.2. The Nanobeacons

The NanoBeacon is an optical device containing a small number of LEDs (one or two) mounted on a mechanical structure included inside the multi-PMT DOM, and pointing outwards to illuminate other OMs located on the same DU (Fig. 3 b ).
Figure 3: a) Laser beacon - mechanic structure, equipped with ROD cylinder, polarizer filter, laser source, control board and connectors. b) Nanobeacon - mechanical support, in which is integrated the LED, and the corresponding control board.

Figure 4: The scheme of the Laser setup, with details about the polarizer filter mechanism.

The main component of the NanoBeacon electronics (a general scheme is shown in Figure 5) is the pulser circuit that provides the electrical signal to enable the LED flashing. A PVC support offers the mechanical housing for the NanoBeacon pulser. The control electronics board provides the required voltage to set the flash intensity of the LED and the trigger signal, either from an external clock signal setting the trigger rate, or generated in the same board, by means of a I2C command that would set the trigger rate. The selection between both configurations is done with an I2C command.

3.2.1. In situ tests

Several LED models have been tested in the laboratory. According to the studies carried out in terms of amplitude and rise-time of the emitted pulses and angular distribution of light, four models were preselected as suitable to be used in the NanoBeacon device. In particular the CB26, CB30, AB87 LED models from the AVAGO Technologies [6] and the NSPB500S model, produced by MARL International Limited [7], have been chosen. Following the recovery and redeployment of ANTARES line 12, these new models were incorporated in the lowest of the LED Optical Beacon of the line and tested in-situ at a depth of 2500m (pressure 250 bar). Compared with the LED types used in ANTARES (CB15, from AVAGO), these new models are more powerful but have a smaller opening angle.
The ANTARES LED beacons were originally designed also to illuminate nearby lines, and the caps of the LEDs were machined off to widen the angular distribution of the light emitted. However, in a decoupled system in which the nanobeacons are used to illuminate only the floors in the same detection unit, a modified LED angular distribution is not necessary and uncleaved LEDs allow for longer ranges.

As shown in the plot of Figure 6, a comparison between the ANTARES LED and the four candidate LEDs for KM3NeT has been obtained. The plot shows the light relative intensity of each tested LED as a function of the distance: in this way it is possible determine the maximum reachable distance for each LED type. In both 1 photo electron (pe - 1 hit per flash), or in 0.1 pe level (0.1 hit per flash), the NSPB500 seems to be the better choice, with higher intensity and an attractive angular FWHM, it will be the candidate LED for KM3NeT.

4. Conclusions

To achieve the high angular resolution required by the KM3NeT Consortium, an accurate study to develop the time calibration systems has been performed, and an optimized system is proposed. The time calibration system designed for the new neutrino telescope will guarantee time resolution measurements at the nanosecond level. To simplify the system and reduce the cost, decoupling the intra-line and inter-line calibration has been proposed.
After a general introduction to the calibration systems designed for KM3NeT, the main features of the Laser Beacon and of the nanobeacon system have been described. The Laser beacon, based on the one used in ANTARES, has been improved: in particular a more powerful model will be installed equipped with the electronics; also the titanium container has been optimized. The nanobeacon, based on the ANTARES LED Optical Beacon design, uses short light pulses produced by blue LEDs to measure time differences between the optical modules of the detector. The system also makes it possible to monitor the influence of the water on the light propagation. First laboratory tests have been done, and later confirmed by in-situ test performed thanks to the ANTARES collaboration.

5. Acknowledgments

We gratefully acknowledge the support of Ministerio de Ciencia e Innovacion (MICINN), Grants FPU AP2008-00775, FPA2006-04277, FPA2009-13983-C02-01 and ACI2009-1020 and of the Generalitat Valenciana, Prometeo/2009/026. The work described in this paper is supported through the EU, FP6 Contract no. 011937 and FP7 grant agreement no. 212252

6. References