Time calibration system for the KM3NeT deep sea neutrino telescope

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Abstract. **In this contribution we review the time calibration system proposed for the future underwater KM3NeT neutrino telescope. Building on the experience gained with the pilot projects, ANTARES, NEMO and NESTOR, and the results in-situ from the ANTARES Optical Beacons, we propose a decoupled optical system, based on LEDs and lasers, to perform an *intra-line* and *inter-line* relative time calibration. The design of these devices and first feasibility studies are presented.**

Keywords: **Neutrino Telescope, Time calibration, Nanobeacon.**

I. INTRODUCTION

In the new era of neutrino astronomy three European collaborations, ANTARES [1], NEMO [2] and NESTOR [3], have joined efforts to develop, construct and operate a cubic kilometre-scale neutrino telescope, KM3NeT [4], in the deep Mediterranean Sea. KM3NeT will complement the sky coverage of IceCube [5] and will have an unsurpassed angular resolution, better than 0.1° at 100 TeV. The aim of this telescope is the detection of high-energy cosmic neutrinos using a 3-dimensional array of photomultipliers (PMTs) distributed on anchored structures. The PMTs detect the Cherenkov light emitted by muons from neutrino charged current interactions in the surrounding sea water and the rock below. The information provided by the number of photons detected and their arrival times is used to infer the neutrino track direction. The quality of the reconstructed track direction thus depends on the timing resolution and position accuracies of the PMTs. High angular resolution can be achieved if Cherenkov photons are detected with sufficient timing and positioning precision. In the following sections we discuss the time calibration system proposed for the KM3NeT neutrino telescope. Considerations of the intrinsic time uncertanties due to the transit time spread (TTS) in the PMTs, the electronics delay and the scattering and chromatic dispersion of light in sea water, lead to the conclusion that a relative time accuracy with a precision better than 2 ns (RMS) is needed.

II. THE TIME CALIBRATION SYSTEM

The time resolution of the detector has to be known with great accuracy since it impacts on the angular resolution. To ensure the desired angular resolution and a precise absolute pointing, a system is required that allows a relative and absolute timing calibration.

Two factors contibute to the relative time uncertanties in the timing of the optical sensors. The first is the TTS of the PMTs and the second comes from variation in the delays within the electronics. Different systems are under study to determine these contributions [6].

- *The internal clock calibration.* The system consists of a master clock that provides a common clock signal to many slave clocks. A designated calibration signal is distributed through the same clock system and returned by the slave clocks. The relative time offsets are measured on shore by recording the propagation delays of the calibration signal with respect to the original clock signal emission time. The master clock is also synchronised with respect to Universal Time by assigning the GPS timestamp to the data, to provide an absolute time with an accuracy better than 1 μs.

- *Transit Time calibration.* This system is used to calibrate the path travelled by the signal starting at the PMT photocathode up through read-out electronics. It can be achieved by using an LED pulser mounted close to the PMT and capable of illuminating the photocathode, or via an optical fibre illuminated with a laser or LED outside the OM.

- *Optical system calibration.* Experience with the previous projects has shown that a system of external sources is very useful to ensure the timing calibration of the detector and measure water optical parameters.

To simplify and reduce the cost a decoupled system based on optical devices, LEDs and lasers, has been proposed.

  - *Intra-line calibration.* The system determines the time offsets among optical modules (OMs) along the same vertical structure. Based on the idea of the ANTARES LOBs (LED Optical Beacons) [7], a system made of one LED housed inside the OMs, the *Nanobeacon*, and pointing upwards is under study. To ensure redundancy in the time calibration and optimise

the production line efficiency, the possibility to install one Nanobeacon in each OM is under study.

– *Inter-line calibration.* To determine the time offsets among vertical structures, calibration requires less redundancy. Side emitting sources (possibly lasers) in dedicated housings could be used to perform the calibration of a few strategic OMs. One or two Laser Beacon, installed at the bottom and/or central part of the vertical structures, could be used to illuminate the first floors of the lines.

III. THE NANOBEACON

The Nanobeacon will comprise a blue LED mounted in a mechanical structure to be included in the OM and pointing upwards to illuminate the upper floors. Geometrical considerations show that a $15°$ opening angle is sufficient to illuminate OMs above the beacon even in a perpendicular arrangment (i.e. the NEMO tower [8]), including allowance for potential misalignments smaller than $10°$.

The main component of the Nanobeacon electronics is the pulser that provides the electrical signal to enable the LED flash. A new circuit, alternative to the ANTARES solution, has been developed for KM3NeT. It offers at least as much light and does not require an external trigger. It operates nominally at 24 V, 25 kHz and requires only an on/off interface [9].

The total power consumption of the Nanobeacon will be known exactly when all the internal components are finalized but it is not expected to exceed 0.5 W.

The total number of devices to be installed will depend on the final detector geometry and vertical structure adopted.
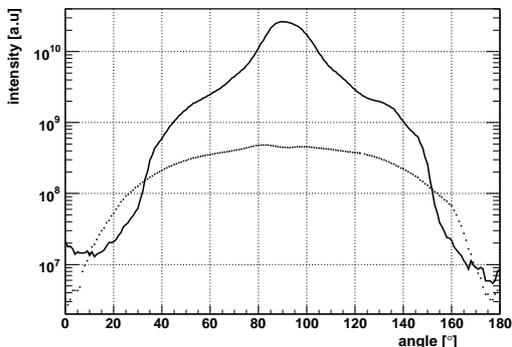

Fig. 1: Angular distribution of the non-cleaved HLMP-CB11 (continuous line) compared with the ANTARES (HLMP-CB15) cleaved LED (dotted line). The non-cleaved LED emits about 50 times more light than the cleaved one.

A. The LEDs

In-situ measurements from ANTARES have shown that an LED[1] emits optical pulses that can illuminate up to 200 meters with light enough to performe calibration. The ANTARES LOBs were originally designed to illuminate also nearby lines. To increase the angular occupancy of the light emitted by the LEDs, which was originally restricted to $15°$, the caps of the LEDs were machined off. Nevertheless, it has been shown that inter-line calibration with LEDs is more challenging due to movements of the lines and changes in the OM orientations.

However, in a decoupled system in which Nanobeacons are used just to illuminate the floors in the same line, the altered angular distribution of modified LEDs is not necessary and non-cleaved LEDs can be used. Fig. 1 shows the angular distribution in arbitrary units of one of the selected models (Avago HLMP-CB11) for KM3NeT (non-cleaved) compared with the ANTARES LED (cleaved). In the peak region (+/- $10°$) the non-cleaved is 1.5 orders of magnitude more powerful than the ANTARES one.

New LED models have been proposed for the KM3NeT time calibration system and tested in 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 have been pre-selected as the most suitable to be used in the Nanobeacon device. Following the recent recovery of ANTARES line 12 for refurbishment and redeployment, deployment of a new LOB with each of these models is planned for *in-situ* validation. In table I all the selected LEDs are reported together with their spectral and angular characteristics.

TABLE I: Characteristics of the four LED models preselected for the Nanobeacon. In the first columns is reported the LED model; the second and third columns show the spectral informations in nm; in the last column is reported the angular occupancy (FWHM) of the light in degree.

Model	λ [nm]	FWHM(λ) [nm]	FWHM [$°$]
Avago HLMP-CB30	472	40	28
Avago HLMP-CB11	470	25	14
Avago HLMP-AB87	470	30	14
NSPB520S	470	25	51

B. Electronics

The Nanobeacon electronics consists of two parts:

1) *The pulser.* In its default solution, based on the pulser of fig. 2, the LED intensity is controlled and can be varied with a voltage variable between 0 and 24 V. This circuit offers a very short rise time (< 2 ns) and equivalent or greater intensity than the ANTARES pulser.

In addition, a Voltage Controlled Oscillator (VCO)

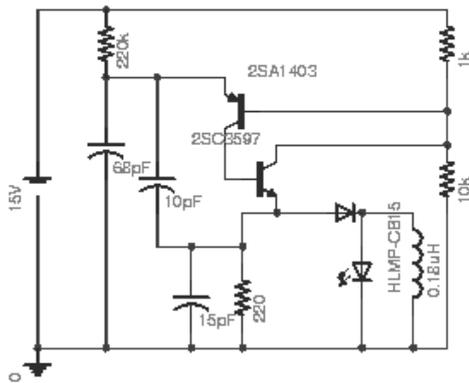[1]The LED model used in ANTARES LOB was the Agilent HLMP-CB15-RSC00

Fig. 2: Diagram of the LED pulser circuit, developed by the KM3NeT group at Sheffield University.

is under study, to offer the possibility of changing the frequency as well.

2) *The control electronics.* Since the supply voltage will be controlled from OM electronics, the Nanobeacon control electronics is highly dependent on the final OM design.

C. Mechanics

The main feature of the Nanobeacon mechanics is to hold the LED inside the OM and maintain correct pointing. The final design will depend on the solution adopted for the OM mechanics. Nevertheless, a preliminary version already exists (fig. 3) consisting of two independent pieces: a mechanical support for the LED and its pulser inserted in a cylinder designed to fix the Nanobeacon to the glass of the OM sphere.
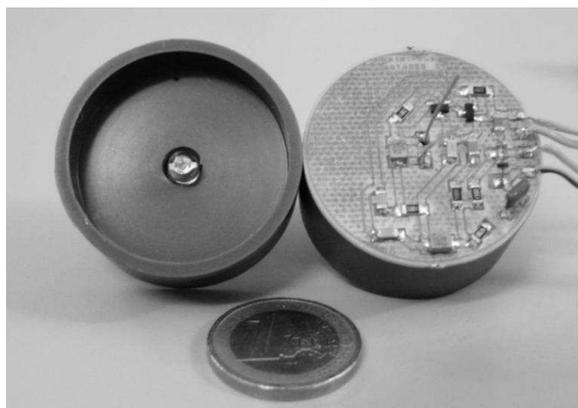

Fig. 3: Preliminary version of the mechanical structure supporting the LED of the Nanobeacon and its electronics.

IV. THE LASER BEACON

The system is based on the Laser Beacon used in ANTARES [7]. The Laser Beacon source is a diode pumped Q-switched Nd-YAG laser which produces very short light pulses, below 1 ns (FWHM), of high intensity

(~ 1 μJ) and at a wavelength of 532 nm. It can be is housed in a glass or titanium container and fixed at the bottom of few (central) vertical structures. The light emitted by the laser can be varied using a voltage controlled optical attenuator, a linear polarizer followed by a liquid-crystal retarder and a second linear polarizer. The polarization of output light can be changed through variation of the voltage applied to the retarder, varying the transmission of the attenuator. Since the light from the Laser Beacon is linearly polarized, the attenuation can be achieved with only one linear polarizer. The retarder is a Liquid Crystal Head (model LVR-100-532) [10] from Meadowlark Optics and the polarizer is a Broadband Beamsplitting Cubes (model BB-050-VIS-B7669) [11]. Fig. 4 shows the final configuration of the optical variable attenuator, composed of a liquid crysral variable retarder and a single linear polarizer.
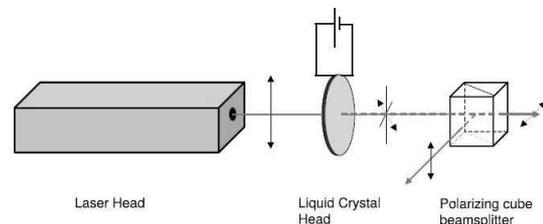

Fig. 4: Schematic view of the Variable Intensity Laser Beacon. The amount of outgoing light can be changed by varying the voltage applied to the liquid crystal retarder.

The possibility of using a laser emitting in the blue region (λ = 473 nm), where the light absorption length in water (about 60 m) is twice as long as in the green, is also under research. Its characteristics are summarized in table II.

TABLE II: Characteristics of the blue laser under study.

Average Power	20 mW
Rep Rate	1÷5 kHz (variable)
Pulse Energy	3μJ (min), 5μJ (typ)
Pulse duration	2.5 ns (+/- 15%)
Rise time	<1.5 ns

V. CONCLUSIONS

To achieve the high angular resolution required by the KM3NeT Consortium, a R&D study to develop different time calibration systems has been started. The time calibration system proposed for the new neutrino telescope will guarantee time resolution measurements at the nanosecond level.
To simplify the system and reduce the cost, the possibility of decoupling the intra-line and inter-line calibration has been proposed. After a general introduction to the different calibration systems under study, the main features of the Nanobeacon system have been described. This system, 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 are under way and in-situ validation is planned to verify the final design.

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