

Time calibration systems for the ANTARES Neutrino Telescope

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The ANTARES collaboration is deploying an underwater neutrino telescope in the Mediterranean Sea which consists of a tridimensional matrix of photomultipliers (PMTs). Muon neutrinos will be detected through the Cherenkov light induced by the muon produced in the neutrino interaction with matter. The muon track will be reconstructed using the available information given by the number of photons and their different arrival times at the PMTs. Other types of neutrino events will also be detected. Calibration is a key issue in the reconstruction of the muon tracks, therefore different calibration systems will be employed in the ANTARES telescope. In order to achieve the best possible pointing resolution for astronomy, an accuracy of $\sigma \sim 0.5$ ns in the relative time calibration among PMTs is desirable. Before the deployment of the strings this calibration is performed in a dedicated dark-room. Once in the sea, it will be achieved using an echo-based clock calibration system and pulses of light emitted by LEDs within the Optical Modules and Optical Beacons distributed along the strings. On the other hand, an absolute time calibration of around 1 ms will be sufficient for the correlation with all the interesting astrophysical sources.

1. Introduction

The ANTARES neutrino telescope [1] will consist of 12 strings, with 25 storeys each. A storey will hold three 10" photomultiplier tubes (PMTs) each one housed in a pressure-resistant glass sphere looking down-wards at 45° from the horizontal. This optical unit is called Optical Module (OM) [2], and contains also a pulsed LED for calibration purposes. ANTARES high pointing power is closely linked to the accuracy in the determination of the arrival times of the photons on the surface of the OMs. The relative time resolution (RTR) between OMs is, therefore, of an utter importance. The RTR will be limited by the transit time spread (TTS) of the signal in the PMTs ($\sigma \sim 1.3$ ns), and the optical properties of the seawater such as light scattering and chromatic dispersion [3] ($\sigma \sim 1.5$ ns at a distance of 40 meters). Therefore, all electronics and calibration systems are required to contribute less than 0.5 ns to the overall timing resolution if a good angular resolution is aimed.

Apart from the relative timing between OMs, an absolute time calibration, i.e. the detector's clock correlation with Universal Time, should be provided. An absolute time resolution of ~ 1 ms is required for correlations with respect to any conceivable physic phenomenon like gamma ray bursts, flares or supernova events.

2. Time Calibration systems

Different *in situ* timing calibrations are foreseen in the ANTARES telescope. These calibrations are performed by several systems:

1. The **internal clock** calibration system. A very precise time reference clock distribution system has been implemented in the ANTARES detector. This clock system uses an echo-based time calibration whereby the clock electronics is able to send a return signal through the same optical path as the outgoing clock signals. It consists of a 20 MHz clock generator on shore, a clock distribution system and a clock signal transceiver placed in the Local Control Modules (LCM) where the electronics of each storey is located. A common clock signal is provided to all the Analogue Ring Sampler (ARS) read-out chips of all the

OMs. Synchronized data commands can be superimposed on the clock signal, in particular *start* and *stop* commands, which together with a high precision Time to Digital Converter (TDC) are an essential component of the clock calibration system. This system allows to measure the time delay between storeys by recording the time delays of the return signals of each storey when the original clock signal reaches them. Another feature of this system is the synchronization with respect to the Universal Time by assigning the GPS time to the data.

2. The **internal Optical Module LEDs**. Inside each Optical Module there is a pulsed LED attached to the back of the PMT and capable to illuminate the photocathode from the inside. The blue LED is an HLMP-CB15 from Agilent whose peak intensity is at around 470 nm with a FWHM of 15 nm. These LEDs are used to measure the PMT transit time and dedicated runs of the LED calibration system are taken in the sea.
3. The **Optical Beacons**. The Optical Beacons will allow the relative time calibration by means of independent and well-controlled pulsed light sources. This calibration system will perform timing calibration including also the optical influence of the water which is an integral part of the detector. Two kinds of different but complementary beacons will be located throughout the detector: the LED beacons and the Laser beacons. There will be four LED beacon devices distributed regularly on every string. Each LED beacon contains 36 individual LEDs arranged in groups of six on six vertical boards (*faces*) which are placed side by side forming an hexagon. On each face, one LED points up-wards (*top LED*) and the other five sideways, with one of the latter in the middle of the face (*central LED*) and the remaining four surrounding it. Each of the six faces can be flashed independently or in combination with the others and within a face the top, central and group-of-four LEDs can be flashed independently or in combination. The 36 LEDs have been synchronized in the laboratory to better than 0.1 ns. The light pulse emitted by the LED beacons has a *risetime* of ~ 2.8 ns. The Laser beacon is a much powerful device that will be located at the bottom of some strings. It uses a diode pumped Q-switched Nd-YAG laser to produce pulses of $\sim 1 \mu\text{J}$ with a FWHM of ~ 0.8 ns at a wavelength of 532 nm. The beam is widened by a diffuser which spreads the light out to a cosine distribution, therefore, it is not designed to illuminate its own line. Figure 1 shows an example of an output light pulse from the LED beacon and the Laser beacon.

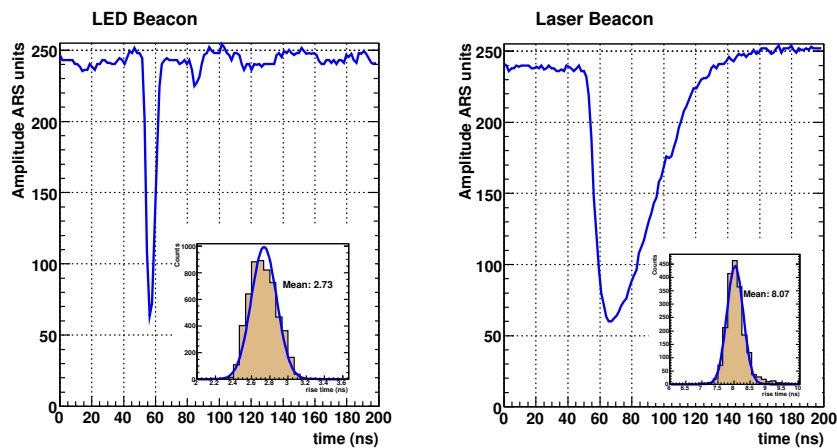


Figure 1. Example of a recording of an output light pulse from the LED beacon using the small internal PMT (left) and a Laser light pulse measured by its photodiode (right). Inserts show the corresponding *risetime* distributions.

4. The last calibration in the sea can be achieved using muon tracks. In the future it is expected that the several thousands down-going muons reconstructed per day in the detector will allow time alignment and calibration cross-checks.

Nevertheless, before the deployment of the strings, verification of the functionality of all string elements is performed in a dedicated dark room where a set of different but complementary timing calibration systems are also used. After integration of each sector of the line¹, the sector is tested in the dark room. An optical signal is sent to each OM of the storey. Such a signal is provided by a laser similar to the one used in the Laser beacon. It is a Nd-YAG solid state laser that emits intense and short light pulses. The light needs to be attenuated from a nominal value to a few photoelectrons before being sent to the OMs. The light is guided through an optical fiber to a 1-to-16 optical splitter located in the dark room. Fifteen of these signals are connected to all the 15 OMs of the sector. The 16th signal is sent to a reference control module that is used to relate the timing of the different sectors. The resulting information from timing calibration in the dark room is redundant, and will be used as a reference for the validation of the *in situ* timing calibrations. The verification of the response of the clock system is also performed in the dark room.

3. Time Calibration with the MILOM

Recently, the ANTARES collaboration has deployed a line called MILOM (Mini Instrumentation Line with Optical Modules). This line is a version of the instrumentation line planned in the TDR that contains several devices for monitoring and calibration purposes. A special feature of the version deployed is the inclusion of Optical Modules that allow to measure the RTR between OMs. The time calibration systems incorporated in the MILOM are the Optical Beacons, Optical Module LEDs and the Clock Calibration System.

- With the MILOM the **clock calibration system** has been fully proven in the sea environment for the first time. Figure 2 (left plot) shows the measured delay in the clock system within the MILOM between the bottom of the line and the top storey. The histogram (right plot) gives the calibration inside the MILOM indicating a time resolution $\sigma \sim 0.01$ ns well within the specifications.
- Dedicated runs using the **internal LED calibration system** have been taken during the MILOM operation. The flashes emitted by the LED are controlled by means of the clock system. The LED trigger pulse is recorded as a time-stamped event and therefore can be subtracted from the OM event time. With this methodology the transit time of the OMs will be measured. Studies of the results of this system are under way.
- As mentioned above two kinds of **Optical Beacons** will be distributed within the detector: the LED beacons and the Laser beacons. The MILOM line is provided with two LED beacons located on the first and third floors, and one Laser beacon located at the bottom of the string. The LED beacon on the first floor can illuminate the three OMs on the second floor which are at a distance of about 15 m. Such scheme allows to test the calibration system. The second LED beacon, integrated in the upper storey, and the Laser Beacon at the bottom of the line, are aimed to calibrate the future first line or *Line 1*. In the MILOM, emission of light by the LEDs has been performed by pulsing the LEDs with a frequency of a few Hz. Figure 3 shows a histogram with the time difference between signals measured by different OMs after the calibration provided by the dark room results. The peak of the distribution shows a $\sigma \sim 0.7$ ns, which yields a timing resolution of one optical module of ~ 0.5 ns ($0.7 / \sqrt{2}$ ns). This resolution is for large light pulses and therefore not dominated by the PMTs transit time spread.

¹A sector is a fifth of a complete line (5 storeys) and in several aspects is the minimum detector unit.

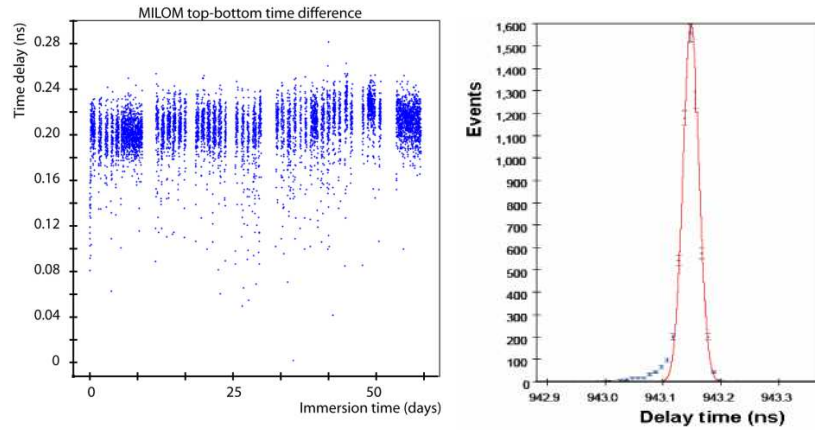


Figure 2. Left: Measurement of the time delay in the clock system between the bottom and the top storeys of the MILOM as function of time during the 48 day operation. Right: Histogram of the data for the time delay in the clock system. A resolution of $\sigma \sim 10$ ps is achieved.

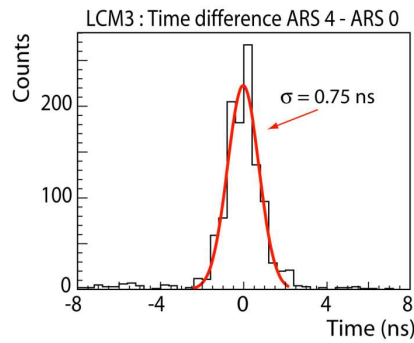


Figure 3. Distribution of difference in time between signals measured by adjacent optical modules in the storey.

4. Conclusions

The systems to calibrate the ANTARES detector described in this contribution have to provide an accurate relative timing precision between OMs to achieve a good angular resolution. The operation of the MILOM has been an immense advance towards this goal. All calibration systems needed to achieve a good angular resolution have been proven in real conditions and results show that the desirable time calibration accuracy of 0.5 ns is realistic.

References

- [1] ANTARES Collaboration. *A deep sea telescope of high energy neutrinos*, astro-ph/9907432, 1999.
- [2] Amram P. et al., Nucl. Instr. and Meth. Phys. Res. A484 (2002), 369.
- [3] Aguilar J.A. et al., *Transmission of light in deep sea water at the site of the ANTARES neutrino telescope*, astro-ph/0412126, 2004.