PROCEEDINGS OF SCIENCE

KM3NeT Time Calibration

The KM3NeT Collaboration‡*

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The KM3NeT Collaboration aims at the construction of a distributed research infrastructure under the Mediterranean Sea that will host two underwater neutrino detectors: ARCA and ORCA. They are optimised to detect neutrinos using the Cherenkov technique and will play an important role in the detection of high energy astrophysical neutrinos, ARCA, and in the study of the neutrino mass hierarchy exploiting the flux of atmospheric neutrinos, ORCA. Both detectors share the same technology: thousands digital optical modules, each hosting 31 3-inch photomultipliers, distributed along tall detection units. The main difference is the distance between the optical modules, optimised to meet the requirements of the different scientific objectives.

The reconstruction of the neutrino direction exploits the Cherenkov photons emitted along the path of the charged particles produced in the neutrino interactions and requires a nanosecond synchronisation between the photomultipliers in order to get high angular resolution. This contribution describes the accurate time calibration procedures developed to synchronise the time references of the photomultipliers within an optical module and of each optical module within the detection unit and also between detection units.

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1. Introduction

The KM3NeT detectors are large three-dimensional arrays, so-called building blocks, under construction in the Mediterranean Sea [1]. Each building block is composed of 115 strings (or detection units, DUs) of 18 digital optical modules (DOMs) that have 31 photomultiplier tubes (PMTs) each. Each detection unit is a mechanical structure standing upright from the sea floor, on which it is anchored. KM3NeT consists of KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss) at 2500 m depth about 40 km off the shore of Toulon, France and KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) at 3500 m depth about 80 km off the shore of Capo Passero, Sicily. The main objectives of KM3NeT/ARCA are the discovery and subsequent observation of high-energy neutrino sources in the Universe [2] and the determination of the neutrino mass hierarchy for KM3NeT/ORCA [3].

Neutrinos can interact with matter inside or in the vicinity of the detector producing secondary particles that can be detected through the Cherenkov light measurements. Due to their long range in water, muons, produced mainly in charged current interaction of muon neutrinos, provide the detection channel that better allow the neutrino direction reconstruction, although the apparatus has excellent reconstruction performance for all types of neutrino-induced events [4]. The arrival time of the Cherenkov light is registered by the PMTs. The accuracy on the measurement of the Cherenkov photon arrival time affects the angular resolution on the reconstructed track. All measured times need to be referred to a common clock; this can be obtained as a result of a time calibration procedure.

The detector is connected to the shore via a main electro-optical cable. The information recorded from a PMT consists of the start time and a measurement of the Time over Threshold (ToT). The start time is defined as the time at which the pulse exceeds a 0.3 single photoelectron level (s.p.e.) threshold and the ToT is the time the pulse remains above such threshold. Data collected by the PMTs are digitised in the DOMs and sent to shore, where the physics events are filtered from the background by online trigger algorithms and stored on disk. Accurate measurements of the light arrival times and charges and precise real-time knowledge of the positions and orientations of the PMTs are required for the accurate reconstruction of the direction of the detected particles.

The general layout of the KM3NeT detector can be considered as a large Ethernet network with thousands of nodes in the deep sea and on shore. An accurate time synchronization of all offshore nodes in the network, i.e. the DOMs and the electronics modules at the base of the DUs, is required for the time calibration. The signals from the PMTs are timestamped by the offshore nodes. The timestamping is done on the Central Logic Board (CLB) inside the DOM. The KM3NeT detector makes use of a clock distribution based on a fiber-optic broadcast by using a customised implementation of the White Rabbit (WR) technology [5] for distribution of absolute time from GPS on shore to the nodes. A schematic picture of the KM3NeT network is shown in figure 1. White Rabbit provides a means of synchronizing two clocks in two separate devices in an Ethernet network. Two non-standard WR features have been specifically developed for the KM3NeT network: the communication from shore is performed in a broadcast mode, in which the same data stream is distributed, by means of adequate optical filtering and splitting devices, to all offshore nodes, and secondly only the communication between shore and the electronic modules at the bases of the DUs is fully implemented in WR, the data streams from the DOMs to the shore being transported in standard Ethernet.

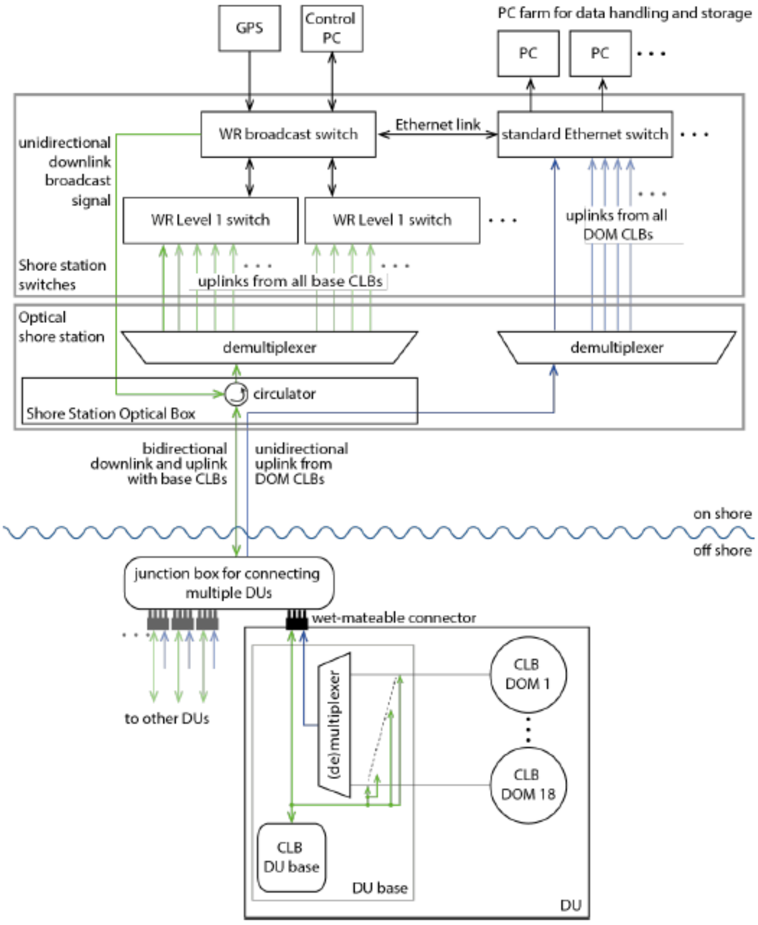

Figure 1: Simplified schematic view of the KM3NeT network where only one DU is shown. The green lines indicate the path of the slow control and clock data, the blue paths indicate the PMT data from the 18 DOMs. The time synchronization signal is sent from the WR broadcast switch to all CLBs in the detector. The return signals from the CLB in the electronic modules at the base of the DUs are routed to the WR switch fabric through the same fiber as the clock signal. The data from the CLBs in the 18 DOMs are routed through a separate set of fibers and then distributed via a standard Ethernet switch to a farm of PCs. To allow for slow control communication between the Control PC and the CLBs in the DOMs, the WR broadcast switch and the standard Ethernet switch are connected with a simple Ethernet link. In order to synchronise the WR switches using standard WR, the link between the WR broadcast switch and the WR Level 1 switches is bidirectional.

2. Time Calibration

For the neutrino event reconstruction with a precision better than 1°, the optical modules need to be synchronized with nanosecond precision, see figure 2, and their position determined with less than 20 cm accuracy [6]. Each DOM and base module have identical CLBs which perform the signal processing and transfer, time synchronization and control of the instruments. Time synchronization between different detector components is monitored in-situ by light propagation time measurements between light emitters and the PMTs. The time calibration of the PMTs is obtained by a combination of several calibration procedures: determination of the relative time offsets 1) between the PMTs in the DOM (intra-DOM); 2) between DOMs in the DU (inter-DOM); 3) and between different DUs (inter-DU).

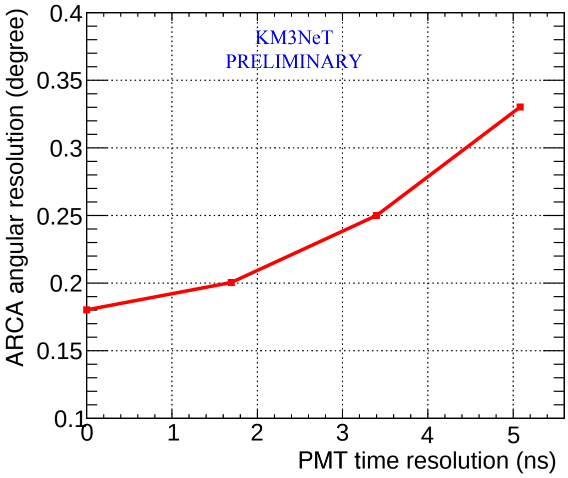

Figure 2: The plot shows the angular resolution of ARCA based on present analysis for track events from ν_μ charge current as a function of the time resolution, considering an energy spectrum of E^{-2} with $E_\nu \geqslant 10$ TeV. The PMT time resolution represents a combination of the different sources of timing uncertainties (intra-DOM, inter-DOM, inter-DU) in addition to standard PMT Transit Time spread (TTS). The KM3NeT time calibration procedure is designed to achieve O(1ns) time synchronisation among DOMs.

Prerequisite for the time calibration is the PMT gain equalisation through tuning of the PMT base High-Voltage (HV): all the PMTs in the DOM have to be set to the same gain value. As mentioned above, the information recorded from a PMT consists of the start time of the hits along with the ToT duration. The HV tuning consists in scanning the HV in order to find the value for which one single detected photon is measured in a ToT range of [26 ns; 27 ns] assuming a threshold of 0.3 s.p.e. for the hit signal detection. This ToT range corresponds, in average, to a gain of 3×10^6, as it has been determined from a study on a subset of properly calibrated PMTs [7]. The scan is performed with steps of 25 V and, for each step, the mean ToT value is extracted from the Gaussian fit to the ToT histogram for 5 min of data taking, figure 3. The relationship between the high voltage value and the mean ToT value obtained with the scan allows to estimate the tuned HV value that provides the target ToT value.

2.1 Intra-DOM calibration

The intra-DOM time offsets that is the relative time delay between PMT of the same DOM primarily depend on the PMT transit time and on the different propagation delays for the different

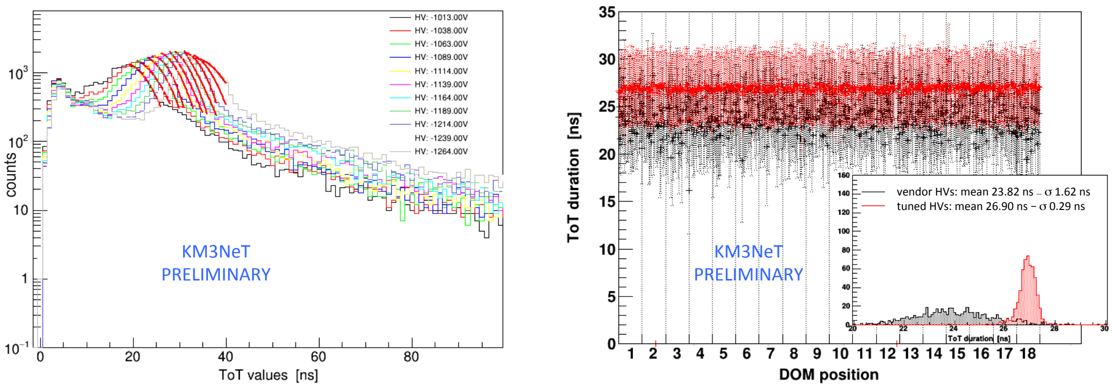

Figure 3: Example of ToT histograms for a single PMT and the corresponding Gaussian fit for several high voltage offset values. The tuning is done with 25 V steps of HV and ToT is calculated by means of a Gaussian fit function to the ToT distribution during 5 min of data taking for each step. Right: Mean ToT value as a function of the DOM position for the PMTs with vendor HV in black and tuned HV in red. DOM position corresponds to the vertical sorting of the DOMs from bottom to top. In the embedded pad, the corresponding histograms.

PMT channels. Radioactive potassium decay in the sea water can be simultaneously seen by the neighbour PMTs in the DOM, and can produce up to 150 Cherenkov photons per decay [8]. These decays are the main source of the single PMT rate. A single decay occurring in the vicinity of the DOM has a chance to produce a genuine coincidence between signals of different PMTs, which can be exploited for time calibration of the DOM. This feature is used to verify the PMT mapping and to perform inter-PMT time calibration.

To this purpose, distributions of time differences between signals detected in different PMTs in the same DOM are studied as a function of the angular separation of the PMTs involved [9]. The ^{40}K signature is particularly exploited for in-situ calibration of the PMTs contained in a single DOM and for long-term monitoring of the PMT performances [4, 10].

The intra-DOM time calibration is also performed in a dark-room, during the pre-deployment tests of the DU, via the radioactive potassium contained in the DOM glass.

2.2 Inter-DOM calibration

Reference inter-DOM time calibration is performed for each DU in a dedicated dark-room before DU deployment. This time calibration, obtained with a blue laser source, that illuminates simultaneously 2 PMTs on each DOM at s.p.e. level, figure 4, has the purpose to measure the time delays between DOMs of a single DU, due to the propagation time of the clock to reach the different DOMs. In particular, since the relative origin of time, given by the clock distributed from the shore station to the DU, reaches the lower DOMs first and the upper DOMs later, the simultaneous pulses sent by the calibration laser to the reference PMTs of the 18 DOMs will be time stamped earlier for upper DOMs than the lower DOMs, results are shown in figure 5. This will allow to estimate the correction offsets to be added to the intra-DOM time offsets measured previously so that the full string is calibrated with respect to the DU base.

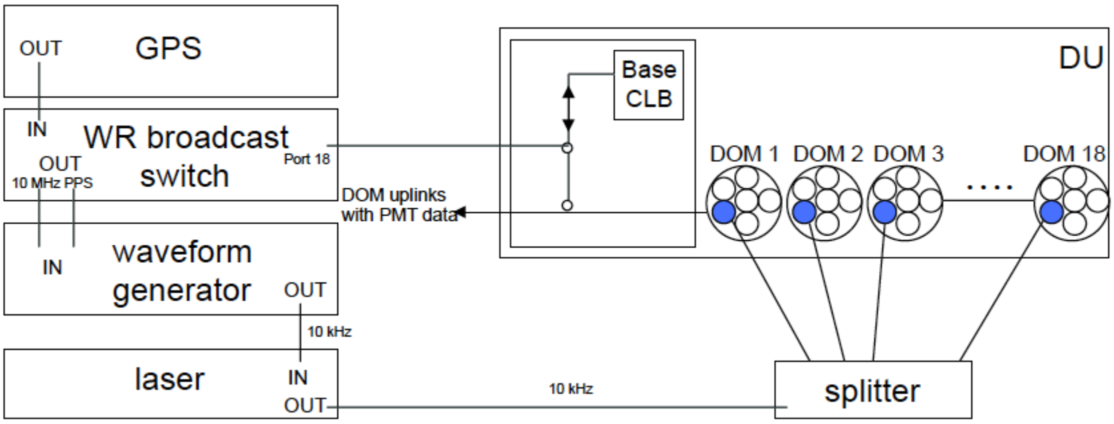

Figure 4: Laser calibration system in the dark-room for time calibrating 2 PMTs on each DOM in a DU. This setup provides the inter-DOM calibration.

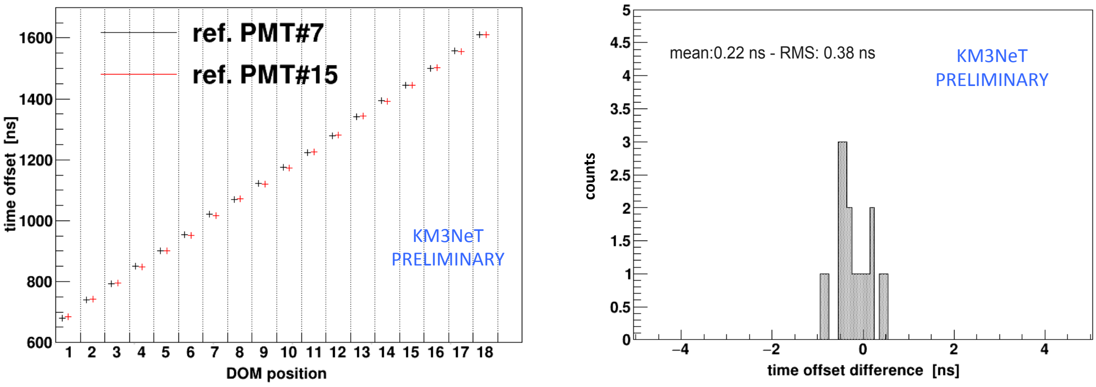

Figure 5: Laser Calibration; on the left the plot shows the time offsets for the reference PMTs as a function of the DOM position, numbered from bottom to top, in a ORCA DU; while on the right the graph displays the histogram of the time offset difference between the 2 reference PMTs for each DOM.

The inter-DOM time calibration performed in the dark-room is checked in-situ taking advantage from both: Light Emission Diode (LED) beacons and the time residuals for the reconstructed down-going atmospheric muons. Down-going atmospheric muons provide an abundant, coherent signal source that can be used to evaluate the relative time offsets between different DOMs and DUs. The time residual distribution is obtained as the difference between the PMT measured time and the PMT expected time for down-going muon tracks reconstructed. Figure 5 on the left shows the time residuals for two DOMs on the same ORCA DU.

LED beacons, located one in each DOM, produce short-duration, low-luminosity pulses ($\lambda = 470$ nm). Single photon hits are selected in both receiving and emitting DOM to measure the time of flight of light between PMTs of two adjacent DOMs. A comparison between the in-situ measurements from reconstruction of down-going muons and LED beacons is displayed in figure 5 on the right.

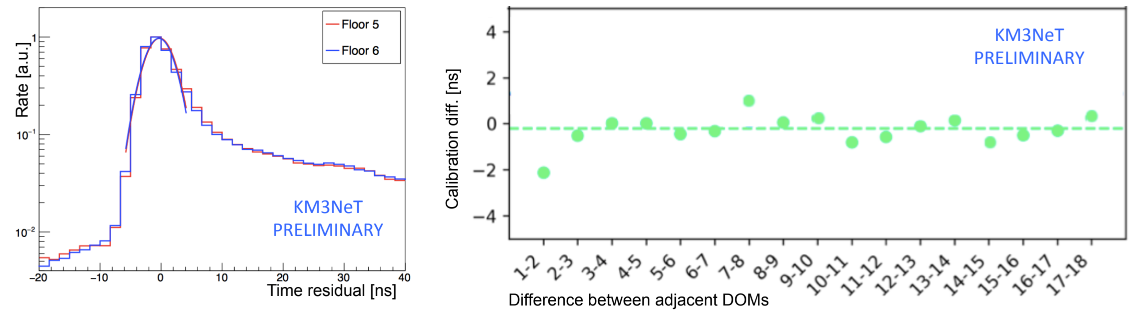

Figure 6: Left: the plot shows an example of the distribution of time residuals of the down-going muons for 2 DOMs of an ORCA DU. Right: difference between inter-DOM time delays measured, in-situ, using down-going muons and LED beacons for an ORCA DU.

2.3 Inter-DU calibration

The inter-DU time calibration relies on the accurate, WR-based, measurement of Round-Trip-Time (RTT) of the optical signal between the master clock (on shore) and each DU base. The RTT measurement is performed and then needs to be corrected by including all relevant latencies and asymmetries, i.e. the time delay for the one-way propagation of the clock signals from shore to the base of each DU. The time asymmetry due to the seabed infrastructure arises from the different paths of the signals in the junction box, with negligible dependance on the wavelength, and the chromatic dispersion in the fibers of the main electro-optical cable connecting the detector to shore. The chromatic dispersion is due to the difference between the wavelength that is used for the downlink clock signal and the wavelength that is used for the uplink signal from the CLB in the base containers, figure 1.

As a final check a procedure has been implemented based on reconstruction of down-going atmospheric muons. The procedure works such that a set of events is reconstructed with different detector geometries (e.g., inter-DU time offsets), and from that the average quality of the fit, L, is evaluated. From the resulting curve, like the one shown in figure 7, an optimal value is determined. This can then be used to test or, if needed, correct the calibration.

3. Conclusions

To achieve the nanosecond time accuracy and therefore obtain the high angular resolution required for the KM3NeT detector, the time calibration procedure has been optimised both in the dark-room measurements and in-situ. These procedures allow to regularly monitor and to adjust the operation of all PMTs in the apparatus, in order to ensure optimal performance of the detector.

References

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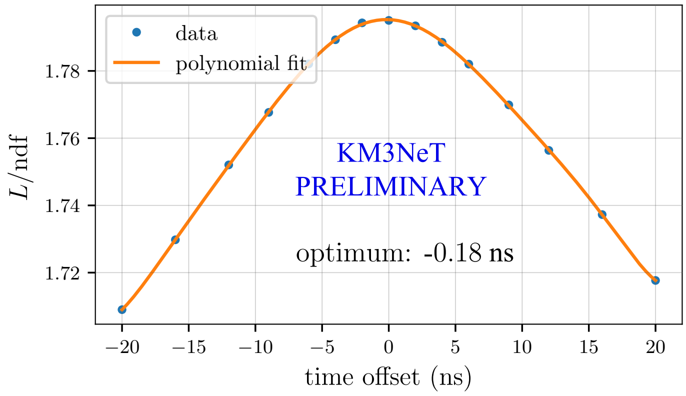

Figure 7: Cross checks of the calibration can be performed by maximising the likelihood L of the reconstructed muon tracks, here shown for the inter-DU time offset of the ORCA 2-string detector.

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