KM3NeT Time Calibration

By

Aliaa Afify

Erasmus Mundus Joint Master Degree in Nuclear Physics (NucPhys)

Prof. Silvio Cherubini

Dr. Rosa Coniglione

Dr. Giorgio Riccobene

UNIVERSITÀ degli STUDI di CATANIA

Erasmus Mundus JMD on Nuclear Physics

INFN Istituto Nazionale di Fisica Nucleare

KM3NeT

Abstract

KM3NeT/ARCA detector consists of a three-dimensional array of optical sensors that aims at the detection and study of high energy neutrino from cosmic origin. KM3NeT/ARCA is under construction in the deep-sea water of Mediterranean Sea. The optical sensors (Digital Optical Module - DOM), made of 31 small PMTs hosted inside a glass sphere, will detect the weak light emitted by the secondary particles generated in the neutrino interaction with the medium surrounding the detector. The detector will consist in two blocks of 115 Detection Units (DU) each one hosting 18 DOMs with a total detector volume of 1 km^3.

The objective of this thesis if the calibration of a DU and of a Junction Box. Moreover, the estimate of the effect of the time offset inaccuracy on the angular resolution of the detector has been performed by means of MonteCarlo simulations.

Introduction

The accuracy on the measurement of the Cherenkov photon arrival time affects the angular resolution of the reconstructed track. To get a good angular resolution, key parameter for the detection of point-like sources, a nanosecond synchronization between the photomultipliers is required. The time calibration of the KM3NeT PMTs is obtained by a combination of several calibration procedures that allows the determination of the relative time offsets:

1) between the PMTs in the DOM (intra-DOM);
2) between DOMs in the same DU (inter-DOM);
3) between different DUs (inter-DU).

The evaluation of the effect of the inaccuracy of the time synchronization on detector performances is performed by means of Monte Carlo (MC) simulations.

DU time calibration

For the Inter-DOM calibration, a laser system was used. For the intra-DOM genuine coincidence, due to ^{40}K beta decay in the glass sphere, used. The inter-DU time calibrations are based on the White Rabbit system. A dedicated setup for the measurements of these time offset was installed in our laboratory. The measured time offsets from the three calibrations will be summed together and will provide the time offsets for all PMTs of the DU. Results, shown in Figure 1 for reference PMT 7 of each DOM, demonstrate the capability to clearly identify photons from the laser source and determine the time offsets between the DU base and the different DOMs. DOMs are separated by a fiber length of about 40 m, thus the typical time offset is 200 ns, well in agreement with the results of Figure 1. Figure 2 shows summed time offsets for all the PMTs of the DU-38 of ARCA.

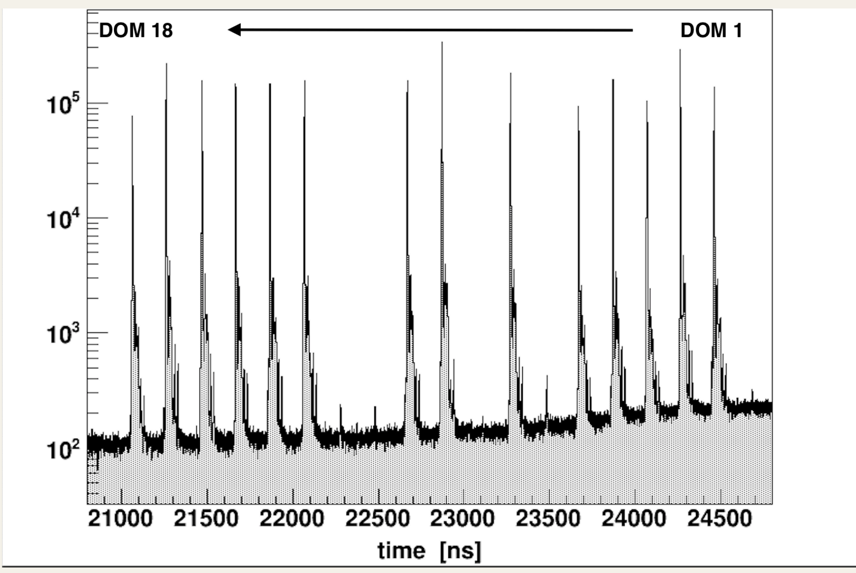

Figure 1. Results of inter-DOM calibration .for ARCA DU 38, using reference PMT 7 in each DOM.

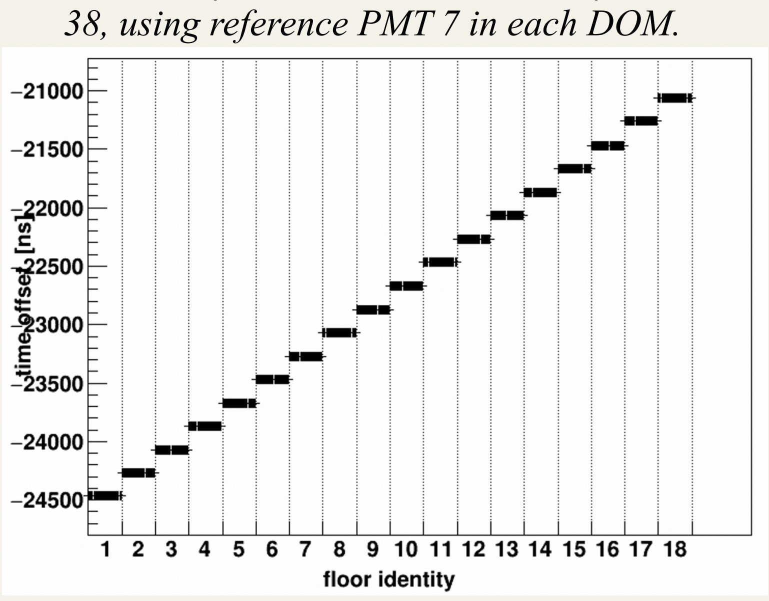

Figure 2. Time offsets of PMTs, relative to DU Base for ARCA DU38

Time asymmetry of submarine Junction Box of ARCA

The Junction box is a mandatory element of the submarine network of KM3NeT, used to split optical fibers and conductors from the main cable termination to the DUs, in a star-like architecture.

The bidirectional fibers connecting the White Rabbit (WR) master boards (located on-shore) to the DU bases (namely the "slave" boards running WR) are split, inside the junction box, into two: upward, shore-to-sea, and downward, sea-to-shore, fibers. This is needed to allow the insertion of Optical amplifiers. This set-up produces a time asymmetry in the optical path sea-to-shore that must be corrected to allow proper determination of the absolute time of the DU Bases. In the WR Precision Time Protocol, the absolute time of a slave is recovered using equation

$$L\frac{c(\lambda_M)+c(\lambda_S)}{c(\lambda_M)\,c(\lambda_S)} = RTT - \Delta$$

Where RTT is the round trip time of a proper synchronization signal (measured), D is the sum of electronics boards time latencies (calibrated in advance) and c(λ) is the speed of light in fiber for master and slave lasers' wavelengths (known by fiber manufacturer). In case of a fully bidirectional fiber, whatever is the length L, the WR protocol permits accurate synchronization of the slaves.

When fiber paths upward and downward are different (over a short length in the full path), it is enough to measure, and add properly in the D coefficient, the time asymmetry upward-downward to re-synchronize the system.

A special device was designed and run to measure the upward/downward time asymmetry of the junction box. Four time-asymmetries were calculated (see Tables 1 and 2) to take into account all possible combinations of working conditions for the four optical amplifiers installed in the JB. The results are measured with an accuracy well below 1 ns.

Table 1. RTT measurements for the upward (SC) and downward (DC) optical paths of the ARCA JB OPA.

RTT_upward_SC_ED01	749566.10 ± 41.56 ps
RTT_upward_SC_ED02	750863.82 ps ± 30.63 ps
RTT_downward_DC_ED03	755296.79 ± 19.78 ps
RTT_downward_DC_ED04	747431.62 ± 42.56 ps

Table 2. The time of the calculated four asymmetry upward downward

ED01/ED03	-5730.69 ± 61.34 ps
ED02/ED03	2134 ± 84.12 ps
ED01/ED04	-4432.97 ± 50.41 ps
ED02/ED04	3432.20 ± 73.19 ps

Monte Carlo Simulations

Monte Carlo simulations play a significant role in the data analysis of neutrino telescopes. Simulations are used to design reconstruction algorithms for neutrino events, as well as to estimate cosmic and atmospheric signals in different physics analyses. In this work the simulations were used to estimate the effect of the inaccuracy of the time calibration in the angular resolution. The inaccuracy of the three different calibration, before described (inter-DOM, intra-DOM and intra-DOM), were separately considered in the MC. This estimate was done for a detector made of only 2 DUs in order to study the time calibration uncertainties on the data that have been collected in the period from May 2016 to April 2017 when the first two strings of the ARCA detector were operational.

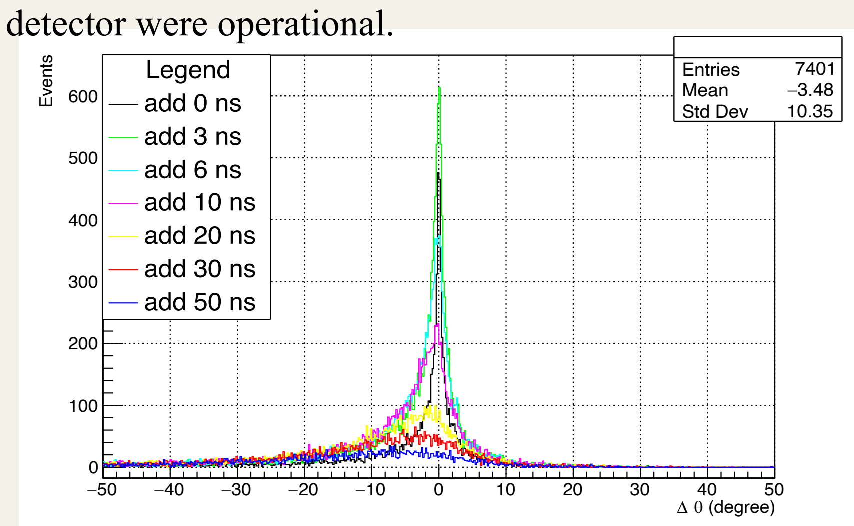

Figure 3. Difference between the reconstructed zenith angle and the generated zenith angle (Δθ) for different Intra-DOM time uncertainties.

In Figure 3 is reported the distribution of the difference between the reconstructed zenith angle and the generated zenith angle ($\Delta\theta$) for different Intra-DOM time uncertainties. With a gaussian fit the sigma values of the distributions, that is related to the angular resolution, were extracted. Same examples of the fit are shown in Figure 4.

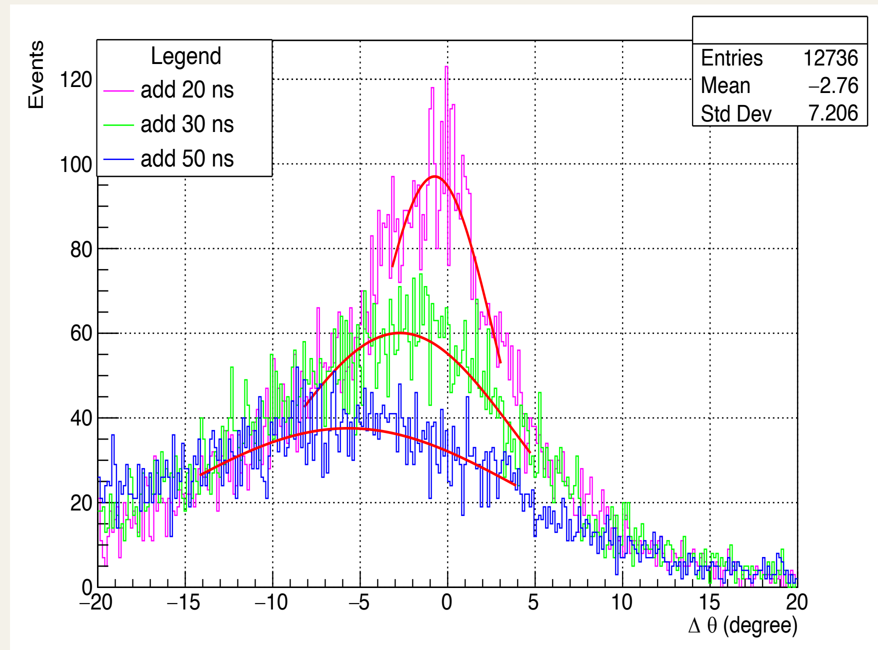

Figure 4. Difference between the reconstructed zenith angle and the generated zenith angle (Δθ) for three Inter-DOM time uncertainties. The red lines are the Gaussian fits.

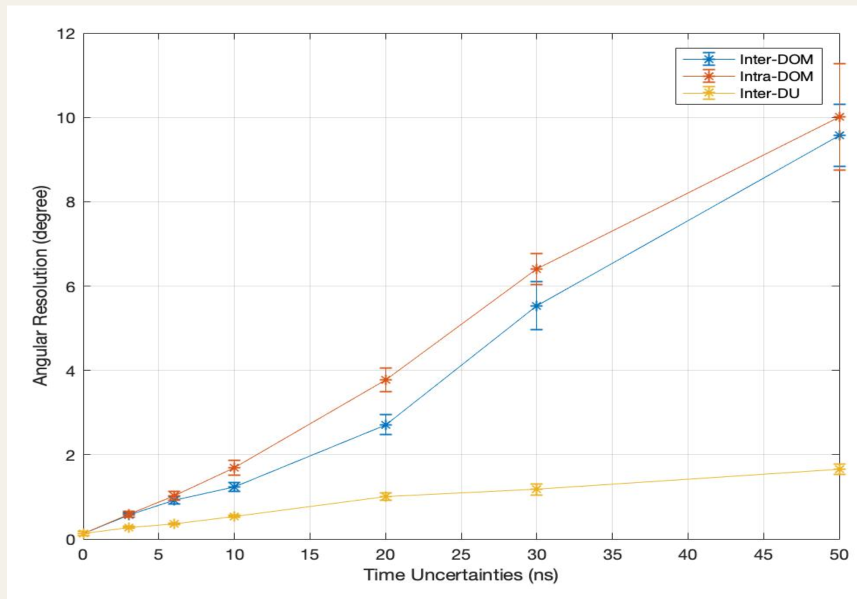

Figure 5. Angular resolution as a function of the time uncertainties for inter-DU, inter-DOM and intra-DOM time uncertainties.

In Table 3 the sigma values extracted from all the fits for all the three calibrations are reported. In Figure 5 the sigma values shown in Table 3 are plotted as a function of the time uncertainties for the inter-DU, inter-DOM and intra-DOM. The result from this study indicates that the intra-DOM and Inter-DOM inaccuracy have the largest impact on the angular resolution. Summing in quadrature the uncertainties of the three different calibrations, supposing for each an uncertainties of 3 ns, an angular resolution of about 0.9º is obtained. This indicates that also for a small detector made of only two strings a synchronization with a precision of 1-2 ns in each calibration procedure is needed to maintain the angular resolution inside 0.5º.

To confirm this results further studies are needed. In particular the inaccuracy from each calibration should be combined following the real estimate of the uncertainties in the calibration procedures and larger detector configuration tested.

Table 3. Zenith angular resolution as a function of the time uncertainties for the three different calibrations.

Time-offset	**0 ns**	**3 ns**	**6 ns**	**10 ns**	**20 ns**	**30 ns**	**50 ns**
Inter-DOM	0.14±0.05º	0.57±0.05º	0.92±0.09º	1.23±0.11º	2.71±0.24º	5.53±0.56º	9.57±0.74º
Intra-DOM	0.14±0.05º	0.59±0.06º	1.03±0.10º	1.69±0.17º	3.77±0.27º	6.40±0.36º	10.01±0.99º
Inter-DU	0.14±0.05º	0.28±0.03º	0.36±0.02º	0.45±0.03º	1.01±0.08º	1.17±0.13º	1.65±0.12º

References

[1] A. Creusot, I. Di Palma, D. Guderian, G. Riccobene, and O. De Paris, "KM3NET Time Calibration," 2019.

[2] R. Coniglione, J. Hofestädt, A. Sinopoulou, E. Tzamariudaki, and D. Zaborov, "Atmospheric neutrinos detected with the first KM3Net detection units of ARCA and ORCA," Proc. Sci., vol. 358, no. July, 2019

[3] R. Coniglione, "Results from the Mediterranean neutrino detectors," Proc. Sci., vol. 358, pp. 0–17, 2019.