PROCEEDINGS OF SCIENCE

The White Rabbit Time Calibration system for KM3NeT/ARCA

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The KM3NeT neutrino telescope consists of two detectors: ARCA, at 3500m depth offshore Capo Passero, Sicily, and ORCA, at 2500m depth offshore Toulon. Both detectors consist in a 3D-grid of Detection Units (DUs), each with 18 Digital Optical Modules (DOMs), anchored on the seabed and linked to the shore station via optical fibers. Each DOM houses 31 3-inch photomultiplier tubes (PMTs) and the relative front-end electronics. The KM3NeT neutrino detector reconstructs the Cherenkov light wavefront emitted by charged particles produced in a neutrino interaction in water. In order to guarantee the expected physics goals in terms of angular resolution and sensitivity to astrophysical sources, the time resolution and timing offsets between all PMTs must be kept at the nanosecond level, knowledge of DOM positions at circa 20 cm accuracy and orientation at few degrees. The Collaboration has recently adopted the standard White Rabbit time-synchronization technology as the optimal solution to synchronize the detector electronics. After a strict qualification process, the first 17 DUs using standard White Rabbit have been produced and, since September 2024, three of them are fully operational in the ARCA detector, showing optimal time accuracy. The novel time calibration procedure and results from the ARCA detector will be shown and discussed.

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1. Introduction

The KM3NeT Collaboration is constructing two deep-sea neutrino telescopes in the Mediterranean: KM3NeT/ARCA and KM3NeT/ORCA [1]. These detectors serve different scientific goals: KM3NeT/ARCA is tailored to identify high-energy cosmic neutrinos in the TeV to PeV energy range, whereas KM3NeT/ORCA is designed for lower-energy neutrinos, in the GeV regime, to enable detailed measurements of neutrino oscillation parameters and mass hierarchy.

Neutrinos interacting with matter in or near the instrumented volume generate secondary charged particles that travel faster than the speed of light in water, producing Cherenkov radiation. This light is detected by an array of Digital Optical Modules (DOMs) [2], that contain multiple 3-inches photomultiplier tubes (PMTs) within pressure-resistant spherical housings. The detected light patterns are used to reconstruct the direction and energy of the secondary particles, from which properties of the initial neutrinos can be inferred. The DOMs are installed along flexible vertical structures known as Detection Units (DUs), which are fixed to the seabed and stabilized in a vertical position by buoyancy elements.

Inside DOMs, the Central Logic Board (CLB) [3] is deputed mainly to the readout of PMT data and the time synchronization of the module. Each DU also has, on its anchoring frame, a titanium container named "Base Module", that hosts the power distribution electronics, a CLB and, in the case of KM3NeT/ARCA Phase 2, two White Rabbit switches.

2. Time synchronization requirements

A comprehensive simulation campaign was carried out to identify and study the impact of timing calibration and synchronisation systematics on the detector performance for the reconstruction of track-like events. Three types of timing uncertainties were considered: inter-PMT, inter-DOM, and intra-DU contributions as systematic errors in calibration procedures. As discussed elsewhere [1], it was determined that in order to guarantee the target tracking performance (angular resolution $< 0.1°$ for ν_μ with energies $>$ 100 TeV) the overall contribution of the timing systematics between any pair of DOMs in the detector due to calibration should be in the order of 1 ns.

Synchronization between DOMs is guaranteed by the employment of White Rabbit technology, as discussed later, while a set of calibration processes guarantees the correct characterization and compensation of the timing uncertainties due to the electro-optical links between DOMs and the shore station.

3. The White Rabbit project

White Rabbit (WR) [4] is an Ethernet-based technology that enables sub-nanosecond synchronization with precision on the order of hundreds of picoseconds, while ensuring deterministic data transfer. It integrates the Precision Time Protocol (PTP) with Synchronous Ethernet and operates through a hierarchical network of WR-compliant nodes, that can be either White Rabbit switches or devices with a White Rabbit PTP core implemented in the Field Programmable Gate Array.

White Rabbit links connect Master and Slave nodes via bidirectional optical fibers, tipically using Small-Form Pluggable (SFP) transceivers. Each WR link begins with a dedicated initialization phase, the White Rabbit *Link Setup*, during which exclusive WR packets are exchanged. This phase establishes the clock synthonization using Synchronous Ethernet, and distributes the fixed transmission and reception delays across the link.

Once the WR link is established, standard PTP messages are used to synchronize clocks. This process includes an initial synchronization, to determine and correct the Master-Slave phase offset and the *Phase tracking*, to maintain synchronization through continuous delay measurement and compensation.

Obtaining a sub-nanosecond synchronization precision requires knowledge of the fixed transmission and reception delays, i.e., constant latencies introduced by transceivers, PCB traces, electronic components, and FPGAs. These are combined with fiber propagation delays to compute link asymmetry, allowing the Slave to correct its clock relative to the Master.

4. The KM3NeT case

In the KM3NeT/ARCA two different network and timing architectures are in operation simultaneously [5]. Both architectures are based on the White Rabbit technology, although with two different network implementations, namely the *Broadcast* and the *Standard White Rabbit*, corresponding respectively to two different sectors of the detector. Indeed, due to a technical transition that was decided during the early years of construction, 32 KM3NeT/ARCA DUs (Phase 1) are operated according to the *Broadcast* architecture, while the remaining 198 will be operating in the *Standard White Rabbit* architecture (Phase 2).

For timing alignment purposes, the reference timeplane of the KM3NeT detectors is represented by the arrival of optical photons at the PMT surface (optical window). All calibration procedures, either for Phase 1 or Phase 2 detectors, employ this timing reference scheme to measure and compensate detector time delays. In this contribution, we focus only on the case of Phase 2. In Phase 2, time information is dispatched from a topmost WRS in the shore station, synchronized to a GPS, to the CLBs off-shore, through a chain of point-to-point master-slave links over two layers of WRS in the station, and through links to two WRS, named *Wet* WRS (WWRS), inside the Base Module of the DU. All fixed delays in the links between the WRS in the shore station have been measured and compensated according to the official White Rabbit calibration procedure, so that any White Rabbit switch in the shore station network is synchronized with the GPS at sub-nanosecond level. Instead, the additional time offsets due to the optical network asymmetries and peculiar hardware delays of specific boards are corrected offline, using (as for the Broadcast sector) a set of time calibration constants: these values are the result of the measures obtained during the DU calibration inside a darkroom and during the calibration of the optical network. This set of offset is used during the detector normal operation to correct the time of each PMT hit in order to retrieve the true hit time. In situ calibration is also foreseen in this approach.

The use of a common time reference plane across both the Broadcast and Standard White Rabbit architectures ensures consistent and reliable reconstruction of events involving DUs from either system. Additionally, the application of the time offset corrections enables accurate determination of the absolute events time, which is particularly crucial in multi-messenger astrophysics, where precise time correlation with external observatories is essential.

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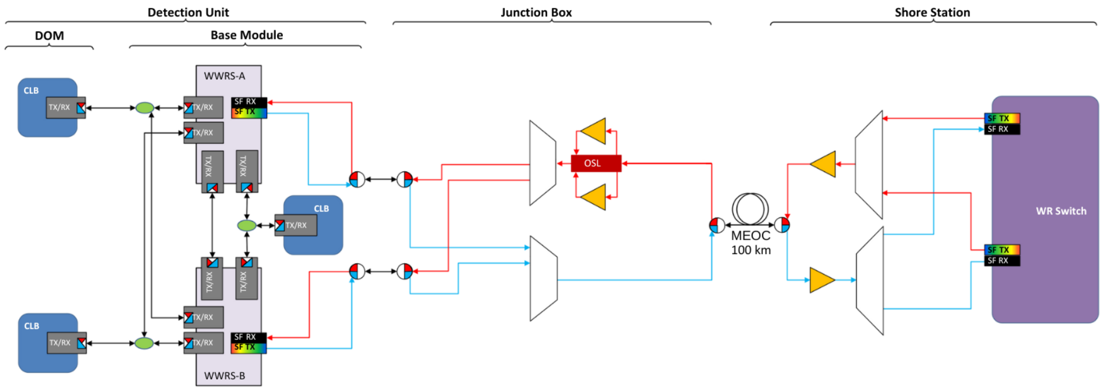

Figure 1: Scheme of the optical path of KM3NeT Phase 2. The optical lines from shore-to-sea (TX) are represented with red (meaning larger optical wavelengths), the sea-to-shore (RX) connections are represented with blue lines.

4.1 The ARCA optical fiber network

The main concept of the calibration is that each WRS (or WR node) has some constant transmission and reception delays on every port. To achieve the best synchronization across all WR devices deployed in ARCA, these delays must be properly compensated, with two fundamental conditions to be fulfilled.

First, all time delays introduced by the optoelectronic components must be calibrated and corrected. Second, each point-to-point optical connection between master and slave devices must employ either a single fiber or a pair of identical fibers, and the chromatic dispersion must be either negligible or accurately characterized.

In KM3NeT ARCA, as shown in Figure 1, the optical paths from shore to sea and back are not perfectly symmetric. This asymmetry arises both from differences in fiber lengths and from chromatic dispersion, particularly relevant when different wavelengths are used for transmission and reception. Therefore, a detailed understanding and correction of these effects is essential for precise timing synchronization. The full optical path of KM3NeT Phase 2 can be factorized as follow:

- Vertical Electro-Optical Cable: it is the optical link between the DOM and the WWRS at the DU base. It uses a single fiber for bidirectional communication. Given its short length (∼ 700 m), the chromatic dispersion is negligible and the path can be considered symmetric.

- DU Base: the connection between each WWRS optical transceiver and the cable to the Junction Box is realized through two separate fibers, one for transmission and one for reception, operating at different wavelengths. However, symmetric optical components are used by construction, ensuring that the resulting delay remains below 50 ps.

- Junction Box-DU Interlink: this link, embedded in the interlink subsea cable, also uses a single fiber for transmission and reception over distances shorter than 200 m. Similar to the Vertical Electro-Optical Cable the asymmetry here is negligible due to both the short length and the minimal chromatic dispersion.

- Junction Box: the internal optical connections of the Junction Box are inherently asymmetric. This is primarily due to the use of a pair of optical amplifiers, which are optimized for unidirectional data transfer from shore to sea. The asymmetries introduced along the paths from the WWRS (A and B) to the DUs are measured and characterized during the integration and testing of the Junction Box.
- Shore Station: asymmetries also exist in the on shore fiber network, due to the differing optical components (including amplifiers) used for transmission and reception. These are carefully measured and included in the system calibration model.
- Main Electro-Optical Cable: it is about 100 km long and it is responsible for both long-distance data transmission and power delivery. Due to its length, chromatic dispersion plays a significant role and cannot be neglected: the introduced asymmetry is measured and added in the set of time calibration offsets.

5. Results

Even though the KM3NeT/ARCA shore station White Rabbit fabric is synchronized at sub-nanosecond level and all optical asymmetries in the network between the shore station switches and the DOMs are measured and included in the time calibration offsets, there are residual electro-optical asymmetries which arise from intrinsic offsets of the readout chain of the CLBs and of the non-compensated fixed delays of the CLBs and of the Wet White Rabbit switch ports inside the Base Modules. To accurately measure all these contributions, dedicated calibration measurements are performed in darkroom test sites which are eventually validated in-situ during the detector operation.

5.1 Results of darkroom calibration

The darkroom calibration procedure is designed to measure and correct residual timing offsets between DOMs. In this setup, a laser source delivers pulses at the single photoelectron level simultaneously to two reference PMTs within each DOM. Both the DOMs and the laser system are synchronized to a common White Rabbit switch, ensuring a shared timing reference. By recording the time difference between the laser pulse emission and the corresponding hit timestamp registered by the CLBs of DOMs, and accounting for the known light propagation delay, it is possible to evaluate residual electro-optical asymmetries and intrinsic delays. These systematic offsets are then quantified and stored as calibration constants, which are later applied during detector operation to correct the PMT hit times. Initial results from this calibration procedure show that DOMs from 15 different Detection Units exhibit time offset values contained within less than 5 nanoseconds, to be mostly ascribed to the variability of the residual offsets. This consistency confirms both the expected sub-nanosecond precision of the White Rabbit synchronization and the limited variability of the residual offsets across different DOMs. More details can be found in [7]. The timing offsets for the remaining, non-reference PMTs within each DOM are determined in situ using coincidences from the natural radioactive decay of ^{40}K. By measuring the time differences between coincident photon hits on the reference PMTs and each of the other PMTs, the relative delays are extracted and used to complete the intra-DOM time calibration.

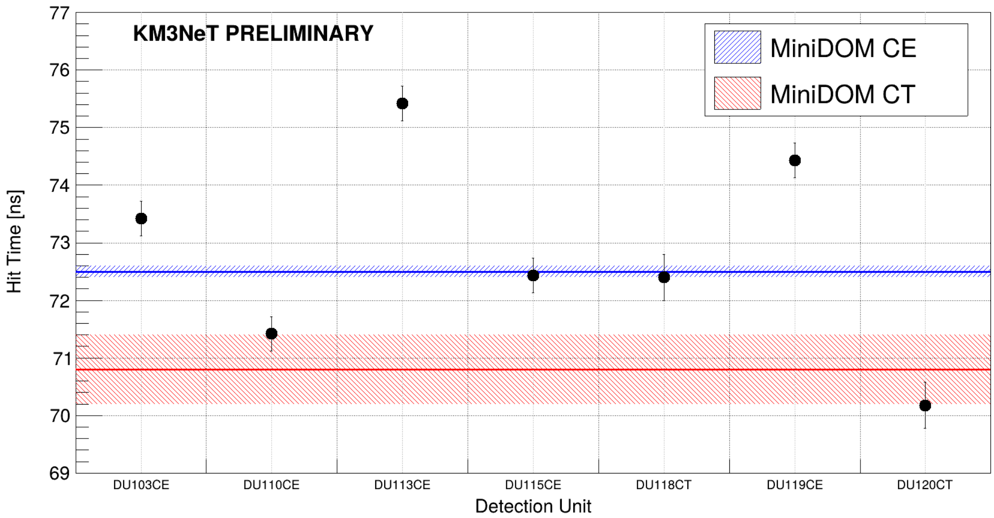

Figure 2: Comparison between the MiniDOM and the DUs integrated at the INFN-LNS Catania (CT) and INFN Caserta (CE) test stations. The red and the blue lines represent the average hit time of the MiniDOM, with the surrounding shaded bands indicating the ± 1σ uncertainty.

5.2 Inter-darkrooms calibration

The darkroom calibration is carried out in three different locations: INFN-Laboratori Nazionali del Sud, INFN-Caserta and INFN-Genova.

Although all systems are based on the same architecture and follow and identical time calibration procedure, systematic differences arise due to the different darkroom setups. Each site, indeed, is equipped with its own laser calibration setup, including different laser sources and optical splitters.
To inter-calibrate the different darkroom calibration sites and assess any systematic delay between them, a dedicated device has been developed, the *MiniDOM*. It is a portable calibration module identical to a standard DOM with only three PMTs and a CLB which replicates the same timing and calibration conditions applied to standard DUs.
A first validation test was conducted at the INFN-Caserta test station, where the MiniDOM was used to compare its timing performance with all the DUs integrated at this darkroom site. In particular, the comparison involved the three new integrated DUs: D0DU103CE, D0DU110CE and D0DU115CE. The results were found compatible within few nanoseconds, in agreement with the expectation that the measurements from the MiniDOM closely match those from the integrated DU at the same site.
This device was subsequently employed to compare the darkroom calibration setups at the INFN-Laboratori Nazionali del Sud and INFN-Caserta test stations, identifying minimal systematic differences between the two arising from specific features of the darkroom setups, as shown in Figure 2. Each marker, in the figure, represents the average hit time of all 18 DOMs in a DU, while the horizontal bands correspond to the average values obtained from the three PMTs of the MiniDOM.

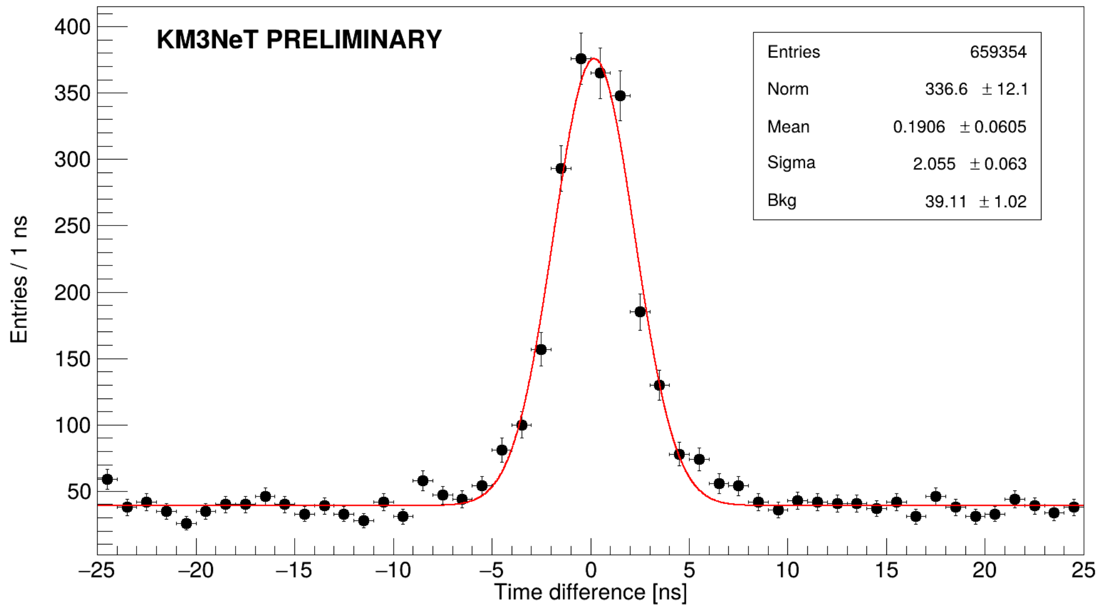

Figure 3: Time difference distributions between pairs of close PMTs: PMT 13 and PMT 14. Each distribution is fitted by a Gaussian function and a constant polynomial. Measurements taken at sea using the laser beacon.

5.3 In-situ validation

The time calibration of the detector was validated in-situ through the Laser Beacon (LB), a powerful light source installed inside the Junction Boxes of KM3NeT/ARCA on the seafloor. The beacons emits intense and isotropic green laser pulses at 532 nm, with subnanosecond pulse width, enabling independent checks of the timing calibration across multiple DOMs.
The LB can be used for multiple calibration purposes including: intra-DOM calibration to verify the timing offsets among PMTs within the same DOM, inter-DOM calibration to determine timing offsets between different DOMs on the same DU and inter-DU calibration to synchronize DOMs located on different DUs across the detector.

A first validation, presented in Figure 3, was carried out to check the timing calibration of D0DU115CE (ARCA 47), for which the timing offsets among PMTs were found to be in agreement with the ones determined by the studies based on ^{40}K decays. Additionally, in Figure 4 the timing between DOMs of the same DU is studied and compared, at different laser amplitudes, with the results obtained in the darkroom calibration, showing an agreement within 1.5 ns.

6. Conclusions

In this contribution, we have presented the novel time calibration strategy developed for the Standard White Rabbit architecture of KM3NeT/ARCA. The darkroom calibration procedure, carried out across multiple calibration stations, has demonstrated that DOMs from different Detection Units can be synchronized with an accuracy of a few nanoseconds. Combined with a detailed characterization of optical network asymmetries and latencies, this ensures the required timing

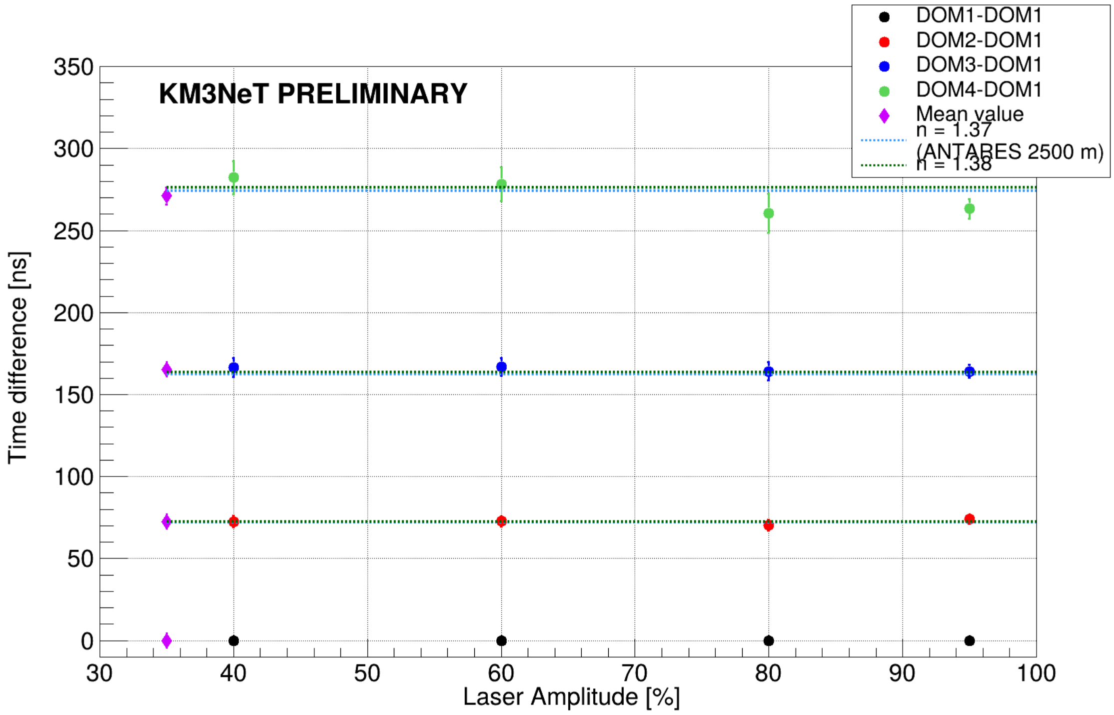

Figure 4: Measured time differences vs laser amplitude for different DOM pairs. The violet points at 35% are the mean values of each DOM pair at different laser amplitudes.

precision to achieve the detector's target angular resolution. Undersea in-situ verification using a laser beacon allows for cross-checking synchronization both among PMTs within a single DOM and across DOMs within the same DU. Preliminary results from a deployed DU confirm a strong consistency with the darkroom calibration, validating the overall calibration approach.

References

[1] S. Adrian-Martinez *et al.* [KM3NeT], *Letter of intent for KM3NeT 2.0, J. Phys. G* ***43****, 084001 (2016).* https://doi:10.1088/0954-3899/43/8/084001

[2] S. Aiello *et al.* [KM3NeT], *The KM3NeT multi-PMT optical module, JINST* ***17****, no.07, P07038 (2022).* https://doi.org/10.1088/1748-0221/17/07/P07038

[3] S. Aiello *et al.* [KM3NeT], *KM3NeT front-end and readout electronics system: hardware, firmware and software, J. Astron. Telesc. Instrum. Syst.,* ***4****, 046001 (2019).* https://doi.org/10.1117/1.JATIS.5.4.046001

[4] The White Rabbit Collaboration website: https://www.white-rabbit.tech/

[5] I. Del Rosso *et al.* [KM3NeT], *The data acquisition system for Phase 2 of the KM3NeT-ARCA neutrino telescope, These Proceedings*

[6] S. Aiello *et al.* [KM3NeT], *KM3NeT broadcast optical data transport system*, *JJournal of Instrumentation, **18**, 02 T02001 (2023).* https://doi.org/10.1088/1748-0221/18/02/T02001

[7] F. Badaracco *et al.* [KM3NeT], *Tests and calibration of detector strings for the KM3NeT/ARCA neutrino telescope*, *These Proceedings*

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