In situ Time Calibration of KM3NeT ARCA

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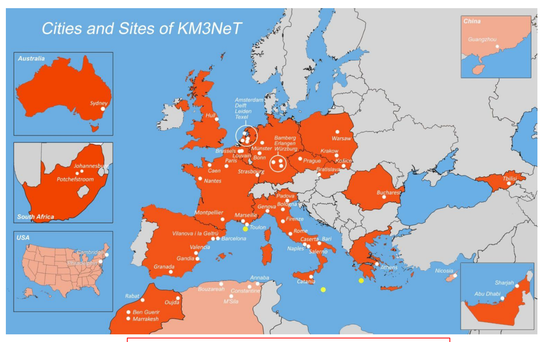
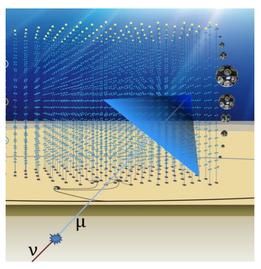
1 KM3NeT: Cubic Kilometre Neutrino Telescope

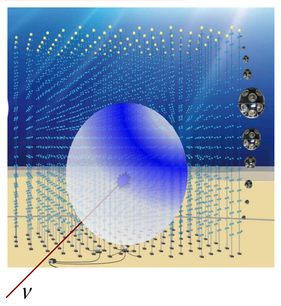
Large-scale underwater neutrino telescope designed to detect high-energy neutrinos (> 100 GeV) by observing the Cherenkov light emitted.
Two detectors:

- ARCA (Astroparticle Research with Cosmics in the Abyss), for high-energy astrophysical neutrinos.
- ORCA (Oscillation Research with Cosmics in the Abyss), for atmospheric neutrinos and determining the neutrino mass hierarchy.



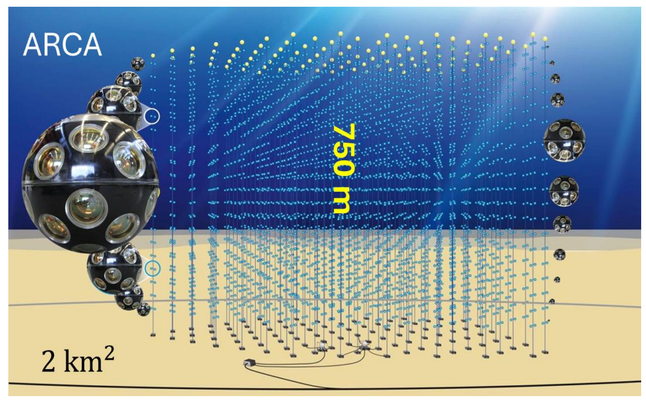
$$\nu_\ell + N \rightarrow \ell + X$$

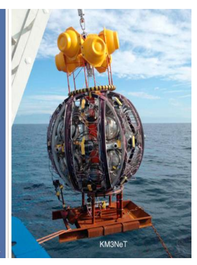


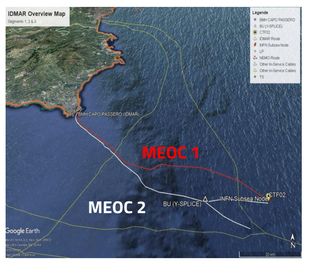


2 The KM3NeT ARCA detector

Located about 100 km off the coast of Sicily, at a depth of 3500 m.
Array of Digital Optical Modules (**DOMs**), anchored on the seabed, grouped into Detection Units (**DUs**).
Power distribution and data communication by Junction Boxes (**JBs**) connecting the system to the shore via two main electro-optical cables (**MEOC 1 and 2**).
Since October 2024 total of **33 strings** currently anchored on the seabed.







3 Calibration of ARCA detector

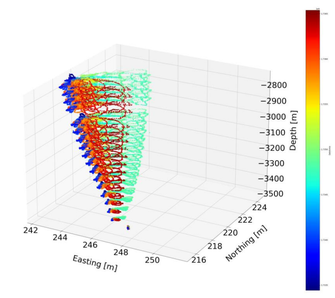
Angular resolution (< 0.1°) requirement for accurate neutrino event reconstruction and background suppression.

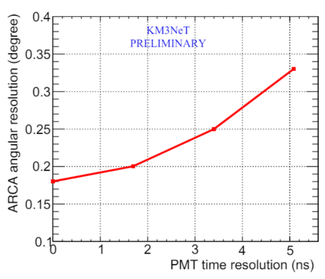
- Accurate spatial calibration through a relative **Acoustic Positioning System**.
- Accurate time calibration through a **nanosecond-level synchronization** across the detector.

Determination of the relative time offsets:

- between PMTs within the same DOM **(intra-DOM)**,
- between DOMs in the same DU **(inter-DOM)**,
- between different DUs **(inter-DU)**.

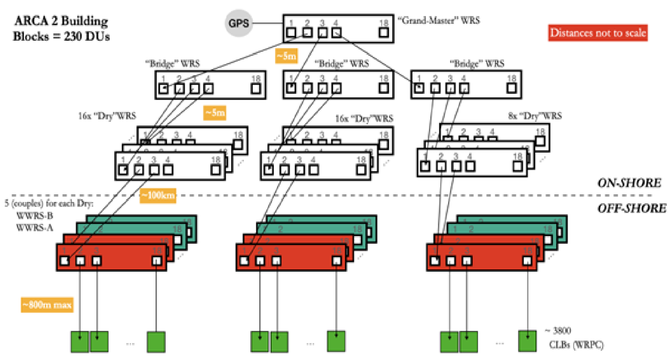
In situ checks through two independent methods: atmospheric muons and laser beacons.





4 The novel White Rabbit time calibration system for KM3NeT-ARCA (Phase 2)

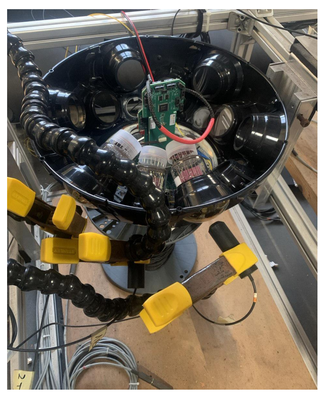
Sub-nanosecond synchronization through the WR protocol over **point-to-point** optical links, using round-trip-time measurements to a common reference. Shore master clock distributes timing through WR switch hierarchy to each DOM via CLB and WWRS.

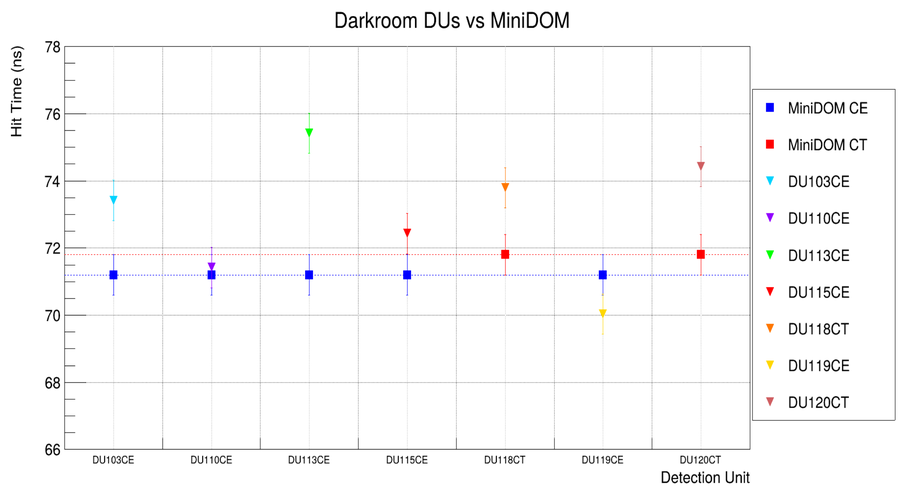


5 The Darkroom Calibration

Prerequisite for time calibration: High-Voltage (HV) tuning, setting the PMT gain to detect photons equal to **3x10⁶** and to ensure a uniform response among PMTs.
DOM time calibration performed with a unique laser source illuminating DOMs on one DU. Laser runs then measure inter-DOM timing using two reference PMTs per DOM, correcting the average hit times for known delays.

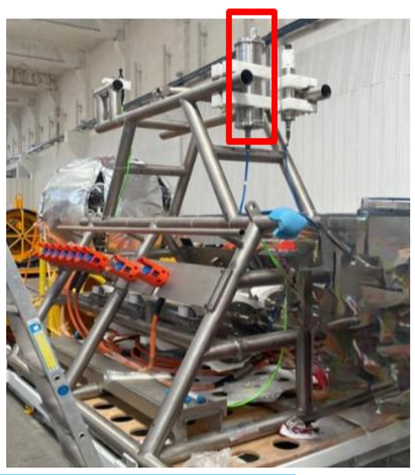
DU time calibration performed at three different darkrooms: Catania, Caserta and Genova with systematic differences due to the **different darkroom setups**.
Intercalibration of the three darkrooms performed with a portable DOM (the MiniDOM).

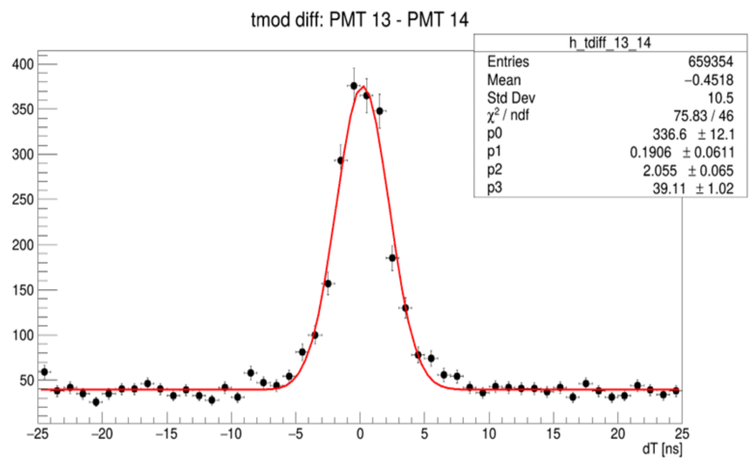




6 The Laser Beacon

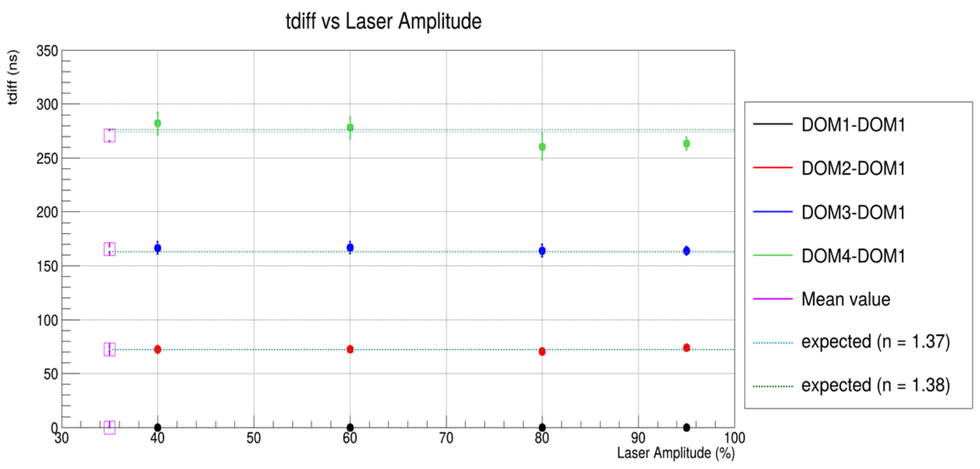
Auxiliary device, installed on the seafloor onboard ARCA-JBs, designed to perform **in situ time calibration** of the detector.
Emits short, intense and isotropic green laser pulses (532 nm) with **sub nanosecond light width.**





Time differences **between PMT pairs** within the same DOM, finding **mean values close to 0**, in agreement with the one determined by intra-DOM time calibration and **sigma values** in a range around **2.2-2.3 ns**, consistent with the PMT Transit Time Spread (TTS).

Time differences calculated by the time of flight measurements, considering **the relative distances between each DOM and the LB** and varying laser amplitudes.
Using an index of refraction of 1.38 for **light group velocity**, the agreement between data and expectations is below 1.5 ns.



7 Conclusions

- White Rabbit Standard successfully implemented, improving time synchronization across the detector.
- A new device, called MiniDOM, developed and used to cross-calibrate the darkrooms laser systems.
- First in situ application of the Laser Beacon for: intra-DOM calibration and inter-DOM calibration. Results consistent with ^{40}K decays and muon track residuals.

References:

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