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The Calibration Units of KM3NeT

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KM3NeT is a deep-sea infrastructure composed of two neutrino telescopes being deployed in the Mediterranean Sea : ARCA, near Sicily in Italy, designed for neutrino astronomy and ORCA, near Toulon in France, designed for neutrino oscillations. These two telescopes are 3D arrays of optical modules used to detect the Cherenkov radiation, which is a signature of charged particles going faster than light in the sea water. To achieve the best performance for the events reconstruction in the telescopes, the exact location of the optical modules, affected by sea current, must be known at any time and the timing resolution between optical modules must reach the nanosecond. Moreover, the properties of the environment in which the telescopes are deployed, such as temperature and salinity, must be continuously monitored because they affect the timing and positioning calibration. KM3NeT is going to deploy several dedicated Calibration Units to meet these calibration goals. The Calibration Base will host several instruments : a Laser Beacon for time calibration and an acoustic emitter and a hydrophone for positioning of the optical modules. To complete the positioning calibration, some of these Calibration Units will be equipped with an Instrumentation Unit hosting environmental monitoring instruments. Because of the difference in size between ARCA and ORCA, the design of the Calibration Unit is not the same for the two sites. This proceeding describes all the devices, features and purposes of the Calibration Units with a focus on ORCA Calibration Unit and its status.

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1. KM3NeT

The KM3NeT [1] infrastructure is composed of two telescopes, ORCA and ARCA. They are built with the same technology, based on the so-called Digital Optical Module (DOM) hosting 31 photomulipliers (PMT), but they have different geometry in order to probe different ranges of neutrino energy. ORCA is mainly dedicated to the study of neutrino oscillations with atmospheric neutrinos at the GeV scale, and ARCA is mainly dedicated to neutrino astronomy through the detection of TeV to PeV neutrinos. Thanks to these DOMs, arranged in a 3D array, we are able to detect the Cherenkov radiation that can be the signature of a neutrino interaction, but also to reconstruct the energy and direction of the incoming particle. To properly do these reconstructions, all the elements of the telescope need to be calibrated in time at the ns level timing accuracy, and in position with an accuracy of about 10 cm, in order to reach the required angular resolution. To perform these calibrations, KM3NeT is therefore equipped with a complete set of instruments and tools that will be described in this paper. Moreover, water properties such as for example salinity, transparency and temperature, have an impact on light and sound propagation, which are two crucial parameters for calibrations. The evolution of environmental conditions must be monitored, that is mainly why Calibrations Units (CU) will be deployed in the vicinity of the telescopes. Finally, sea currents, which induce displacement of the DU, will also be monitored in order to measure possible correlations with other environmental parameters, such as bioluminescence. These studies are also of great interest for Earth and Sea Sciences.

2. Time Calibration

KM3NeT time calibration is done is 3 steps, from the smallest scale to the largest :

1. **Synchronisation of PMTs in the same DOM (intra-DOM):** the Cherenkov radiation coming from electrons produced by the decay of K40 (constant rate) in the sea water is measured on PMTs. Time delays between pairs of PMTs are computed.
2. **Synchronisation of DOMs in the same DU (intra-DU):** thanks to a LED on top of all DOMs, the DOMs above can be illuminated. Knowing the distances between the DOMs, time delays can be computed between DOMs of the same DU. This can be cross checked with down-going muons.
3. **Synchronisation of DUs between them (inter-DU):** This can be done with down-going muons, but thanks to the Calibration Units (CU), a laser source at 532nm with sub nanosecond pulses will be used, the so-called Laser Beacon (LB).

3. Positioning Calibration

Sea currents at the bottom of the sea make the DU move. To know the position of all the elements, acoustic triangulation is used, and to know the orientation of the PMTs, a compass is enclosed in each DOM. The KM3NeT positioning system is hence based on a network of acoustic emitters and receivers, distributed in the volume of the telescope or in its vicinity: receivers are installed on all the DOMs and DU bases and emitters are installed on autonomous tripods and on selected DU bases. In this context, the CU is going to add a permanent acoustic emitter and hydrophone to this long-baseline reference system (see section 4.1.2).

4. Calibration Units

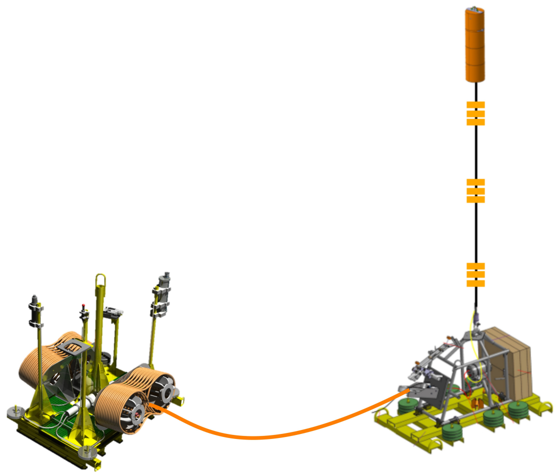


Figure 1: General design of the KM3NeT Calibration Units. The Calibration Base is on the left, and is linked to Instrumentation Unit, on the right. (Not to scale)

The CUs (see figure 1) are composed of two main subsystems: the Calibration Base (CB) and the Instrumentation Unit (IU). The IU is connected to the CB by a ROV wet-mateable interlink cable, about 50m apart in the case of ORCA, and about 700m apart in the case of ARCA. The CB hosts the time and positioning calibration devices on dedicated masts: an acoustic emitter, an acoustic receiver (hydrophone), and, in the case of ORCA, a Laser Beacon (LB). Indeed, the design of the CU is not exactly the same for ORCA and ARCA, mainly because the telescopes have different sizes, but also because of deployment constraints. For example, the ARCA CU will be deployed much farther from the DUs than in ORCA. The LB would be too far away (see section 4.1.4) to illuminate the array, that is why the ARCA LB will be deployed on a Junction Box[1] (JB). The IU is composed of an Instrumentation Base (IB) and an inductive, semi-autonomous and recoverable Instrumentation Line (IL). The IB hosts a titanium container in which there are an interface board and an inductive modem necessary to handle the connection to the IL and the communication with its environmental monitoring instruments. The height of the ILs correspondsto the water columns to be monitored, about 200m for ORCA and about 750m for ARCA. This paper focuses on the ORCA CU, but ultimately, CUs on both sites have the same functions.

4.1 ORCA Calibration Base

The CB will be deployed 40 meters from the ORCA array of DUs. The scientific goals of the CB is to participate to the different steps of the time calibration, but in particular to the time synchronisation between DUs, thanks to the LB. It will also be part of the long baseline acoustic positioning system thanks to the addition of a hydrophone and permanent acoustic emitter. There are also two technical goals, which are to connect and command the IU, that is described in section 4.2. The main components of the CB are described in this section 4.1.

[1]This is where the DUs are plugged to the optical and power network on the seabed.

4.1.1 Steel Anchor

The steel anchor (see figure 2) is painted with a yellow water-resistant painting. It has three masts in order to host the instruments for calibrations, designed to withstand the weight of the instruments, particularly the LB (more than 50kg). The anchor also hosts the interlink cables, one that is going to the IU, and the other to a DU. The dimensions have been optimised for the instrument efficiency (reduce echos of acoustic waves on the seabed) and deployment and transportation constraints. Anodes for protection against corrosion have been added on the bottom sides. The green duck-board is used to protect the painting during transportation and assembly of the instruments. The blue part is a support for one end of the interlink cable so that the remotely operated vehicle that is used for the submarine connections (ROV) can grab it more easily. The Base Module (BM), described in section 4.1.3, is located below the main lifting mast in the middle. The centre of gravity can be adjusted to be on the centre of the whole structure thanks to additional weights placed on the bottom corners.

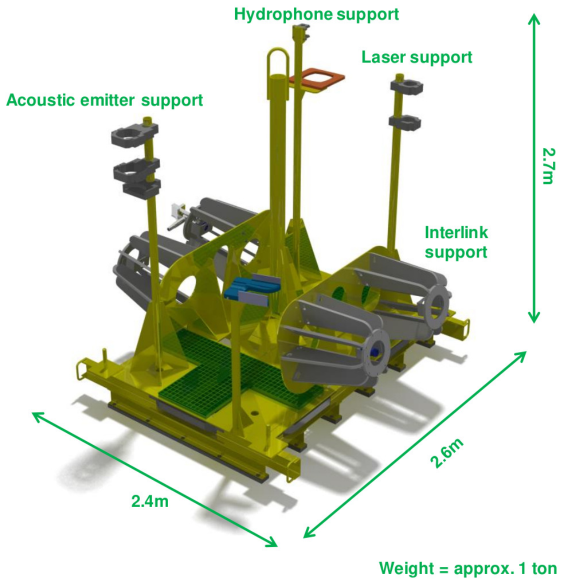


Figure 2: The steel anchor of ORCA CB.

4.1.2 Acoustic Instruments

Hydrophone

It is a commercial device, available at Colmar S.r.l [2] (double gain, DG330 POM-C, Gisma Connector), and primarily used to compute the position of the CB on the seabed. It can also be used for cetaceans monitoring. The hydrophone data are sent to the Central Logical Board (see section 4.1.3) for time-stamping and transmission to shore. The physical connection is made by a RJ45 connector through which the power, data and clock signals are routed from the hydrophone. In the case of the CB, the double-gain feature is useful to avoid saturation due to the LBL emitter being close, but it also allows to study fainter acoustic signals. The sampling frequency of the device is 195.3 kHz, and can be used to record signals from 5kHz to 90kHz. The hydrophone is designed to accept power supply from +9VDC to +18 VDC.

Acoustic emitter

It is a commercial item, available at Mediterraneo Senales Maritimas [3] (MAB 100, Ti Body, Gisma connector), and used for DOM positioning. The emitter has its own modulation signature carried by a signal ranging from 10kHz to 40kHz. The acoustic sensors on the DOMs can then detect unambiguously signals from different emitters at the same time. The core of the device is a FFR SX30 acoustic transducer, and the electronic boards are hosted in a shielded container resisting up to 400 bars (ORCA is operating at 250 bars, ARCA at 350 bars). The emitter is connected to the CB container by MCIL6F/MCIL6M connectors. Communications (commands, emission, acoustics signals properties) and triggers synchronised with the detector master clock are handled through a RS232 line.

4.1.3 Base Module

The base module (BM) is the central unit of the CU. This is where the optical connections between the DU[2], CB and IU are handled. A power board is used to control and dispatch power to all the instruments. All the commands sent from the onshore station are handled by the Central Logical Board (CLB), which comes with a FPGA Mezzanine Board (FMC) where the instruments and instrumentation unit are plugged in. All the elements are described in figure 3.

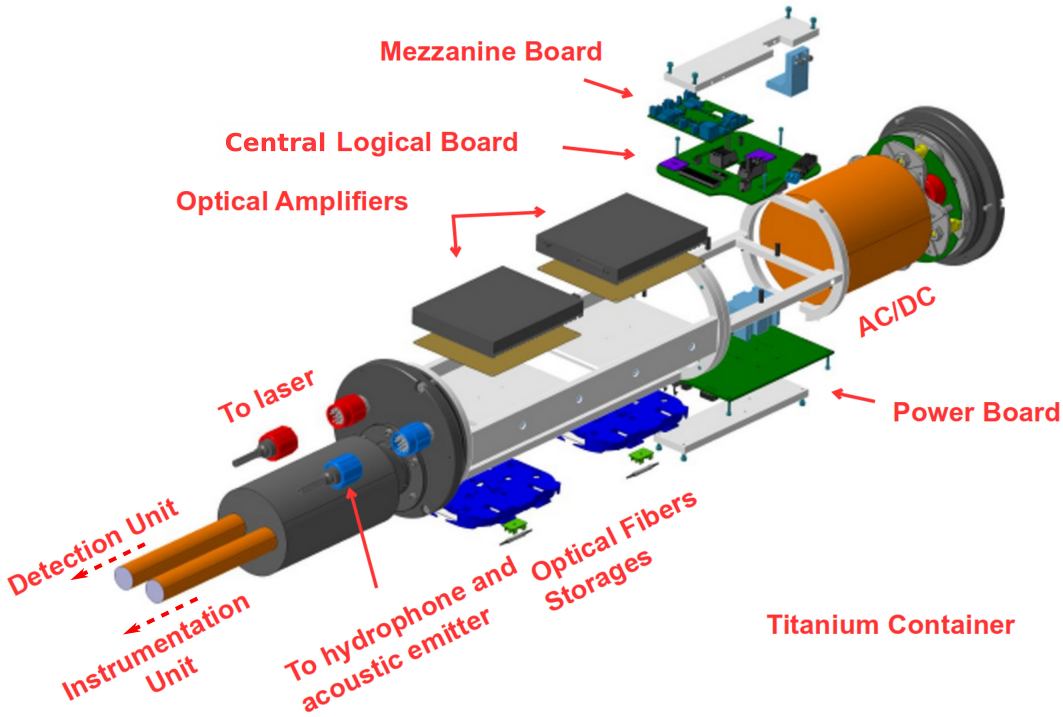
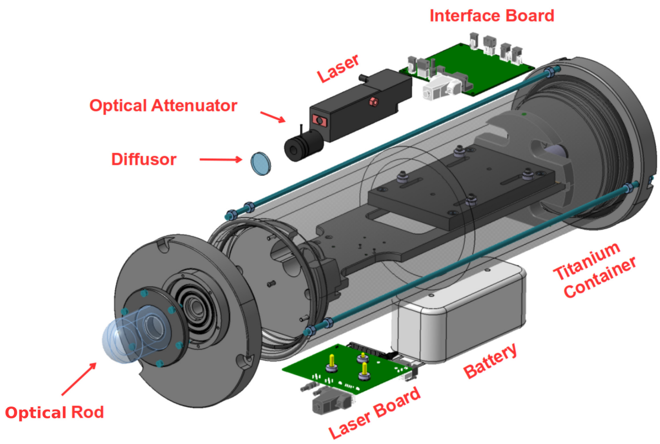


Figure 3: Exploded view of the BM of the CB with its main components. Everything is enclosed in a titanium container.

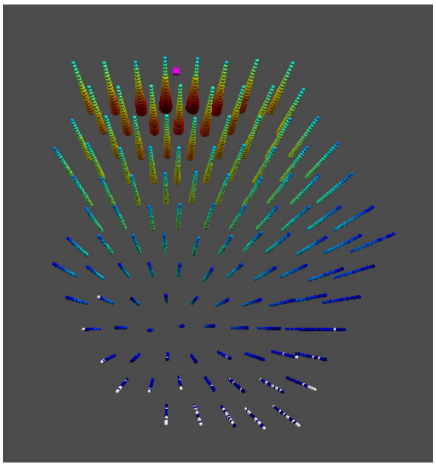
[2]The CB is linked to the main network by the last DU of a daisy chain.

4.1.4 Laser Beacon

The Laser Beacon (LB), entirely developed by the collaboration, will perform time calibration as well as water properties measurements (see figure 4a). The LB is based on a commercial Nd-YAG pulsed laser[3] with sub nanosecond pulses (3.8μJ, 0.4ns FWHM). The frequency of the pulses can be changed from 1Hz to 4kHz. In order to artificially modify the energy of the pulses (*e.g.* to avoid saturation of PMTs close the the LB), an optical attenuator[4] is installed just after the exit of the laser: this is a liquid crystal device in which the polarising axes can be changed thanks to an electrical signal. The laser being polarised linearly, when these two axes are orthogonal, the attenuation is maximal (more that 90% with respect to when the axis are parallel). Then the light goes through a diffuser[5] in order to have a maximum amount of light leaving the LB by the vertical sides of the optical rod in borosilicate, located on one end of the LB. Simulations were made to validate the design of this rod, and check the performances of the LB (see figure 4b). Because the optical part is made from a brittle material, this is the most critical part of the LB. Pressure qualifications are scheduled to validate the design with respect to mechanical constraints.



(a)



(b)

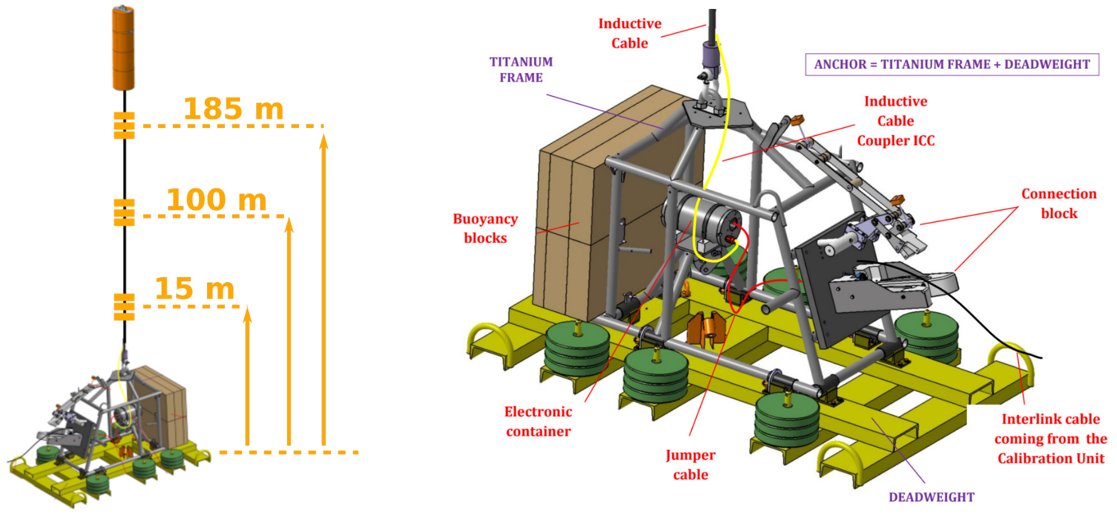
Figure 4: (a): Exploded view of the LB. (b): Simulation for **one laser pulse**. The LB is located on the purple box. All the DUs can be reached and statistics can be increased for the farthest DUs by integrating in time.

The current needed for the laser operation cannot be drawn directly from the main power supply. This is why a nickel-metal hybrid rechargeable battery[6] has been added to the system, to be used as a local power accumulator. The battery is monitored regularly and automatically. It will be charged during periods when the LB is not used. It is foreseen to use the LB from once a month up to once a week. A custom electronics card, the Laser Power Management and Interface (LPMI), has been designed to allow the control of the LB and the battery. This LPMI communicates with the FMC in the BM through a RS232 connection.

[3]STG-03E-140 and MLC-03A-BP1 control board from Teem Photonics [4]
[4]LVA-100-VIS from Meadowlark Optics [5]
[5]OPAL diffuser 10DIFF-VIS from Newport [6]
[6]RS Ni-MH HTD cells connected in series [7], typical 7000mAh capacity, 0.1CmA charge rate, 0.2CmA discharge.

4.2 Instrumentation Unit

The other half of the CU is the IU. It will be used to monitor the water properties along the water column of ORCA, in order to compute the speed of sound in water, which is a crucial parameter for positioning calibration. It is composed of: an Instrumentation Base titanium container (IB), hosting the electronics boards for power management and communication with the CB and the penetrator for the IU to CB interlink cable; an anchor to keep the system on the seabed; and an Instrumented Line (IL) hosting the autonomous instruments powered by internal batteries and kept vertical thanks to a buoy in synthetic foam. An Inductive Cable Coupler[7] (ICC) makes the links between the inductive cable of the IL and the IB. The IU hosts three main instruments, replicated at three different elevations (see figure 5). Because these instruments need to be re-calibrated and batteries changed every couple of years, the IU was made recoverable.



(a) (b)

Figure 5: (a) : The IU will host three main instruments, replicated at three different elevations. (b) : Zoom on the IU anchor, with its main elements highlighted. Not visible on the figure are sacrificial anodes for protection against corrosion in sea water.

4.2.1 Instrumentation Base container

The IB is connected to the CB by a RS422 serial link (50m). Its base module hosts an Inductive Modem Module[8] (IMM) and a serial converter (RS422 to RS232). It also hosts the DC/DC converter to adapt the 12V sent by the CB to the operating voltages of the different components of the IU, one penetrator for the CB/IU connection and another one for the connectivity toward the ICC.

4.2.2 Instrumentation Line

The inductive cable is made of a steel wire protected by a polypropylene layer, except on its ends to allow grounding with seawater. The IMM couples inductively to the cable along the

[7] From Seabird [8], transforms the data from inductive modulation in the cable into an electrical signal.
[8] From Seabird [8], an IMM is using Differential Phase-Shift Keying to allow data transmission with low error rates.

insulated part of the cable, without direct electrical connection, thanks to the ICC. The inductive cable allows for only one current path, so data can only be polled sequentially from one instrument at a time (half-duplex communication). The IL hosts three main commercial probes, replicated at three different elevations (see figure 5a):

- A probe (SBE SMP CTD device from Seabird [8]) to measure conductivity, temperature and depth to compute the sound velocity as a function of temperature, pressure and salinity thanks to the seawater equation of state. The instrument has to be re-calibrated every couple of years.
- A sound velocimeter (Mini SVS from Valeport [9]). This instrument has no native inductive interface, so in order to sent data through the inductive line, it is interfaced with the latter thanks to an RS232-inductive link. Power is provided by a battery, that need to be changed every couple of years.
- A current meter (AQUADOPP from Nortek [10]). Measurements are made thanks to the Doppler effect. The instrument need to be re-calibrated every couple of years.

4.3 Conclusion and Outlook

All the parts of the ORCA CU, including the firmware, software and user interface necessary to control the whole system, are in final configuration and under tests. The final integration and tests between the CB and the IU will start during summer 2021, and the deployment of the CU is currently foreseen in the second half of 2021.

5. Acknowledgement

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[2] Colmar: https://www.colmaritalia.it/
[3] Mediterraneo Senales Maritimas https://mesemar.com/
[4] Teem Photonics: https://www.teemphotonics.com
[5] Meadowlark Optics: https://www.meadowlark.com/index.php
[6] Newport: https://www.newport.com/
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