# The multi-PMT optical module of KM3NeT

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**Abstract.** The KM3NeT Collaboration has developed a multi-PMT optical solution for construction of the two deep-sea ARCA and ORCA telescopes. This approach has several advantages compared to the single-PMT optical modules which have been traditionally used in neutrino telescopes, including a larger photocathode area which is equivalent to three 10-inch photomultipliers. In addition, the multi-PMT approach allows for a high resolution, good positioning and timing calibration. The integration of the optical modules follows a strict protocol and a standardised procedure. It takes place in parallel at eight different integration sites in the labs of the collaboration. In this way, it is possible to reach a significant production rate of more than 100 well-qualified modules per month. In this proceeding, we present details of the technology of the KM3NeT optical module and the integration process.

## 1 Introduction

The extremely low neutrino cross-section and low high-energy neutrino fluxes motivated the scientific community to instrument cubic kilometers of water and ice with arrays of light detectors around the world. These light detectors, called "optical modules", are typically distributed in vertical structures and coupled to electro/optical cables. Such structures have a typical length of several hundreds of meters: they can be distributed according to specific geometries, optimized for the targeted energy region of the neutrino telescope. Moreover, the optical modules can host one or more Photomultiplier Tubes (PMTs), which can have different photocathode areas.

## 2 KM3NeT telescope design

The KM3NeT experiment is currently under construction at two different sites in the Mediterranean Sea:

- **KM3NeT/ARCA** (Astroparticle Research with Cosmics in the Abyss), 90 km offshore Portopalo di Capo Passero (Sicily) at 3500 m depth, aiming at the detection of HE cosmic neutrino sources ($E_\nu \sim$ GeV-PeV).
- **KM3NeT/ORCA** (Oscillation Research with Cosmics in the Abyss), 40 km offshore Toulon (France) at 2500 m depth, aiming at the study of the neutrino oscillations ($E_\nu \sim$ MeV-GeV).

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The two infrastructures share the same technology with different geometries, each optimized for its scientific goal. For ARCA are foreseen 230 Detection Units (DU), divided into two building blocks, to instrument 1 $km^3$ of water; for ORCA are foreseen 115 DUs (only one building block) that will instrument seven megatonnes of water.
To detect an adequate neutrino flux and to exploit the 70 m absorption length and the 100 m scattering length (in water, at 440 nm), sparse instrumentation is sufficient. For example, each 800 m string of ARCA hosts only 18 digital optical modules (DOMs).

## 3 The KM3NeT Digital Optical Module

The digital optical module of KM3NeT has an innovative design: it consists of a 17” diameter high-pressure resistant glass sphere that hosts a dense packing of 31 PMTs and calibration devices (for positioning and timing), electronics for power, readout, data acquisition, and transmission, fig.1 [1]. The segmented photocathode area of about 1200 $cm^2$ in each sphere


[a]

[b]

**Figure 1. Left:** Picture of a multi-PMT digital optical module. **Right:** The components mounted inside a module.

increases the sensitivity of each DOM for the incoming direction of the detected photons: this leads to a broad angular coverage and good photon counting performance. Moreover, the impact of a PMT failure on the performance of the telescope is lowered as the module can still be operated efficiently with fewer PMTs.
The PMTs adopted for the KM3NeT optical module are the Hamamatsu R12199-02 (for the first optical modules) and R14374 [2], which has an improved timing performance (lower TTS). The PMT design is based on a convex bialkali photocathode with a 3” diameter and a 10-stage dynode structure. At an angle of 45° around the head of the PMT, a collection ring made of polished metal provides a 92% reflectance for photons in the 375-500 nm wavelength range [3]. In this way, the acceptance is increased by 20-40%. A light collection ring is shown in fig.2.

The calibration devices mounted inside the DOM, which are used to monitor its orientation with respect to the telescope coordinate system, are a compass and an accelerometer. Their data are sent to shore and converted into the orientation coordinates "Pitch", "Yaw", and "Roll" of the optical module. In addition, an acoustic piezo sensor glued inside the glass of the lower hemisphere constantly monitors the position of the module compared to a long baseline of acoustic emitters anchored to the seabed at known positions. This information is

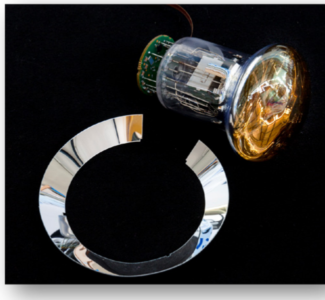

**Figure 2.** A photomultiplier tube with its light collection ring.

updated every minute and stored in the database.

Every DOM is equipped with a 470 nm LED pulsing circuit referred to as a ”nanobeacon”, that emits fast light pulses for timing calibration of neighboring DOMs. The intensity, timing, and pulse frequency of the LED can be controlled remotely from the onshore control station during dedicated timing calibration runs: the aim is to measure the propagation time of light from one module to the adjacent ones.

For the KM3NeT experiment, the PMT photon-signal measurement is reduced to two values only: the photon arrival time and the time-over-threshold (ToT). In this way, the required bandwidth for data transmission is minimized but it is still possible to deliver sufficient information. Then, all data collected offshore are digitized and sent without reduction to shore, where a farm of processors, with data trigger and selection algorithms, reduces the data volume and filters the signals from the background. Afterwards, the observables needed for physics analysis are identified. This approach requires that the electronics clocks of the DOMs are synchronized to sub-nanosecond precision. Moreover, the nanosecond accuracy on the measurement of the arrival times of the photons helps to filter out the background due to $^{40}$K decay and bioluminescence.

## 4 Production model

In its final configuration, KM3NeT will consist of more than 6000 DOMs. In order to build such a large number of optical modules in a reasonably short amount of time, the production has been distributed among over eight integration sites inside the Collaboration. For this, the DOM integration procedure has been optimized for protection against errors and maximization of the production rate: as of today, the KM3NeT DOM integration sites are able to guarantee a baseline production rate of 100 fully qualified DOMs per month.
To build an optical module, the procedure foresees that the two glass hemispheres are filled bottom-up. The integration follows a strict protocol, and is composed of several steps that can be mainly listed as follows: 1) gluing a cooling mechanical structure in the top hemisphere and the acoustic piezo in the bottom hemisphere, 2) mounting the electronics and a penetrator, through which the DOM can be connected to a backbone cable of the DU, followed by a helium leak test and optical fiber splicing, 3) installation of the PMTs and light collection rings into the PMT support structures, 4) functional test, 5) pouring of a transparent two-component silicone gel that ensures optical contact between the PMTs and

the glass, 6) DOM closure, 7) final acceptance test. A dedicated software called "KM3DIA" (KM3 DOM Integration Assistant) guides the integrators through the right sequence of operations, logs all relevant information, and registers all DOM details. In this way, the history of all the components can be tracked in a central database, including functional and acceptance test results.
This organization ensures significant advantages, but it also requires a very high level of quality control and quality assurance for procurement of components and logistics.

## 5 Performance

Given the typical rate of the deep-sea environment, to minimize the effect of ageing (thus maximizing the lifetime of the PMTs), a low nominal gain of $3*10^6$ has been chosen. This corresponds to a ToT for a single photoelectron signal of 26.4 ns for a PMT read with a KM3NeT base.
At such gain value, the ToT response of the PMTs detecting multiple photons has been studied in lab measurements and in situ. The shape of the distribution of the ToT values due to single photoelectron signals can be described with an analytic model that takes into account as free parameters the *gain* and the *gain spread*. Following the model, the PMT gain can be monitored in situ and, if needed, the High Voltage (HV) can be adjusted.

Thanks to the multi-PMT design, it is possible, even with a single DOM, to distinguish the signal due to atmospheric muons from the background induced by $^{40}K$ and bioluminescence, exploiting multi-PMT coincidences, as shown in fig.3.

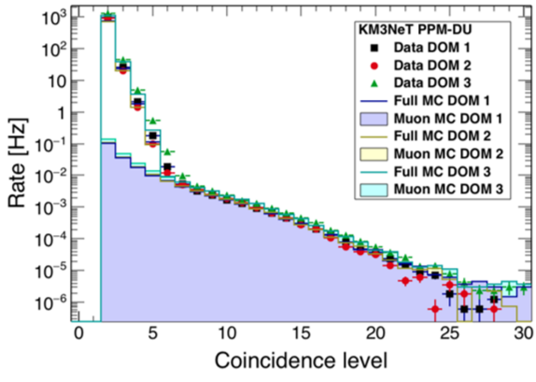


**Figure 3.** Rate of coincident photon detection as a function of the number of coincident PMTs for three different optical modules. This study has been made on the optical modules of the Pre-Production Module DU (PPM-DU) of KM3NeT

## References

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