The Digital Optical Module of KM3NeT

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Abstract. The KM3NeT Collaboration is currently building neutrino telescopes with a total volume of about a cubic kilometre at the bottom of the Mediterranean Sea. The detectors consist of matrices of photodetectors, called digital optical modules, suspended in the depths of the sea by means of vertical structures, called detection units. For the optical modules, KM3NeT uses a new design that hosts 31 3-inch photomultiplier tubes and all the associated electronics inside a pressure-resistant glass vessel with a 17-inch diameter. This solution represents an innovative design with several advantages with respect to optical modules that comprise single large photomultipliers, currently used in all other operational neutrino telescopes. The digital optical module mass production phase has already started in several integration sites, together with the installation of detection units in the depths of the Mediterranean Sea.

1. Introduction

KM3NeT [1] started building a marine research infrastructure hosting new generation cubic kilometer sized neutrino telescopes located at the bottom of the Mediterranean Sea. The detector can be described as a three dimensional matrix of photosensors that are sensitive to the Cherenkov radiation emitted by products of neutrino interactions in the deep water. The arrival time of the Cherenkov light at each sensor, together with the knowledge of their spatial position, are used to reconstruct the trajectory of the particle that produces the Cherenkov light and the direction of the neutrino. The amount of the detected light can provide in addition information about the energy of the neutrino. The photosensors are called digital optical modules (DOMs), and they are suspended in the sea in vertical structures, called detection units (DUs). The modular design allows different spacing between DUs and DOMs in order to cover different energy ranges according to the physics targets. Following its first phase of construction, KM3NeT 2.0 has two scientific objectives: the discovery and observation of high-energy neutrino sources in the Universe and the determination of the mass hierarchy of neutrinos. Two goals for two detectors: ARCA (Astroparticle Research with Cosmics in the Abyss), which is optimized for the observation of astrophysical neutrinos above TeV energies, and ORCA (Oscillation Research with Cosmics in the Abyss), a denser detector that targets atmospheric neutrinos oscillations in few-GeV range [1]. Two goals, two detectors, located at two different marine sites: ARCA located at the KM3NeT-It site, at the South of the Sicilian coast in Italy, 100-km offshore from Capo Passero, at 3400 m of depth, and ORCA located at the KM3NeT-Fr site, 40-km offshore of Toulon, France, at 2475 m of depth.
2. KM3NeT detection units

In the depths of the Mediterranean Sea, the optical modules are suspended in vertical structures named detection units (DU), composed of two parallel vertical Dynema® ropes, anchored to the seabed and kept taut with a system of submerged buoys at the top, to reduce the horizontal displacement of the top relative to the base on the bottom [2].

Each DU is equipped with 18 DOMs, and contains also all the devices required for data transmission and power supply. In deep water, all the DOMs are attached to the ropes by an external titanium collar. Attached to the ropes, there is also the vertical electro-optical cable (VEOC), which contains two copper wires for power transmission and 18 optical fibres for data transmission. In figure 1, an artistic view of the KM3NeT detection unit is shown. At the position of each DOM, two power conductors and a single fibre are branched out by means of the breakout box (BoB) positioned externally to each DOM. For marine deployments, the DU string-like structure is coiled around a large spherical frame, the launcher vehicle, in which the DOMs are positioned in cavities. A surface vessel is used to deploy the launcher vehicle at its designated position on the seabed with a 1-m accuracy. In the depths of the marine sites, a mechanical system activated by a remote operating vehicle (ROV) triggers the vertical unfurling of the string. The launcher vehicle starts to rise to the surface while slowly rotating and releasing the DOMs. At the end, the empty launcher vehicle floats to the surface and is recovered for following deployments, leaving behind the DU in vertical position. In ArCa configuration, with target energies above 1 TeV, each DU has a height of about 700 m, with DOMs 36-m vertically spaced. The DU horizontal spacing is about 95 m. For the ORCA configuration, which targets lower energies in the few GeV range, each DU has a height of about 200 m with DOMs vertically spaced 9 m. The DU horizontal spacing is about 20 m.

3. KM3NeT digital optical modules

The digital optical modules (DOMs), which represent the sensitive part of the neutrino telescope, are composed of pressure-resistant 17-inch diameter transparent glass vessels, each hosting 31 photomultiplier tubes (PMTs) with a 3-inch photocathode diameter and all associated front-end and readout electronics. In figure 2 a picture of a DOM. The multi-PMT solution represents an innovative design, considering that the optical modules of all the other neutrino telescopes, ANTARES, Baikal and IceCube, have optical modules with a single large photomultiplier, typically with a photocathode diameter of 10 inch. The multi-PMT DOM offers several advantages over traditional optical modules using single large PMT: it reaches almost three times the photocathode area of a single glass sphere equipped with a 10 inch PMT and has an almost uniform angular coverage. The influence of the Earth’s magnetic field on small size PMTs is negligible, and thus a magnetic shield is not required. Since each PMT works independently, accurate photon counting can be performed, because the arrival of more than one photon at the DOM can be identified with high efficiency. The segmented photocathode layout also offers directional information with an almost isotropic field of view and provides rejection of optical background in water at the DOM detection level. The proposed DOM design matches with all the main requirements imposed by the project: a low rate of noise signals; a timing accuracy of the order of 1 ns, necessary for an accurate particle-track reconstruction and an efficient background rejection. It has also to withstand to environmental and handling conditions such as hydrostatical pressure up to 400 bar, corrosion, shocks and vibration and to ensure a lifetime of over 10 years.

3.1. DOM main components

The DOM is composed of a transparent spherical glass vessel that contains the 31 PMTs, the associated frontend and readout electronics, calibration components and accessory systems for monitoring and controls. An artistic view of the DOM inside is shown in the figure 2. The vessel is a 17-inch pressure resistant glass sphere produced by Nautilus, composed of two separate hemispheres.
of 14-mm thick borosilicate glass (Vitrovex®). The glass provides an adequate resistance against the water and the extreme hydrostatic pressure of the deep-sea environment, while maintaining a transparency of more than 95% at a wavelength of 350 nm. The two hemispheres comprise the two different parts of the DOM, usually called top and bottom parts. The 31 PMTs are arranged in 5 rings of 6 PMTs plus a single PMT at the bottom pointing vertically downwards. The bottom hemisphere contains 19 PMTs, the top hemisphere 12 PMTs.

**Figure 1.** Artistic view of a detection unit

**Figure 2.** On top: a picture of a DOM with the breakout box and the fixation on the two parallel ropes. On bottom: a sketch of the inner components of the DOM. CLB, power board, octopus boards and PMTs are indicated
In the first phase of the project, a batch of 15000 3-inch Hamamatsu PMT R12199-02 was used for DOM production. The PMTs have a convex bialkali photocathode, with a diameter of 80 mm and a 10-stage dynode structure [3]. Inside the DOM, all the PMTs are kept in place by a nylon 3D-printed support structure, which ensures great accuracy, strength and lightness. In order to increase the photon collection efficiency without increasing the PMT diameter, a reflector ring surrounds the face of each PMT, with an angle of 45° with respect to the PMT axis. The efficiency is thus increased by 20–40%. The space between the support structure, the PMT windows and the glass sphere is filled with an optical silicone gel, which ensures optical and mechanical coupling. It is the Silgel 612 A/B produced by Wacker. The support structure and the gel are sufficiently flexible to be resistant to vibration and shocks during handling and deployment and allow for the deformation of the glass sphere under the hydrostatic pressure in deep-sea sites. An aluminum cooling structure provides heat conduction between the components inside and the environment outside of the sphere. The main warm parts are mounted inside the DOM in thermal contact with this aluminum structure. The power consumption of the DOM with all operating systems is around 7 W. A custom-designed titanium penetrator is mounted on the top hemisphere of the DOM, and contains two copper wires for power transmission and one optical fibre for data communication. On the top hemisphere is also installed a vacuum valve, to evacuate the DOM with a 0.2 Bar under pressure during the closure of the two hemispheres. A pressure gauge is installed inside to monitor the relative pressure into the DOM. Figure 3 shows an exploded view of the whole DOM. The optical module also contains three accessory sensor systems. A LED beacon [4] is mounted on the top hemisphere, to inject calibrated light pulses in water to illuminate the neighboring optical modules for time calibration. An acoustic piezo sensor [5] is glued to the inner surface of the bottom hemisphere for position measurements, in conjunction with the acoustic positioning system at the seabed. A compass system, installed as a mezzanine on the main electronic board, provides compass, tilt- and accelerometer data used to reconstruct the DOM orientation in water.

3.2. DOM electronics

All the electronic devices operative in DOMs have been developed to allow for a readout based on the “All-data-to-shore” concept, in which all the analogue signals from each PMT that pass a preset threshold are digitized and all the digital data are sent to shore via an Ethernet network of optical fibres. Each PMT works as an individual optical sensor, with an individual low-power high-voltage base with integrated amplification and tunable discrimination [6]. The photon arrival time and the time-over-threshold (ToT) of each PMT, are recorded by an individual time-to-digital converter implemented in a field programmable gate array (FPGA). The threshold is set at the level of 0.3 of the mean single photon pulse height and the high voltage base is set to provide a gain of 3×10^4 for each PMT. The FPGA is mounted on the central logic board (CLB) [7], which transfers the data to shore via an Ethernet network of optical fibres by means of a laser receiver/transceiver. The data provided by the PMT bases is collected and distributed to the CLB by means of two so-called octopus boards. The power board [8] provides the DC power for all the systems. This board is monitored and controlled by the FPGA. It is powered with 12V DC supplied via the penetrator mounted in the upper hemisphere of the DOM and connected to a DC/DC converter hosted in the breakout box external to the glass sphere (see figure 2). Each DOM in a detection unit communicates at a dedicated wavelength, which is multiplexed with the other DOM wavelengths for transfer via a single optical fibre to the shore. The broadcast of the onshore clock signal, needed for time stamping in each DOM, is embedded in the Gb-Ethernet protocol. The White Rabbit protocol [9] has been modified to implement the broadcast of the clock signal, and allows for synchronization with 1-ns resolution of all the PMTs inside the DOM and all the DOMs installed in the KM3NeT DUs.
3.3. DOM production
Each digital optical is composed of over 80 different elements: mechanical objects, electronics and sensors. The production is then a delicate process performed following a well-defined procedure that contains over 20 different phases.

Figure 3. Exploded view of the DOM. The main components are indicated and described in the text.

All the components of each DOM are identified by means of a unique code, named UPI (Unique Product Identifier). During the production, all the components are properly registered in the KM3NeT database by means of dedicated assembly software.
The glass vessel is composed of two halves, thus the two parts of the DOM, top and bottom, are constructed separately. The support structures for the PMTs are also segmented in two halves, and each one made of two parts. The white 3-D printing quarters are black painted at the beginning of the assembly phase.

In the top hemisphere, the aluminum cooling system is glued to the inner glass sphere by means of a special tool that define its height and the distance from the glass. Power board and CLB are mounted on the inner part of the aluminum system. The penetrator is mounted in the top glass sphere, and its water tightness is tested by means of a helium leakage test. The optical fibre coming from the penetrator is connected to the laser transceiver/receiver operating an optical splice on the fibre inside. The resulting optical power and attenuation are checked, and results are stored in the database. The piezo sensor is glued to the inner surface of the bottom glass hemisphere. All the PMTs are mounted in the support structures, and their positions are stored in the database. After the positioning of the PMTs, the equipped structures are placed into the glass hemispheres, all the PMT bases are connected to the octopus boards, and a functional test of all systems is performed before applying the optical gel. Whether the test failed, is still possible replace the failing components. The pouring of the gel definitely couples optically and mechanically all the PMTs and the structures to the glass hemispheres of each half DOM. After the proper time of gel polymerization, the two halves are firstly connected electrically, and then mechanically, joining the two surfaces of the glass hemispheres. A 0.2 bar under-pressure inside the DOM is achieved by means of the external vacuum port. The application of a sealant and an anti-marine-corrosion tape on the junction of the two halves close definitely the sphere. Finally, the titanium collar is mounted externally on the DOM.

Each produced digital optical module is submitted to an accurate acceptance test. The results are stored in the KM3NeT database and used during the underwater operative conditions.

**Conclusion**

An innovative multi-PMT digital optical module was designed as the sensitive part of the cubic-kilometer sized KM3NeT neutrino telescope. The mass production of the KM3NeT digital optical modules is currently underway at several integration sites. Installation of detection units at the two KM3NeT sites in the deep Mediterranean Sea has already started. Two detection units have been operational for more than a year at the KM3NeT-It site. Another detection unit is operational at the KM3NeT-Fr site.

**References**

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