Design of a tower-like structure for the KM3NeT underwater neutrino telescope

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***Abstract*. The KM3NeT consortium is presently carrying out R&D activities towards the construction of a cubic kilometre scale Mediterranean deep-sea Cherenkov detector for high-energy astrophysical neutrinos. The goal is to define a complete design of the detector. Several technological options are presently under study, one of which is based on semi-rigid mechanical towers, as high as 800 m, with horizontal extent. The basic concepts of this option are presented.**

***Keywords*: deep-sea neutrino telescope, KM3NeT, neutrino astronomy**

I. Introduction

The European KM3NeT consortium [1], [2] is presently carrying out R&D activities towards the construction of a cubic-kilometre-scale deep-sea Cherenkov detector for high-energy astrophysical neutrinos. The goal is to define a complete design of the detector. Several technological options are presently under study [3]; the final choice will be made following an evaluation based both on physics sensitivities and priorities, technical issues. reliability and costs.

Schematically the detector will consist of an array of vertical structures, the detection units (DU), that support the optical sensors, arranged in such a way to optimally instrument a volume of water of the order of at least one cubic kilometre. The Dus will be interconnected by a seabed cable network, used to distribute power and transmit data and controls to and from the DUs. Finally, one or more electro-optical cables link the array to shore.

The basic elements of the detector are the DUs which are deployed to the seabed; the number of DUs is of the order of hundreds. A DU contains several storeys which are vertically distributed to a height of up to several hundreds metres above the seabed. Each storey hosts PMTs, usually arranged in groups of two or more. The final layout of the DUs on the seabed is still to be defined. However, a spacing exceeding 100 m between DUs is imposed by deployment considerations.

One of the designs under study for the detection units is based on semi-rigid mechanical towers, as high as 800 m, with horizontal extent. In this paper the main characteristics of this design are described.

II. Tower-like structure: general concept

The DU mechanical structure is a semi-rigid system composed of a sequence of up to 20 horizontal elements (storeys) interlinked by a system of tensioning ropes arranged in such a way to force each storey to be perpendicular to its vertical neighbours (Fig. 1). At the bottom of the structure a disposable deadweight anchors the DU to the seabed. A buoy located on top of the structure provides the pull to keep the structure vertical and ensure its rigidity. The storeys support the optical modules and the pressure vessels for the local storey electronics as well as the ancillary instrumentation needed (hydrophones for the acoustic positioning system, environmental probes, etc.). The storeys will have a length ranging from 6 to 10 m, depending on the results of physics optimisation studies.

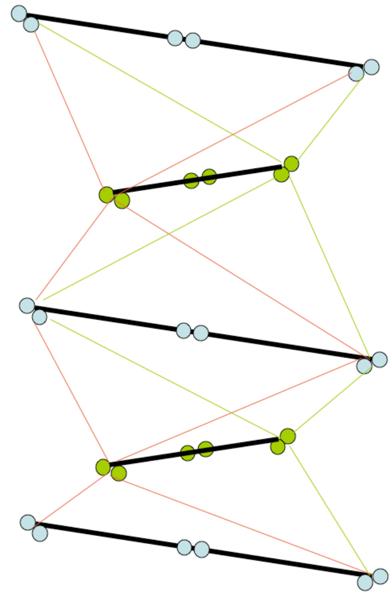

Fig. 1: Layout of the Detection Unit

The exact position and orientation of the optical modules as well as the total number of storeys and their vertical spacing will be defined according to optimisation studies to maximise the neutrino telescope sensitivity to astrophysical neutrinos. These studies will include detailed Monte Carlo simulations of the detector performance [4].

Interconnection of the storeys for power feeding and readout is provided by a lightweight cable that is kept separated from the system of tensioning ropes.

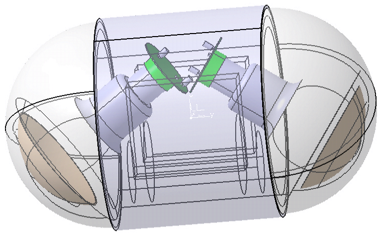

Fig. 2: The "capsule" Optical Module.

III. Optical Modules

Two options for the construction of the Optical Modules are under evaluation:

- a 13" diameter pressure-resistant glass sphere housing one 8" or 10" PhotoMultiplier Tube (PMT) similar to the solution adoped by ANTARES [5] and NEMO [6];
- a 10" capsule housing two 8" PMTs (Fig. 2). This capsule is composed by two glass hemispheres joined by a metal cylinder. The readout electronics could be located inside the capsule in thermal contact with the metal housing with advantage also of a simpler insertion of the signal and power cable penetrator into the metal cylinder.

IV. Data readout and transmission

Since the requirement for the KM3NeT telescope is to transmit all digitised data to shore and perform all triggering on-shore, each PMT needs a bandwidth of about 20 Mb/s. The DU is operated far from the shore laboratory; typically it is placed at distances of several tens of kilometers, and produces a stream of data on the order of 4 Gb/s.

The data produced by the Optical Modules in a storey and signals form calibration equipment including optical beacons and acoustic triangulation systems are collected by electronic boards located in a vessel placed on the storey. These data are then transmitted to shore, using optical fibres because of the distance and the high data rate. DWDM techniques must be used to provide the necessary bandwidth using the limited number of fibres in the main electro-optical cable. Each DU will use a maximum of 2 DWDM colours. Considering that up to 128 colours with 50 GHz spacing can be used on a single fibre, the data of 100 DUs could in principle be transported with 4 fibres with a bidirectional system and 100% redundancy.

A. *Storey electronics*

A single electronics board, placed in the storey either in a dedicated container or in one of the Optical Module containers, will manage all the data transmission and interfaces with storey peripherals. The storey electronics has interfaces to the vertical backbone electro-optical cable and to all the peripherals on the storey: the Optical Modules; the hydrophones for acoustic positioning; the slow control devices; the timing calibration modules.

Each PMT signal will be digitised at 200 MHz, which allows for a sub-nanosecond time resolution thanks to an interpolation processing. The samples are collected during all the time the pulse height is above an adjustable threshold and two "pre trigger" samples are added to the data. A typical s.p.e. signal is described by at most 10 samples (100 bits on average). Considering a constant rate due to optical noise up to 250 kHz per PMT, the contribution to the data flow from 6 PMTs amounts to 150 Mb/s per storey.

Each storey will contain two hydrophones for acoustic positioning purposes. Their front-end digitisation electronic is integrated in the single storey board. The samples are then packed and sent through the data transmission interface to a real-time sampling system on-shore. The hydrophones are synchronously sampled and phased with respect to a common time reference (GPS). Each hydrophone signal will be digitised at 192 kHz, with a 24 bit ADC producing a data flow of 10 Mb/s per storey. This solution allows for transmitting to shore all hydrophone data with a minor increase of the total data rate.

Data from PMTs and hydrophones will be merged in a unique data frame that, including overhead, will amount to less than 200 Mb/s.

For the front-end electronics two options are foreseen: the first is based on the design of a custom ASIC capable of sampling the PMT signal in analogue way, while the second is based on commercial Fast ADCs. The slow control data flow is managed by an embedded processor that controls all the needs of the electronics status, monitoring, environmental instruments, timing calibration module setup.

Even though the standard solution is to have all the electronics inside the storey container, the use of front-end boards inside each optical module is also considered. This choice depends on the power dissipation and cost.

B. *Detection Unit backbone*

The DU backbone architecture consists of a daisy-chained unidirectional optical path (Fig. 3). Control information from shore arrives at a Tower Junction Box (TJB) located in the tower base. From there it is passed directly to the highest node of the chain. Each node extracts the clock from the stream and regenerates it locally in order to clean the timing jitter. Each node of the chain handles the payload of all the connected nodes, receiving the stream from the previous node and transmitting it to the next one. At each stage, a node can "Drop" its own payload and "Add" new information to the stream.

This daisy-chain structure can be implemented using either a copper or a fibre backbone. The final decision will be taken when the telescope geometry, the number of sensors per DU and per storey, the distance between

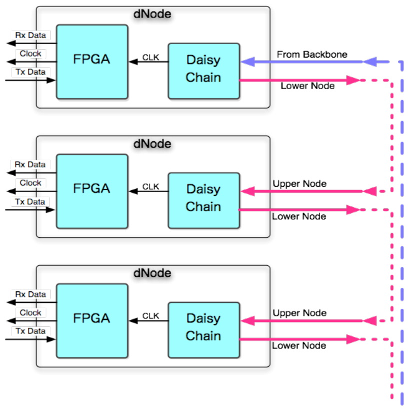

Fig. 3: Scheme of the daisy chain architecture.

storeys will be fixed. The choice will be determined taking into account cost, power dissipation, and redundancy.

The fibre option proposed has several advantages over already assessed and proven systems. Since each node communicates only with adjacent nodes, the backbone can be implemented with single tracts of fibre driven using "Black and White" (B&W) lasers; moreover, since the distance between storeys is on the order of 50 m, there is a big optical power budget that allows for using cheap and standard connectors and cables. In addition, a simple mechanism based on a optical splitter can be used to bypass faulty nodes. In order to increase the backbone reliability, the DU is served by two separated backbones, for example one for even and the other for odd storeys. With this architecture, we have as many data streams as backbones; each backbone can then be assigned a colour to exchange data to the shore. The backbone will be routed into the optical network either in the TJB or just changing the last B&W laser with a DWDM device.

The use of a copper backbone implies a stringent limitation on cable length depending on maximum data rate. Therefore the implementation of the copper backbone is based on a quadruple-backbones architecture. Each backbone in turn is based on a double daisy-chain, one of which carries clock and control data and the other to transmit the digitised PMT signal. The transmission is highly asymmetrical reflecting the nature of the experiment which produces a high amount of data and requires a small amount of information for system control and monitoring. Therefore, the up-going chain is at a lower speed than the down-going chain. Both chains transmit clock and data on the same medium: the receiver of the slow chain recovers the clock and regenerates it to provide a clean and stable reference for the storey devices. The system is thus inherently synchronous. In the TJB, an electronics board will be placed to bridge the signals from the copper backbones to the optical fibre of the optical network. The data rate transmission on the slow chain has been tested at 163.84 Mb/s, with a line signal rate of 196.608 Mb/s due to the synchronous protocol redundancy. This relatively low value allows for clock recovery and cleaning up to hundreds of meters guaranteeing a sub-nanosecond precision as required by the experiment constraints. The down-going chain is designed to allow a data rate of 1.2 Gb/s over distances between nodes up to about 50 meters.

The two implementations share many aspects: the daisy-chain has the same topology, with short tracts of cable connecting adjacent floors; the integration and testing process is much simplified by the possibility of adding one node after the other regardless of the rest of the chain. A main advantage of copper versus fibre backbone is the safe handling of the backbone cables, the cheap submarine connectors, the low cost of electronics components and the high reliability of the components themselves. For an optical daisy-chain, the high optical power budget allows for using less demanding fibres, thus increasing the safety in cable handling and integration with respect to previous systems (NEMO and ANTARES). For the same reason it will be possible to use standard cables and connectors which are widely used in submarine operations. The backbone will be routed into the optical network either in the TJB or just changing the last B&W laser with a DWDM device. Typically small form-factor pluggable (SFP) lasers are used which proved to be highly compatible.

C. Seafloor network

The seafloor cable network will comprise several Secondary Junction Boxes (SJB), to which groups of DUs are connected, and a Primary Junction Box (PJB) that connects to the Main Electro Optical Cable (MEOC). This network will ensure both the power distribution from shore to the DUs and the distribution and multiplexing/demultiplexing of the data exchanged with the shore station (Fig. 4).

Each off-shore DU transmits two serial data streams at 2.5 Gb/s to shore. The shore station transmits slow-control signals to the apparatus using the WDM technique. Each group of 5 DUs needs 11 wavelengths: two for each DU and one for the slow control signal broadcasted to the group. A 11-channels band filter can route and distribute the channels for the group.

In order to implement the mux-demux function for the 11 channel bands over the same fibre, a ring topology is proposed. Each node of the ring is a band filter. The ring has a double path for redundancy: in each path the band filters can operate as Add&Drop devices. To further minimise the usage of the the fibres of MEOC, a bi-directional data transport is realised between the optical network off-shore and the dual part on-shore using optical circulators.

Eight groups will use 80 channels for data transport (off-shore to on-shore) and 8 channels for slow control

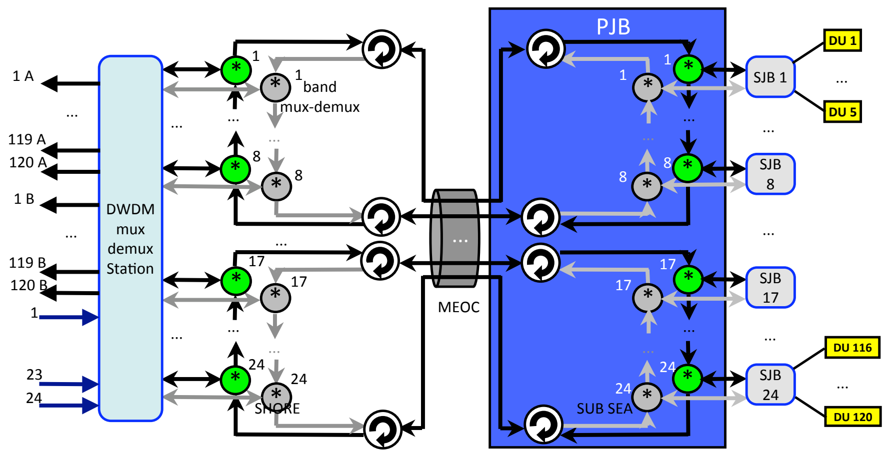

Fig. 4: Layout of the optical network.

signals (on-shore to off-shore); all these channels can be allocated in the conventional transmission window (C-band) centred at 1550 nm. In order to serve an apparatus of 120 DUs only 6 fibres in the MEOC are needed.

V. Deployment

An essential aspect of the design is the deployment concept. The described detection units are transported and deployed as compact packages. The package is dimensioned to fit in the space of a standard 20-feet transport container so to have the possibility of final integration at distributed locations and easy transport to the deployment site. During deployment each compact package is lowered to the seabed and then self-unfurls to its final height upon an acoustic signal.

Deployment operations will be performed using a surface vessel equipped with a Dynamic Positioning (DP) system. Such kinds of vessels are needed to allow a safe operation and correct positioning of the detection units. Operations on the seabed will be performed by means of a Remotely Operated Vehicle (ROV) controlled from the surface.

VI. Conclusions

KM3NeT is well advanced on its way towards the design of a cubic kilometre scale underwater high neutrino detector. Several technological options for the construction are presently under study. The final choice will be made following an evaluation based both on physics sensitivities and priorities, technical issues and costs, and will be described in a Technical Design Report that will be published at the end of the Design Study project. One of designs under study is based on semi-rigid mechanical towers with horizontal extent. The main elements of this design, mechanical structure, optical sensors, data readout and transport, have been described.

VII. Acknowledgements

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