KM3NeT: Next-generation neutrino telescope in the Mediterranean Sea

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Abstract

The successes of the ANTARES detector have demonstrated the feasibility and value of deep sea neutrino telescopes, as well as their versatility through Earth and Sea sciences. KM3NeT is a distributed undersea research infrastructure in the Mediterranean Sea that will host a network of next-generation neutrino telescopes. With the ORCA telescope at the KM3NeT-Fr site, the main objective is to determine the neutrinos mass hierarchy by studying atmospheric neutrino oscillations. The ARCA telescope at the KM3NeT-It site will allow for high energy neutrino astronomy. The telescopes consist of a regular 3D array of Digital Optical Modules, each composed of 31 photomultipliers, equally spaced along flexible lines anchored on the seabed. This multi-photomultipliers concept yields a factor three increase in photocathode area, compared to a design with a single 10 inch photomultiplier, leading to a significant cost reduction. Moreover, this concept allows for an accurate measurement of the light intensity and offers directional information with an almost isotropic field of view. A detailed overview of the detectors, their construction status and their physics program will be presented. The calibration techniques will be discussed, with an emphasis on time calibration, water properties and positioning measurements.

Keywords: KM3NeT, ANTARES, Neutrino Telescope, Deep Sea, Digital Optical Module, ARCA, ORCA, Neutrino Mass Hierarchy, High Energy Neutrino Astronomy

1. Introduction

The ANTARES neutrino telescope [1] has demonstrated the feasibility of large volume detectors in the deep sea to perform neutrino studies. The detected Čerenkov light produced by relativistic particles is the signature of a neutrino interaction (see figure 1). Only neutrinos can cross the Earth without being absorbed. Thus, the strategy is to focus on identifying upward-moving muons. The key concept of the KM3NeT experiment is that the same technology can be used to study neutrinos over a wide energy range: from GeV (KM3NeT/ORCA) to PeV and above (KM3NeT/ARCA). Because of its deep-sea environment, the KM3NeT Research Infrastructure will also provide almost real-time and long-term Earth and Sea science measurements. For further information, see [2].

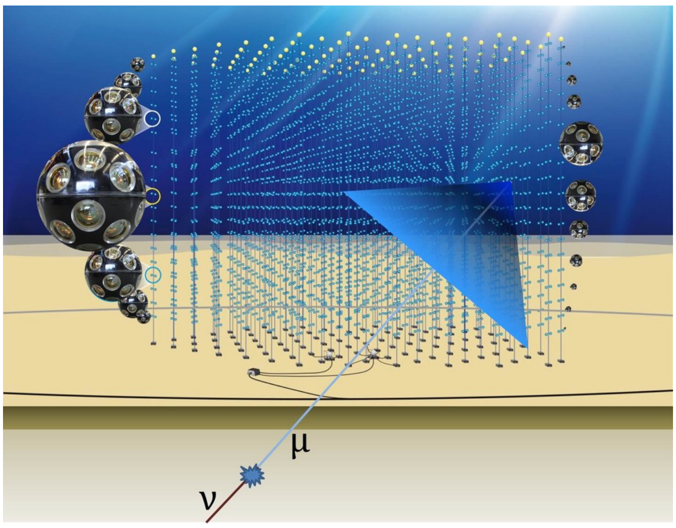

Figure 1: Simulated Track event display.

2. The KM3NeT Collaboration

The KM3NeT Collaboration has participants from 51 institutes and groups in 41 cities, distributed over 15 countries in

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Europe, Russia and Africa. More than 250 researchers take part in this experiment. Because of its great potential in fundamental physics, the astroparticle and astrophysics communities have included KM3NeT as a high priority project in their European road maps (APPEC/ASPERA, AstroNet) and the European Strategy Forum on Research Infrastructures (ESFRI) in their priority project list.

3. The Detectors

The Čerenkov light detected in a neutrino telescope comes from two event topologies. The first one, labeled as *shower*, includes Neutral Current (NC) interactions of all three neutrino flavours and Charged Current (CC) interactions of ν_e and ν_τ. The second one, labeled as *track*, indicates the presence of muons produced in ν_μ and ν_τ CC interactions.

For both event topologies, tracks and showers, the size of the detector depends on the energy of the primary neutrino, scaling with energy. To investigate high energy neutrinos (PeV), the detector should hence be bigger than for low energy (GeV) neutrinos. The key technical concept of KM3NeT is then to have the exact same technology shared among different detectors, and to allow a *flexible design* in order to have different detector sizes for an almost identical technical implentation.

This so-called *flexible design* is usually referred to as a *building block*. The KM3NeT infrastruture will consist of three building blocks, each composed of 115 *lines* (DUs, Detection Units). Equaly spaced along these strings are 18 Digital Optical Modules (DOM), each composed of 31 Photo-Multiplier Tubes (PMTs). A whole building block is thus a 3D array of photo sensors.

The first detector, described in subsection 3.2, will allow for high energy astronomy (from TeV to PeV neutrinos and above), and will be composed of two of these building blocks. It is referred to as ARCA, Astroparticle Research with Cosmics in the Abyss, and is located on the KM3NeT-It Site, offshore Capo Passero in Sicily-Italy.

The second detector, described in subsection 3.3, will allow for the study of neutrino oscillations at the GeV scale. It is composed of one building block, and it is referred to as ORCA, Oscillation Research with Cosmics in the Abyss. It is located on the KM3NeT-Fr site offshore Toulon, France.

Initiated in ANTARES, the *All-data-to-shore* concept is used for the readout of the detectors. The two sites are linked to shore with a network of cables for electrical power and high-bandwidth data communication.

3.1. The Digital Optical Module

The true improvment from KM3NeT's precursor ANTARES lies in its Digital Optical Modules (see example in picture 2). They consist of a transparent 43 cm diameter glass sphere, same size as the ANTARES Optical Modules, each containing 31 photo-multiplier tubes (PMT) and their associated readout electronics.

Compared to optical modules using a single large PMT, the DOMs are able to house three to four times the photo-cathode area, with an almost uniform angular coverage (see picture 3). Moreover, the segmented photo-cathode area enables the high efficiency identification of more than one photon arriving at the DOM. Optical background rejection is highly improved using this directional information.

Figure 2: Picture of a DOM.

Inside these DOMs, all the PMTs are fixed by a 3D printed support. A reflector ring placed around the top of the PMTs increases the photon collection up to 40%. Optical contact between the support and the glass is made possible via an optical gel. Both the 3D printed support and the gel are flexible enough to resist to huge hydrostatic pressure constraints on the glass.

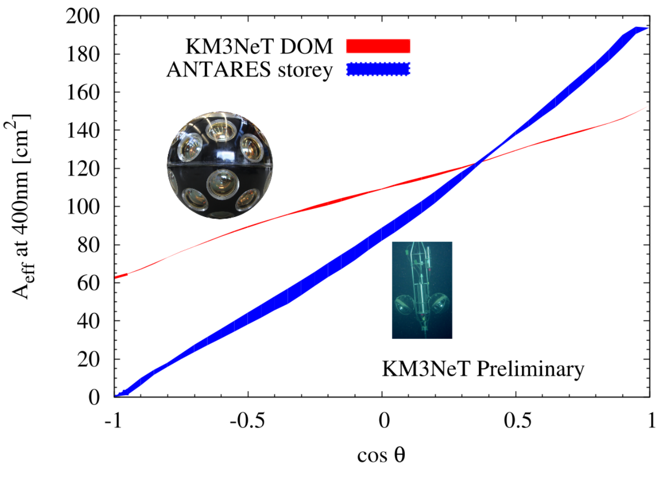


Figure 3: Comparison of the effective area at 400nm, for KM3NeT and ANTARES. θ is the zenith angle.

Each of the PMTs' recordings and conversion of the arrival time and the time-over-threshold (ToT) are made by individual time-to-digital converter implemented on a FPGA (Field-Programmable Gate Array). The FPGA is installed on the central logic board and enables the transfer of data to shore on an Ethernet network of optical fibres. As the data transfer to shore is made by a single optical fiber, the data from each DOM (1 Gb.s^{-1}) of a line are multiplexed with a dedicated wavelenght.

The PMTs have a photo-cathode diameter of at least 72 mm and a length of less than 122 mm. The photo-multiplier tubes have a minimum gain of 10^6 (ten stages dynode structure).

3.2. ARCA

The two ARCA building blocks will be implanted at a depth of 3500m. The horizontal spacing between the lines is 90m and the vertical spacing between the DOMs is 36m (full height of ~ 700m). One full block corresponds to 0.5 Gton of instrumented sea water.

The main science objective of ARCA is the detection of high-energy neutrinos coming from sources in our Galaxy and from further cosmic origin. For this purpose, the Mediterranean Sea is a perfect location, since most of the potential Galactic sources are in the Southern sky. The design of ARCA has been set in order to optimize the sensitivity to these sources.

The first goal of ARCA is to measure the signal of cosmic neutrinos observed by IceCube using a different methodology, improved resolution and a complementary field of view. In less than a year of operation, ARCA will have a sensitivity better than 5σ for the diffuse neutrino flux.

3.3. ORCA

The ORCA building block will be implented at a depth of 2500m. The horizontal spacing between the lines is 23m and the vertical spacing between the DOMs is 9m (full height of ~ 200m, more than 2 times smaller than ARCA). It corresponds to 8 Mton of instrumented sea water.

From MeV to tens of GeV, neutrino oscillations have been observed by a series of experiments using solar, atmospheric, reactor and accelerator neutrinos. These oscillations imply the existence of non-zero neutrino masses. But oscillation experiments are only sensitive to squared-mass differences between two neutrino eigenstates and not to their absolute value. In a 3 ν scheme, there are two independent squared-mass differences: the first one can be measured from solar and long baseline reactor experiments and the second one from atmospheric neutrinos.

The main goal of ORCA is thus to determine the Neutrino Mass Hierarchy (NMH), the ordering of neutrino mass eigenstates, which is presently not known. The strategy is to probe the impact of matter effect in the ν_μ survival probability and ν_μ ν_e appearance at atmospheric mass scale. The same method will be followed in HyperKamiokande [3] and PINGU [4]. The expected ORCA performance for NHM is 3σ in 4 years of operation.

The science goals of ORCA also include the improvement of the measurement of oscillation parameters like Δm^2_{32} and the θ_{23} mixing angle from the PMNS matrix. ORCA will also be able to perfom indirect searches for low mass dark matter and supernovae monitoring. Other science topics include Earth tomography, seismology but also sea science related topics like oceanography, bioacoustics and bioluminescence [5, 6].

4. Construction Status

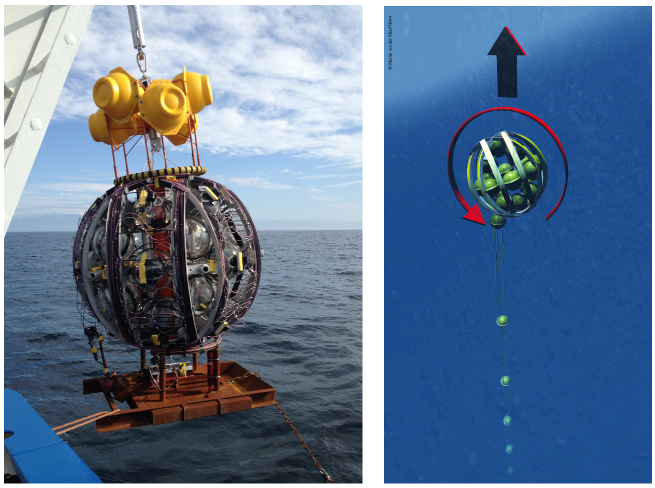
4.1. The production chain

The integration of the DOM and DUs are made on different sites, because of the different equipments and storage facility needed. In May 2018: 5 DOM integration sites (in Netherland, Italy, Germany and Greece) were operational and 3 (in France and Marocco) were in preparation; 3 DU integration sites in Netherland and Italy were operational, 1 in preparation in Italy. PMTs, electronics, PMT 3D support, glass spheres and optical gel are assembled on the DOM integration sites, and then the DOMs, line base, cables, line structure and buoy are assembled in the DU integration sites. Throughout the integration procedure, the quality is controlled following a rigorous list of QA/QC tests that was carefully designed and is continuously updated.

4.2. Deployment

The deployment process, inspired from ANTARES, has been developed in order to optimize storage and boat transportation, thus reducing the overall cost by enabling the transportation of many DUs on the deployment boat. The string is furled around the *launcher vehicle*, which is a spherical frame with dedicated slots for the DOMs. The anchor at the bottom of the string is external to the *launcher vehicle* and is used as the interface with the seabed infrastructure, to provide sufficient weight to keep the string properly fixed on the seabed and to house the electronics needed to make the link between the string and the onshore station (interlink cable with a wet-mateable connectors) and the *base container*.

Optical components and acoustic device (receiver) used for positioning of the line with respect to the detector are located in the *base container*. Before the unfurling of the string (see picture 4a), the connection of the string to the network, made by a Remotely Operated Vehicle (ROV), has to be verified onshore. Then, an acoustic signal is emitted. The launcher vehicle is released and starts to rise to the surface while slowly rotating and releasing the DOMs (see picture 4b). The DU is finally inspected by the ROV.



(a) (b)

Figure 4: (a): Picture of a launcher vehicule. (b): scheme of the unfurling process, courtesy Marijn van der Meer/Quest.

4.3. Timelines and costs

2/3 of KM3NeT budget will be used for the lines, 1/3 for the PMTs only. The remaining 1/3 is shared among the shore station, computing, deployments and deep-sea cable network. One DU costs ~ 300k euros. Concerning ORCA, 1 line has been deployed by the end of 2017, and 7 lines will be deployed by the end of 2018. The full detector (115 lines) will be in operation by the end of 2020. For ARCA, 2 lines have been deployed by the beginning of 2016, and 24 lines will be deployed by the beginning of 2019. The full detector (115 x 2 lines) will be in operation by the end of 2020.

5. Calibration Technics

The performance of neutrino telescopes strongly relies on the precise timing calibration of the detectors elements. Using external light sources, the time precision of the detectors will reach the sub-nanosecond. These external light sources are also used to measure water properties.

As the sea environment continuously changes, the positioning calibration of the detector elements is crucial. The exact location of the optical modules, which is particularly affected by sea currents, is monitored with an acoustic system.

Other environmental conditions like water temperature and salinity are also going to be continuously monitored since they affect light and sound propagation.

For calibration purposes, KM3NeT will deploy several so-called *Calibration Units* (CUs) on a peripheral position with respect to the neutrino detector. Each one of them will be at least composed of a Calibration Base (CB) hosting the calibration devices. Some of these CUs will also be equipped with an *Instrumentation Unit* (IU), composed of a base and a semi-autonomous and recoverable inductive line supporting environmental monitoring instruments. Optical backgrounds and nanobeacons are also used as calibration tools.

The KM3NeT positioning system is based on a network of acoustic transmitters and receivers distributed in the detector field: on the CBs and on the base of the strings. This network forms a long-baseline (LBL) reference system for the triangulation of the positions of the DOMs. On each DOM, there is a Digital Acoustic Receiver (DAR). (See picture 5) The achieved precision is expected to be ~ 10cm.

The mechanical frame of the Calibration Base is composed of several masts on top of which are fixed the different calibration instruments. It also houses one aluminium shielded container hosting the electronics board of the device which can resist pressures up to 400 atm. The instruments of the CB are: a Laser Beacon (time calibration and measurement of water optical properties), an acoustic receiver (for the position of the CB on the seafloor), an acoustic long-baseline emitter (DOM positioning) and a KM3NeT Central Logic Board (CLB) and its FPGA mezzanine card (FMC) for data transmission and acquisition.

The Instrumentation Unit (IU), directly inspired by the ALBATROSS project, is composed of an Instrumentation Base (IB) that fixes an inductive Instrumentation Line (IL) on the seafloor. The instruments work on batteries and some of them require periodical calibrations. The line is recoverable in order to make these calibrations and to change the batteries. The technology used by the IL will be the same for ORCA and ARCA. The height of the IL will be adapted to the detector configuration in order to instrument the full water column. The typical measurement periodicity of the instruments will be 20 minutes. The instruments of the IL are: Current meter (inclination of the lines), Sound Velocimeter and CTD probe to measure Conductivity, Temperature and Depth in order to infer sound velocity through seawater equation of state. Moreover, such instrumented lines are very usefull for real-time and long-term observation of the sea environment, providing for example useful informations on climate change and on deep-sea ecosystems.

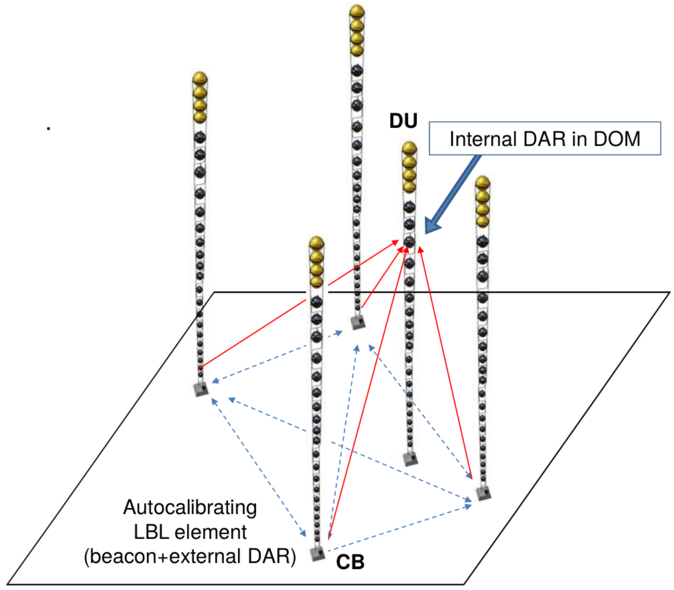


Figure 5: Principles of the acoustic triangulation system.

The decays of ^{40}K, which has a stable concentration, constitute one of the main optical background and are used to make internal DOM calibration, such as time calibration and PMT efficiency measurement. Up to 150 Čerenkov γ are emitted per decay. A cross calibration is possible by analysing down-going muons. In addition, nanobeacons on the top of each DOM allow for inter-line calibration using light pulses. These pulses are seen by the DOM directly above, but also by higher ones due to light diffusion in water.

References

[1] M. Ageron et al., ANTARES Coll, 2011 , ANTARES: the first undersea neutrino telescope, arXiv:1104.1607

[2] S. Adrián-Martínez et al., 2016, Letter of Intent for KM3NeT

[3] K. Abe et al., 2011, Letter of Intent: The Hyper-Kamiokande experiment detector design and physics potential, arXiv:1109.3262

[4] M. G. Aartsen et al., 2014 , IceCube PINGU Coll., Letter of Intent: The Precision IceCube Next Generation Upgrade (PINGU), arXiv:1401.2046

[5] S. Bourret et al., 2018, Neutrino oscillation tomography of the Earth with KM3NeT-ORCA

[6] A. Holford et al., 2015, Sub-sea environmental observatory integrated with the KM3NeT neutrino telescope infrastructure in the Mediterranean Sea