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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].

2. The KM3NeT Collaboration

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

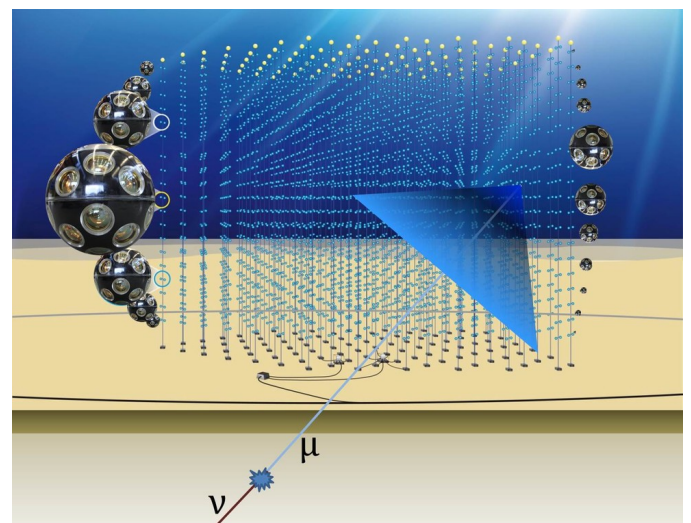


Figure 1: Simulated Track event display.

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18 Europe, Russia and Africa. More than 250 researchers take
 19 part in this experiment. Because of its great potential in fun-
 20 damental physics, the astroparticle and astrophysics communi-
 21 ties have included KM3NeT as a high priority project in their
 22 European road maps (APPEC/ASPERA, AstroNet) and the Eu-
 23 ropean Strategy Forum on Research Infrastructures (ESFRI) in
 24 their priority project list.

25 3. The Detectors

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

32 For both event topologies, tracks and showers, the size of the
 33 detector depends on the energy of the primary neutrino, scal-
 34 ing with energy. To investigate high energy neutrinos (PeV),
 35 the detector should hence be bigger than for low energy (GeV)
 36 neutrinos. The key technical concept of KM3NeT is then to
 37 have the exact same technology shared among different detec-
 38 tors, and to allow a *flexible design* in order to have different
 39 detector sizes for an almost identical technical implementation.

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

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

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

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

62 3.1. The Digital Optical Module

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

69 Compared to optical modules using a single large PMT, the
 70 DOMs are able to house three to four times the photo-cathode



Figure 2: Picture of a DOM.

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.

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 be-
 tween 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.

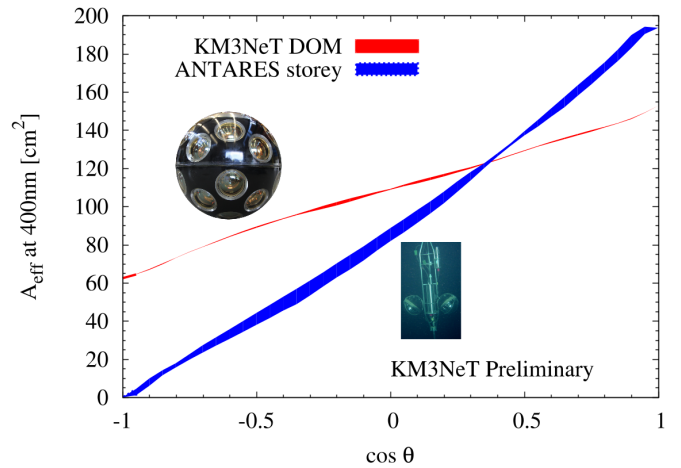


Figure 3: Comparison of the effective area at 400nm, for KM3NeT and ANTARES. θ is the zenith angle.

Each of the PMTs' recordings and conversion of the arrival
 time and the time-over-threshold (ToT) are made by individ-
 ual time-to-digital converter implemented on a FPGA (Field-
 Programmable Gate Array). The FPGA is installed on the cen-
 tral 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 wavelength.

The PMTs have a photo-cathode diameter of at least 72 mm

91 and a length of less than 122 mm. The photo-multiplier tubes¹⁴⁴
92 have a minimum gain of 10^6 (ten stages dynode structure).¹⁴⁵

93 3.2. ARCA¹⁴⁷

94 The two ARCA building blocks will be implanted at a depth¹⁴⁸
95 of 3500m. The horizontal spacing between the lines is 90m and¹⁴⁹
96 the vertical spacing between the DOMs is 36m (full height of \sim ¹⁵⁰
97 700m). One full block corresponds to 0.5 Gton of instrumented¹⁵¹
98 sea water.¹⁵²

99 The main science objective of ARCA is the detection of high¹⁵³
100 energy neutrinos coming from sources in our Galaxy and from¹⁵⁴
101 further cosmic origin. For this purpose, the Mediterranean Sea
102 is a perfect location, since most of the potential Galactic sources
103 are in the Southern sky. The design of ARCA has been set in
104 order to optimize the sensitivity to these sources.¹⁵⁶

105 The first goal of ARCA is to measure the signal of cosmic¹⁵⁷
106 neutrinos observed by IceCube using a different methodology,¹⁵⁸
107 improved resolution and a complementary field of view. In less¹⁵⁹
108 than a year of operation, ARCA will have a sensitivity better¹⁶⁰
109 than 5σ for the diffuse neutrino flux.¹⁶¹

110 3.3. ORCA¹⁶³

111 The ORCA building block will be implanted at a depth of¹⁶⁴
112 2500m. The horizontal spacing between the lines is 23m and¹⁶⁵
113 the vertical spacing between the DOMs is 9m (full height of \sim ¹⁶⁶
114 200m, more than 2 times smaller than ARCA). It corresponds¹⁶⁷
115 to 8 Mton of instrumented sea water.¹⁶⁸

116 From MeV to tens of GeV, neutrino oscillations have been¹⁶⁹
117 observed by a series of experiments using solar, atmospheric,¹⁷⁰
118 reactor and accelerator neutrinos. These oscillations imply the
119 existence of non-zero neutrino masses. But oscillation exper-¹⁷¹
120 iments are only sensitive to squared-mass differences between¹⁷²
121 two neutrino eigenstates and not to their absolute value. In a 3 ¹⁷³
122 ν scheme, there are two independent squared-mass differences:¹⁷⁴
123 the first one can be measured from solar and long baseline reactor
124 experiments and the second one from atmospheric neutrinos.¹⁷⁶

125 The main goal of ORCA is thus to determine the Neutrino
126 Mass Hierarchy (NMH), the ordering of neutrino mass eigen-
127 states, which is presently not known. The strategy is to probe
128 the impact of matter effect in the ν_μ survival probability and
129 $\nu_\mu \nu_e$ appearance at atmospheric mass scale. The same method
130 will be followed in HyperKamiokande [3] and PINGU [4]. The
131 expected ORCA performance for NHM is 3σ in 4 years of op-
132 eration.

133 The science goals of ORCA also include the improvement
134 of the measurement of oscillation parameters like Δm_{32}^2 and the
135 θ_{23} mixing angle from the PMNS matrix. ORCA will also be
136 able to perform indirect searches for low mass dark matter and
137 supernovae monitoring. Other science topics include Earth to-
138 mography, seismology but also sea science related topics like
139 oceanography, bioacoustics and bioluminescence [5, 6].

140 4. Construction Status

141 4.1. The production chain

142 The integration of the DOM and DUs are made on different
143 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 Morocco) 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 assem-
bled 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 ex-
ternal 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 elec-
tronics needed to make the link between the string and the on-
shore 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.

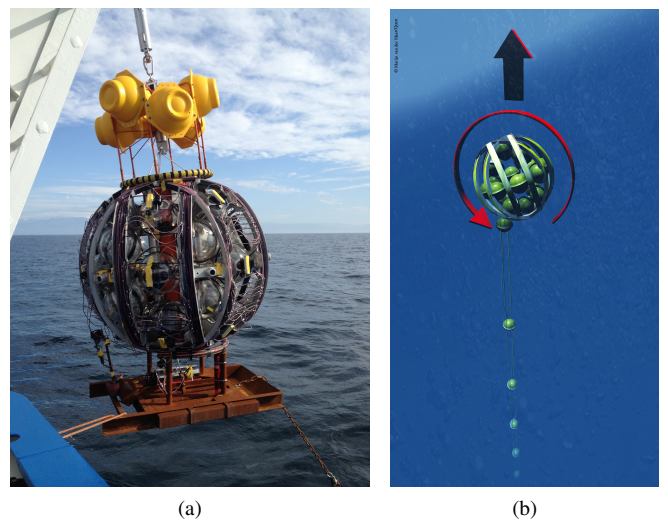


Figure 4: (a): Picture of a launcher vehicle. (b): scheme of the unfurling process, courtesy Marijn van der Meer/Quest.

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

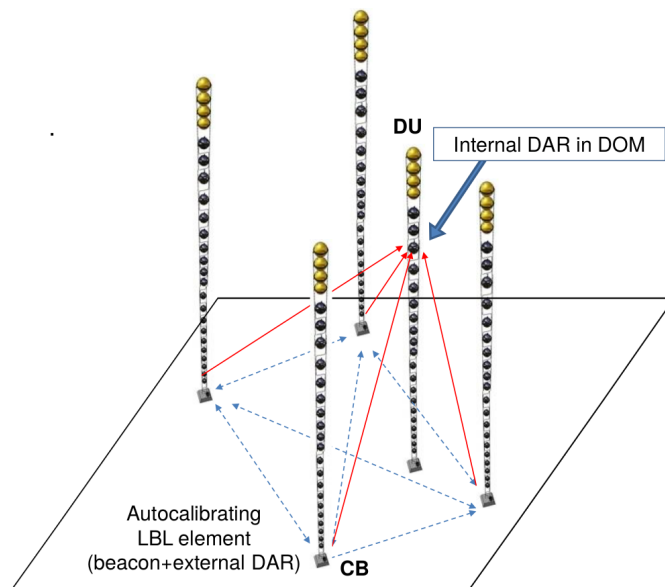


Figure 5: Principles of the acoustic triangulation system.

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 useful for real-time and long-term observation of the sea environment, providing for example useful informations on climate change and on deep-sea ecosystems.

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.

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