KM3NeT status and plans

Paul Kooijman (for the KM3NeT consortium), *University of Amsterdam, the Netherlands*

Abstract

The KM3NeT project is aiming to produce the most sensitive neutrino telescope ever built. Its envisaged location in the deep Mediterranean Sea provides optimal sensitivity for neutrino sources near the centre of our Galaxy. In 2010 a number of major decisions have been made on technical implementations of the telescope. An optical module containing many small (3”) photomultipliers was adopted. The readout electronics is incorporated into this digital optical module, as are several calibration instruments. The site-to-shore communication is provided by an electro-optical cable allowing for point-to-point communication between each optical module and the shore station carried on a single optical channel. A mechanical supporting structure consisting of twenty 6 m long bars with an optical module at each end is being designed. The bars have a vertical separation of 40 m, giving the full structure a height of about 900 m. The foreseen budget allows for construction of 300 such structural units. Together they will create an instrumented volume of 4 km^3, when the layout is optimised for the detection of Galactic sources. The sensitivity to these point sources surpasses that of any other telescope by two orders of magnitude, and allows for a 5 σ discovery in 5 years for RXJ1713.

Introduction

Detecting high energy neutrinos from sources in the cosmos unambiguously indicates the presence of charged pion production. This process is by its nature accompanied by production of neutral pions which through their decay generate photons. Whereas high energy photons can also be produced by the energy boosting process of inverse Compton scattering, the only process for producing charged pions is that of the interaction of high energy protons with either matter or photons. Neutrinos therefore act as a marker for the presence of high energy protons in astrophysical objects. These objects would then be candidates of the sought-after sites producing the (ultra-)high energy cosmic rays that bombard our atmosphere.

An underwater neutrino telescope works mainly on the principle of detecting particles formed in the interaction of neutrinos with the seawater or the nearby rock of the seabed. The interaction products, most notably the muon formed in the charged current interaction of a muon-neutrino, travel at a velocity exceeding the speed of light in water and therefore emit Cherenkov radiation along their path. The excellent transparency of the sea water allows for this light to be detected at distances exceeding 100 m from the muon track. The telescope therefore consists of a three dimensional array of photo-sensors distributed sparsely over a large volume of sea water. Using the expected time-space correlations of the detected light, the muon track can be reconstructed and its direction determined.

Major backgrounds are expected from the interaction of cosmic rays in our atmosphere, which produce large fluxes of high energy muons traversing the detector from above. Therefore the telescopes are most sensitive to the neutrinos that traverse the Earth and are registered through the detection of upward travelling muons. As a consequence the position on Earth defines, to a large extent, to which part of the sky the telescope is sensitive. Telescopes in the northern hemisphere are predominantly sensitive to the southern sky, which contains the Galactic centre. This area, that contains many sources of high energy photons [1], is therefore the prime objective for the KM3NeT detector, the new telescope network to be built on the bottom of the Mediterranean Sea.

Technical design

In designing a detector to be placed at the bottom of an ocean there are several difficulties that must be addressed:

- the ambient hydrostatic pressure, up to 50 MPa;
- the corrosive environment of the seawater;
- the distance from shore for the communication;
- the force on the structure due to the sea currents;
- the backgrounds due to downward going muons;
- the backgrounds due to ^{40}K decay.

For the physical process of detecting neutrinos from sources near the Galactic centre there are additional requirements

- optimal angular resolution of the reconstructed muon;

combined with a

- large sensitive area facing the Galactic centre.

This led during the KM3NeT design study[1] to an investigation of many feasible designs, which have been studied in detail. In 2010, during the preparatory phase, a decision on the optimal technical design was taken.

Optical Modules

The optical sensors are housed in commonly used deep-sea glass instrumentation spheres. In order to address the backgrounds from ^{40}K, multiple photons (most likely signal) must be distinguished from single photons (most likely potassium background) with high efficiency and purity. To provide an efficient measurement of the atmospheric muon background the efficiency of the module should have as uniform an acceptance in angle as possible. Finally to reduce the number of high pressure feed-throughs as large a photo-sensitive area as possible is put in a single sphere. The final design [2] is shown in **Error! Reference source not found.**. The major optical component is a 10-stage photomultiplier of 76 mm diameter, surrounded by a light concentrator ring [3]. A custom low power (<45 mW) Cockroft-Walton base [4] provides the high voltage for the photomultiplier. It includes an amplifier-discriminator, for time-over-threshold readout, on the output, contained in a custom ASIC [5]. The photomultipliers are run at relatively low gain (~10^6), to reduce the collected anode charge over the lifetime of the experiment.

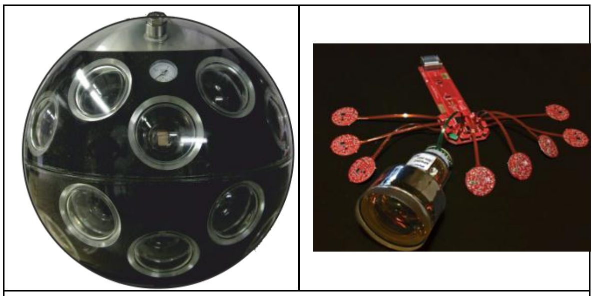

Figure 1: The Multi-PMT digital optical module, PMT, HV base and signal collection board.

The spheres house 31 of these tubes (19 in the lower hemisphere and 12 in the upper). Following the IceCube example, all digitizing and readout electronics is housed in this KM3NeT digital optical module (DOM). Finally the DOM also has instrumentation that allows for the reconstruction of the position (acoustic piezo-sensor) [6], determination of the orientation (compass and tilt meter) and calibration of the timing (the "nano-beacon" LED pulser) [7].

Four manufacturers[2] have expressed interest in the production of the photomultiplier tubes. Some of them have already produced prototypes that are close to or pass specification [8,9]. Typical quantum efficiency achieved for instance by ETEL surpasses 30% and dark noise is kept to a level of 1250 Hz at 22º C with a threshold set at 30% of the mean pulse height expected for a single photon [10]. Four prototype modules are presently being assembled for deployment in the sea in spring 2012.The manufacturers have indicated that the large scale production needed for KM3NeT are within their capabilities.

The electronics necessary for the readout of the DOM is based on an FPGA. The time stamping of the signals from the 31 photomultipliers is performed by a set of time-to-digital converters configured inside the FPGA [11]. The FPGA also controls the photomultiplier high voltages and the additional sensors in the DOM, via standard bus protocols I^2C and SPI. A full description of this system is provided in the paper of F. Louis submitted to this conference [12].

Mechanical support structure

The sensors must be distributed over a large volume of seawater and to that end are supported on narrow vertical structures that are weighted down on the seabed by an anchor and held vertical with the aid of a buoy at the top of the structure. To simplify the seafloor network and connectivity A large number of DOMs must be placed on a single structure. For the performance of the detector, it then turns out to be advantageous to have a horizontal extension to the structure. This allows for more efficient triggering and an increase of efficiency for low energy neutrinos and a reduction of ambiguities in the tracking. The size of the horizontal extent is of course a compromise of performance and ease of handling of the structure during assembly and deployment. These considerations have led to a

[1] European Union: FP6 – 011937/FP7 – 21225

[2]ET Enterprises Ltd, Riverside Way, Uxbridge, U.K.; Hamamatsu Photonics K.K, Japan; Zhan Chuang Photonics, Hainan, China; MELZ-EVP, Zelenograd Moscow, Russia

structure of 6 m length with a DOM positioned at each end (a storey). Twenty of such storeys are suspended, alternately perpendicular, from four 5 mm Dyneema® ropes with an inter-storey distance of 40 m. The active storeys start at 100 m from the seabed, so that the total height of the structure (a tower) is 860 m.

Two cables run the length of the structure. These cables have been developed using the pressure balanced oil filled technique and incorporate two copper conductors for the power delivery to the optical modules and 11 single mode fibres for the data transfer [13].

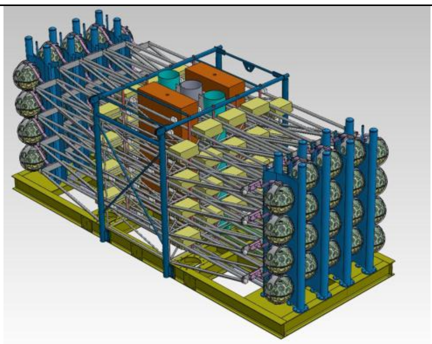

Figure 2: The stack of storeys before unfurling.

For deployment a full tower is brought as a single package to the seabed. The buoy is released and the storeys are drawn from the package one-by-one. During this process the ropes held taut by unwinding them from braked synchronized drums. The readout cables are stored, spiralled around two of the ropes. The storey includes sufficient buoyancy to stabilize the structure during unfurling, while still allowing for a controlled release of each storey. Hydrodynamic calculations have shown that the structure can be held vertical within 160 m (top displacement) in sea currents of up to 30 cm per second. At present a full set of prototype structures are being manufactured for test deployments in 2012 [14].

Readout Network

To allow for the data selection to take place in a computer farm on shore, where the data of the full detector are brought together, the connection from the telescope to the shore must have a high bandwidth. Taking into account the counting rate produced by the ^{40}K background and the overall size of the detector, this leads to a total transfer rate of several hundred gigabits per second. The scheme uses fibre-optics with dense wavelength division multiplexing (DWDM) to provide up to 80 readout channels (wavelengths) per optical fibre running from telescope to shore. Each DOM will have its own optical channel directly to shore. In this scheme all communications lasers are housed on shore, reducing undersea power requirements. The continuous wave laser light is amplified in the deep sea and split such that individual wavelengths are sent, on one downlink fibre, to each tower. There the wavelengths are split into 20 separate fibres that each run to a DOM. At the DOM the carrier wave is modulated with the data from the photomultipliers and reflected back using reflective electro-absorption modulators (REAM)[3]. The data from all DOM fibres are collected, multiplexed and transferred via an uplink fibre to shore. Because of the reflection at the DOM it is possible to incorporate a system to measure the time delay incurred by the signals in the transport to shore. The system has been lab-tested and industry standard bit-error rates have been achieved for transfers over 100 km of fibre. The timing accuracy for this situation has been measured to be better than 50 ps.

A system using partial modulation of the downlink carrier signal provides a means of broadcasting slow-control messages for setting of the DOM high voltages and control of the instrumentation. More detailed descriptions of the optical readout and the shore data acquisition can be found in other contributions to this conference [15,16]

Sensitivity to Galactic Sources

In the KM3NeT technical design report [17] the sensitivity to different physics channels has been investigated. As an initial design criterion an energy spectrum behaving as E^{-2} was assumed. The plethora of high energy gamma ray data from the H.E.S.S. collaboration has shown quite convincingly that this is, for Galactic sources, an oversimplified and indeed an overoptimistic spectrum. The best measured sources all exhibit a cut-off in the spectrum depleting the flux significantly for energies above a few tens of TeV. The detector layout presented in the TDR has been revisited.

The super nova remnant RXJ1713.7-3946 is an example of a Galactic source. Assuming the measured HESS gamma ray flux is attributable fully to neutral pion decay, the neutrino flux can be easily predicted. This assumption has been

[3] CIP Technologies, Ipswich, U.K.

strengthened by the data of Suzaku [18] and Fermi [19] and subsequent analyses of the spectral shape of the high energy photon spectrum [20]. This source has been used as a benchmark for optimising the detector layout. The lower average energy produced by this source requires a reduction of the inter-tower distance from the 180m value used in the TDR to a value of 130 m. The lower mean value of the energy also has a negative influence on the angular resolution of the detector as the scattering angle between the neutrino direction and the produced-muon direction becomes more significant. Three independent simulation and reconstruction packages have been used to determine for how many years KM3NeT would have to collect data to observe a 5σ signal above background from RXJ1713.7-3946. For the TDR detector (two hexagons comprising 157 towers each with a tower spacing of 180 m) all simulations give a data taking period in the range of 12 to 13 years to obtain 5 σ. A more circular setup with randomised positions, with the same average distance, gives equal results. By reducing the distance between towers to 130 m the data taking period decreases to 7 to 8 years. Distributing the optical modules more uniformly by increasing the length of the bars to 15 m reduces this still further to around 6 years. Table 1 shows for one of the simulation-reconstruction packages the development of signal and background. Further information on two of the analyses are presented by P. Sapienza [21] and A.Tsirigotis [22] in this conference

Table 1: Background and signal events for different detection units, together with 5σ discovery time.

Dist	Bar length	Years for 5σ	N_{source} $[year]^{-1}$	N_{back} $[year]^{-1}$
180	6 m	12.5	3.2	4.1
130	6 m	8.0	2.7	1.6
130	15 m	6.0	2.5	0.9

The present reconstruction packages only use crude energy estimates to separate signal from background. First indications are that using a more sophisticated algorithm could improve the sensitivity by of the order of 20%. The use of an unbinned likelihood method will improve the signal significance by again some 20% especially if the morphology of the source is taken into account. The angular resolutions obtained in the three analyses are all in the 0.25° to 0.3° range. The extent of the source is taken to be a uniform disk with opening half-angle of 0.6°, whereas the H.E.S.S. measurements show significant hotspots within the disk. All in all a reasonable estimate of the time needed to obtain a 5 σ discovery of neutrino production in RXJ1713.7-3946 is 5 years.

Technically placing so many towers so close together is challenging although feasible. However the cluster size of 157 towers remains somewhat problematic. An investigation has been performed into how small the cluster size could be made before a significant impact on the physics would be felt.

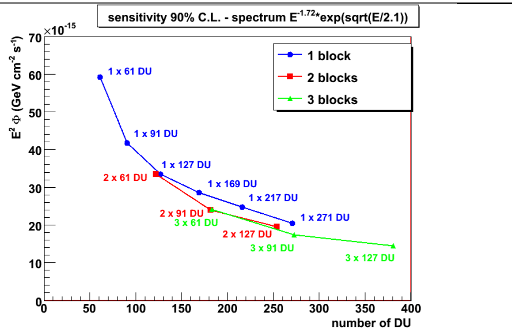

Figure 3:Evolution of the sensitivity as a function of the number of towers and the number of blocks.

Figure 3 shows the flux sensitivity evolution for increasing numbers of towers in a detector. This is done for one two and three clusters. It shows clearly that the splitting of the detector into smaller building blocks is not detrimental for the sensitivity to sources of the type RXJ as long as the size of these building blocks contains of the order of 60 to 80 towers. Therefore the most likely scenario will be that the detector will be built in 4 or 5 such blocks. It is interesting to note that each building block is very similar in size to the IceCube detector. Such a separation opens up the possibility of placing units in different sites in the Mediterranean, which could be advantageous for funding and for the associated sciences which are also part of the KM3NeT consortium, while not impacting on the Galactic source sensitivity and only marginally increasing costs.

Other Sources of Neutrinos

The reduction of the overall volume of the detector does of course impact on some of the other physics topics hoped to be covered using the KM3NeT Telescope. Compared to the TDR configuration the triggered effective area has increased by 40% in the region of 10 to 100 TeV but has decreased at the highest energies by about 25%. This means that the sensitivity to signals from extragalactic sources has diminished by approximately this amount.

For the cosmogenic neutrinos for which the best signature is the presence of an extremely high energy shower contained within the detector, the sensitivity has decreased proportional to the volume by 30%. The expected number of signal events for cosmogenic neutrinos varies according to the distribution of acceleration sources in the universe and the chemical composition of ultra-high energy cosmic rays from about 0.01 to 1 events/km^3/year. This would correspond to 0.4 to 40 events in the lifetime of the experiment down from 0.6 to 60 (see R. Shenadze in this conference [23]).

The sensitivity to dark matter annihilation will improve, but a reanalysis of this topic in the light of the new detector configuration is not yet finalised.

Finally the regions above and below the galactic plane that have recently been observed by the Fermi satellite to emit gamma radiation, “Fermi Bubbles”, are potentially a source of high energy neutrinos. One model for explaining this phenomenon [24] predicts a significant flux of neutrinos from these same bubbles. The flux is such that with the KM3NeT sensitivity a 5 σ signal will be observed in about one year making the bubbles the most significant neutrino production sites (See R. Coniglione [25] in these proceedings).

Planning

The major technical decisions have been taken and at the end of the Preparatory Phase, the consortium is ready to move via a preproduction phase to construction. The consortium has received sufficient funding to initiate the construction once the full design is validated. A series of validation tests are planned for 2012. These include the in situ test of DOMs including the full read-out, the tests of the deployment of the full mechanical structure and the validation of the vertical readout cable. The design and construction of the first production assembly lines will also take place in the near future. Presently the consortium is defining the legal structure for after the end of the Preparatory Phase. The most likely scenario will be the establishment of KM3NeT as a European Reasearch Infrastructure Consortium (ERIC).

Conclusions

The technical design of the KM3NeT detector has been optimised and prototype construction is underway in order to validate all elements of the design. The telescope will have sufficient sensitivity to observe neutrino production in Galactic sources.

Bibliography

[1] H.E.S.S colaboration. H.E.S.S. source catalogue. [Online]. http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/sources/

[2] P.Kooijman et al. (ed.), Conceptual design report for KM3NeT. 2008.

[3] O. Kavatsyuk, Q. Dorosti-Hasankiadeh, H. Löhner , "Photo-sensors for a Multi-PMT optical module in KM3NeT," *Nucl.Instrum. and Meth.*, A626-627(2009)S154.

[4] P.Timmer et al., "Very low power, high voltage base for a Photo Multiplier Tube for the KM3NeT deep sea neutrino telescope," *J. Inst.*, 5(2010)C12049.

[5] D. Gajana et al., "A frontend ASIC for the readout of the PMT in the KM3NeT detector," *J.Inst*, 5C12040(2010).

[6] K. Graf, "Studies of acoustic neutrino detection methods with ANTARES," *Nucl.Instrum. and Meth.*, A626-627(2009)S217.

[7] F. Salesa-Greus, *Nucl. Instrum. and Meth.*, A626-627(2010)S237.

[8] L. Classen (for the KM3NeT consortium), "Status of the PMT development for KM3NeT," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11 (these proceedings)*, Erlangen, 2011; http://www.vlvnt11.org/.

[9] Q. Dorosti, "Performance of Photo-Sensors for KM3NeT," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11 (these proceedings)*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[10] A. Cormack (ET Enterprises Ltd), in *Workshop on Very Large Volume Neutrino Telescopes, VLVNT11*, Erlangen, Germany, 2011;http://www.vlvnt11.org/.

[11] G. Kieft, "A TDC for characterization of KM3NeT PMTs," in *Workshop on Very Large*

Volume Neutrino Telescopes, VLVnT11 (these proceedings), Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[12] F.Louis, for the KM3NeT consortium, "Embedded electronics and data acquisition of a detection node for the European KM3NeT telescope.," in *Workshop on very large volume neutrino telescopes, VLVnT11 (these proceedings)*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[13] G.J. Mul (for the KM3NeT Consortium), "A vertical electro-optical data cable for KM3NeT," in *Workshop on Very Large Volume Neutrino Telescopes; VlVnT11*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[14] M. Musumeci, "Mechanical design of the Pre-Production Detector Unit Model of KM3NeT," in *Workshop on Very Large Volume Neutrino Telescopes, VLVNT11*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[15] K. Manolopoulos, A. Belias and V. Koutsoumpos (For the KM3NeTConsortium), "FPGA shore station demonstrator for KM3NeT," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[16] J.Hogenbirk, J.W. Schmelling, S. Mos, M. van der Hoek (For the KM3NeT Consortium), "Photonics-oriented data transmission network for the KM3NeT prototype detection unit," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[17] *KM3NeT: Technical design report*. ISBN 978-90-6488-033-9, 2010.

[18] T. Tanaka et al., *ApJ.*, 685(2008)988.

[19] A.A. Abdo et al., *ApJ*, 734(2011)28.

[20] Q. Yuan, P.-F. Yin, and X.-J. Bi, *Astrop. Phys.*, 35(2011)33.

[21] P. Sapienza , "KM3NeT sensitivity and discovery potential for galactic point-like sources," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11 (present proceedings)*, Erlangen, Germany, 2011; http://www.vlvnt11.org/..

[22] A. Tsirigotis, "Reconstruction efficiency and discovery potential of a Mediterranean neutrino telescope: A simulation study using the Hellenic Open University Simulation & Reconstruction (HOURS) package," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11 (these proceedings)*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[23] R. Shenadze (for the KM3NeT consorrtium), "Cosmogenic neutrinos in KM3NeT," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11 (these proceedings)*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.

[24] M. Crocker and F. Aharonian, *Phys. Rev. Lett.*, 106(2011)101102.

[25] R. Coniglione (For the KM3NeT Consortium), "The KM3NeT high energy neutrino telescope and Fermi bubbles: some predicitions," in *Workshop on Very Large Volume Neutrino Telescopes, VLVnT11 (these proceedings)*, Erlangen, Germany, 2011; http://www.vlvnt11.org/.