KM3NeT: The next generation neutrino telescope

M. DE JONG[1,2]

[1] *Nikhef, Amsterdam, the Netherlands*
[2] *Leiden University, the Netherlands*

mjg@nikhef.nl

Abstract: KM3NeT is a deep-sea research infrastructure to be constructed in the Mediterranean Sea hosting the next generation neutrino telescope. The infrastructure will be shared by a multitude of other sciences, making continuous and long-term measurements in the area of oceanography, geophysics, and marine biological sciences possible. The primary aim of the KM3NeT project is the detection of high-energy neutrinos from the cosmos. Based on reasonable modelling of known astrophysical sources, the figure of merit of KM3NeT can be summarised as a 5-sigma discovery of a neutrino source within five years. Three suitable sites in the Mediterranean Sea have been identified. Several cost-effective design innovations have been adopted in the final technical solution.

Keywords: Neutrino, Astronomy

1 Introduction

The primary aim of the KM3NeT project is the detection of high-energy neutrinos from the cosmos. Following the construction and operation of the ANTARES neutrino telescope, the completion of the EU funded Design Study and Preparatory Phase Study, and the acquisition of substantial funds (about 20% of the envisaged total budget), KM3NeT phase-1 was launched early 2013. The construction has started off-shore Porto Palo di Passero, Italy and Toulon, France and will be extended later off-shore Pylos, Greece.

The construction of a neutrino telescope is extremely challenging. In short, a systematic study of cosmic neutrinos requires a massive telescope with a size of several cubic kilometres. A solution to make such a large mass sensitive to neutrinos is to build a three dimensional array of very sensitive light sensors in the sea. Neutrinos can then be detected indirectly through the detection of the Cherenkov light produced by charged particles emerging from a neutrino interaction. The transparency of the water makes it possible to distribute the light sensors in a cost effective way. The absorption length of the water has been measured at the selected sites in the Mediterranean Sea and was found to be about 50 metres (at a wavelength of 470 nm). The angular resolution of such a detector is limited by the lever arm between the light sensors and the measurement precision of their positions and the arrival times of the Cherenkov light. The mechanical structure that accommodates the light sensors does not form a static system due to changing sea currents. Hence, their positions must be monitored continuously through acoustic triangulation. Of the three neutrino species that exist in nature, the muon neutrino yields the best angular resolution because the muon that emerges from a neutrino interaction has the longest range.

The KM3NeT infrastructure will also host a network of cabled observatories with a wide array of dedicated instruments for oceanographic, geophysical and marine biological research.

2 Technology

The KM3NeT infrastructure will consist of a large number (about 12,320) of optical modules that will be deployed in the Mediterranean Sea at a depth between 2 and 5 kilometres. Each optical module consists of a 17 inch pressure resistant glass sphere equipped with 31 small photomultiplier tubes (PMTs), various instruments and all necessary electronics. The PMTs have a diameter of 3 inch, standard bialkali photo-cathode (maximal quantum efficiency of 30%) and good timing (FWHM of transition time spread is less than 5 ns). Each PMT is surrounded by a light concentrator ring which increases the photon detection efficiency by a factor of about 1.3–1.5, depending on the angle of incidence of the photon. A low-power base (45 mW) has been developed for high voltage, signal amplification and signal discrimination. The time to digital (TDC) functionality is implemented inside an FPGA that has a time resolution of $1/\sqrt{12}$ ns. Finally, the optical module also contains instrumentation that allows for the reconstruction of its position (acoustic sensor), determination of its orientation (compass and tilt meter) and calibration of its timing (nano-beacon).

All analogue pulses that pass a preset threshold (typically 0.3 photo-electrons) are digitised and all data are sent to shore where they are processed real-time using a farm of computers. This concept is commonly referred to as 'All-data-to-shore'. The filtered data are sent to various computer centers around Europe for offline analyses. The remote operation of the deep-sea facility and the fast access to these computer centers make it possible to take and analyse data from anywhere in the world. An artist impression of the KM3NeT detector is shown in Figure 1.

Each optical module requires about 10 W of electrical power and has 1 Gb/s readout bandwidth. The different readout channels are multiplexed using DWDM technology. A detection unit consists of two vertical ropes with a length of about 1 kilometre which support up to 20 optical modules with a spacing of 30–40 metres. This configuration is referred to as a string. A custom cable is being developed for the fiber-optic readout and electrical power of the optical modules of a string.

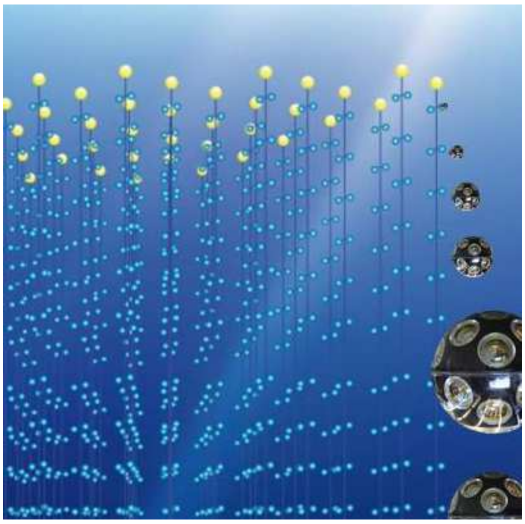

Figure 1: Artist impression of the KM3NeT detector. On the right, a zoom in of the optical module.

Figure 2: Photograph of the launcher vehicle on board the ship Meteor with a mockup of a string.

Previously, the approach to light detection was based on the use of the largest possible PMT that can be housed in a glass sphere. The alternative put forward by KM3NeT consists of putting many small PMTs inside the same glass sphere. This will not only maximise the total photo-cathode area in a single sphere (there is about three times more photo-cathode area inside a single glass sphere compared to an optical module with one large PMT), it also improves photon counting purity at the same time. The classical approach relies on the accurate integration and digitisation of a slow analogue pulse, whereas the new approach makes use of discrete photon detection. After all, a photon is a single quantum and hence digital by nature. The photon counting with a multi-PMT optical module is primarily based on counting the number of hits within a certain time window, rather than measuring the charge of an analogue pulse. As a result, the purity of identifying hits with multiplicity 2 (5) is better by a factor 10 (100). Furthermore, a set of small PMTs with limited fields of view allows for pointing the detected photon back to the muon trajectory. This improves the detection efficiency by about 30% for neutrinos with energies in the range 1–50 TeV.

A new technique has been developed to deploy strings. In this, each string is first wound on a launcher vehicle. The launcher vehicle is lowered to the seabed from a surface vessel. Once the launcher vehicle has reached the seabed, the buoy is released, the string unfurls and rises to its full height. The launcher vehicle is then recovered for subsequent deployments. Several launcher vehicles will be used to deploy a number of strings during a single cruise. The launcher vehicle is shown in Figure 2.

3 Concept of building blocks

The detector can be considered as a three dimensional array of optical modules. In general, the configuration of such an array is defined by 1) the number of strings, 2) the number of optical modules on each string, 3) the horizontal spacing between strings and 4) the vertical spacing between the optical modules along a string. A study has been made of the detection efficiency as a function of these four parameters for various absorption lengths. In this, the absorption length is varied by simply scaling the default values with one of the following fixed values: 0.9, 1.0, 1.1 or 1.2. The assumed signal corresponds to a flux of neutrinos from RXJ1713-39.43. The energy spectrum of this source is taken from reference [1]. The detection efficiency is defined as the number of events with at least 5 L1 hits. An L1 hit is a coincidence of two (or more) hits in the same optical module within a time window of 10 ns. This definition corresponds to the typical configuration of the real-time data filter. Hence, these events are written to disk and will be available for offline analysis in the future. Furthermore, only light from the muon is simulated to avoid a possible bias due to light from secondary particles. The number of signal events as a function of the number of strings and the number of optical models per string is shown in Figure 3. The default configuration corresponds to 120 strings, 20 optical modules per string, horizontal spacing between strings of 100 m and vertical spacing between optical modules of 40 m. The total number of optical modules was fixed to 12,320.

As can be seen Figure 3, the detection efficiency –for a fixed total number of optical modules– gradually improves with the number of strings and the number of optical modules per string up to a certain point where it flattens out. Beyond 120 strings per detector and 18 optical modules per string, the normalised detection efficiency no longer improves. This result is primarily due to the assumed energy spectrum which is rather hard and has a well defined end-point. Such a spectrum is, however, characteristic for that of any known candidate source in our Galaxy, such as Super Nova Remnants. Hence this result generally applies to the most promising neutrino sources.

The limited size of an optimally efficient detector compared to the envisaged size of the complete infrastructure is about 1/6 which makes it possible to define building blocks. A building block is the smallest size detector with an op-

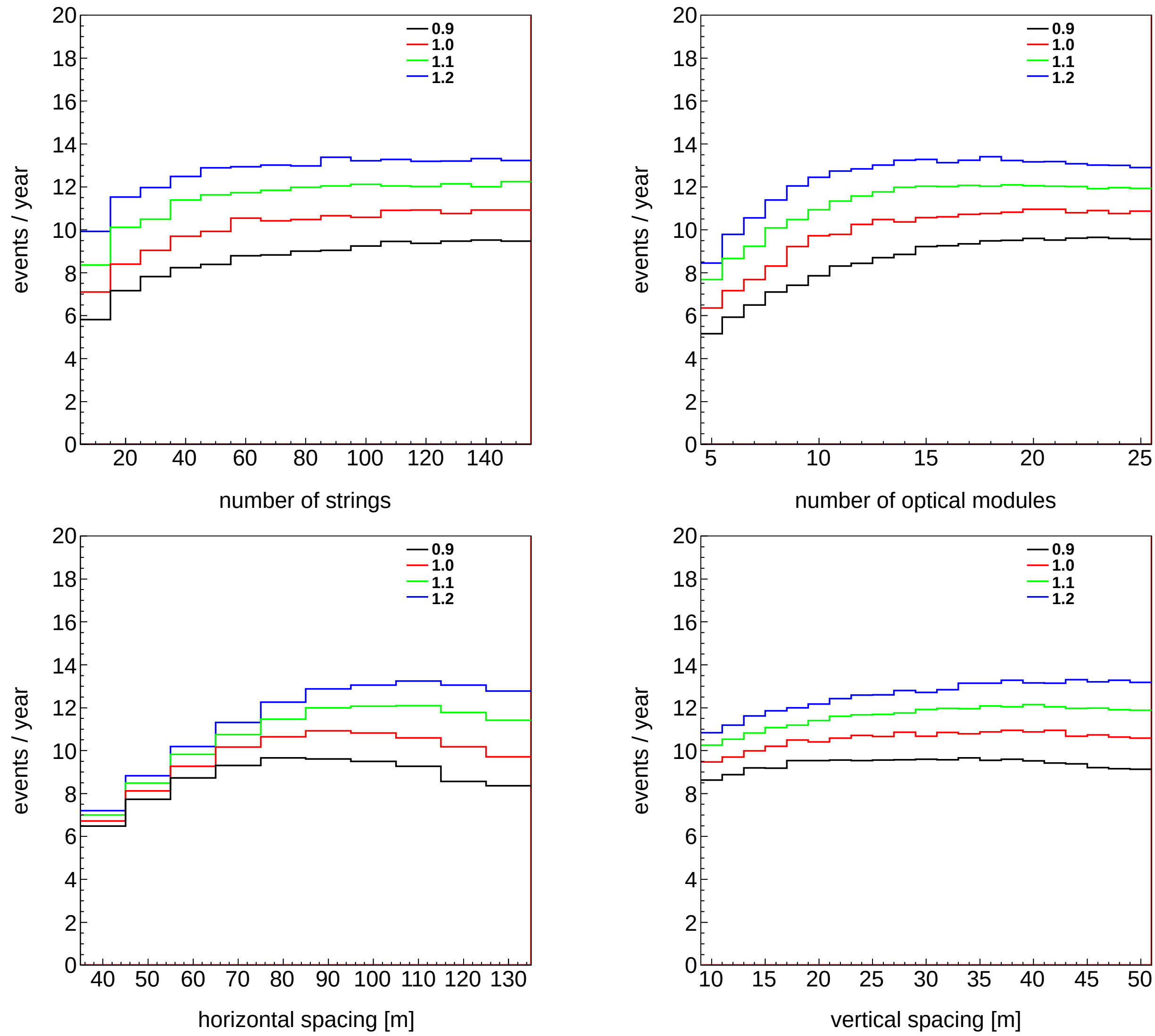

Figure 3: The expected number of events from an assumed flux of neutrinos from RXJ1713-39.43 [1] as a function of the number of strings (top-left); the number of optical modules per string (top-right); the horizontal spacing between strings (bottom-left) and the vertical spacing between optical modules (bottom-right). The default configuration corresponds to 120 strings, 20 optical modules per string, horizontal spacing between strings of 100 m and vertical spacing between optical modules of 40 m. The colour coding refers to the scaling factor applied to the absorption length (see text).

timal efficiency. These building blocks can then be distributed in compliance with the funding constraints without loss of the figure of merit. The overall impact of a multi-site solution is thus limited to finances and management.

The number of signal events as a function of the horizontal spacing between strings and the vertical spacing between optical modules is shown in Figure 3. In this, the number of strings was fixed to 120 and the number of optical modules per string was fixed to 18. As can be seen from Figure 3, there is a maximum of the normalised detection efficiency around 90 m horizontal spacing between strings and 36 m vertical spacing between optical modules. In the vicinity of the optimum, the dependence of the detection efficiency on the configuration is very small.

The total costs of the construction of the infrastructure is estimated at 220–250 M€. The operational costs of a distributed network of neutrino telescopes in the Mediterranean is estimated to be about 3% per year of the total investment. The overall conclusion is then that the advantage of additional funding and human resources resulting from adopting a multi-site solution significantly outweighs any financial or scientific advantage from adopting a single site solution.

4 Science

4.1 Neutrino astronomy

It is often advocated that the observed high-energy gamma rays from Super Nova Remnants are produced by inverse Compton scattering. In this process, a high-energy electron exchanges energy with a low-energy photon. However, an alternative production mechanism has been suggested based on the production and subsequent decay of neutral pions. At present, neither of the two production mechanisms can be excluded. The neutral pions are naturally accompanied by charged pions that decay predominantly to neutrinos. The flux of neutrinos can then be calculated on the basis of the observed flux of gamma rays and well known particle physics. Detection of these neutrinos will confirm the hadronic origin of high-energy gamma rays and provide evidence for the source of cosmic rays.

The angular resolution, the geographical location and the size make KM3NeT an ideal instrument to observe neutrinos from Galactic sources. As a prime example, the sensitivity of the detector for an assumed flux of neutrinos from Super Nova Remnant RXJ1713-39.43 has been determined [2]. Based on reasonable modelling of known astrophysical sources, the figure of merit of KM3NeT can be summarised as a 5-sigma discovery of a neutrino source within five years.

In a similar way, if a hadronic mechanism is responsible for the emission of the observed gamma-rays from the Fermi bubbles, a flux of high-energy neutrinos could be detected. The detection capability for high-energy neutrinos from the Fermi bubbles is presented in reference [3].

Following the observation by IceCube of an excess of high-energy showers, a study is launched to quantify the detection capability of such events with KM3NeT.

4.2 Earth and Sea sciences

The infrastructure it requires will be shared by a multitude of other sciences, making continuous and long-term measurements in the area of oceanography, geophysics, and marine biological sciences possible. The synergy is exemplified by several ANTARES publications [6, 7, 8].

4.3 Neutrino mass hierarchy

A study was launched to find out whether a measurement of the mass hierarchy of neutrinos using the same technology but a different detector layout is feasible. This study is known as ORCA and a designated paper has been submitted to this conference [4].

5 Future prospects

The feasibility of neutrino astronomy with a detector in the Mediterranean Sea was proved by the successful deployment and operation of the ANTARES prototype detector [5]. KM3NeT phase-1 will demonstrate the feasibility of a distributed network of neutrino telescopes in the Mediterranean Sea. KM3NeT phase-2 can be realized by 2020.

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