

Reconstruction efficiency and discovery potential of a Mediterranean neutrino telescope: A simulation study using the Hellenic Open University Reconstruction & Simulation (HOURS) package

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Abstract

We report on the evaluation of the performance of a Mediterranean very large volume neutrino telescope. We present results of our studies concerning the capability of the telescope in detecting/discovering galactic (steady point sources) and extragalactic, transient (Gamma Ray Bursts) high energy neutrino sources as well as measuring ultra high energy diffuse neutrino fluxes. The neutrino effective area and angular resolution are presented as a function of the neutrino energy, and the background event rate (atmospheric neutrinos and muons) is estimated. The discovery potential of the neutrino telescope is evaluated and the experimental time required for a significant discovery of potential neutrino emitters (known from their gamma ray emission, assumedly produced by hadronic interactions) is estimated. For the simulation we use the HOU Reconstruction & Simulation (HOURS) software package.

Keywords: Neutrino Telescope, Event Simulation, Detector Evaluation

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1. Introduction

KM3NeT (km³ Neutrino Telescope) is planned to be a deep-sea multidisciplinary observatory in the Mediterranean Sea that will provide innovative science opportunities spanning Astroparticle Physics and Earth and Sea Science [1]. Various astrophysical sources are expected to produce high-energy neutrinos that may be detected with KM3NeT. The observation of even a handful of events emanating from a cosmic source could provide useful information. The existence of these neutrino sources will be proved and more importantly knowledge of their behavior, which cannot be acquired by other means, will be gained.

In this work we study the performance of KM3NeT, by estimating the sensitivity in detecting cosmic neutrino fluxes from astrophysical neutrino point or extended sources. In Sections 2 and 3 we describe the neutrino telescope configuration under study and the simulation framework. The telescope's performance in detecting neutrinos from astrophysical sources is described in Section 4, while the experimental time required for a significant discovery of potential Galactic neutrino emitters is estimated in Section 5.

2. Detector description

KM3NeT will consist of several hundreds of vertical structures (Detection Units - DUs), which carry photosensors and devices for calibration and environmental measurements, arranged vertically on Storeys. Each Storey will support one or two photo-sensors. The photo-sensor unit is a digital optical module (DOM) consisting of a 17-inch diameter pressure resistant glass sphere housing 31 3-inch photomultiplier (PMT) tubes, their high-voltage bases and their interfaces to the data acquisition system with nanosecond timing precision [2]. The segmentation of the photocathode area in such a Multi-PMT Optical Module will aid in distinguishing single-photon from multiphoton hits, and thus provide a better optical background rejection and trigger efficiency. The front-end electronics is based on the use of the time over threshold (ToT) as the main signal processing technique [2, 3]. The ToT technique is based on the use of a time to digital converter (TDC) that performs time-tagging of the leading and trailing edge of the PMT signal above a certain voltage threshold. The signal goes through a comparator that compares it against the desired threshold. The output of the comparator is then fed to the TDC that performs the time-tagging of the leading and trailing edge. These values are subsequently used for the reconstruction of the pulse shape and its charge.

In the present study the telescope layout considered

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is the one optimized during the KM3NeT Design Study, exhibiting optimal sensitivity in discovering astrophysical point sources emitting neutrinos with an energy spectrum of E^{-2} and a high energy cut-off or without one. According to this layout, the KM3NeT detector will consist of 12320 DOMs distributed over 308 DUs. Each DU consists of 20 Storeys, and each Storey consists of a bar with one DOM at either end. The distance between the centers of the DOMs is 6 m. The distance between Storeys is 40 m, while the position of the lowest Storey is 100 m above the seabed. The bars have a direction orthogonal to their neighbors. The distribution of the positions of the detection units on the seabed (the so-called footprint) is homogeneous. The footprint forms a roughly circular shape and has a typical DU density corresponding to an average distance between neighboring detection units of about 180 m. The total instrumented volume of the detector is 5.8 km^3 . In the present study the depth of the seabed is considered to be 3500 m.

3. Simulation Framework

For the evaluation of the KM3NeT performance in detecting high energy astrophysical neutrinos the HOURS (Hellenic Open University Reconstruction & Simulation) physics analysis package was used. HOURS comprises a realistic simulation package of the detector response, including an accurate description of all the relevant physical processes, the production of signal and background as well as several analysis strategies for triggering and pattern recognition, event reconstruction, tracking and energy estimation [4]. In HOURS the Kalman filter is used as a recursive track fitting method, as described in [5]. Using the Kalman filter technique a large number of candidate tracks are found for each event. The best candidate (hereafter reconstructed track) is chosen using the likelihood value corresponding to the directional sensitivity of the Multi-PMT DOM [5] and the probability density function of the arrival time residuals of the hits¹. The available quality cuts for the final event selection are the number of candidate tracks found, the likelihood value and number of hits of the reconstructed track, and the number of candidate tracks with an angular deviation to the reconstructed track less than 5° .

For the present study we have simulated the response of the detector configuration described in Section 2 to a generic neutrino flux distributed isotropically (in a 4π solid angle) on the Earth’s atmosphere. We assumed that the energy distribution of these neutrinos follows a power law spectrum, with a spectral index of -2.0 , in the range of $15 \text{ GeV} - 100 \text{ PeV}$ ².

¹In the calculation of the likelihood value the hits are common for all candidate tracks.

²The lower energy limit in the event generation has been chosen to be of the order of the neutrino energy threshold of the simulated

detector which is about 30 GeV (see also Fig. 2). In the event generation the cross section of the neutrino interaction is taken into account. The energy spectrum of the interacting neutrinos that produce a detectable signal has a peak at 16 TeV, while 90% of them are in the range of $100 \text{ GeV} - 1 \text{ PeV}$.

Using the expected neutrino flux for each point or extended source, we estimated the number of neutrino signal events per observation year. The estimation was based on reweighting each of the signal events (produced by a cosmic neutrino) according to the energy of the parent neutrino and taking into account the functional form of the generic flux, used in the Monte Carlo event production, and the energy dependence of the source spectrum.

In our studies we have included the contribution of two main background sources, namely atmospheric neutrinos and energetic muons. In order to simulate the first background source we used the Bartol flux parametrization [6], including the high energy component from charm interactions (prompt neutrinos). For the atmospheric muon component we have used the MUPAGE package [7] to simulate the generated muons from energetic Extensive Air Showers. Although we have generated a large statistical sample of cosmic and atmospheric neutrinos, the atmospheric muon background corresponds to only 1 h equivalent of integrated flux (lifetime), due to CPU time constraints.

The search for cosmic neutrino signals is based on statistical techniques that are appropriate for the detection of small numbers of events. The discovery potential of the neutrino telescope is evaluated using the model discovery potential (MDP) calculated for a level of significance 5σ and probability to make a discovery 50%. In this case the quality cuts to the reconstructed tracks are optimized in order to obtain the least signal necessary to claim a discovery. When no significant signal is observable, limits are set using the model rejection factor (MRF). In this case, the quality cuts to the reconstructed tracks are optimized in order to obtain the lowest possible expected upper limit for the experiment, assuming that no true signal is present.

For point-like (or with a small angular size) source searches the sensitivity of the detector has been obtained applying a “binned” method where the sky is divided in bins of declination and right ascension and the numbers of events detected per bin are analyzed. The parameters that are optimized in order to minimize the MRF and MDP are the size of the search cone around the source and the quality cuts to the reconstructed tracks. The average number of signal events from the source, at a given declination, and the average number of background events inside the selected search cone centered on the source direction is estimated.

4. Telescope performance

The observation of point-like sources of neutrinos would bring unique new insights on the nature of cosmic accelerators and resolve the enigma of the origin of cosmic rays.

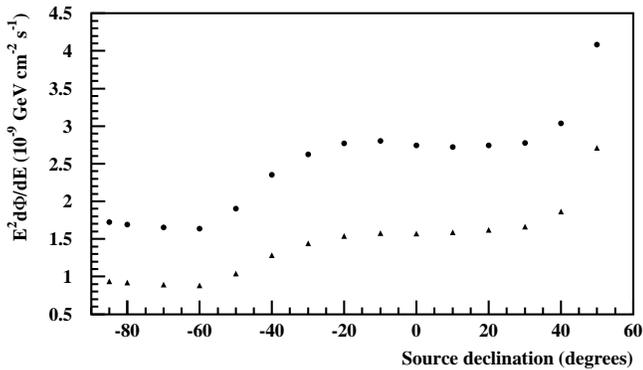


Figure 1: The KM3NeT flux sensitivity (triangles) and discovery flux (circles) for one year of observation and assuming an E^{-2} source spectrum without cutoff.

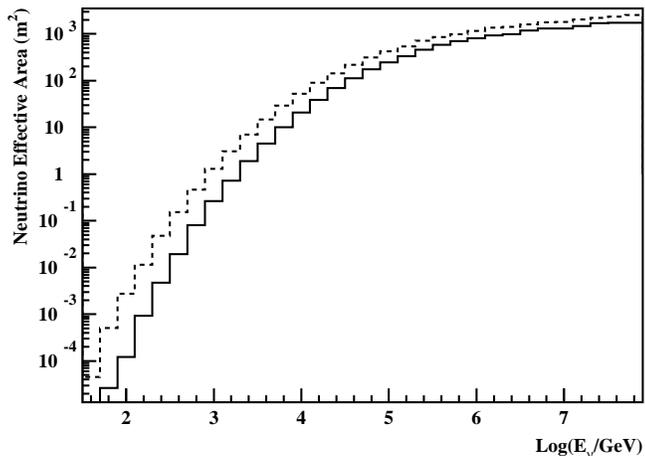


Figure 2: The effective area of the neutrino telescope as a function of the neutrino energy, for the triggered (dashed line) and the reconstructed (solid line) events. The quality cuts applied to the reconstructed tracks are the same as those applied in evaluating the detector's flux sensitivity seen in Fig. 1.

Observations by gamma ray telescopes have revealed many astrophysical objects, in which high-energy processes at and beyond the TeV level take place. However, measurements with gamma rays alone cannot clearly distinguish whether the accelerated particles are leptons or hadrons. Only the observation of neutrinos from a source can unambiguously establish the hadronic nature of that source.

The sensitivity of the detector to neutrino point sources, based on one year of data taking, is shown in Fig. 1 as a function of the declination. The detector performance is presented as the flux that can be excluded at 90% CL (flux sensitivity) and the flux that can be detected at 5σ with 50% probability (discovery flux). This calculation assumes a neutrino energy spectrum proportional to E^{-2} with no energy cutoff.

In Fig. 2 the Neutrino effective area as a function of the neutrino energy is shown for the triggered and recon-

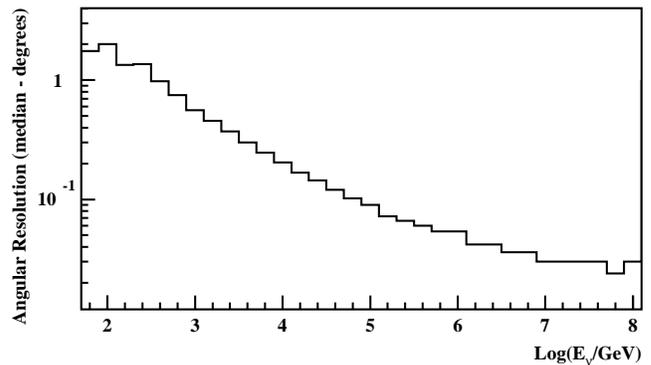


Figure 3: The angular resolution as a function of the neutrino energy. The quality cuts applied to the reconstructed tracks are the same as those applied in evaluating the detector's flux sensitivity seen in Fig. 1.

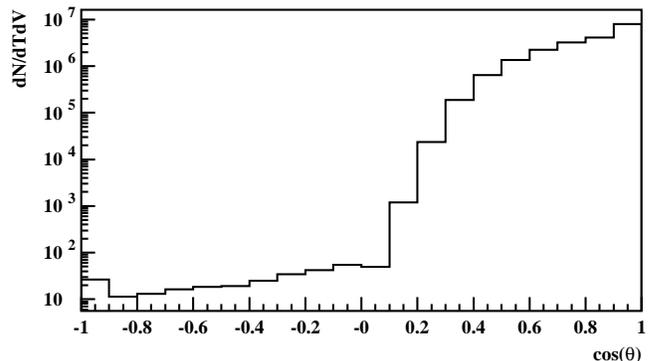


Figure 4: The number of background events per unit time (days) and per unit solid angle as a function of the zenith angle.

structed events. The event trigger used in the present study is minimal and is based on five (or more) L1 hits on different DOMs due to the signal from a neutrino interaction or atmospheric muons. An L1 hit is defined as a local coincidence, within a time window of 10 ns, of two (or more) photons detected within the same optical module by different PMTs. The angular resolution, in reconstructing the neutrino direction, is shown in Fig. 3 as a function of the neutrino energy.

The rate of background events due to atmospheric neutrinos and atmospheric muons, remaining after the application of quality cuts to the reconstructed tracks, is presented in Fig. 4. The peak in the vertically up-going and down-going ($\cos(\theta) = -1$ and $\cos(\theta) = 1$) bins is due to the increased efficiency of the detector for low energy vertical muon tracks passing close to one Detection Unit. The number of reconstructed upcoming atmospheric neutrinos per day is about 170, while the number of reconstructed downcoming atmospheric muon events is about 20 million per day.

Gamma Ray Bursts are also potential very high energy neutrino emitters according to the fireball model [8]. High

energy neutrinos from prompt emission consistent with the detected gamma rays are expected to arrive within a short time window (2 – 1000 s) [9]. The narrow time window results in reduced background noise and with the combination of an appropriate cut on the reconstructed energy of the neutrino induced muon, the detection of down-going GRB neutrinos is feasible [10]. Studies have shown that KM3NeT could observe about 5 neutrinos per year from GRBs (according to the optimistic model of [8], and assuming that 300 GRBs per year are observed by space born experiments).

The ultra high energy neutrinos from: a) a multitude of objects such as Active Galactic Nuclei or GRBs, and b) from the interaction of cosmic rays with intergalactic matter and radiation or even with the cosmic microwave background, are expected to form an isotropic diffuse flux. Without the possibility of using a tight angular cut for reducing the background of atmospheric neutrinos, diffuse neutrino flux searches have to rely on a cut on the reconstructed muon energy, $E_{\mu reco}$. The method, used in HOURS, to estimate the energy of a reconstructed muon, is described in [4]. The sensitivity of KM3NeT, for one year of observation time, to an isotropic diffuse neutrino flux with a spectrum proportional to E^{-2} , and an energy cut $E_{\mu reco} > 500$ TeV has been estimated to be 3×10^{-9} ($\text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$).

5. Observation of Galactic neutrino sources

Supernova remnants (SNR) of the shell type are the most probable sources of cosmic rays in the Galaxy. The material ejected during the explosion forms shock waves when it propagates into the interstellar matter. Particles are assumed to be accelerated in these shock waves, which can persist for several thousand years. The shell-type SNRs with the most intense gamma rays fluxes are RX J0852.0-4622 (Vela Junior) and RX J1713.7-3946. These sources have an angular size larger than the resolution of the neutrino telescope. Moreover, they are generally expected to have a cut-off in their energy spectra in the range 1 – 10 TeV. However, the neutrino telescope layout, optimized during the KM3NeT Design Study, exhibits optimal sensitivity in discovering astrophysical sources emitting neutrinos with an energy spectrum of E^{-2} and a high (or without any) energy cut-off [11]. Such a detector has lower sensitivity in detecting galactic neutrinos in the energy range of 1 – 10 TeV.

Assuming that the dominating mechanism of gamma ray production is hadronic, the most luminous gamma ray Galactic source, the SNR RX J1713.7-3946, is estimated to emit neutrinos with a flux [12]

$$\Phi(E) = 16.8 \times 10^{-15} \left[\frac{E}{\text{TeV}} \right]^{-1.72} \times e^{-\sqrt{\frac{E}{2.1 \text{ TeV}}}} \text{ GeV}^{-1} \text{ s}^{-1} \text{ cm}^{-2}. \quad (1)$$

Such a source can be detected in 13.1 years of experimental running time of the previously described detector. By reducing the average distance between the DUs from 180 m to 130 m the number of years required for a 5σ discovery with a 50% probability is reduced to 9 years. Furthermore, if we replace each DU by two strings of DOMs, and redistribute them homogeneously with an average distance between them of 100 m, the detector running time required for the discovery of this Galactic source can be reduced to about 7 years.

Preliminary studies have shown [13] that the most luminous Galactic sources can be detected in less than 5 years (e.g. using the telescope configuration of 616 strings of DOMs described above) of detector running time by applying more sophisticated experimental and data analysis techniques, that take into account: (a) the track reconstruction resolution and the reconstructed energy of the neutrino induced muon on a track by track basis, as described in [14], (b) the known source direction as described in [15], and (c) the source morphology [13].

6. Conclusions

In this work we have studied, using the HOURS package, the performance of the Mediterranean very large volume neutrino telescope, KM3NeT, in discovering Galactic and extragalactic neutrino sources. KM3NeT will cover most of the sky with unprecedented sensitivity and in the first few years of operation will unambiguously discover neutrinos from many promising Galactic candidate sources.

Acknowledgments

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References

- [1] P. Bagley, et al., [KM3NeT consortium], *Conceptual Design for a Deep-Sea Research Infrastructure Incorporating a Very Large Volume Neutrino Telescope in the Mediterranean Sea*, ISBN 978-90-6488-031-5
- [2] P. Bagley, et al., [KM3NeT consortium], *Technical Design Report for a Deep-Sea Research Infrastructure in the Mediterranean Sea Incorporating a Very Large Volume Neutrino Telescope*, ISBN 978-90-6488-033-9
- [3] KM3NeT consortium, *Technical description of the PPM of the KM3NeT detection unit*, http://www.km3net.org/PPM/KM3NeT_FL.REP.PPM-description.pdf, 2010
- [4] G. Bourlis, et al., Nucl. Instr. and Meth. A **626-627** (2011) S163
- [5] A.G. Tsirigotis, et al., Nucl. Instr. and Meth. A **626-627** (2011) S185
- [6] A.G. Tsirigotis, et al., Nucl. Instr. and Meth. A **602** (2009) 91
- [7] V. Agrawal et al, Phys. Rev. D **53** (1996) 1314
- [8] G.Carminati et al., Comput. Phys. Commun. **179** (2008) 915
- [9] D. Guetta, et al., Astroparticle Physics **20**, (2004), p 429

- [9] R. Abbasi, et al. [IceCube Collaboration], *Astrophys. J.* **710**, (2010), p 346
- [10] A.G. Tsirigotis et al., *Nucl. Instr. and Meth. A* **639** (2011), p. 79
- [11] A.G. Tsirigotis et al., *Nucl. Instr. and Meth. A* **626** (2011), p. S188
- [12] S. R. Kelner, F. A. Aharonian and V. V. Bugayov, *Phys. Rev. D* **74** (2006) 034018
- [13] A. G. Tsirigotis, A. Leisos and S. E. Tzamarias, under preparation
- [14] A. Leisos et al., *Evaluation of the discovery potential of an underwater Mediterranean neutrino telescope taking into account the estimated directional resolution and energy of the reconstructed track*, this issue
- [15] A.G. Tsirigotis et al., *A reconstruction method for neutrino induced muon tracks taking into account the apriori knowledge of the neutrino source*, this issue