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Detection potential to point-like neutrino sources with the NEMO-km$^3$ telescope

Received: date / Accepted: date

Abstract The NEMO Collaboration is conducting an R&D activity towards the construction of a Mediterranean km$^3$ neutrino telescope. In this work, we present the results of Monte Carlo simulation studies on the capability of the proposed NEMO telescope to detect and identify point-like sources of high energy muon neutrinos.

Keywords NEMO · point-like neutrino sources

PACS 95.55.Vj · 95.85.Ry · 96.40.Tv

1 Introduction

The detection of high energy neutrinos is considered one of the most promising means to investigate non-thermal processes in the Universe. A first generation of small scale detectors has been realized (NT-200 \cite{1} in the Baikal lake and AMANDA \cite{2} at the South Pole), demonstrating the possibility to use the Čerenkov technique to track high energy neutrinos. Besides, these experiments have set limits on neutrino fluxes. Other small scale detectors are at different stage of realization (ANTARES \cite{3} and NESTOR \cite{4}).

Actual expectations on neutrino fluxes, mainly based on the measured cosmic ray fluxes and the estimated fluxes for several high energy sources from theoretical models \cite{5}, require detectors of km$^3$ scale. Following the success of AMANDA, the largest operating detector, the realization of the IceCube km$^3$ detector \cite{6} has started at the South Pole. On the other hand, many issues, as the full sky coverage, strongly support the construction of a km$^3$ scale detector in Mediterranean Sea.

2 The NEMO project

The NEMO Collaboration \cite{7} is performing R&D towards the design and construction of the Mediterranean km$^3$ neutrino detector. The activity was mainly focused on the search and characterization of an optimal site for the detector installation and on the development of a feasibility study for the detector. A deep sea site with optimal features in terms of depth and water optical properties has been identified at a depth of 3500 m about 80 km off-shore Capo Passero and a long term monitoring of the site has been carried out \cite{8}. The feasibility study of the km$^3$ detector includes the analysis of all the construction and installation issues and the optimization of the detector geometry by means of numerical simulations. The validation of the proposed technologies via an advanced R&D activity, the prototyping of the proposed technical solutions and their relative validation in deep sea environment will be carried out with the two pilot projects NEMO Phase-1 and Phase-2 \cite{9}.

3 Detector lay-out

The geometry of the NEMO-km$^3$ telescope simulated in this work is a square array of 9 × 9 towers equipped with 5832 optical modules (10" diameter PMTs) \cite{9}. The towers, moored on the seabed at 3500 m depth, have an instrumented height of 680 m, with a storey-storey distance of 40 m, and are spaced of 140 m. The detector response is simulated using the codes developed by the ANTARES Collaboration \cite{10}. In the simulation codes, the light absorption length, measured in the site of Capo Passero ($L_a \approx 68$ m at 440 nm \cite{8}), is taken into account. Once the sample of PMT hits is generated, spurious PMT hits, due to the underwater optical noise (40K decay), are introduced, with a rate of 30 kHz for 10” PMTs, corresponding to the average value measured in Capo Passero site.

The simulated detector lay-out reaches an effective area of 1 km$^2$ at a muon energy of about 10 TeV and an
angular resolution of a few tenths of degrees at the same energy as plotted in Fig. 1.

![Fig. 1](image1.png)

**Fig. 1** Effective area and angular resolution of the simulated NEMO detector as a function of the muon energy. The detector response is simulated considering a diffuse flux of up-going muons reaching the detector surface.

4 Detector pointing accuracy

The detector angular resolution is one of the most important parameters in the identification of point-like sources. Therefore, an experimental determination is required. A possible method, already adopted in cosmic ray detectors, consists in the observation of the so-called *Moon shadow* [11]. Since the Moon absorbs cosmic rays, we expect a lack of atmospheric muons from the direction of the Moon disk. The detection of the muon deficit provides a measurement of the detector angular resolution.

Monte Carlo simulations show that the NEMO telescope could be able to detect the *Moon shadow* and that about 100 days are needed to observe a 3σ effect. Assuming a detector point spread function with a Gaussian shape, the same simulations yield a detector angular resolution $\sigma = 0.19^\circ \pm 0.02^\circ$ (see Fig. 2). Besides detecting its position in the sky allows us to determine the absolute orientation of the detector [12].

![Fig. 2](image2.png)

**Fig. 2** Detected muon event density versus the angular distance from the Moon center, assuming 1 year of data taking. The points are fitted assuming a Gaussian shape for the point spread function, obtaining an angular resolution of $\sigma = 0.19^\circ \pm 0.02^\circ$ [12].

5 NEMO-km$^3$ sensitivity to neutrinos from point-like sources

5.1 Calculation of the detector sensitivity

The detector sensitivity spectrum is calculated according to the following formula:

$$
\left( \frac{d\phi_\nu}{d\varepsilon_\nu} \right)_{90} = \overline{\Phi}_{90}(b) \left( \frac{d\phi_\nu}{d\varepsilon_\nu} \right)_{0},
$$

where $\overline{\Phi}_{90}(b)$ is the 90% c.l. average upper limit for an expected background $b$ and calculated as suggested by Feldman and Cousins [13]: $(d\phi_\nu/d\varepsilon_\nu)_0$ is an arbitrary point source spectrum inducing a mean signal $N_\mu$. The detector sensitivity is calculated taking into account both atmospheric neutrino and muon backgrounds.

5.2 Simulation of the atmospheric muon and neutrino background

A sample of $7\cdot10^9$ atmospheric neutrinos have been generated using the ANTARES event generation code, based on a weighted generation technique [10]. The events were generated in the energy range $10^2 \div 10^8$ GeV, with a spectral index $X = 2$ and a $4\pi$ isotropic angular distribution. The events were then weighted to the sum of the Bartol flux [14] and of prompt neutrino $\nu_{\text{prompt}}$ model [15] flux. When the event weight is calculated, the neutrino absorption in the Earth, as a function of neutrino
energy and direction, is taken into account. So doing, we compute a number ≈ 4 · 10^4 of detected atmospheric neutrino events per year of data acquisition.

Atmospheric muons are generated at the detector, applying a weighted generation technique. We generated a sample of \( N_{\text{total}} = 2.5 \cdot 10^7 \) muons, in the energy range 1 TeV \( \div \) 1 PeV, with a generation spectral index \( X = 3 \). We also generated \( N_{\text{total}} = 4 \cdot 10^7 \) events in the range 100 GeV \( - \) 1 TeV, with a generation spectral index \( X = 1 \). Muons are generated with an isotropic angular distribution. The events are weighted to the Okada parameterization by Bugaev et al.\[18\] and also considered. In this case the expected number of reconstructed events is \( 5 \cdot 10^5 \) per year but no significant differences are observed in the detector sensitivity values.

The simulated statistics cover only a few days. Considering that reconstructed events have a flat distribution in Right Ascension (RA), we can project the simulated events in a few degrees bin \( \Delta \text{RA} \), centered in the source position. So doing, we get statistics of atmospheric muons corresponding to a time \( \approx 1 \) year at all source declinations.

Major details on the Monte Carlo simulation of the NEMO detector could be found in ref.\[16\].

5.3 Criteria for the atmospheric background rejection

The used reconstruction algorithm is a robust track fitting procedure based on a maximization likelihood method.\[10\] In this work, we used, as a goodness of fit criterion, the variable:

\[
A = \frac{\log(\mathcal{L})}{N_{\text{DOF}}} + 0.1(N_{\text{comp}} - 1),
\]

where \( \log(\mathcal{L})/N_{\text{DOF}} \) is the log-likelihood per degree of freedom (\( N_{\text{DOF}} \)) and \( N_{\text{comp}} \) is the total number of compatible solutions found by the reconstruction program. In particular, events are selected if the variable \( A \) is greater than a given value \( A_{\text{cut}} \). This quality cut is here applied together with other selection criteria as listed in the following:

- the number of hits \( N_{\text{fit}} \), used to reconstruct the muon track, must be greater than a given value \( N_{\text{cut}} \);
- the muon must be reconstructed with \( \varrho_{\mu}^{\text{rec}} < \varrho_{\mu}^{\text{max}} \), in order to reject down-going events;
- only events reconstructed in a circular sky region centered in the source position and having a radius of \( r_{\text{bin}} \) are considered.

The optimal values of \( A_{\text{cut}} \), \( N_{\text{cut}}^{\text{fit}} \), \( \varrho_{\mu}^{\text{max}} \), and \( r_{\text{bin}} \) are chosen to optimize the detector sensitivity.

5.4 Detector sensitivity to neutrino point-like sources

In this section, we calculate the expected detector sensitivity to neutrinos from point-like sources. We simulated muons induced by \( \sim 10^9 \) neutrinos with energy range \( 10^2 \) \( - \) \( 10^6 \) GeV and \( X = 1 \). These events are weighted to the neutrino spectrum \( \frac{d\varphi_{\nu}}{d\varepsilon} = 10^{-7} \varepsilon_{\nu,\text{GeV}}^{-\alpha} \) (GeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\)). As a first case, we consider a source at a declination of \( \delta = -60^\circ \). Such a source has a 24 hours of diurnal visibility and it covers a large up-going angular range \( (\vartheta_{\mu} = 24^\circ - 84^\circ) \). The sensitivity for this source is therefore representative of the average response of the NEMO detector.

In Table 1 we report the expected sensitivity for different values of the spectral index \( \alpha \), considering 3 years of data taking. In Fig. 3 we show how the energy spectrum of reconstructed events is reduced after the event selection, varying the neutrino spectral index \( \alpha \). The same plots show also as the spectrum peak moves towards lower energies for softer spectral indices.

### Table 1 Sensitivity to a point-like neutrino source at \( \delta = -60^\circ \), for different spectral indices \( \alpha \) and 3 years of data taking. The sensitivity spectrum \( \varepsilon(\frac{d\varphi_{\nu}}{d\varepsilon})_{90} \) is expressed in GeV\(^{\alpha-1}\) / cm\(^2\) s.

| \( \alpha \) | \( A_{\text{cut}} \) | \( N_{\text{cut}}^{\text{fit}} \) | \( \varrho_{\mu}^{\text{max}} \) | \( r_{\text{bin}} \) | \( \mu_{90}(b) \) | \( \varepsilon(\frac{d\varphi_{\nu}}{d\varepsilon})_{90} \) |
|---|---|---|---|---|---|---|
| 1.0 | -7.6 | 30 | 90° | 0.4° | 2.4 | 1.9 \cdot 10^{-15} |
| 1.5 | -7.6 | 30 | 90° | 0.4° | 2.5 | 2.6 \cdot 10^{-12} |
| 2.0 | -7.3 | - | 90° | 0.5° | 2.8 | 1.2 \cdot 10^{-9} |
| 2.5 | -7.3 | - | 90° | 0.6° | 2.9 | 2.3 \cdot 10^{-7} |

The detector sensitivity was calculated as a function of the years of data taking and reported in Table 2. Results for \( \alpha = 2 \) are also plotted in Fig. 3 compared to the IceCube sensitivity obtained for a \( 1^\circ \) search bin.\[12\] Our results show that the proposed NEMO detector reaches a better sensitivity to muon neutrino fluxes with a smaller search bin.

### Table 2 Sensitivity to a point-like neutrino source at \( \delta = -60^\circ \), for different spectral indices \( \alpha \) and for different number of years of data taking. The sensitivity spectrum \( \varepsilon(\frac{d\varphi_{\nu}}{d\varepsilon})_{90} \) is expressed in GeV\(^{\alpha-1}\) / cm\(^2\) s.

| \( \alpha \) | 1 | 1.5 | 2 | 2.5 |
|---|---|---|---|---|
| years | 1 | 2.9 \cdot 10^{-15} | 3.9 \cdot 10^{-12} | 3.5 \cdot 10^{-9} | 6.5 \cdot 10^{-7} |
| 2 | 3.9 \cdot 10^{-15} | 4.9 \cdot 10^{-12} | 1.8 \cdot 10^{-9} | 3.4 \cdot 10^{-7} |
| 3 | 1.9 \cdot 10^{-15} | 2.6 \cdot 10^{-12} | 1.2 \cdot 10^{-9} | 2.3 \cdot 10^{-7} |
| 4 | 1.5 \cdot 10^{-15} | 2.0 \cdot 10^{-12} | 8.9 \cdot 10^{-10} | 1.7 \cdot 10^{-7} |
| 5 | 1.2 \cdot 10^{-15} | 1.6 \cdot 10^{-12} | 7.2 \cdot 10^{-10} | 1.4 \cdot 10^{-7} |
| 10 | 5.9 \cdot 10^{-16} | 8.1 \cdot 10^{-13} | 3.7 \cdot 10^{-10} | 7.1 \cdot 10^{-8} |
The expected astrophysical neutrino spectra could not extend up to $10^8$ GeV, especially in the case of Galactic sources. For this reason, we also computed the detector sensitivity as a function of the high energy neutrino cut-off $\varepsilon_{\nu}^{\text{max}}$. Results of our calculations are plotted in Fig. 5. Decreasing the energy cut-off, the sensitivity doesn’t get worse until that $\varepsilon_{\nu}^{\text{max}}$ reaches the energy peak of reconstructed neutrino spectra (see Fig. 3). In the case of hard spectrum sources, the detector sensitivity is better and it gets better if the spectrum extends to VHE. Expected astrophysical neutrino spectra could be softer ($\alpha \leq 2$); in this case the sensitivity value doesn’t vary much with $\varepsilon_{\nu}^{\text{max}}$.

We finally consider the dependence of the sensitivity on the source declination. In particular, the detector sensitivity gets worse with increasing declination due to the decrease of the diurnal visibility (to respect with the latitude of the Capo Passero site). Fig. 6 shows the sensitivity versus the source declination, considering three years of data taking and $\alpha = 2$. The worst sensitivity is $2.5 \cdot 10^{-9}$ GeV/cm$^2$/s, calculated for a source declination of $\delta = 50^\circ$ for which the diurnal visibility reduces to a few hours per day.

6 Physics cases

In this section, we consider the case of two particular sources: microquasar LS 5039 and SNR RX J1713.7-3946, both observed in the TeV gamma-ray region. For each source, we compute the detector sensitivity and the expected number of source events compared with the background.

6.1 Microquasar LS 5039

The H.E.S.S. telescope has recently detected TeV $\gamma$-rays from LS 5039 [19]. This discovery provided the first unambiguous evidence for presence of multi-TeV particles in microquasars.

Aharonian et al. [20] discussed different possible scenarios for the production of the observed $\gamma$-ray flux. They
considered both leptonic and hadronic production mechanisms and argued in favor of a TeV photon flux originating from pp interaction. If so, $\gamma$-rays should be accompanied by TeV neutrinos with an average energy flux $f_{\nu,th} = 10^{-10}$ erg/cm$^2$ s.

In Tab. 3 are summarized the detector sensitivities for microquasar LS 5039, assuming neutrino fluxes with spectral indices $\alpha = 1.5$ and 2, in the energy range 0.1 TeV and $\epsilon_{\nu,max} = 10$ and 100 TeV. The expected number of selected events, induced by the flux $f_{\nu,th}$, is given in the same table. The comparison with the atmospheric background shows that an evidence could be expected in a few years of data taking.

### 6.2 SNR RX J1713.7-3946

The CANGAROO Collaboration observed $\gamma$-rays from SNR RX J1713.7-3946, claiming the hadronic origin of the measured energy spectrum [21]. Alvarez-Muñiz and Halzen (A&H) [22] calculated the high-energy neutrino flux associated with this source. Their calculations yield to an expected neutrino spectrum

$$ \epsilon_{\nu}^{th}(d\phi_{\nu}/d\epsilon_{\nu}) = 4.14 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}, \quad (3) $$

with spectral index $\alpha = 2$ and extending up to $\sim 10$ TeV. More recent calculations were performed by Costantini and Vissani (C&V) [23], based on the $\gamma$-rays flux measured by the H.E.S.S. experiment [24]. According to their calculations, we expect a neutrino spectrum

$$ \epsilon_{\nu}^{th}(d\phi_{\nu}/d\epsilon_{\nu}) = 3 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ GeV}^{-1}, \quad (4) $$

with $\alpha = 2.2$ and a neutrino energy ranging between 50 GeV and 1 PeV.

In this paper, we calculate the expect detector sensitivity for RX J1713.7-3946. Despite it is an extended source, in a first approximation we can consider it as point-like since its diameter ($\Theta = 1.3^\circ$) [24] is comparable or smaller than the detector search bin. Results are reported in Tab. 4 where the dependence of the sensitivity on the spectral index $\alpha$ and on the high energy cut-off $\epsilon_{\nu,max}$ is shown. In the same table, we also report the number of expected events surviving the selection criteria, considering both the theoretical predictions. The comparison with the atmospheric background shows that, also in this case, the NEMO telescope could identify the source in a few years of data taking.
Table 4 Detector sensitivity to neutrinos from the SNR RX J1713.7-3946. The sensitivity is expressed in units of $cm^{-2}$ s$^{-1}$ GeV$^{-1}$ and refers to a detector live time of 3 years. The corresponding values of $\theta^{\max}_{\mu}$, $A_{cut}$ and $r_{bin}$ are also given. We also report the number $N^s_{\mu}$ from the source compared to the atmospheric background events $N^b_\mu$ surviving the event selection.

| Model | $A_{cut}$ | $\theta^{\max}_{\mu}$ | $r_{bin}$ | $\varepsilon_{\nu}^{\alpha}(d\nu_{\nu}/d\epsilon_{\nu})_{90}$ | $N^s_{\mu}$ | $N^b_{\mu}$ |
|-------|-----------|------------------------|-----------|--------------------------------------------------------|----------------|----------------|
| A&H   | -7.3      | 99°                    | 0.6°      | 1.4x10$^{-8}$                                           | 8.5            | 0.6            |
| C&V   | -7.3      | 101°                   | 0.4°      | 1.7x10$^{-8}$                                           | 4.8            | 0.4            |

7 Conclusions

The possibility to detect TeV muon neutrinos from point-like sources with the proposed NEMO-km$^3$ underwater Čerenkov neutrino telescope has been investigated. In particular Monte Carlo simulations were carried out to determine the expected response of the km$^3$ telescope.

Our simulations show that it could be possible to observe the Moon shadow in about 100 days. This detection provides a measurement of the detector angular resolution and of the detector pointing accuracy.

We also computed the detector sensitivity to muon neutrinos from point-like sources, defined as the minimum flux detectable with respect to the atmospheric muon and neutrino background. The dependence of the sensitivity on the neutrino spectral index and energy range, on the source declination and on years of data taking has been studied.

Finally, we consider the case of two particular sources: microquasar LS 5039 and SNR RX J1713.7-3946; both observed in the TeV gamma-ray region. For each source, we compute the detector sensitivity and the expected number of source events compared with the background. Our results show that, assuming present predictions of TeV neutrino fluxes, the proposed NEMO telescope could identify both sources in a few years of data taking.

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