Monte Carlo simulation studies of the timing calibration accuracy required by the NEMO underwater neutrino telescope

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Abstract

The results of Monte Carlo simulation studies of the timing calibration accuracy required by the NEMO underwater neutrino telescope are presented. The NEMO Collaboration is conducting a long term R&D activity toward the installation of a km3 apparatus in the Mediterranean Sea. An optimal site has been found and characterized at 3500 m depth off the Sicilian coast. Monte Carlo simulation shows that the angular resolution of the telescope remains approximately unchanged if the offset errors of timing calibration are less than 1 ns. This value is tolerable because the apparatus performance is not significantly changed when such inaccuracies are added to the other sources of error (e.g., the accuracy position of optical modules). We also discuss about the optical background rate effect on the angular resolution of the apparatus and we compare the present version of the NEMO telescope with a different version.

Key words: `timing calibration`, neutrino telescope, Monte Carlo simulation
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1. Introduction

Since 1998 the NEMO (NEutrino Mediterranean Observatory) Collaboration is studying the feasibility of a km^3 underwater neutrino telescope (1).
An optimal site has been found and characterized at 3500 m depth, 80 km south east off the Sicilian coast, after the NEMO Collaboration has examined several deep sea marine areas close to the Italian coast (2). The selected site, named Capo Passero site, has:
- average speed sea current = 3 cm/s (speed maximum < 12 cm/s);
- average optical background due to ^{40}K and bioluminescence = 28.5 ± 2.5 kHz;
- absorption length = 70 m (at 440 nm);
- attenuation length = 36 m (at 440 nm).

The NEMO telescope will have a three-dimensional structure, in fact the layout will be made by a square lattice with:
- 9×9 towers, 830 m height, 140 m distance;
- 18 floors per tower, 20 m length and two by two orthogonal, 40 m distance;
- 4 optical modules per floor, 2 with down-view and 2 with horizon-view.

In each optical module (OM) will be arranged a photomultiplayer (PMT) of 10" and the front-end electronics.
The NEMO underwater neutrino telescope will be optimized for the reconstruction of the muons tracks, generated by muon neutrinos by weak charge current interaction. The tracks reconstruction will be by the Čerenkov light produced by the muon transit in the sea water. For a good track reconstruction is fundamental the role of the timing calibration. Moreover in a muon track reconstruction there are other causes of uncertainty:

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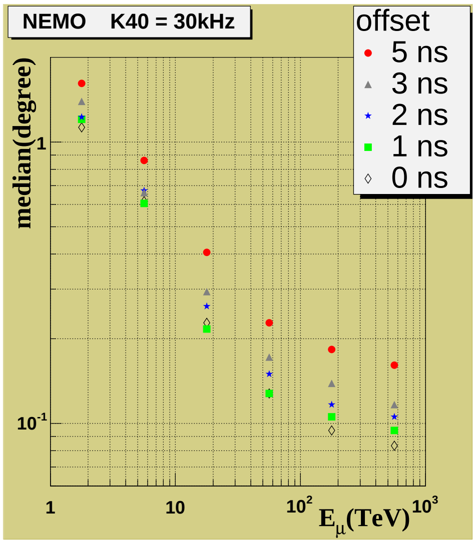

Fig. 1. Angular resolution (median) of the NEMO apparatus versus muon energy, at 30 kHz optical background (K40) for several values of the timing calibration error (offset).

(i) light dispersion in the water > 1 ns;
(ii) positioning error of the OMs ∼ 0.5 ns;
(iii) impact point of the photon on the OM ∼ 0.5 ns;
(iv) formation of the signal in the PMT ∼ 1.5 ns;
(v) front-end electronics error ∼ 0.3 ns.

In this paper we present a study on the timing calibration accuracy required by the NEMO underwater neutrino telescope and we compare its angular resolution with another NEMO telescope version called the String apparatus (3).

2. Timing calibration accuracy study for the NEMO apparatus

To obtain the timing calibration accuracy required by the NEMO telescope, we have to determine which value of accuracy does not change significantly the apparatus performances. We studied the angular resolution of the detector by means of Monte Carlo simulation.
The ANTARES Monte Carlo simulation codes (4) were adapted for the NEMO km^3 apparatus (5).
In this study, for each Monte Carlo simulation, about $5 \cdot 10^4$ up-going muon events were generated on a cylindrical surface of radius ∼ 1 km and height ∼ 1 km (*can*). In the can center was simulated the NEMO apparatus. The characteristics of the simulated muon tracks were:
– isotropic distribution of the azimuthal angle ϕ, with $0 \leq \phi \leq 2\pi$;
– isotropic distribution of the cosine zenithal angle θ, with $-1 \leq cos(\theta) \leq 0$;
– range energy 1 TeV ÷ 1 PeV;
– energy spectrum index = -1.

The emission and the propagation of the Čherenkov light were simulated assuming the characteristics of sea water at the Capo Passero site. The diameter of the PMTs was 10" and the photoelectron thereshold was 0.33 single. Random optical background was simulated. Then electronics response was simulated and the reconstruction procedure was applied, without quality cuts. We used Aart strategy (6).
For each 5832 PMTs of the NEMO apparatus we assigned a timing calibration error (*offset*) smaller than, in absolute value, a maximum error = 1, 2, 3 and 5 ns. The offset-distributions were truncated Gaussians at 1 standard deviation.
We defined the angular resolution of the NEMO apparatus by the median of the angle difference (α) distribution between the muon track reconstruction with offset and the "true" muon track.
Fig. 1 shows the angular resolution NEMO telescope (median) versus muon energy, by the offset values simulated. The optical background was assumed to be 30 kHz. This is a conservative value than the measured average value in the Capo Passero site. If the timing calibration error increases, the angular resolution increases even by a factor of 2. The case with offset < 1 ns is agreement to the case with offset =

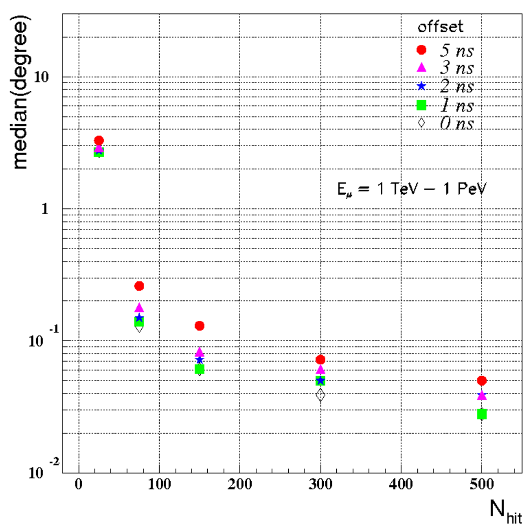

Fig. 2. Angular resolution of the NEMO telescope (median) versus the PMTs hit number (N_{hit}), at 30 kHz optical background for several values of the timing calibration error (offset).

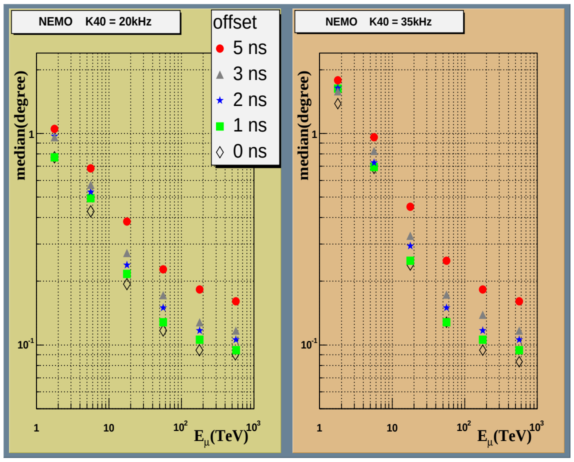

Fig. 3. Comparison between angular resolution of the NEMO telescope (median) versus the muon energy at 20 kHz and 35 kHz (left and right) optical background for several values of the timing calibration error (offset).

0 ns, indeed the small differences are compatibles with Half Width at Half-Maximum α-distributions: HWHM $\simeq 0.04° \div 0.02°$ in the muon energy range $E_\mu = 1$ TeV $\div$ 1 PeV. Even if we consider 5 s.d. instead of 1 s.d. the agreement of their values are still consistent by HWHM. Moreover a timing calibration error < 1 ns is tolerable if compared by errors in the list of the uncertainty causes on the muon track reconstruction.

With a neutrino telescope the muon track reconstruction is obtains by the PMTs hit number, that is the illuminated PMTs number by Čerenkov light. Fig. 2 shows the angular resolution versus the PMTs hit number (N_{hit}). If $N_{\mathrm{hit}} < 50$ (1^{st} bin) the NEMO telescope has not good reconstruction tracks (median $\sim 3°$), instead if $50 \leq N_{\mathrm{hit}} < 100$ (2^{nd} bin) it has a good angular resolution ($\sim 0.1°$), at last if $N_{\mathrm{hit}} \geq 100$ (in the other bins) the apparatus has a very good angular resolution ($< 0.1°$). The $N_{\mathrm{hit}} > 50$ corresponds to $E_\mu > 20$ TeV. The timing calibration accuracy effects are evident, with a maximum factor ~ 2 by the angular resolution values.

We also studied the angular resolution NEMO apparatus versus muon energy having changed the optical background value about its mean value. Fig. 3 shows a comparison between the median versus muon energy at 20 kHz and 35 kHz optical background. The differences of the angular resolution practically are evident just at low muon energy (less than some tens TeV). In both cases the offset < 1 ns is agreement to offset $= 0$ ns by the HMWM of the α-distributions.

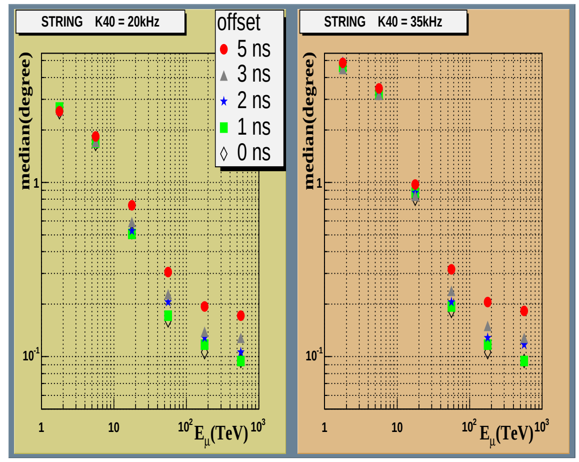

Fig. 4. Comparison between angular resolution of the String telescope (median) versus the muon energy at 20 kHz and 35 kHz (left and right) optical background for several values of the timing calibration error (offset).

2.1. *The String apparatus*

The NEMO telescope discussed in Section 1 is the most layout accredited, another realistic configuration for a km^3 underwater neutrino telescope (7) could be the String telescope. The differences between this apparatus with NEMO apparatus are just the floors length (equal to 1 m) and the floors distance (equal to 20 m). The same Monte Carlo simulation charateristics of the NEMO telescope we used for the study on the String telescope.

A comparison between the angular resolution versus muon energy at 20 kHz and 35 kHz optical background for the String apparatus was made, it is shown in Fig. 4. It is evident a worsening even by a factor of 2 of the angular resolution (at low muon energy), if the optical background increases from 20 kHz to 35 kHz. The timing calibration accuracy effects are evident specially at high muon energy (greater than some tens TeV), indeed in this muon energy range is required an offset < 1 ns (in agreement to offset $= 0$ ns by the HMWM of the α-distributions).

2.2. *Comparison NEMO-String apparatus*

A first comparison between the angular resolution of the NEMO apparatus and of the String apparatus is possible observing Fig. 3 and Fig. 4. There is a drastic worsening of the angular resolution between the two apparatus for equal optical background at low muon energy. The worsening reduces consider-interaction. The muon energy is $\sim 0.6 \div 0.7$ times E_ν at TeV $\div$ PeV range neutrino energy (9), therefore at the muon energy range $< \vartheta_{\nu\mu} > \simeq 0.54° \div 0.009°$. This values range is smaller than the angular resolution of the NEMO telescope and of the String telescope, therefore the kinematic angle does not significantly worse the pointing source (> some TeV).

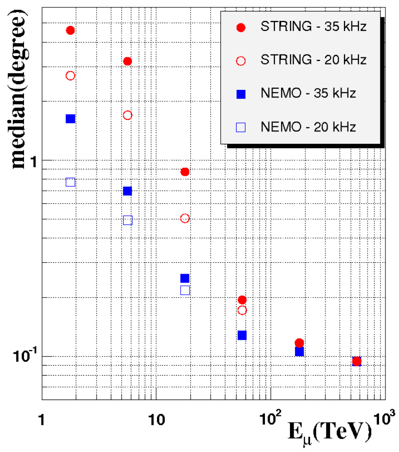

Fig. 5. Comparison between the angular resolution (median) versus muon energy of the NEMO apparatus and of the String apparatus with offset < 1 ns. The optical background is equal to 20 kHz and 35 kHz.

ably at high muon energy.
The timing calibration accuracy with offset < 1 ns is an optimal compromise if we consider that this value is agreement to offset = 0 ns for angular resolution and that we can have such accuracy with an electronics realistically achievable.
Fig. 5 shows a comparison between the angular resolution of the NEMO apparatus and of the String apparatus with offset < 1 ns. For the same apparatus the two different background effects on the angular resolution are very evidents at low muon energy and they are zero just at high muon energy. Also the angular resolution differences between the two apparatus are very evidents at low muon energy, even by a factor of 4.5 (2^{nd} bin at 35 kHz optical background), they are zero just in the last bin. The cause of the worse angular resolution for the String apparatus is probably due at the Čerenkov light attenuation. Indeed for this apparatus the Čerenkov light has to go through greater distance (in the sea water) from muon track to PMTs, with greater attenuation probability.
An optimal muon track reconstruction is the fundamental step for to determine the astrophysical neutrino direction (pointing source). Moreover we have to consider also the kinematic angle of muon production in the neutrino-matter weak current interaction (8):

$$< \vartheta_{\nu\mu} > = \frac{0.7°}{[E_\nu(\mathrm{TeV})]^{0.6}} \tag{1}$$

that is the average angle between neutrino direction and muon direction, E_ν is the neutrino energy before

3. Conclusions

In this paper we had discussed about the timing calibration accuracy required by the NEMO underwater neutrino telescope, analysed by Monte Carlo simulation. We studied the angular resolution versus muon energy and the angular resolution versus the PMT number of hits. The timing calibration accuracy value has to be less than 1 ns for each OM. We studied also the time calibration accuracy for the floors (the OMs on the same foor had the same offset value) and for the towers (the OMs on the same tower had the same offset value), not reported here. In both cases the timing calibration accuracy value has to be less than 1 ns.
The timing calibration accuracy required by the String apparatus (a NEMO apparatus variant) was studied. Also for this apparatus is required an accuracy value smaller than 1 ns for each OM.
A comparison between the NEMO telescope and the String telescope shows a better angular resolution of the NEMO telescope, specially at low muon energy.

References

[1] E. Migneco et al., NIM A 588 (2008) 111-118.
[2] G. Riccobene et al., Astrop. Phys. 27 (2007) 1-9.
[3] R. Coniglione, NIM A 567 (2006) 489-491.
[4] D.J.L. Bailey, PhD dissertation, University of Oxford, UK, 2002. http:/antares.in2p3.fr
[5] P. Sapienza, Proceedings of the First VLVnT Workshop, Amsterdam, 2003, available at http://www.vlvnt.nl/proceedings/
[6] An algorithm for track reconstruction in ANTARES, Aart Heijboer ANTARES-soft/20002-002. http:/antares.in2p3.fr
[7] KM3NeT Web Site, http://www.km3net.org/
[8] The ANTARES Coll., Proposal, 31 May 1999, 31. arXiv:astro-ph/9907432 v1
J.A. Aguilar et al., NIM A 555 (2005) 132.
[9] R. Gandhi et al., Astrop. Phys. 5, 1996, 81-110.