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

R. Megna on behalf of the NEMO Collaboration

Dipartimento Interateneo di Fisica dell'Università degli Studi di Bari & INFN Sezione di Bari, via Orabona 4, 70126 Bari, Italy

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 km^3 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 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 configuration.

Key words: `timing calibration`, neutrino telescope, Monte Carlo simulation
PACS: 01.30.−y

1. Introduction

Since 1998 the NEMO (NEutrino Mediterranean Observatory) Collaboration has been 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 of the Sicilian coast, after the NEMO Collaboration had examined several deep sea marine areas close to the Italian coast (2). The selected site, the Capo Passero site, has:

– average speed sea current = 3 cm/s (maximum speed< 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. The layout will be made using a square lattice with:

- 9×9 towers, 830 m height, 140 m distance;
- 18 floors per tower, 20 m length, alternately orthogonal, 40 m spacing;
- 4 optical modules per floor, 2 with down-view and 2 with horizon-view.

Each optical module (OM) will house a 10" photomultiplier tube (PMT) and its front-end electronics. The NEMO underwater neutrino telescope will be optimized for the reconstruction of muon tracks generated by muon neutrinos in weak charge current interactions. The track reconstruction will use the Čerenkov light produced by the muon transit in sea water.

While timing calibration plays a fundamental role in the accurate reconstruction of muon tracks, there are other causes of uncertainty:

Email address: `Rosario.Megna@ba.infn.it; Fax: +39 080 5442470` (R. Megna on behalf of the NEMO Collaboration).

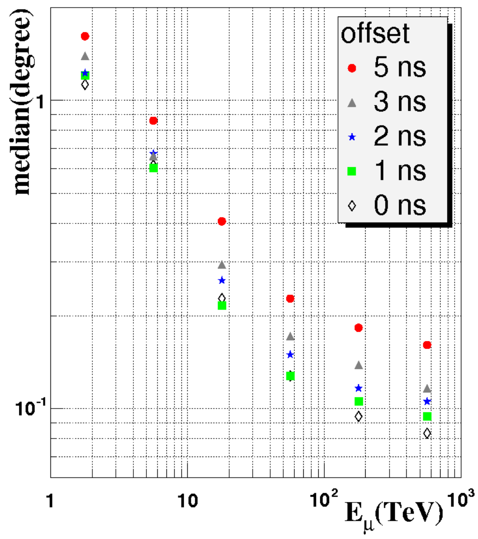

Fig. 1. Angular resolution (median) of the NEMO apparatus versus muon energy, at 30 kHz optical background (^{40}K) for several values of the timing calibration error (offset).

(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 first needed to determine the value of accuracy that does not significantly modify the detector performance.
We studied the angular resolution of the detector by means of Monte Carlo simulation, using ANTARES simulation codes (4) adapted for the NEMO km^3 apparatus (5). In this study, for each Monte Carlo simulation, around $5 \cdot 10^4$ 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 $0 \le \phi \le 2\pi$;
– isotropic distribution of the cosine zenithal angle θ, with $-1 \le cos(\theta) \le 0$;
– energy range 1 TeV to 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 threshold was set to 1/3 of the signal expected from a single photoelectron. Random optical background was simulated. Then electronics response was simulated and the reconstruction procedure was applied, without quality cuts, using the "Aart strategy" (6).
For each of the 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 as 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 of the NEMO telescope (median) versus muon energy, for the different offset values simulated. The optical background was assumed to be 30 kHz. This is a more "conservative" value than the measured average value in the Capo Passero site. As the timing calibration error increases over the tested range, the angular resolution degrades by up to a factor of 2.

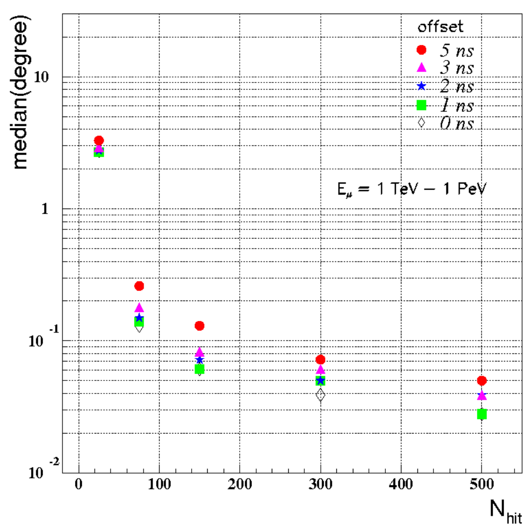

Fig. 2. Angular resolution of the NEMO telescope (median) versus the number of hit PMTs (N_{hit}), at 30 kHz optical background for several values of the timing calibration error (offset).

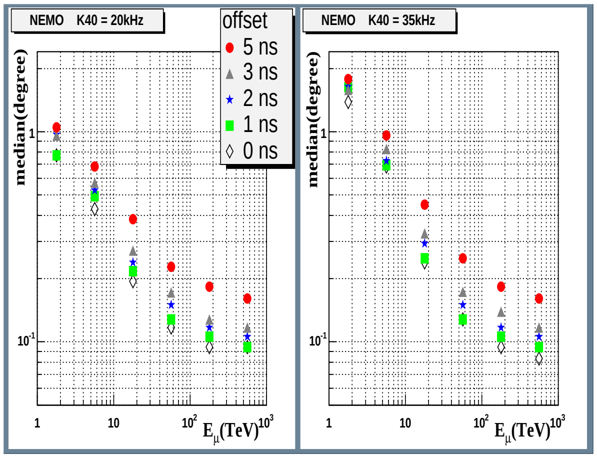

Fig. 3. Comparison between the angular resolution of the NEMO telescope (median) versus the muon energy at 20 kHz and 35 kHz (left and right) optical background for several values of the timing calibration error (offset).

The case with offset < 1 ns is agreement with the case with offset $= 0$ ns: indeed the small differences are compatible 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 HWHM-consistent. Moreover a timing calibration error < 1 ns is tolerable when compared with the other uncertainties affecting the muon track reconstruction.

With a neutrino telescope the muon track reconstruction is determined by the hit PMTs number ($N_{\rm hit}$) - the number of PMTs illuminated by Čerenkov light. Fig. 2 shows the angular resolution versus $N_{\rm hit}$. If $N_{\rm hit} < 50$ (1^{st} bin) the NEMO telescope has poor track reconstruction (median $\sim 3°$). However, if ($50 \leq N_{\rm hit} < 100$) ($2^{nd}$ bin) it has a relatively good angular resolution of ($\sim 0.1°$), while lastly if $N_{\rm hit} \geq 100$ (in the other bins) the apparatus has a very good angular resolution ($< 0.1°$). The case of $N_{\rm hit} > 50$ corresponds to $E_\mu > 20$ TeV. The timing calibration accuracy effects are evident, with a maximum factor ~ 2 change in the angular resolution values.

We also studied the angular resolution of the NEMO apparatus versus muon energy, having changed the optical background value about its mean value. Fig. 3 compares the median angular resolutions at 20 kHz and 35 kHz optical background. The differences in the angular resolution are evident only at lower muon energies (less than some tens of TeV). In both cases the offset < 1 ns is in agreement with offset $= 0$ ns by the HMWM of the α-distributions.

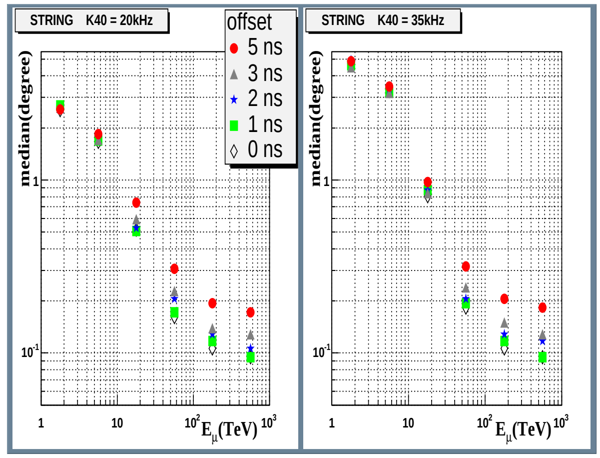

Fig. 4. Angular resolution of a "String" telescope (median) versus the muon energy at 20 kHz and 35 kHz (left and right) optical background for several values of the timing calibration error (offset).

2.1. *The String apparatus*

The NEMO telescope discussed in Section 1 is the most accredited layout. Another realistic configuration for a km^3 underwater neutrino telescope (7) could be the String telescope. The differences between this apparatus and the NEMO apparatus are just the floor length (equal to 1 m) and inter-floor distance (equal to 20 m). The same Monte Carlo simulation charateristics of the NEMO site were 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, and is shown in Fig. 4. It is evident that the angular resolution worsens by a factor of 2 (at low muon energy), when 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 of TeV); indeed in this muon energy range an offset < 1 ns is required (in agreement with 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 the String apparatus is possible comparing Fig. 3 and Fig. 4. There is a drastic worsening of the angular resolution of the String apparatus for equal optical background at low muon energy. The worsening reduces considerably at high muon energy.

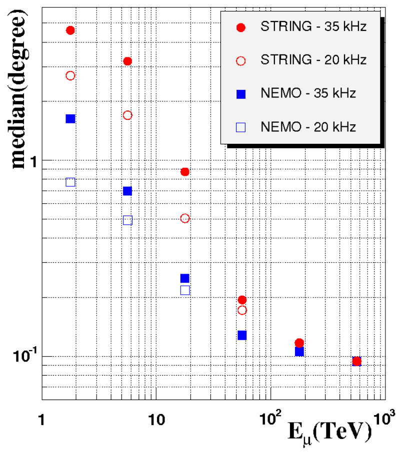

Fig. 5. Comparison between the angular resolution (median) versus muon energy of the NEMO apparatus and of the String apparatus with offset < 1 ns. The optical background is equal to 20 kHz and 35 kHz.

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

$$< \vartheta_{\nu\mu} >= \frac{0.7^\circ}{[\mathrm{E}_\nu(\mathrm{TeV})]^{0.6}} \quad (1)$$

that is the average angle between neutrino direction and muon direction, where E_ν is the neutrino energy before interaction. The muon energy is $\sim 0.6 \div 0.7$ times E_ν at TeV ÷ PeV range neutrino energy (9), therefore at the muon energy range $< \vartheta_{\nu\mu} >\simeq 0.54^\circ \div 0.009^\circ$. Since the range of this value is smaller than the angular resolution of the NEMO telescope and String telescope, the kinematic angle does not significantly worsen the pointing source at energies > some TeV.

3. Conclusions

In this paper we have discussed the timing calibration accuracy required by the NEMO underwater neutrino telescope, as analysed by Monte Carlo simulation. We have studied the angular resolution versus muon energy and the angular resolution versus the number of hit PMTs. The timing calibration accuracy value has to be less than 1 ns for each OM. We have also studied the time calibration accuracy for the floors (with OMs on the same floor having the same offset value) and for the towers (with OMs on the same tower having 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 variant) was studied. Also for this apparatus a timing calibration accuracy smaller than 1 ns is needed for each OM.
A comparison between the NEMO telescope and the String telescope shows a better angular resolution of the NEMO telescope, especially 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.