Performance of flexible-tower geometries for KM3NeT: simulation results

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***Abstract*. The objectives of the KM3NeT Design Study include the definition of the design and the technical issues related to the construction, installation and operation of a cubic kilometre size neutrino telescope to be deployed in the deep Mediterranean Sea. In this paper the results of a simulation study to estimate the performance of a km^3 telescope with flexible towers are presented as a function of several detector parameters.**

***Keywords*: Neutrino telescope, KM3NeT**

I. Introduction

Estimates of neutrino fluxes indicate that detector volumes of cubic kilometre size are needed to detect high energy neutrinos ($E_\nu \geq 100$ GeV) from astrophysical sources. High energy neutrino telescopes observe the sky using the Earth as a filter for neutrinos and a full sky coverage requires two telescopes located in opposite hemispheres. Indeed, a detector placed in the Mediterranean Sea will survey a large part of the galactic plane, including the Galactic Center, thus complementing the observation of the IceCube detector [1] which is halfway to completion at the South Pole and observes the Northern Sky.

To realise such a telescope, an EU funded Design Study was started in 2006 by the KM3NeT consortium [2], formed from groups working in the Mediterranean Sea neutrino telescope projects (ANTARES [3], NEMO [4] and NESTOR [5]) together with additional collaborators.

The realisation of the KM3NeT telescope will provide the scientific community with a very powerful instrument to study many astrophysical objects, including supernova remnants, active galactic nuclei, gamma-ray bursts and possibly also dark matter. The scientific goals and the concepts behind the design, construction and operation of the telescope are reported in the Conceptual Design Report [6] that has been published in April 2008. The next milestone of the Design Study will be in 2009 with the publication of the KM3NeT Technical Design Report (TDR), detailing the most promising technologies and the expected physics performance of the future detector. Concurrent with the publication of the CDR an EU funded Preparatory Phase (KM3NeT-PP) has started which will pave the way to the construction of the KM3NeT telescope.

The optimisation of the telescope sensitivity is focused to point source searches in the TeV-PeV energy range. In addition the performance at lower energy that is relevant for indirect searches for dark matter candidates and at higher energies looking for diffuse fluxes and gamma ray bursts is being evaluated.

In the Conceptual Design Report of KM3NeT [6] possible solutions are presented for the Detection Unit which is the basic modular structure of the detector and hosts the Optical Modules containing the photon sensors. One of them is a flexible tower that, once unfurled after the deployment to sea bottom, is a three-dimensional structure. Moreover, two possible options are considered for the Optical Modules which can contain either a single large photomulti plier (PMT) (8" - 10" in diameter) or many (31) 3" PMTs.

The final choice for the design of the KM3NeT telescope will be made following an evaluation based both on physics objectives, technical issues, reliability and costs. In this paper we present some of the simulation results performed for a km^3-scale detector with flexible towers with Optical Modules containing a single large PMT. The most relevant technological issues for a km^3-scale neutrino telescope based on flexible-towers are described in [7].

II. Simulations

With a MonteCarlo simulation [8] developed in the ANTARES collaboration adapted for use with km^3-size detector geometries [9] several detector configurations were studied. In the following we present some simulation results for a telescope consisting of 127 towers arranged in a hexagonal lay-out. Each tower consists of 20 extended rigid storeys (6-10 m long), each storey being orthogonal to the adjacent one, equipped with three pairs of optical modules containing an 8" PMT each with a quantum efficiency peak value of 35% at 380 nm [10]. The PMTs are placed in three pairs on the storey: a pair at each end - with one downward-looking PMT and the other horizontally-looking - and a third pair at the center with both PMTs looking downward at 45°. The spacing between storeys is one of the parameters to be optimised; in this work a spacing of 40 m is considered. Of course the detector is scalable to a higher or smaller number of towers. In this work the effects of tower distance and bar length are investigated.

The main input parameters of the simulations are:

- E^{-2} up-going neutrino energy spectrum
- optical parameters of the sea water: absorbtion length of 67m at 440nm and scattering length of 55m at 480m [6]
- depth of the detector site of 3400 m
- 47 kHz uncorrelated optical background per PMT uniformly distributed in a $\pm$ 1 μsec window around the event
- event selection based on double coincidence between any pair of PMTs in the bar in logic OR with the presence of high-charge hits ($\geq$ 2.5 p.e.)
- reconstruction algorithm based on maximum likelihood estimator [11].

One of the parameters that determine the efficiency of a neutrino telescope is the effective neutrino area for reconstructed muon neutrino events. Another critical parameter for the performance of a neutrino telescope is the angular resolution, especially for individual point sources of cosmic neutrinos. Indeed, a good angular resolution allows for a decrease of the cone search size and therefore for a reduction of the atmospheric neutrino background, thus improving the telescope sensitivity [12].

Well reconstructed events are selected by means of quality cuts on the likelihood. Indeed the likelihood is the parameter most related to the quality of the track reconstruction. The stronger are the quality cuts on the likelihood the better is the angular resolution.

In fig. 1 the effective neutrino area for reconstructed muon neutrino events is reported, after quality cuts providing an angular resolution $\Delta\Omega \sim 0.1°$ at 30 TeV, for a 127 tower detector with 10 m long bars and a spacing between towers of 180 m.

The main advantage of the tower configuration is the three dimensional arrangement of optical modules within one detection unit that provides a good quality in track reconstruction [13], especially since tracks segments confined to a single detection unit benefit from a reduction of ambiguities in the azimuthal angle reconstruction. Moreover, a detector based on towers allows for a larger spacing between detector units with respect to a string detector. The dependence of telescope performance on the tower spacing in the various energy ranges has to be investigated. Although the final answer will be provided by the maximization of the sensitivity for expected physical neutrino fluxes (neutrinos from dark matter annihilation, galactic and extra-galactic point-like sources, diffuse neutrino fluxes,...), some indications can be provided by the trend of the effective neutrino areas. In fig. 2 relative neutrino effective areas are reported as a function of the distance between towers. In the top panel of fig.2 the ratio of the effective area with respect to that of the same detector configuration with a tower spacing of 100 m is given for the energy range between

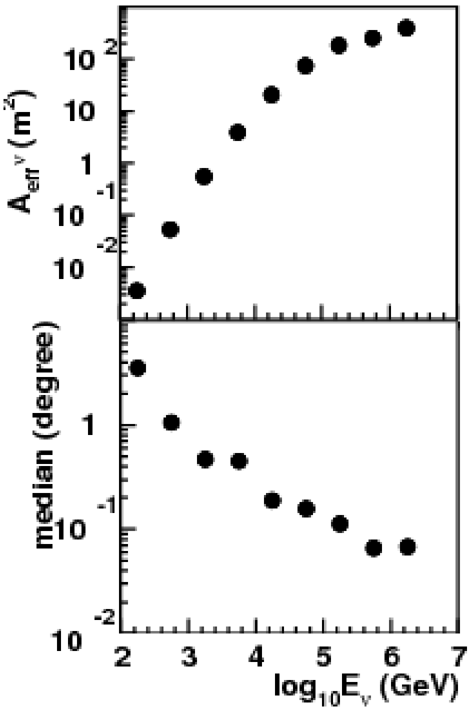

Fig. 1: Neutrino effective areas (top panel) and median of the angle between simulated and reconstructed muon directions (bottom panel) as a function of the neutrino energy for a 127 tower 180m spaced geometry (see text).

100 GeV and 500 GeV. The results of the simulations are displayed after a quality cut on the likelihood that gives a median angle between the muon direction and the reconstructed muon direction smaller than 2°, a value close to intrinsic neutrino-muon angular spread.

In the middle panel of fig.2 the effective area ratio for the energy range between 3 TeV and 100 TeV is displayed after a quality cut on the likelihood that gives a median of the simulated and reconstructed muon angle distribution smaller than 0.4°. This value is close to the value of the cone search bin found in our preliminary sensitivity studies for point-like source search with energy spectra $E^{-\alpha}$ with $\alpha \simeq 2$.

TABLE I: Median of the simulated and reconstructed muon angle distribution for different tower distances and neutrino energy $E_\nu \geq$ 100TeV.

DU distance (m)	$\Delta\Omega$ (degree)
100	0.1
150	0.2
180	0.2
250	1.0

In the bottom panel of fig. 2 the effective area ratio for the neutrino energy larger than 100 TeV is displayed without any quality cut on the likelihood. Median angles between the muon direction and the reconstructed muon

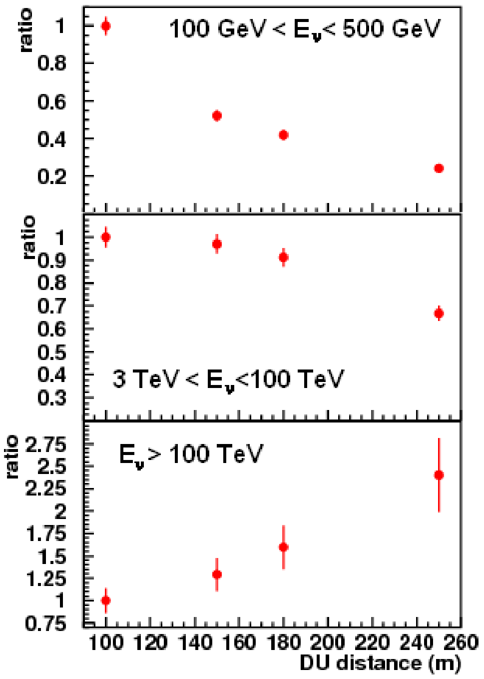

Fig. 2: Ratio of neutrino effective areas with respect to the 100m tower spacing is reported as function of the tower spacing for different energy ranges. Quality cuts are applied for top and middle panels (see text).

direction are reported in table I. For $E_\nu \geq 100$ TeV rather good values of the angular resolution are found without any quality cuts.

The sensitivity to point like sources has been estimated calculating the 90% average flux limit [12]. The average flux limits have been estimated by optimizing the search cone, the cuts on the reconstruction likelihood and on the energy threshold (number of hits).

The ratio of the sensitivity for point-like sources with energy spectra $E^{-\alpha}$ ($\alpha \simeq 2$) and one year of observation time with respect to 100 m tower spacing sensitivity is reported in fig. 3 as a function of tower distance.

In conclusion, a tower distance of about 180 m appears to be reasonable for point source searches with spectral index close to 2 and high energy neutrinos $E \geq 100$ TeV, while it implies a rather strong reduction of the effective area at lower energy (100 GeV$\leq E \leq$500 GeV) where more detailed studies are needed.

The design of a flexible-tower detection unit foresees a storey length between six and ten meters. The final choice will be driven by considerations of physics performance, technical feasibility and costs. In fig. 4 the effective area ratio for the various neutrino energy ranges is reported as a function of the storey length. A storey length of three meters, while not considered as competitive option for the structure, is used as basis for comparison.

In the top panel of fig. 4, a strong increase of the effective area is observed at low energy (events with an

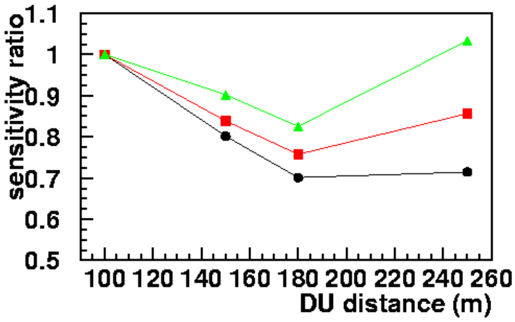

Fig. 3: Ratio of sensitivity to point-like sources with respect to 100m tower distance sensitivity as a function of tower distance for three different spectral indexes. Circles α =1.8, squares α =2, triangle α =2.2.

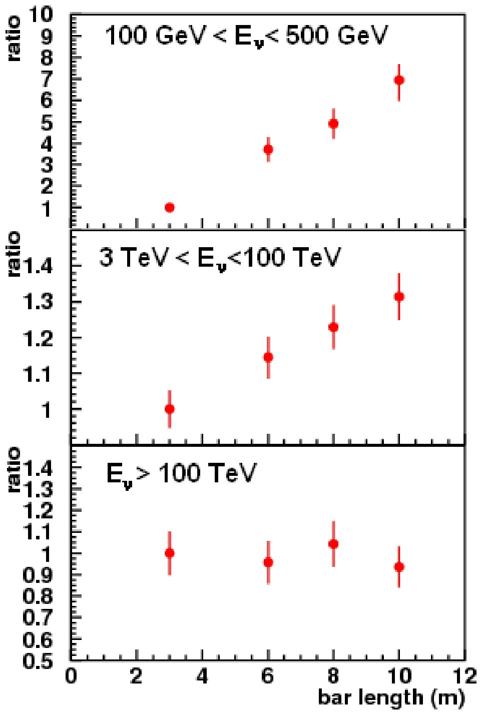

Fig. 4: Ratio of neutrino effective areas with respect to the 3m bar length structure is reported as function of the bar length for different energy ranges. Quality cuts are applied for top and middle panels (see text).

angular resolution comparable to the intrinsic neutrino-muon angular spread are selected) with increasing storey length. In particular, in the range between six and ten meters, a gain of about a factor two in effective neutrino area is observed. In middle panel of fig. 4 a moderate increase, at 10% level, is observed between six and ten meters. These results are in reasonable agreement with preliminary results on sensitivity to point-like sources with energy spectra $E^{-\alpha}$ with $\alpha \simeq 2$. In the bottom panel of fig. 4, for high energy neutrinos ($E \geq 100$ TeV) no dependence on the storey length is observed as expected.

The angular resolutions for events with E≥100 TeV are reported in table II.

TABLE II: Median of the simulated and reconstructed muon angle distribution for different bar length for neutrino energy $E_\nu \geq$ 100TeV.

storey length(m)	$\Delta\Omega$ (degree)
3	0.9
6	0.2
8	0.2
10	0.2

Since the trend of the effective neutrino area as a function of the storey length for the various energy ranges shows that the effect is more relevant at lower energy, the estimate of the detector sensitivity for possible neutrino signals in this energy region, such as neutrinos from dark matter annihilation, can play an important role in the choice of the storey length of the tower.

III. Conclusions

In this work some results of simulations aiming at the optimisation of a high energy neutrino telescope based on flexible towers are presented. The main feature of the flexible tower detector concept, with its three-dimensional placement of OMs within one detection unit, is the improvement of the track reconstruction quality due to the possibility for track reconstruction within a single tower detection unit. The effect of the spacing between towers and of the storey length, which are the essential parameters of the tower configuration, were investigated comparing effective neutrino areas and sensitivities for neutrinos with energy between 100 GeV and 10 PeV. Sensitivity studies for diffuse fluxes are ongoing and the sensitivity to neutrinos from dark matter annihilation will be also estimated.

IV. Acknowledgements

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