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Performance studies for the KM3NeT Neutrino Telescope

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ABSTRACT

Due to its multi-km^3 size and its location in the Mediterranean Sea, the KM3NeT Neutrino Telescope has the unique ability to detect neutrinos from Galactic sources. In order to evaluate the performance of the current design of the detector (based on a "flexible tower" design with "multiPMT" digital optical modules), studies based on Monte-Carlo simulations have been performed. Using a dedicated reconstruction algorithm, the sensitivity to E^{-2} fluxes and the discovery potential for an expected neutrino spectrum from the supernova remnant RX J1713.7-3936 have been determined. The effects of a more homogenous optical module placement within the detector volume compared to the one possible with the current tower design are also presented.

1. Introduction

The KM3NeT Neutrino Telescope is a prime contender for the discovery of neutrinos from cosmic sources, with a unique opportunity to detect a neutrino flux from galactic sources. With the release of the KM3NeT technical design report (TDR) [1], the foundation for the detector's design has been established. The document does, however, describe several different detector design options. During the recent months, a hybrid design of two of those options has been chosen as the technical solution to be pursued by the consortium (see also this issue [2]). The current detector design is based on "multiPMT" digital optical modules (DOMs) mounted on a tower-like three-dimensional structure.

Due to the fact that such detectors were not considered in the TDR, new simulation studies were necessary. In addition, a reconstruction algorithm specific to multiPMT DOMs had to be implemented. Using these tools, the detector performance for E^{-2} benchmark point-source fluxes and for other promising sources, such as the SNR RX J1713.7-3936 can be determined.

This article will first give a high-level overview of the detector design (see Ref. [2] for more details) and of the simulation software. Then, the reconstruction algorithm is briefly presented. Finally, the sensitivity of the detector to a E^{-2} point-source flux and the discovery potential for the supernova remnant RX J1713.7-3936 as an example of a possible Galactic neutrino source are shown.

2. KM3NeT detector design

The current iteration of the KM3NeT detector design is based on self-unfurling "flexible tower" detection units (DUs), placed on the seafloor at distances of about 180 m. The detector consists of two blocks of 127 towers each, arranged an approximately hexagonal grid (see Fig. 1). The two building blocks are considered as independent that corresponds to two nodes in the distributed KM3NeT network of Neutrino Telescopes, which can be located either on the same site or at different sites. Slight variations in the seafloor positions of the DUs from the perfect grid have been introduced on purpose to reduce symmetries in the detector which could affect the azimuthal distribution of the detector acceptance. Each tower consists of 20 floors (or storeys) made of horizontal metal bars, with two "multiPMT" digital optical modules (DOMs) mounted, one at each end. The length of these bars is 6 m, their vertical spacing is 40 m. A DOM, in turn, consists of 31 PMTs, each with a diameter of 3 in., housed in a 17 in. glass sphere. Reflective rings around the PMTs are used to increase their light collection area. PMT readout is simulated on a time-over-threshold basis using a threshold of 0.3 photoelectrons.

This reference design is a starting point for optimization studies within the constraints set by existing decisions on which technologies to use. Properties like the DU distance or the bar length are still relatively easy to change, whereas, for example, the DOM design would require considerably more engineering work to be changed from the version presented in the TDR.

As there is no decision on the detector site for KM3NeT yet, the "Capo Passero" site near Sicily at a maximum depth of 3600 m has been arbitrarily chosen for these studies.

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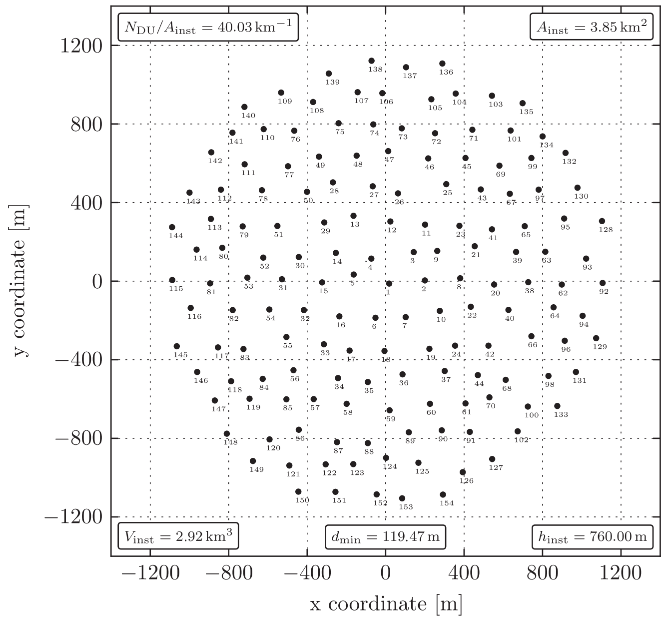

Fig. 1. Seafloor layout (or "footprint") of the current KM3NeT reference detector design. Each dot shows the position of a tower detection unit. The final detector consists of two of such building blocks.

For this work, the performance of the reference design itself has been studied. In addition, in order to determine the effects of the non-uniform distribution of DOMs within the detector volume (i.e. concentrated on towers with large inter-DU distances), the bar length has been scaled from its current default value of 6–12 m, 24 m and up to 48 m. The latter two versions are probably not feasible from an engineering point of view, but they were chosen to be able to gain insight into the effects of an even more homogenous distribution of DOMs in the detector volume.

3. Simulation software

Detector simulation was done using a combination of tools that have already been in use by the IceCube collaboration and new tools developed specifically for KM3NeT [3,4].

The simulation chain starts with ANIS [5] as the neutrino generator. Generation of neutrinos starts at the atmosphere according to a user-defined spectrum. From there, the particles are propagated through the Earth to the detector. Once a neutrino reaches a pre-defined volume around the detector, it is forced to interact within this volume and its interaction probability is stored. The νN structure functions in *ANIS* are chosen compatible to the CTEQ5 parameterization [6]. Only up-going muon–neutrinos are considered for this work. The background of down-going atmospheric muons accidentally reconstructed as up-going is assumed to be on the level of 10% of the atmospheric neutrino background after quality cuts, involving track direction, etc. The detailed simulation of atmospheric muons is, therefore, neglected for this study.

This propagation of neutrino-induced muons from their point of interaction up to and through the detector volume is performed using the MMC simulation code [7]. MMC propagates muons through matter while simulating their energy losses.

In order to propagate Cherenkov light from muons and cascades to individual optical modules, a table-based simulation algorithm has been implemented [3]. Exploiting all available symmetries, this algorithm uses a database of pre-propagated photons to decrease the time spent on tracking all individual photons from a source (i.e. either a muon or a cascade) to an optical module. The time-consuming process of tracking individual photons through the sparsely instrumented volume can thus be omitted.

Once photons have been propagated to an optical module, the PMT and readout electronics are simulated using dedicated algorithms.

4. Event reconstruction strategy

Unlike previous algorithms used for "multiPMT" event reconstruction [3], which were based on a log-likelihood reconstruction algorithm adapted from IceCube, the current version uses a probability density function (PDF) parameterization based entirely on first principles. The only input data necessary for the calculation of this PDF are properties such as absorption lengths, scattering lengths, scattering angle distributions and DOM/PMT acceptances. No fits to Monte-Carlo simulated distributions are necessary. This avoids biasses due to insufficient simulation statistics and provides a much better description of the data than the previous model, which only used a small number of parameters which had to be fitted to simulated events. This, in turn, avoids the degradation in angular resolution seen with the previous approach when compared to similar detectors using the older "singlePMT" setup with a single 10 in. phototube per OM.

Prior to this, a fast linear pre-fit algorithm is used to find a start value for the final log-likelihood fit, since finding a good start value has turned out to be one of the major obstacles when using the improved PDF parameterization. The pre-fit uses the so-called "L1" hits, which are defined as all hits that occur in coincidence with others in PMTs on the same DOM within a time window of 10 ns. Using this simple filtering scheme yields a set of hits with a highly reduced contamination from bioluminescence and ^{40}K backgrounds. For each event, the pre-fit algorithm scans a large number of directions, covering the whole sky on a grid of about 1°. During each scan iteration, the assumed track direction is stays fixed. This allows for determining if a pair of hits are causally connected assuming that track direction and neglecting scattering of Cherenkov photons. The largest cluster of hits where all hits are connected to each other is determined. These hits are then used for a χ^2 fit, again neglecting scattering. Using the number of hits per cluster and χ^2/N_{dof} as quality estimators for each direction, the 10 best directions are chosen from all scanned directions and used as starting points for the final log-likelihood fit.

As demonstrated with the ANTARES detector, a pre-fit algorithm such as the one presented here can double as an online trigger by simply reducing the number of scan directions to about 100 and requiring a certain minimum cluster in any of the scanned directions. The assumption made for this work is thus that such a trigger would be used for KM3NeT and no special trigger simulation is performed.[1]

5. Detector performance

Two different benchmark fluxes were chosen to determine the performance of the reference detector design presented above: an unbroken E^{-2} point-source flux, representative for the sensitivity to high-energy neutrino sources and an expected neutrino spectrum

[1] There are more, even simpler, trigger strategies available for KM3NeT. One of them is to just require a certain number (two or three) of coincident L1 hits on two DOMs on each bar. For the current work, the trigger algorithm should be independent of the bar length, so this option has been disregarded.