

Event reconstruction in KM3NeT with multi-PMT optical modules

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Abstract. High-energy neutrino telescopes are sensitive to the Cherenkov light emitted by relativistic charged particles. Their performance strongly depends on the characteristics and arrangements of the photo-sensors used in the optical modules. For the next-generation neutrino telescope KM3NeT, which will be built in the Mediterranean Sea, a new concept for OMs is considered. Instead of a single large (10") photo-multiplier tube (PMT), 31 small 3" PMTs are mounted in the same glass sphere. In addition to the increased quantum efficiency and total photo-cathode area of such multi-PMT OMs, they are also sensitive to the direction of incoming photons. The combination of these features could lead to a significant improvement in the reconstruction of neutrino events in KM3NeT. First results obtained from MC simulations of such multi-PMT OMs will be presented.

Keywords: Neutrino telescope, KM3NeT, reconstruction

I. INTRODUCTION

High-energy neutrino telescopes are relatively new tools of the astroparticle physics. These telescopes are installed in the very large natural transparent target volumes and detect the Cherenkov photons from relativistically moving charged particles.

The first neutrino telescope was realized about 10 years ago in Lake Baikal in Siberia, Russia. The AMANDA neutrino telescope at the South Pole followed soon after. Recently the first deep-sea neutrino telescope in the Mediterranean Sea, ANTARES, started data-taking in its final configuration. The results from these detectors, together with the observations of very high energy (VHE) gamma astronomy indicate, that for a statistically significant detection of high-energy cosmic neutrinos, a neutrino telescope with at least a km³-size instrumented volume is required. The first telescope of this size, IceCube, is now under construction at the AMANDA site. IceCube will search for cosmic neutrinos from the Northern sky.

The neutrino telescope for the observation of the Southern neutrino sky (KM3NeT) is currently in the design study phase [1]. This study is performed by the KM3NeT consortium and supported by the EU through the FP6 program. In April 2008 the consortium released the conceptual design report for a deep-sea research infrastructure in the Mediterranean Sea incorporating a very large volume neutrino telescope [2].

The KM3NeT neutrino telescope will detect neutrino interactions with the different event signatures. For high-energy neutrino astronomy, the muon neutrino charge-current interactions will play a major role:

$$\nu_{\mu} + N \rightarrow \mu + X. \quad (1)$$

The muons in these interactions carry a large fraction of the neutrino energy and can travel up to several kilometers through the telescope volume. Due to the strong Lorentz boost at high energies, the muon almost follows the parent neutrino direction, thus making the search for neutrino point sources possible. The good angular accuracy of muon reconstruction is essential for this search.

Electron neutrino interactions as well as neutral-current interactions of all neutrino flavors will produce different event signatures in the telescope. The distances traveled in water (ice) by the charged hadrons and electrons produced in the electromagnetic or hadronic showers are much shorter than the light absorption length (≈ 55 m in the Mediterranean Sea for photons with $\lambda=420$ nm). The shower events therefore can be considered as almost point-like Cherenkov radiation inside the detector. The angular resolution of the neutrino direction reconstructed from the showers is significantly worse, however the neutrino energy in these events can be reconstructed with better accuracy, as the source of the Cherenkov photons is contained inside the instrumented volume. The events with a shower signature are good candidates for the investigating cosmic neutrino diffuse flux.

The final configuration of the KM3NeT neutrino telescope will be fixed in the upcoming technical design report. Various configurations are under consideration in the KM3NeT consortium. One of these configurations, the SeaWiet design (SEnsor Architecture for a Wide Energy range Telescope) with a new type of optical module and enhanced capabilities for neutrino event reconstruction is discussed in this paper.

II. KM3NeT DETECTOR CONFIGURATIONS

The KM3NeT neutrino telescope will have a modular structure, where each module can be deployed on the sea bed independently. The KM3NeT module is called a detection unit (DU) and consists of storeys. Each storey can include one or several optical modules (OM) which may in turn contain a single PMT or multiple PMTs. The OM version with multiple PMTs, (multi-PMT OM) was developed during the KM3NeT design study phase [3].



Fig. 1. Multi-PMT OM, developed in the KM3NeT design study project.

The conventional OM, used in ANTARES and IceCube, is a glass sphere, holding one large (10" diameter) PMT. In the deep-sea telescope, each detector storey should contain at least 2 PMTs. This is necessary for the reduction of the deep-sea environmental optical background, due to radioactive decays (mainly ^{40}K) and bioluminescence. This random background is reduced by using coincidences on the same storey in a short time interval or by taking hits with large amplitudes. For example, the ANTARES storey has 3 OMs and coincidences are detected within a $\Delta t=20$ ns time window. In the SeaWiet configuration, the multi-PMT OM is housed in the 17" glass sphere (similar to ANTARES), where 31 PMTs of 3" diameter are mounted. A multi-PMT OM prototype is shown in Fig. 1.

The obvious advantages of this multi-PMT OM include:

- Larger photocathode area in comparison to the ANTARES/IceCube OMs
- Homogeneous coverage of the OM surface, hence more isotropic detection of Cherenkov photons
- Improved PMT parameters, such as quantum efficiency and time resolution
- Better photon counting
- Possibility of direction reconstruction of the Cherenkov photon field radiation

A. Optimisation of the detector design

The instrumented volume of the KM3NeT neutrino telescope will be defined by the number of deployed DUs and their configuration on the sea-bed. Assessment of the SeaWiet costs indicate that up to 300 DUs, each with 20 storeys of a single multi-PMT OM, could be used in the KM3NeT neutrino telescope. The length of the deep-sea DU is limited to about 700 m, due to constraints of the deep-sea environment, in particular the sea currents. The instrumentation of each unit starts 100 m from above the sea bottom.

For a wide energy range telescope, the preferred geometry configuration on the sea-bed is a homogeneous grid. This grid could be considered as a collection of the quadrilateral structures, formed by 4 DUs in a rhombic geometry. The surface area of the single structure is $A = l^2 \sin\Theta$, where l is the distance between neighboring DUs, and Θ is the rhombic angle. The IceCube geometry is based on similar quadrilateral structures, formed by 80 modules (strings), in a hexagonal configuration with $l=125\text{m}$ and $\Theta = 60^\circ$. Note that rectangular structures ($\Theta = 90^\circ$) maximise the area covered by the DUs.

Rectangular and hexagonal geometry with 289 and 290 DUs respectively were assumed for the SeaWiet configuration. The requirement for the KM3NeT instrumented volume ($>1 \text{ km}^3$) sets the minimal distance between DUs at $l > 81$ m. These two layouts are depicted in Fig. 2 for $l=100$ m. The area covered on the sea floor is about 13% larger in the case of a rectangular geometry, although it has 1 DU less.

The KM3NeT telescope will be optimised for the detection of high-energy neutrinos. After fixing the number and structure of the DUs the only free parameter for the detector optimisation is the distance l . The optimisation of the KM3NeT performance depends on the instrumented volume and event reconstruction. The KM3NeT performance was evaluated with the help of Monte Carlo (MC) simulations. The optimal geometry configuration for the SeaWiet design will be selected on the basis of these simulations.

III. MONTE CARLO SIMULATIONS

Two main parameters, which define the physics performance of the KM3NeT neutrino telescope, are the effective area $A_\nu(E_\nu)$ and the angular resolution of the reconstructed events. The neutrino effective area defines the event rate R in the telescope for the neutrino flux $\Phi(E_\nu)$. Neglecting the angular dependences for brevity,

$$R \approx \int \Phi(E_\nu) A_\nu(E_\nu) dE_\nu. \quad (2)$$

The effective area is defined as

$$A_\nu(E_\nu) = V_G \rho N_A \sigma(E_\nu) P_E(E_\nu) \cdot \epsilon(E_\nu); \quad (3)$$

again only energy dependence is shown.

Here V_G is the volume in which the neutrino events could cause detectable signatures in the telescope, ρ is the density of the volume, N_A is the Avogadro number, $\sigma(E_\nu)$ is the neutrino nucleon cross-section and $P_E(E_\nu)$ is the Earth absorption factor, which depends on the neutrino energy and the distance the neutrino travels through the Earth. Finally, ϵ is the event selection efficiency factor

$$\epsilon(E_\nu) = \epsilon_A(E_\nu) \cdot \epsilon_T(E_\nu) \cdot \epsilon_R(E_\nu), \quad (4)$$

which is a product of the telescope acceptance (ϵ_A) and the trigger (ϵ_T) and reconstruction (ϵ_R) efficiencies. The modified software chain of the ANTARES collaboration

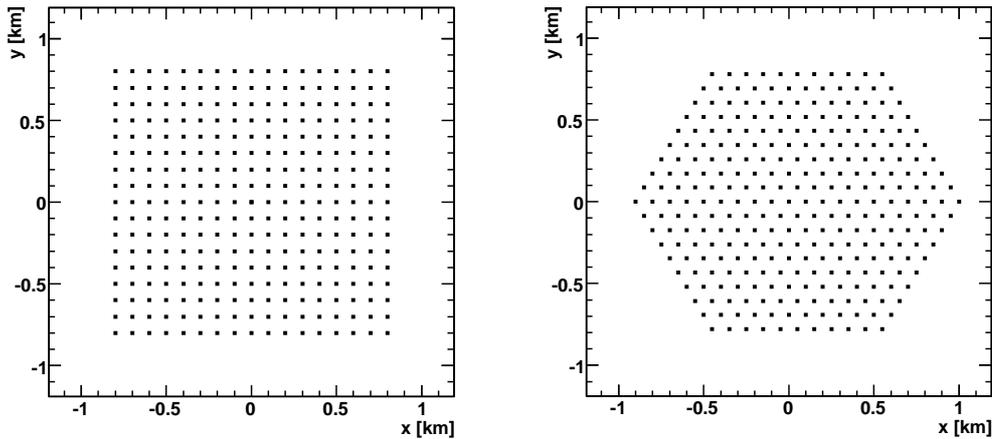


Fig. 2. The rectangular (left) and hexagonal sea-bed configurations of the KM3NeT telescope with 289 and 290 detector units respectively. The area covered for $l=100\text{m}$, is 2.56 km^2 for the rectangular and 2.26 km^2 for the hexagonal configuration.

was used in the study [4]. This includes the simulation of neutrino events, generation of Cherenkov photons from the relativistic charged particles and their propagation, and simulation of the hits in the OMs.

The KM3NeT acceptance $\epsilon_A = \frac{N_s}{N_G}$ is the ratio of the events which are generating signals in the KM3NeT instrumented volume to the events simulated in the volume V_G . The acceptance is a function of the instrumented volume and for the fixed number of DUs varies as a function of the distance l between DUs.

The final selection of neutrino events and the physics performance of KM3NeT will depend on trigger and reconstruction efficiencies, which are discussed below.

IV. EVENT SELECTION AND RECONSTRUCTION

A. Trigger rates

The PMT signals above a defined threshold and the corresponding times are the main data collected from the neutrino telescope. The neutrino events are reconstructed from these signals (PMT hits), which are usually referred as initial level or L0 hits. The L0 rate is a convolution of the photon flux in the deep-sea and the PMT properties, such as photo-cathode area, quantum efficiency and photo-electron (p.e.) counting capabilities.

The L0 rates in deep-sea neutrino telescopes are defined by the flux of background optical photons, which is about $350\text{ photons/cm}^2\text{s}$ in the Mediterranean Sea [2]. The main source of this constant flux are ^{40}K decays. An additional contribution is coming from the time dependent bioluminescence flux, including short bursts of photons from macro-organisms. For the 3" PMTs considered in the SeaWiet design, these rates are up to 7 kHz per PMT, or about 200 kHz per OM. These rates were recalculated from the ANTARES OM data for the 3" PMT parameters. The PMT parameters

were measured at ECAP (Erlangen) [5] and included in the MC simulations of optical background within the GEANT framework.

Atmospheric muon and neutrino events are expected in the neutrino telescope with significantly smaller rates, therefore the background L0 rates should be filtered out before event selection and reconstruction.

The KM3NeT neutrino telescope data acquisition model will be based on the "all-data-to-shore" concept, which is successfully used in ANTARES [6]. This concept gives the possibility to introduce flexible software triggering schemes. These triggers will be initiated by high-level (L1) hits, which are formed from coincidence L0 signals in the same storey, or from the hits with large amplitudes. The final triggers are then formed from these L1 and further L0 hits, which are causally connected to the each other.

The algorithms which are used in the ANTARES software trigger are considered as a basis for KM3NeT. The preliminary analysis of these algorithms indicates that multi-PMT OMs could lead to an enhanced performance of these algorithms and a higher trigger efficiency ϵ_T . This is expected due to the enhanced photon counting purity and the compact storey design which will help to reduce the coincidence time window and thus reduce background.

B. Directionality of multi-PMT OMs

The OM in the KM3NeT SeaWiet configuration has an additional feature, such as a possibility of photon direction reconstruction. PMT in the OM is represented with a unit vector \vec{u}_i . The direction can be considered as a weighted sum of the

$$\vec{OM} = \sum w_i \cdot \vec{u}_i. \quad (5)$$

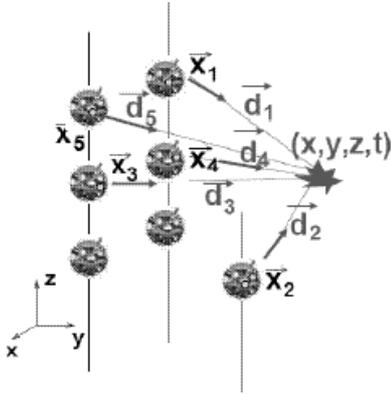


Fig. 3. Schematic view of the shower type neutrino event reconstruction with the KM3NeT SeaWiet configuration. The OMs with large number of hits are pointing to the shower production point (x, y, z) .

Here each unit vector is weighted according with the charge collected in the PMT:

$$w_i = \frac{q_i}{\sum q_j} \quad (6)$$

where q_i is the charge (in p.e.) collected in a PMT_{*i*}.

Preliminary studies indicate that the direction in a multi-PMT OM of the SeaWiet design can be reconstructed with sufficient accuracy to be useful for the event reconstruction.

C. Event reconstruction

Reconstruction algorithms are applied to the triggered hits for events with a neutrino-induced muon or with electromagnetic or hadronic showers. The current KM3NeT event reconstruction is based on the algorithms developed for the ANTARES neutrino telescope[7]. The muon events are reconstructed by a multi-stage algorithm. In a first stage ("prefit") the muon track is approximated with a straight line passing through the preselected hits. The preselection is done using the causality criteria. The muon track is defined by a vector a with 5 parameters, 3 of them related to the initial spatial point and the other 2 parameters are the polar and azimuthal angles of the track direction.

The linear prefit is not very accurate and serves only as a starting point for the next stages, where the final parameters of the muon track are calculated with the maximum likelihood (ML) method. The likelihood function can be written as

$$L = \prod_i P(x_i, x_i^{th}, a), \quad (7)$$

where the probability density function (PDF) depends on x_i - a vector of hit parameters (position, time, amplitude), x_i^{th} is the vector of the expected theoretical values and a is the vector of the muon track parameters.

For the SeaWiet configuration, the ML could include information about the photon direction. This should lead to a significant reduction of the "ghost solutions",

which is difficult to eliminate in ANTARES and other KM3NeT configurations due to the lack of information about the photon and OM directions. Currently these modifications are tested on the MC events.

Significant improvements are expected also in the reconstruction of neutrino events with shower signatures [8]. Shower events are characterised by a smaller number of hits, however with larger amplitudes. The photon directions could be reconstructed with better precision in the OMs, leading to an improved precision in the shower event reconstruction. This is shown schematically in Fig. 3, where each OM with large hits (x_i) is pointing to the neutrino-induced shower.

V. CONCLUSIONS

A possible design option for the next Mediterranean deep-sea neutrino telescope KM3NeT, called SeaWiet, with multi-PMT OMs has been considered in this paper. The preliminary studies indicate, that the unique properties of the multi-PMT OM, such as enhanced photon counting purity, possibility of photon direction reconstruction and compact storey design could lead to significant improvements in event reconstruction and the performance of the KM3NeT neutrino telescope.

VI. ACKNOWLEDGMENT

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REFERENCES

- [1] www.km3net.org/.
- [2] *KM3NeT Conceptual Design Report for a Deep-Sea Research Infrastructure in the Mediterranean Sea Incorporating a Very Large Volume Neutrino Telescope.*, KM3NeT Consortium, ISBN 978-90-6488-031-5
- [3] P. Kooijman *Nucl. Instrum. Meth. A*, 567(2006), 508
- [4] R. Shanidze, S. Kuch, U. Katz, *Nucl. Instrum. Meth. A*, 602(2009), 104
S. Kuch, *Nucl. Instrum. Meth. A*, 567(2006), 490
- [5] B. Herold, ICRC-2009 contribution 0596
- [6] ANTARES Collaboration (J.A. Aguilar et al.), *Nucl. Instrum. Meth. A*, 570(2007), 107
- [7] A. Heijboer, PhD thesis, ANTARES-06-08-2004 <http://www.nikhef.nl/t61/thesis/index.html>
B. Hartmann, PhD thesis, astro-ph/0606697
- [8] R.Auer, *Nucl. Instrum. Meth. A*, 602(2009), 84