Evaluation of Very Large Volume undersea neutrino Telescope configurations using the HOU Reconstruction & Simulation (HOURS) package

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In the framework of the KM3NeT Design Study
The HOURS software chain

**Underwater Neutrino Detector**
- Generation of atmospheric muons and neutrino events (F77–CORSIKA, Pythia)
- Detailed detector simulation (GEANT4-GDML) (C++)
- Optical noise and PMT response simulation (F77)
- Filtering Algorithms (F77 –C++)
- Muon reconstruction (C++)
- Effective areas, angular resolution and sensitivities calculation (scripts)

**Extensive Air Shower Calibration Detector (Sea Top)**
- Atmospheric Shower Simulation (CORSIKA) – Unthinning Algorithm (F77)
- Detailed EAS detector response Simulation (GEANT4) (C++)
- Reconstruction of the shower direction (F77)
- Muon Transportation to the Underwater Detector (C++)
- Estimation of: resolution, offset (F77)

CORSIKA
(Extensive Air Shower Simulation)

All Flavor Neutrino Interaction Events
(Secondary Particles Generation)

Atmospheric Muon Generation from CORSIKA

GEANT4
(Muon Propagation to KM3NeT)

GEANT4
(KM3NeT Detector Description and Simulation)

Optical Noise, PMT response and Electronics Simulation

Prefit & Filtering Algorithms

Muon Reconstruction

Neutrino Telescope Performance

EAS detector Simulation

Shower direction reconstruction

SeaTop Calibration
Event Generation – Flux Parameterization

- Atmospheric Muon Generation (CORSIKA)
- Neutrino Interaction Events (PYTHIA)
- Atmospheric Neutrinos (Conventional Flux+Neutrinos from charm)
- Cosmic Neutrinos (AGN – GRB – GZK and more)

Survival probability

Earth Density Profile

Probability of a $\nu_\mu$ to cross Earth
GEANT4 Simulation – Detector Description

• Any detector geometry can be described in a very effective way
  Use of Geometry Description Markup Language (GDML-XML) software package
• All the relevant physics processes are included in the simulation
  • (OPTICAL PHOTON SCATTERING ALSO)

Fast Simulation

EM Shower Parameterization

• Number of Cherenkov Photons Emitted (~shower energy)
• Lateral and Longitudinal profile of emitted photons

Angular Distribution of Cherenkov Photons

Visualization

Particle Tracks and Hits

Detector components
**Simulation of the PMT response to optical photons**

PMT Quantum Efficiency  |  Standard PMT electrical pulse for a response to a single p.e.
Arrival Pulse Time resolution  |  Single Photoelectron Spectrum

**Prefit, filtering and muon reconstruction algorithms**

- Local (storey) Coincidence (Applicable only when there are more than one PMT looking towards the same hemisphere)
- Local clustering (causality) filter
- Prefit and Filtering based on clustering of candidate track segments

- Combination of $X^2$ fit and Kalman Filter (novel application in this area) using the arrival time information of the hits
- Charge – Direction Likelihood using the charge (number of photons) of the hits

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**Track Parameters**

- $\theta$: zenith angle
- $\phi$: azimuth angle
- $(V_x, V_y, V_z)$: pseudo-vertex coordinates
- $(x, y, z)$: pseudo-vertex coordinates
- $d$: distance
- $L - d_m$: distance
- $d_\gamma$: distance
Muon Track Reconstruction

Chi-square probability

Angular resolution

Energy (log(E/GeV))

Neutrino

Muon

(\theta_{\text{muon\_reco}} - \theta_{\text{muon\_real}}) / \sigma_{\theta\_reco}

(\phi_{\text{muon\_reco}} - \phi_{\text{muon\_real}}) / \sigma_{\phi\_reco}

\chi^2/\text{ndf} = 461.5 / 194

\chi^2/\text{ndf} = 324.8 / 194
Charge Likelihood – Used in muon energy estimation

\[
L(E) = \ln \left( \prod_{i=1}^{N_{\text{hit}}} P(V_{i,\text{data}}; E, D, \theta) \times \prod_{i=1}^{N_{\text{nohit}}} P(0; E, D, \theta) \right) + \frac{(N_{\text{hit}} + N_{\text{nohit}})}{\theta \times \theta}
\]

\[V_{i,\text{data}} \equiv \text{Hit charge in PEs}\]

Probability depends on muon energy, distance from track and PMT orientation

\[P(V_{i,\text{data}}; E, D, \theta) = \sum_{n=1}^{\infty} F(n; E, D, \theta)G(V_{i,\text{data}}; n, \sqrt{n}\sigma_{\text{PMT resolution}})\]

\[F(n; E, D, \theta) \quad \text{Not a poisson distribution, due to discrete radiation processes}\]

\[\text{E}=10\text{TeV} \quad \text{D}=37\text{m} \quad \theta=0\text{deg} \quad \langle n\rangle=6.22\text{ pes}\]

\[L \cdot (N_{\text{hit}} + N_{\text{nohit}})\]
Muon energy reconstruction Results

Simulation data from $E^{-2}$ neutrino flux
True muon energy at the closest approach to the detector center (impact point)

True and reconstructed muon energy distribution

![Graph showing RMS and Mean of Delta (Log(E/GeV))]

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Neutrino Detector Performance

**Point Source Sensitivity for E^{-2} source flux (100GeV-100PeV)**

1 year of observation

67 meters maximum abs. length, 60m optical photon scattering length

Atmospheric Muon background (CORSIKA files – 1 hour lifetime) + Atmospheric Neutrino Background (bartol flux)

\[ \bar{\mu}_{90}(n_{bg}) = \sum_{n_o=0}^{\infty} \mu_{90}(n_o, n_{bg}) \frac{(n_{bg})^n e^{-n_{bg}}}{n_o!} \]

Sensitivity \( K_{90} = K \frac{\bar{\mu}_{90}(n_{bg})}{n_s} \)

\( \Phi(E) = K \cdot E^{-2} \) signal

Estimation of sensitivity errors (0.02~0.04 in the following results)
SeaWit neutrino telescope configurations

**Horizontal layout**

300 strings

![Diagram of horizontal layout with 20 OMs and 300 strings]

**Vertical layout**

20 OMs

20m, 30m, 40m, 50m

100m, 130m, 180m, 210m
Multi PMT Optical Module

- 31- 3inch multi PMT OM housed in a 17inch benthos sphere
- 35% Maximum Quantum Efficiency
- NIKHEF Parametrization for PMT angular acceptance (0.1 + 0.9 cos(θ))

7KHz of K⁴⁰ optical noise
SeaWiet Optimization - Results 1
Vertical (between OMs) distance fixed at 30m

- 60 degrees source declination

\[ \Phi(E) = K \cdot E^{-2} \cdot e^{-E/E_c} \]

Point Source sensitivity vs distance between strings

Source energy spectrum cutoff

- 10 TeV
- 20 TeV
- 50 TeV
- 100 TeV
- 100 PeV
SeaWiet Optimization - Results 2
Horizontal (between strings) distance fixed at 130m
-60 degrees source declination

Point Source sensitivity vs distance between OMs

\[ \Phi(E) = K \cdot E^{-2} \cdot e^{-E/E_c} \]

- Source energy spectrum cutoff

100PeV
100TeV
50TeV
20TeV
10TeV

Distance between floors (m)

x10^{-9}E^{-2} (cm^{-2} s^{-1} GeV^{-1})
NuOne neutrino telescope configuration

NuOne: 127 Towers in a hexagonal grid, separated by 180m. 20 floors each Tower. 40m between floors. Bar length 8m

Tower Geometry

Floor Geometry

Single PMT Optical Module
• 8 inch PMT housed in a 17inch benthos sphere
• 35% Maximum Quantum Efficiency
• Genova ANTARES Parametrization for OM angular acceptance

50KHz of K\textsuperscript{40} optical noise
SeaWiet vs NuOne Detector Comparison – Point Source Sensitivity
SeaWiet → 180m horizontal interstring distance, 50m vertical interOM distance (7 km³, ~100MEuro)
NuOne → 180m horizontal intertower distance, 40m vertical interfloor distance (2.4 km³, ~100MEuro)

-60 degrees source declination

\[ \Phi(E) = K \cdot E^{-2} \cdot e^{-E/E_c} \]

Flux energy cut (TeV)

SeaWiet vs NuOne Detector Comparison – Point Source Sensitivity
SeaWiet \( \rightarrow \) 180m horizontal interstring distance, 50m vertical interOM distance (7 km³, \(~100MEuro\))
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Flux energy cut (TeV)
SeaWiet vs NuOne Detector Comparison – Effective Area
SeaWiet vs NuOne Detector Comparison – Angular resolution

Angular Resolution (median - degrees)

Log($E_\nu$/GeV)
The galactic center, a region of several identified gamma ray sources and potential neutrino emitters, will be visible (declination of -30°) by the KM3NeT during 65% of the time. A point source around the galactic center is detectable with a sensitivity of $1.5 \times 10^{-9} E^{-2} \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1}$ for the SeaWiet detector, while the vOne detector has a sensitivity of $2.5 \times 10^{-9} E^{-2} \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1}$ at this declination.
Neutrino Detector Depth Effect

SeaWiet detector (300 strings, 180m interstring distance, 50m inter OM distance)

With atmospheric muon background

3500m detector depth

4500m detector depth

Without atmospheric muon background

4500m detector depth
Detection capability of known gamma ray point sources and potential neutrino emitters

1 year observation (blind sky search)
Diffuse flux sensitivity (VERY PRELIMINARY)

SeaWiet detector (300 strings, 180m interstring distance, 50m inter OM distance) deployed at 4500m depth

100PeV energy spectrum cutoff

100TeV reconstructed muon energy cut

1 year observation

\( \sim 1 \times 10^{-9} \) (90%CL)
**Work in progress**

360m distance between strings

631 strings (6310 OMs)
75 strings (750 OMs)

Other topologies
Conclusions

• The HOU Reconstruction & Simulation (HOURS) software package is a complete simulation package of the detector response from the expected neutrino fluxes to the event reconstruction and sensitivity estimation for different neutrino sources.
• 1 km\(^3\) undersea Neutrino detector is not enough for the detection of potential astrophysical neutrino emitters. Even a 10 km\(^3\) detector is marginal.
• Studies have to be done for the optimization of a very large detector (~100 km\(^3\))