Reconstruction efficiency and discovery potential of a Mediterranean neutrino telescope: A simulation study using the Hellenic Open University Simulation & Reconstruction (HOURS) package

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H.O.U

- The HOU Reconstruction & Simulation (HOURS) software package
- New tool developments
  - Advances in track reconstruction and error estimation combining Kalman Filter with a Likelihood
- Neutrino Detector performance
  - Sensitivity and discovery potential for point sources
  - Point sources discovery improvements
  - Signal from Gamma Ray Bursts & Diffuse flux sensitivity

VLVnT 2011, ECAP, Erlangen, October 2011
Simulation software chain

CORSIKA
(Extensive Air Shower Simulation)

GEANT4
(Muon Propagation to KM3NeT)

EAS detector Simulation

Shower direction reconstruction

SeaTop Calibration

All Flavor Neutrino Interaction Events
(Secondary Particles Generation)

GEANT4
(KM3NeT Detector Description and Simulation)

Optical Noise, PMT response and Electronics Simulation

Prefit & Filtering Algorithms

Muon Reconstruction

Atmospheric Muon Generation from CORSIKA

MuPage
~one hour life time for this study

Neutrino Telescope Performance

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Prefit and Filtering based on:
- Optical Module Hit clustering (causality) filter & clustering of candidate track segments (no apriori knowledge of the neutrino source)
- Causality filter using the apriori known direction of the neutrino source (talk “A reconstruction method for neutrino induced muon tracks taking into account the apriori knowledge of the neutrino source” by A. Tsirigotis)

Muon reconstruction algorithms
- Combination of $\chi^2$ fit and Kalman Filter is used to produce many candidate tracks
- The best candidate is chosen using the Multi-PMT Direction and arrival time Likelihood (track quality criterion)
- Muon energy reconstruction using the Charge Likelihood

Track Parameters
- $\theta$: zenith angle
- $\phi$: azimuth angle
- $(V_x,V_y,V_z)$: pseudo-vertex coordinates

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A new tracking criterion based on the directional information offered by the Multi-PMT and the time residuals distributions
Multi-PMT direction Likelihood

- PDFs of the angle, $\theta$, between the Ch wavefront direction and the active direction of the Multi-PMT

$$PDF_{d,s}(\theta;n)$$

- Separate parametrization for $n=1,2,\ldots,18$ active small PMTs.

- For the parametrization only the angular acceptance and the directions of the small PMTs in the OM are used.

$$\hat{D} = \sum_{i=1}^{N} q_i \hat{d}_i$$

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The directionality criterion is used for the selection of the best track candidate.

\[ PDF_{d,s,i}(\theta_i; n_i) \]

\[ PDF_{d,n} = constant \]

\( i = 1, 2, \ldots, N \) the active Multi-PMTs
\( n_i \) = the number of active elements in the \( i \)th Multi-PMT
\( \theta_i \) = the angle between the weighted average direction of the \( i \)th active Multi-PMT with the reconstructed Cherenkov wavefront

For the selection of the best candidate track also the timing likelihood is used

\[ PDF_{t,s,i}(t_i - t_{exp}; q_i, d_i) \]
\[ PDF_{t,n,i}(t_i - t_{exp}; d_i) \]

\( t_i \): hit arrival time,
\( t_{exp} \): expected arrival time of direct photon
\( q_i \): hit charge, \( d_i \): Hit distance from track

The timing PDFs depend on the filtering and prefit stage
They are created for the hits that pass these stages

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For all the candidate tracks form the direction*timing likelihood for all hits that pass the final filtering stage (common for all candidate tracks)

\[
L_{\text{total}} = \prod \left[ p_{n,i}(N_{\text{hit}}, q_i) \text{PDF}_{t,n,i} \text{PDF}_{d,n} + (1 - p_{n}(N_{\text{hit}}, q_i)) \text{PDF}_{t,s,i} \text{PDF}_{d,s,i} \right]
\]

\[
p_{n,i}(N_{\text{hit}}, q_i) \equiv \text{Probability of a hit to be noise}
\]

**Timing PDFs**

- **Signal** \( \text{PDF}_{t,s,i}(t_i - t_{\text{exp}}; q_i, d_i) \)
- **Noise** \( \text{PDF}_{t,n,i}(t_i - t_{\text{exp}}; d_i) \)

**Direction PDFs**

- **Signal** \( \text{PDF}_{d,s,i}(\theta_i; n_i) \)
- **Noise** \( \text{PDF}_{d,n} = \text{constant} \)

- The candidate track with the largest Likelihood is chosen
- Maximize further the Likelihood for the chosen candidate track
Charge Likelihood – Used in muon energy estimation

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

Hit charge in PEs

Probability depends on muon energy, \( E \), distance from track, \( D \), and PMT orientation with respect to the Cherenkov wavefront:

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

\( F(n; E, D, \theta) \) Not a poisson distribution, due to discrete radiation processes

Convolution with the PMT charge response function (simplified model with Gaussian)

Muon energy estimation resolution

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Simulated Detector Geometrical Layout

154 Towers (\textit{Half KM3NeT detector}) with a mean distance 180m between them.
Each Tower consists of 20 bars, 6m in length and 40m apart.
One MultiPMT OM at each end of the bar.
Instrumented Volume $\sim 2.9\text{km}^3$

Detector Footprint
(not optimized for Galactic $\nu$ point sources)

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Sensitivity & Discovery Potential (Half KM3NeT detector) 
1 year of data taking (point source with neutrino energy spectrum ~ E^{-2})

\[ x10^{-9} E^{-2} GeV^{-1} cm^{-2} s^{-1/2} \]

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Cuts optimized for best sensitivity (0.3125° bin size)

Discovery Potential (5 sigma, 50% probability)

Discovery Potential (3 sigma, 50% probability)

Sensitivity (90% CL)

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Neutrino Effective Area (Half KM3NeT detector)  
Cuts for best sensitivity

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Angular resolution vs Neutrino Energy
Neutrinos and Anti-Neutrinos

Point Spread Function
Neutrinos and Anti-Neutrinos
Background event rate (Half KM3NeT detector)
Cuts for best sensitivity

Event rate
Atmospheric Neutrinos and
Atmospheric Muons (Bundles)

~100 reconstructed atmospheric neutrinos per day

VLvNT 2011, ECAP, Erlangen, October 2011
5σ discovery potential (Half KM3NeT detector)  
1 year of data taking (point source)
Galactic Candidate ν Sources – SNRs

Origin of Cosmic Rays => SNR paradigm
Assuming that VHE γ emitters are CR accelerators.
As an example, assuming that the RXJ1713.7-39.46 (the most luminous γ ray source) is a hadron accelerator then the ν spectrum can be calculated from the γ spectrum:

\[
\Phi(E) = 16.8 \times 10^{-15} \left( \frac{E}{\text{TeV}} \right)^{-1.72} e^{-\sqrt{\frac{E}{2.1 \text{ TeV}}}} \text{GeV}^{-1} \text{s}^{-1} \text{cm}^{-2}
\]

Discovery Potential for RXJ1713.7-3946
Sky bin search radius is 0.77 degrees
Neutrino Source Generation disk radius is 0.6 degrees

- # background/year: 1.99
- 3s Discovery Pot. (1y-Half KM3NeT): 3.85 x Φ(E)
- 8.6 y for 3s discovery (Half KM3NeT)
- 4.3 y for 3s discovery (Full KM3NeT)
- # signal/year: 1.44
- 5s Discovery Pot. (1y-Half KM3NeT): 7.39 x Φ(E)
- 24 y for 5s discovery (Half KM3NeT)
- 12 y for 5s discovery (Full KM3NeT)
Galactic Candidate $\nu$ Sources – Discovery Improvements

Use of the full experimental information on a track by track basis:
- reconstructed muon energy, and
- track resolution (muon reconstruction parameter errors)

(Talk “Evaluation of the discovery potential of an underwater Mediterranean neutrino telescope taking into account the estimated directional resolution and energy of the reconstructed track” by A. Leisos)
Galactic Candidate \( \nu \) Sources – Discovery Improvements

154 DUs (half KM3NeT)

E\(^{-2}\) \( \nu \) point source at -60\(^\circ\) declination

Discovery Potential (3 sigma) vs Flux for one year of data taking

\[ \text{Flux in units of } 10^{-9} \text{ (GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}) \]

**Without energy information**

Improved method

**Without energy information**

Using full exp. information: 1.2\( \times 10^{-9} \) (GeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\))

Binned technique: 1.9 \( \times 10^{-9} \) (GeV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\))

**With energy information**

1y Discovery potential WITH energy and shape

- 3\( \sigma \) : 3.0 \times RXJ1713 flux for 50% discovery
- 4\( \sigma \) : 4.1 \times RXJ1713 flux for 50% discovery
- 5\( \sigma \) : 5.6 \times RXJ1713 flux for 50% discovery

RXJ1713.7-39.46 (0.6\(^{\circ}\) angular radius)

1y Discovery potential WITHOUT energy and shape

- 3\( \sigma \) : 3.7 \times RXJ1713 flux for 50% discovery
- 4\( \sigma \) : 4.6 \times RXJ1713 flux for 50% discovery
- 5\( \sigma \) : 7.4 \times RXJ1713 flux for 50% discovery

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Extragalactic \( \nu \) Sources – GRBs

- Alert from satellite detectors (known time & direction)
- Short time window (<2h) for GRB prompt neutrino emission
- High energy neutrinos (> 100TeV)
- Application of energy cut on the reconstructed muon energy

### Expected Neutrino fluence from GRBs


- Detection of down-going GRB neutrinos events is feasible

**The expected number of detected neutrino events from GRBs per year and steradian.**

- 1000 GRBs/year (4500m depth)
- 300 GRBs/year (3500m depth)
- 4500m detector depth 8.4ev/y
- 3500m detector depth 7.5ev/y
- Background 1000 GRBs/year

**Expected Neutrino fluence**

2.5 signal events/year
0.45 background events/year

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Diffuse Flux $\nu$

Ultra high energy neutrinos from
- A multitude of objects such as Active Galactic Nuclei or GRBs
- The interaction of cosmic rays with intergalactic matter, radiation, cosmic microwave background

Isotropic diffuse flux

- No tight angular cut for reducing the background of atmospheric neutrinos
- Rely on a cut on the reconstructed muon energy.

KM3NeT ($E^{-2}$) diffuse $\nu$ flux sensitivity (effective energy cut $E_\nu > 500$ TeV)

$3 \cdot 10^{-9}$ (GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$)

Diffuse flux sensitivity of the KM3NeT neutrino telescope for one year of observation time.
Conclusions

- We improved the track reconstruction and the tracking error estimation by employing a Likelihood criterion and a fit at the last stage of the tracking chain.

- KM3NeT will cover most of the sky with unprecedented sensitivity.

- Promising Galactic Candidate ν Sources.

- Discovery potential for Galactic Candidate ν Sources can be further improved using the reconstructed energy estimation, the angular resolution on a track by track basis and the application of advanced filters using the known source's direction.

Acknowledgments
The KM3NeT project is supported by the EU in FP6 under Contract no. 011937 and in FP7 under Grant no. 212525.
Backup slides
Event Generation – Flux Parameterization

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

Survival probability

Earth Density Profile
GEANT4 Simulation – Detector Description

• Any detector geometry can be described in a very effective way
• All the relevant physics processes are included in the simulation

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
Parameters and Definitions

Neutrino Flux: \( k = 1.0 \times 10^{-9} \text{ } \text{E}^{-2} \text{ (GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}) \)

\( n_{bg} \) = mean number of expected background events
\( n_s \) = mean number of expected signal events

Sensitivity (90\% CL): \( k \frac{\bar{\mu}_{90}(n_{bg})}{n_s} \)

\[ \bar{\mu}_{90}(n_{bg}) = \sum_{N_o=0}^{\infty} \mu_{90}(N_o, n_{bg}) P(N_o \mid n_{bg}) \]

\( \mu_{90}(N_o, n_{bg}) \equiv 90\% \text{CL Feldman\textendash}Cousins Upper Limit \)

\( N_o \) = number of observed events

Discovery Potential (\( m \) sigma, 50\%): \( k \frac{d_m(n_{bg})}{n_s} \)

\( d_m \) = the mean number of signal events in order to have \( n_0 \) or more observed events with probability 50\%

\( n_0 \) = the minimum number of observed events to have a discovery of \( m \) sigma

\[ 0.5 = \sum_{N_o=n_0}^{\infty} P(N_o \mid [d_m+n_{bg}]) \]

\[ \sum_{N_o=\lceil n_0 \rceil}^{\infty} P(N_o \mid n_{bg}) \leq p_m \]

\( p_3 = 2.7 \times 10^{-3} \)
\( p_5 = 5.73 \times 10^{-7} \)

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