HOU Reconstruction & Simulation (HOURS): A simulation and reconstruction package for neutrino telescopy

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- Overview
- Event generation
- Detector description and Simulation
- Optical noise, PMT response and electronics simulation
- DOM charge reconstruction/Pulse arrival time corrections
- Prefit and filtering algorithms
- Event reconstruction
  - Event direction estimation
  - Energy reconstruction
- Analysis Tools
HOURS - Simulation software chain

- CORSIKA (Extensive Air Shower Simulation)
  - All Flavor Neutrino Interaction Events (Secondary Particles Generation)
  - Atmospheric Muon Generation from CORSIKA

- GEANT4 (Muon Propagation to KM3NeT)
  - EAS detector Simulation (GEANT4)
  - Optical Noise, PMT response and Electronics Simulation
  - Prefit & Filtering Algorithms
  - Muon Reconstruction
  - Neutrino Telescope Performance

- SeaTop Calibration
- Shower direction reconstruction
- MuPage
Developed by HOU physics laboratory team
- Event generation (A. Tsirigotis, D. Lenis)
- Detector description and Simulation (A. Tsirigotis)
- Optical noise, PMT response and electronics simulation (A. Tsirigotis, G. Bourlis)
- DOM charge reconstruction/Pulse arrival time corrections (G. Bourlis)
- Prefit and filtering algorithms (A. Tsirigotis)
- Event reconstruction (A. Tsirigotis, D. Lenis)
  - Event direction estimation
  - Energy reconstruction
- Analysis Tools (A. Tsirigotis, S. Tzamarias, A. Leisos)

Users
- HOU physics laboratory team

Documentation/availability
- Documentation and will be soon available (preparing user guide)
- Older package version already available at HOU website
  [http://physicslab.eap.gr/EN/Simulation_software.html](http://physicslab.eap.gr/EN/Simulation_software.html), will be updated soon

Simulation data format
- ANTARES evt format
Event Generation – Flux Parameterization

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

Survival probability

- Probability of a $\nu_\mu$ to cross Earth
- $\log(E_\nu \text{ (TeV)})$ vs Nadir Angle
- Earth Density Profile
- Radius [km]
- Density $\rho$ [gm/cm$^3$]
Detector description & Simulation

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

**Full GEANT4 simulation**

**Fast Simulation**

- EM showers (from e-, e+, γ)
- HA showers (from long lived hadrons)
- Low energy electrons (from ionization)
- Direct Cherenkov photons (from muon)

**Parametrizations for:**

- EM showers (from e-, e+, γ)
- HA showers (from long lived hadrons)
- Low energy electrons (from ionization)
- Direct Cherenkov photons (from muon)

Each parametrization describes the number and time profile of photons arriving on a PMT in bins of:
- Shower energy (E) (EM and HA showers)
- PMT position (D,θ) relative to shower vertex/muon position,
- PMT orientation (θ_{pmt},φ_{pmt})
Angular Distribution of Cherenkov Photons for 10 GeV EM shower

10 GeV EM Shower
- Full Simulation
- Fast Simulation

Arrival time distribution of Cherenkov Photons for 100 GeV muon (R=25m)

Full simulation
Fast simulation

(0.1348±0.0005) pes/event
(0.1379±0.0020) pes/event

Comparison between Full & Fast Simulation
Detector description & Simulation - Parametrized simulations/improvements

Comparison with and without parametrization (full simulation) for various pmt orientations

\( \theta_{\text{pmt}} \) = angle between pmt axis and direct Cherenkov photon track

Number of pes/event with parametrized simulation divided by corresponding number with full simulation

Differences for \( \cos(\theta) < 0.1 \) is due to coarse photon tables for these pmt orientations

\( E_{\text{muon}} = 0.1 \text{ TeV} \)

\( E_{\text{muon}} = 1 \text{ TeV} \)

Difference < 5% (investigated)

Difference < 5%

Differences for \( \cos(\theta) < 0.1 \) is due to coarse photon tables for these pmt orientations
Optical noise, PMT response and electronics simulation

$^{40}$K Optical noise includes single and multiple genuine coincidence rate (up to 6-fold coincidence)
- Rates per DOM estimated with full Geant4 simulation of $^{40}$K decays, taking into account DOM functional characteristics

PMT response simulation
- Quantum/collection efficiency
- Time Jitter
- Single Photoelectron charge spectrum
- Waveform production

Electronics simulation
- Single – Multiple Threshold ToT electronics
DOM charge reconstruction/Pulse arrival time corrections

Take into account correlations between neighboring pmts in a DOM
- The DOM charge can be estimated with 10-20% accuracy depending on the number of the active pmts
- Adequate for the muon energy reconstruction
Optical noise filtering, prefit and muon reconstruction

**Prefit and Filtering based on:**
- Linear+Scanning likelihood prefit (using only L1 hits)
- Optical Module Hit clustering (causality) filter & prefit using the clustering of candidate track segments (no apriori knowledge of the neutrino source)
- Causality filters and prefit using the apriori known direction of the neutrino source

**Point source neutrino astronomy**

**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 (>1TeV muons), or estimated muon track length (<1TeV)

**Track Parameters**
- $\theta$: zenith angle
- $\varphi$: azimuth angle
- $(V_x, V_y, V_z)$: pseudo-vertex coordinates
Optical noise filtering, prefit and muon reconstruction

Background filtering technique using the apriori known neutrino point source

\( \vec{H} \) Optical Module (OM) position
\( \vec{V} \) pseudo-vertex
\( \hat{d} \) Muon momentum direction (generated by a neutrino from a hypothetical source)

A reconstruction method for neutrino induced muon tracks taking into account the apriori knowledge of the neutrino source

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On behalf of the KM3NeT Consortium

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Background filtering technique using the apriori known neutrino point source

- $E^{-2}$ neutrino generated spectrum (15GeV – 100PeV)
- 2.9km$^3$ neutrino detector with 6160 DOMs (arranged in 154 Detection Units (Towers))
- Reconstructed tracks with at least 8 hits on different DOMs

Reconstruction efficiency vs neutrino energy for events with at least 3 L1 signal Hits

![Graph showing reconstruction efficiency vs neutrino energy](image1)

Point spread function for reconstructed events

![Graph showing point spread function](image2)

This technique

Direct Walk technique (clustering of candidate track segments)

Log scale for $E_\nu/GeV$ vs angular deviation (degrees)
Muon Reconstruction - Kalman Filter

State vector 
\[ x = (V, \theta, \phi) \]

Initial estimation 
\( x_0, C_0 \)

Update Equations
\[ x_k = x_{k-1} + K_k(t_k - t_k^{exp}(x_{k-1})) \]
\[ C_k = (1 - K_k H_k)C_{k-1} \]

Kalman Gain Matrix
\[ K_k = C_{k-1} H_k^T (V_k + H_k C_{k-1} H_k^T)^{-1} \]

Updated residual and chi-square contribution (rejection criterion for hit)
\[ r_k = t_k - t_k^{exp}(x_k) \]
\[ R_k = (1 - K_k H_k)V_k \]
\[ \chi^2_k = r_k^2 / R_k \]

Many (40-200) candidate tracks are estimated starting from different initial conditions \((x_0, C_0)\). The best candidate is chosen using the Multi-PMT Direction and arrival time Likelihood (track quality criterion).

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 $n=1,2,...18$ active small pmts.

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

$$D = \sum_{i=1}^{N} d_i$$

31 3" PMTs inside a 17" glass sphere

Averaged direction of active PMTs
The directionality criterion is used for the selection of the best track candidate.

\[ \text{Signal} \quad PDF_{d,s,i}(\theta_i; n_i) \]
\[ \text{Noise} \quad PDF_{d,n} = \text{constant} \]

- \( i = 1, 2, \ldots, N \) 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

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

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

1 p.e. charge

OM distance from track: 50m, 100m, 140m

3 p.e. charge

OM distance from track: 50m, 100m, 140m

- The timing PDFs depend on the filtering and prefit stage
- They are created for the hits that pass these stages
For all the candidate tracks form the direction*timing likelihood for all hits that pass the final filtering stage (common for all candidate tracks)

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

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

Timing PDFs

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

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
Muon energy estimation (Charge Likelihood)

\[ L(E) = \ln \left( \prod_{i=1}^{N_{\text{hit}}} P(Q_{i,\text{data}}; E, D, \theta) \prod_{i=1}^{N_{\text{nohit}}} P(0; E, D, \theta) \right) \quad Q_{i,\text{data}} \equiv \text{Hit charge (assumedly known exactly)} \]

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

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

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

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

Muon energy estimation resolution

\[ L(E) = \text{Muon energy estimation resolution} \]
Muon energy estimation (Track length)

- Projections (with the Cherenkov angle) of the hit positions on the fitted track
- Accept only hits with residual < 10 ns and distance < 40 m from fitted track, to reduce the $^{40}$K noise contribution
- From the first hits projection estimate the neutrino vertex
- The last hit defines the track end

Results (ORCA)

- RMS: 12 m
- RMS: 2.5 GeV
Analysis Tools

Point/extended sources
- Binned technique
- Unbinned technique

SeaTop Calibration
- Estimation of angular systematic effects of the underwater telescope with the synchronous detection of Extensive Air Showers by an EAS sea surface detector

Supernova detection
- Multiple coincidences between the PMTs of the same DOM are utilized to suppress the noise produced by $^{40}$K and to establish a statistical significant signature of the SN explosion.

Neutrino Oscillations
- Event re-weighting taking into account oscillation probabilities for various oscillation parameters and Normal or Invert Hierarchy
- Extraction of the hierarchy (under construction)
Analysis Tools (point sources)- Unbinned technique

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

Energy distribution of signal (RXJ1713) and background (atmospheric neutrinos)

Reconstructed Energy (log(E/GeV))

Histogram: True Line: Predicted from reconstruction errors

10 TeV < Eν < 100 TeV

Angle between reconstructed muon track and parent neutrino (Degrees)
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.

HOURS comprises a realistic simulation package of the detector response, including an accurate description of:
- all the relevant physical processes,
- the production of signal and background
- several analysis strategies for triggering and pattern recognition
- event reconstruction, tracking and energy estimation.

Further improvements/additions are scheduled.
Backup slides
Background filtering technique using the apriori known neutrino point source
Causality criterion

\[ \hat{H} \quad \text{Optical Module (OM) position} \]

\[ \hat{V} \quad \text{pseudo-vertex} \]

\[ \hat{d} \quad \text{Muon momentum direction (generated by a neutrino from a hypothetical source)} \]

Expected arrival time to OM of a photon emitted by the muon with the Cherenkov angle, \( \theta_c \) (direct photon):

\[ ct_{expected} = a + b \tan \theta_c \]

\[ a = \hat{d} \cdot (\hat{H} - \hat{V}) \]

\[ b = |\hat{H} - \hat{V} - a \hat{d}| \quad \text{The vertical distance of OM to the muon track} \]
Background filtering technique using the apriori known neutrino point source

Causality criterion

Two direct photons with arrival times $t_1, t_2$ on the OMs with positions $\vec{H}_1, \vec{H}_2$ should satisfy:

\[
\frac{c\Delta t - \hat{d} \cdot \Delta \vec{H}}{\tan \theta_c} = \Delta b
\]

\[
\Delta t = t_1 - t_2
\]

\[
\Delta \vec{H} = \vec{H}_1 - \vec{H}_2
\]

\[
\Delta b = b_1 - b_2
\]

Project the hits position and vertex on a plane perpendicular to the known direction.

Then from simple geometry:

\[
|\Delta b| = \left| \frac{c\Delta t - \hat{d} \cdot \Delta \vec{H}}{\tan \theta_c} \right| < |\Delta \vec{H} - (\hat{d} \cdot \Delta \vec{H}) \hat{d}|
\]
Background filtering technique using the apriori known neutrino point source

Causality criterion

Two direct photons with arrival times \( t_1, t_2 \) on the OMs with positions \( \vec{H}_1, \vec{H}_2 \) should satisfy:

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Then from simple geometry:

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|\Delta b| = \left| \frac{c\Delta t - \hat{d} \cdot \Delta \vec{H}}{\tan\theta_c} \right| < |\Delta \vec{H} - (\hat{d} \cdot \Delta \vec{H}) \hat{d}|
\]

Causality criterion between two hits using the known direction of the source

\[
|c\Delta t - \hat{d} \cdot \Delta \vec{H}| < \tan\theta_c |\Delta \vec{H} - (\hat{d} \cdot \Delta \vec{H}) \hat{d}| + c t_s
\]

\( t_s = 10\text{ns} \)

Relax the criterion (light dispersion, time jitter)

\[
|\Delta \vec{H} \cdot \hat{d}| < 800\text{m}
\]

Longitudinal distance between the two OMs to the direction of the muon track

\[
|\Delta \vec{H} - (\hat{d} \cdot \Delta \vec{H}) \hat{d}| < 67.5\text{m (one absorption length)}
\]

Lateral distance
Prefit and reconstruction technique using the known neutrino direction

- Causality criterion is used as background filtering
  - <0.3% of noise hits survive
  - >90% of signal hits survive

- For every three OMhits (on different OMs) that satisfy the causality criterion a pseudo-vertex can be found analytically.

- Many candidate pseudo-vertexes are found using different triplets of hits

- For signal events \( (E_\nu > 100\text{GeV}) \) the clustering in space of all the candidate pseudo-vertexes can estimate the MC-true pseudo-vertex with accuracy \( \sim 2m \)

- The estimated pseudo-vertex and the known direction is used to further reduce the number of noise hits
  - \( \sim 0.03\% \) of noise hits survive
  - \( \sim 90\% \) of signal hits survive

- Combination of \( \chi^2 \) minimization and Kalman Filter is used to produce many candidate tracks

- The best candidate is chosen using the timing and Multi-PMT direction Likelihood
Prefit and reconstruction technique using the known neutrino direction
Reconstruction efficiency and angular resolution

- $E^{-2}$ neutrino generated spectrum (15GeV – 100PeV)
- 2.9km$^3$ neutrino detector with 6160 DOMs (arranged in 154 Detection Units (Towers))
- Reconstructed tracks with at least 8 hits on different DOMs

Reconstruction efficiency vs neutrino energy for events with at least 3 L1 signal Hits

Point spread function for reconstructed events

This technique

Direct Walk technique (clustering of candidate track segments)

This technique

$\log \left( \frac{E_\nu}{GeV} \right)$

$\nu_\mu$ – fit space angle difference (degrees)
Reconstruction technique using the known neutrino direction
Estimation of fake signal

For each atmospheric neutrino/shower event:
- Assume a candidate neutrino direction pointing to a hypothetical astrophysical source
- Apply filtering and prefit using the assumed direction
- Track reconstruction
- Accept the event if the angular difference between the assumed direction and the reconstructed muon direction $< 1^\circ$ (For point source searches this angular difference is further optimized)

With the application of this technique the required observation time for 5$\sigma$ discovery of the RXJ1713 galactic source is reduced from 13 years to 9 years (Towers 180m and binned technique)

- Fake signal can be further reduced by applying tracking quality criteria using the estimated tracking error.
- Fake tracks carry a very small weight in the unbinned method

Figure 4: Probability of an atmospheric neutrino induced event to produce fake signal versus the cosine of the angular difference, $\theta$, between the true neutrino direction and the assumed direction of the source.