Evaluation of the performance of the Time over Threshold technique for the digitization of the signal of KM3NeT

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Outline

Time over Threshold technique for a Very Large Volume Neutrino Telescope
- The KM3NeT telescope and the detection units
- Muon track reconstruction and energy estimation
- The Time over Threshold technique
  - Slewing estimation
  - PMT charge estimation
  - OM charge estimation
- Conclusions
Optical Module (OM): pressure resistant sphere containing photomultipliers

Detection Unit (DU): mechanical structure holding OMs, environmental sensors, electronics,...

DU is the building block of the telescope

KM3NeT in numbers
- ~12200 DOMs
- ~620 DU
- ~20 DOM/DU
- ~40m DOM spacing
- ~1 km DU height
- ~100 DU distance
- ~4 km$^3$ volume
Digital Optical Module – Multi-PMT

- 31 3" PMTs (~30% max QE) inside a 17" glass sphere with 31 bases (total ~6.5W)
- Cooling shield and stem
- Full prototypes under testing

- Single vs multi-photon hit separation
- Large (1260 cm$^2$) photocade area per OM
Digital Optical Module – Multi-PMT

PMTs under testing (Nikhef, ECAP, LNS Catania)
- 30 Hamamatsu R12199 PMTs
- 94 ETL PMTs
- 7 HZC PMTs

Tested for
- Quantum efficiency
- Gain slope
- Dark current rate
- Transit Time Spread (TTS)
- After pulse fraction
- Peak-to-valley ratio

KM3NeT specifications for PMTs:
- QE @ 470nm > 20%
- HV for 5x10^6 gain 1000-1400V
- TTS <2ns sigma
- Dark current rate <1kHz
- Peak-to-valley ratio >3
Time over threshold technique: the analogue pmt signals are converted to digital data (time stamps)

- The Time over Threshold technique is implemented through FPGA and system on chip within the optical module
- Data to shore via ethernet link
- Time synchronization and slow control
Muon track reconstruction and Energy estimation

The muon track reconstruction is based on:
- the arrival times of the Cherenkov photons on the PMTs and
- the positions and orientation of the PMTs.

For the energy estimation we use:
- the charge deposited on the PMTs,
- the parameters of the reconstructed muon track and
- the positions and orientation of the PMTs.
Muon Energy Estimation

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

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

$Q_{i, \text{data}}$ ≡ $P(Q_{i, \text{data}} ; E, D, \theta)$

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

Conservation of charge

Muon energy estimation resolution

Hit charge (assumedly known exactly) normalized to the charge of a single p.e. pulse

Convolution with the PMT charge response function (simplified model with Gaussian)
The Time Over Threshold technique

Time-tagging of the leading and trailing edge of the PMT signal above a certain threshold

- Use of adjustable threshold comparators
- Significantly reduced data to send to shore
- Small power consumption, high reliability

1 threshold utilized for KM3NeT

t1 used for the timing of the pulses
- but bias of the timing of the pulses depending on the pulse height (slewing)

tot can be used for the estimation of the charge of the pulses

\[ \text{tot} = t_2 - t_1 \]
Slewing Examples

Data from 2003 NESTOR run (15 inch pmts) with calibration LED in deep sea

Bias (slewing) in evaluating the pulse arrival time using the pulse inflection point (black dots) or threshold crossing (red dots)

Data from HELYCON scintillator counters (¾ inch fast pmts, used also in H.E.S.S.) using atmospheric muons

Operation and performance of the NESTOR test detector

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KM3NeT signal simulation

Pulses from the ET Enterprise Ltd. D783FL 3" PMT diameter (tested in NIKHEF), Q.Dorosti Hasankiadeh in VLVnT11 proceedings

12 strings, 21 OMs each at 10m vertical distance, various distances from track

Generated with the HOURS simulation package (talk by A. Tsirigotis)

Energies 1TeV, 5TeV, 10TeV, 50TeV, 100TeV

Distances from center 10m, 20m, 30m, 40m, 60m, 90m, 120m

41 different thresholds implemented

0.252pe the one used for the results that follow

PMT TTS equal to 2ns
Slewing parameterization

Slewing = time that the pulse crosses the threshold – arrival time of the first photon

For each PMT of the optical module slewing is parametrized as a function of the tot values

The slewing RMS in each bin is also parametrized as a function of the tot values

~0.6ns error in estimating the slewing
Slewing parameterisation

The “real” slewing is calculated from the simulated data as the difference of the time that the pulse crosses the threshold and the arrival time of the first photon.

The estimated (via the parametrizations) slewing is compared to the real slewing.

Slewing can be estimated with a resolution of 5.5%.

Unbiased estimation:

Weighted distributions for energy and distance:

\[ \text{weight} = \text{distance} \cdot \text{energy}^{-2} / N \]
\[
\begin{align*}
\vec{H} & \quad \text{Optical Module (OM) position} \\
\vec{V} & \quad \text{pseudo-vertex} \\
\hat{d} & \quad \text{Muon momentum direction} \\
& \quad \text{(generated by a neutrino from} \\
& \quad \text{a hypothetical source)} \\
\end{align*}
\]

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

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

\[
\begin{align*}
residual & = t_{\text{expected}} - t_{\text{observed}} \\
a & = \hat{d} \cdot (\vec{H} - \vec{V}) \\
b & = |\vec{H} - \vec{V} - a \hat{d}|
\end{align*}
\]

The perpendicular distance of the OM to the muon track
Residuals

1st photon
Mean photon
Threshold crossing
Threshold crossing corrected

1st photon: 2.25ns
Threshold crossing: 2.34ns
Threshold crossing corrected: 2.31ns

Weighted distributions for energy and distance

\[ \text{weight} = \text{distance} \cdot \text{energy}^{-2} / \text{N} \]

1st photon: 2.57ns
Threshold crossing: 2.60ns
Threshold crossing corrected: 2.57ns
PMT charge parameterization

PMT charge can be parametrized employing the tot values

... but it is not very promising

Corresponds to almost synchronous photons and is dominated by the large pulses

Very poor charge resolution for higher pulses

Of course, for real data the peak would be much smaller due to the electronics deforming high pulses
The total charge of the OM is the sum of the PMTs' charges

\[ OM \, total \, charge = \sum_{i=1}^{i=31} Q_i \]

The OM total tot is the sum of the tot values of each individual PMT

\[ OM \, total \, tot = \sum_{i=1}^{i=31} tot_i \]
OM charge parameterization

The total charge of the OM is the sum of the PMTs' charges

\[ OM \text{ total charge} = \sum_{i=1}^{31} Q_i \]

The OM total tot is the sum of the tot values of each individual PMT

\[ OM \text{ total tot} = \sum_{i=1}^{31} \text{tot}_i \]

OM total charge resolution using one threshold \(\sim 20\%\)

Unbiased estimation
OM charge parameterization

Specific parametrizations taking into account:
- the number of hit PMTs (more hit PMTs indicate larger pulses)
- the number of hit PMTs and the RMS of the pulses' arrival times (higher RMS would indicate more widespread pulses)
Summary and Outlook

- Using 1 threshold per 3'' inch PMT of the OM allows the correction (slewing) of the photon arrival time with an accuracy of ~5.5%
- A single threshold is not sufficient to estimate the charge of a single 3'' PMT
- However, the resolution of the estimation of the charge of the whole optical module is ~22%
- The 20% charge resolution changes the reconstructed muon energy resolution within the statistical errors (employing the muon energy reconstruction of the HOURS simulation package that takes into account the deposited charge on the optical modules)
- The OM charge resolution can be further improved by taking into account the correlations between neighbouring PMTs

The analysis will be performed again using waveforms and the measured transit time spread (TTS) of the Hamamatsu R12199-02 PMTs, currently under testing for the KM3NeT telescope.