Abstract

One of the main challenges in astroparticle physics is the detection of cosmic neutrinos. The Antares detector and its successor KM3NeT, are designed to detect muons which arise from cosmic neutrino interactions in the vicinity of the detector. The detection of neutrinos is based on a software trigger. The trigger should lower the data output without losing physics events. The triggers are based on two different concepts: a local coincidence filter or time-position correlations over the whole volume of the detector. For both detectors different correlation filters can be designed to reduce the background. A special case of a trigger in which the direction of the muon is assumed is studied. It is shown that this provides for a general solution. This document describes the properties of the triggers and improvements are proposed.
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1 Introduction

One of the main questions in astroparticle physics is the origin and composition of high-energy cosmic rays. While the energy spectrum is measured up to high energies (∼ $10^{20}$ eV), their origin remain unclear. It is generally believed that cosmic rays are composed of protons and nuclei. High energy protons and nuclei will interact with the cosmic microwave background which limits their range to about $100 Mpc$. The (center) galactic magnetic fields will also deflect the cosmic rays. Potential sources also producing high energy neutrinos include supernova remnants, active galactic nuclei, gamma-ray bursts and microquasars. Detection of neutrinos from these sources can explain and reveal the origin of cosmic rays. Neutrinos are neutral and stable particles that only interact weakly with matter.

The Antares neutrino telescope and its successor KM3NeT, are designed to detect muons which arise from neutrino interactions. The Antares detector has been build as a proof of concept for a deep sea detector. A large array of under water sensors detect light from secondary particles from neutrino interactions. The light sensors also detect light from other processes in the deep sea, such as radio active decays, which is the optical background. A trigger system is necessary to reduce this background and save the data from the physics events we want to see. This study is about the triggers used at Antares.

The Antares detector is situated in the Mediterranean sea, 40 km off-shore Toulon in France. The detector consists of 12 strings (cables) of 450 meters length located on the sea bottom at 2.5 km depth. There are 900 photo multiplier tubes (PMTs) that can detect light at the quantum level. All data are sent to shore for real time triggering. On shore, the trigger has to process the data and decide whether or not the data has to be saved to disk for further analysis. The data acquisition framework (Antares-DAQ) runs on a computer farm. The power needed for the data acquisition depends on the implementation of the algorithms used for filtering the data.

1.1 Purpose of study

The purpose of this study is to evaluate the triggers for Antares. For this the sensitivity for muons and background are quantified. To reduce the required computer power for data acquisition, the main triggers have been scrutinized. The results of the simulations and tests of the Antares-DAQ framework applied to the KM3NeT detector will also be presented.

1.2 Outline

This thesis describes the results of my Master’s research project in the Antares group of Nikhef. The project is part of the Master’s programme Particle and Astroparticle Physics of the University of Amsterdam and takes one year of research.

After an introduction into particle and astroparticle physics and the Antares project, different techniques of suppressing the background are described. For this we need a deeper view into the data acquisition software framework. The effective volume of the detector is used as a measure for the sensitivity of the trigger for physics events. Also the number of computers needed for a trigger is determinative in the analysis. The analysis is applied to both detectors; the Antares detector and the KM3NeT “WPD reference detector”. Finally some properties of the triggers are scrutinized for Antares and KM3NeT and new ideas are introduced.
2 Neutrino astrophysics

In astrophysics the origin and composition of high-energy cosmic rays are studied. Cosmic rays include protons and nuclei with lifetimes of order $10^6$ years or longer. Primary cosmic rays are usually referred as particles produced in astrophysical sources and secondaries are those particles produced in interactions of the primaries. Apart from particles associated with solar flares, cosmic rays come from outside our solar system. Cosmic ray detectors like Auger [2] have measured the energy spectrum per nucleus up to $10^{20}$ eV. In addition to cosmic rays, high-energy photons have been detected [1] and neutrinos are expected from cosmological sources.

A neutrino is an elementary particle described by the standard model of particle physics [4]. High-energy neutrinos travel with the speed of light and are neutral in charge. An important difference between a neutrino and a photon is the cross section. Since the cross section for neutrinos with ordinary matter is much smaller, neutrinos are much harder to detect. On the other hand neutrinos can travel through dense matter such as interstellar clouds or can escape from the core of a star. Neutrinos are also considered as cosmic “messengers”.

Neutrinos can be created in various processes. Low energy neutrinos (< 1MeV) will be created in neutron decay. The nuclear fusion reactions in the core of the sun creates neutrinos with energies of up to a few MeV. Pions can be created by interactions of protons with ambient photons or matter. The pions will decay to a lepton and a neutrino. The energy of the lepton and neutrino is than correlated to the energy of the proton. These processes can be summarized as follows:

\[ p + p \rightarrow \pi^\pm + X \]
\[ p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n \]
\[ p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p \]
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]
\[ \pi^0 \rightarrow \gamma + \gamma \]

The low-energy neutrino flux on Earth is dominated by neutrinos from the sun. An often-used upper limit for the neutrino flux with energies between $1 GeV$ and $10^{11} GeV$ is the Waxman-Bahcall bound [3].

2.1 Neutrino telescopes

The particles of main interest are cosmic neutrinos. A neutrino can not be detected unless it interacts with another particle. Neutrinos only interact via the weak-force. There two types of neutrino interactions; the “neutral current” and the “charged current” interaction. At high energies the neutral current interaction produces a neutrino and a hadronic shower and the charged current interaction produces a charged lepton and also a hadronic shower. The interactions can be formulated as:

\[ \nu_l(\bar{\nu}_l) + N \rightarrow l^+ (l^-) + X \quad (CC) \]  
\[ \nu_l(\bar{\nu}_l) + N \rightarrow \nu_l(\bar{\nu}_l) + X \quad (NC) \]

where $\nu(\bar{\nu})$ is the (anti-)neutrino, $N$ is the nucleon, $l^-(l^+)$ is the (anti-)lepton and $X$ is the hadronic shower.

In case of a charged current, the lepton can be an electron, tau or a muon. The electron gives rise to an electro-magnetic shower and the tau will decay (lifetime $\tau = 290.6 \pm 1.0 \cdot 10^{-15}$ s). The muon has a low stopping power in water and rock and therefore a long range.
Charged particles traveling in a transparent medium, faster than the speed of light in that medium, produce Cherenkov radiation which can be detected. Detectors like Super-Kamiokande and Sudbury Neutrino Observatory use large basins of (heavy) water with photo multiplier tubes pointing to the inside. Bigger detectors such as Antares and IceCube exploit a large volume of sea water or Arctic ice.

### 2.2 Detection principle

The main detection signal for Antares is the charged current neutrino interaction where a lepton is produced. Of the three leptons the muon has the longest track since the tau will decay quickly and the electron will create a shower. The angle between the muon and the neutrino can be approximated by:

$$\Delta \Theta_{\nu-\mu} \leq \frac{1.5^\circ}{\sqrt{E_\nu [TeV]}}$$  \hspace{1cm} (3)

where $\Delta \Theta_{\nu-\mu}$ is the angle and $E_\nu$ is the energy of the neutrino. The angular resolution of the detector is dominated by the interaction angle and the track reconstruction. The direction of the muon is highly correlated with that of the neutrino. Since the neutrino travels in a straight line, the muon points back to the source of the neutrino.

Charged particles traveling through a medium faster than the speed of light in that medium produce Cherenkov radiation. The radiation has a angle $\theta_C$ with respect to the direction of the charged particle. The angle $\theta_C$ can be expressed as:

$$\cos(\theta_C) = 1/\beta n$$ \hspace{1cm} (4)

where $\beta$ is defined as the ratio between the velocity of the particle and the speed of light in vacuum and $n$ refers to the index of refraction of the medium. For relativistic particles $\beta \approx 1$. Detection of the Cherenkov radiation, makes it possible to reconstruct direction of the muon track.

A muon passing through the detector can be defined by a starting position, time and a direction. The coordinate system can be rotated such that the muon is traveling in the direction of the $z$-axis (Figure 1). The relation between a muon and the arrival time of the Cherenkov radiation at a given PMT is than:

$$t_j = t_0 + \frac{z_j - z_0}{c} + tan(\theta_C) \frac{r_j}{c}$$ \hspace{1cm} (5)

where $r_j$ is the minimal distance of approach of the muon track and the PMT. In this $t_0$, $z_0$ refer to a point along the muon trajectory.

The intensity of the Cherenkov light depends on the distance travelled. It can be expressed as:

$$I(r) \propto I_0 \frac{1}{r} e^{-r/\lambda_{abs}}$$ \hspace{1cm} (6)

where $\lambda_{abs}$ is the absorption length of light in water which is typically 50m.

### 2.3 Signal and background

If the neutrino has an interaction near the detector a muon might be produced that can be detected. Once the muon is up-going, we know the muon is from a neutrino, since only neutrinos can travel through Earth. This neutrino can be a cosmic neutrino or an atmospheric neutrino. The main approach is a point source analysis where multiple neutrinos from the same part on the sky indicate a cosmic origin.

The muon count rate is however dominated by down-going atmospheric muons. Atmospheric muons are produced by cosmic rays interacting with the atmosphere above the detector. These secondary
Figure 1: Schematic view of a muon passing an PMT. The $z$-axis is rotated to the muon direction. $r_j$ is the minimal distance between the muon track and the PMT. $z'_j = z_j - z_0$ is a correction for the distance in the $z$-direction.

Particles can also be neutrinos. These neutrinos can possibly pass through Earth and interact near the detector creating an up-going detectable muon. The three scenarios are shown in Figure 2.

An omnipresent light source in water is Potassium-40 which undergoes $\beta$ decays. The electron from the decay also produces Cherenkov light. Besides potassium-40 decays, the detector undergoes sometimes periods of high bioluminescence. The average photon counting rate of a single PMT in Antares is typically $60\,kHz$.

Figure 2: Schematic overview of three sources for muons in the detector. At the top right a cosmic ray creates a particle shower including a detectable muon. At the bottom left a cosmic ray interacts with the atmosphere and creates a neutrino which travels through the Earth creating a muon near the detector. At the bottom right a cosmic neutrino interacts with Earth and creates a muon near the detector.
3 Neutrino Telescopes

The construction of the Antares detector has been completed in 2008. It serves as a proof of concept for a deep-sea neutrino telescope. KM3NeT is its successor. Both detectors consist of a three-dimensional array of PMTs detecting photons from relativistic charged particles.

3.1 Antares

Antares consists of 12 strings anchored at the sea bottom separated by roughly 60 - 70 meters. Each string has 25 stories where 3 PMTs are mounted at an angle of 45°, facing downwards (see Figure 3). The PMTs are placed in a glass sphere to withstand the pressure, referred to as optical module. The angle between the three PMTs is 120°. Each PMT has a sensitive area of 440 cm². A PMT can detect single photons in a wavelength range between 300 nm and 600 nm with a maximal quantum efficiency around 25%.

![Figure 3: Schematic view of the Antares neutrino telescope.](image)

The strings are connected to a central junction box which is connected via a 40 km long electro-optical cable to shore. The power feed for the detector is situated on shore, as well as the processing center.
3.2 KM3NeT

The intended successor of Antares is KM3NeT (KM3 stands for km$^3$, the typical size of the detector, and NeT stands for Neutrino Telescope). The detector will be larger than Antares ($\approx 5$ km$^3$) and the optical modules will be distributed in the volume more sparsely. This will result in a larger effective volume and a better angular resolution. Since KM3NeT is still in the design phase, this study is performed on the “WPD reference detector”. This detector is meant as a generic geometry of the detector. With some minor adjustments, the Antares DAQ framework has been applied to simulated data of the KM3NeT reference detector.

The “WPD reference detector” has 154 towers attached to the sea bottom placed in a circular footprint. The towers are separated about 180 m. Each tower has 20 floors, separated at 40 m where the first floor is at 100 m above the sea bottom. Each floor consist of a 6 m mechanical bar with an optical module on each end. The horizontal direction of each consecutive bar is perpendicular to the previous one. An optical module contains 31 PMTs, each with a diameter of 3 inch. As a comparison, “WPD reference detector” has 20 times more photocathode area than Antares$^1$ and the instrumented volume is 390 times larger. Including an extra road width on each side of the detector makes the volume 90 times larger.

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<td>2</td>
<td>31</td>
<td>46 cm$^2$</td>
<td>180 m</td>
<td>40 m</td>
</tr>
</tbody>
</table>

Table 1: Specification summary of the Antares and KM3NeT neutrino telescope. For the KM3NeT detector the OMs are placed on either end of a 6m horizontal bar.

3.3 Data Acquisition

The Antares detector is read out by a software based data acquisition system. The software framework is used for digitizing, transporting, filtering and storing of the data. To achieve flexibility and performance, the system relies on the “all-data-to-shore” concept. In this all the raw data are sent to shore where the processing is done. The same framework is used for the analysis of the “KM3NeT WPD reference” detector. Data processing is done on a farm of computers.

A PMT is read out using a ‘analog ring sampler’ chip (ARS). The ARS typically uses a threshold of 0.3 photo-electrons and a gate of 30 ns. The combined time and integrated charge information is referred to as a L0-hit. The hit data is organized in frames with a period of 104.848 ms. The frames are sent via the local control module to shore. All the frames that belong to the same time window are sent to the same computer in the computer farm. The set of frames is referred to as a time slice.

A software trigger runs on every computer to filter the data for physics events. For each triggered event, a snapshot of the data will be written to disk. A snapshot includes all the data during the event plus 2µs before the event and 2µs after the event.

3.4 Effective volume

The number of detected neutrinos per unit time as a function of its energy can be expressed as

$$dN(E) = \Phi(E) \cdot \sigma(E) \cdot N_A \cdot \rho \cdot V_{\text{eff}}(E) \cdot dE$$

\(^1\)The photocathode area is not corrected for its quantum efficiency.
where $\Phi$ is the neutrino-flux, $\sigma$ the cross section, $N_A$ Avogadro’s constant, $\rho$ the density of the interaction medium, and $V_{\text{eff}}$ the effective volume of the detector. The effective volume is defined as the volume in which a neutrino interaction produces a detectable muon. The last factor is related to the performance of the detector and the trigger. The higher this number, the more events we can detect. The number of neutrinos per unit time can also be expressed as

$$dN(E) = \Phi(E) \cdot A_{\text{eff}}^{\nu}(E) \cdot dE$$

(8)

where $A_{\text{eff}}^{\nu}$ is the neutrino effective area. This area is the effective surface of the detector. It is obtained from the ratio of the rate of detected events over the incident flux. The effective volume and the effective area are used as a measure for the performance of a trigger.

For comparison, an effective volume is made with a majority trigger. The majority trigger simply checks for sufficient hits within a preset time window. As a reference the effective volume for a trigger requiring at least 10 L0-hits is shown in figure 4. Events with low energy ($10^2 - 10^4 \text{GeV}$) are hard to detect because of the small cross section and the limited range of the muon. At high energy, the plateau of the effective volume can be seen. This corresponds to the geometrical size of the detector.

![Figure 4: Effective volume for Antares (left) and KM3NeT (right) requiring at least 10 L0-hits within a preset time window.](image-url)
4 Triggers

In general, a trigger is used to reduce the data output of a detector. Due to bioluminescence and potassium decays, a 10 inch PMT has an average counting rate of 50 kHz. The Antares detector consists of 900 PMTs which generate a total output of 4 TB per day. The KM3NeT detector consists of 190,960 PMTs counting with an average rate of 5 kHz. These generate a total output of 80 TB per day. Not all the data can be saved for later analysis. The trigger should therefore look in the data whether there is an event which has to be saved.

The signals from a muon passing the detector are correlated. The use of coincidences and cluster algorithms can distinguish the signals from random background. The coincidences refer to time correlated hits nearby. A cluster algorithm searches for a group of hits anywhere in the detector that comply with causality.

The limit of the trigger rate caused by the background is usually set to 10% or less compared to the rate from physics events. The physics event rate is dominated by atmospheric muons which is for the Antares and KM3NeT detector 10 Hz and 150 Hz, respectively. The rate differs due to the sizes of the detectors. This results in a maximum background rate of 1 Hz and 15 Hz, respectively.

4.1 Coincidence filter

A coincidence filter searches for coincidences in a subset of PMTs within a preset time window. Some filters use a sampling rate, $R_s$. The number of hits in a time window $(1/R_s)$ are then counted. When this number exceeds a preset minimum, the corresponding data are passed. The calculation of the output rate can then be done by simple statistics. The relation between the sampling rate of a filter and the output rate is given by:

$$R_{\text{out}} = R_{\text{sample}} \cdot P_{(k|n)}$$

where $P_{(k|n)}$ is the probability of having k coincidences from n PMTs. This probability depends on the input rate $R_{\text{in}}$ and the time window $\Delta T$. The probability is given by the binomial distribution:

$$P_{(k|n)} = \binom{n}{k} \cdot p^k \cdot (1-p)^{(n-k)}.$$  \hspace{1cm} (10)

where $p$ is the probability of finding one or more hits in a time window $\Delta T$. This probability is given by:

$$p = 1 - e^{-\Delta T \cdot R_{\text{in}}}$$  \hspace{1cm} (11)

From the Maclaurin series of the exponential function,

$$e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!},$$  \hspace{1cm} (12)

it can be seen that this probability is approximately $p \approx \Delta T \cdot R_{\text{in}}$ for $\Delta T \cdot R_{\text{in}} \ll 1$. For large values of $n$ and small $p$, the Binomial distribution approaches the Poisson distribution:

$$P_{(k|n)} = \frac{\mu^k e^{-\mu}}{k!},$$  \hspace{1cm} (13)

with the mean $\mu = np$. The approximation is valid if $n > 100$ and $np < 10$.

The calculation of the output rate of a majority trigger is slightly different. Here the sampling rate is the summed input rate of the n PMTs. The output rate is then given by:
\[ R_{\text{out}} = n \cdot R_{\text{in}} \cdot Q(\Delta T, \lambda, k - 1) \]  

where \( Q(\Delta T, \lambda, k - 1) \) is the integrated Gamma distribution [4]. The Gamma distribution gives the probability of having \( k - 1 \) coincidences from \( n \) sources based on the summed input rate \( \lambda = n \cdot R_{\text{in}} \). The integrated Gamma distribution is given by:

\[ Q(\Delta T, \lambda, k - 1) = \int_0^{\Delta T} dt \quad \Gamma(t; \lambda, k - 1) = 1 - e^{-\Delta T \lambda} \sum_{n=0}^{k-1} \frac{(\Delta T \lambda)^n}{n!} \]  

\[ (15) \]

### 4.2 Trigger levels

Antares DAQ implements multiple trigger levels. Each raw hit is first calibrated. The calibrated hit is referred to as L0-hit. After the calibration, a first coincidence filter is applied. The output data are referred to as L1-hits. An L1-hit is due to two L0-hits on the same floor in different PMTs within a time window \( \Delta T = 20 \text{ ns} \), or a large pulse (typically \( \geq 3 \text{ p.e.} \)). Using (9) and (10) the L1-rate based on random background can be expressed as:

\[ R_{\text{L1}} = (\Delta T)^{-1} \cdot \left( \frac{3}{2} \cdot p^2 (1 - p) + \frac{3}{3} \cdot p^3 \right) \approx (\Delta T)^{-1} \cdot 3 \cdot (\Delta t \cdot R_{\text{in}})^2 \]  

\[ (16) \]

where \( p = \approx \Delta t \cdot R_{\text{in}} \). The contribution of triple coincidences can be neglected.

The next coincidence level is the so-called T-level where coincidence of L1-hits between different floors on the same string are made. Here a T2-hit is defined as two L1-hits in adjacent floors and a T3-hit is defined as two L1-hits in adjacent floors or next-to-adjacent floors. The time windows are 100 ns and 200 ns, respectively. Multiple T-hits within the maximum event time are required to reduce the background further.
4.3 Cluster of correlating hits

The expected trigger rate due to random background is based on the expected T-hit rate. The expected T2- and T3-hit rate are calculated using (14) with the exponential distribution (11). The T2-hit rate is given by:

$$R_{T2} = R_{L1} \cdot (1 - e^{L1 \cdot \Delta T_l}) \cdot (N_{floors} - 1) \cdot N_{strings}$$

where $R_{L1}$ is the L1-rate due to random background and $\Delta T_l$ the local time window for a T2-hit. The total T2-rate of the detector is the single T2-hit rate multiplied by the total possible combinations of finding two adjacent floors. The trigger rate for $k$ T2-hits within the maximum event time is given by:

$$R_{T2, trigger} = R_{T2} \cdot Q(\Delta T_e, R_{T2}, k - 1)$$

where $\Delta T_e$ is the maximum event time. The T3-hit rate is given by:

$$R_{T3} = R_{L1} \cdot \{(1 - e^{L1 \cdot \Delta T_l}) \cdot (N_{floors} - 1) + (1 - e^{L1 \cdot 2 \Delta T_l}) \cdot (N_{floors} - 2)\} \cdot N_{strings}$$

where both the T2- and the T3-events contribute to the rate. The trigger rate for $k$ T3-hits within the maximum event time is given by:

$$R_{T3, trigger} = R_{T3} \cdot Q(\Delta T_e, R_{T3}, k - 1)$$

For the KM3NeT “WPD reference” detector the definition for an L1-hit is two or more L0-hits within 20 ns, from 31 PMTs instead of 3. A T2- and T3-hit has now two PMTs per floor for the L1-hits. The time window for T-hit is 200 ns per floor. An extra definition is the T1 coincidence level consisting of two L1-hits on the same floor within 55 ns. The maximum event time for KM3NeT is 8300 ns.

### 4.3 Cluster of correlating hits

A different approach to increase the signal to background ratio (S/N) is based on finding a cluster of correlating hits. Within the cluster, all the hits correlate with each other according to a predefined causality relation. Background hits are uncorrelated and will unlikely match this relation. Antares DAQ has two boolean operators for triggering on muon tracks; the match3D and match1D operator. Given two hits the operator determines if there is a causal correlation between them.

The group velocity of the Cherenkov light ($v = c/n$) is lower than the speed of the muon traveling in the water ($c$). The three dimensional match operator (match3D) checks if the difference between two hit-times is less than the time the Cherenkov light needs to travel the distance between the PMTs. The three dimensional causality relation is given by:

$$|t_i - t_j| \leq |\bar{x}_i - \bar{x}_j| \cdot \frac{n}{c}$$

where the index refers to given PMT.

A special case of the causality relation can be defined by assuming a direction. Once the direction of the muon is assumed, the geometry of the detector can be rotated such that the muon is traveling along the z-direction. The time difference can now be corrected for the separation of two optical modules in the z-direction (see figure 1). The separation in the xy-plane gives the two most extreme values for the corrected time difference. The one dimensional causality relation is given by:

$$|(t_1 - t_2)c - (z_1 - z_2)| \leq \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \cdot \tan \Theta_C.$$
4.4 Trigger overview

The Antares DAQ system can operate with multiple triggers simultaneous. Once the data is calibrated and the first trigger level (L1) is applied, it is relatively cheap to run multiple triggers. Besides the background reduction method there are more properties of the triggers listed in Antares DAQ. Most triggers are designed to trigger on muons but, the 1S and 3S triggers detect slowly moving monopoles. These triggers are outside the scope of this thesis. The 1S and 3S trigger are exactly the same algorithms as the other triggers except for the match operators which are designed for detecting slow moving monopoles instead of relativistic muons.

The triggers assuming the muon direction initially look only in one direction. This direction can be an interesting point in the sky (e.g. galactic center). To observe all sky with the trigger one needs to scan over the sky and run the algorithm for each direction. The 3N and the TQ triggers scan the sky using the match1D operator.

The MX trigger also assumes the muon direction but uses data sets with two different coincidence levels; L0- and L1-data. The TQ trigger scans the sky using the MX trigger.

Once the direction of the muon is assumed, two extra procedures can help distinguishing a background event from a signal event. The fit procedure for the track can there be linearized [5]. From the track fit, the $\chi^2$ value is calculated. This can be a measure for the likelihood of the data, to be a muon signal. The convex hull can be a measure of the hit density in the xy-plane. Muon signal hits tend to be close to the track unlike background hits. The convex hull can therefore also be a measure for the likelihood of the data to be signal [6].

The main properties of the triggers are summarized in table (2) followed by a detailed description. From this point, the triggers will be referred as triggerXX where XX is referenced in the table.

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Table 2: Some properties of the triggers available in Antares DAQ.

trigger_L0

The trigger_L0 is used for data calibration. The position of the PMT is obtained from a logical address based on the combination of the LCM identifier and the ARS identifier. For each raw data frame all hits are calibrated using the SPE reader class and added to the calibrated data.

trigger_L1

The trigger_L1 triggers on local coincidences of two L0-hits within 20 ns or a large pulse (> 3p.e.).

For each LCM a calibrated data frame is made. The position of the frame corresponds to the LCM identifier (i.e. the average positions of the PMTs on the same floor). For each LCM, a loop over the corresponding data frames containing the L0 hits is made. For all hits, the pulse is checked if the amplitude is above the high threshold. If so, the hit is added to the calibrated data frame. The hit
is also added to a buffer. From the buffer, the local coincidences are checked and added to the same calibrated data frame. The data in the frames are time sorted and duplicates are removed.

**trigger2T and trigger3T**

The trigger2T and trigger3T triggers on local clusters of hits on same lines and (next to) adjacent floors. For 3T the number of floors can be adjusted. For the 2T the number of floors is always two.

The algorithm first makes a list of pairs of cluster hits for which the distance is limited to the number of floors and the time to a preset time window (local cluster time). In a pair, the first is always the earliest.

The list of pairs is time sorted. When the number of consecutive pairs within a preset time window exceeds a given minimum, a trigger is set.

**trigger3M**

The trigger3M provides for an implementation of a majority trigger. The trigger could be made by hardware. It is frequently used as a reference.

A timesorted queue of all calibrated data frames is made. If the number of consecutive hits within a preset time window exceeds a given minimum a trigger is set.

**trigger3D**

The logic of the trigger3D trigger is similar to that of the trigger3M. However, each group of hits is processed through a cluster algorithm using the match3D operator. Only when the resulting subset of hits is large enough, a trigger is set.

**trigger1D**

The logic of the trigger1D trigger is similar to that of the trigger3D. However, the positions of the PMTs are rotated such that muon direction is along the z-axis and the cluster algorithm uses the match1D operator instead of the match3D operator.

Besides, each hit is assumed to be the root hit. The road width that is implicitly used in the match1D operator can now be used explicitly. Only data frames are considered that comply with the road width condition. The explicit use of the road width yields a significant gain in speed that depends on the typical number of frames that needs to be considered.

**trigger3N**

The trigger3N proceeds in two steps. First clusters of hits are made like in the trigger3D. This is referred to as a pre-trigger. These clusters are then processed through a cluster algorithm using the match1D operator. In this, a scan over the sky is made.

**triggerMX**

The triggerMX combines L0 and L1 trigger data. The direction of the muon is assumed. The L1 data are used to provide a root hit as used in trigger1D. There are two possibilities, namely one L1, or two L1s. Only L0 data frames are considered that comply with the road width condition. The hits in the L0 data are associated to each root hit. This makes it possible to use L0-data to trigger. When sufficient number of hits are associated, a trigger is set.
triggerTQ
The triggerTQ applies the triggerMX trigger to a preselected part of the sky.

triggerOB
The triggerOB is used to filter the data during designated calibration runs. In this a LED (or laser) beacon is flashed. The trigger searches for all hits that causally relate to the light flash. For every light flash, a trigger is set.
5 Performance of the triggers

Each trigger has a sensitivity for background which will be studied first. A well designed trigger reduces as much as possible background, without losing signal. The sensitivity for muons will be expressed with the effective volume. The final property of interest for a trigger is the CPU power it needs. The purity, efficiency and CPU power will determine what trigger is suitable for a detector.

5.1 Background rate

The first step in reducing background is the cut on the integrated charge in the PMT per hit. This cut is usually set to 0.3 photo-electrons. The analogue pulse that passes this threshold is referred to as a L0-hit. The L0-rate is mainly due to potassium decays and bioluminescence. The average L0-rate per PMT is 50 kHz for Antares and 5 kHz for KM3NeT.

The L1-rate is dominated by random coincidence of the L0-hits and real coincidences of potassium decays. The L1-rate due to random coincidences is proportional to the square of the L0-rate. The estimated average L1-rate due to random L0-hits is 1 kHz for Antares and 500 Hz for KM3NeT (see figure 6). The genuine coincidence rate due to potassium decays is 30 Hz for Antares and 500 Hz for KM3NeT. Because in an optical module of KM3NeT more PMTs look in the same direction, this coincidence rate is higher than that of Antares.

In figure 6 the simulated and the calculated background rates for the T-triggers are shown, for different minimal number of T-hits. Requesting more T-hits in the event lowers the background event rate but increases the dependency on the L0-rate. The steepness is correlated with the total number of L0-hits requested to trigger. In general, the event rate is proportional to \( R_{mL0} \), where \( m \) is the minimum number of L0-hits.

For Antares this study shows that at least two T3-hits (and two T2-hits) are needed to lower the event rate below the limit of 1 Hz (see section 4). For KM3NeT the triggers based on T3, T2 and T1-hits need four, three and two T-hits, respectively, to suppress the background to an acceptable level. Especially the trigger based on a coincidence of two T1-hits is very promising; only 8 L0-hits are needed to trigger an event. The typical L1-rate per optical module is reduced to \( \leq 0.1 \) Hz T1-rate per floor due to random coincidence of L1-hits. The contribution to the T1-rate due to atmospheric muons is estimated to be 0.14 Hz per floor. The rate of two T1-hits is about 4.5 Hz. The contribution of potassium decays to the T1-rate is very small [7].

For Antares this study shows that the trigger3D needs at least six L1-hits and the trigger1D five L1-hits to suppress the event rate to an acceptable level. The rate for the trigger1D is lower but one has to keep in mind that this trigger needs to be applied many times to cover the sky. The standard set of directions used in Antares consist of 210 directions, equally spread. With a full scan on the data, the event rate will increase by a factor of 210.

For KM3NeT the trigger1D needs a cluster of four L1-hits to reduce the background to an acceptable level. Even though the size of the detector is bigger, the detector is sparsely instrumented. Per root hit there are less optical modules within the road width. The average number of optical modules within the road width is 14 for KM3NeT and 43 for Antares (see figure 8). Due to the size of the detector, the match3D operator used in trigger3D, does not work for KM3NeT. The time window in the match3D operator corresponds to the size of the detector. For KM3NeT the time window is much larger than (the inverse of) the typical rate. Also from the calculation it can be seen that the trigger is saturated. An improvement has been found which is described in chapter 6.1.
5.1 Background rate

Figure 6: Trigger rate due to random background. The left and right column shows the results for the Antares and KM3NeT detector, respectively. The first, second, third and fourth row show the results for the L1, T3, T2 and T1 coincidence level respectively. The T-rates due to one T-hit and increasing from above. Both the simulated rates (histogram) and calculated rates (curves) are shown.
Figure 7: Trigger background rate based on clustering of correlated hits with the match3D operator (first row) and the match1D operator (second row) for the Antares and KM3NeT detector (left and right column, respectively). The rates due to a cluster of two L1-hits and increasing from above. Both the simulated rates (histogram) and calculated rates (curves) are shown.

The assumption of the muon direction gives us the opportunity to apply the convex hull and track fit to increase the S/N [5] [6]. The standard cut using the convex hull reduces the background by a factor three, and the standard cut using the track fit reduces the background by a factor of ten. These procedures have not been studied for this thesis. The methods are not combined. The background rate caused by random coincidences, potassium decay and atmospheric muons are summarized in table 3.

Figure 8: The probability to find an optical module within the road width for KM3NeT (red) and Antares (blue) averaged over all directions.
5.2 Effective volume

The sensitivity of the detector for signal events can be expressed with the effective volume. To quantify the efficiency, a trigger based on \( n \) L1-hits can be compared using a reference effective volume based on all events in the simulation with at least \( n \) L1-hits. The effective volumes are determined from simulations with only signal hits.

From the background study it is shown that the Antares detector typically needs two T-hits to suppress the background to an acceptable level. For the KM3NeT detector the trigger1T and trigger2T have similar effective volumes although the trigger2T needs one more T2-hit. The trigger3T needs yet again one more T3-hit and therefore has a smaller effective volume. These triggers may show a slightly higher effective volume at low energies than the reference trigger which is based on four L1-hits. This effect is due to the possible sharing of L1-hits. Two T-hits can then be constructed from three L1-hits.

The trigger3D needs six L1-hits to reduce the background for the Antares detector. The effective volume for this trigger is slightly worse than the trigger1D since we need an extra L1-hit. In the simulation, the direction of trigger1D is set to the neutrino direction. The trigger3N implements the one dimensional trigger for a set of directions. The average angle between two directions is usually set to 10 degrees. The effective volume is then not affected by finite spacing between the directions. For KM3NeT the trigger1D has the highest effective volume. Although the trigger3N works with a pre-trigger using the match3D operator, the simulation could be made in the absence of background. The effective volume turns out to be smaller than the effective volume of the trigger1D, probably due to miss-match of the assumed direction.

The standard configuration for the triggerMX and triggerTQ are two L1-hits and a minimum of four L0-hits. The triggerMX uses the same cluster techniques as the trigger1D and the triggerTQ scans over a fixed set of directions. The effective volume is on average a factor of two higher than the trigger1D and trigger3N, respectively.

The standard cuts using the convex hull reduces the effective volume by 2% and the standard cut using the track fit reduces the effective volume by 20% (TeV) to 10% (PeV).

5.3 CPU usage

From the background- and Monte Carlo studies, the purity and efficiency of the triggers has been quantified. A third important aspect is the computer power usage of the trigger (CPU usage). We can express the performance of the trigger as the ratio of CPU time needed to process a timeslice of a
5.3 CPU usage

5 PERFORMANCE OF THE TRIGGERS

Figure 9: Effective volumes for Antares. a) The effective volume for the trigger2T (red) and trigger3T (green). b) The effective volume divided by the reference trigger based on four L1-hits. c) The effective volume for trigger1D (red), trigger3D (green), trigger3N (blue) and triggerMX (light blue).

Figure 10: Effective volumes for KM3NeT. a) The effective volume for the trigger1T (pink), trigger2T (red) and trigger3T (green). b) The effective volume divided by the reference triggers. c) The effective volume for trigger1D (red) and trigger3N (blue).
5.3 CPU usage

The performance of the triggers can be divided into three parts: the data calibration, the L1-generation and the trigger process. After the data calibration and the L1-generation, multiple triggers can analyze the data. The number of CPUs needed for the first two steps grow linearly with the L0-rate. The number of CPUs needed for the trigger process are strongly dependant on the L0-rate. The triggers using a coincidence filter need less CPU power compared to the trigger1D, trigger3D or triggerMX. The trigger3N is optimized for the scan of directions by making use of a pre-trigger based on the match3D operator. The convex hull and the track fit produces typically 10% and 1% extra CPU power, respectively.

For KM3NeT, operating at a singles rate of 5 kHz, the data calibration needs 60 CPUs and the L1-generation needs 350 CPUs. The real coincidences from potassium decay will not require more CPU power, but only increase the L1-rate. Without optimizing the triggers for KM3NeT, the performance of the triggers is shown in figure 11.

Besides the CPU power needed to process the data, the triggered events have to be written to disk. The dominating event rate is the rate from atmospheric muons. From simulations, the atmospheric muon rate is found to be about 10 Hz for Antares and 150 Hz for KM3NeT. On a triggered event a snapshot of $2 \times 10^{-5}$ s will be written to disk. In this snapshot, all the hit data are saved. If one hit takes 8 Bytes, then this results in a total data rate for the central storage of 115 kB/s for Antares and 22 MB/s for KM3NeT.

![Figure 11](image_url)

Figure 11: Number of CPUs needed for triggering. The left column is for Antares, the right column is for KM3NeT. The upper two plots show the CPU needed for the data calibration (checkered) and the L1-generation (striped). The bottom two plots show the trigger2T (solid), trigger3T (solid), trigger3D (dotted), triggerMX (dash-dotted), trigger1D (dashed) and trigger3N (dashed).
6 Trigger improvements

Some parts of the trigger software need some more attention to realize their usability. Some possible improvements for the Antares and/or for the KM3NeT detector are presented in the following.

6.1 Time window analysis for match3D operator

From the background studies it has been shown that the trigger3D saturates for typical L0-rates. The KM3NeT detector is much bigger than the Antares detector, consequently the time window for the match3D operator is larger. The time window can be reduced by using the road width as a limit for the travel distance of the Cherenkov light.

Given two PMTs, the corresponding time window can be calculated. Summing the time window over all possible combinations of PMTs, gives the time window profile.

![Time window profile](image)

Figure 12: The time window profile of the Antares (left column) and KM3NeT (right column) detector. The dashed line is the standard time window and the solid line is the optimized time window. The upper two plots are the time window from the three dimensional causality relation, the bottom two plots are from the one dimensional causality relation. All graphs are normalized.

Also in the three dimensional case, the range of the Cherenkov light can be limited by the road width. This applies if $|\vec{x}_1 - \vec{x}_2| > \text{road width}$. Furthermore, if two PMTs are separated more than two times the road width, the time difference between the two hits can no longer be zero. In the following, the relation between the time difference of two hits and the positions of two PMTs is studied. From this relation, the minimum and maximum time difference are derived.
The relation between the time difference and the position of the PMTs depends on the direction an
position of the track. Defining the z-axis along the muon trajectory, the time difference can be expressed
in terms of the 3D distance \( d \), the minimum distance of approach of the muon to the PMTs, \( r_1 \) and
\( r_2 \) and the angle \( \phi \) between \( r_1 \) and \( r_2 \). By considering all possible values of \( r_1 \), \( r_2 \) and
\( \phi \) the relation \( \Delta T(d, r_1, r_2, \phi) \) will give us \( \Delta T_{\text{min}}(d) \) and \( \Delta T_{\text{max}}(d) \). The topology of a muon passing two PMTs is
shown in Figure 13.

![Figure 13: The side and top view of a muon track traveling in the z-direction with two Cherenkov cones. The two cones each hit a PMT at a distance \( r_1 \) and \( r_2 \) from the track at the time \( t_1 \) and \( t_2 \). The angle between \( r_1 \) and \( r_2 \) is \( \phi \) and the distance in the xy-plane is \( r \). The distance in z between the two rims of the Cherenkov cones is \( m \), and between the fronts of the Cherenkov cones is \( l \).](image)

The time difference between the two hits is the same as the time difference between the two wave
fronts, which can be formulated as:

\[
c\Delta T = m + (r_2 - r_1) \cdot \tan \theta_C
\]

where \( \theta_C \) refers to the Cherenkov angle. The 3D distance between the PMTs can be expressed in terms of
\( \Delta z, r_1, r_2 \) and \( \phi \). From the top view of the track the position of the two PMTs and the muon track form
a triangle. If \( r \) is the line connecting the positions of the two PMTs, then

\[
r = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \phi}.
\]

The separation of the two rims rims can be expressed as

\[
\Delta z = \sqrt{d^2 - r^2}
\]

which will lead to the equation:

\[
c\Delta T(d, r_1, r_2, \phi) = \sqrt{d^2 - r_1^2 - r_2^2 + 2r_1r_2 \cos \phi + (r_2 - r_1) \tan \theta_C}
\]

To get the minimum and maximum value of \( \Delta T \) we use a numerical method. From the above
equation, the domains of the parameters are scanned. The domains of the parameters are \( 0 < \phi < \pi \)
and \( 0 < r_i < R \) where \( R \) is the road width. During the scan the values for the parameters are saved in
a matrix on the points where a minimum or maximum is found.

For \( \Delta T_{\text{max}}(d) \) two domains are found, the border between the domains is at \( D_0 \). Over the whole
domain \( \phi = 0 \) and \( r_1 = 0 \). In the first domain \( (d < D_0) \) \( r_2 \) is a function of \( d \) and in the second domain
\( (d > D_0) \) \( r_2 = R \). Solving (24) for the two domains with the parameters found leads to:
where \( r_2 \) is dependend on \( d \). This dependence can be solved by taking the first derivative of \( \Delta T \) and set this to zero which leads to \( r_2 = d \sin \theta_C \). Now \( d \) can be solved from the above equations. It is found to be \( d = R(1 + \sqrt{2}) \).

For \( \Delta T_{\min}(d) \) three domains are found with the two bounds called \( D_1 \) and \( D_2 \). In the first domain \( \Delta T_{\min}(d) = 0 \) thus the parameters are not of any interest. In the second domain \( \phi = \pi \) and \( r_1 = R \) and \( r_2 = R \). In the third domain \( \phi = 0 \), \( r_2 = 0 \) and \( r_1 = R \). Solving (24) for the three domains with the parameters found leads to:

\[
\begin{align*}
T_{\min} & = \frac{d}{\Delta T(d)} = 0, \\
D_1 < d < D_2 & \quad \Delta T(d, R, R, \pi) = \sqrt{d^2 - 4R^2}, \\
D_2 < d & \quad \Delta T(d, R, 0, 0) = \sqrt{d^2 - R^2 - R \tan \theta_C}
\end{align*}
\]

where the borders can be found by solving above equation which lead to \( D_1 = 2R \) and \( D_2 = 2R \sqrt{9/\tan^2 \theta_C + \tan \theta_C + 7} \.

On figure 14 the result from the scan together with the analytical functions and its bounds is shown. From this it can be seen that the optimization has a large affect for distances larger than 200 meter. The difference is therefore large for the KM3NeT detector.

![Figure 14: The minimum and maximum \( \Delta T \) as a function of the distance between two PMTs (blue). The old time windows is also shown (red).](image)

6.2 CPU power reduction of trigger1D

The one dimensional trigger has to be applied 210 times to scan the sky. At the Antares detector, for a second of data with an average singles rate of 80 kHz, the trigger needs per direction \( 0.2 \) CPUs which results in 50 CPUs in total. KM3NeT needs \( 5 \) CPUs per direction which results in more than 1000 CPUs in total. The trigger3N uses a pre-trigger based on the match3D operator before the direction scan is made. Optimizing the one dimension trigger could reduce the size of the computer farm.

The trigger1D consists of two nested loops over the data frames. A frame is a representation of an PMT and consists of a position and a list of arrival times. The first loop points to a frame of root hits. The first nested loop makes a list of other frames that comply with the road width. The second loop then picks root hits from the root frame and a buffer is filled with correlating hits from the selected other frames. Each time the second loop ends, the buffer is complete. A cluster algorithm is then applied to
find the largest cluster of hits which correlates with each other. If the remaining cluster size is larger than a preset minimum, an event will be triggered.

Two changes are made to optimize the process. The first one is done by representing the data in a different structure, the second one by optimizing the cluster algorithm. The results are shown in Figure 15.

A cluster hit is an object representing a frame and a hit in this frame. If the detector has \( n \) PMTs, the data are represented by \( n \) frames. A time sorted queue is initially filled with \( n \) cluster hits where each cluster hit is pointing to the first hit of a frame. The time sorted queue ensures that the first cluster hit in the queue is the earliest (corrected for the separation in \( z \)). After removing the first cluster hit from the queue the next hit in the frame is reinserted in the queue. We can repeat this until all cluster hits are processed. Because the data are sorted in time (corrected for the separation in \( z \)) only one loop is needed to make a buffer with potentially correlating hits. The downside of this method is that two hits that are outside the road width will be in the buffer.

The cluster algorithm takes a list of hits and returns the largest cluster of hits where all hits correlate with each other. The algorithm is an implementation of the “clique” algorithm. The first step is to determine for each hit the number of other hits it is correlating with. This number is denoted as \( C \). The second step is to take the hit with the lowest \( C \), remove it from the list and lower \( C \) for all the hits it is correlating to. The second step is repeated until \( C \) equals the size of the list. At this point we know that all hits in the list correlate with each other.

The cluster algorithm can be optimized by taking into account the minimum cluster size (\( m \)). The minimum cluster size gives a margin which is the difference between the number of hits in the list and the minimum cluster size. For each hit with \( n < m \) in the first step the margin can be lowered by 1. If the margin is less than zero we know we never can find a cluster big enough and the algorithm can terminate. In step two, the cluster hits with lowest \( n \) will be removed from the list as before, but if the size of the list gets below \( m \) the algorithm can terminate immediately.

![Figure 15: The number of CPUs needed for the data loop (left). The solid line refers to the standard implementation and the dashed line to the time sorted queue. The right plot shows the CPUs needed for the cluster algorithm. The solid and dashed line represent respectively the standard and optimized cluster algorithm.](image)

### 6.3 Improvement of L1-hit generation

An optical module of the KM3NeT detector contains 31 PMTs. To generate the L1-hits the triggerL1p class checks for all combinations of frames if there are two hits within 20 ns. The standard implementation
requires 500 CPUs. A CPU improvement of a factor two can be made by implementing the typical time sorted queue. Without much extra CPU power, multiple sets of L-trigger levels can be generated. As shown in figure 16, 10% extra CPU power is needed to generate L1, L2, L3, L4 and L5 hits.

The L-rate by random coincidences is lowered dramatically by requiring more L0-hits within the time window. Each extra L0-hit lowers the rate by a factor of more than 300. The L-efficiency due to a muon signal drops for each additional L0-hit about a factor of two. The rate due to genuine coincidences from potassium decays is reduced by a factor of ten for each additional L0-hit.

Figure 16: The number of CPUs needed for the L1 generation. The gray line represents the number of CPUs needed with the standard algorithm, the black solid line represents the number of CPUs needed with the optimized algorithm. The dashed line represents the optimized algorithm where multiple data sets are generated with different L0 multiplicities.
7 Discussion and outlook

The Antares and KM3NeT data can be processed at multiple trigger levels. The lowest level is the L0-data, the next one is the L1-data. For KM3NeT we can also define L2- and L3-data. A L2 hit is defined as three L0 hits within 20 ns, a L3 hit as four L0 hits within 20 ns. The next level is the T-level. Some algorithms can use different data types to trigger. The MX trigger searches for clusters with 2 L1-hits and 4 L0-hits. In this way, a triggered event has a minimum of 8 L0-hits. On their turn, also T-hits and higher level L-hits can be clustered. In general, fewer L0-hits to trigger an event increases the effective volume. In addition, the algorithm could be faster since there are less root hits to be considered.

The optimized match3D operator can be used to make a general pre-trigger. Because of the increased S/N, the match3D operator can now also be used to process real data of the KM3NeT detector.

In general, the T-triggers require multiple T-hits within a predefined time window to increase the S/N. It is obvious, but worth noting, that the optimized match3D operator can also be used to increase the S/N for the T-trigger.

The trigger1D is a general solution. Assuming the direction of the muon, the time window for correlating hits can be reduced. The road width can also be used to reduce the number of PMTs for which possible correlations should be searched for. As described above, the road width has its origin in the absorption length of light in water. This gives two regimes in the relation between the separation of the PMTs and the time difference of the hits. In the first regime, the muon may pass through one PMT, leaving the Cherenkov radiation to travel the road width. This yields a maximum value for the time difference. In the second regime the PMTs are separated by more than the road width. It then is unlikely that a muon passes through one PMT. Still it could be the case that the muon passes between PMTs. The distance between the two hit PMTs thus may become twice as large (See figure 17).

![Figure 17: The time differences between hits from a muon as a function of the 2D distance between the PMTs. The time difference is corrected for the propagation of the muon.](image-url)
8 Comparison between Antares and KM3NeT

The future neutrino telescope KM3NeT is at the moment of writing this thesis in the design phase. In this thesis the so-called ‘WPD reference’ detector is considered. Compared to Antares, the instrumented volume of the KM3NeT detector is much larger, but therefore more sparsely instrumented.

The KM3NeT detector has 25 times more photo-cathode area. The geometrical volume of the detector is about 60 times larger for KM3NeT. The effective volume for all events with at least one $L1$-hit is 30 times bigger. The effective volume for all events with at least five $L1$-hits is 40 times larger for energies above 10 TeV, at energies below 1 TeV the ratio drops dramatically.

![Figure 18: The ratio, R, of effective volumes between KM3NeT and Antares for all events with at least one $L1$-hit (squares) and for all events with at least five $L1$-hits (circles) as function of the logarithm of the neutrino energy.](image-url)
9 Conclusion

The Antares data-acquisition software framework was used for trigger studies of the future KM3NeT detector, this includes a background- and signal evaluation. To reject background while maintaining signal efficiency data filters are introduced. A L0-hit is referred to as an analogue signal passing a preset threshold. A L1-hit is referred to time coincidence of two (or more) L0-hits within a optical module. A T-hit is referred to time coincidence of two (or more) L1-hits within near floors.

From the background study it is shown that the T-triggers can reduce the background to a reasonable level without losing much efficiency and with low CPU usage. The bar design of the ‘WP D reference’ detector makes it possible to define a T1 coincidence level. The time window for this coincidence level is very small which makes it very suitable for suppressing the background. The length of the bar is set to 6 metres, which is larger than the correlation length of Potassium decays. The T1-rate is then primarily due to random coincidences and atmospheric muons. The T1-hits can also be used in combination with higher level triggers.

The higher level triggers are usually based on the general causality relation. In some cases, the general causality relation is used as a pre-trigger. Due to the size of KM3NeT, the time window of the general causality relation is larger than the typical rate, preventing the trigger process to converge. The time window can be reduced by introducing the concept of a road width. In that case, the time window is much smaller than the typical rate. This provides for a general solution of the trigger problem.

The special case of the causality relation where the direction of the muon is assumed lowers the time window dramatically. PMTs can be excluded from the trigger algorithm by using a road width. This trigger can be used to detect events from all directions by applying it to a set of directions. The one-dimensional trigger is a general solution for each detector design.

To lower the CPU usage the ‘time sorted queue’ is implemented for the L1 filter and the one-dimensional trigger. The new L1 filter can also make different data sets with each L0 multiplicity. The clusterize algorithm is augmented with a minimal cluster size. By using the minimal cluster size, the algorithm may stop at the moment it is clear a sufficiently large cluster will not be found. These improvements speed up the overall process by a factor of two.

The implementation of a road width in the one-dimensional causality relation has been scrutinized. It is shown that for two PMTs separated twice the road width, they can still see light from the same muon, when it is passing through the middle.

10 Authors contribution

I have written a software tool for the studies on the background, efficiency and CPU usage for the MK3NeT detector. For the calculation of the effective volume I’ve used a tool designed by Dr. Maarten de Jong. All the improvements described in chapter 6 are my work. Besides the usual colloquium to present my research I have spoken at the KM3NeT Collaboration meeting in Amsterdam.

11 Acknowledgments

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12 Samenvatting

Een van de hoofdvragen in de astrodeeltjesfysica is de bron en samenstelling van hoog energetische kosmische deeltjes. Men neemt aan dat de kosmische deeltjes bestaan uit protonen en atoomkernen. De potentiële bronnen van de kosmische deeltjes die daarnaast ook neutrinos produceren zijn supernovas, active sterrenstelsels, gammaflitsen en microquasars. Neutrinos hebben geen lading en vertonen alleen interactie via de zwakke wisselwerking en hebben dus een groot bereik zonder afgebogen te worden. Neutrinos worden geacht meer van de kosmische bronnen te kunnen verklaren.

De neutrinos die bij de aarde komen kunnen hier via de zwakke wisselwerking een interactie aangaan waar een muon geproduceerd wordt. Relativistische muonen die sneller dan de snelheid van het licht in water gaan, stralen Cherenkov licht uit. Het Cherenkov licht heeft ten opzicht van het muonspoor een typische hoek $\theta_C$. Het muon is te reconstrueren door het detecteren van het Cherenkov licht. De intensiteit van het Cherenkov licht neemt af naarmate het verder van het muonspoor is. De afstand waarop 90% van het licht geabsorbeerd is noemen we de ‘road width’ en is typisch 90 meter.


Antares en haar beoogde opvolger KM3NeT, zijn neutrinotelescopen en detecteren de muonen die kunnen ontstaan bij neutrino-incidenties. De Antares detector is gebouwd als ‘proof of concept’ van een diepzeek detector. Vele lensensoren geplaatst in een groot volume, meten het licht van relativistische muonen die kunnen vrijkomen bij neutrino-incidenties. De lensensoren meten tevens licht van andere processen onder water, zoals radioactief verval van kalium en bioluminescentie. Het filtersysteem van de detector probeert het achtergrondsinaal van het muonsignaal te scheiden zodat alleen de laatste worden opgeslagen voor verdere analyse.

Al het licht dat de lensensoren meten wordt verstuurd naar de controle kamer. De detector wordt uitgelezen door een softwarematig data-acquisitisiesysteem. Het systeem wordt gebruikt om het analoeg signaal te digitaliseren, transporteren, filteren en op te slaan. Het achtergrondsinaal is ongecorreleerd, het muonsignaal is causaal gecorreleerd. Voor het filteren van de data worden coincidentie filter gebruikt die gebruik maken van deze eigenschap. Hierin onderscheiden we twee niveaus; het L- en T-niveau. Het L-niveau is gebaseerd op locale coincidenties, het T-niveau is gebaseerd op coincidenties tussen aangrenzende verdiepingen. Om de verhouding tussen het signaal en de achtergrond (S/A) op een acceptabel niveau te krijgen hebben Antares en KM3NeT twee T-metingen nodig.

Er zijn ook filters die een groep van gecorreleerde metingen zoeken. Binnen de groep moeten alle metingen met elkaar correleren gegeven een causaliteitsrelatie. Het systeem kent twee toetsoperatoren die gegeven twee metingen bepalen of zij correleren. De algemene drie-dimensionale operator (match3D) kijkt of de afstand tussen de metingen overeen komt met het verschil in tijd van de metingen. De speciale een-dimensionale operator (match1D) neemt de richting van het muon aan, en kan zo een tijdscorrectie toepassen op de metingen, waarna de zelfde causaliteitscontrole wordt gedaan. Om de S/A op een acceptabel niveau te krijgen heeft Antares een groep van zes correlerende metingen nodig met de match3D operator en een groep van vijf metingen met de match1D operator. KM3NeT heeft een groep van vier correlerende metingen nodig met de match1D operator. De match3D operator werkt niet voor de KM3NeT detector. Het tijdsvenster voor twee correlerende metingen hangt af van de afstand tussen de twee corresponderende PMTs. De KM3NeT detector is zo groot dat het tijdsvenster te groot is.

Het is voor de KM3NeT detector van belang dat de match3D operator werkt gezien het in meerdere filters wordt toegepast. De causaliteitscontrole moet aangepast worden door naast een maximaal tijdsverschil in meting, ook een minimaal tijdsverschil in meting in te voeren door gebruik te maken van de ‘road width’. Om de capaciteit van het computer-park te reduceren zijn een aantal filters geoptimaliseerd in snelheid.
References


[7] [KM3NeT general meeting], (28-31 march 2011), Amsterdam