

Faculty of Science (FNWI)

# Particle detection and direction reconstruction 

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#### Abstract

Air showers can be detected in multiple ways. This thesis focuses on measuring air showers by detecting muons with a Cherenkov detector. This detector is an easily assembled and cheap way of measuring muon particles. A drum filled with water is located inside a barrel with a photomultiplier (PMT) just touching the water. The Cherenkov radiation produced when a muon passes through water is measured by the photons hitting the PMT. A good detector optimizes the reflectivity of the detector to measure as many photons as possible with the aid of the PMT. The PMT detects the photons and sends a signal to the oscilloscope which transforms this signal into a pulse. The research has been done in three steps. Firstly, the water is tested for the impact of dirty water after a significant amount of time. The intensity of the measurement was significantly reduced after three years. Secondly, the barrels were calibrated. A scintillator detector was placed under and on top of each of the barrels. When a coincidence between the three took place it was documented. This resulted in comparable, dimensionless values of $\mu / \sigma$ of 2.32 to 2.94 . Then the situation in which a muon passes through the barrel was simulated and the photons were counted. The reflectivity of the drum was adjusted to find a value that was consistent with the experiment. With this simulation, a similar value of $\mu / \sigma$ could be obtained when the reflectivity was set to $55 \%$. The simulation can be used for further study and is calibrated as well.

Lastly, for the directional reconstruction of an air shower, approximated as a plane, three detectors are needed. With the time difference and the spatial distance between the barrels an approximation of the zenith and azimuth angles can be calculated. This gives an indication of the direction of the air shower. The time resolution of the detectors is measured to be between 3.8 ns and 5.3 ns . When a muon travels at the speed of light the muon would travel 1.14 m in 3.8 ns which means that the maximum distance of 6.33 m in the experiment is relatively small given the time resolution is it important to improve the time resolution before any conclusions can be drawn. The assumption was that the angles were equally distributed in 3D. This was partly visible in the analyzed data but the time resolution proved to be a hurdle to asses this assumption.

My research focused on how the detector works and where it can be useful, e.g. in schools for educational purposes. For measurements over a longer period of time, e.g. multiple years, there should be fresh water inside the barrel, because the intensity of the measurements drops over time. But for educational purposes, the intensity does not matter as much for the purpose of having any measurement as an example to show. So even after years of measuring it will not be a problem. For educational purposes it is interesting to look at the rate of air showers in order to know if there are any measurements expected during one hour of class (for the dutch school system this means 50 minutes). Therefore they should be placed at a distance of a maximum of 3 m . A directional reconstruction in the form of calculating the azimuth angle (phi) and the zenith angle (theta) has been done but requires further research. At this moment the time resolution is not good enough to ensure a good result. A possible solution might be a direct connection between the PMT and the computer to improve the time resolution. This requires further study.


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## 1 Introduction

Particles are detected in a lot of different ways with specific kinds of detectors. The goal of this internship has been to find a way to bring particle detection to schools. The educational system should be able to benefit from a detector that is cheap and easy to use to give better insights into particle physics. The experiments of this internship specifically have been created in order to understand the usage of a cheap and simple detector through measurements and simulation. After understanding one single detector, the idea is to use three detectors and evaluate how precise the measurements are to be able to determine the direction of small air showers with muons. Also, the rate of measurements as a function of the distance is evaluated. This has been done for educational purposes to know if it is possible to get measurements that are useful within the parameters of a classroom and school hours.The simple design makes the detector very cheap and gives easy access to use it for the purpose aimed for, although the rate and precision have to be high enough to make it useful. To evaluate the viability, three series of measurements were performed during this internship.

## 2 Theory

### 2.1 Air showers

Muons originate in air showers. An air shower is created by a single high-energy primary cosmic ray nucleus or proton. They interact in the atmosphere and start a chain reaction. [4] This is visualized in Figure 1. The primary cosmic ray interacts and creates multiple rays and particles at the top of the atmosphere, because of the chain interactions and decay. The particles mentioned in this section are mostly elementary particles. In this first interaction, different particles are created which together form a disc or plane approaching the surface of the Earth. For example, possible particles are neutrons but also pions which both are depicted in the picture. The focus of this internship is on the muon $(\mu)$.This is a highly energetic particle with similar characteristics as an electron, e.g. they carry the same charge but have a much greater mass. [6] They are distinguishable from electrons in the measurements because of their mass. This creates much higher intensity peaks in the detector. Because muons have such a high energy they penetrate deeper into matter. This is the reason muons can be measured inside the Huygens building but electrons and other particles, from the same shower, can not.

An air shower like this is approximated to be like a disc moving toward the Earth (as mentioned earlier). This means multiple particles moving with the same speed from the same direction but not all in the same line so it forms the so-called disc. If multiple detectors (that are relatively close to each other) are hit at approximately the same time by muons they are probably from one air shower. This information can be used for the reconstruction of the direction of an air shower.

### 2.2 Cherenkov effect

The Cherenkov effect is used for the detection of the muons. It describes the effect charged particles have on a dielectric medium, such as water. When a highly energetic, charged particle passes through such a medium with a speed that is faster than light would pass through that medium, the interaction of the particle with the medium emits photons. These photons are called Cherenkov radiation. [2]

A more profound description of the effect is as follows. Accelerating charged particles always emit electromagnetic waves. These waves are emitted because of the Huygens principle in the form of spherical wavefronts. Molecules of the dielectric medium are excited by the charged particles and when they return to the ground state they emit the energy in the form of photons. The charged particle moves with a velocity v and the wavefronts move with a phase velocity of $\frac{c}{n}$. C is the speed of light and n is the refractive index. So if $v<\frac{c}{n}$ then there will be a symmetric polarization field and there will be no interference between the wavefronts. But if $v>\frac{c}{n}$ then the polarization field will become asymmetric along the direction of motion because it does not have enough time to return to the original state after the excitation. These overlapping wavefronts contribute to constructive interference and in the end emit a cone-like light signal which is called Cherenkov light.


Figure 1: This is a sketch of an air shower. [3]

## 3 General setup

Our Cherenkov detector consists of a white wide-neck drum with 110 liters of water inside. This is placed inside a black oil barrel which can seal air-tight which also means that light can not enter or leave the barrel. This is important because the goal is to measure the light emitted by the muons, the Cherenkov radiation. 2.2

In this case, the charged particle is a muon passing through a barrel filled with water (which is the dielectric medium). The purpose of this is to keep these photons inside the drum so the photons reflect until they finally are measured with a photon multiplier (PMT). When these photons hit the drum, which contains the water, they are either reflected or absorbed. Some photons hit the drum a lot until they hit the PMT and others just get absorbed or even hit the PMT immediately. This is purely by chance which means that the measurements have a big uncertainty and the signal does not arrive at the same time each instance. The wide neck drum is white to increase the reflectivity for the photons to guide them to the PMT. This means that the photons do not get absorbed as often as with a darker material. With this heightened possibility of reflection, the chance is a lot higher to measure at least some photons with the PMT. The black barrel shields the PMT from normal light (e.g. the light in the laboratory) to avoid large currents inside the PMT which reduces its lifetime. Furthermore, the photons from outside the barrel do not disturb the measurement when they are kept outside the barrel and the photons inside do not escape.


Figure 2: A sketch of one of the barrels. The blue bottom symbolizes the water inside the wide neck drum and the red top is the lid of the white drum. Through the lid goes the gray tube holding the photon multiplier which touches the water slightly. The black lines represent the black barrel around the drum.


Figure 3: Setup in reality

| barrel | original name |
| :--- | :--- |
| A | ton 2 |
| B | ton 4 |
| C | ton 6 |

Table 1: These are the original names written on the barrels themselves but for simplicity, the new names are used throughout this paper.

For all experiments, except the ageing experiment, a R\&S®RTB2004 Digital Oscilloscope [7] was used. An oscilloscope can measure the pulses from the PMT. This more modern oscilloscope was used to measure coincidences which could not be done with the older, available model. This means the oscilloscope itself can distinguish between when only one or two detectors have a pulse at approximately the same time or, as we need it for the final experiment, only show and save the measurements when all three detectors detect a pulse. A trigger is created when a pulse is measured that exceeds the threshold value. To make the measurements possible, the pattern trigger option was used which allowed to trigger on a coincidence, which means that all three barrels are triggered almost at the same time. For each trigger, a time trace consisting of the output voltage (in millivolt( mV ) ) as a function of time (in nanoseconds(ns)) was saved for each of the detectors. This means the pulses were measured and saved. The area under the pulse is proportional number of measured photons and thus the energy deposited in the detector. These time traces were saved on a USB stick as a PDF and simultaneously the values of the barrels were saved in steps of 0.23 ns . These steps are assumed small enough to measure a time difference of a few nanoseconds. In the remainder, 0.23 ns will be taken as the time uncertainty of the measurements from the oscilloscope.

## 4 Experiment 1: Ageing of the detector

### 4.1 Method

For simplicity and cost efficiency the drums have been filled with tap water. In a closed drum after a while, the water gets a little dirty, especially at the bottom. The first measurement is used in order to get familiar with the detector and to check the influence of the ageing of the water. For this purpose, the pulse height of each individual trigger has been measured and saved. Firstly, a trigger as mentioned earlier is the event that the oscilloscope measures a fluctuation of energy which surpasses the threshold value. Secondly, the pulse height is the pulse height of the pulse measured, which is proportional to the amount of emitted photons. We expect the fluctuation of energy to be a highly energetic muon which emits energy on top of the noise measured constantly. In the first measurements, the muons first pass through a barrel with water that has not been cleaned or changed since its construction three years ago. Afterwards, the barrel was emptied, cleaned and refilled. Then the measurement was repeated but with a drum with clean water. All measured values were written down manually in an Excel sheet.

### 4.2 Measurements

In total 49 measurements were taken and the pulse-height distribution was evaluated. There is no exact reason for using 49 measurements. It was estimated to contain enough values for a good conclusion and would not take too much time and effort. The distribution was evaluated by calculating the mean value and the standard deviation. With these values, the results can be compared, and from the standard deviation it can be determined if the results are significantly different.

| drum with | $\mu \pm \sigma$ in mV |
| :--- | :--- |
| old water | $40.0 \pm 2.4$ |
| fresh water | $47.8 \pm 2.2$ |

Table 2: These are the mean values of the two experiments and the standard deviation of the 49 measurements.

The mean value was calculated as follows.

$$
\begin{equation*}
\mu=\frac{\sum_{i=1}^{N} v_{i}}{N} \tag{1}
\end{equation*}
$$

The $v$ represents the value of the pulse-heights in $m V$ and $N$ the number of measurements in this case 49. Furthermore, the standard deviation is calculated as the square root of the variance divided by the amount of measurements.

$$
\begin{array}{r}
\sigma=\sqrt{\frac{V A R}{N}} \\
V A R=\frac{\sum_{i=1}^{N}(\nu-\mu)^{2}}{(N-1)} \tag{3}
\end{array}
$$

These formulas are standard for these kinds of errors with large amounts of data. The errors of the equipment are neglected because they are assumed to have the same error on all the measurements. So the errors described are the statistical errors. This is also used in the other experiments, which means the formulas will be used later on as well.

### 4.3 Conclusion and discussion

After performing the experiment and analyzing the results, a better understanding of the setup is achieved. The intensity of the measurements drops approximately three times the standard deviation for a single series 2 . This means there is a significant change in intensity due to the ageing of the detector.

$$
\begin{equation*}
\Delta \mu=7.8 \pm 3.3 m V \tag{4}
\end{equation*}
$$

This change in intensity can have different reasons. The change in cleaning the water could have an effect on the
reflectivity of the drum. This means that if the drum was not as white everywhere when it was dirty, the photons of the Cherenkov radiation were reflected fewer times and more easily absorbed by the material. The result is less photons reach the PMT and measure a lower intensity. The reason assumed to have the biggest impact is the absorption of the dirt floating in the water. On the one hand, for educational purposes, the change in intensity is not the most important factor. The detector would not be used frequently to show the same exact values as results but would just show that there is a simple possibility to measure muons. The measurements would be done individually and as long as muons can be measured it will still be a good option for presenting this kind of experiment in a classroom. The explanation will not depend on an exact value but will depend on the visibility of the pulse. It is still visible after three years and the assumption can be made that it will still be visible after more than ten years. On the other hand, if this detector is used within research it should be noted that there is a significant change over time. It could be wise to change the water every few months or use purified water so it does not get as easily influenced over time. To be able to compare the values exactly the cleanliness of the water is vital.

## 5 Experiment 2: Calibration incl. simulation

### 5.1 Method

The next experiment entails the calibration of the detectors. The previous experiment was focused on one barrel but for this one two more drums were filled with water and assembled just like the first detector. Before the measurements to reconstruct the direction of the muons showers can be conducted the barrels have to be calibrated so that it is known what data to expect from each detector and how to interpret it. The values of the three detectors are difficult to compare because they all have different materials which means a different outcome in measured values that do not necessarily depend on the muons. To be able to compare values the average voltage is divided by the standard deviation of the statistical distribution ${ }^{1}$. The pulse height of the measured particles is the speed of light times the amount of photons. The statistical error according to the Poisson distribution is the speed of light times the square root of the number of photons. So as a result the pulse height divided by the statistical error is the square root of the number of photons.

$$
\begin{gather*}
p . h .=c \times N_{\gamma}  \tag{5}\\
\sigma \simeq c \times \sqrt{N_{\gamma}}  \tag{6}\\
\Rightarrow \frac{p . h .}{\sigma}=\sqrt{N_{\gamma}} \tag{7}
\end{gather*}
$$

With Cherenkov detectors, a calibration can be done via two different approaches. One way is to estimate the trigger rate and compare that to the measurements. The other way is to compare the rate and energy of the muon showers to what is expected with a simulation of one muon. To get the idea of a shower this muon is simulated a lot of times but it still is not the same as a shower.

Because it is unknown how to compare the trigger rate to the measurements. Instead, the measurements are converted to the photon count. The necessary values can be obtained by the measurement of the muons by the detectors and also with the simulation. More about the simulation will be explained under the headline simulation.

The actual measurements of the muons have been done by creating a muon telescope by placing two small slabs of scintillator detectors on and under the detector in question 4. When these scintillator detectors recorded a pulse at the same time, it was assumed that a charged particle (most likely a muon) had passed through both slabs of the scintillators and thus through the self-made detector. The signals created in the Cherenkov detector have been recorded by the oscilloscope and saved in a CVS file on a USB stick.


Figure 4: This is the setup for the calibration. One slab on top and one under the detector, all three connected to the oscilloscope.

[^0]
### 5.2 Measurements

An example of the measurements recorded by the oscilloscope is given in Figure 5. The resolution of the three pulses is the same as can be seen in the left-down corner. The green graph shows the signal of the scintillator slab on the top of the detector and the orange graph the signal of the scintillator under the detector. But both pulses are very steep especially compared to the yellow pulse. This pulse is the one from the detector which has been calibrated. It is less steep because the detector is a lot bigger thus the photons do not all arrive at the same time in the PMT. Some are being reflected once or even several times. This also explains why the pulse is a few ns after both of the scintillator detector's pulses. The detector works but is a lot slower. For this calibration, only the muons directly hitting the detector from above have been measured and saved. This has multiple reasons. It is easier to put a scintillator slab on top and on the bottom instead of slightly next to the detector. Also, the rate is assumed to be higher directly from above because the atmosphere is curved around the Earth so the zenith of the detector should cover most of the particle showers. This works like a funnel, more atmosphere that can possibly react with a particle above less ground to cover so they will intensify on the way to the surface of the Earth. Also, the energy measured should be greater if the particle passes the entire barrel. If it only passes a corner there should be fewer photons emitted because there is less time to react with the water. And the last reason is that the simulation simulates a photon entering from above. This means a better comparison between the experiment and the simulation.


Figure 5: This is an example screenshot from a measurement, the first one of barrel C. The yellow line is the measurement inside the barrel and the orange and green ones are the scintillator slabs.

(a) The calibration of barrel A with a Gaussian fit

(b) The calibration of barrel B with a Gaussian fit

(c) The calibration of barrel C with a Gaussian fit

Figure 6: The total charge is still in Volt but when multiplied by the time difference and divided by the input impedance it is in Coulomb. But because these are two constants the form of the graph would not change.

The total charge of each series of measurements has been displayed in the histograms shown in Figure 6. Included in these figures is a Gaussian fit. From these data, the mean values and the with of the distributions are extracted. These make a comparison possible.

| barrel | $\mu \pm \sigma$ in Volt | $\mu / \sigma$ |
| :--- | :--- | :--- |
| A | $2.5 \pm 1.2$ | $2.32 \pm 0.02$ |
| B | $11.5 \pm 4.4$ | $2.63 \pm 0.03$ |
| C | $7.5 \pm 2.5$ | $2.94 \pm 0.02$ |

Table 3: Calibration analysis of measurements

### 5.3 Simulation

For the simulation a program was used which was created by Harm Schoorlemmer [5] using the GEANT simulation toolkit [1]. After adjusting the dimensions of the tank as well as the properties of the material the program was used to simulate the experiment. The environment simulates one muon shooting from a zero zenith angle ${ }^{2}$ through a water tank ${ }^{3}$ with a PMT inside which measures the photons from the Cherenkov radiation. Because the muon is being traced through the water at a very high speed, Cherenkov photons are created that reflect inside the barrel until they hit the PMT or are absorbed. The properties of the material have been adjusted such that the chance of the reflection of the photons is adjusted to match the measured number of photons.


Figure 7: Simulation of one muon going through water. The green line represents the muon whereas the red lines indicate photons that are being reflected inside the barrel.

In figure 7 the green line represents the one muon being shot through the barrel. The red lines indicate the paths of the photons that were created by the Cherenkov radiation and are reflected inside the barrel. The reflection coefficient used here is $55 \%$ initially, meaning $55 \%$ of the photons are reflected, and the others are absorbed. It was not known what should be a good reflection coefficient but this one came close to the observations. The blue bulb represents the photomultiplier tube. However, the PMT in the simulations is bigger than the one used for my experiment, therefore only the particles that hit the PMT within the radius of the original tube ( 3 cm ) are being taken into account.

For each value of the reflection coefficient, 1000 muons were simulated passing through the detector in order to estimate the average number of photons hitting the PMT as well as the width of this distribution. As the measurement of the total charge has a linear correspondence to the number of photons, these simulations are used to evaluate the reflection coefficient of the barrel.

[^1]
(a) Simulation of 1000 muons with a reflection coefficient of 0.15 of the material of the drum

(b) Simulation of 1000 muons with a reflection coefficient of 0.55 of the material of the drum

(c) Simulation of 1000 muons with a reflection coefficient of 0.95 of the material of the drum

Figure 8: Histograms of the amount of photons per muon launch.

In these graphs the number of photons per simulation of one muon hitting the detector from above are displayed in histograms for three different reflection coefficients. After that the same Gaussian fit has been used on the measurements to determine the mean value and the standard deviation, see Figure 8 and Table 4. The assumption is again that this is the photon count. This is useful data because different things have been measured in the experiment compared to the simulation. The biggest difference is that the detector has been hit with maybe more than one muon and the simulation simulates exactly one at a time and accumulates them. The error of the mean values divided by the standard deviation is calculated using Formula 8. The $N$ is the total amount of measurements so in this case 1000 for the 1000 muons.

$$
\begin{equation*}
\frac{\sigma}{\sqrt{N}} \tag{8}
\end{equation*}
$$

| reflection coefficient in $\%$ | $\mu / \sigma$ |
| :--- | :--- |
| 15 | $0.77 \pm 0.03$ |
| 55 | $2.44 \pm 0.03$ |
| 95 | $5.00 \pm 0.03$ |

Table 4: This is the useful data of the graphs of the simulation.

The chosen reflection coefficients give very different results. This means it could have been sensible to conduct more simulations close to the value. It has been done and can be seen in Table 5. The results are very similar so it is not realistic to get this precision from the data. It is possible to get more data and make a fit but due to time, this is not part
of this paper.

| reflection coefficient in $\%$ | $\sigma / \mu$ |
| :--- | :--- |
| 55 | $2.44 \pm 0.03$ |
| 56 | $2.63 \pm 0.03$ |
| 57 | $2.50 \pm 0.03$ |

Table 5: This is an attempt to closer determine the perfect reflection coefficient.

### 5.4 Conclusion and Discussion

First the conclusion of the experiment. The barrels had similar photon counts although barrel A showed an anomaly. The mean value was much lower and this is probably because of the PMT. In this barrel, another kind of PMT was used which shows different results within the same setting. But still, even with this deviation, it can be concluded that the photon count of the detectors is between 2.32 and 2.94 . This is the photon count per measurement which is assumed to be just one muon at a time but is more probable to be a shower of muons. It is difficult to take account of the randomness of the experiment so this is not directly reflected in the errors.

The simulation shows promising results. Around $55 \%$ the photon count is approximately the same as the experiment showed. The values are within each other's uncertainties. The photon count is around 2.4 photons measured per muon. The simulation still has a lot to offer in the future. The muons could be launched from an angle and compared to an experimental setup with the same kind of measurement. Another extension can be to simulate a shower of muons all in one plane, straight down or from an angle. It still has a lot of potential to be more exact. However, the simulation already gave a good indication that the calibration of the barrels was successful. For what is known at this moment they are well calibrated and ready for the next step.

## 6 Experiment 3: Directional Reconstruction

### 6.1 Method

The goal of this part of the thesis is to achieve a directional reconstruction of air showers. To make this possible the calibrated muon detectors were placed in a triangle fashion similar as is shown in Figure 9.


Figure 9: This is the way the barrels were standing with different distances between them.

The assumption that an air shower approaches the surface of the Earth as a plane is required. With this assumption, it can be argued that when the detectors are triggered in a specific order the time difference and the spacial distance form the basis to calculate the angles of the incoming particles. More specifically if barrel C has been triggered before barrel A and B and the latter two are triggered at exactly the same time it can be assumed that the shower came horizontally from down below. Because these terms are not very scientific the zenith and azimuth angles are used to describe the direction. The definition of these angles can be found in Figure 10.


Figure 10: These are the azimuth $\phi$ and zenith $\theta$ angles presented in a sketch.

Firstly, like in the calibration, the time resolution has to be determined to be able to correct the time differences. The length of all the cables is the same so this should not influence one or the other barrel in any way. So for the first measurement the barrels were placed as close together as possible the distance between their centers being twice the radius of the barrels as can be seen in Figure 11.


Figure 11: This is the first setup of the detectors as close together as possible.
The further the distance between the detectors the bigger the time differences and the easier it is to determine the direction of the muon shower because the time resolution has less of an influence on the measured data. However, the detectors have a limited space to be apart from each other because this setup has cables with a limited length and the space in the wing of the building was limited. In addition, it is not very useful to space them too far as the rate would be very low. The detectors were placed in the hallway of the department at three different distances. The intention was to have approximately the same distance between each of them. In addition, the knowledge of the number of triggers per minute is wanted in order to see if this experiment can be used inside a classroom. So the time stamps were collected as well. An example of a measurement of an assumed air shower is shown in Figure 12.


Figure 12: This is an example measurement of a coincidence between the barrels at the furthest distance.

### 6.2 Time uncertainties

In order to determine the time resolution of the experiment with the three detectors the time differences were recorded when the barrels were placed as close together as possible. If the time difference would be 0 it was theoretically a perfect experiment. Under the assumption that the air shower was very muon-rich. In reality, the measurement is influenced by a non-flat air shower front and particle fluctuations. The time differences between the detectors are measured and shown in Figure 13. There are also negative time differences, the reason for that is that some muons first pass through barrel A and then B or the other way around. If it is the other way around, first passing through barrel B and then A, the time difference will be negative. An absolute value would distort the graph and the Gaussian fit would not work well.


Figure 13: The time differences between the different barrels when they were standing against each other.

The time differences in Table 6 present the mean Gaussian fit $\pm$ the width of the Gaussian fit from Figure 13.

| Time difference | $\mu \pm \sigma$ in ns |
| :--- | :--- |
| $t_{A}-t_{B}$ | $9.4 \pm 6.8$ |
| $t_{B}-t_{C}$ | $-2.3 \pm 6.5$ |
| $t_{A}-t_{C}$ | $7.1 \pm 5.7$ |

Table 6: The measured time differences.

The uncertainty calculated for the formula $t_{A}-t_{B}$ is the following.

And the same is done for $t_{A}-t_{C}$ and $t_{B}-t_{C}$.

$$
\begin{align*}
\sigma_{t_{A}-t_{B}}^{2} & =\sigma_{A}^{2}\left(\frac{d\left(t_{A}-t_{B}\right)}{t_{A}}\right)^{2}+\sigma_{B}^{2}\left(\frac{d\left(t_{A}-t_{B}\right)}{t_{B}}\right)^{2}  \tag{9}\\
\Leftrightarrow \sigma_{A-B}^{2} & =\sigma_{A}^{2}(1)^{2}+\sigma_{B}^{2}(-1)^{2}  \tag{10}\\
\Leftrightarrow \sigma_{A-B}^{2} & =\sigma_{A}^{2}+\sigma_{B}^{2}  \tag{11}\\
\sigma_{t_{A}-t_{C}}^{2} & =\sigma_{A}^{2}+\sigma_{C}^{2}  \tag{12}\\
\sigma_{t_{B}-t_{C}}^{2} & =\sigma_{B}^{2}+\sigma_{C}^{2}  \tag{13}\\
\Rightarrow \sigma_{A} & =\sqrt{\frac{\sigma_{A-B}^{2}-\sigma_{B-C}^{2}+\sigma_{A-C}^{2}}{2}}  \tag{14}\\
\Rightarrow \sigma_{B} & =\sqrt{\frac{\sigma_{A-B}^{2}+\sigma_{B-C}^{2}-\sigma_{A-C}^{2}}{2}}  \tag{15}\\
\Rightarrow \sigma_{C} & =\sqrt{\frac{-\sigma_{A-B}^{2}+\sigma_{B-C}^{2}+\sigma_{A-C}^{2}}{2}} \tag{16}
\end{align*}
$$

This results in the following time resolution of each barrel.

| $\sigma_{A}$ | 4.3 ns |
| :---: | :---: |
| $\sigma_{B}$ | 5.3 ns |
| $\sigma_{C}$ | 3.8 ns |

Table 7: The calculated time resolution per barrel.

These values are very similar, meaning that the different PMTs only have a small influence. The main component of the uncertainty is likely the path difference of the light in the barrel.

### 6.3 Rate determination

Determining the rate of muons is an important part of this thesis. This largely depends on the distance between the detectors. The closer they are together the smaller the shower necessary to trigger all three detectors. As is shown in Figure 14, the further the barrels are apart, the longer the time between the triggers. When all three detectors are triggered at the almost same time, it is called a coincidence.

| distance | minimum $\Delta \mathrm{t}$ | maximum $\Delta \mathrm{t}$ | number of triggers | total exposure time in minutes |
| :--- | :--- | :--- | :--- | :--- |
| a) | $6 \min 46 \mathrm{~s}$ | 4 s | 47 | 88 |
| b) | $1 \mathrm{~h} 15 \min 16 \mathrm{~s}$ | 4 s | 220 | 2272 |
| c) | $1 \mathrm{~h} 28 \min 30 \mathrm{~s}$ | 26 s | 61 | 1327 |
| d) | $2 \mathrm{~h} 26 \min 14 \mathrm{~s}$ | 38 s | 28 | 892 |

Table 8: This is the measured data from the experiment, which forms the basis for the analysis.

The Table 8 aids with the comprehension of the large differences in between the triggers. The further the detectors stood apart the longer it could possible take to have a coincidence but is was also always possible to measure a coincidence within the next minute.

| Distance $(\mathrm{m})$ | average time between triggers (minutes) |
| :--- | :--- |
| $0.42 \pm 0.05$ | $1.8 \pm 0.2$ |
| $1.57 \pm 0.05$ | $10.3 \pm 0.7$ |
| $3.54 \pm 0.05$ | $21.4 \pm 2.4$ |
| $6.33 \pm 0.05$ | $34.3 \pm 6.4$ |

closest distance (a) next to closest distance (b) next to furthest distance (c) furthest distance (d)

Table 9: The results of the series of measurements in numbers.


Figure 14: The time in minutes between recording a coincidence between three detectors as a function of the distance between the barrels.

The distances per sequence of measurements between each of the three barrels were slightly different therefore the distance shown in Table 9 and used in Figure 14 is an average. The time between triggers is also an average. The average and the errors on them have been calculated by using Formulas 1, 2, and 3. The next to closest distance measurements series has a relatively small error which is logical because the series of measurements is the largest.

### 6.4 Data analysis

To analyze the measured data further the angles phi and theta as zenith and azimuth angles respectively are implemented as shown in Figure 15. To be able to reconstruct the direction of the air showers the range for theta was chosen to be from 0 to 90 degrees and phi should describe a range from 0 to 360 degrees. With the use of a time difference and a spacial difference the calculated muon trajectory could be from above or below. Because it only makes sense if the muon from the air shower comes from above this is assumed within the formulas.


Figure 15: These are the azimuth $\phi$ and zenith $\theta$ angles presented in a sketch. The labeling of the axis changed in comparison to the first sketch (10) to be in line with the labeling of the axis used in the experiment.

The formula bases its functionality on the assumption that the time differences divided through each other should be the same as the spacial differences times divided by each other times the cosine of the difference of the angles as shown in Formula 17. The theta angles were introduced to determine where the air shower came from in the azimuth angle. $t_{B}$ and $t_{C}$ represent the time differences between barrels $A$ and $B$ and between barrels $A$ and $C$ respectively. The distances between the barrels are indicated by $l_{B}$ and $l_{C}$, which represent the distance between barrels A and B and between barrels A and C respectively also shown in Figure 16. $\phi$ is the azimuth angle as mentioned above but the other two, $\phi_{A B}$ and $\phi_{A C}$ represent the mutual azimuth angles between the barrels. To better quantify these constant angles an angle $\psi$ was introduced.

$$
\begin{equation*}
\frac{t_{B}}{t_{C}}=\frac{l_{B}}{l_{C}} \times \frac{\cos \left(\phi_{A B}-\phi\right)}{\cos \left(\phi_{A C}-\phi\right)} \tag{17}
\end{equation*}
$$

In Figure $15 l_{b x}$ is the same as $l_{B}$ but in reality barrel B was moved a little down to the positive y-axis and had a $l_{b y}$ component as well. Also, barrel C was placed in the negative part of the x -axis. This means that the value for $l_{c x}$ is always negative. The figure should be taken as an indication but not for the entire situation and therefore the other lengths also are used and do exist. Only barrel A was located constantly in the origin.
$\psi$ is a constant to quantify the angle between the detectors in each setup. $\theta$ could be deducted from the time and spacial differences with the already calculated value for $\phi$.

$$
\begin{align*}
d & =\left(\left|l_{b x}-l_{c x}\right|\right) \times\left(\left|l_{a x}-l_{c x}\right|\right)+\left(\left|l_{b y}-l_{c y}\right|\right) \times\left(\left|l_{a y}-l_{c y}\right|\right)  \tag{18}\\
\psi & =\arccos \left(\frac{d}{l_{c} \times l_{B}}\right)  \tag{19}\\
\phi & =\arctan \left(\frac{\frac{l_{B} \times t_{C}}{l_{C} \times t_{B}}-\cos (\psi)}{\sin (\psi)}\right)  \tag{20}\\
\theta & =\arcsin \left(\frac{t_{B} \times c}{l_{B} \times \cos (\phi)}\right) \tag{21}
\end{align*}
$$



Figure 16: Schematic view of the used setup with the defined variables.

The uncertainties of $\theta$ and $\phi$ are the most important factors to consider because the uncertainty of $\psi$ only depends on the distance. Thus they are constant during the measurements and they are relatively very small which means they can be neglected.

$$
\begin{align*}
z & =\frac{\frac{l_{B} \times t_{C}}{l_{C} \times t_{B}}-\cos (\psi)}{\sin (\psi)}  \tag{23}\\
\frac{\partial \phi}{\partial t_{A}} & =\frac{1}{1+z^{2}} \times \frac{l_{B}}{l_{C} \times \sin \psi} \times \frac{1}{t_{B}-t_{C}}  \tag{24}\\
\frac{\partial \phi}{\partial t_{B}} & =\frac{1}{1+z^{2}} \times \frac{l_{B}}{l_{C} \times \sin \psi} \times \frac{t_{A}-t_{C}}{\left(t_{B}-t_{C}\right)^{2}}  \tag{25}\\
\frac{\partial \phi}{\partial t_{C}} & =\frac{1}{1+z^{2}} \times \frac{l_{B}}{l_{C} \times \sin \psi} \times \frac{t_{A}-t_{B}}{\left(t_{B}-t_{C}\right)^{2}}  \tag{26}\\
\Rightarrow \sigma_{\phi} & =\frac{1}{1+z^{2}} \times \frac{l_{B}}{l_{C} \times \sin \psi} \times\left(\frac{1}{t_{B}-t_{C}}\right)^{2} \times \sqrt{\left(t_{B}-t_{C}\right)^{2} \times \sigma_{A}^{2}+\left(t_{A}-t_{C}\right)^{2} \times \sigma_{B}^{2}+\left(t_{A}-t_{B}\right)^{2} \times \sigma_{C}^{2}} \tag{27}
\end{align*}
$$

The same is done for theta, which is much simpler.

$$
\begin{align*}
q & =\frac{t_{B} \times c}{l_{B} \times \cos (\phi)}  \tag{28}\\
\frac{\partial \theta}{\partial t_{B}} & =\frac{1}{\sqrt{1+q^{2}}} \times \frac{C}{l_{B} \times \sin \phi}  \tag{29}\\
\frac{\partial \theta}{\partial t_{C}} & =-\frac{1}{\sqrt{1+q^{2}}} \times \frac{C}{l_{B} \times \sin \phi}  \tag{30}\\
\Rightarrow \sigma_{\theta} & =\frac{1}{\sqrt{1+q^{2}}} \times \frac{C}{l_{B} \times \sin \phi} \times \sqrt{\sigma_{B}^{2}-\sigma_{C}^{2}} \tag{31}
\end{align*}
$$

This is the groundwork for the error bars found in the graphs shown in Figure 17.


Figure 17: All the axes are in degrees. Shown is the analysed data from the coincidences of the three barrels to the angles with different distances.

Theta is in these graphs shown in Figure 17 the zenith angle and phi the azimuth angle. As expected when the barrels are standing next to each other 17a there are no direction reconstruction results from the time differences. This measurement contributed to the time resolution but is not insightful when it comes to the zenith and azimuth angle. The dots at $\theta=90$ or 0 degrees are created exactly there by default. The time resolution is in the best case 3.8 ns (see Table 7) but this means when the particles travel with the speed of light the distance traveled within this time is 1.14 m which is more than the distance between the barrels.

On the contrary Figures 17 b and 17 c show the expected thus promising results. The data points are approximately evenly distributed which can be expected given that the air showers can come from random directions. The data points that accumulate at the top of the graphs are also created there by default. Possible explanations for the default points could be that two air showers were measured and assumed to be one which caused problems with the assumptions made while constructing the formulas. Another possible explanation might be that the assumption of the shower being a plane caused problems because air showers are not perfect planes.

In the last Figure 17d the data points are not equally distributed and the error bars are constantly in $\phi$ larger than in $\theta$. This phenomenon could be further studied but for now, the conclusion is that from a certain distance, this setup does not work as well as when the barrels stand closer together.

## 7 Conclusion

The first part of the internship was the measurement with the old and dirty water as opposed to the fresh and clean water in the barrel of the detector. There was a difference of $7.8 \pm 3.3 \mathrm{mV}$ resulting from the $40.0 \pm 2.4 \mathrm{mV}$ with the dirty water and $47.8 \pm 2.2 \mathrm{mV}$, which is a significant change. When not solely used for demonstration it should be advised to change the water and clean the detector.

The next step involved the calibration of the three detectors. For this, a scintillator slab was placed on top and under each detector. When they both triggered at the same time it was assumed that a muon had passed directly from above through the detector. In this instant, the measurements were taken and compared to each other. The dimensionless, similar values of the $\frac{\mu}{\sigma}$ are all between 2.32 and 2.94 which set the basis for the simulation. In the simulation a muon is shot through a similar detector and the photon count is given. To compare the simulation to the measurements of the detectors the values $\frac{\mu}{\sigma}$ are calculated from the data of the simulation as well. The component that was calibrated in the simulation was the reflection coefficient of the drum with water to match reality. The absorption of the material depends on the material and the cleanliness of the water as mentioned before. The reflection coefficient is determined at about $55 \%$. The simulation now gives an accurate representation of the experiment and can be further used in the future for more estimates, for example, signals generated when a muon is shot under different angles.

In order to obtain a direction reconstruction, the final experiment with a triangular setup of the detectors recorded the time differences of muon signals and spacial distance. With this information and the knowledge that the muons travel with the speed of light, the direction reconstruction in the form of the azimuth and zenith angle is obtained. For reference purposes, the time differences between all the barrels are documented and evaluated. The time resolution is estimated as the time difference when the barrels are close together, varies between 3.8 ns and 5.3 ns . This is a relatively bad resolution considering that the muon travels with the speed of light. Within 3.8 ns the muon would travel approximately 1.14 meters. Considering the distance between the barrels at the maximum of 6.33 m means that the error is large compared to the mean value. This is for obvious reasons problematic. On top of the bad time resolution comes the trigger rate. It is very unpredictable and the further the barrels are placed apart the longer it takes on average for a trigger to coincide between all three detectors. In conclusion, the time resolution needs the detectors to stand further apart to use the time differences and the trigger rate is better when the barrels stand closer together. The trigger rate is difficult to influence so the main problem to be addressed is the time resolution. The use of the oscilloscope has a big influence on the time resolution thus this could be improved in a study following this one. Nonetheless, the collected data was analyzed. The final graphs of the angles shown in Figure 17 do not all contribute to a good result. The first graph, Figure 17a, does not show a lot because the detectors stood as close together as possible. The data was mostly used to determine the time resolution. The next two graphs, Figure 17b and Figure 17c are more conclusive. The distribution is assumed to be more or less uniform which can be observed. A lot of data points are also in the 90-degree line for theta but this is likely due to the time difference being more than expected from a particle that travels with the speed of light. The assumption that a particle travels at the speed of light has been made during the assembly of the formulas used to calculate the angles. When the detectors were placed further apart, shown in Figure 17d, something strange happened.

For the usage in a classroom, there are three requirements which are important: It should not take too long before something happens, it should not take up too much space and there should be good results. The first requirement is met when the barrels stand very close together as can be seen in Figure 14 that the rate is very high and the second one obviously is also met if they stand close together but the last one is not as can be seen in Figure 17 that the data is inconclusive when the detectors stand very close together. If the barrels would stand further apart then the measurements are useful but take up more time and space. If used over a longer amount of time in a bigger space it would be very useful so if schools have that kind of luxury it would be recommended. Also, the improvements in the time resolution could make the measurements more useful.

## 8 Outlook

As mentioned above the time resolution needs an upgrade. To replace the oscilloscope a system with chips that would convert the signal directly from the PMT to useful data was designed. The chips were soldered but unfortunately due to a sick technician, it could not be implemented within the limited time of the internship which makes it a viable option for future studies. The time resolution could have been upgraded to a time resolution of 0.1 ns . The error of the new time differences would have been around 4 to 5 ns thus it would have been a better resolution in contrary to the oscilloscope. A further study is recommended to find out more about the detectors with a better setup and thus a better time resolution for a more obvious data analysis.


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[^0]:    ${ }^{1}$ Which is also in Volt of course and this makes the result dimensionless.

[^1]:    ${ }^{2}$ totally vertically
    ${ }^{3}$ in the case of this experiment a drum with water inside an oil barrel

