

Bachelor's thesis

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Optical Simulation of a Water Tank Measurement System

Abstract

The **P**acific **O**cean **N**eutrino **E**xperiment (P-ONE) is a neutrino detector currently under construction in the Northeast Pacific Ocean and will extend the coverage of the southern sky. In order to reconstruct particle paths correctly, the optical modules need to be calibrated and the angular acceptance known. In this thesis, a water tank measurement system is simulated, and an angular acceptance measurement of the **P**-ONE **O**ptical **M**odule (P-OM) is carried out and the total flux, as well as the flux distribution through the PMTs analysed. Additionally, a muon passing through the tank is simulated.

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1 Introduction

Throughout history, humans have used photons to explore the night sky. Beginning with visible light, the observation range has broadened to enclose the electromagnetic spectrum from radio to gamma rays [1]. Due to the absorption of photons on their way to earth, photons have limited reach as messenger particles about the Universe around us [2]. Charged particles, such as cosmic rays, are influenced by magnetic fields and are therefore diverted from their path and thus cannot be used to reconstruct the position of their source [1]. Neutrinos, however, are neutral particles, which prevents them from being deflected in magnetic fields [2]. Additionally, they interact very sparsely, as they only interact via the weak force and gravity [3]. These qualities enable their use to explore fundamental laws of physics under extreme conditions, as well as high-energy particle interactions. Additionally, neutrinos might provide insight into the nature of dark matter [2]. In order to explore the cosmos through neutrinos, neutrino detectors such as the **Pacific Ocean Neutrino Experiment** (P-ONE) use Cherenkov radiation that occurs after the interaction of neutrinos, when charged secondary particles pass through the detector medium. P-ONE is still under construction and will use so called **P-ONE Optical Modules** (P-OMs) to detect the Cherenkov radiation [4]. To reconstruct the paths of the particles, the angular acceptance of the module needs to be known in order to calibrate the photon count and timing [5].

In this thesis, a water tank is simulated, and an angular acceptance measurement, as well as scattering measurements and the simulation of a muon passing through the water, are carried out with the help of Ansys Zemax OpticStudio 2026 R1.00 (Zemax). The first objective of this thesis is to set up an environment for the measurements, which includes creating a water tank with the desired optical properties, controlling the scattering and reflectivity of the faces of the tank, importing the module, and inserting appropriate materials. Secondly, a Python script used to analyse the data is presented. This code includes separating the individual photocathodes, as well as rotating and mapping the photocathodes to create heat maps. The effect of scattering in the water is analysed, before an angular acceptance measurement is carried out for a wide and a narrow light beam. Additionally to the total flux through each photocathode, the distribution of the flux through individual photocathodes is analysed and regions of higher flux explained. Lastly, a muon passing through the water tank and emitting Cherenkov light is simulated, and the PMT response analysed.

In section 2 of this thesis the physics background needed for this thesis is provided. In section 3 the simulation environment is set up and studied. The analysis of the data is described in section 4. In section 5 the scattering measurements, the angular acceptance measurement and the muon simulation are carried out and analysed.

2 Neutrinos and Their Detection

2.1 Neutrinos

In the Standard Model of Particle Physics, neutrinos are elementary particles with no charge and eV-scale masses [3]. Three neutrino flavours are known: electron-neutrinos (ν_e), muon-neutrinos (ν_μ) and tau-neutrinos (ν_τ). Together with their charged counterparts, the electron e^- , the muon μ^- and the tau τ^- , they form the lepton family. Neutrinos only interact via gravity and the weak interaction, which has an extremely small cross section compared to other known fundamental forces. This makes neutrinos extremely challenging to detect [3].

2.2 Detection of Neutrinos

Neutrino detectors are built in order to discover neutrino sources in the sky, to investigate the diffuse neutrino flux [4] and neutrino properties [1]. Other goals include gaining a better understanding of high-energy particle interactions and the laws of nature under extreme conditions, studying neutrino oscillations, and searching for axions [2]. One method of detecting neutrinos is detecting the Cherenkov light emitted by products of interaction of neutrinos with matter [6].

2.2.1 Interactions of Neutrinos

Neutrinos are subject to the weak interaction, whose exchange particles are the bosons W^+ , W^- and Z^0 . Interactions via a W boson are called charged currents. If a neutrino interacts in that manner, a charged boson is exchanged and the charged counterpart of the neutrino is formed as a product. An interaction via the Z boson is called a neutral current. In this case no charge is transported and the neutrino remains [3]. Both interactions are visualised in Figure 1. Charged particles, that move faster through a

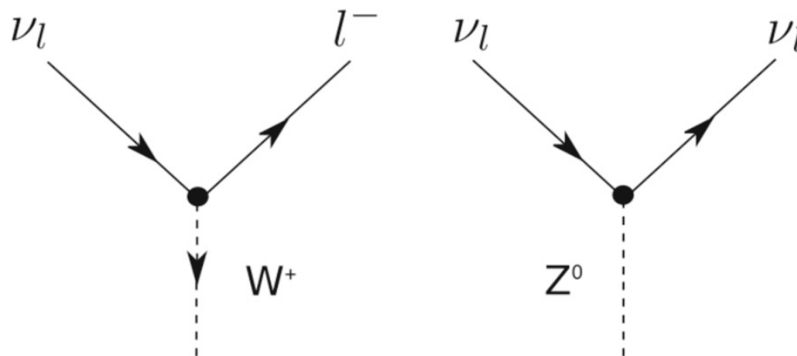


Figure 1: Interactions of neutrinos with charged bosons (left) and neutral bosons (right), where $l = e, \mu, \tau$. Taken from [3].

medium than the speed of light in that medium, cause Cherenkov radiation, which can then be detected and used to reconstruct the neutrino energy and direction [6, 7].

2.2.2 Cherenkov Effect

The Cherenkov effect occurs when a charged particle passes through a medium faster than the phase velocity of light in that medium [6, 8].

When the particle passes through a dielectric medium, its electromagnetic field polarises the atoms, which then relax back and emit a short electromagnetic impulse. If the velocity of the particle is slower than the phase velocity of light, the polarisation of the atoms is symmetric around the direction of propagation of the particle and at a distance the occurring electromagnetic fields cancel out, as can be seen in Figure 2. If the particle moves faster than the phase velocity of light in the medium, the particle moves faster than the polarisation and relaxation processes. As shown in Figure 2, the polarisation is then no longer symmetric around the direction of propagation of the particle and constructive interference of the electromagnetic impulses leads to a cone shaped field with a wave propagating under the angle θ_C . The angle θ_C can be derived from Figure 3 as follows:

$$\cos(\theta_C) = \frac{c_n t}{vt} = \frac{\frac{c_0}{n} t}{vt} = \frac{1}{\beta n} \quad (1)$$

with the time t , the refractive index of the medium n , the phase velocity of light in vacuum c_0 , in the medium c_n and $\beta = \frac{v}{c_0}$. [6]

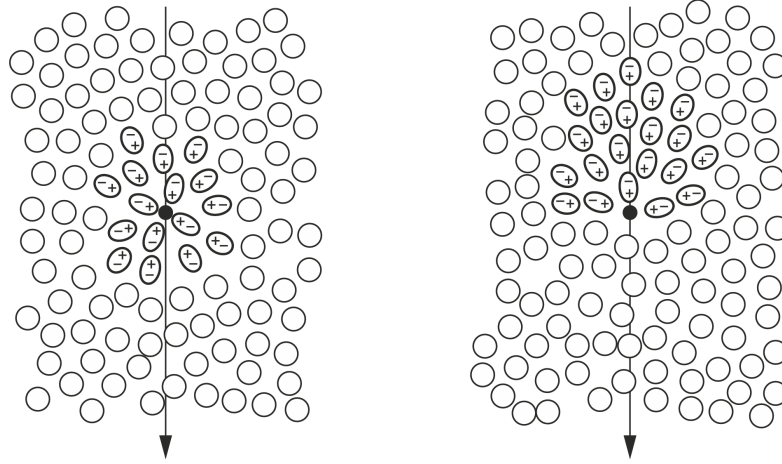


Figure 2: Depiction of the polarisation causing the Cherenkov effect. Left: The particle moves slower than the speed of light in the medium and the polarisation is symmetric. Right: The particle moves faster than the speed of light in the medium and the polarisation is asymmetric. Taken from [6].

2.3 Neutrino Detectors

2.3.1 Detection Principle

This principle of detecting Cherenkov radiation of neutrino interaction products is used by neutrino detectors such as the IceCube Neutrino Observatory [9], the Cubic Kilometre Neutrino Telescope (KM3NeT) [10] and the Pacific Ocean Neutrino Experiment (P-ONE) [4]. In order to detect the Cherenkov light emitted by these products, a transparent

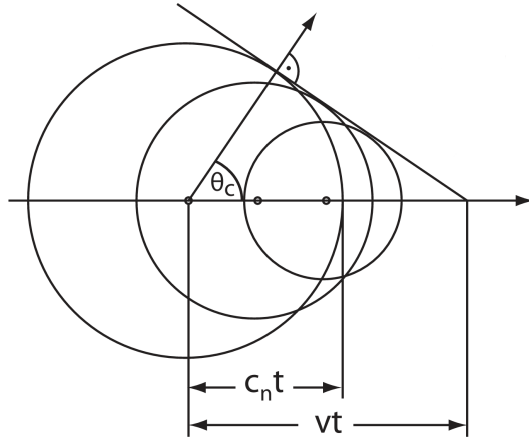


Figure 3: Visualisation of the origin of the cone shaped Cherenkov radiation. Taken from [6] and modified.

medium is equipped with light sensors. As neutrinos interact so rarely, volumes of cubic kilometre scale are needed to detect neutrinos in a statistically significant number. Therefore, natural bodies of water or ice are used as detector medium [11]. Typically, these detectors consist of vertical strings which host multiple optical modules that act as light sensors. These optical modules consist of one or multiple PMTs which are enclosed by a glass sphere [4, 9].

2.3.2 The Pacific Ocean Neutrino Experiment (P-ONE)

In the case of P-ONE, a neutrino telescope currently under construction in the Northeast Pacific Ocean near Vancouver Island, Canada [4, 12], the layout will consist of vertical strings that are anchored to the ground. Each string will be hosting 20 **P-ONE Optical Modules (P-OMs)** with 50 m distance between them, and several calibration modules. One plan to lay out P-ONE is that ten strings will form a cylindrical cluster with a radius of 200 m and 80 m distance between the strings. One cubic kilometre of water will then be instrumented by seven of these clusters, as seen in Figure 4a. As P-ONE is still under construction, the described layout will be further optimised to achieve the best angular and energy resolution, as well as the largest neutrino detection area [4]. The **P-ONE Optical Modules (P-OMs)** each consist of two hemispheres. Each hemisphere will host 8 3-inch (≈ 7.6 cm) PMTs, all enclosed by one 17-inch (≈ 43.2 cm) glass sphere [12, 13]. The PMTs are optically coupled to the glass sphere via silicon-based gel pads, where total internal reflection and refraction increase the effective photocathode area. Besides this, the gel pads aim to increase the photon collection efficiency by directing photons that otherwise would have missed the PMT, towards adjacent PMTs [13]. One hemisphere of the P-OM is shown in Figure 4b.

2.3.3 Photo Multiplier Tubes (PMTs)

Photo Multiplier Tubes (PMTs) are detectors that use the photoelectric effect as detection mechanism to detect even single photons from the ultra-violet to near-infrared region of the spectrum [8, 14]. Figure 5 shows the schematic of PMTs: a photocathode, as well as several dynodes and an anode, are housed inside a glass envelope which has

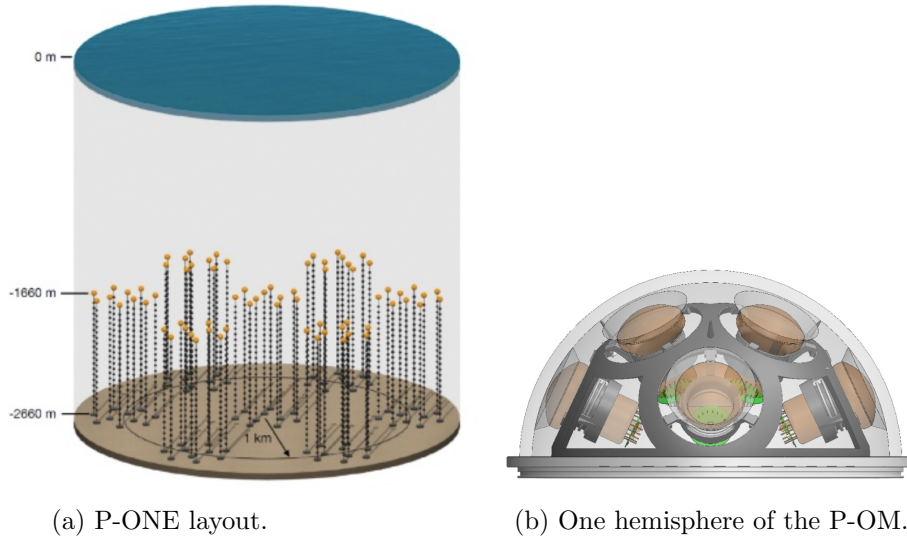


Figure 4: Design of the P-ONE layout and a P-OM hemisphere. Taken from [4] and [12]

a vacuum inside. If a photon hits the photocathode, electrons are produced via the

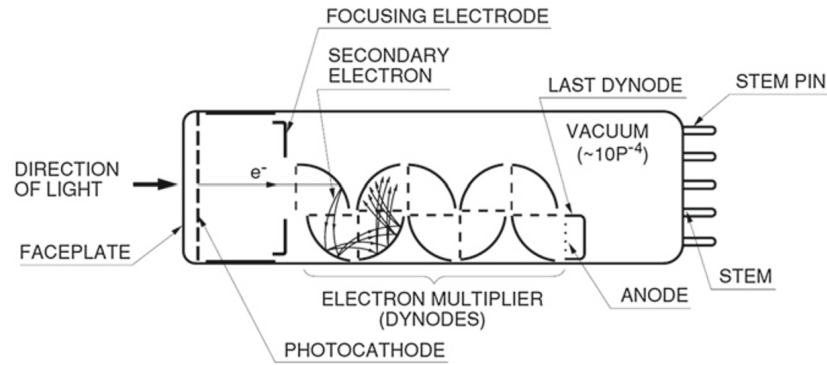


Figure 5: Scheme of a PMT. Taken from [14].

photoelectric effect. The focusing electrode then directs the electrons onto the first dynode of the electron multiplier, which consists of multiple dynodes, each at a higher voltage than the previous one. When the electrons hit a dynode, additional electrons are emitted from the dynode and accelerated towards the next. In each step, an increasing number of electrons is emitted until this electron avalanche reaches the anode, and a sharp current pulse is measured [8].

In order to reconstruct the paths of particles through the detector, the angular acceptance of the PMTs needs to be known, as it is an important parameter used to calibrate the photon count, as well as their timing [5]. For this reason, this thesis will analyse the flux through the photocathodes of the PMTs in the P-OM in an angular acceptance measurement in addition to other measurements.

3 Setup

3.1 Ansys Zemax OpticStudio

Ansys Zemax OpticStudio 2026 R1.00 (Zemax) is a software tool for optical ray tracing and imaging [15], and is used as the main simulation tool in this thesis. It operates in one of the two modi: The Sequential Mode can be used to design imaging systems, while illumination systems can be analysed using the Non-Sequential Mode. A mixed mode is also possible [16]. The Non-Sequential Mode was used to simulate all measurements carried out in this thesis.

3.2 Simulation Setup

The environment for the experiments in this thesis is a rectangular water tank. The module that will be analysed, as well as a light source, is housed inside it. The source sits on the opposite end of the water tank from the module and points towards it.

3.2.1 Water Tank

To simulate a water tank, a 2 m high and wide, and 4 m long “Rectangular Volume” was created, and the material was set to “WATER”. This sets the properties to the reflective, refractive, and absorptive values of water [17]. The reflective and absorptive

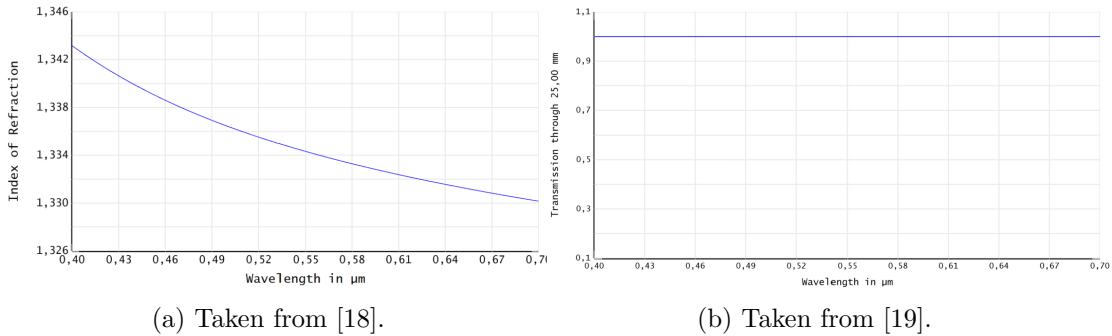


Figure 6: Used water optical properties showing in index of refraction (left) and transmission through 25 mm of water (right). Both are shown as a function of wavelength between 400 and 700 nm.

values are visualised in Figure 6. The refractive index follows the normal dispersion, and rises with decreasing wavelength. The transmission is modelled as a constant value of 1, implying that no photons are absorbed. Therefore, the effects of absorption are not taken into consideration.

3.2.2 Light Sources

Zemax simulates the propagation of light using rays, which are normal to the wavefront of the light and point in the direction of its propagation [20]. In this thesis, all light sources were simulated with a wavelength of 550 nm and a power of 1 W. Additionally, all rays emitted by the same light source had the same power and wavelength [21]. For the measurements in this thesis, three different light sources were used, which are

explained in the following.

The “Source Gaussian” (in this thesis also referred to as “Gaussian beam”) emits a Gaussian distribution of rays. The radius of the beam is given as the beam radius at the $\frac{1}{e^2}$ point of intensity. The distance from the apparent point of divergence of the rays to the point source plane can be varied. In this thesis, this parameter was set to zero, which resulted in collimated rays [22]. The ray distribution of this source is shown in Figure 7a.

The “Source Point” (in this thesis also referred to as “point source”) emits rays from a point into a cone. The semi-cone angle can be varied from 0° to 180° [23]. The ray distribution within this cone is uniform, as can be seen in Figure 7b.

The “Source Object” is used to create a source in the shape of any other Zemax object that was defined prior to the source. The angular distribution of the rays to the object surface can be controlled [24]. This source was used in subsection 5.4 to create a Cherenkov cone, with rays emitted normal to the surface.

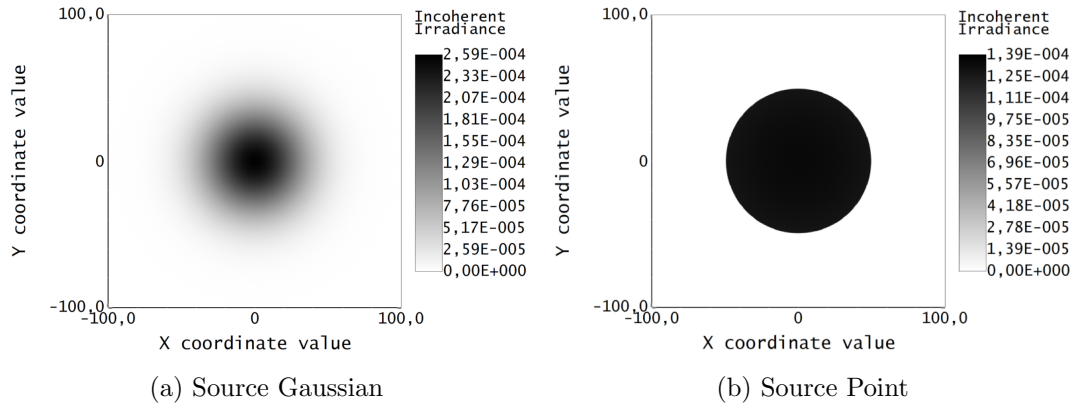


Figure 7: Incoherent irradiance on a detector for the Source Gaussian and the Source Point. Taken from [25].

3.3 Reflectivity & Scattering

3.3.1 Reflectivity

To control the reflectivity of the walls of the water tank, coatings were created and applied to the faces of the water tank. The coatings were defined by using “IDEAL coatings” and setting the transmission coefficient T to zero and the reflection coefficient R to the desired proportion. The absorption coefficient A is then calculated by $A = 1 - R - T$. Independent from wavelength and the incident angle, the proportion R of the ray energy is reflected [26]. In this experiment, no scattering model was applied to the faces, therefore the rays were reflected specularly [27]. To visualise this, a planar, rectangular detector the same size as the back face was placed 10 cm in front of it. A source point with a semi-cone angle of 45° and a power of 1 W was simulated 10 cm inside the water tank over the centre of the front face. Due to the opening angle of the light source, rays hit the side faces of the water tank and were then reflected or absorbed, as shown in Figure 8. Figure 9 shows the incoherent irradiance detected by the planar detector for different proportions of reflection and absorption. With higher reflection proportions,

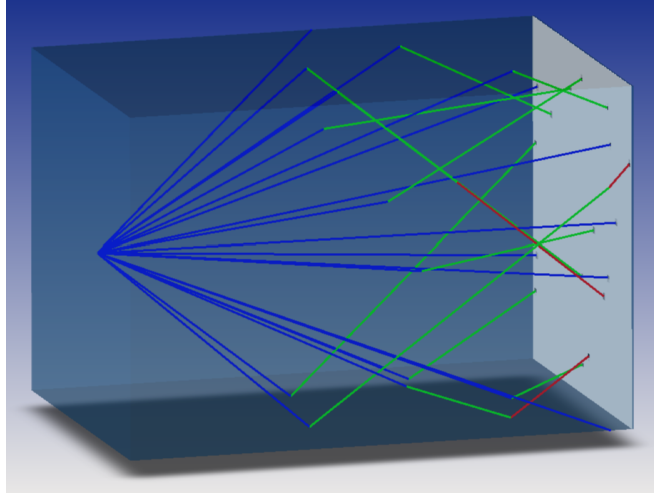


Figure 8: The water tank with the planar detector and the point source. Rays are coloured by segment, meaning their colour changes every time they interact or scatter. Visualized using [28].

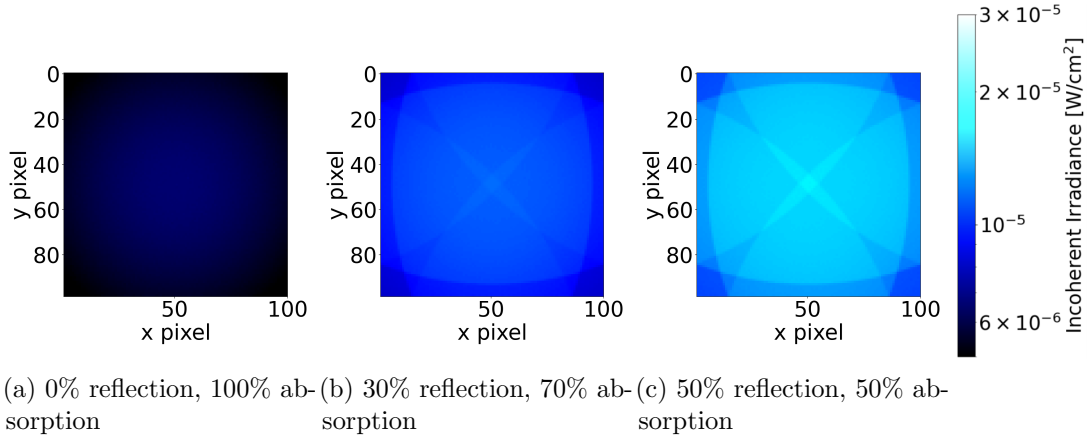


Figure 9: Measured incoherent irradiance for different reflection and absorption values of the water tank faces.

reflection patterns are more clearly visible due to more rays reflecting off the walls. For the purposes of this proof-of-concept study, the faces were set to absorb all incident rays, thus no reflectivity of the walls was used in the following measurements.

3.3.2 Scattering

The scattering of the water was controlled in the “Volume Physics” section of the “Object Properties”. The model “Angle Scattering” was chosen to approximate the scattering in water. It allows for two parameters to be controlled: the mean path x_{mp} and the semi-cone angle α . In this model, rays have an integrated probability of having scattered after travelling a distance x of

$$p(x) = 1 - e^{-\mu x} \quad \text{where} \quad \mu = \frac{1}{x_{\text{mp}}}. \quad (2)$$

The expression is set to a random number between 0 and 1 and solved for x . If x is greater than the travelled distance to the next ray-object intersection of the ray, the ray is not scattered. If x is smaller, the ray gets scattered at the calculated position x . The new direction of the ray is chosen so that the new ray directions, with respect to their previous directions, lie uniformly distributed in a cone with the semi-cone angle α [29]. To visualise this, the planar detector, and a narrow Gaussian beam with a power of 1 W, instead of the source point, were simulated. The mean path and the scattering angle of the water were then varied to visualize their effects. Figure 10 shows the incoherent irradiance without any scattering. Figure 11 shows the incoherent irradiance for a variation of the angle and Figure 12 for a variation of the mean path. In all three figures, the maximum of the incoherent irradiance is higher than $10^{-3} \frac{\text{W}}{\text{cm}^2}$, which was chosen as the limit of the scale, to be able to see the scattered rays in the plots.

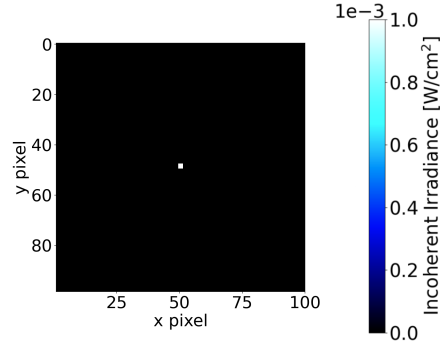


Figure 10: Incoherent irradiance without scattering.

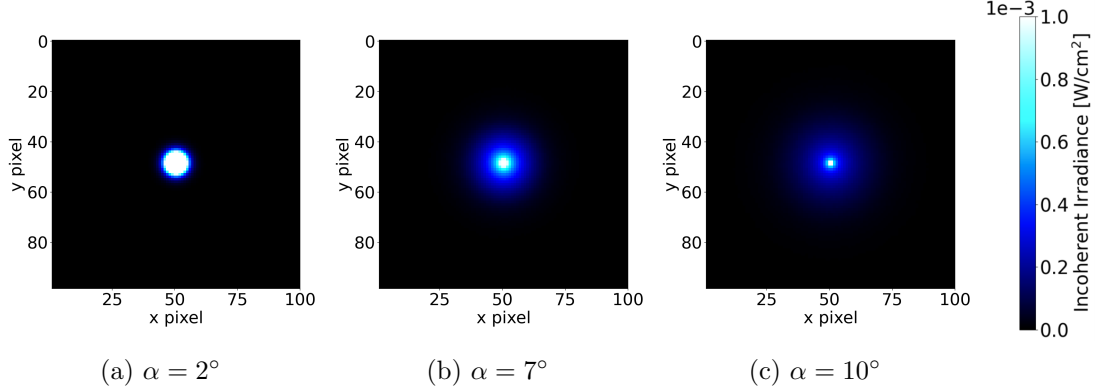


Figure 11: Incoherent Irradiance measured by the planar detector for different angles (α) at a constant mean path ($x_{\text{mp}} = 1 \text{ m}$).

Figure 11 demonstrates that, with an increasing scattering angle, the illuminated area around the centre of the beam grows, while a visible point in the middle, where the non-scattered rays hit the detector, remains. Figure 12 shows how the number of rays that do not scatter decreases with a decreasing mean path. Additionally, it can be seen that regions close to the centre of the beam are more illuminated, which indicates that small divergences from the beam are more likely than larger ones.

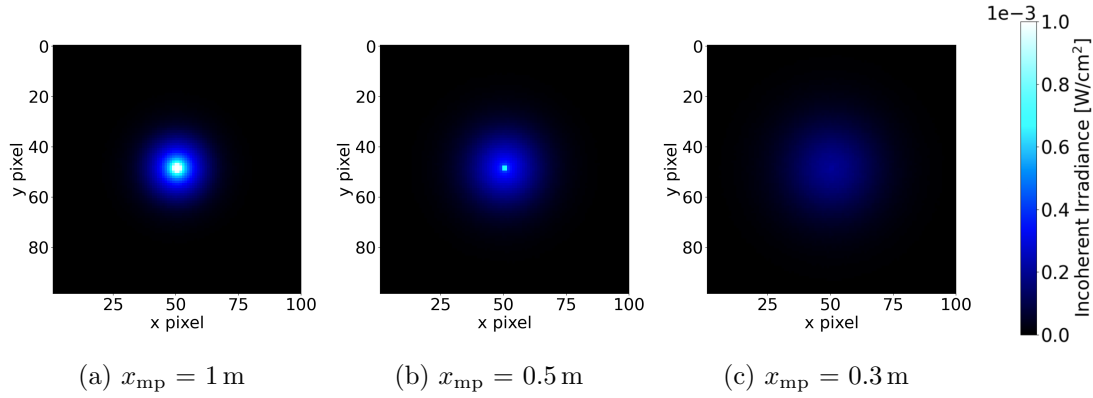


Figure 12: Incoherent Irradiance measured by the planar detector for different mean paths (x_{mp}) at a constant angle ($\alpha = 7^\circ$).

3.4 Module

In this thesis, one hemisphere of the **P-ONE Optical Module (P-OM)** is analysed. A computer-aided design (CAD) file of the P-OM, as shown in Figure 13, was provided by the P-ONE Collaboration for the purpose of this thesis.

If a Zemax object is set as a detector, the entire object detects photons, therefore the PMTs have to be imported as a separate object from the rest of the module. Additionally, each object can only have one material, which is set for the entire object. To be able to simulate different materials for different components, they have to be imported as separate objects. To construct an accurate model of the module, all gel pads were exported as one CAD file from the provided CAD file of the P-OM and imported to Zemax. All PMTs were ex- and imported in the same manner and set as detector. Additionally, the mounting structure was exported from the CAD file and imported to Zemax as well. The glass sphere was constructed by nesting one Zemax sphere with a radius of 20.2 cm inside another sphere with the same origin and a radius of 21.6 cm. The material of the outer sphere, which represents the glass sphere, was set to “N-BK7” to approximate glass, and the material of the inner sphere was set to “VACUUM”. In order to prevent the rays from passing through the PMTs or the mounting structure, the material of both was set to “ABSORB”, meaning that every ray that hits them gets absorbed. The refractive index of the gel pads is effectively constant for the considered wavelengths, therefore, the material of the gel pad was approximated by defining a constant refractive index of $n = 1.4$ [30].

Behind the PMTs, as a separator of the two hemispheres, a spherical plane with a radius of 21.6 cm was added and its material set to “ABSORB”. This was done to prevent rays entering the hemisphere from the back. Figure 13 shows the assembled module, which was placed at 3 m distance inside the water tank over the centre of the front face, facing towards it.

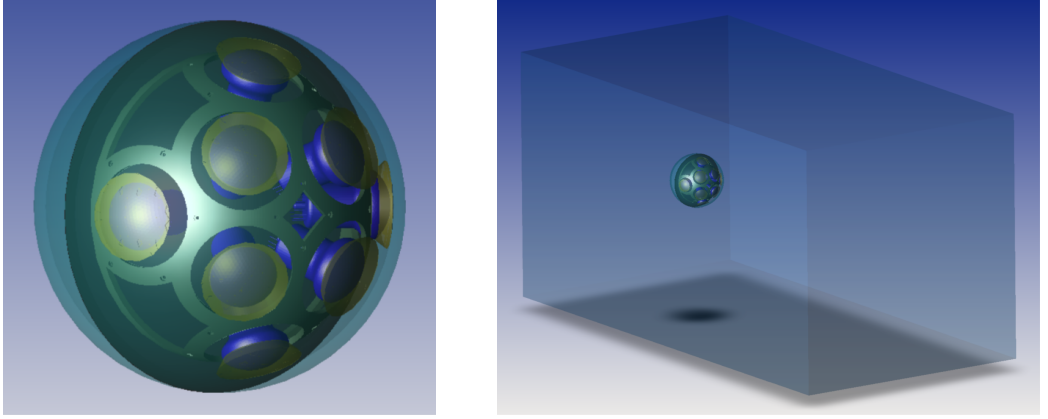


Figure 13: The assembled module in Zemax after all imports. The PMTs are shown in dark blue and the gel pads in yellow. The mounting structure is drawn in grey and the spherical plane in black. All is enclosed by the glass sphere, which is drawn in light blue. Visualised using [28].

4 Data Analysis

4.1 Extracting PMT Fluxes

To analyse the flux measured by the different PMTs the total flux through the photocathode of each PMT was calculated, using a code described in this subsection. The entire code used in this thesis was written in Python 3.14.5 (Python) [31]. This code was then used to analyse the data from the angular acceptance measurement, as well as the measurements with different scattering properties and the simulation of the detection of a muon.

All PMTs were imported as one object to Zemax and pixelated by it. The detector data was given as one .txt file where each pixel, position and flux through the pixel were listed. Only the photocathode of the PMTs can detect photons, therefore a Python script was written to filter out the pixels that did not belong to any photocathode. The PMTs all face radially outwards, therefore to isolate the photocathode, the radius of every pixel was calculated. Only the pixels with a radius greater than 0.19 m were estimated to be part of the photocathode and taken into further account.

To differentiate between the photocathodes of different PMTs, the areas in which the cathodes were located were read off. For each PMT a boolean mask was created that separates the points inside the area from the ones outside and thus separating the points of one photocathode. The separated photocathodes are shown in Figure 14. For each the x-, y-, and z-coordinates, as well as the flux, a dictionary was created with an array of the corresponding values as entry for each PMT.

4.2 Individual PMT Analysis

To calculate the total flux through a photocathode, all fluxes of the pixels of the photocathode were added up. This was done by taking the sum over all elements of the

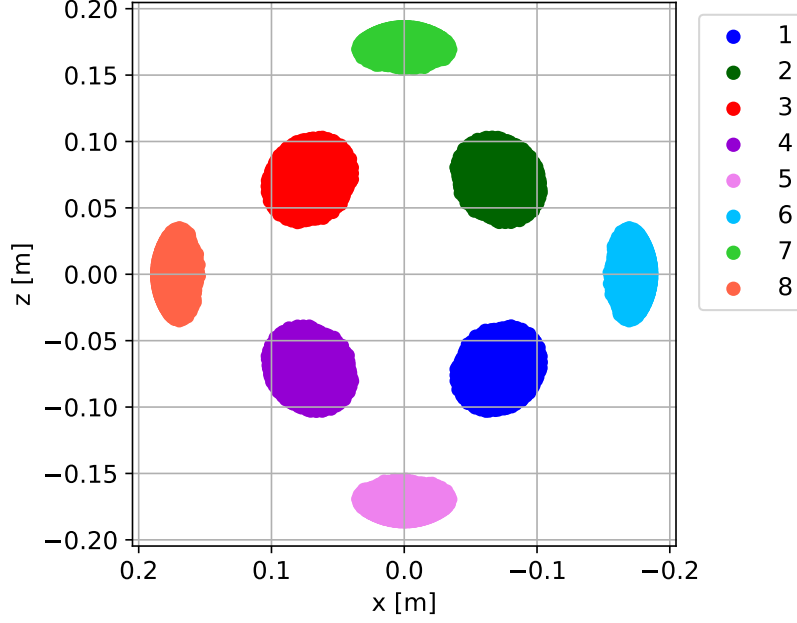


Figure 14: Visualisation of the separated photocathodes and labelling of the individual PMTs. The x-axis is inverted so that the plot aligns with a front view of the module.

array in the corresponding entry of the flux dictionary.

To analyse the change of the flux through one PMT with the rotational angle of the module, a heat map, showing the flux through one slice in the middle of the PMT for different angles was created. The following figures shown in this subsection are examples meant to demonstrate the method. The plots resulting from the data obtained during the measurements will be shown in subsection 5.3.

4.2.1 Rotation of the PMTs

In order to be able to take a slice through the middle of the PMT regardless of its orientation in the simulation, a rotation has to be applied to normalize the PMTs direction. This was done by first calculating the centre of the photocathode and then creating a vector with the x-, y-, and z-coordinates of the centre as components. With the `align_vectors` function from `scipy.spatial.transform` Rotation a rotational matrix was computed that, if multiplied with the vector, rotates it, so that it aligns with the y-axis. The corresponding coordinates of the centre were subtracted from the coordinates of each pixel of the photocathode, moving it to the centre of the coordinate system. The rotational matrix was then applied to the shifted points. The shifted and rotated points were then shifted back to their original x-, and z-position, resulting in the PMT sitting at $y = 0$, pointing in the direction of the y-axis, as can be seen in Figure 15.

4.2.2 Creation of a Heat Map

As shown in Figure 16a, the pixels of the photocathode are arranged in a hexagonal grid. A new rectangular grid was created using `numpy.mgrid`, and the flux was interpolated

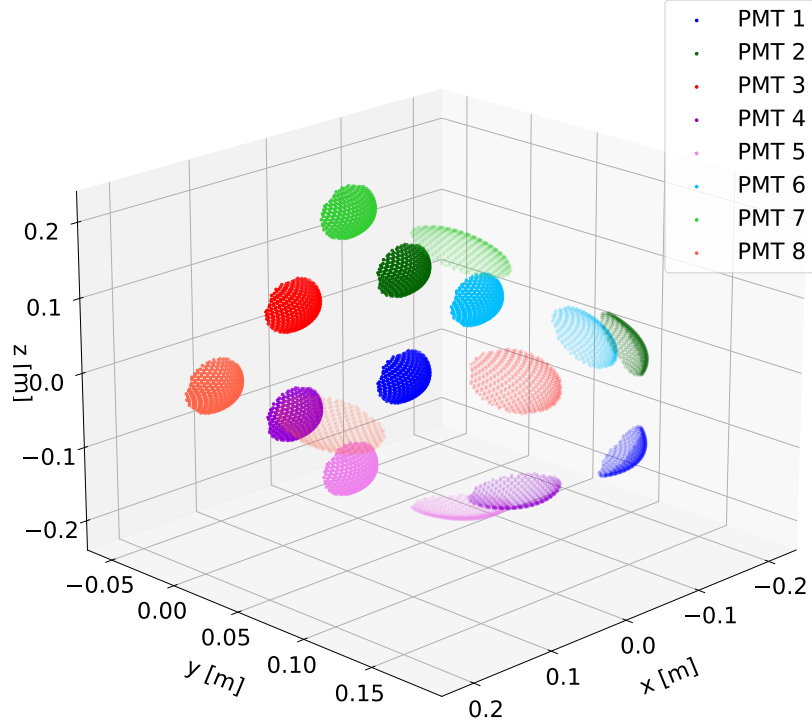


Figure 15: Rotated PMT photocathode grids in three-dimensional space. The different point clouds show the normalized projections of the PMTs grids after correcting their relative rotations. The original grids before rotation are shown in a fainter colour.

via `scipy.interpolate.griddata`. The result of this can be seen in Figure 16b.

To create a heat map of the columns, the flux values of the middle column of the photocathode (as marked by the red line in Figure 16b) were saved in an array and then appended to a list. This was done for multiple rotational angles of the module and resulted in a list of arrays which contained the flux values. This list was then converted into an array, transposed and plotted over the rotational angles via `matplotlib.pyplot.pcolormesh`, as can be seen in Figure 17.

A heat map of the middle rows of the photocathode was created analogously, with the only differences being not transposing the new array.

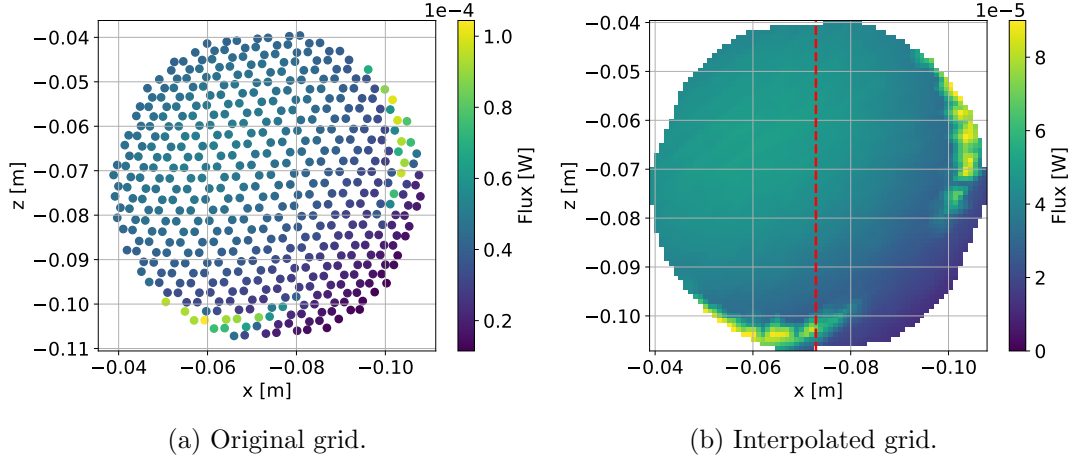


Figure 16: Front view of the photocathode before and after rotation and interpolation as described in subsubsection 4.2.1. In the original grid the pixels lie on a hexagonal grid, whereas the interpolated grid is rectangular. Due to the original grid not being perfectly circular, the interpolated grid is not either. The red line marks the slice through the photocathode that will be used for further analysis.

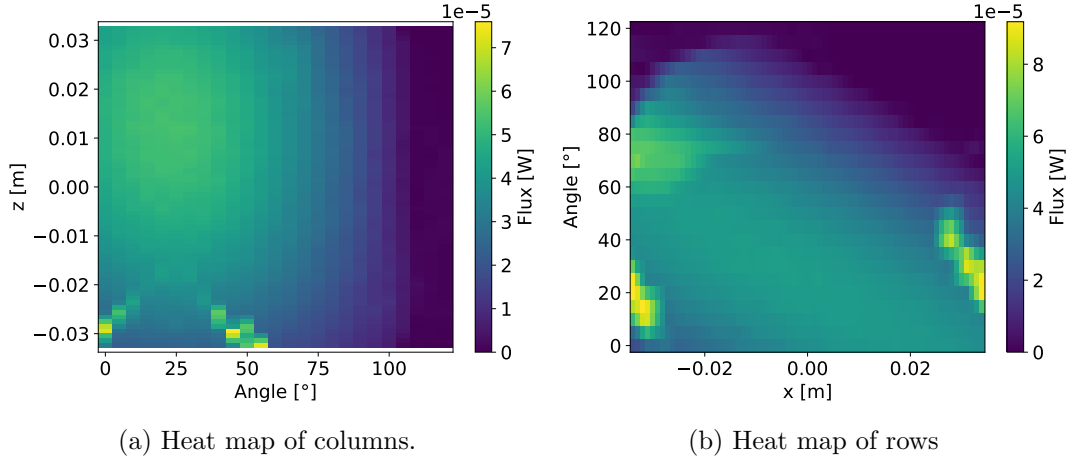


Figure 17: Heat maps of cathode slices over the rotational angle of the module. The white stripes in plot a) occur because the photocathode data is not perfectly circular.

5 Measurements

5.1 Scattering in Water

To analyse the effect of scattering, a point source with a semi-cone angle of 0.5° , simulating 10^7 rays was generated in the centre of the front face. The beam passed through the middle between the PMTs, so that without any scattering, all PMTs registered a total flux of 0. Figure 18 shows this setup with and without scattering.

The flux through the photocathodes was then measured for different mean paths with a constant scattering angle and for different angles with a constant mean path, using the scattering model described in subsubsection 3.3.2.

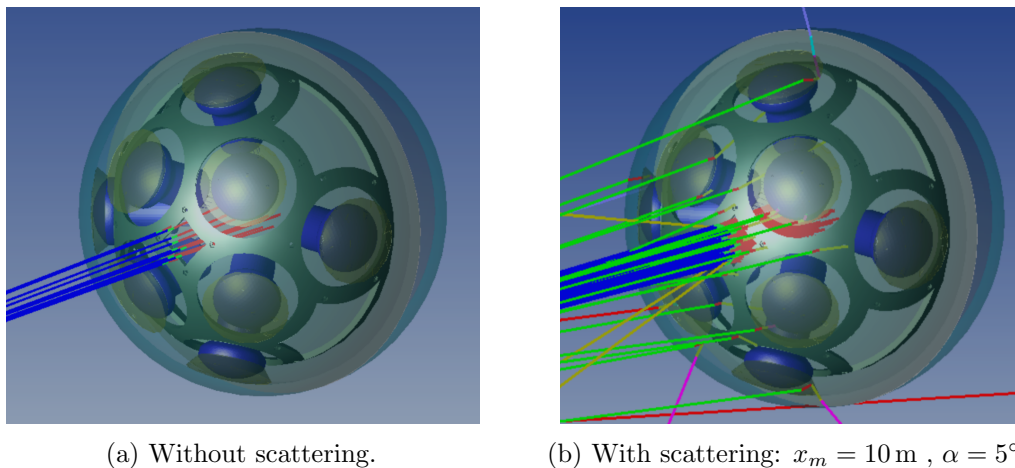


Figure 18: Rays hitting the P-OM with and without scattering. The rays are coloured by segment. Visualised using [28].

5.1.1 Scattering Angle

To analyse the effect of the scattering angle, a constant mean path of 10 m was chosen. The angle was then varied between 1° and 180° and the flux through each PMT photocathode recorded for every scattering angle. The module is symmetric about its centre and the scattering is not dependent on the direction of the rays, leading to a radially symmetric distribution of the flux. Therefore, the PMT groups 1-4 and 5-8 each measure the same flux. Therefore, the average of the flux through the photocathodes of these PMT groups was taken and plotted over the scattering angle. The resulting plot can be seen in Figure 19.

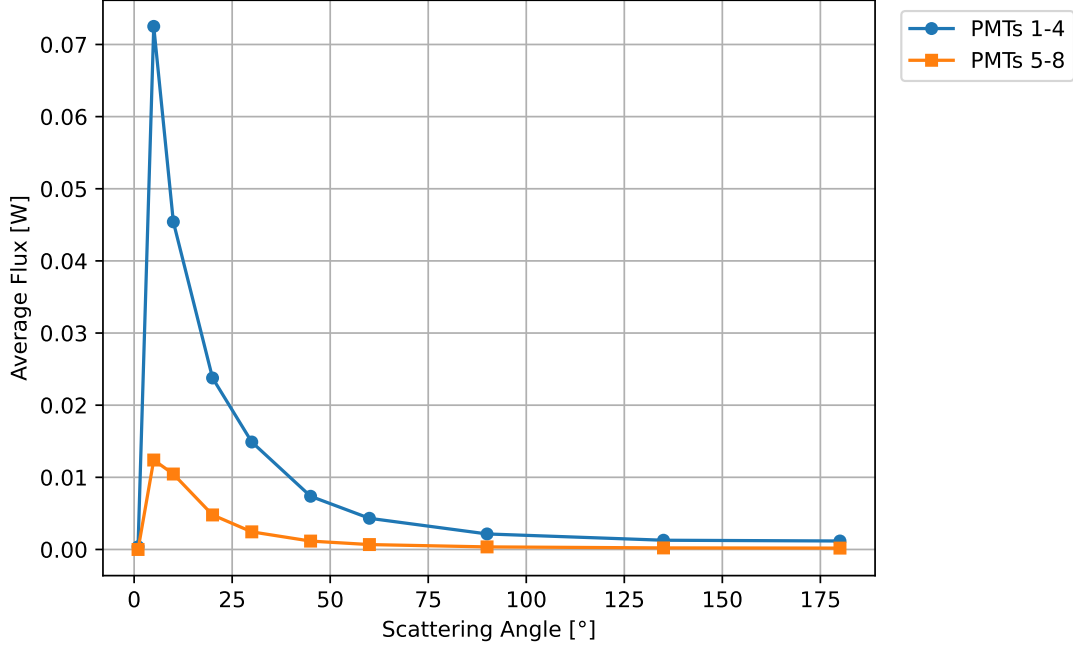


Figure 19: Average over the flux through the photocathodes of the PMTs in the two PMT groups as a function of the scattering angle.

As expected, the PMTs 1-4 measure a higher flux than the PMTs 5-8. This is due to the geometry of the module, the PMTs 1-4 face towards the light source and therefore have a greater area pointing towards the beam. Another reason for this is that, as seen in subsubsection 3.3.2, a smaller divergence of the rays from the original beam is more likely than a great divergence.

Noticeably, the measured flux rises with a smaller angle down to 5° . Reason for this is, that with a smaller scattering angle, the beam stays narrower and thus less scattered rays fly past the module.

Figure 19 demonstrates, that for the scattering angle of 1° the measured flux is zero. This implies that the scattering angle is small enough that even the scattered rays pass through the middle of the module and thus do not hit any photocathode.

5.1.2 Mean Path

In this measurement, the mean path was varied between 1 m and 80 m, while the scattering angle was kept constant at 5° . For every mean path the flux through every photocathode was recorded. As in the previous measurement, the PMTs 1-4 and 5-8 measure the same flux, which is due to the radially uniform distribution of the scattering probability and the symmetry of the module. The average of the measured flux of the PMT groups was taken and plotted over the mean path. The resulting curves are shown in Figure 20.

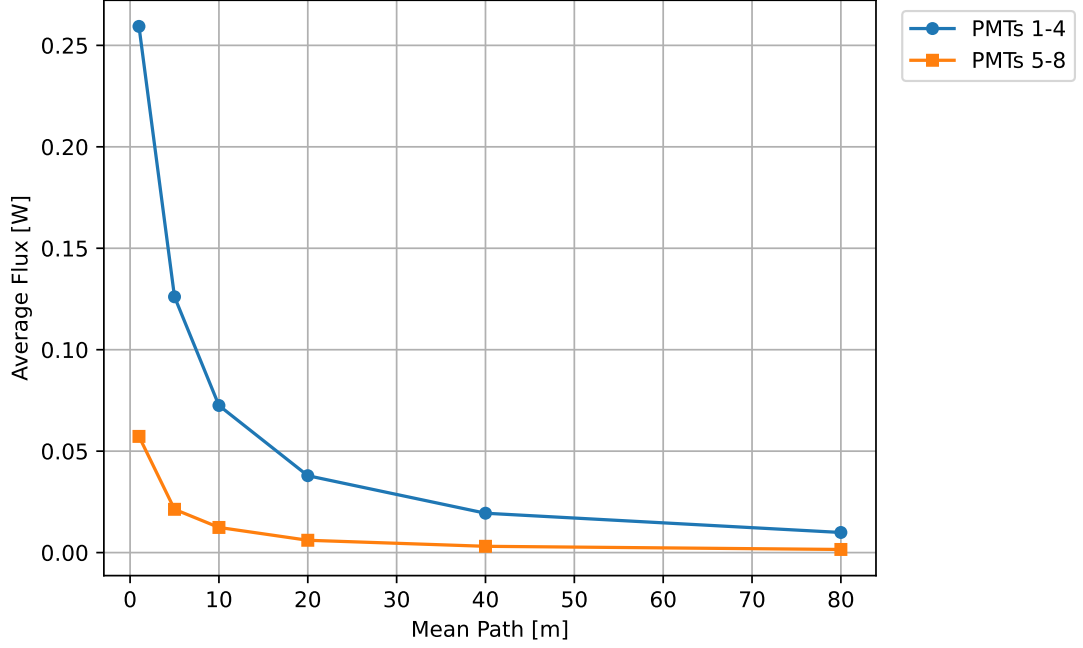


Figure 20: Average over the flux through the photocathodes of the PMTs in the two PMT groups as a function of the mean path.

Again, the PMTs 1-4 measure a higher flux than the PMTs 5-8, as expected due to the geometry of the module. Another reason for this is, that the scattering angle is limited to 5° . A light source that emits rays in a cone with a semi-cone angle of 5° in the centre of the front face, would cover slightly more than the entire module. Therefore, rays that scatter closer to the module or with a smaller angle can not reach the PMTs 5-8.

As expected, the average flux rises with smaller mean path values. The reason for this is that with a shorter mean path, more rays scatter and don't pass through the middle of the module without hitting any photocathodes.

5.2 Angular Acceptance Measurement

In this section an angular acceptance measurement was simulated with two beams, one with a wider and one with a narrower semi-cone angle.

5.2.1 Wide Beam

To perform an angular acceptance measurement, a point light source with a semi-cone angle of 5° and a power of 1 W was simulated 10 cm inside the water block over the centre of the front face, pointing towards the back face. At a distance of 3 m from the front face the module was put with the PMTs facing towards the front face. With this setup the photon beam covered a little more than the entire module, as shown in Figure 21.

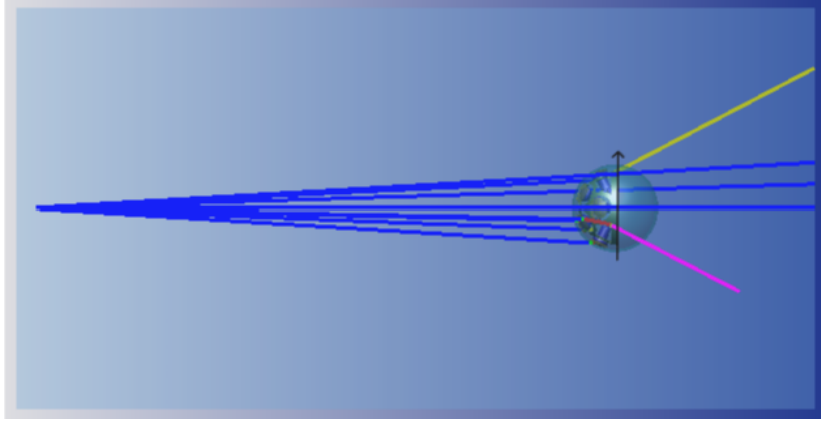


Figure 21: Side view of the light source and the P-OM. The arrow visualises the y-axis. The rays are coloured by segment and cover the entire module. Visualised using [28].

The module was then rotated in 1° steps from 0° to 120° around its y-axis with 10^7 rays simulated for each step. The total flux through the separate photocathodes of the PMTs was then calculated as described in section 4 and plotted over the rotational angle of the module. The resulting plot can be seen in Figure 22.

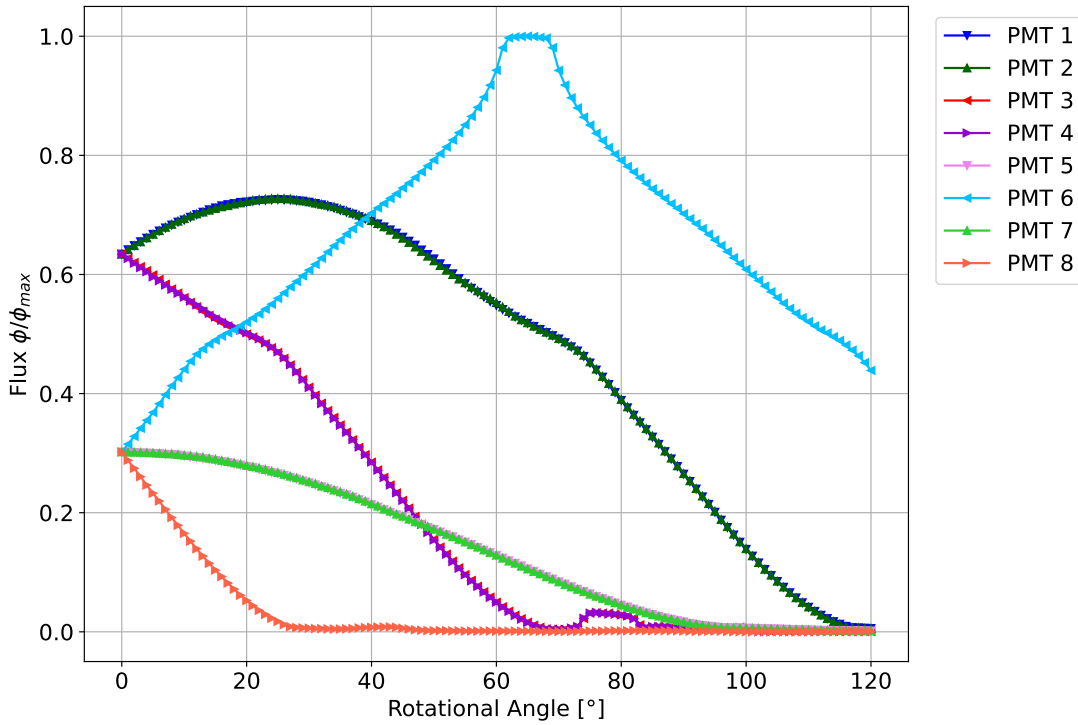
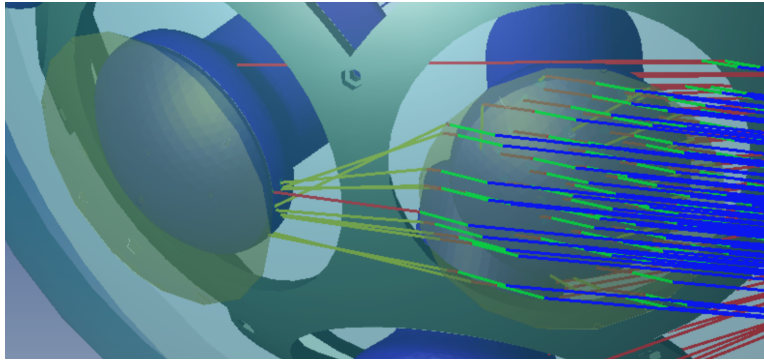


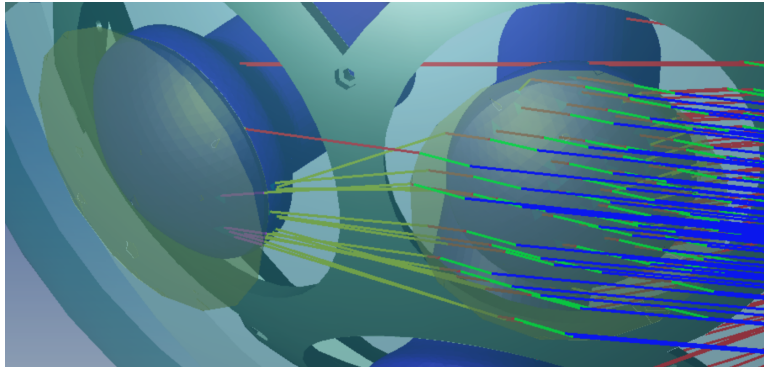
Figure 22: Measured flux through the photocathode of each PMT relative to the highest measured flux plotted over the rotational angle of the module about its y-axis. The maximum of the measured flux is $\phi_{max} \approx 0.35 \text{ W}$. As light source, a point source with a semi-cone angle of 5° was used.

At a rotational angle of 0° the PMTs 1-4 all measure the same flux which is higher than the flux for PMTs 5-8. This is expected, as the light illuminates the module symmetrically and the PMTs 1-4 face the light source. The pairs of PMTs, that have the same x-position (1 & 2, 3 & 4, 5 & 7) have the same angle with respect to the y-axis and thus always measure the same flux. PMTs 1 and 2 first measure a higher flux with increasing rotational angle, as they rotate towards the light and reach a maximum at about 26° . As they are not pointing directly at the light source but up and down at an angle, the maximum flux they measure is smaller than the one PMT 6 measures. At a rotational angle greater than 26° the flux they measure declines until it reaches zero. The curves of the PMTs 1, 2 and 3, 4 are identical but shifted in angle. The reason for this is that the module rotates around its axis of symmetry, so that the PMTs 1 and 2 move over the starting positions of PMTs 3 and 4 and thus measure the same decline of the flux. PMTs 5 and 7 start facing the light source and then rotate away, therefore they measure a decreasing flux with increasing rotational angle. PMT 8 too turns away from the light and measures smaller flux values with higher rotational angles. PMT 6 rotates towards the light source and the flux increases until it flattens. Between about 62° and 68° the flux seems constant. At about 65° PMT 8 points directly towards the light source and should thus measure the greatest flux. One possible explanation for this plateau is total internal reflection in the gel pads. For angles greater than 68° the flux decreases, as the PMT rotates away from the light source.

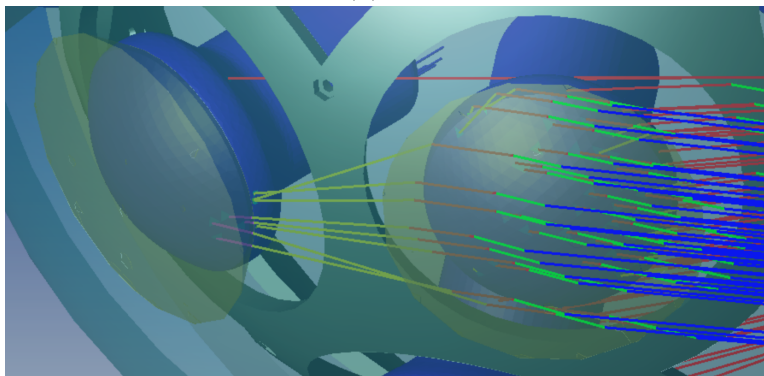
An interesting feature is that PMTs 3 and 4 measure a flux between the rotational angles of 73° and 83° even though they are pointing away from the light source. The reason for this was found using the NSC Shaded Model of Zemax [28] and applying a filter so that only the rays that hit the PMT object are shown. Figure 23 demonstrates that in this range of the rotational angle, some rays that enter the gel pad of PMT 1 do not hit the PMT. Instead they are redirected towards PMT 4, and when entering its gel pad, scattered towards the photocathode, which then registers this flux. For angles outside of this range, this effect does not seem to occur. The effect for PMT 3 is the same, with the rays passing through the gel pad of PMT 2.



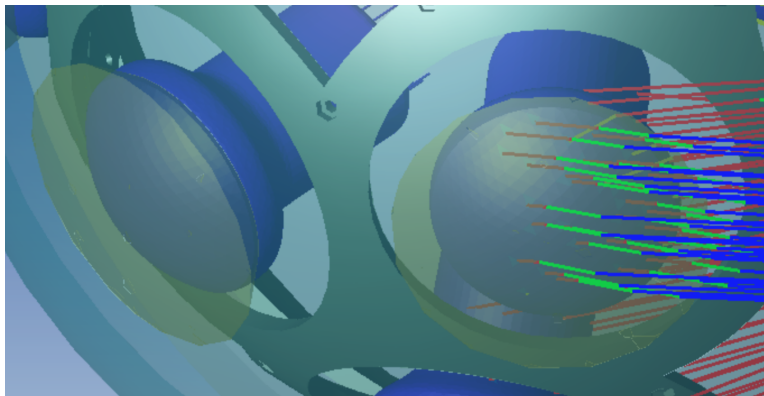
(a) 71°



(b) 75°



(c) 80°



(d) 84°

Figure 23: Visualisation of the effect that leads to the PMTs 3 and 4 measuring flux even though they are turned away from the light source. The rays scatter on the gel pad of PMT 1 (right), enter the gel pad of PMT 4 (left) and hit the photocathode of PMT 4. Rays are coloured by segment and a filter is used to only show rays that hit the PMT object. Visualised using [28].

5.2.2 Narrow Beam

The angular acceptance measurement was repeated with a narrower beam with a semi-cone angle of 3° , so that the PMTs 1-4 were illuminated without rays hitting the PMTs 5-8. The light source was placed at the same position as before, in the centre of the front face. The module was again rotated around its y-axis, this time in 5° steps. The

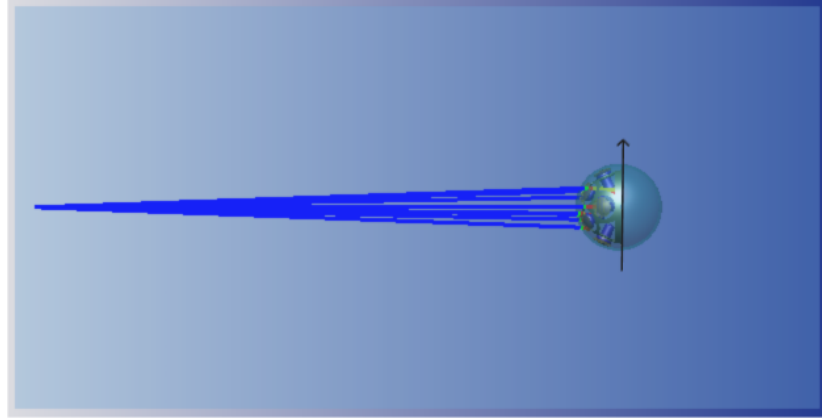


Figure 24: Side view of the light source and the P-OM. The arrow visualises the y-axis. The rays are coloured by segment and cover PMTs 1-4 but not the PMTs 5-8. Visualised using [28].

area from 60° and 70° was measured in 1° steps, to measure out the plateau. Again, 10^7 rays were simulated for each step. The flux through each photocathode was recorded and plotted over the rotational angle, as can be seen in Figure 25. The PMTs in the two PMT groups 1-4 and 5-8 measure the same flux in their starting position. The flux measured by the PMTs 5-8 is significantly lower than in the previous measurement because the narrower beam does hardly illuminate them. The curves behave as in the previous measurement, PMTs 3, 4, 5, 7 and 8 rotate away from the light source and therefore measure a declining flux with rising rotational angle. PMTs 1 and 2 first rotate towards the light source and measure a rising flux and then rotate away and measure a declining flux. PMT 6 rotates towards the light source and measures an increasing flux, until the PMT points directly towards the light source, where the flux reaches a plateau, which is presumably caused by the reflection on the side faces of the gel pad. With a rising rotational angle, the PMT then rotates away from the light source and measures a declining flux.

A notable differences to the measurement with the wider beam is that the slopes of the curves are steeper for the narrower beam. For PMT 6 this occurs in the range 5° to 30° and from 100° on. The reason for this is, that in the range 5° to 30° the PMT rotates into the light cone, and for the angles greater than 100° rotates out of the light cone. This changes the flux stronger than a rotation inside the light cone, which leads to a steeper slope. The same effect of rotating out of the light cone occurs for the PMTs 1 and 2 after about 55° and for the PMTs 3 and 4 after about 10° .

In this measurement, the PMTs 3 and 4 do not measure a flux between about 73° and 83° , because, due to the narrower beam, the PMT 1 already rotates out of the beam and the rays do not get redirected towards PMT 4. This is demonstrated in Figure 26.

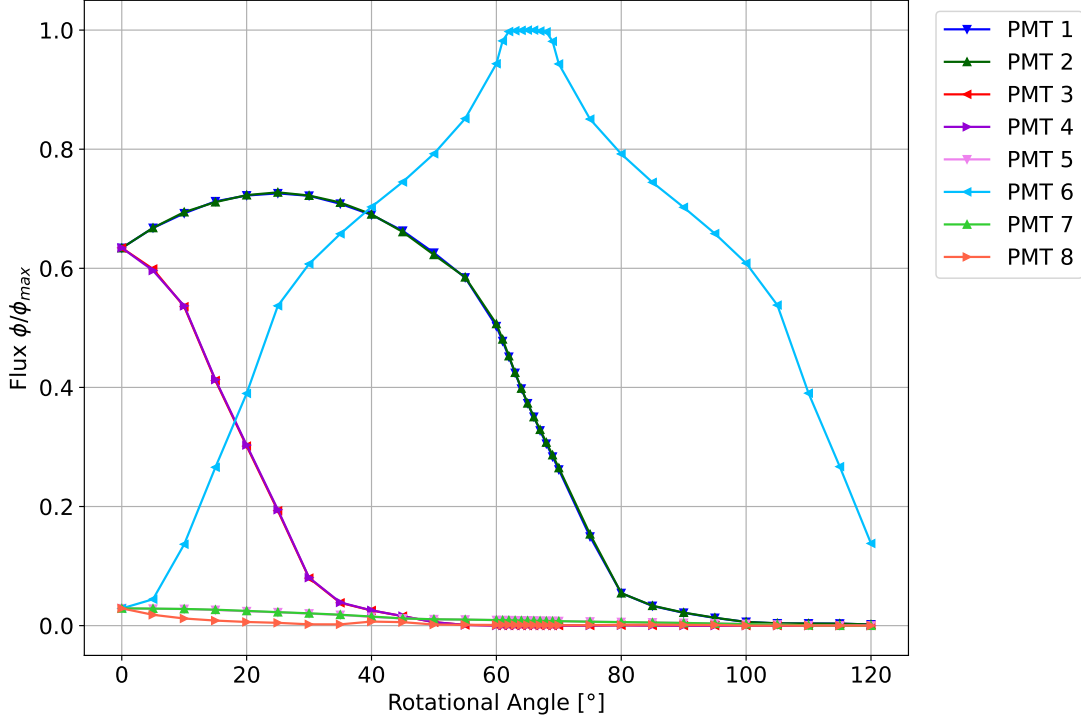


Figure 25: Measured flux through the photocathode of each PMT relative to the greatest measured flux plotted over the rotational angle of the module about its y-axis. The maximum of the measured flux is $\phi_{max} \approx 0.95$ W. A point source with a semi-cone angle of 3° was used as light source.

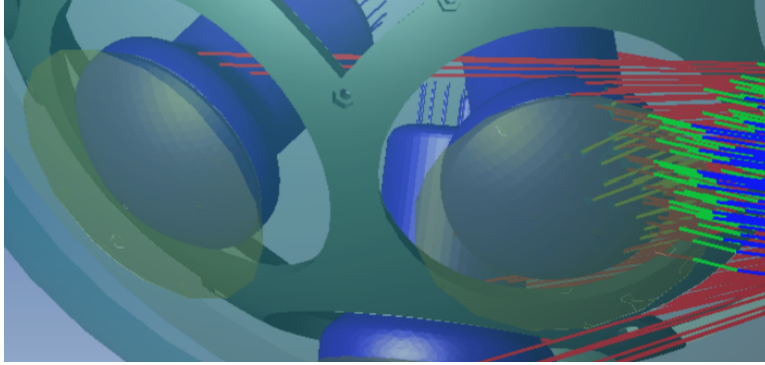


Figure 26: The PMTs 1 (right) and 4 (left) at a rotational angle of 75° . The rays do not cover enough of the gel pad of PMT 1 to leave it on the other side and propagate towards PMT 4. The rays are coloured by segment and a filter is used to only show rays that hit the PMT object. Visualised using [28].

As the wider and the narrower beam both had a power of 1 W, but the narrower beam focussed it on a smaller region, the greatest measured flux $\phi_{max} \approx 0.95$ W is higher for the narrow beam than for the wide beam.

5.3 Individual PMT Analysis

To analyse the distribution of the flux through individual PMTs, heat maps of rows and columns were created of the PMTs 1 and 6. The data used for this analysis stems from the angular acceptance measurement with the wide beam (subsubsection 5.2.1). A point source with a semi-cone angle of 5° was simulated 10 cm over the centre of the front face with the beam pointing towards the back. The module was placed inside of the beam, 3 m over the centre of the front face, as shown in Figure 21. It was then rotated in 1° steps around its y-axis and the flux through each pixel of the PMTs recorded. The heat maps of the rows and columns of the PMTs 1 and 6 were then created, as described in subsubsection 4.2.2.

5.3.1 PMT 1

Figure 27 shows the heat maps of columns and rows through the middle of PMT 1. With greater angles, the flux through PMT 1 decreases as it rotates away from the light source. This matches the curve of PMT 1 in Figure 22.

In both heat maps, areas of higher flux can be observed. To understand these features, the interpolated grid of the photocathode, as shown in Figure 28, was plotted for 5° steps.

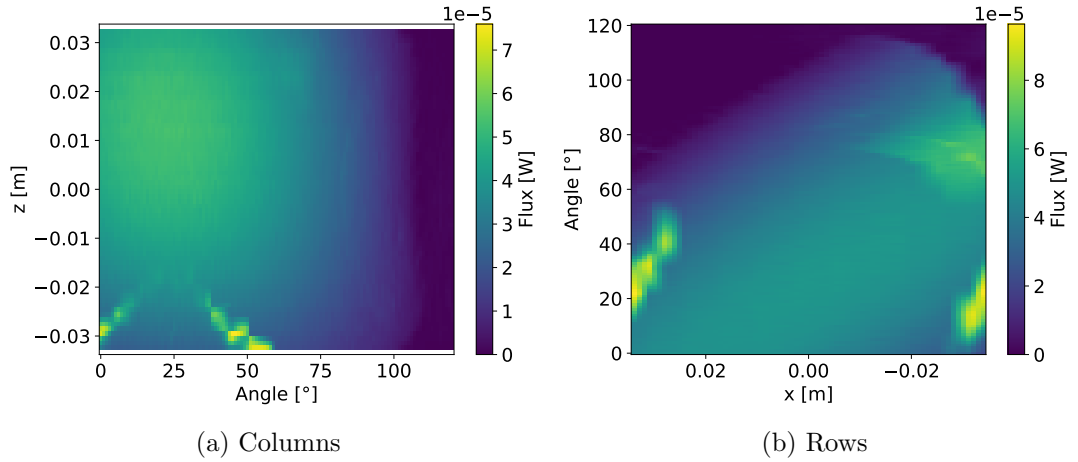


Figure 27: Heat maps of the columns and rows of PMT 1. The coordinates refer to the centre of the photocathode.

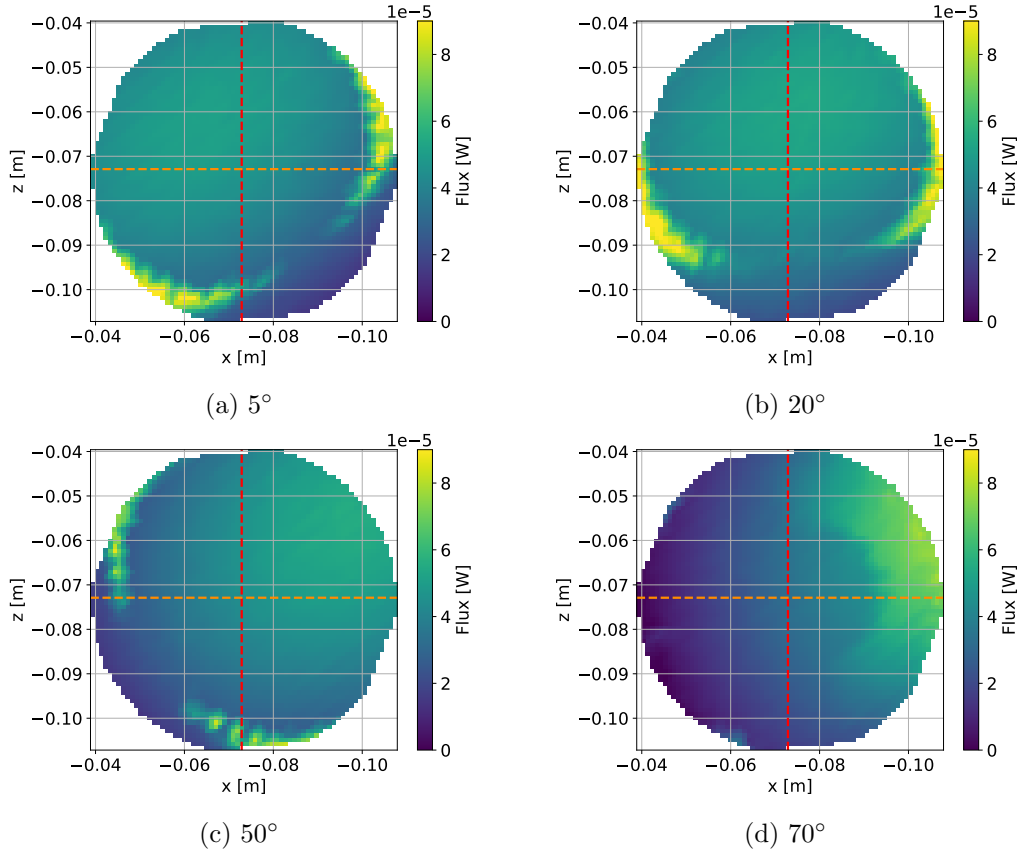


Figure 28: Interpolated grid of the photocathode of PMT 1 for different rotational angles of the module. The coordinates refer to the centre of the module. The red line marks the slice used for the columns heat map and the orange line the slice for the rows. A ring of higher flux caused by the internal reflection in the gel pad is moving over the photocathode.

In Figure 28 a ring of higher flux can be seen moving over the photocathode. The overlap of the ring with the red and orange lines corresponds to the areas of higher flux in the two heat maps. To determine the origin of the ring, the NSC Shaded Model of Zemax was consulted. As shown in Figure 29, rays that enter the gel pad but do not immediately hit the photocathode hit the side face of the gel pad from the inside, where they get reflected back onto the photocathode, which leads to a ring of higher flux.

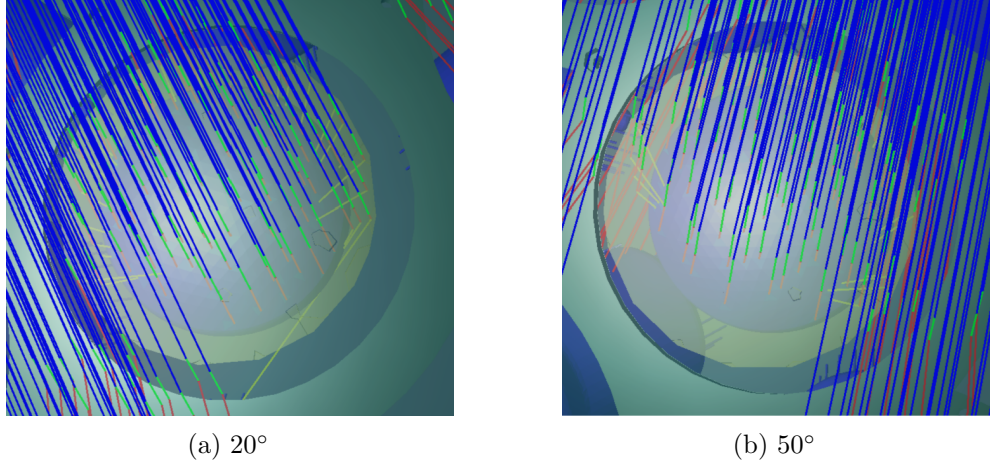


Figure 29: PMT 1 at different rotational angles of the module. Rays hit the side of the gel pad from the inside and get reflected onto the photocathode, causing a ring of higher flux. The rays are coloured by segment and a filter was applied to filter out all rays that did not hit the PMT object. Visualised using [28].

5.3.2 PMT 6

The heat maps of the columns and rows of PMT 6 are shown in Figure 30.

In accordance to the respective curve in Figure 22, the flux through PMT 6 first rises with the angle, until the PMT points directly towards the light source, and then decreases again. Similar to the heat maps PMT 1, areas of higher flux can be seen on the heat maps. Again, the interpolated grid of the photocathode was plotted in 5° steps. Figure 31 shows these interpolated grids. A ring can be seen that moves over the photocathode and corresponds to the areas of higher flux in the heat maps.

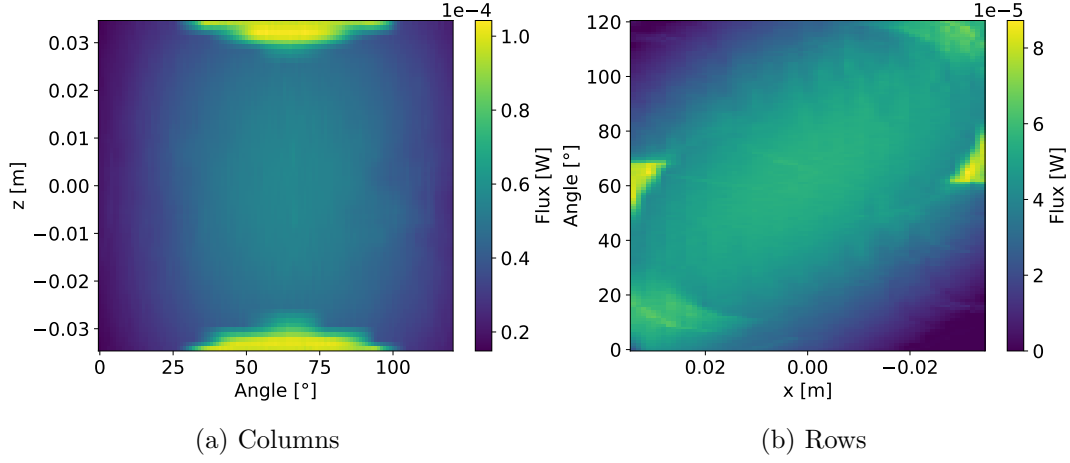


Figure 30: Heat maps of the columns and rows of PMT 6. The coordinates refer to the centre of the photocathode.

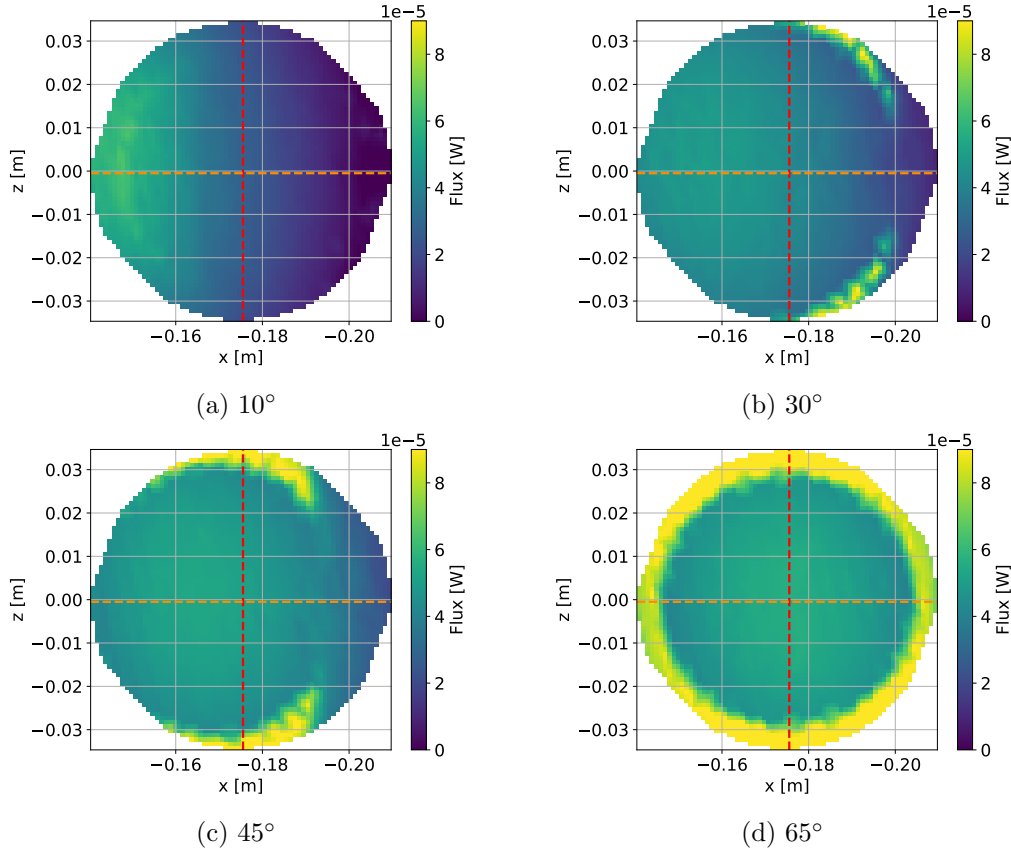


Figure 31: Interpolated grid of the photocathode of PMT 6 for different rotational angles of the module. The coordinates refer to the centre of the module. The red line marks the slice used for the columns heat map and the orange line the slice for the rows. Rings of higher flux are moving over the photocathode.

Analogous to PMT 1, the ring occurs because rays that enter the gel pad of PMT 6 but do not hit the photocathode hit the side face of the gel pad from the inside and get reflected back onto the photocathode. This effect is shown in Figure 32. In Figure 32b, the PMT points approximately towards the light source, therefore rays all around the photocathode can hit the inner face of the gel pad and reflect back onto the photocathode, which causes the ring to enclose the entire photocathode.

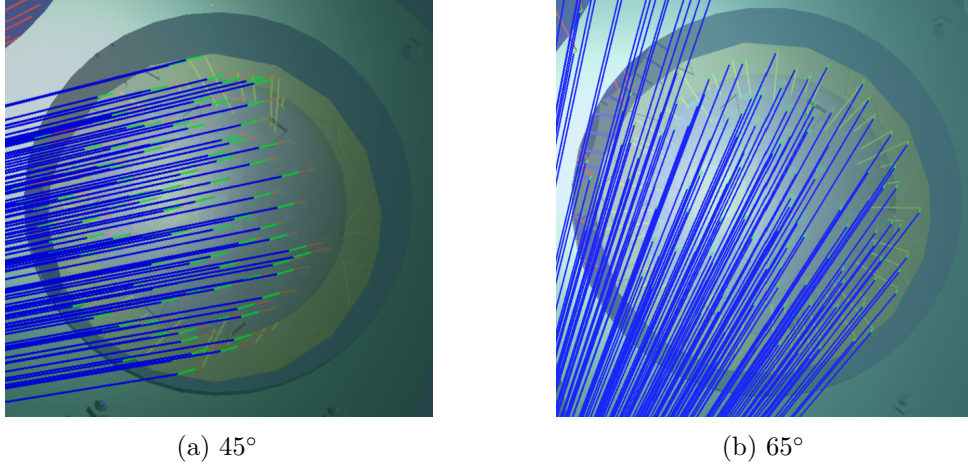


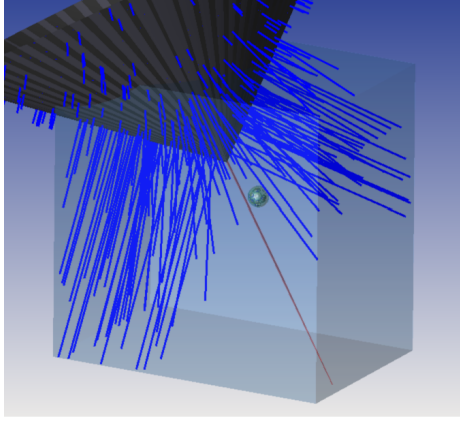
Figure 32: PMT 6 at different rotational angles of the module. Rays hit the side of the gel pad from the inside and get reflected onto the photocathode, causing a ring of higher flux. The rays are coloured by segment and a filter was applied to filter out all rays that did not hit the PMT object. Visualised using [28].

5.4 Muon Simulation

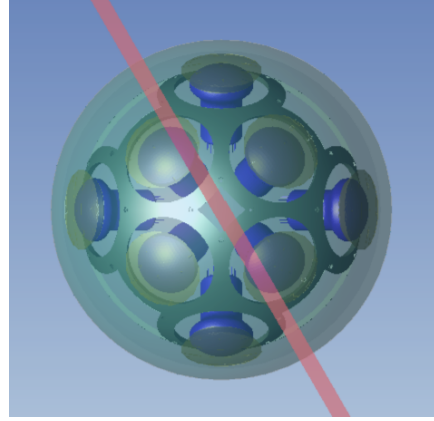
Lastly, a muon passing through the water tank was simulated. This was done by simulating a cone object that emits rays perpendicular to its surface and moves on a line through the water tank. Firstly the angle of the Cherenkov cone was calculated. Notably, the cone object in Zemax uses a different definition of the opening angle θ as the Cherenkov angle θ_C described in subsection 2.2.2, therefore the opening angle is given by

$$\theta = 90^\circ - \theta_C = 90^\circ - \arccos\left(\frac{1}{n\beta}\right) \approx 49^\circ \quad (3)$$

As an approximation, $\beta = 1$ was chosen. For the refractive index $n = 1.32681$ was used, which is the refractive index of water at a wavelength of 550 nm [18] which is the wavelength of the used light source. To be able to start propagating the cone from an adequate distance, the water tank was made wider and now had a width and height of 6 m. A line was created as a reference object to control the path of the cone, as well as to visualise it. Figure 33 shows the water tank with the module, as well as the cone and its path marked by the red line, which was not considered during the simulation. The path of the cone was parallel to the front and back face of the water tank and passed through the water tank 2.5 m away from the front face, therefore having a distance of 0.5 m from the centre of the glass sphere of the module. The path passed over the middle of the module at a downward angle of 30°.



(a) Side view of the setup.



(b) Close-up of the cone path crossing over the module.

Figure 33: The setup for the simulation of the Cherenkov cone of a muon. The cone is emitting rays perpendicular to its surface. Its path is visualised by the red line. Visualised using [28].

The cone was then moved along the path with 0.1 m steps and the flux through the photocathodes recorded and plotted over the position of the cone on its path. When moving the cone from 0.8 m to -1 m the cone moved from the top left to the bottom right of Figure 33a.

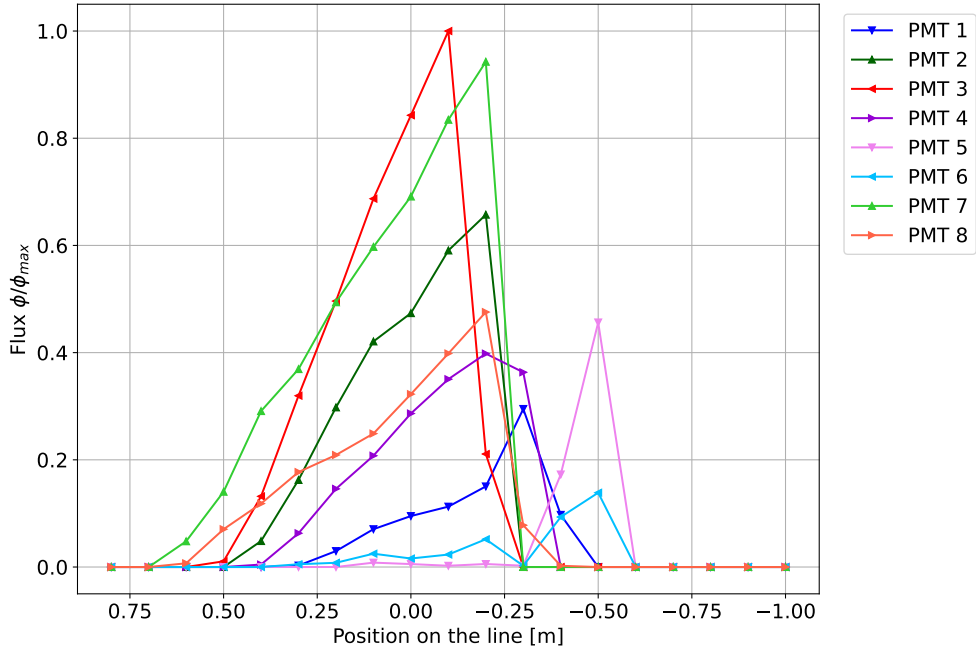


Figure 34: The flux through the photocathode of each PMT plotted over the position of the cone on its path. At the position of 0 m, the peak of the cone is positioned over the middle of the module.

As expected the flux of each PMT rises until the photocathode of the respective PMT

enters the cone, at which point the flux declines rapidly and reaches zero when the cathode is completely inside the cone. The exception from this are the PMTs 5 and 6 which measure almost no flux until the cone has propagated far enough for other PMTs to be inside the cone. Reason for this is, that the PMTs are in the geometrical shadow of the module until the cone is next to them.

6 Conclusion

In this thesis, a model of a water tank, as well as one hemisphere of the **P-ONE Optical Module (P-OM)** have been simulated in Ansys Zemax OpticStudio 2026 R1.00 (Zemax) and analysed in various measurements. These measurements comprised an analysis of the flux measured by PMT groups for different scattering properties of the water, an analysis of the flux through the PMTs angular acceptance measurement carried out for two different light sources, as well as an analysis of the distribution of the flux through two single PMTs. Additionally, the Cherenkov radiation of a muon passing through the water tank was simulated and the PMT signal analysed.

The analysis begins with a description of the simulated setup, such as the properties of the simulated water, as well as the light sources used in this thesis. The control and effect of the reflectivity of the water tank side faces are illustrated, and the effects of a variation of the parameters of the scattering model used in this thesis was analysed. In addition, the import of the module and setting of the materials of its components is recounted.

Following the description of the setup, the Python script used to analyse the data of the measurements is explained. The pixels of the photocathodes have been defined by considering their radius and the PMTs separated by their position in the x-z plane. The photocathode point clouds have been rotated and mapped in order to create heat maps of the flux through the rows and columns of the photocathodes.

Subsequently, the data acquired during the measurements was investigated. The flux through the PMTs for different scattering properties of the water behaves in accordance with expectations and rises with decreasing scattering angles and mean paths. An angular acceptance measurement with a larger beam was carried out, and the flux through the PMTs recorded, plotted, and the resulting curves explained. The detection of photons that enter a gel pad but miss the respective PMTs by adjacent PMTs could be verified during this step. A repetition of this measurement with a narrower beam showed steeper slopes of the curves for PMTs rotating in and out of the beam. The heat maps derived from the flux through the rows and columns of two individual PMTs showed features of higher flux, which corresponded to rings of higher flux on the interpolated grid of the photocathodes. The origin of these rings was found to be the internal reflection at the side faces of the gel pads. Lastly, the event of a muon passing through the water in front of the module and causing Cherenkov radiation was simulated. The flux through the PMT photocathodes rose as the muon moved closer until the photocathodes entered the cone, where the flux dropped with a steep slope.

In summary, the flux through the photocathodes of the PMTs was recorded and analysed for different water properties, light sources, and angles. While not all features of the obtained curves could be explained yet, the general behaviour of the flux was in accordance with expectations. Additionally, an insight into the distribution of the flux through the photocathodes could be gained. In further studies of the **P-ONE Optical Module (P-OM)**, a real-life equivalent of the measurements carried out in this thesis might provide a better understanding of the PMT response as well as of the effect of real water and its impurities.

Acronyms

CAD computer-aided design.

KM3NeT Cubic Kilometre Neutrino Telescope.

P-OM P-ONE Optical Module.

P-OMs P-ONE Optical Modules.

P-ONE Pacific Ocean Neutrino Experiment.

PMT Photo Multiplier Tube.

PMTs Photo Multiplier Tubes.

Python Python 3.14.5.

Zemax Ansys Zemax OpticStudio 2026 R1.00.

A Appendix A: Flux through Individual Pixels

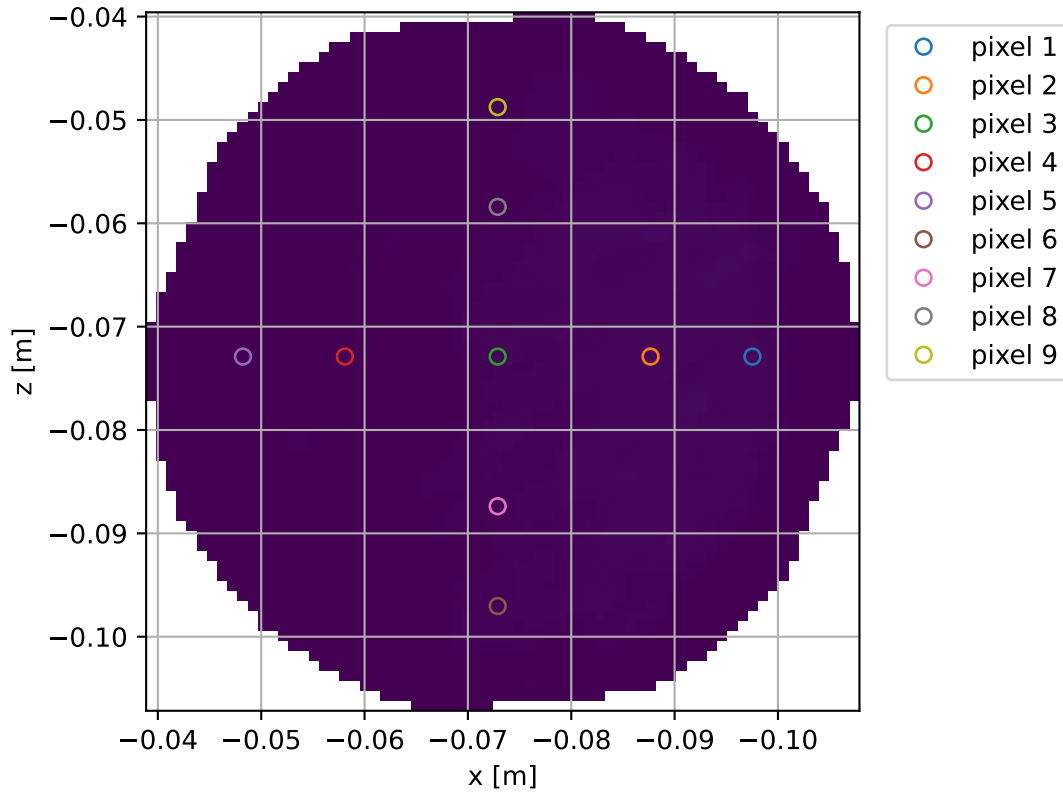


Figure 35: Front view of the interpolated grid of the photocathode with the position of the individual pixels marked with circles.

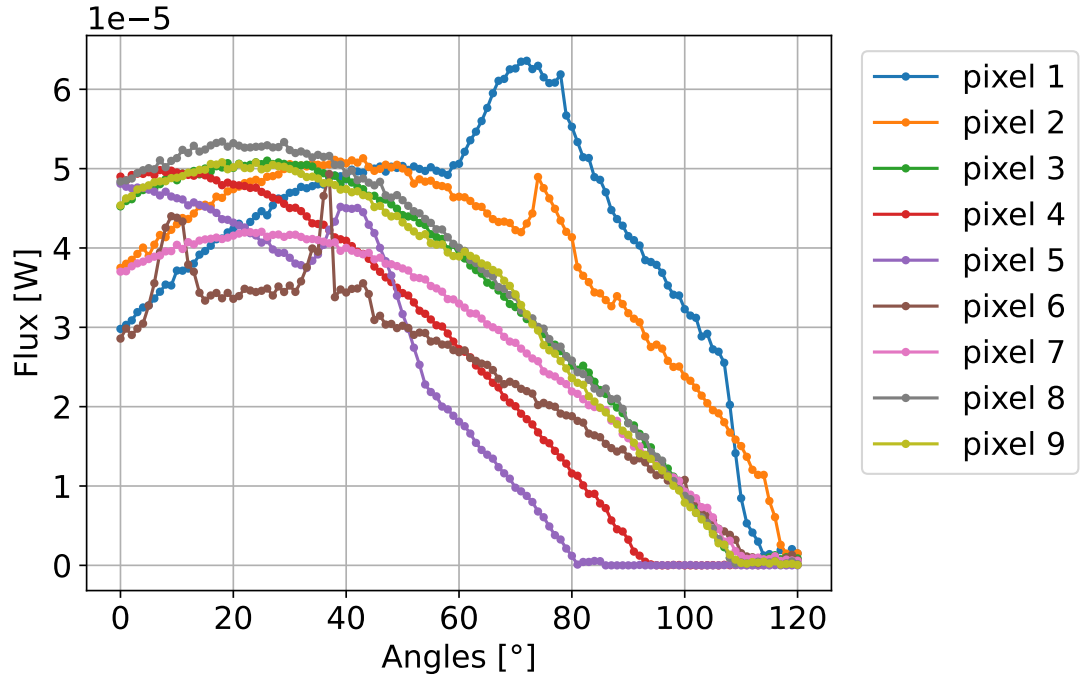


Figure 36: The Flux through the chosen pixels on the photocathode of PMT 1 plotted over the rotational angle of the module. As light source a point source with a semi-cone angle of 5° was used.

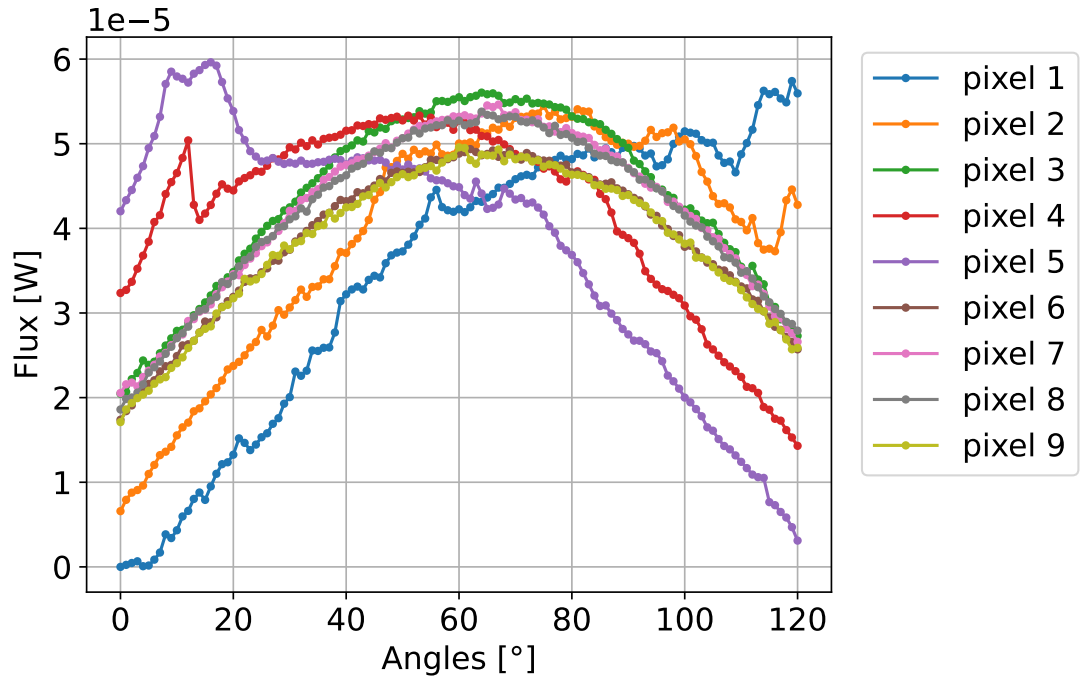


Figure 37: The Flux through the chosen pixels on the photocathode of PMT 6 plotted over the rotational angle of the module. As light source a point source with a semi-cone angle of 5° was used.

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I, Sarah Bräuer, student registration number: 23314114, hereby confirm that I completed the submitted work independently and without the unauthorized assistance of third parties and without the use of undisclosed and, in particular, unauthorized aids. This work has not been previously submitted in its current form or in a similar form to any other examination authorities and has not been accepted as part of an examination by any other examination authority.

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In this thesis, AI was used for the following purposes: Aid and debugging of my own Python and LaTeX code, and Zemax configuration; the search of scientific sources for specific information; translation of individual words from German to English where necessary; and grammar suggestions of the internal AI provided by Overleaf. All AI paraphrased content or provided information and sources were carefully reviewed.

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