Estimation of water properties in deep sea - Light pollution due to artificial light sources.

Scientific Watch - Project Report

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Abstract
In this project, we studied the counting rate of photons seen by the KM3NeT PMTs (Photomultiplier tubes) by artificial light sources with different setups. Taking into account only one scattering by the photons, some previous calculations of the counting rates were reproduced calculating probabilities of photons arriving to the PMT given different setups. Considerations for future implementations of multiple scattering or Monte Carlo simulations were also commented.

1 Introduction

The KM3NeT neutrino telescope in under construction at a depth of 2500m in the Mediterranean Sea. The detector works by measuring the neutrino interactions in the water, these interactions produce Cherenkov light which will be gathered by the PMTs in the detector [1]. As the detector mainly works with light from this effect, the light absorption and diffusion along water must be characterized properly to produce high precision measurements and good quality reconstruction of the original neutrino interactions in the water.

Some general theory of light scattering in water has been studied in different branches of physics [5] [4][6], these knowledge has been previously applied by the KM3NeT collaboration for previous simulations [1][2] on deep sea light scattering. As the PMTs used by the telescope are very sensible, some background noise is detected due to natural bioluminescence and radioactive isotopes, also the sea-floor where the detectors are located is not regularly shaped, this gives the detector some particular environment not characterized by previous general studies. Therefore, some data must be acquired with known light sources in order to calibrate the simulation parameters to have a better understanding of the environment properties.

2 Theoretical framework

As a start for this project the general topic to be developed corresponds to photon propagation, photon propagation in a medium is mediated by some optical parameters such as the absorption length λ_{abs}, the group velocity of light in the medium v_g and the volume scattering function $\beta(\theta)$ with units $m^{-1}sr^{-1}$. The scattering function is in general described by the scattering length λ_{sca} and the average cosine of the scattering angle distribution (which is also called the asymmetry parameter in the mie scattering theory [3]) $\langle\cos\theta\rangle$, assuming a determined shape for the scattering angle distribution.

The scattering angle distribution for our case is selected by taking only the molecular scattering also called the Rayleigh scattering, and ignoring the particular scattering on the first hand[5]. This type of scattering can be described analitically in terms of its wavelength dependency

$$L_{sca}(\lambda) = \left(\frac{\lambda}{550nm}\right)^{4.32} 667m, \tag{1}$$

as well as its angular probability profile

$$\frac{dp_{sca}}{d\Omega}(\beta) = \frac{1}{4\pi}\frac{3}{3+b}(1 + b\cos^2\beta), \tag{2}$$

with $b = 0.835$ being a factor attributable to the anisotropy of the water molecules and β the scattering angle.

As the idea here is to understand the photon counts on the PMTs due to artificial light sources, some calibration relating the light sources and the detection must be made. To obtain the photon counting rate at the PMTs, the flux unit lumen (lm) needs to be converted into photons. At a wavelength of $555nm$ 1 lm corresponds to $C_0 = 4.11 * 10^{15}$ photons per second. For other wavelengths the sensitivity of the human eye is needed for the conversion from lumen to photons per second. To simplify this conversion, some approximate conversion factors C_l are used, shown in Table 1.

Wavelength	<450nm	450nm	500nm	550nm	600nm	650nm
C_l	20	20	2	1	2	20

Table 1: Conversion factors form lumen (lm) to photon count according to human eye sensitivity.

Here the values far from 550nm have a conversion of 20 as a 20 times larger number of photons are needed to obtain the same luminosity (lm) compared to 550nm.

3 PMT and water parameters

Some extra parameters that need to be considered relate to how photons propagate though the sea water, here the absorption and scattering effects must be taken into account. The molecular scattering in terms of its wavelength dependency and angular probability profile were already considered by Equations (1) and (2) respectively.

In Figure 1 the top left and right subfigures illustrate the behavior of the water absorption length and the water scattering length as a function of the wavelength measured respectively. The water absorption length data is calculated according to the measured data of the PMTs while the scattering length is the one given by Equation (2). Some more parameters are necessary such as the ones of the photons arriving to the optical modules with the PMTs, the PMT efficiency as viewed with absorption effects in gel and glass (bottom-left) and also the PMT angular acceptance as they are used in the general KM3NeT simulations.

4 Results for different setups

As the detector is located in the sea floor, several obstacles such as artificial reefs are present when the light travels and scatters in the sea bottom, this accounts to the necessity to model different scenarios of light sources coming to the detector. Three scenarios are attempted to reproduce in this work, following some previous calculations on the topic. Figure 2 illustrates the setups considered in the analysis. On Setup a) the light source at position L emits light as a uni-directional source (such as in the case of a laser) in direction $\overrightarrow{LS}$ away from the source in general, this setup is made to provide a lower limit of the light pollution. The calculation will consider at position S a Rayleigh scattering process occurs with scattering angle $\pi - \beta$. The distance from the light source until the scattering process $s = |\overrightarrow{LS}|$ is considered to vary in small steps from 0 to 500m and each contribution is summed up. The position for the PMT P looks at the light source at a distance $d = \overrightarrow{LP}$ and an angle δ with respect to the light emission direction. The light will then travel a distance $s+x$ from source until arrival to the PMT with $x = \overrightarrow{SP}$ at an angle of α with respect to the inverse PMT axis.

Now the differential probability of a scattering process to occur at point S is given by

$$\frac{dP_{sca}}{ds}(\lambda, s) = \frac{e^{-s/L_{sca}(\lambda)}}{L_{sca}(\lambda)}, \tag{3}$$

with $L_{sca}(\lambda)$ the Rayleigh scattering length and the probability for a photon to arrive unabsorbed at the PMT after a distance $s + x$ is given by the exponential distribution

$$P_{abs}(\lambda, s + x) = e^{-(s+x)/L_{abs}(\lambda)}, \tag{4}$$

with $L_{abs}(\lambda)$ the absorption length. Now the photon rate R at the PMT can be written as an integral with the contribution of the probabilities of all the processes previously mentioned as

$$R(\lambda, d, \delta) = \Phi_0(\lambda) QE_{PMT}(\lambda) \int_0^{\inf\approx 500} ds P_{abs}(\lambda, s + x) \frac{dP_{sca}}{ds}(\lambda, s) P_{PMT}(\alpha) \frac{dp_{sca}}{d\Omega}(\beta) \frac{A_{PMT}}{x^2} \tag{5}$$

where $\Phi_0(\lambda) = L_0 C_0 C_l(\lambda)$ is the total photon flux of a source with L_0 lumen (lm). The last term on the right hand side considers the angular size of the PMT as seen from the scattering point S with $A_{PMT} = 45.36cm^2$ from the KM3NeT simulations. The Equation (5) is very versatile as it allows to calculate the photon PMT rates for different wavelengths, distances to the source and angular arrangements. This integral is calculated numerically using the parameters previously stated.

For Figure 3, the different rates are computed for a fixed wavelength source of $500nm$ as a function of the location of the PMT facing the light source, the different curves correspond to different distances d of the PMT from the source. This Figure shows a weak dependency on the angle δ specially in the back part of the hemisphere $0 < \delta < \pi/2$, which corresponds to the mostly uniform isotropic angular profile of the Rayleigh scattering.

To improve the initial considerations, setup b) deals with multidirectional light emission on half an hemisphere i.e. with an angular space of $0 < \delta < \pi/2$, here the PMT location will now be fixed behind the light source. For this setup, a replacing of Φ_0 by an angular differential probability $d\Phi/d\Omega$ and including an extra angular integration over the emission directions must be done in Equation (5). The results are very similar as for the ones in setup a), they are shown on the left hand side of Figure 4.

Now setup c) can be treated fairly easily as Equation 5 simplifies by not including a scattering probability as it is included in the emission profile. For this setup the light emission is considered to be isotropic in 4π. The motivation of this setup is the general properties of observation of a light source, that at large distances the light profile of sources approaches to an isotropic source due to scattering and reflection. The result of these simplifications gives

$$R(\lambda, d) = \Phi_0(\lambda) QE_{PMT}(\lambda) P_{abs}(\lambda, d) P_{PMT}(0) \frac{A_{PMT}}{4\pi d^2}, \tag{6}$$

the calculations of this setup are shown on the right hand side of Figure 4.

These calculations allow to understand preliminary the count rates on each PMT detector for different light sources allowing to have a better understanding of the saturation of the detector when real sources are used. For the particular conditions of the experiment, these artificial light sources have to be compared with the natural background light pollution levels in the deep sea. The decays of the radiactive isotope ^{40}K are seen by the PMTs with a rate of about $6kHz$ as a usual background noise. Therefore, for the different wavelengths calculated, the distance at which the photon counts are over the background radiation can be read from the figures. This initial data allows to plan the distance at which different wavelengths should be used for the detector to measure from the artificial light sources in order to not saturate the detector with the incoming source.

A next step into the framework used here will be to include multiple scattering effects, for this to be effective, a more detailed azimuth integration must be taken into account (different from this initial stage where there is an azimuth angle invariance on the count rates). This could be done by doing another bibliographic revision on different ray-tracing research articles on the domain of visual arts, as these calculations are often used in realistic image rendering. These multiple scattering can also be combined with a more general theory of particle scattering which is the Mie scattering theory, which corresponds to the generalization of the angular probability profile compared with the near isotropic approach of the Rayleigh theory.

Another step will be to include single photon propagation using Monte Carlo simulations, which may be compared with the integral approach. With these two tools, some free parameters may be used to calibrate the results using real data taken from submarine campaigns with artificial light sources.

5 Conclusion

These preliminary calculations are in agreement with the ones previously done by Dr. Jürgen Brunner inside the KM3NeT collaboration. The calculations reproduced in this project were initially used as a reference for real submarine campaigns in the water to gather data and for future analysis and parameter estimations. The future steps of this project will try to include the rates taking into account multiple scattering effects and some Monte Carlo simulations for individual photons.

References

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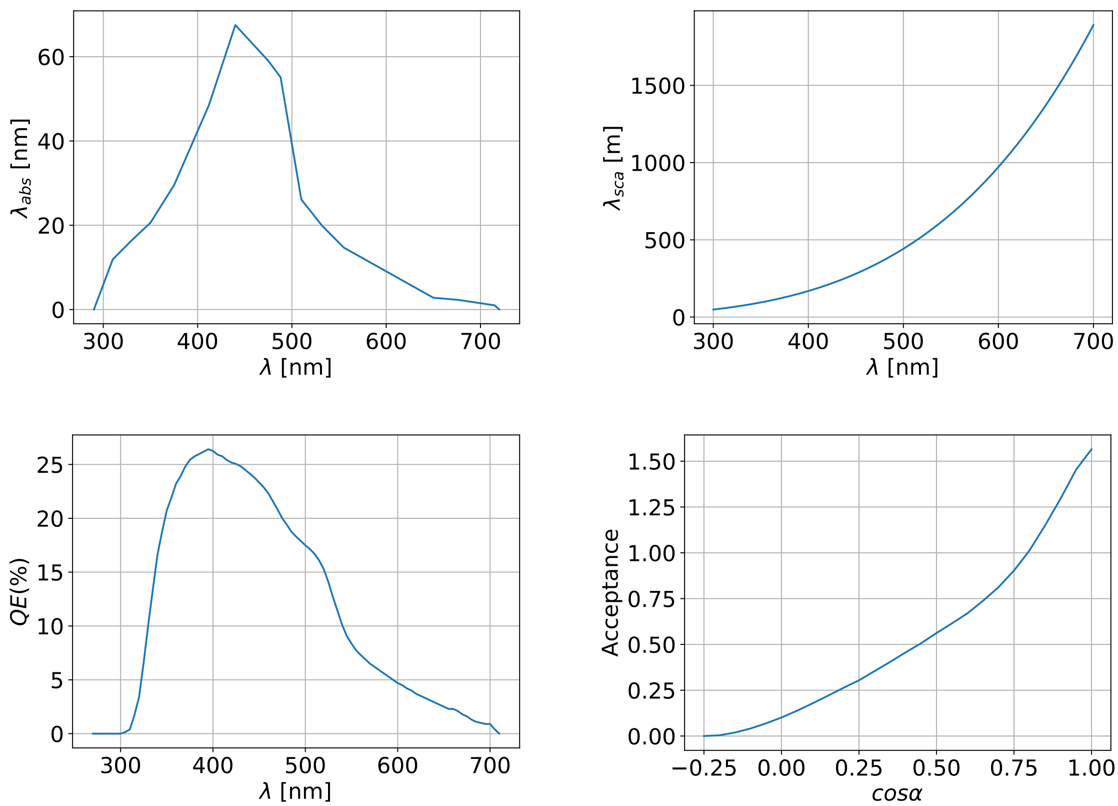

Figure 1: Wavelength dependency of absorption length $L_{abs}(\lambda)$ (top-left), Rayleigh scattering length $L_{sca}(\lambda)$ (top-right) of sea water as used in KM3NeT simulations, wavelength dependency of PMT quantum efficiency $QE_{PMT}(\lambda)$(bottom-left) and PMT angular acceptance $P_{PMT}(\alpha)$(bottom-right) as used in KM3NeT simulations.

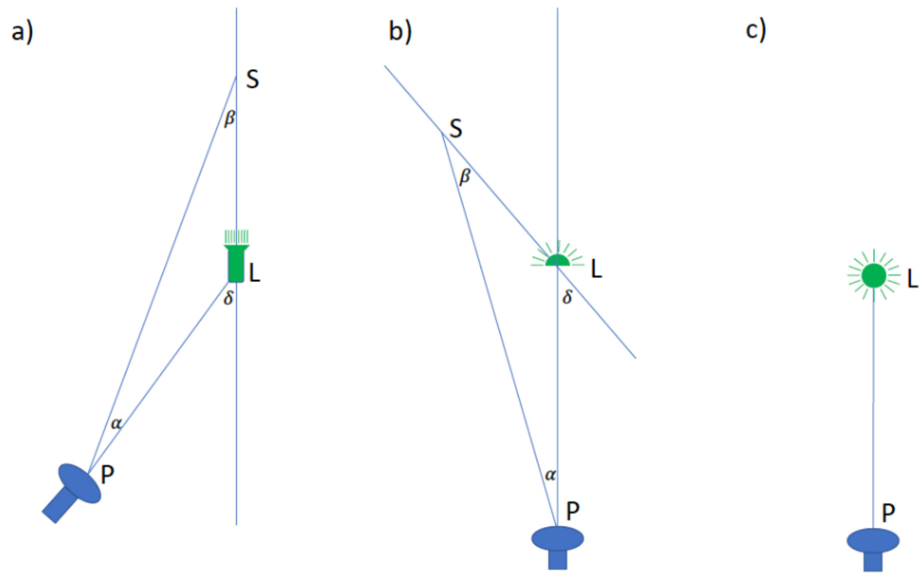

Figure 2: Different setups simulated.

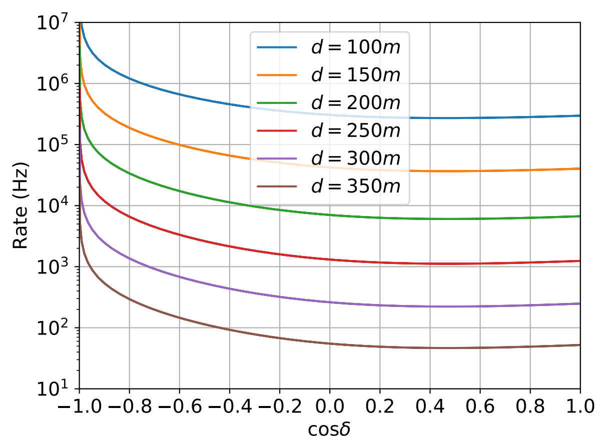

Figure 3: Photon rate at a KM3NeT PMT for a uni-directional light source of $500nm$ and 1 lumen as a function of the angle δ between the PMT axis and the light emission direction for different distances d of the PMT to the light source.

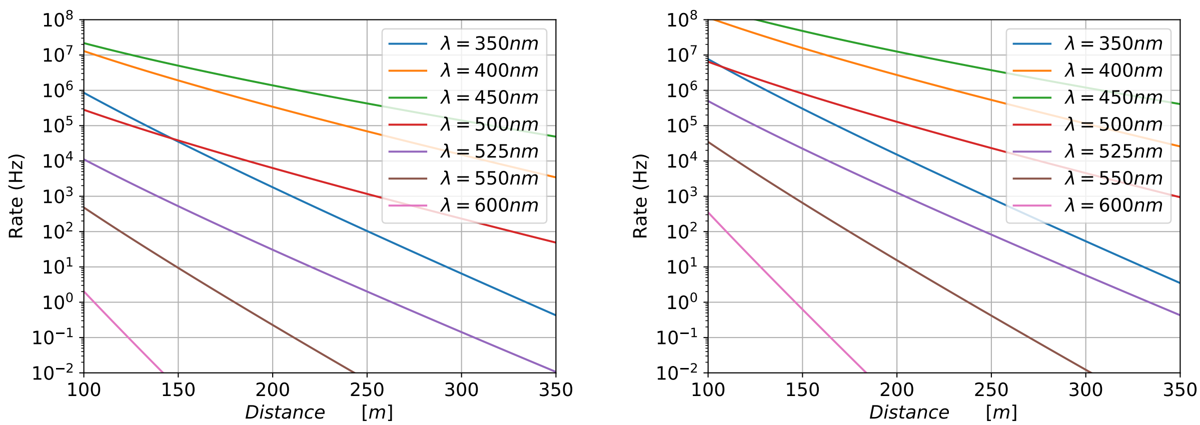

Figure 4: Photon rate at a KM3NeT PMT for 1 lumen light sources of different wavelengths as function of the distance between PMT and the light source. Left: Setup b) with light emission into the hemisphere opposite to the PMT, Right: setup c) with isotropic light emission.