FAST METHOD FOR SIMULATION OF PHOTON PROPAGATION FOR LARGE-SCALE UNDERWATER NEUTRINO CHERENKOV TELESCOPES*

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Large-scale neutrino telescopes, such as Baikal-GVD or ORCA, require calibration and testing of the optical modules. The calibration methods typically use laser and LED-based systems to test the telescope's response to light. These systems are also used in monitoring the optical parameters of water which has strong seasonal variation. The high-energy laser is an intense light source that can damage the optical modules. In the present work, an efficient and fast simulation has been developed for light propagation in a medium. The parameters of the light source such as its wavelength/energy, intensity, and direction as well as the properties of the medium such as its absorption and scattering lengths are used as inputs to the simulation. This simulation can be used in the optimization of the parameters of an intense light source like laser such that the optical modules are not damaged. In this paper, the simulation technique is presented and the results obtained using this approach are compared with the output of Geant4 simulations.

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1. Introduction

The deep underwater neutrino telescopes such as Baikal-GVD or ORCA use the same neutrino detection principle, *i.e.* detecting Cherenkov light from secondary particles produced in neutrino interactions. These experiments are designed as an array of optical modules arranged on vertical strings to form a 3D lattice in a transparent medium. The time and intensities of these Cherenkov light pulses are measured by these optical modules.

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The simulation of light propagation is a very important part of the simulation chain used in the studies of these telescopes. There is a need for fast and precise methods to calculate photons propagation in a medium for these experiments as the detailed simulations can take a very long time and need extensive computational resources. The method described in the present work is a compromise between optimal time efficiency and the precision required in photon propagation. This environment for photon propagation developed by using a combination of Forward and Backward RT techniques is named *Pretorian*. The environment is so named as the key motivation to develop it was to protect optical detectors from getting damaged while using high-intensity laser for calibration. Hence, one of the goals of this work is to identify safe operation parameters such as wavelength/energy, intensity, direction, *etc.* for the laser beam used in the calibration of optical modules.

2. Absorption, scattering and attenuation

The decrease in the total number of photons in a particular direction from the source is mainly due to the two main interactions in the medium — absorption and scattering. In the process of scattering, the direction of photons is changed, whereas in absorption, the particle is absorbed into the medium. The number of photons in a particular direction from the source can be described by $\frac{N}{N_0} = \mathrm{e}^{-x/L}$, where x is a distance, N_0 is a total number of emitted photons from the source, N is a number of observed photons, and L is the distance in meters where the number of photons will be decreased e-fold [1]. The influence of absorption, scattering, and the resultant attenuation in the number of photons as a function of distance to source in a particular direction is shown in Fig. 1.

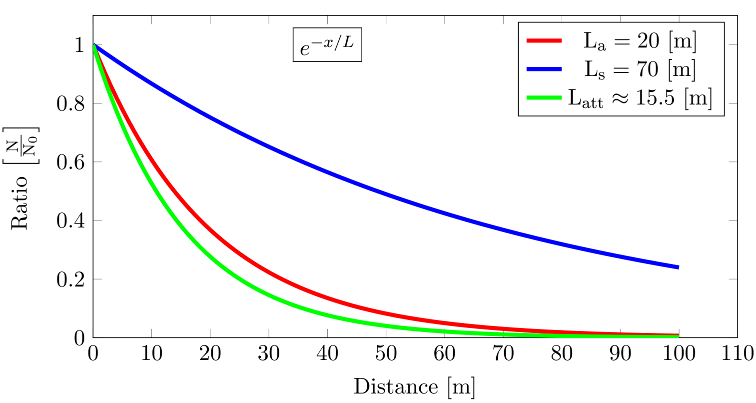

Fig. 1. The decrease in the number of observed photons as a function of distance.

3. Ray Tracing

The simulation of light propagation can be approximated as propagation of particles in a medium with the interactions of scattering and absorption. For calculation of the effects of particle transport, the *Forward* and *Backward* Ray Tracing (RT) techniques are implemented in the simulation.

In the case of the Forward RT (Fig. 2, top), the photons are sent from the source in a particular direction (called a 'ray') and can interact with the medium. The detection of photon is defined as the intersection of the ray with the object or detector defined in the simulation. In Forward RT, the length of each step taken by the photon is determined by the attenuation coefficient. At the end of the step, the direction vector of the photon is changed using the ratio of probabilities of scattering and absorption. The end of each step is identified as a *scattering point*. This is a very inefficient method especially for underwater neutrino telescopes as the fraction of photons which escape the detectors is high, but it is very accurate in estimating of the number of photons which are detected.

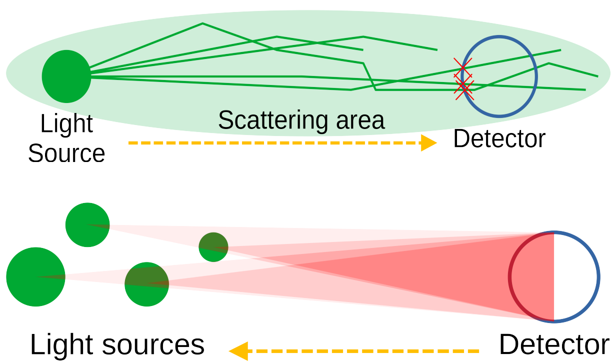

Fig. 2. Forward and Backward RT. Top: in the Forward Ray Tracing rays can be single or a bunch of particles (photons) emitted from light source. Bottom: the area subtended by the detector back to the source in Backward RT.

In the Backward RT (Fig. 2, bottom), the ray is traced from the detector through all the scattering points back to the source. This method is much faster than the Forward RT, but the knowledge of the exact mapping of scattering points and interactions at these points, such as absorption and scattering, is required.

In this work, a method which uses a combination of Forward and Backward RT, named the *Hybrid* method, is described. In the method, the Forward RT is used for propagating the photon from the source and the scattering points are computed considering the parameters of light emission and the scattering function. In the next steps, these scattering points are considered as new light sources and the method is repeated. The Henyey–Greenstein function [2] is used for calculating the probabilities of scattering in this method. These scattering points or new light sources are then used for the Backward RT calculations. In this approach, only the most probable scattering points are used in the photon propagation, which helps in making these computations faster. The effects of absorption by the medium and the detectors are included during photon propagation. This method is demonstrated in Fig. 3.

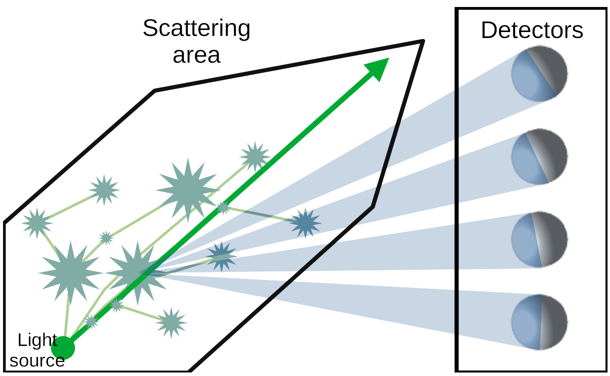

Fig. 3. Hybrid method allows photon detection by direct hits from the Forward RT, and from scattering points using the Backward RT method.

4. Simulation

In the simulation, the detectors are represented as spheres of radius of 25.4 cm located at fixed points in the medium. The detectors are assumed to have uniform angular acceptance and 100% detection efficiency for the purposes of the simulation here although the real detector properties such as angular acceptance, photon detection efficiency can be added to make the simulation more realistic. The Hybrid method is tested with two example geometries of detectors and the results of the method are presented here.

The *inline* geometry is shown in Fig. 4, left. In this geometry, the spherical detectors are positioned along a straight line with a distance of 15 m separating them. For this geometry, a monochromatic collimated laser beam pointing parallel to the straight line is considered which is positioned 1 m away from the line of detectors and 15 m below the bottom-most detector. The inline geometry considered here is identical to the position of detectors in underwater/under-ice neutrino telescopes. The *spherical* geometry, where the detectors are spread at a fixed distance from the source is shown in Fig. 4, right. In this geometry, an isotropic monochromatic source of light is con-

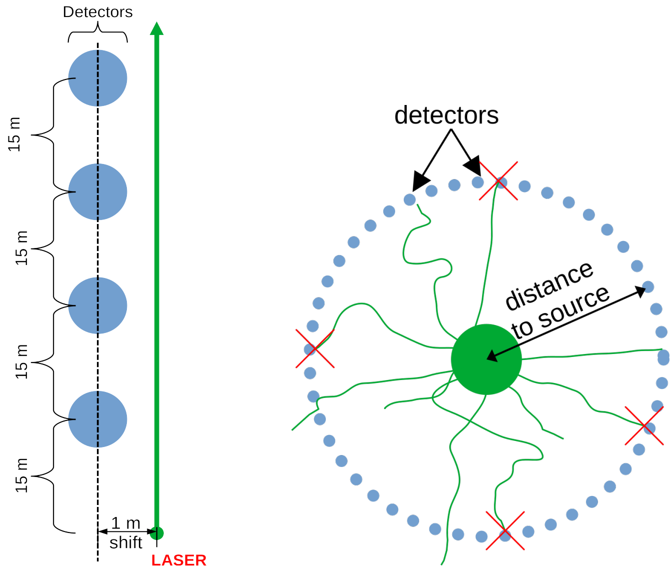

Fig. 4. Simulation geometries used in this paper. Left: Inline geometry of detectors for collimated laser beam simulations (part of a telescope). Right: Spherical geometry for isotropic source simulations.

sidered to generate the photons. Also, identical geometries are constructed for another simulation made using Geant4 framework [3], to compare the results of the Hybrid method. In both the Geant4 and Pretorian simulations, the number of photons detected by the detector in the interval of 5 ns is recorded.

5. Results

In Figs. 5 and 6, the results of the simulation for inline geometry are presented. The results are in the form of a two-dimensional map, where the X-axis represents the arrival time of photons, the Y-axis represents the vertical distance between the detector and source, and the Z-axis represented the ratio of a number of photons detected to the total number of photons simulated at the light source. The horizontal bands observed in these figures correspond to the time profile of photons detected in the individual detectors at different distances. For results represented in Fig. 5, only the RT technique for photon propagation is activated during the simulation. Hence, the detected photons are mainly due to the photons directly reaching the detector during the Forward RT. For the results shown in Fig. 6, the Hybrid method is used for the simulation. It is clearly demonstrated that the better estimation of the number of photons detected is obtained using the

Hybrid method. The reason for the ratio of detected photons on the Z-axis, showing values as low as 10^{-16} in Fig. 6, is due to the fact that the Hybrid method allows for detection of scattered photons from scattering points by considering them as new sources of light.

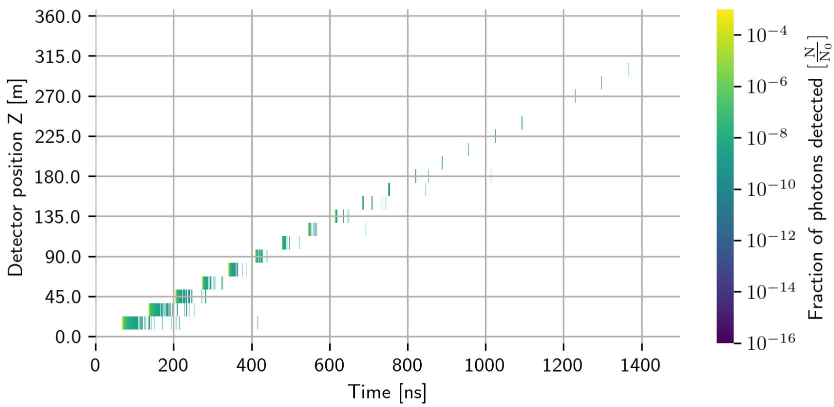

Fig. 5. Time histogram from the Pretorian RT method simulation results for inline geometry.

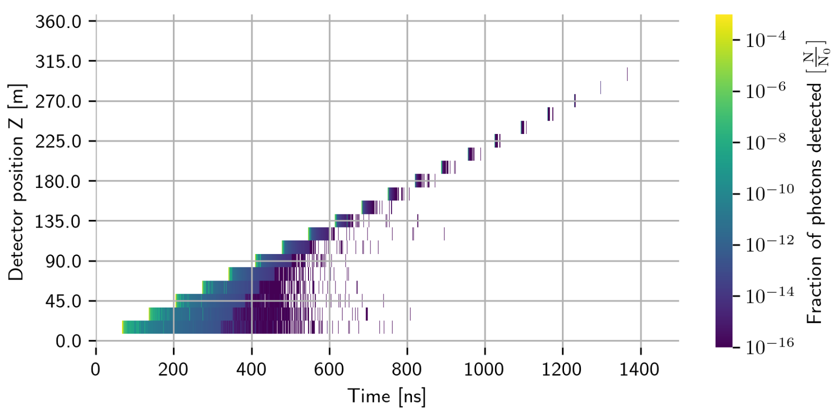

Fig. 6. Time histogram from the Pretorian Hybrid method simulation results for inline geometry.

In Fig. 7, the simulation results from Geant4 and Pretorian are presented together for comparison. These results are obtained by performing a series of simulations for the spherical geometry with different values of the source to detectors distance for increasing size of spherical spread of detectors. In Fig. 7 (a) and (c), the total number of photons detected by the detectors which are equidistant from the source is shown on the Y-axis and the distance from the source to the detector is represented on the X-axis. In the bottom graphs of these figures, the ratio of a number of photons detected in Pretorian to that in Geant4 is shown as a function of a distance to the source. As Geant4 uses the standard RT technique for optical photon propagation, the results of RT show a better agreement with the results of Geant4 simulation. In Fig. 7 (d), a constant shift in the ratio of the results of Pretorian Hybrid to Geant4 is observed. This shift is due to the reason that the combination of Forward and Backward RT is applied in the Pretorian Hybrid algorithm.

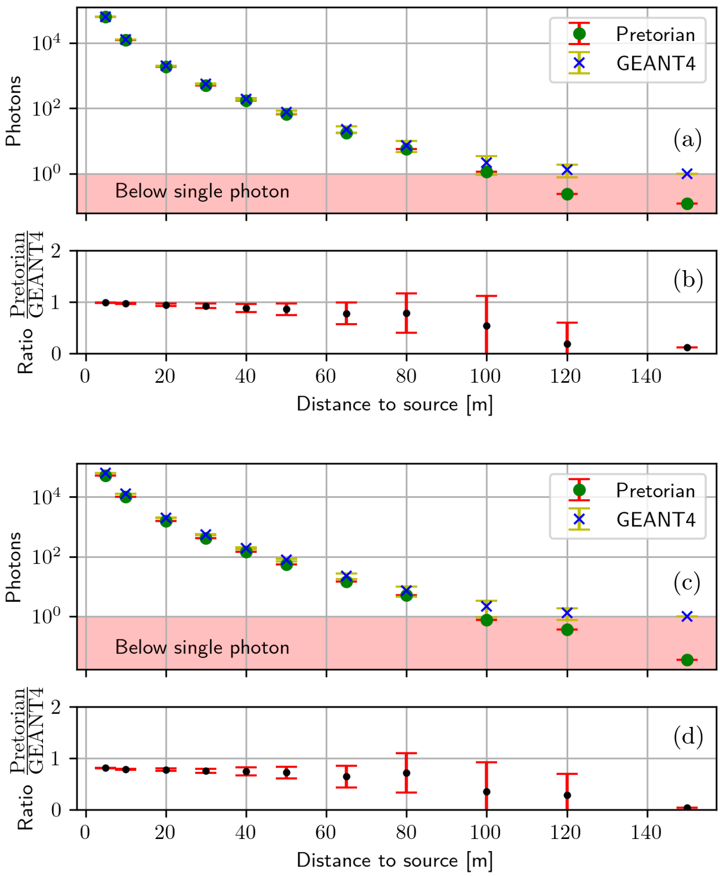

Fig. 7. Comparison of simulation results from Pretorian and Geant4 for spherical geometry with isotropic source. Top: Comparison between Pretorian with only RT and Geant4 simulation. Bottom: Comparison between Pretorian Hybrid and Geant4 simulation.

6. Conclusions

The simulation of photon propagation for large-scale underwater neutrino telescopes has been developed. The Pretorian Hybrid method provides a better estimation of detection of photons from various scattering points in the medium as compared to the Forward RT technique. For the case of Neutrino Telescopes, the detectors are much smaller than the distances for the photon propagation. For the Forward RT techniques, the simulation requires a very large number of photons initially at the source and propagates them throughout the volume. The main advantage of using the Pretorian Hybrid technique over the Forward RT is that it allows for precise estimation of the photons at the detectors after propagation with the much less initial number of photons. The results of the Pretorian Hybrid method were also compared to the simulation of optical photons using the Geant4 framework. The Hybrid technique also gives a better profile of the time of arrival of photons at the detector. This will help further when using the Pretorian Hybrid technique to propagate the photons from the Cherenkov signals by the passage of particles in the water and using them for studies.

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