A Proposal of the DOM response implementation method for the Photonics table production

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In order to implement the DOM response without increasing size of the photonics table, a simple analytical formula of the wave length spectrum is proposed. Its validity has been investigated by the toy Monte Carlo simulation code, and we found that a systematic error in the photoelectron intensity estimation resulted from this approximation is within 5 %, which is probably better than the accuracy of our absolute detector calibration we are able to achieve.

I. A POSSIBLE ALGORITHM TO IMPLEMENT THE DOM RESPONSE

In AMANDA, the photonics table has integrated the detection processes all the way down to the photoelectron level to save computer memory. The photoelectron fluctuation, however, would not be able to be taken into account, except the statistical one. The IceCube DOM is being measured in lab carefully to understand its behavior and it is important to implement their measured results properly in the detector MC even in the case when it has to rely on the pre-produced photonics table. A possible solution to achieve this goal without enlarging the table size further would be to let the photonics calculate number of photons (not photo-*electrons*) arriving at individual DOM locations. The conversion process to photoelectrons including the angular factor is simulated in the DOM Monte Carlo module in "real time" manner in the event generator. In this approach, the photonics consider a DOM as a perfect 4π detector with 100 % collection efficiency. An algorithm for the DOM simulator to calculate number of photo electrons in the event generation chain will be something like:

1. Assume a photon beam is parallel from the light emission point to the DOM location.

2. Sample the hit location of photons at the DOM glass sphere.

3. Ray-trace a photon until it hits the PMT photocathode or somewhere else in the DOM sphere. This can be done using the pre-calculated table to save CPU time.

4. Simulate the PMT/DOM electronics response.

5. Repeat this procedure for all the photons the photonics table predicted.

A drawback of this method is that you are not able to know wavelength of an individual photon because the wavelength factor is convoluted in the photonics table, although the DOM response depends on the wavelength.

II. THE ANALYTICAL WAVELENGTH SPECTRUM AFTER THE PROPAGATION AND ITS VALIDITY

The wavelength spectrum for photons propagating in ice can be approximated as

$$\frac{dN_\gamma}{d\lambda} \simeq \frac{1}{\lambda^2} \exp\left[-d\sqrt{a(\lambda)b(\lambda)}\right], \qquad (1)$$

where d is the distance from the light origin to a DOM location, $a(\lambda)$ and $b(\lambda)$ are the coefficient of the absorption and the scattering of photons, respectively. If this approximation works good enough, the DOM simulator can assign a wavelength for an individual photon following this spectrum.

In order to see how well this formula would reconstruct the real wavelength distribution, we built a toy Monte Carlo simulation code where we ray-traced photons running in ice with uniform property. The ice property is characterized by the coefficients a and b in Eq. 1 and we took them from the Ped's PhD thesis [1]. Three cases are assumed. One is to represent the "homogeneous" ice case, the second is supposed to follow the AMANDA ice at depth of 1690 m as the representative "clean" ice, and the last is to assume those at depth of 1740 m as a "dust" ice. We run photons in these three cases but compare the results with the analytical model, Eq. 1, of the "homogeneous" ice case only, because the DOM simulator does not know the accurate ice profile of a given photon path in our proposed algorithm anyway because of limitation of the photonics table dimension, even if we had a perfect knowledge of the ice characteristics.

FIG. 1 shows the direct comparison. Although the analytical mode is very simple, it reconstructed the simulation results reasonably well, but not perfectly. Note that the analytical model represented by Eq. 1 predicts both the intensity of photons without being absorbed and the wavelength distribution. The photon intensity

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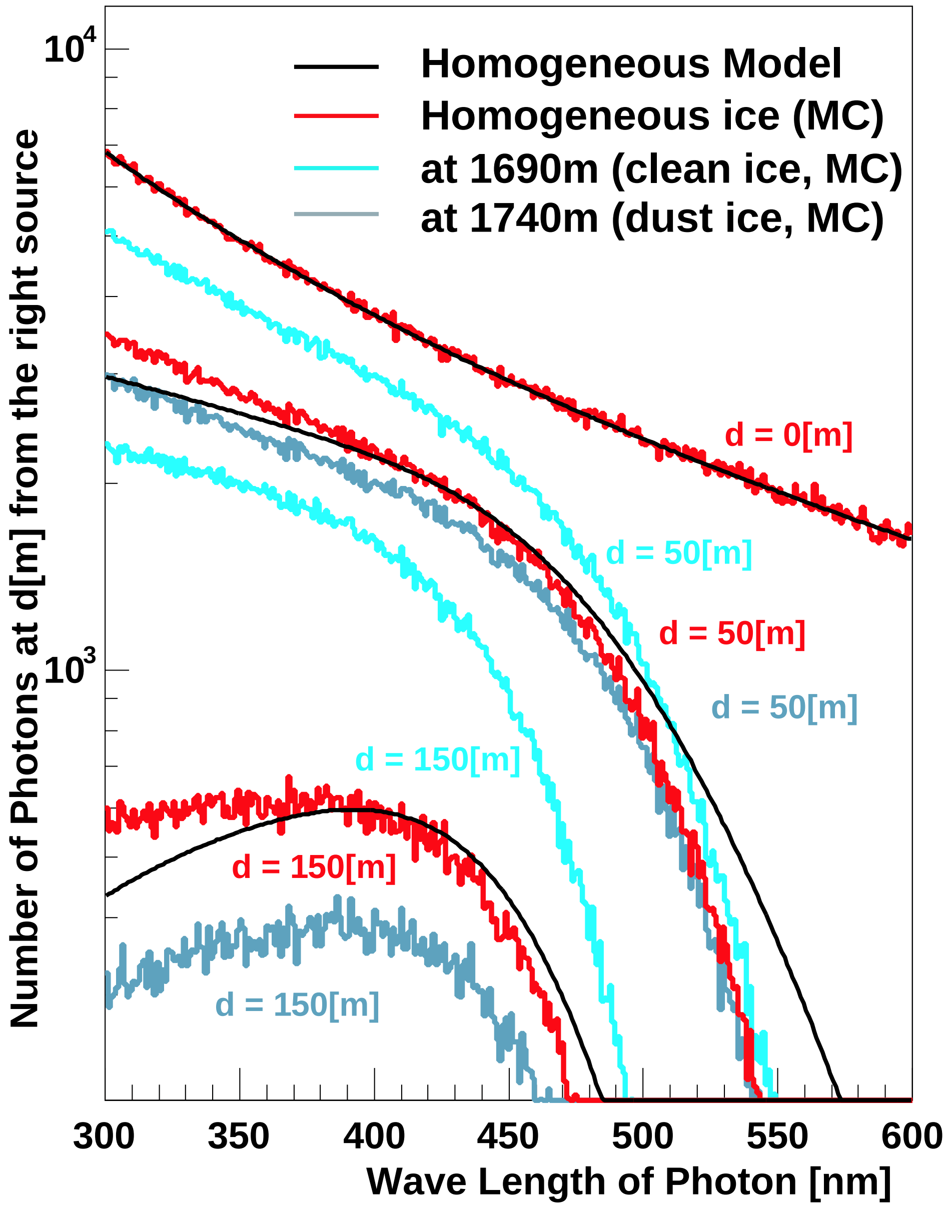

FIG. 1: Number of Photon spectra and their intensity. Both numerical results obtained by the toy Monte Carlo and the simple analytical formula are shown for comparison.

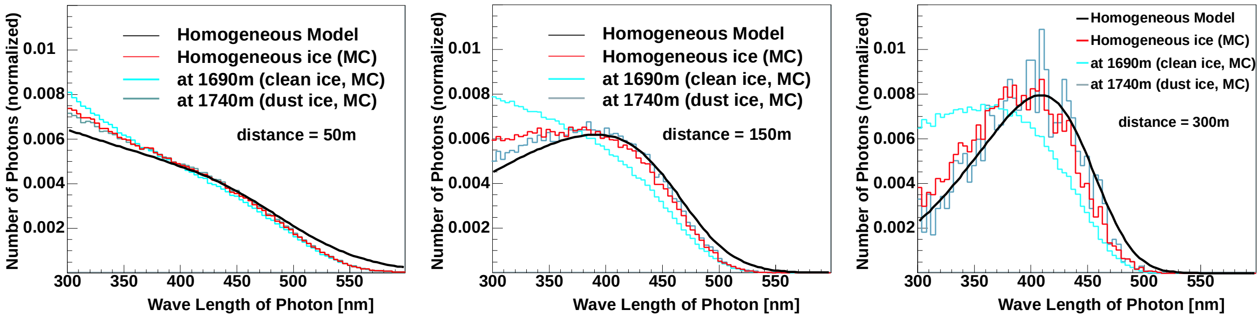

FIG. 2: The relative photon wavelength spectrum. The normalized numerical data and the (normalized) simple model prediction are shown. Here three case in distances are plotted: 50, 150, and 300 m from the light source to the "OM".

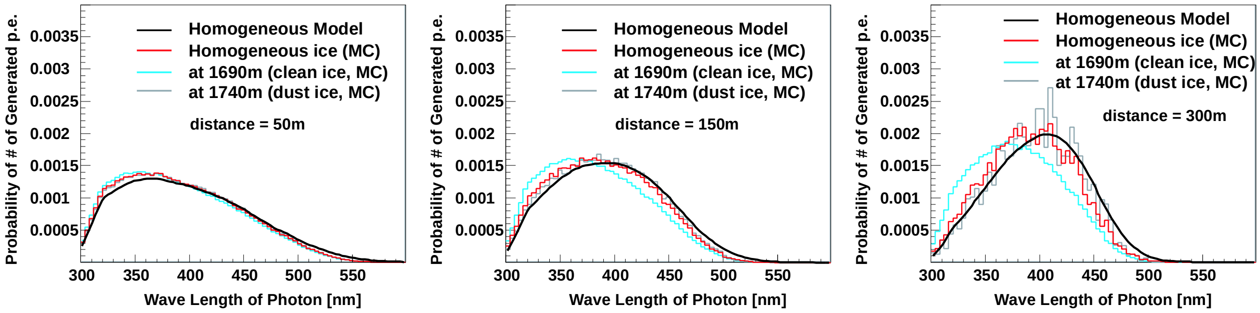

FIG. 3: Same as in FIG. 2, but the quantum efficiency shown in FIG. 4 is convoluted.

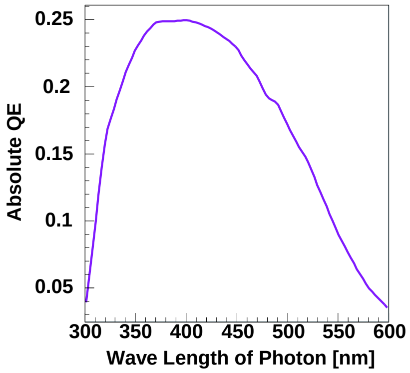

FIG. 4: QE of HAMAMATSU R7081-02 used in this study.

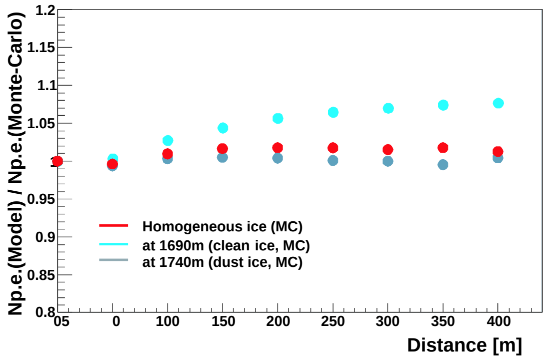

FIG. 5: Ratio of number of photoelectrons obtained by the real photon wavelength spectrum to those calculated by the model spectrum as a function of distance.

are told by the photonics table itself, and the DOM simulator would use Eq. 1 as a probability distribution to sample the wavelength. It is, therefore, more appropriate to compare the simulation data with the analytical model normalized to the data. FIG. 2 shows this comparison. Now the matching becomes much better even for the cases of longer propagation.

You may be concerned that the case of "clean" ice exhibits some discrepancy between the Monte Carlo data and the analytical model prediction at the shorter wavelengths below 350 nm. But the optical sensitivity of the DOM below 350 nm decreases rapidly. An example is shown in FIG. 4 where the PMT quantum efficiency is plotted. So this discrepancy would not be significant at all in the end.

To demonstrate this hypothesis, FIG. 3 shows the spectrum of *photoelectrons* by integrating the QE curve to the photon wavelength spectrum. You can see that now the agreement is quite good.

The area of the curves shown in FIG. 3 corresponds to expected number of photoelectrons. We should check if we have a systematics of number of photoelectrons by introducing approximated analytical formula of wavelength spectrum. In FIG. 5 is plotted the ratio of the "real" number of photoelectrons (which corresponds to the area of the MC curve in FIG. 3) to those estimated by assumption that the incoming photons at DOMs follows the wavelength spectrum estimated by our analytical model (which corresponds to the area of the black curve in FIG. 3). The systematics difference is within 5 % for $d \leq 200$ m. Systematic errors in cases of the longer distances would probably be smeared out by low statistics of photons and systematic uncertainty of the ice profile in the actual event generation.

III. CONCLUSION

The simple wavelength spectrum model would allow the DOM simulator to fully simulate the DOM response including the angular efficiency and the photoelectron fluctuation in the Monte Carlo event generation based on the photonics table. It also allows the event generator to use a different DOM simulator (say, a newer version, or the one to implement the wavelength shifter) without repeating the photonics table production efforts.

The systematic shift of the number of photoelectrons would be 5 %. This is comparable to our most optimistc goal of the absolute detector calibration and would certainly be better than the uncertainty due to our incomplete knowledge of the IceCube ice profile.

[1] Predrag Miocinovic, PhD Thesis (University of California, Berkeley, 2001).