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Improved Cherenkov light propagation methods for the IceCube neutrino telescope

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Abstract: In the field of neutrino astronomy, optically transparent media like glacial ice or deep ocean water are commonly used as detector medium. Elementary particle interactions are studied using in situ light detectors recording time distributions and fluxes of faint photon fields of Cherenkov radiation, typically generated by ultra-relativistic muons. For simulations of such photon fields, the IceCube collaboration uses a versatile software package, PHOTONICS, which was developed to determine photon flux and time distributions throughout a large volume with spatially varying optical properties. Photons are propagated and time distributions are pre-calculated as binary photon tables for fast and transparent access from event simulation and reconstruction. This is the main tool by which IceCube event simulations take into account how depth and wavelength dependent variations of the optical properties of the South Pole glacier distort the footprints of elementary particle interactions.

Introduction

In optical high energy neutrino astronomy, light from charged particle interactions is observed using a large number of sensors (photomultipliers) placed in transparent natural media like glacial ice, lake water, or deep ocean water. Successful simulation and reconstruction of such events relies on accurate knowledge of light propagation within the detector medium. The typical scattering lengths in these detector media are of the order of tens to hundreds of metres. Since this scale is comparable to the typical sensor spacing for neutrino telescopes, scattering effects can not be ignored, and analytical calculations do not suffice. The problem is further complicated by the anisotropy of the light emitted in particle interactions and the heterogeneity of natural detector media.

The software package PHOTONICS[1] contains routines for detailed photon simulations in heterogenous media like the South Pole glacier. Photon simulation results are pre-calculated and used in event simulation and reconstruction through interpolation of lookup tables for fast and accurate access to photon signal timing and amplitude probabilities.

Photon flux simulation technique

At any location throughout the medium, the local optical properties for a given wavelength are described by the absorption length λ_a, the geometrical scattering length λ_s, and the scattering phase function which is the probability density function for angular deviations at each scatter. For ice, the Henyey-Greenstein (HG) phase function[2] is used to describe the strongly forward peaked scattering. It is completely characterized by a single parameter, the mean of the cosine of the scattering angle, $\tau = \langle \cos\theta \rangle$. For most physical media, a strong correlation between λ_s and τ is observed. One therefore considers the effective scattering length, $\lambda_\mathrm{e} \equiv \lambda_\mathrm{s}/(1-\tau)$.

Photons are generated according to emission spectra specific for the given light source (particle physics events or calibration light sources) and propagated throughout the medium in accordance with the heterogeneous propagation medium description. Each photon's spatial and temporal path is calculated and its contribution to the overall light field is recorded in a cellular grid throughout a user defined portion of the simulation volume. The locations of sensors are not fixed, but can be dynamically specified when accessing the simulation results.

The detector efficiency as function of angle and wavelength, as well as the effects of absorption, is accounted for by applying appropriate weights during the photon recording.

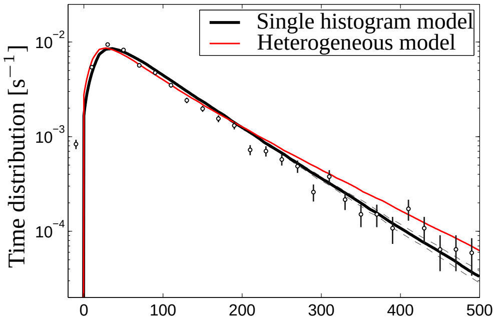
The local photon flux is calculated in each recording cell with one of two independent methods. In the volume-density method, photons are propagated in small (typically equidistant) steps between scattering points, so that the contribution to each recording cell is related to the number of photon steps taken in that particular cell. In the surface-crossing method, photons are instead interrupted only at scattering points and recording cell boundaries. The flux contribution is then related to the number of cell boundary crossings, taking into account the projected cell surface area of each cell boundary crossing. The two methods typically give compatible results at a comparable simulation speed, depending slightly on the layout of the simulation grid and the optical parameters.

To improve the speed of the Monte Carlo simulation, importance-weighted scattering is supported; Photons can be propagated using scattering parameters $(\lambda_{e'}, \tau')$, different from those of the physical scattering situation at hand. For example, straighter paths can be oversampled by choosing scattering angles θ from a HG phase function $f_{\tau'}$ with τ' closer to 0, while applying a weight of $f_\tau(\theta)/f_{\tau'}(\theta)$.

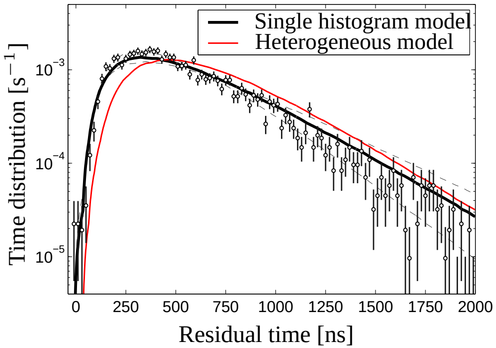
The result of the photon simulation is multidimensional binary photon tables, containing the expectation number of photo-electrons produced at photomultiplier tubes and the corresponding differential or cumulative time distributions.

Modeling of glacial ice and applications to neutrino astronomy

A detailed study of the properties of the glacial ice at the South Pole has been performed by the AMANDA collaboration[3]. The ice is very clear in the optical and near UV region with absorption lengths of 20–120 m, depending on wavelength. The effective scattering lengths are around 25 m, less for shorter wavelengths. Both scattering and absorption are strongly depth dependent. The vari-

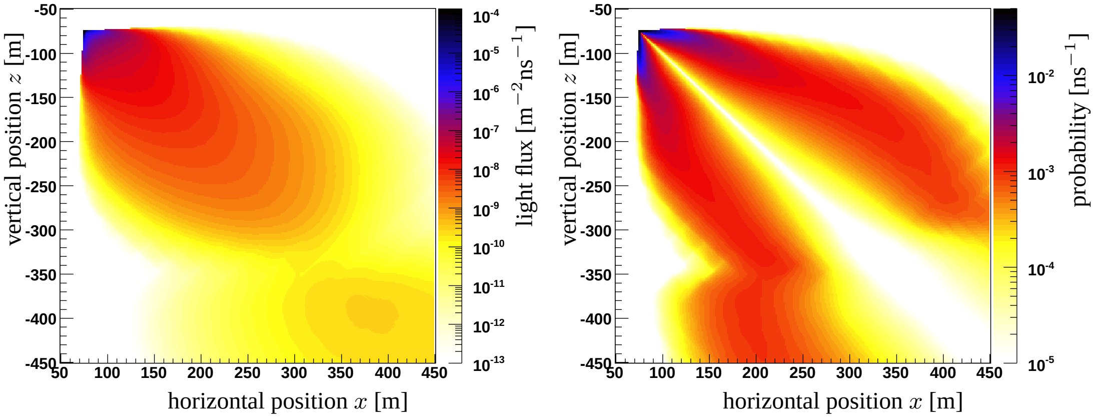


(a) Nd:YAG laser, 532 nm in ice



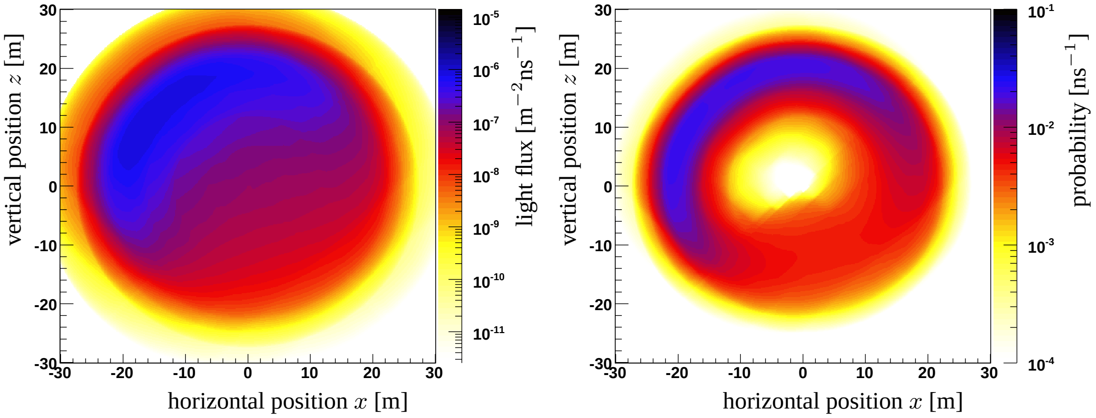
(b) Blue LED beacons, 470 nm in ice

Figure 1: Residual time distributions of simulated light pulses in deep glacial ice. In (a), for a 532 nm Nd:YAG isotropic laser pulse, emitted at a depth of 1825 meter, as seen from a horizontal distance of 75 m. In (b), for an upward pointing 470 nm LED emitter located at a depth of 1580 m as seen from a horizontal distance of 140 m. The black dots show two time distributions of glacial ice surveys[3], with vertical Poissonian error bars. The thick black lines show our results using the scattering and absorption parameters of these particular source–receiver combinations, and thin dashed lines represents the model uncertainty. The thin (red) lines show the simulation results with the heterogeneous ice model[3] which was constrained by other data.



(a) $\Phi(t)$ (b) $f_{\mathrm{pdf}}(t)$

Figure 2: A snapshot of the light distribution produced by a simulated ultra-relativistic muon which entered from below, at an angle $\Theta_\mathrm{s} = 135°$ diagonally towards the glacier surface ($\Theta_\mathrm{s} = 180°$ would be straight upwards) passing through the origin at a depth of 1730 m below the glacier surface. Stronger fluxes $\Phi(t)$ are observed both above and below the particularly dusty region around $z = -350$ m which has stronger scattering and absorption. Scattering causes a bending of the Cherenkov light cone, most easily seen in the differential probability distribution $f_{\mathrm{pdf}}(t)$, whose time integral is by definition normalized to unity at each spatial location. Inhomogeneities in the optical properties of the medium cause the additional structure seen in the figure, especially around -350 m.



(a) $\Phi(100\ \mathrm{ns})$, $Z_\mathrm{s} = 0$ m (b) $f_{\mathrm{pdf}}(t = 100\ \mathrm{ns})$, $Z_\mathrm{s} = 0$ m

Figure 3: The figures show the simulated light flux, $\Phi(t)$ and the probability distribution $f_{\mathrm{pdf}}(t)$ of the light emitted from an idealized shower placed 1730 m below the glacier surface. The snapshot is taken $t = 100$ ns after light emission at the origin. The shower direction is $\Theta_\mathrm{s} = 135°$, as for the muon in figure 2.

ations at depths greater than 1450 m, where air bubbles no longer exist, are explained by changes in climatic conditions which correlate with concentrations of insoluble dust deposits. At each 10 m depth interval, the effective scattering and absorptions lengths, λ_e and λ_a as function of wavelength were determined. As an example, the time distributions corresponding to two different wavelengths and light source–receiver positions were calculated and compared with experimental distributions, see figure 1.

The photon propagation and recording methods were applied to various idealized event types, such as the light emission from minimum ionizing muons, and from electromagnetic showers generated when ultra-relativistic electrons interact with the detector medium. Using a charged particle propagator such as MMC[4], the photon tables of idealized events types are dynamically combined to describe realistic composite events. The PHOTONICS photon simulation results are accessed directly through ROOT compliant C++ interfaces. The IceCube simulation programs query these interfaces and apply detector specific details such as simulation of electronics, data acquisition and triggers. For event reconstruction, PHOTONICS provides individual photon probability density functions (pdfs), and the expected number of detected photons. These are used by track-fitting algorithms, for example maximum-likelihood routines. The interface also delivers photon arrival times randomly drawn from the cumulative arrival time distributions.

Figure 2 shows the light distribution of a simulated minimum ionizing muon traveling diagonally upwards, on its way through the point $x = 0, z = 0$. At the front of the track, we observe a cross section of the unscattered Cherenkov wavefront, followed by a diffuse light cloud as the photons are scattered away from the geometrical Cherenkov cone. We also observe a weak deflection of the photons with higher flux $\Phi(t)$ both above and below the dusty ice region near $z = -350$ m.

Figure 3 shows a cross section of the light distribution of a simulated shower at a depth of 1730 m, 100 ns after light emission. Ultra-relativistic electrons deposit their energy much quicker than muons, confining most of the light emission to the vicinity of the interaction point, depending on energy. At the same time, light may propagate hundreds of meters into glacial layers with very different optical properties. Shower-like event are more dependent on a complete implementation of variations in ice properties with depth since the localized light emission makes it harder to reconstruct the lepton direction. The use of PHOTONICS with heterogeneous ice models makes it possible for IceCube to adequately handle such events.

Conclusion

New photon propagation methods were implemented, and are in use in the simulation and reconstruction of particle physics events for IceCube. The PHOTONICS program is used for calculating and tabulating light distributions of calibration sources and ultra-relativistic charged particles, as a function of time and space in the heterogeneous South Pole glacier. The full depth and wavelength dependent ice description of [3] was implemented. Shower-like events (induced by ultra-relativistic electrons) are more sensitive to depthwise ice property variations than are muons. This is increasingly important for higher energies, as light propagates further into different glacial layers. The IceCube simulation can fully take into account how depth and wavelength dependent variations of the optical properties of the South Pole glacier distort the footprints of elementary particle interactions.

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