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Diffuse Optical Tomography with polarized light: a GPU-accelerated polarization-sensitive Monte Carlo simulations for efficient Sensitivity Kernel computation

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ABSTRACT

In an effort to address Monte Carlo (MC) light prorogation shortcomings in terms of computational burden and light polarization-sensitivity, we report an efficient GPU-based MC for modeling polarized light in scattering medium.

Keywords: Polarized light, Monte Carlo simulations, v-RTE, Inverse problem, Diffuse Optical Tomography

1. INTRODUCTION

Polarized light propagation study and understanding continue to captivate the interest of the research community due to its successful applications in modern diagnostics (i.e., dermatology, oncology, etc.). Ever since the recognition of the effectiveness of Monte Carlo simulations for the study of light propagation, several accelerated software packages have been proposed e.g.,.[1,2] Although these GPU-based implementations have concerned highly parallelized architectures, for which sophisticated geometries (voxelized, tetrahedral mesh-based schemes, etc.) have been suggested, none of them has considered polarized light for the inverse problem. In this paper, we report a new GPU-based polarization-sensitive Monte Carlo (MC) for polarized light propagation which addresses the computation of the sensitivity kernel for an efficient resolution of the problem inverse. Our previous work[3,4] showed that using the reciprocity relation of the vector Radiative Transfer Equation (v-RTE) is a promising tool for the computation of the Diffuse Optical Tomography (DOT) sensitivity kernel. In the current work, we propose to further improve the computational efficiency of the sensitivity kernel based on the recent development of graphical parallel computing units. The general steps used for the modeling and computation of the forward GPU-based MC proposed are described in section 2 and simulation results are provided in section 3.

2. EFFICIENT COMPUTATION OF THE SENSITIVITY KERNEL

2.1 Approximation with Spherical Harmonics basis functions

This study considers polarized light propagation through a slab geometry of scattering medium, whose properties are similar to those of biological tissues. The sensitivity obtained for a source-detector pair, (r_a, r_b), and an absorbing perturbation, $\delta\mu_a(r)$, can be written as:[3]

$$\Phi(r_b, \hat{s}_b; r_a, \hat{s}_a) = \int [S_{out}.K(r_b, \hat{s}_b, r_a, \hat{s}_a; r)\, S_{in}]\, \delta\mu_a(r)\, d^3r, \tag{1}$$

where :

$$K(r_b, \hat{s}_b, r_a, \hat{s}_a; r) = \int G(r_b, \hat{s}_b; r, \hat{s})\, G(r, \hat{s}; r_a, \hat{s}_b)\, d^2s. \tag{2}$$

S_{in} refers to the Stokes vector $S = [I, Q, U, V]^T$ for the incident beam, S_{out} represents the output polarization state observed at the detector. The 4×4 matrix K is the sensitivity kernel for the v-RTE. By computing the kernel K for each location and direction on the medium, one can solve the forward model. Yet, this involves computing consistently new Green's function for every single point in the medium, which increases the computational time.

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In our previous study,[3] the v-RTE symmetry and translation as well as reciprocity relations were investigated to reduce MC simulations computational load for the computation of the Kernel K,[3] and equation (2) was therefore simplified to :

$$K\left(r_b, \hat{s}_b, r_a, \hat{s}_a; r\right) = \int PG^T\left(r + r_{ab}, -\hat{s}; r_a - \hat{s}_b\right) PG\left(r, \hat{s}; r_a, \hat{s}_a\right) d^2 s, \tag{3}$$

where $r_{ab} = r_a - r_b$. The computation of K involves only two Green's functions. To do so, we need to record both voxels visited by the photon and importantly the incident polarized Stokes vector $S = [I, Q, U, V]^T$. The latter has been effectively approximated by Spherical Harmonics (SH) element basis.[3] A typical coefficients expansion for a component, e.g. $Q\left(r, \hat{s}\right)$ is given by $Q\left(r, \hat{s}\right) = \sum_{L=0}^{L_{max}} \sum_{M=-L}^{L} c_{LM}^{Q}\left(r\right) Y_{LM}\left(\hat{s}\right)$, where Y_{LM} refer to the real SH basis functions.[5] The parameter L_{max} represents the number SH sufficient for the approximation. The parameter $-L \leqslant M \leqslant L$ indexes the band-L basis function. In this work, we propose to improve the computational efficiency of the Kernel sensitivity using an accelerated GPU-based Monte Carlo simulation.

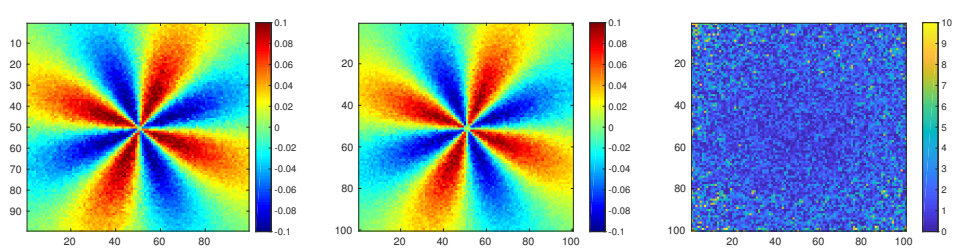
2.2 Implementation of the GPU-Based Monte Carlo simulations

The numerical computation of $K\left(r_b, \hat{s}_b, r_a, \hat{s}_a; r\right)$ is performed here by using MC simulations. To further enhance the computational efficiency of the Kernel, an accelerated GPU-based MC implementation is proposed. More specifically, for a single GPU-based MC run, the code produces the four Stokes vector components in the SH element basis. Our implementation is conceptually straightforward and follows MCML's hop-drop-spin strategy.[6] In practice, each photon uses one thread to achieve its propagation history. Input requirements include three specifications: (i) *the incident polarization beam* (wavelength λ, Stokes vector $S = [I, Q, U, V]^T$, number of photons N_{ph}, illumination angle) (ii) *geometry* (slab thickness size d, source-detector position) (iii) *the medium* (inclusions of micro-spheres of radius r, refraction index n, Mie scattering phase function for these spherical inclusions, absorption μ_a and scattering μ_s coefficients). Another parameter consists of the number of degrees of SH approximation L_{max}. Our implementation supports 64-bit single precision and leverages the parallelism process while avoiding memory bottlenecks. In fact, during parallel computing stages, threads access to different memories layers was optimized in attempt to further reduce computational time. The proposed polarized GPU-based simulation uses a NVIDIA Quadro P6000 GPU card which has 3840 processing cores, $24GB$ of global memory given 60×1024 threads.

3. RESULTS AND DISCUSSIONS

3.1 Performance and validation

To demonstrate the quantitative accuracy of our GPU-based implementation, we present a typical example of simulation with the referenced code in[7] which also considers the propagation of polarized light. The example



(a) (b) (c)

Figure 1. Mueller matrix obtained for light backscattered from solutions of micro-spheres. Element M23 obtained from[7] (a), and from our accelerated Monte Carlo simulation code (b), and the relative error in % between them (c).

illustrated in figure 1 consists of the backscattering Mueller matrices obtained from software[7] and our implementation. The incident laser beam ($\lambda = 632.8nm$) was normal to the sample. A number of 10^8 photons was launched. The simulation was conducted using phase function given by Mie theory for spherical inclusions of the radius $0.15\mu m$ and the refractive index $n = 1.59$. Moderate scattering and absorption coefficients were set to:

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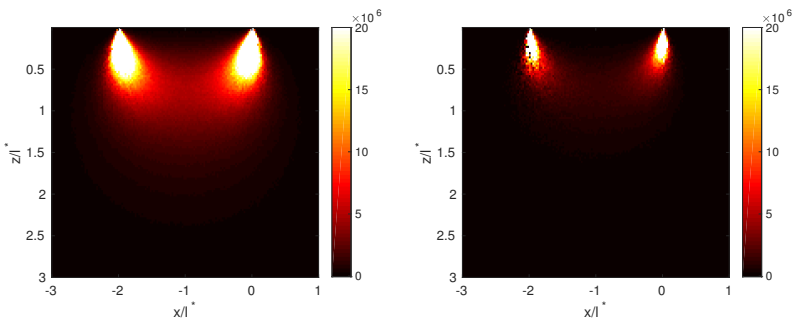
$\mu_s = 20cm^{-1}$ and $\mu_a = 0.01cm^{-1}$. The visual inspection of these plots shows that our GPU code yields successful yet fast calculation of each element of the Mueller matrix which takes at most $1s$ comparing to software[7] that takes about $150s$ per one Mueller matrix element. In addition, the average relative error obtained is reduced to 1.9% (figure 1(c)).

3.2 Representative Sensitivity Kernels

Representative sensitivity Kernel is illustrated in figure 2. A number of 10^8 photons was considered. The optical parameters for a homogeneous slab ($d = 3cm$) were set to $\mu_s = 20cm^{-1}$ and $\mu_a = 0.01cm^{-1}$, the source-detector distance was $2l^*$, where $l^* = \frac{1}{[\mu_a+(1-g)\mu_s]}$ is the transport mean free path, $g = 0.95$ the anisotropy factor. The phase function was computed using Mie scattering for spherical inclusion with size parameter $X = 7.15$. The SH expansion degree was $L_{max} = 11$.



(a) (b)

Figure 2. Matrix elements obtained from our accelerated Monte Carlo simulation code for normal incidence and direction. Element unpolarized K_{11} (a) and a representative linear combination of $K_{41} + K_{44}$ elements (b).

To obtain one complete kernel (figure 2(a)) one needs to run one GPU-based simulation. The kernel in figure 2(b) represents a specific linear combination of Stokes vector elements involving both unpolarized and polarized (circular) light, it requires two GPU-based MC runs. Our numerical simulations enables the computation of these kernels using an efficient computation on GPU. It also provides insights on polarization-sensitive measurements. This opens up new direction for solving the problem inverse based on our approach.

4. CONCLUSION

In this study, we performed a parallel Monte Carlo method to solve the forward model for light propagation in homogeneous media. Unlike previous MC GPU-based software packages, our model incorporates light polarization modeling. Furthermore, a perturbation approach allows to propose a linear formulation, by using reciprocity relation, for incorporation into a reconstruction process. Typical illustrative numerical examples focusing on the performance of our GPU-based implementation will be given at the conference.

5. ACKNOWLEDGEMENTS

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