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# GPU-accelerated polarization-sensitive Monte Carlo simulations for Diffuse Optical Tomography with polarized light

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## ABSTRACT

An efficient GPU-based Monte Carlo (MC) simulator for modeling polarized light propagation in scattering media is reported. By using reciprocity relations, the inverse problem for Diffuse Optical Tomography with polarized light is formulated within the first Born approximation. The approach allows a fast computation of the sensitivity kernels.

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

## 1. INTRODUCTION

Imaging with polarized light is of major interest in tissue diagnostics (e.g. dermatology, oncology), hence understanding the polarized light propagation through such complex media continues to captivate the interest of the research community. Monte Carlo simulations are known to be efficient for the study of light propagation, and several accelerated software packages have been proposed,<sup>1,2</sup> with highly parallelized architectures and sophisticated geometries (voxelized, tetrahedral mesh-based schemes). However, none of them has considered polarized light. In this paper, we report a new GPU-based polarization-sensitive Monte Carlo for polarized light propagation which addresses the computation of the sensitivity kernel for an efficient resolution of the problem inverse. Our previous work<sup>3,4</sup> 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. 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:<sup>3</sup>

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

where :

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

$S_{in}$  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  $4 \times 4$  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. In our previous study,<sup>3</sup> 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  $K$ ,<sup>3</sup> and equation (2) were therefore simplified to :

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

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.<sup>3</sup> A typical coefficients expansion for a component, e.g.  $Q(r, \hat{s})$  is given by  $Q(r, \hat{s}) = \sum_{L=0}^{L_{max}} \sum_{M=-L}^L c_{LM}^Q(r) Y_{LM}(\hat{s})$ , where  $Y_{LM}$  refer to the real SH basis functions. The parameter  $L_{max}$  represents the number SH sufficient for the approximation. The parameter  $-L \leq M \leq L$  indexes the band- $L$  basis function. In this work, we propose to improve the computational efficiency by Kernel sensitivity computation using an accelerated GPU-based Monte Carlo simulation.

## 2.2 Implementation of the GPU-Based Monte Carlo

The numerical computation of  $K(r_b, \hat{s}_b, r_a, \hat{s}_a; r)$  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.<sup>5</sup> In practice, each photon uses one thread to achieve its propagation history. Input requirements include three specifications: (i) *the incident polarization beam* (wavelength  $\lambda$ , 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  $\mu_a$  and scattering  $\mu_s$  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 single GPU of the NVIDIA Quadro P6000 card which have 3840 processing cores, 24GB of global memory given  $60 \times 1024$  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<sup>6</sup> which also considers the propagation of polarized light. The example

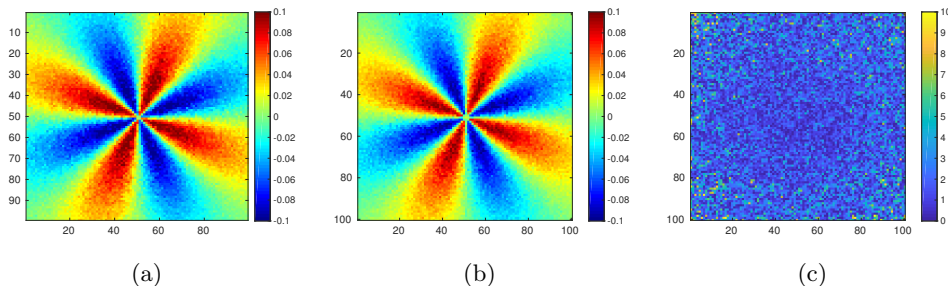


Figure 1. Mueller matrix obtained for light backscattered from solutions of micro-spheres. Element M23 obtained from<sup>6</sup> (a), and from our accelerated Monte Carlo simulation code (b), and the relative error in % between them (c).

illustrated in figure 1 consists of the backscattering Mueller matrices obtained from software<sup>6</sup> 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:

$\mu_s = 20\text{cm}^{-1}$  and  $\mu_a = 0.01\text{cm}^{-1}$ . 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<sup>6</sup> 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 ( $d = 3\text{cm}$ ) were set to  $\mu_s = 20\text{cm}^{-1}$  and  $\mu_a = 0.01\text{cm}^{-1}$ , the source-detector distance was  $2l^*$ , where  $l^* = \frac{1}{[\mu_a + (1-g)\mu_s]}$  is the transport mean free path,  $g$  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  $L_{max} = 11$ .

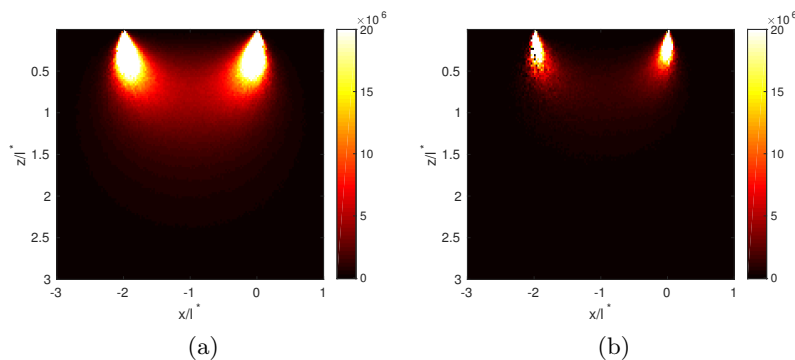


Figure 2. Matrix elements obtained from our accelerated Monte Carlo simulation code for normal incidence and direction. Element unpolarized  $K_{11}$  (a) and a representative linear combination of  $K_{41} + K_{44}$  elements (b).

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 polarization measurements involving both circular and linear polarizations, it requires three 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, a parallel Monte Carlo simulator, that accounts for light polarization, was implemented for a fast and efficient resolution of the forward model for light propagation in tissue-like media. Furthermore, a perturbation approach allows to propose a linear formulation, by using reciprocity relation, for an easy-coupling with a reconstruction process. Typical illustrative numerical examples focusing on the performance of the GPU-based implementation will be given.

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