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Comparison of Phase Space and Quasi-Monte Carlo Ray Tracing for the 3D Compound Parabolic Concentrator

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Abstract. Phase space ray tracing is an alternative to (Quasi-)Monte Carlo ray tracing in 2D. We introduce a 3D phase space algorithm and apply it to the compound parabolic concentrator. Our results show that phase space ray tracing outperforms Quasi-Monte Carlo ray tracing in 3D.

1 Introduction

The target light distribution of an optical system is typically computed using Quasi-Monte Carlo (QMC) ray tracing. There are alternatives in 2D like phase space (PS) ray tracing [1] and (generalized) concatenated backward ray mapping (CBRM) [2, 3]. Both methods use the PS of optical surfaces to determine which rays should be traced from source to target, significantly reducing the number of rays traced. We introduce a PS ray tracing algorithm for 3D rotationally symmetric optical systems.

2 Phase Space

We define phase space as a 4D set of position and momentum coordinates of rays intersecting a surface. The position coordinates $(q_1, q_2) \in Q$ are the x-and y-coordinates of the intersection of the ray with the surface. The momentum coordinates $(p_1, p_2) \in P$ are the projection of the ray's unit direction vector on the tangent plane multiplied by the index of refraction. PS is indicated with $S = Q \times P$, note that PS can be partially empty.

Every optical surface (except the source and target) has a source PS and a target PS. Source PS describes light emitted by the surface and target PS describes light reaching the surface. We denote with T_N the target PS of the target. All rays that follow the same path Π from source to target form a region in T_N. A path is defined as the sequence of surfaces encountered by a ray propagating from source to target.

3 Ray Tracing Using the Phase Space

The target intensity $I(p_1, p_2)$ for a fixed momentum $(p_1, p_2) = \text{const}$ is usually computed by integrating the target luminance in the Q-domain. However, assuming a Lambertian source of constant luminance, $I(p_1, p_2)$ is the area of intersection of a hyperplane $(p_1, p_2) = \text{const}$ and all regions of all paths Π in T_N. This reduces computing $I(p_1, p_2)$ to computing the boundaries of all regions on a hyperplane in T_N.

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We introduce an algorithm that recursively subdivides a hyperplane (p_1, p_2) = const in T_N into rectangles to approximate the PS boundaries. The corner points of the rectangles in PS are the rays that are traced. The recursion continues when a rectangle is larger than $\varepsilon_{q_1}^{\max} \times \varepsilon_{q_2}^{\max}$ and terminates when the size is below $\varepsilon_{q_1}^{\min} \times \varepsilon_{q_2}^{\min}$. Otherwise, the recursion stops when the corner points of a rectangle correspond to the same path.

4 Results

We compare the performance of PS ray tracing and QMC ray tracing on the compound parabolic concentrator (CPC). The CPC (Fig 1) is a standard optical system consisting of an aperture, a receiver and a reflector. However, we take the receiver as the source and the aperture as the target. Fig. 2 shows the PS boundaries on the hyperplane $p_1 = 0.4$, $p_2 = 0$ in T_N of the CPC; recall that every region corresponds to a different path.

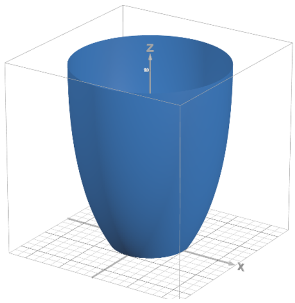

Figure 1. The CPC.

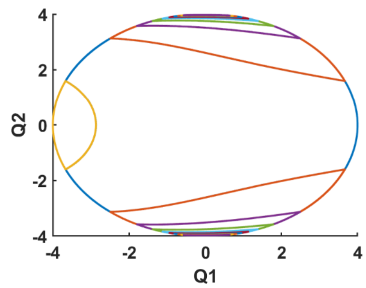

Figure 2. PS boundaries in T_N of the CPC for $p_1 = 0.4$, $p_2 = 0$.

Fig. 3 shows the errors of PS ray tracing and QMC ray tracing as a function of the computation time. The error is the difference between the solutions and a reference solution of 10^{11} QMC rays. PS ray tracing clearly outperforms QMC ray tracing.

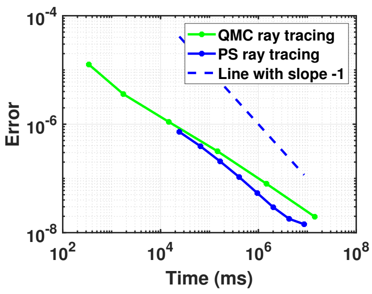

Figure 3. Errors of PS ray tracing and QMC ray tracing as a function of computation time. The QMC solutions are computed by tracing 10^i rays, $i \in \{5, 6, 7, 8, 9, 10\}$. The PS solutions are computed by ray tracing with $\varepsilon_{q_1}^{\max} = \varepsilon_{q_2}^{\max} = 1$ and $\varepsilon_{q_1}^{\min} = \varepsilon_{q_2}^{\min} = 0.05/2^j$, $j \in \{0, 1, 2, 3, 4, 5, 6, 7\}$.

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