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# Application of bidirectional stochastic ray tracing for stray light simulation in optical systems

D. Zhdanov (1), I. Potemin (2), A. Garbul (2), V. Sokolov (2), A. Voloboy (2), V. Galaktionov (2)
1 : NRU ITMO, St.Petersburg, Russia,
2 : The Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
E-mail: voloboy@gin.keldysh.ru

**Abstract:** The article is devoted to computational analysis of stray light in optical systems. Suggested solution provides efficient and physically accurate simulation of light scattered on diffuse surfaces of lens mountings.

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**Keywords:** stray light, bidirectional stochastic ray tracing, image formation, optical systems, lens design, rendering.

## 1. Introduction

Stray light is defined as unwanted light that reaches the focal plane of an optical system. There are a number of reasons of the stray light occurrence: specular or Fresnel reflection from optical surfaces resulted in ghosts, diffraction on diaphragms or gratings, diffuse scattering on the unpolished surfaces of lens, diffuse scattering on the surfaces of supporting structures within the optical system (baffles, mounts, struts, vanes), diffuse scattering on a surface defects (scratches and digs) and dust. The task of stray light simulation is very important and has different engineering solutions [1], [2]. The idea of these solutions is to trace visual rays (either forward or backward), find stray light paths reached the detector and define the power of such rays. In case of diffuse scattering on unpolished parts of lens and mechanical elements the process of simulation becomes very time consuming because of large number of inter-reflections of stray light rays.

We designed the solution which allows not only visualize stray light paths but also to render the virtual image which is formed on the detector. It takes into account a diffuse scattering on all illuminated surfaces. The article presents results of the stray light simulation in typical lens systems.

## 2. Bidirectional stochastic ray tracing

Physically accurate calculation of the light scattering on diffuse surfaces is provided by the rendering equation [3]. In an optical system with multiple diffuse reflections of light rays the rendering equation constructs an infinite recursive sum of brightness integrals. If contribution of secondary lighting to the resultant luminance is essential then the most appropriate method for solution of the rendering equation is the bidirectional stochastic ray tracing [4, 5] based on “Russian roulette” approach.

We elaborate the algorithm of bidirectional stochastic ray tracing which includes two stages. In the first stage the backward rays are traced and the direct luminance is calculated. In addition, the view maps (spheres of integration) of all visible scene surfaces are created and stored. In the second stage the forward rays are traced and the secondary and caustic luminance is calculated in the areas of intersection of the forward rays with the view maps (in the spheres of integration).

For stray light analysis caused by surface scattering the most important unwanted luminance component is the secondary and caustic luminance. For detector point $\vec{p}$ in direction $\vec{v}$ the luminance is calculated as:

$$L^l(\vec{p},\vec{v},c)=\sum_{i=1}^{N_B}\sum_{m=1}^{M_i}\tau_{im}(\vec{p}_{im},\vec{v}_{im},c)\frac{\sum_{j=1}^{N_R} BSDF_{im}(\vec{p}_{im},\vec{v}_{im},\vec{v}'_{imj},c)F_{Rj}(\vec{p}_{im},\vec{v}'_{imj},c)}{\pi^2 N_B N_F r_{im}^2}$$

where:

$N_F$ – number of rays emitted by light sources;

$N_B$ – number of rays emitted from light detector;

$M_i$ – number of integration spheres stored in view map for $i$-th trace of the backward ray;

$N_R$ – number of rays which hit the $m$-th sphere of integration (photon map) for the $i$-th ray trace;

$r_{im}$ – radii of spheres of integration (stored in view map) of the secondary luminance for $i$-th ray on $m$-th surface respectively;

$BSDF(\vec{p}_{im},\vec{v}_{im},\vec{v}'_{imj},c)$ – surface luminance factor of spectral component $c$ in the point $\vec{p}_{im}$ illuminated in $\vec{v}'_{imj}$ direction and observed in $\vec{v}_{im}$ direction;

$F_{Rj}(\vec{p}_{im},\vec{v}'_{imj},c)$ – spectral flux transferred by $j$-th light photon in the point $\vec{p}_{im}$ in $\vec{v}'_{imj}$ direction and which is hit on the integration sphere of photon map.

Two main factors influence on the unwanted luminance. The first factor is a light flux which photons carry to the visible areas (integrated spheres of view map). This flux produces illumination of in the area of observation. The second factor is BSDF of the scattering surfaces. The BSDF transforms the illuminance to the luminance on detector. For Lambertian BSDF the luminance does not depend on observation and illumination directions while narrow BSDF can produce high luminance peak.

Note that simulation time of the rendering practically does not depend on the integral value of the diffuse surface reflectance. That is the speed of simulation of the stray light on detector from surface with total integral scattering (TIS) 10% will be the same as from surface with TIS 1%.

## 3. Simulation of stray light in the optical systems

We applied the developed algorithm to simulate stray light inside of the lens system presented on the fig. 1. This is 6-lenses objective with 360mm focal length (f/7) and rectangular field of view with diagonal ±5°.

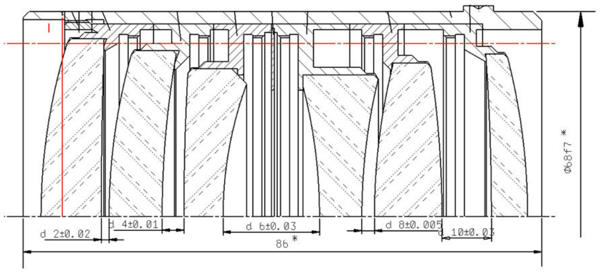


Fig.1. General scheme of lens

The entrance pupil of lens is illuminated by the sun which is out of field of view (FOV) under incidence angle $\omega_{Sun}$ = 7° like it is shown on the fig. 2. As the FOV of simulated lens ($\omega_{FOV}$ =5°) is less than $\omega_{Sun}$ then the sun is not seen by detector directly. The light from sun can reach the detector only if it will be scattered on some element of the lens structure.

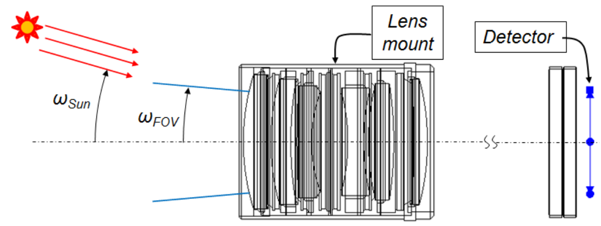



Fig.2. Illumination scheme

In given simulation we took into account only stray light scattered on diffuse surfaces of lens structure (mounts and unpolished surfaces of each lens). All optical surfaces were assumed to be covered with perfect antireflection layer. So no reflection is occurred on the clear surfaces of lens.

The resolution of detector 600 x 600 was specified for all cases of simulation.

In the first case presented on fig. 3 we simulated the scattering on the edge of aperture diaphragm. This edge of 50 um width has Lambertian reflectance 10%. With the exception of the diaphragm edge all other diffuse surfaces were considered as absolutely absorbing.

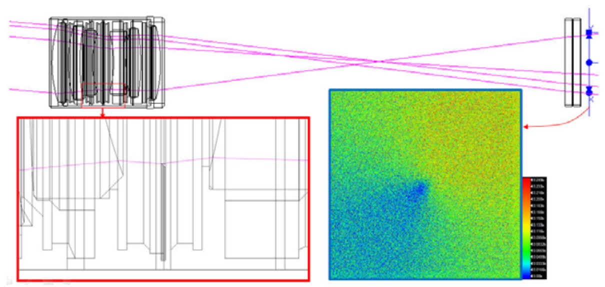
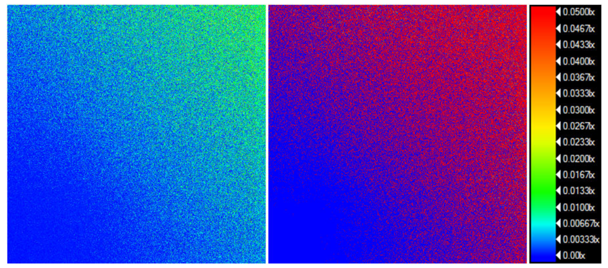


Fig.3. Scattering of out of FOV rays on the diaphragm edge and 2D illuminance distribution on detector

In the next two cases we considered all mounts and lens facets as Lambertian and Gaussian reflectors correspondingly. The diaphragm edge was not considered in the second and third cases as scatter.

In case of Lambertian scattering the 5% reflectance was specified. And in case of Gaussian scattering we also used 5% reflectance but within diagram of 5 degrees half-width. The results of such simulation are presented on fig. 4. We can see that the images formed by stray light are more or less similar in both cases of reflectance.



a) b)

Fig.4. The stray light illuminance distribution for different properties of mount surfaces: a) Lambertian reflectance; b) 5deg Gauss reflectance

But in case of Gaussian reflectance (fig. 4b) the illuminance of detector is essentially higher than in case of Lambertian one (fig. 4a).

## 4. Conclusion

The solution for physically accurate simulation of stray light scattered on diffuse surfaces in optical systems is elaborated. It is demonstrated that the developed software can correctly generate the image formed by stray light for different cases of reflectance distribution and therefore it can be used for sun and sky shades design. The elaborated software is embedded in software package Lumicept [6].

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