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Use of computer graphics methods for efficient stray light analysis in optical design

Dmitry D. Zhdanov*[a], Igor S. Potemin[a], Andrey D. Zhdanov[a], Alexey G. Voloboy[b]
[a]ITMO University, 49 Kronverksky Pr., St. Petersburg, 197101, Russia; [b]Keldysh Institute of Applied Mathematics, Miusskaya sq., 4, Moscow, 125047, Russia

ABSTRACT

The problems of using stray light visualization for the effective analysis and design of complex optical systems are considered. Examples of real applications are given where the use of the light propagation criterion in conjunction with the visual representation of the ray path makes it possible to effectively analyze complex optical design problems. The suggested solution allows not only to visualize source of the stray light in the optical system but alto to render the image on the detector taking into account diffuse scattering on all illuminated surfaces.

Keywords: stray light analysis and prevention, modeling, simulation, stray light, bidirectional stochastic ray tracing, image formation, optical design, computer graphics, 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 when the stray light can occur: a specular or Fresnel reflection from optical surfaces resulted in ghosts, diffraction on diaphragms or gratings, diffuse scattering on the unpolished lens surface, diffuse scattering on the surfaces of supporting structures within the optical system (baffles, mounts, struts, vanes), diffuse scattering on the 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 reaching 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.

The results of computer optical modeling are mainly presented as graphs, tables or images of distributions of such output light characteristics as brightness, illumination or intensity on radiation receivers[3]. Output optical characteristics are the direct result of optical modeling, observed at the radiation receiver. This form of representation of the result is convenient when we are primarily interested in the result of modeling itself, and not in how it was obtained, for example when modeling the brightness distribution on the surface of a liquid crystal display or the image formed by a photographic lens. However, when designing optical systems, it is often necessary to understand how the output was obtained, that is, how the light from the light sources hit the radiation receiver. For example, when analyzing scattered light in a lens optical system, you need to know which surface and which lens creates a glare in the image. To obtain information on how the light propagates in an optical system, it is most convenient to use the visualization of ray paths in that optical system. In addition, visual representation of the paths of light rays in the optical system is also useful for the software developer, for the mean of debugging and optimizing optical simulation algorithms[4].

For physically correct and effective modeling of the light propagation in optical systems, various ray methods are used. The most efficient method of simulation the light propagation in the optical system, which allows solving complex problems of light propagation in light-conducting optical systems with surface and volume scattering elements, is the method of forward Monte Carlo ray tracing. This algorithm was first proposed in[5] and then developed widely in optical modeling systems[6]. For optical modeling, the preferred form of the Monte Carlo method is the "Russian roulette"[1]. This method, on the one hand, has a simple program interface, and on the other hand it has quite high performance in modeling high-efficient optical systems. Forward Monte Carlo ray tracing method simulates the propagation of light rays from the light source to the radiation receiver and thereby statistically reproduces the distribution of illumination, intensity or brightness at the radiation receiver. The Monte Carlo method allows to simulate all the physical effects of ray propagation (diffuse scattering on surfaces, mirror reflection, refraction, polarization state change, birefringence, etc.).

*ddzhdanov@mail.ru; phone 7 921 747-44-74

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When designing optical systems, it is often necessary to determine the effect of the specified components of the optical system on the quality of the image or how these components affect the propagation of light. For example, when analyzing an illuminating system, it may be necessary to know what contribution to the output light distribution is made by light reflected from a particular surface of the system, or, for example, it is necessary to determine how the highlight between two surfaces of the lens optical system is formed.

The use of the Monte Carlo ray tracing method to simulate the propagation of light in optical systems is in good agreement with the possibility to analyze the influence of individual components of the system on the light propagation. When tracing rays, it is necessary to select only rays that satisfy a certain criterion. This criterion can be either simple, for example, to isolate all rays that have undergone a double Fresnel reflection, or more complicated, taking into account the order of events occurring with the ray in time, for example, first the ray must pass through a certain surface, and then undergo a double Fresnel reflection. The ray propagation criterion in the optical system can be used both for visualization of ray trajectories and for calculating the distribution of light characteristics on radiation receivers. The use of ray path criteria makes it possible to clearly demonstrate the effect of individual effects and components of the optical system on the propagation of light in an optical system.

Even if the forward Monte Carlo ray tracing method is rather good for light modeling it is not very effective solution for simulation of light scattering on diffuse surfaces. To effectively solve this problem, we designed the solutions 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 analysis and simulation in the typical lens systems.

2 RAY VISUALIZATION

When designing an optical system, it is required to analyze how light goes through this system, how rays forms an image on the image sensor or what path do rays have that form some effect visible on the final image. Figure 1a shows paths of first 1000 random rays emitted by sun propagating through an optical system. However, visualization of all rays traced through the optical system do not have too much sense. From the figure above, one can see that all rays emitted by sun that gets in optical system do not form glares on the luminance sensor. But if criterion of at least one reflection on the ray path and a hit with image sensor is specified a different picture shown on figure 1b would be seen.

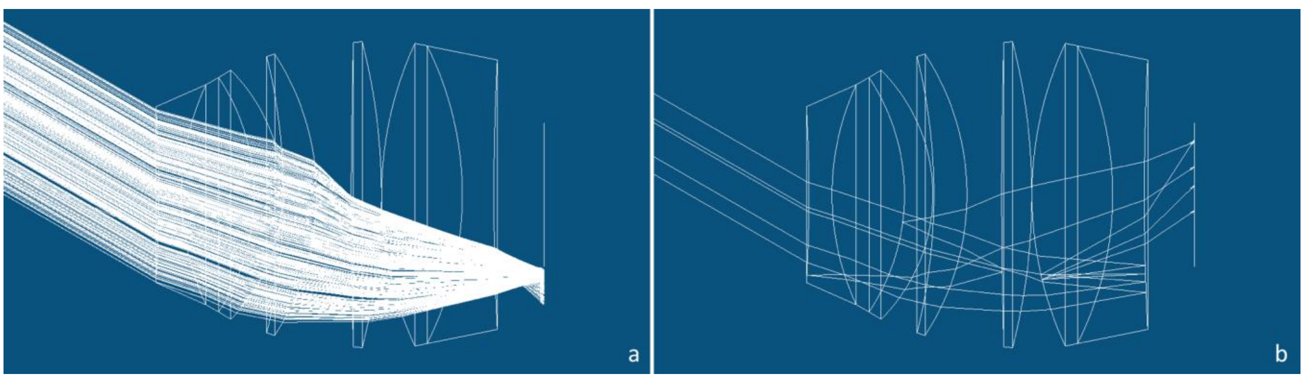


Figure 1. Visualization of a) first 1000 rays paths emitted by sun and traced through the optical system; b) first 1000 rays paths emitted by sun and traced through the optical system qualifying the criterion of two specular reflections

Now we can see that some of rays emitted by Sun hits the image sensor. The percentage of such rays is quite small, however, taking into the account that the Sun luminance is high and as result its influence on the final image formed on the image sensor might be clearly visible. To analyze light propagation in the optical system a criterion should be designed.

2.1 Ray selection criterion

When designing and analyzing the designed optical systems it is required to include in the special criteria into the optical modeling system that allows selection of rays that have certain properties and are the subject of analysis of the light propagation in that optical system. The light propagation criterion is a special program object that analyzes the history of beam propagation in the optical system and decides whether the specific ray satisfies the given criterion or not. If the ray meets the criterion, it is accepted by the optical modeling system and its path can be visualized on top of the optical system image. The light propagation criterion is closely related to the history of ray path in the optical system. The history of the ray path captures all the events that occur on the path of the ray from the light source to the end:

- emission the ray from the light source;
- ray path as a set of linear segments;
- color of the ray at each segment;
- an event that has occurred at the end of each segment:
    - ray emission;
    - ray reflection and its type;
    - ray refraction and its type;
    - volume scattering;
    - absorption on the surface or in media;
    - ray leaving the scene domain;
    - etc.
- scene objects corresponding to the occurred event;
- luminance or illuminance detectors that accumulated the ray energy.

Figure 2 shows two examples of ray propagation path in a reflector light source optical system.

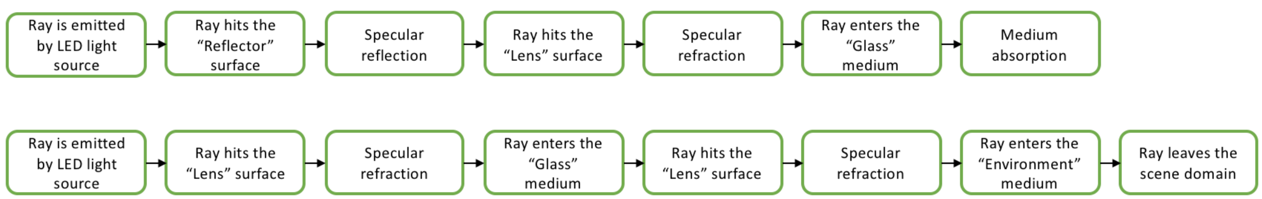


Figure 2. Ray propagation history examples.

To acquire the optimal interaction between the ray propagation criterion and its propagation history, the criterion is implemented as a tree which leaves are elementary events that should occur with the ray on its path and nodes of this tree are logical operations (AND, OR and NOT) that determine the logical connection between elementary events. Possible elementary events are based on the events that can occur in history of ray propagation in the optical system that simplifies the application of the ray path criterion to its history. The main events that criterion can analyze are:

- the ray is emitted from the specified light source;
- the ray hits the specified geometrical object;
- the ray hits the specified luminance or illuminance detector;
- the ray hits a surface with specified optical properties or a medium;
- the specified event occurs with ray.

For each elementary event a counter can be specified that adds a requirement on number of occurrence of this event in ray path history. In addition, a special sequence node can be added to a tree that requires that all its children occur in a specified order. For example, this allows to select rays that before hitting the lens surface either secularly refracts or hits the glass medium. The corresponding tree is shown on figure 3.

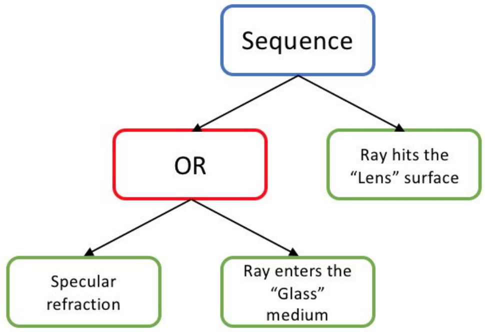


Figure 3. Ray selection criterion example.

Second sequence from figure 3 qualifies this criterion while the first one does not.

For quick execution of the criterion check, the regular expression is commonly transformed into a finite state machine. However, the number of states of that finite state machine increases exponentially with the number of nodes in the criterion tree. Using this approach on real ray path criteria, the number of states of the finite state machine becomes extremely large. So, we have developed an original method for checking if the ray path history qualifies the criterion. The developed method must have high performance and low memory requirements. The following testing method is proposed:

- The sequence of events is checked using the criterion tree described above. Each tree node can be in one of three possible states: "true", "false" or "undefined ". As soon as the state of the root node of the tree changes from "undefined" to "true" or "false," the calculation terminates, and the state of the root node is taken as the result of the criterion checker work.
- The elements of the sequence of events are applied alternately to the ray propagation criterion tree. Each element of this sequence sets "true" values in the corresponding "undefined" tree leaves when the following conditions are met:
    1. The event condition specified in the tree leaf fulfils the next element of the sequence of events.
    2. All parents of this leaf are in the "undefined" state.
    3. If among the parents of this leaf there is a time sequence condition, then all direct children of the time sequence condition located "to the left" of direct leaf parent should be in the "true" state.
- When the value of any node in the tree is changed, the value of its parent node is recalculated. As a result, the parent node can either change its value from "undefined" to "true" or "false" or leave it untouched.
- In the case when the criterion remains in the state of "undefined" at the end of the sequence of events, all leaves of the criterion tree which are still in the "undefined" state are assigned the "false" value and the result of the criterion calculated.

2.2 Simulation results

One of the basic requirements for image quality formed by lens optical systems is absence of the parasitic lighting. More often the parasitic lighting in optical systems is formed either as a result of light interreflections between lens surfaces, forming ghosts, or as a result of diffuse scattering of optical elements like for example lens mounts or butt ends.

To analyze the ghosts in the lens optical system a special criterion for the ray path in the optical system should be used. The criterion consisted of three successive events-the reflection of the ray from the back surface of the fourth lens, then the reflection from the front surface of the fourth lens and, finally, the hit with the image sensor. To analyze the diffuse scattering on the lens mounts, a criterion consisting of two events was used: diffuse scattering on the mounts of lenses and hit with the image sensor. Figure 4 demonstrates simulation results with possible paths of the parasitic rays in the lens optical system with the corresponding output distribution of parasitic illumination that was added to the final image due to light scattering on the lens surfaces and mounts.

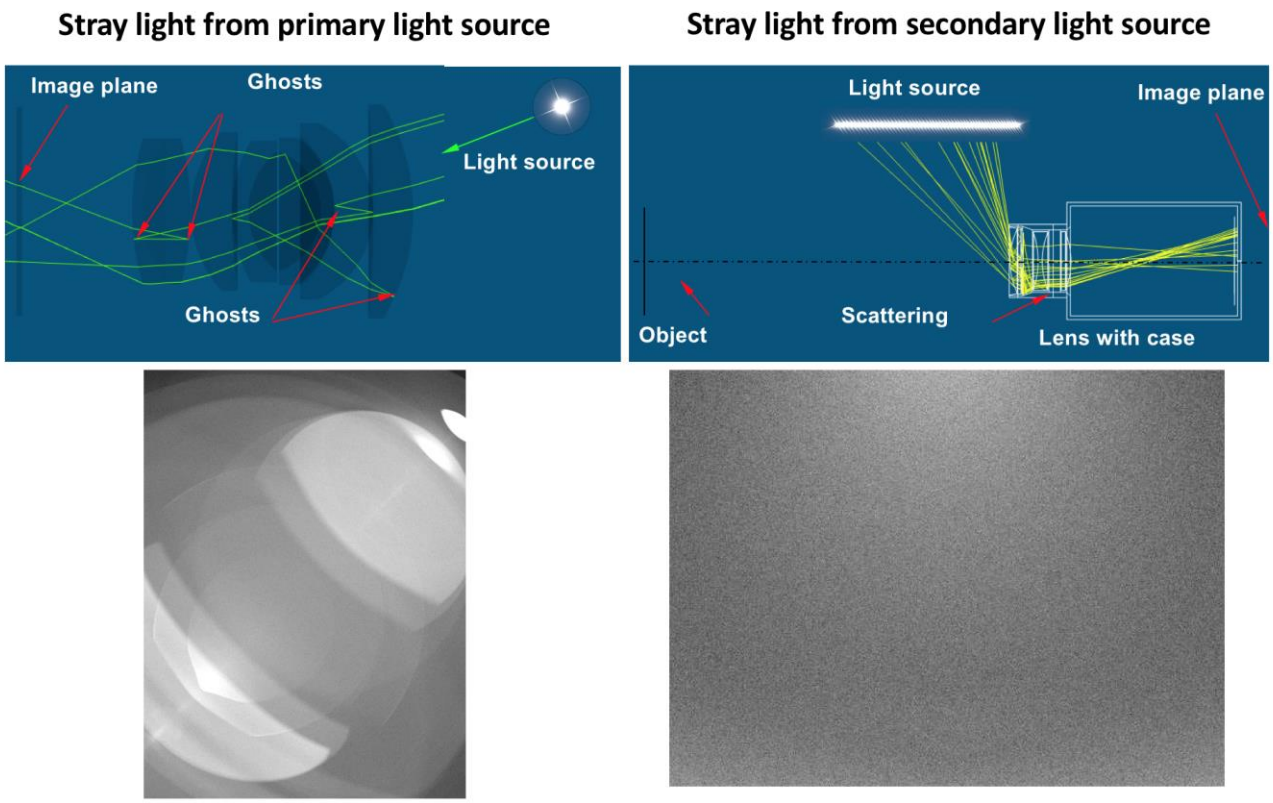


Figure 4. Stray light in lens optical systems formed by the interreflections from the lens surfaces and the scattering on the lens mounts.

These examples show the simplest cases of parasitic light analysis. Figure 5 demonstrate the flexibility and simplicity of the criterion for the paths of the ray that makes it possible to analyze any sources of parasitic light, both composite (all ghosts of all orders) and individual (ghost of a given order between given surfaces).

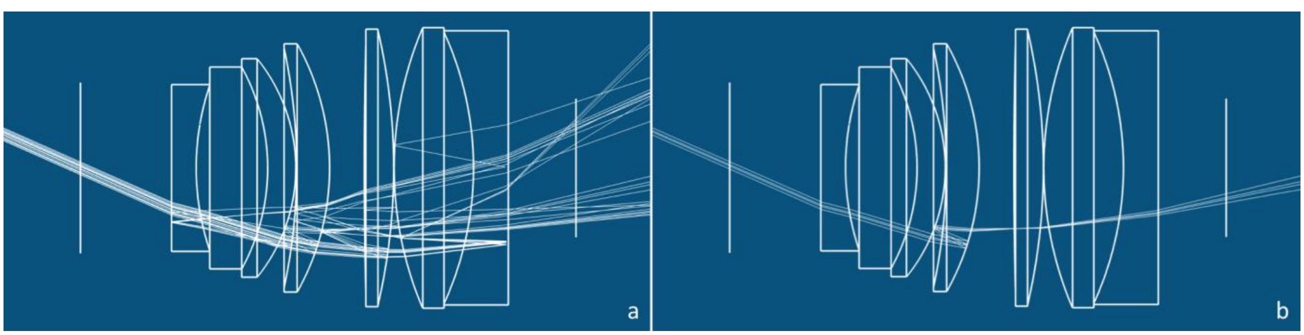


Figure 5. Stray light in lens optical systems formed by a) the interreflection from lenses; b) the interreflection from the forth lens only

In addition, this flexibility allows specifying the source of light scattering for investigation. The following figure 6 shows how source of scattering can be investigated with ray path criterion specification.

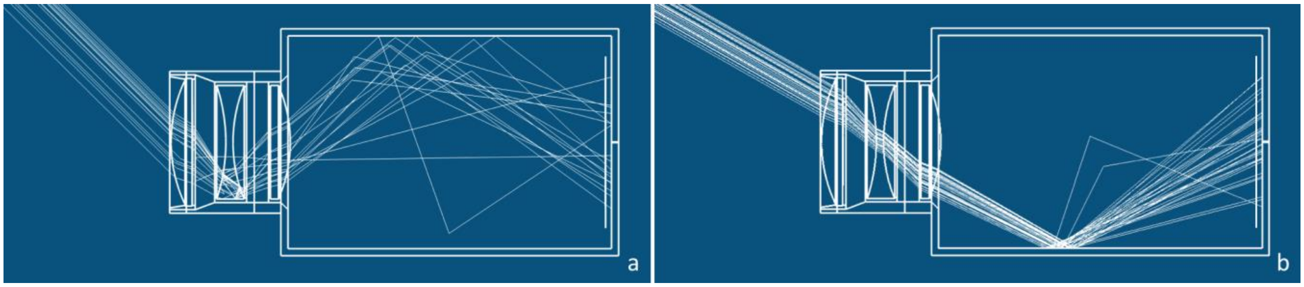


Figure 6. Stray light in lens optical systems formed by a) the scattering on the lens butt ends; b) the scattering on the lens case.

3 STRAY LIGHT SIMULATION

For stray light analysis caused by surface scattering the most important unwanted luminance component is the secondary and caustic luminance. Physically accurate calculation of the light scattering on diffuse surfaces is provided by the rendering equation[7].

For static scenes, the luminance of the color component of the object c at the point of the surface $\overrightarrow{p}$, with the local normal $\vec{n}$ and in the direction $\vec{v}$, can be written as following:

$$L(\vec{p},\vec{v},c) = \tau(\vec{p},\vec{v},c)\left(L_0(\vec{p},\vec{v},c) + \frac{1}{\pi}\int\limits_{4\pi} BSDF(\vec{p},\vec{v},\vec{v}',c)L(\vec{p},\vec{v}',c)(\vec{n}\cdot\vec{v})d\omega\right) \tag{1}$$

where $L_0(\vec{p},\vec{v},c)$ is the own object luminance in an observation point,

$\tau(\vec{p},\vec{v},c)$ – the transmittance (transparency) of the medium between the observer and the observation point

$\frac{1}{\pi}\int_{4\pi} BSDF(\vec{p},\vec{v},\vec{v}',c)L(\vec{p},\vec{v}',c)(\vec{n}\cdot\vec{v})d\omega$ – the luminance formed by primary and secondary illumination of the observed object,

where $BSDF(\vec{p},\vec{v},\vec{v}',c)$ is the luminance factor of the surface (or Bidirectional Scattering Distribution Function (BSDF)) from the source $\vec{v}'$ in direction $\vec{v}$ to the observer,

$L(\vec{p},\vec{v}',c)$ – the luminance of the light sources in a solid angle $d\omega$ in the direction $\vec{v}'$ to the observation point $\overrightarrow{p}$.

To solve rendering equation, the following three basic methods of stochastic ray tracing are applied:

- forward stochastic ray tracing[8];
- backward stochastic ray tracing[9];
- bidirectional stochastic ray tracing[10].

The choice of the ray tracing method depends on the region in which the integration can be performed most efficiently; i.e., the effective region of integration is maximal. In turn, the effective region of integration is determined by parameters of the observer, light sources, and optical properties of the optical system elements.

If contribution of secondary lighting to the integral luminance value is essential then the most appropriate method for solution of the rendering equation is the bidirectional stochastic ray tracing.

The bidirectional stochastic ray tracing is a sequential stochastic tracing of backward and forward rays and special processing of saved paths. In the result of the ray paths processing the following four sources of luminance are formed:

- visible luminance of light sources; i.e. the luminance formed by traces of backward rays without any diffuse scattering;
- primary or direct luminance; i.e. the luminance formed by lights directly illuminating the point of observation;

- caustic luminance; i.e. the luminance of directly viewed diffuse objects formed by light sources which illuminate the point of observation without scattering;
- secondary luminance; i.e. the luminance formed by diffusively scattered rays with two or more scatterings on the traces from light source to the point of observation.

Bidirectional stochastic ray tracing combines all the main advantages of the forward and backward ray tracing and, in addition, allows to find out the most suitable point for the integration of secondary luminance. For effective calculation of caustic luminance component this method should be extended with possibility to form secondary and caustic illuminances on the photon maps and recalculate them into the visible luminance.

We elaborated the algorithm of bidirectional stochastic ray tracing which includes two stages (see Figure 7). On the first stage backward rays are traced and the direct luminance and the luminance of directly visible light sources are calculated. Also, the photon maps as an array of spheres of integration with centers in the point of intersection of backward rays with diffuse surfaces of the optical system are stored. On the second stage, the forward rays are traced and the secondary and caustic luminances are calculated in the areas of intersection of the forward rays with the photon map that were stored on the first stage as the spheres of integration.

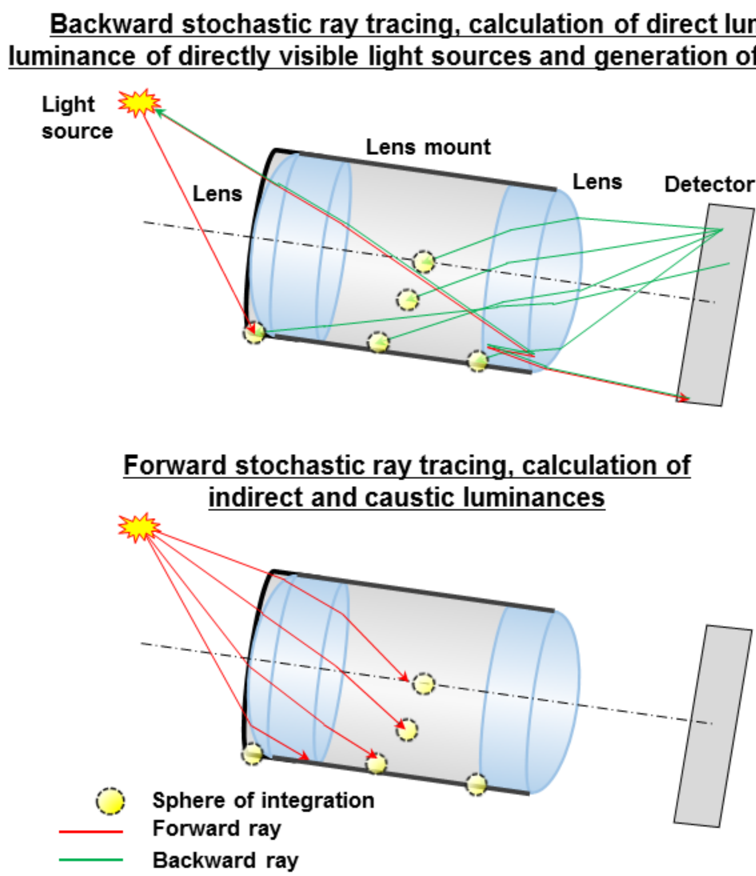


Figure 7. Two stages of bidirectional stochastic ray tracing with photon maps algorithm.

Integration of the calculated luminance of detector point over whole exit aperture allows calculating detector illuminance and repeating the illuminance calculation for all points of detector. It allows to render image created from stray light illumination. Generally, bidirectional stochastic ray tracing with photon maps allows to solve the rendering equation in a physically accurate way. But taking limited computer resources into account equations can be solved only for limited number of forward and backward rays (usually up to tens millions). Usually this number is not sufficient for accurate solution so the simulation process (backward ray tracing, photon map creation, forward rays tracing, and luminance calculations) is repeated and temporary results are accumulated while required simulation accuracy is reached. Stochastic approach of simulation process has a number of advantages. At first, average detector illuminance gives correct value from the first accumulation steps that allows to estimate general parameters of stray light (transmittance of the optical system for stray light illumination) from the beginning. At second, the simulation process can be continued if accuracy of calculated illuminance distribution on light detector is not sufficient.

For stray light analysis of the optical system, the main components of parasitic illumination are caustic and indirect one. The main factors to influence on accuracy of indirect and caustic illuminance calculations are probability of intersection of paths of forward rays with integration spheres (photon maps of backward rays). So in the case of uniform BSDF the method of bidirectional ray tracing allows calculation of stray light illuminance from very dark surfaces with the same efficiency as light ones. For example, computation time to reach the same accuracy of the stray light illuminance distribution for optical system with specially covered lens mount and reflectance about 0.1%, and not covered components of the lens mount and reflectance about 30% will be the same.

The bidirectional stochastic ray tracing solution was integrated in Lumicept software package[10] and efficiently used for stray light analysis of different kinds of optical systems.

3.1 Simulation results

The current article presents the results of the stray light modeling with the help of the developed methods and algorithms for two different optical systems:

- 6-lenses long-focus lens system;
- 2-lens 2-mirror ultra-long-focus catadioptric lens system.

First lens is 6-lenses optical system with 360mm focal length (f/7) and ±5° rectangular field of view (FOV). The light source is the Sun that illuminates the lens entrance pupil from an out of the field of view under an incident angle $\omega_{Sun} = 7°$. As the field of view of the simulated lens ($\omega_{FOV} = 5°$) is less than ω_{Sun} so the detector does not see the Sun directly. General setup design is shown on figure 8.

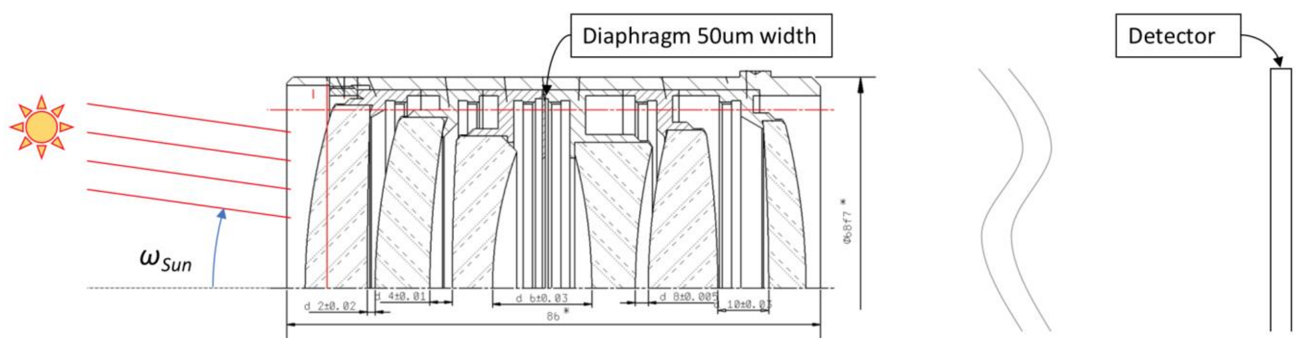


Figure 8. 6-lensel long-focus lens general design with an out of view field light source.

The light from sun can reach the detector only if it is scattered on some element of the lens system. In given simulation we took into account only stray light scattered on diffuse surfaces of lens system components (mounts and unpolished lens butt end surfaces). All image forming optical surfaces are assumed to be covered with perfect antireflection layer so no reflection should occur on the clear lens surfaces.

Figure 9 shows simulation results of the caustic illuminance distribution from the Sun light scattering on the edge of aperture diaphragm. This edge has 50 um width and 10% Lambertian scattering. Excepting the diaphragm edge all other diffuse surfaces were considered as absolutely absorbing. Calculation time was 6 hours and 33 minutes.

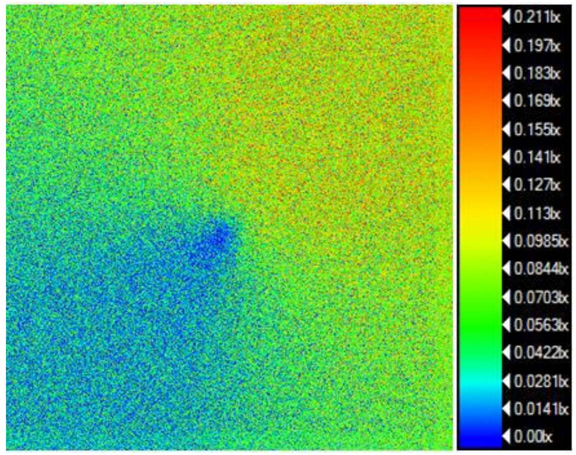


Figure 9. Stray light illuminance distribution on the detector in case of Lambertian scattering on the aperture diaphragm.

Figure 10a shows simulation results of the caustic and indirect illuminance distribution from the Sun light scattering on the optical system lens mounts and lens butt ends. In this simulation all lens mounts and butt ends scatterings are set to 5% Lambertian. Diaphragm edge was considered as an absolutely absorbing. Calculation time was 18 hours and 30 minutes. Figure 10b shows simulation results of the caustic and indirect illuminance distribution from the Sun light scattering on the optical system lens mounts and lens butt ends. In this simulation all lens mounts and butt ends scatterings are set to 5% Gaussian with 5° half-width diagram. Diaphragm edge was considered as an absolutely absorbing. As in the previous case, the calculation time was 18 hours and 30 minutes.

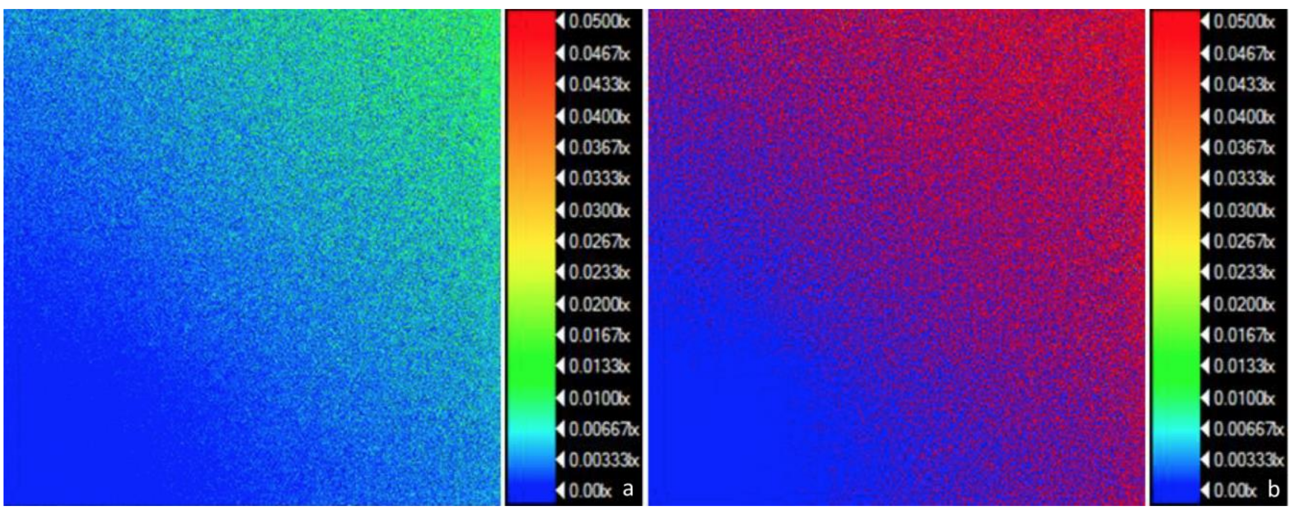


Figure 10. Stray light illuminance distribution on the detector in case of a) Lambertian scattering on the lens mounts and butt ends; b) Gaussian scattering on the lens mounts and butt ends.

From simulation results it can be clearly seen that the images formed by stray light are more or less the same in both cases of scattering on lens mounts and butt ends. But in spite of such a similarity in case of Gaussian reflectance the illuminance of stray light on the detector is essentially higher than in case of Lambertian one.

The second lens is a two-mirror Catadioptric optical system with 2000mm focal length (f/10) and 1°15′field of view. The entrance window of the lens system is uniformly illuminated inside of 3.25° cone. Total flux of the illumination is 0.079833lm. Its general design with illumination setup is shown on figure 11.

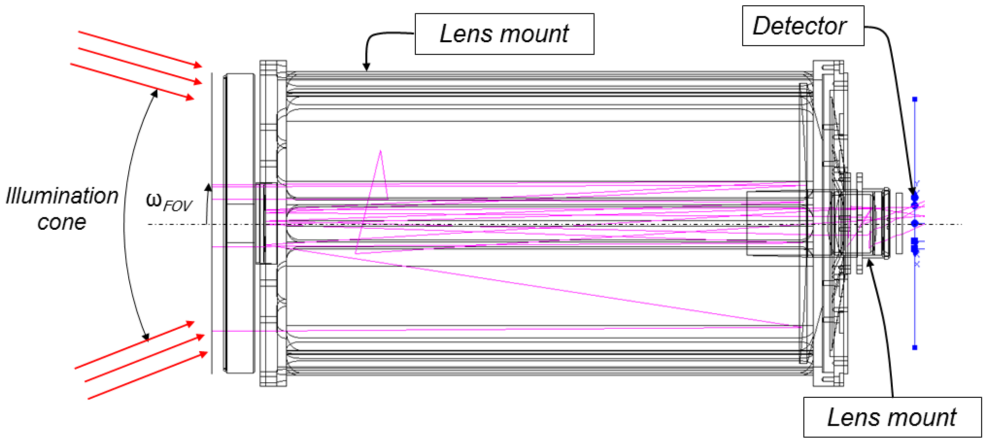


Figure 11. Catadioptric two-mirror lens general design and illumination setup.

The simulation goal was to simulate indirect and caustic components of stray light illumination of detector caused by diffuse scattering on the lens butt ends and mounts. Two independent simulations were performed to find out the stray light cause:

- simulation of light scattering on the lens butt ends and mounts;
- simulation of light scattering on the lens butt ends only.

Figure 12 shows simulation results of the light scattering on the optical system lens mounts and lens butt ends. In this simulation all lens butt ends are diffuse surfaces with 50% diffuse transmittance and 50% diffuse reflectance; lens mounts are almost absolutely absorbing with only 1% diffuse reflectance; lens surfaces are clear with 1% specular reflectance. The calculation time was 8 hours and 33 minutes.

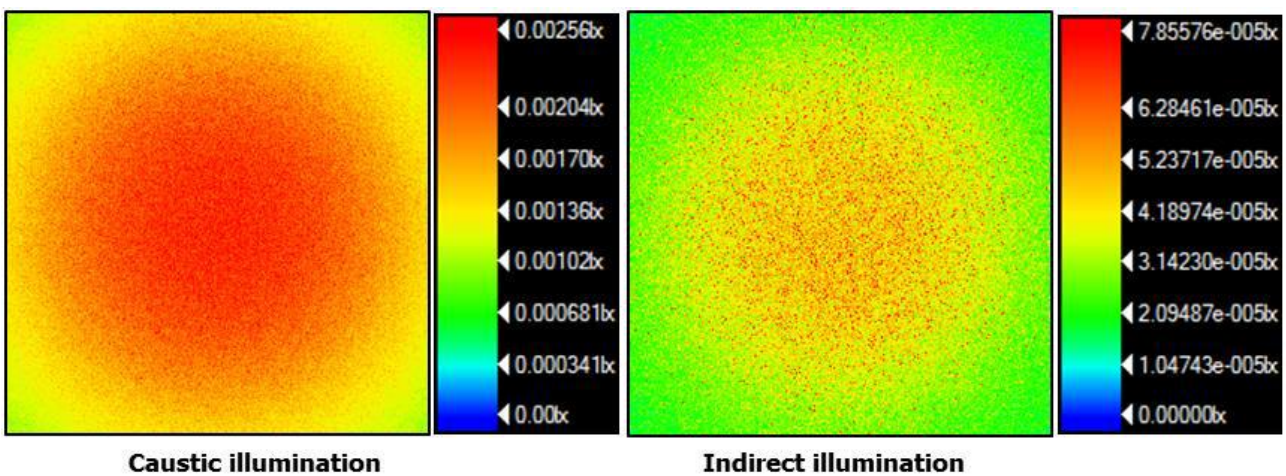
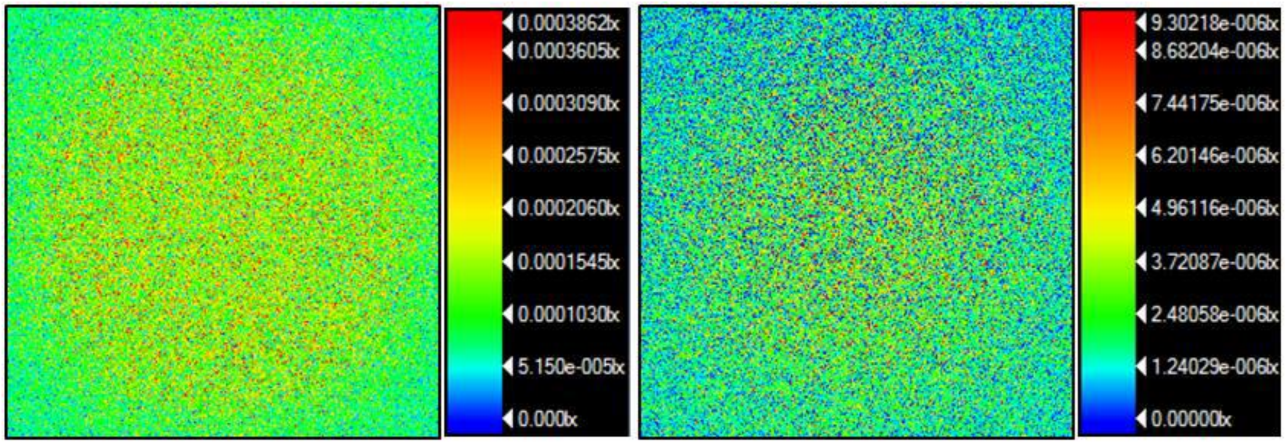


Figure 12. Stray light illuminance distribution on the detector in case of scattering on the lens mounts and butt ends.

Figure 13 shows simulation results of the light scattering on the optical system lens butt ends only. In this simulation all lens butt ends are diffuse surfaces with 50% diffuse transmittance and 50% diffuse reflectance; lens mounts are absolutely absorbing; lens surfaces are clear with 1% specular reflectance. The calculation time was 22 hours and 57 minutes.



Caustic illumination **Indirect illumination**

Figure 13. Stray light illuminance distribution on the detector in case of scattering on the lens butt ends.

From these simulation results we can see that level of light scattered on the lens butt ends that reached the detector is essentially lower than stray light level from mount parts of the lens optical system.

4 CONCLUSION

The computer graphics technology methods provide quite good results in visualization of stray light in complex optical systems. The physically correct method of stochastic bidirectional ray tracing with photon maps was elaborated that allows simulating stray light caused by scattering on the diffuse surfaces of optical systems.

The elaborated solution provides physically accurate and high-efficient rendering of the parasitic light (sky and sun, for example) scattered on lens mount and other scattering elements of the optical system.

All of the elaborated solutions were integrated in the Lumicept software package[11] and can be successfully used for stray light analysis and simulation.

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