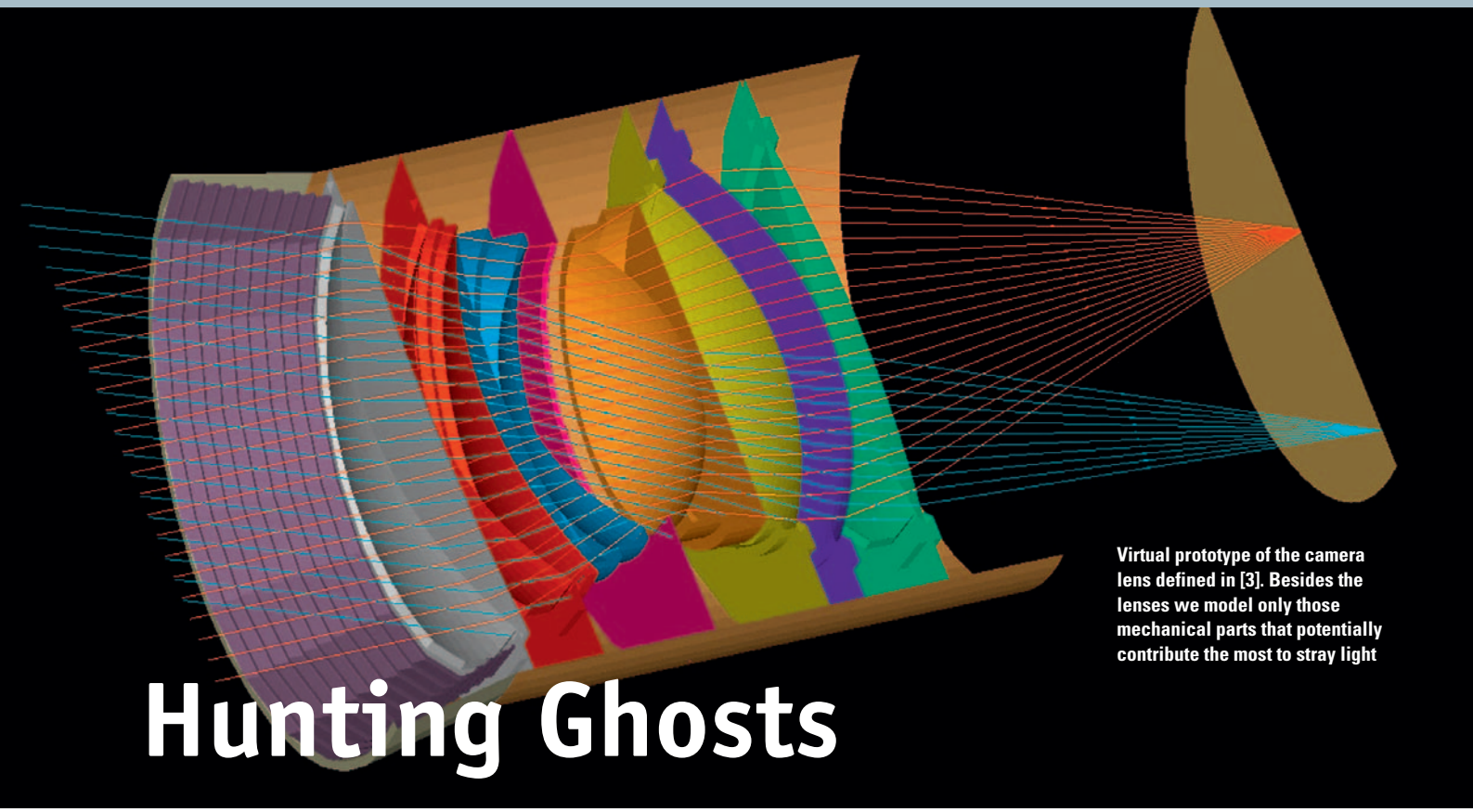


Virtual prototype of the camera lens defined in [3]. Besides the lenses we model only those mechanical parts that potentially contribute the most to stray light

Hunting Ghosts

STRAY LIGHT ANALYSIS IN IMAGING OPTICS

Imaging systems that have been developed with lens design programs are often not suitable for real-world applications. Light scattering at the mechanical and optical surfaces, as well as multiple reflections, often deteriorate image quality to an extent that system specifications are no longer met. If one carries out a stray light analysis early enough, measures to improve stray light performance can be smoothly integrated into the design process.

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BERNHARD MICHEL

For the development of imaging optical systems, for example, lenses, telescopes and microscopes, so-called sequential ray tracers (›lens design programs‹) have been used successfully for decades. In sequential ray tracing, rays hit surfaces in a prescribed order. The system quality parameters, such as spot size, field distortion and curvature as well as other aberrations can be calculated easily and quickly. Sequential ray tracers are therefore ideally suited for optimization of imaging systems. Specifically, this applies to the iterative adjustment of the system data such as vertex positions, radii of curvature or glass types of the lenses, until the process has reached a local or – within the boundary conditions – a global optimum. System tolerances can be analyzed with such a program rather elegantly too.

Sequential ray tracing, however, neglects the following physical phenomena:

- Both lens surfaces as well as the mechanical ›environment‹ of the lenses (lens mounts, beam stops, housing) scatter light. A part of this stray light may reach the image plane. Often, this causes a diffuse, unstructured background. But sharp features (hot spots) may be present too.
- Lens surfaces, but also the detector (for example, the film or CCD-Chip) reflect a certain fraction of the light. By way of multiple reflections, this reflected light may hit the image plane. In addition to the original image, a superposed, blurred, ghost image may appear in the image plane. Often the main cause of such ghosts is the detector itself (so called narcissism).

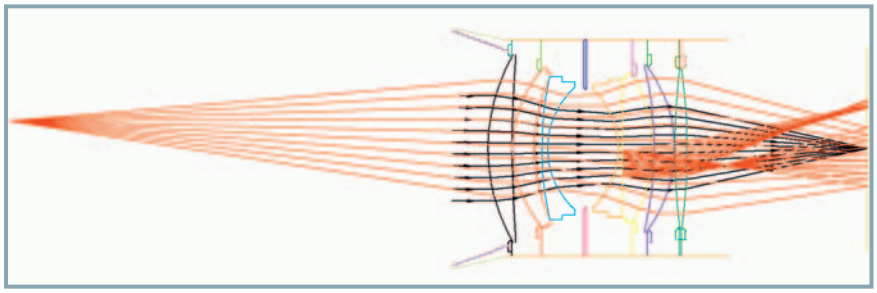
Fixing the prototype can be risky

Light that has hit the image plane through scattering or reflections is called stray light. The source for it can be the imaged object itself, but also other light sources, for example street lights, when observing the firmament with a telescope. In the latter case, the stray light reaches the image plane indirectly, typically through scattering off mechanical parts of the system.

Also other effects like diffraction, birefringence and absorption may influence the image quality negatively, but will not be discussed here.

Frequently, the design developed with sequential ray tracing already constitutes the basis for the prototype. Stray light problems are then studied experimentally using the prototype while hoping that small enhancements suffice to arrive at a fully functional imaging system. With enough experience, this approach may work. However, it bears serious risks:

- If many enhancement steps are needed to fix the problems, the development will be time consuming and expensive.
- Often there is no systematic experimental method to find the source of the problem.
- A comprehensive experimental study of the stray light is too laborious in most cases, because the parameter space is too large (stray light sources at all angles and distances etc.).
- In the worst case, it is impossible to fix the problem with the existing resources in order to meet system specifications. You run the risk that the project fails completely.



1 Ray path for selected pairs of reflections

Better use a virtual prototype

The safest, most efficient and, therefore most recommendable method to evaluate stray light is the analysis of a virtual prototype. With this approach, stray light problems become apparent on the computer and they can often be fixed before having assembled the first real-world prototype. This saves time and costs and makes the progress of the project easier to calculate. Stray light analysis with virtual prototypes can be considered as insurance, which helps to avoid project risks and, thus, economic harm.

So-called non-sequential ray-tracing programs model light propagation in a physically correct manner, and are therefore ideally suited for the simulation of virtual prototypes. The ray path through the system is not fixed beforehand. Rather the ray tracer computes which physical object is hit next during propagation. The term ›physical object‹ refers both to lenses with realistic surface and material properties as well as all mechanical parts of the system. Examples include lens mounts and beam stops, which in most cases are imported from CAD programs.

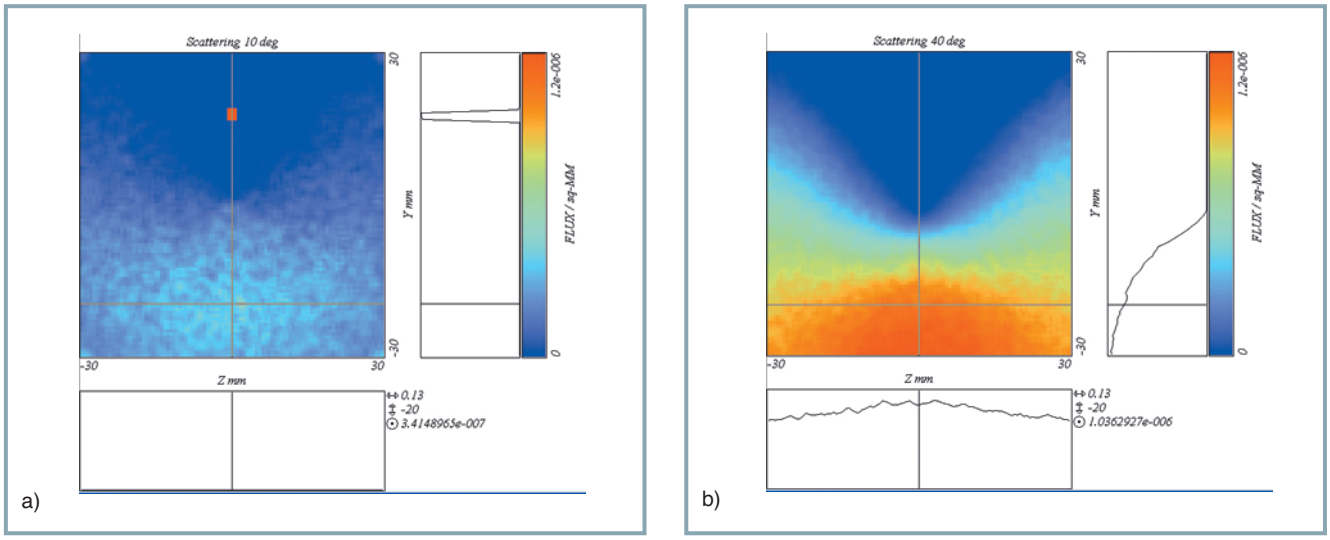
Non-sequential ray tracers take into account both reflection at surfaces and diffuse scattering. Ideally, the scattering models are based on measured data of the BSDF (bi-directional scattering distribution function). Since both reflection at surfaces and scattering may increase the number of rays in the system dramatically, suitable stop criteria (maximum number of reflections, scattering events per ray) are needed to ensure that the simulation is completed within an acceptable timeframe.

Complete reconstruction of the ray path

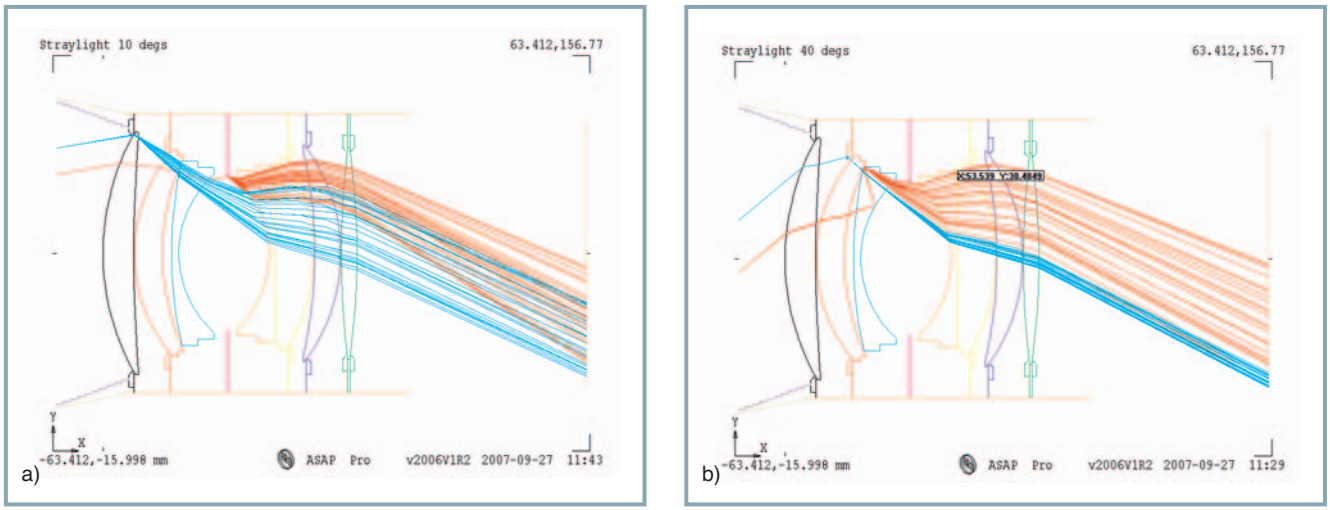
Non-sequential ray-tracing programs not only predict the intensity distribution of the stray light in the image plane, but also allow for a complete reconstruction of the stray light paths.

Suitable strategies make it possible to analyze and locate all sources of the stray light systematically. The effect of corrective measures can be analyzed in this way, too.

In this context it is important to ensure that the utilized non-sequential program supports all these analysis features. Flexibility and the possibility to automate analysis tasks are further important criteria for selecting suitable software. The latter is important, because complicated opto-mechanical systems frequently consist of thousands of objects, which makes a ›manual‹ analysis all but impossible. A powerful scripting language, which ▶



2 **Scattered light distribution in the image plane for collimated light under an angle of incidence of a) 10° and b) 40°**



3 **Ray paths which contribute the most to the scattered light in figures 4a and 4b**

supports automated tasks, is definitively an advantage.

For the following application example, we use the gold standard of non-sequential raytracers, the Advanced System Analysis Program ASAP from Breault Research Organization (BRO). One the original motivations to develop this software tool was to perform stray light analyses in aerospace applications. ASAP therefore offers the necessary ›infrastructure‹ for stray light analysis from the very beginning. An excellent overview of stray light analysis with ASAP can be found at BRO's multimedia gallery web site [4].

Stray light analysis of a camera lens

As an example, we use an existing, freely accessible design of a camera lens [3]. For making it into a virtual prototype, an automatic script adds (in the essential details) realistic lens mounts, a simplified housing and lens edges (figure 1).

We assign suitable anti-reflection coatings to the lens surfaces, and a realistic matt black scattering model to the painted edges of the lens. We model not all mechanics parts, but only parts in direct proximity of the ray path, because those are usually the main cause for stray light problems. The specular reflectivity of the detector, in our example the film, is considered in the model as well. The lens is adjusted to infinite focus with aperture f/1,4.

Hunting ›ghost lights‹

We set up the complete mechanics design only after the stray light analysis. In this way, we iteratively approach the optimal design by updating the the virtual prototype.

Ghost images result from multiple reflections. If no mirrors are in the ray path, at least two reflections are necessary for producing ghost images on the detector. Reflections of still higher order can likewise make a contribution, however, they are usually clearly weaker and negligible in imaging systems, unless total internal reflection occurs. Therefore we confine our search to ghost images of second order, permit however in addition total internal reflection of arbitrarily high order.

Figure 2a shows the light distribution of the ghost images in the image plane. Here we assume a white point source at infinite distance and at an angle of 10° from the optical axis (vertical field of view ±17°). We can clearly distinguish several different reflexes, partly on the same side as the image of the point source, and partly, in addition, on the opposite side. The reflexes differ concerning their inte-

gral power and their distribution in the image plane. Because of a high spectral resolution in the simulation run, reflex colors and color fringes are clearly shown.

In the majority of applications, focused ghost images are particularly disturbing. By means of path analysis, it is simple to identify the different reflexes. **Figures 2b** to **2f** show the isolated causes of the strongest reflexes: b) reflection at the back of the lens 2 (L2R) and the front of lens 6 (L6V), c) L6V+L7V, d) L2V+L7R, e) L1V+L5R. The double reflection at the film and any one of the lens surfaces is particularly pronounced (**figure 2f**). Here, the dominating surfaces are L7V, L6V (bright, overlapping areas) and L2R (gray surrounding area).

Hunting ghosts in reverse gear

With this method it is hardly possible to predict the ghost images for all camera settings. If the main concern is to avoid focused reflexes, however, we can run the simulation in reverse; that is, we set a point source into the image plane, sends the light through the lens backwards, and determines the foci of all ghost images in the object space. Because of the reversibility of the optical path, point sources at this foci produce focused ghost images in the image plane (**figure 3**). There is a number of further analysis methods which cannot be dealt with here.

CONTACT

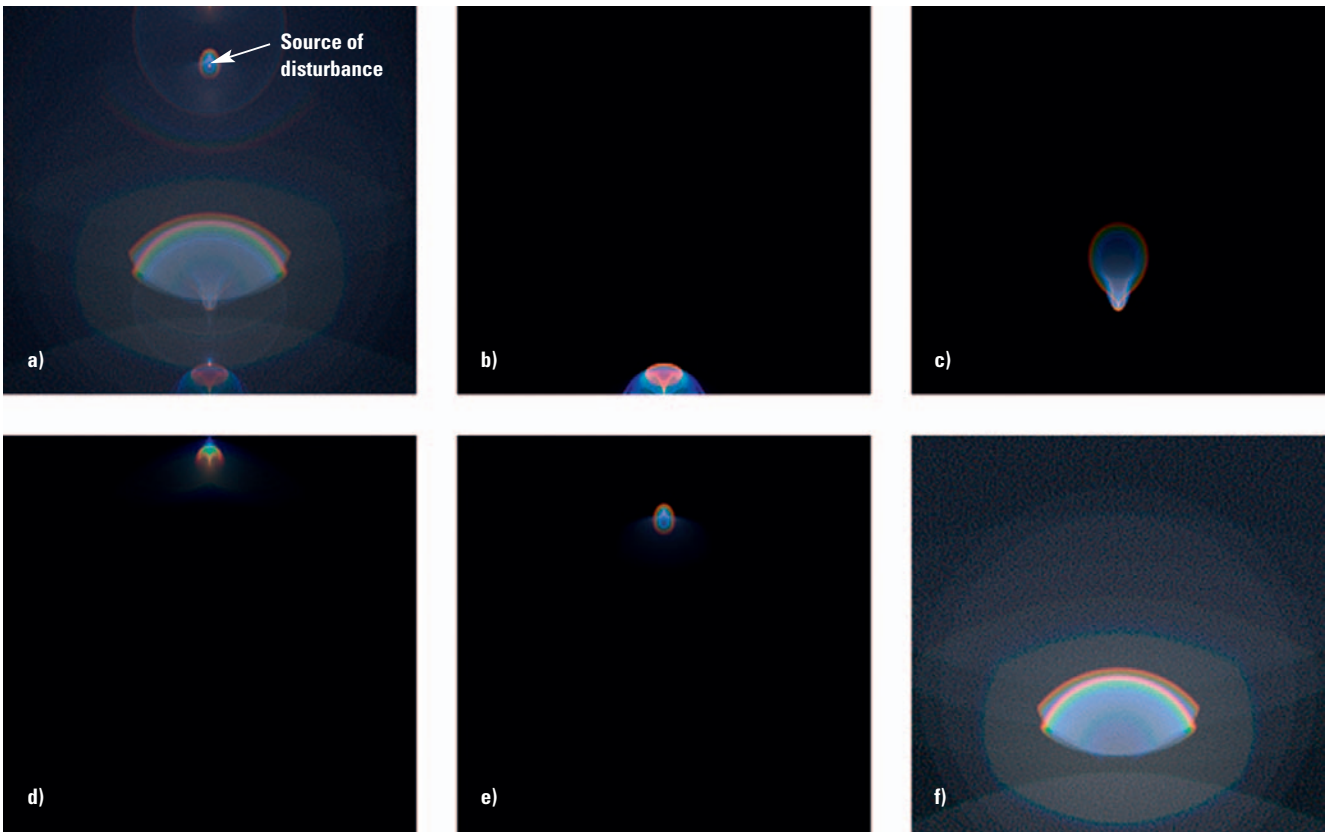
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In order to weaken the most pronounced ghost images, a slight redesign of the lens system is often already sufficient. With respect to ghost images, the imaging characteristics of otherwise equivalent designs often differ completely. Ideally we have several alternative designs available, from which to select the best one with regard to reflexes.

On the trail of scattered light

For the sake of simplicity, we confine the analysis to light that scatters at mechanics parts once, and otherwise reaches the image plane unweakened; that is, directly or over single or multiple total internal reflection. If a ray of light hits a mechanics part, scattered light emerges. We model this light by one or more rays, which are traced through the system. Here it is crucial to generate only such scattered rays that are at least highly likely to hit the the detector in the image plane (importance sampling). All other rays would have no influence on the image quality. They only would waste computing time, sometimes so much that any prospect to perform a meaningful stray light analysis vanishes.

A rule of thumb with regard to stray light analysis says that one typically locates 90 percent of the stray light causes in 10 percent of the time. In the case of simple systems with moderate performance requirements (as in the example treated here), a few days for one stray ▶



4 a) Light distribution of the ghost images in the image plane in realistic color representation (CIE color model); b) to f) the contributions of individual pairs of reflections

light analysis may suffice. With complex high performance optics, however, a stray light analysis can take also several months per iteration step.

When importance sampling for the scattered rays has been set up, the actual stray light simulation can begin. This analysis (light distribution in the image plane, identification of the scattering objects) resembles the ghost image analysis. Figure 4a shows the distribution of scattered light in the image plane, whereby the same source of light as before is used. Figure 4b shows the distribution of the scattered light, if we place the point source 40° from the optical axis, which is far outside of the field of view of the lens. Figures 5a and 5b represent the two paths of rays which contribute most to the scattered light in Figures 4a and 4b, respectively.

For reducing scattered light, a number of techniques are available. For example, one can chose to increase selected lens radii, in order to move particularly strongly scattering mechanics parts further away from the ray path, or one can reduce the scattering surface – for example by reducing the radii of curvature of the scattering lens mounts, or their angle of inclination, script-steered. One evaluates the success of such measures then again with a modified virtual prototype.

Simuloptics distributes the non-sequential raytraycing software ASAP in the name of BRO and performs on request ghost image and scattered light analyses.

Summary

Performing stray light analyses using virtual prototypes helps to predict stray light problems reliably and to develop counter-measures, before a real prototype has been built. This saves time and costs and makes the further course of the project better calculable. The non-sequential ray tracing software, ASAP offers efficient tools for the investigation of ghost images and scattered light. Due to its flexible script language and high computing speed, it is particularly well suited for stray light analysis. ■

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