Software for system-level analysis of space optical instruments

Bernhard Michel[1,*] and *Saroj* Mahalik[2]

[1]Hembach Photonik GmbH, 91126 Rednitzhembach, Germany
[2]European Space Agency, ESTEC, 2291 AZ Noordwijk, The Netherlands

Abstract. The optical software RayJack ONE® is a non-sequential ray-tracer currently being developed by Hembach Photonik under an ESA contract. The development goal is to better meet the needs for optical analysis in space industry by offering innovative techniques for stray-light simulations, comprehensive tools for optical analysis and the capability to simulate deformed optical surfaces imported from FEM software. The talk highlights novel simulation techniques, including differential ray-tracing, advanced importance sampling and a new approach to multiple scattering simulations. Methods for representing deformed geometries are discussed and demonstrated.

1 Introduction

1.1 Optical analysis needs of space industry

Design and optimization of an optical instrument is commonly performed with sequential ray-tracing software. The latter can predict only its *nominal* behavior, which may significantly differ from its *non-nominal*, "real-world" performance for the following reasons:

1. Stray light, which is unwanted light entering the system, can severely compromise optical system performance. It is caused by ghosting (multiple reflections), light scattering from optical and structural components, diffraction and—for IR systems—thermal self-radiation.

2. Thermal and mechanical deformations of the optical instrument may also have a critical impact on system performance.

1.2 Simulating non-nominal optical performance

The non-nominal behavior of an optical instrument is simulated with optical system analysis software based on non-sequential raytracing. One challenge for such software is that it must be able to handle input data from very different provenance, including lens design data, CAD models of the mechanical structure, scattering properties of surfaces (BSDF data), deformed geometry data from FEM simulations, and—possibly—"non-optical" data affecting the total system performance such as sensor noise. Since not all this input is standardized, the software must be easily adjustable to input data formats by a sufficiently experienced user. Another challenge is to set up correct and comprehensive physical models describing the interaction of light with opto-mechanical components. Moreover, the software must produce meaningful results within a reasonable time. Finally, a comprehensive set of analysis tools is required, with sufficient flexibility to adjust it to non-standard situations.

1.3 Software development activities

For efficient optical system analysis, it is necessary to have one single software tool, not a *set of tools*, that meets all these requirements at the same time. The European Space Agency ESA has awarded Hembach Photonik GmbH with a contract to develop such a tool, based on the non-sequential ray tracer RayJack ONE® which has been in development since 2012. Its user interface uses Python as scripting language to guarantee maximum flexibility. The architecture of the software, in these early stages, has already been designed to be extensible to a comprehensive optical analysis tool.

In the following, we highlight some of the features that have been implemented successfully into RayJack ONE during the project which address the needs of space industry. We focus on its stray-light analysis capabilities as well as on the modelling of deformed optical surfaces.

2 Stray light analysis

Assuming a sufficiently well-designed optical instrument, one characteristic of stray light is that its paths through the system are "unlikely" in the sense that only few rays will follow them. As a consequence, simulation results are often very noisy; or very long simulation times are needed to end up with sufficiently stable results. Three strategies have been pursued to cope with this problem which are described in the sequel.

*e-mail: bm@hembach-photonik.de

2.1 Differential ray tracing

In differential ray tracing, rays propagating through the optical system contain information about their derivatives with respect to their start parameters (position and direction) [1]. This information can be used to compute radiometric quantities such as irradiance distributions very accurately and without noise, as exemplified in figure 1.

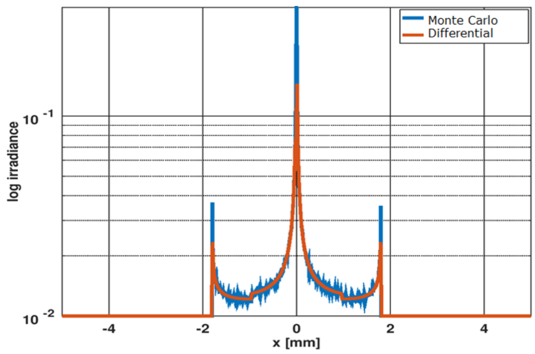

Figure 1. Ghost light distribution on a detector. Compared are the results of differential and conventional ray-tracing.

2.2 Multiple scattering

Very often, single-scattered light and ghosts dominate stray light, but this is not always the case. In any instance, multiple scattered light must be analyzed quantitatively to take it into account in the radiometric error budget of a space optical instrument. A novel technique is introduced that is based on so-called ray-density weighting and allows for analysis of multiple scattered rays with an acceptable noise level. One simple example is shown in figure 2.

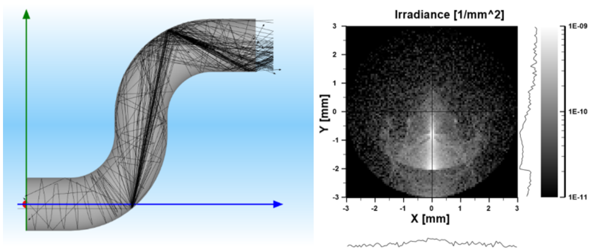

Figure 2. Multiple scattering in a metallic pipe modeled with ray-density-weighting. The irradiance distribution behind the pipe is shown on the right side.

2.3 Advanced importance sampling

Importance sampling has been known for a long time as a powerful method for speeding up light scattering simulations, often by orders of magnitude[2]. Its idea is that scattered rays are created only into directions which are relevant for the analysis. We propose an advanced importance sampling technique, in which Boolean combinations of directions are assigned to a scattering object. For instance, scattered light may be directed towards the image of a detector *and* towards the aperture of a lens. In many cases, this technique greatly enhances ray-tracing efficiency.

3 Deformed optical surfaces

Optical surfaces may be deformed due to mechanical stress imposed by the mounting or by environmental factors like thermal or gravitational loads, leading to a deterioration of optical performance. Deformations are usually calculated in FEM software from a meshed representation of the optical surface. RayJack ONE® can read the simulation output of Nastran, which is widely used within the European space community for FEM analysis. Imported data are approximated by smooth surfaces. Different sets of base functions such as Zernike polynomials can be used as well as bi-cubic spline interpolation. A simple example for a surface imported from Nastran is shown in figure 3.

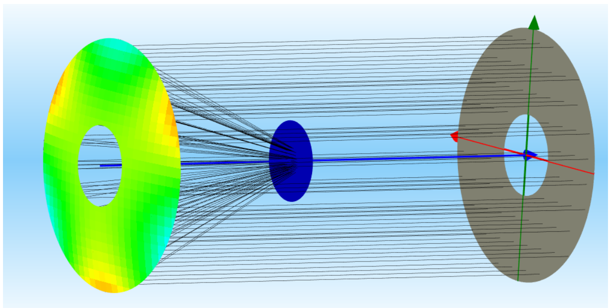

Figure 3. Perturbed parabolic mirror, imported from Nastran output files.

4 Outlook

The described functionality of RayJack ONE® is still under test. Completion of the activity is planned for end of 2021.

This work is being funded under a programme of the European Space Agency ESA.

References

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