HEMBACH PHOTONIK

Executive Summary Report

“Software for System-Level Analysis of Space Optical Instruments”

ESA contract no.	4000122798/18/NL/BJ/qp – Assessments to Prepare and De-Risk Technology Developments – "Differential Ray Tracing"
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Authors:	Bernhard Michel, Horst Greiner
Company:	Hembach Photonik GmbH; Finkenstrasse 1—3, Rednitzhembach, Germany
Responding author:	Bernhard Michel, bm@hembach-photonik.de

1 Introduction

Design and optimization of an optical instrument is commonly performed with sequential ray-tracing software (“lens design software”) which can predict only its nominal behavior but not its "real-world" performance for the following reasons:

1. Unwanted stray light entering the system can severely compromise optical system performance.
2. Thermal and mechanical deformations of the optical instrument may also have a critical impact on system performance.
3. Vignetting caused by mechanical components and non-nominal direct light paths. Both are not predicted by sequential raytracing.

To model the real world performance of an entire optical system requires *optical system analysis software* based on non-sequential ray tracing: the sequence of objects hit by a ray is not predefined, but calculated realistically during the ray propagation. This leads to quantitative simulations results within the limits of geometrical optics, provided accurate input data are used. Thus optical system analysis software is an indispensable means for reducing development risks, by detecting optical performance problems in early stages of a project. Requirements for such software are:

1. Ability 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 others.
2. The software must offer a comprehensive set of physical models of the interaction of light with opto-mechanical components.
3. Fast and efficient raytracing algorithms to obtain results within a reasonable time.
4. A powerful and comprehensive set of analysis tools is required, with sufficient flexibility to adjust it to non-standard situations.
5. A comprehensible user interface which can be used by an experienced optical engineer for accomplishing even complex tasks. This mandates a clear and intuitive concept for the user interface.
6. It is highly desirable to have one single software tool meeting all these requirements at the same time, and not a set of disparate tools.

Within its GSTP programme “Assessments to Prepare and De-Risk Technology Developments”, the European Space Agency ESA has awarded Hembach Photonik GmbH a contract to develop such a tool, based on in-house software RayJack ONE® which has been developed since 2012. The first phase of the project covered a novel simulation technique – differential ray tracing. Here we report about the second project phase, which was started in December 2019. On ESA’s request, the scope of the project was substantially extended, with the goal to convert RayJack ONE® into a full-fledged optical system analysis software meeting commercial standards.

The market of optical system analysis software is dominated by US American products, which all have been developed in previous millennium and reflect the state of the art of that time. Motivations for developing new optical analysis software at Hembach Photonik are as follows:

1. It is much easier to implement state-of-the art simulation technique into the fairly young software RayJack ONE, because its architecture is still flexible.
2. New software can use modern programming paradigms, greatly facilitating interaction with other software, to easily import, handle, and analyze data from external resources,
3. Hembach Photonik is a European company, well integrated into the European space community. This facilitates cooperation, without any barriers imposed by export regulations.

In the following, we give an overview about the developments and highlight details of the features that have been implemented successfully into RayJack ONE during the project.

2 User interface

A key feature of RayJack ONE is the seamless integration of Python – a scripting language which is easy to learn, intuitive, suitable for both beginners and experts, and used widely in industry and academia. Python has access to all public variables and functions of the simulation kernel which is written in C#, allowing for almost complete control of a simulation. If RayJack ONE does not offer a specific feature, it can be implemented by the user through scripting.

Python commands for optical simulation use a hierarchical naming convention. Auto-completion facilitates script generation and provides tool tips and links to online help. RayJack ONE offers a built-in software library, material databases as well as a growing Python solution library which can be extended by the user. Simulation results can be analyzed through scripting or dialogs and displayed in presentation quality graphics.

The online manual contains more than 1000 pages when printed out as a PDF. Embedded in this manual are script examples that can be directly loaded into the editor for inspection and execution. A screenshot of RayJack ONE’s user interface “in action” is shown in Figure 1.

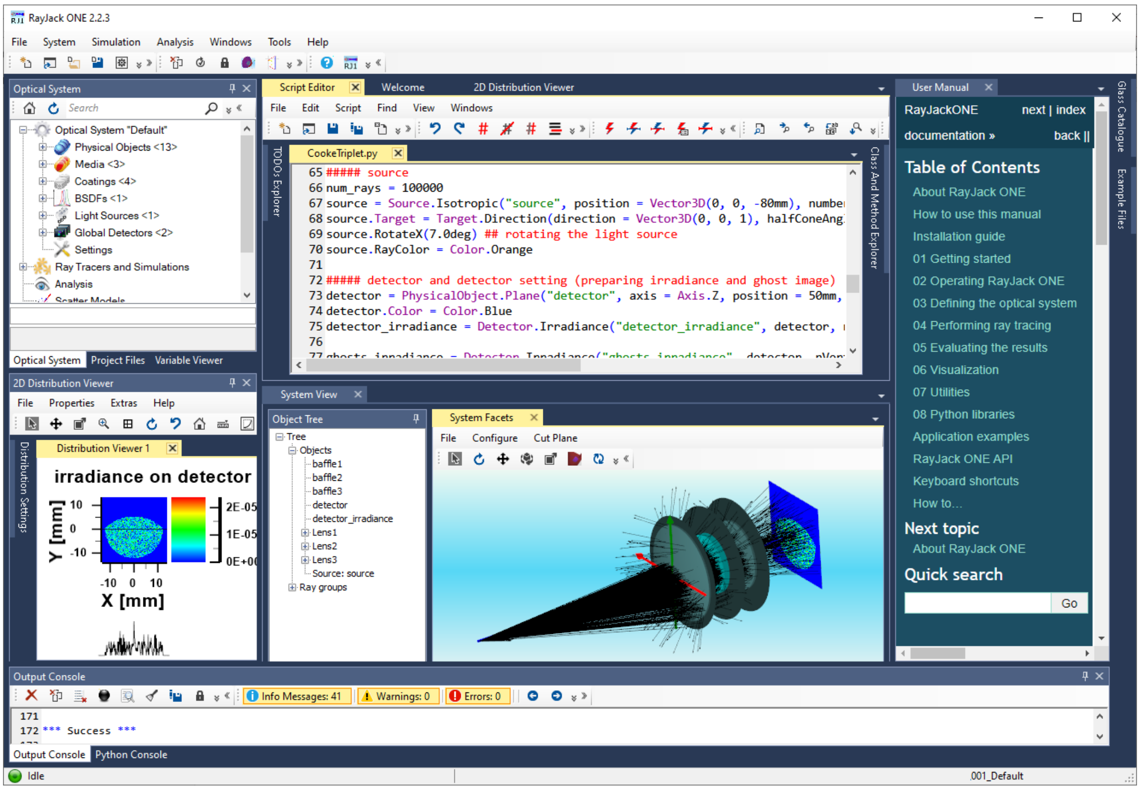

Figure 1: Screenshot of RayJack ONE’s user interface, showing the database viewer, Python script editor, online help, the system viewer, a spot diagram and some other windows.

3 Advanced geometry modeling with RayJack ONE

At project start, RayJack ONE offered only some geometrical primitives for creating optical systems such as planes, aspheres and cylindric lenses. This is insufficient for optical analysis where the system has to be imported from external software, including lens design, CAD and FEM software. To offer maximum flexibility of geometry modeling, a new ray-tracing engine was developed based on so-called "voxel-tracing", the principle of which is explained in Figure 2.

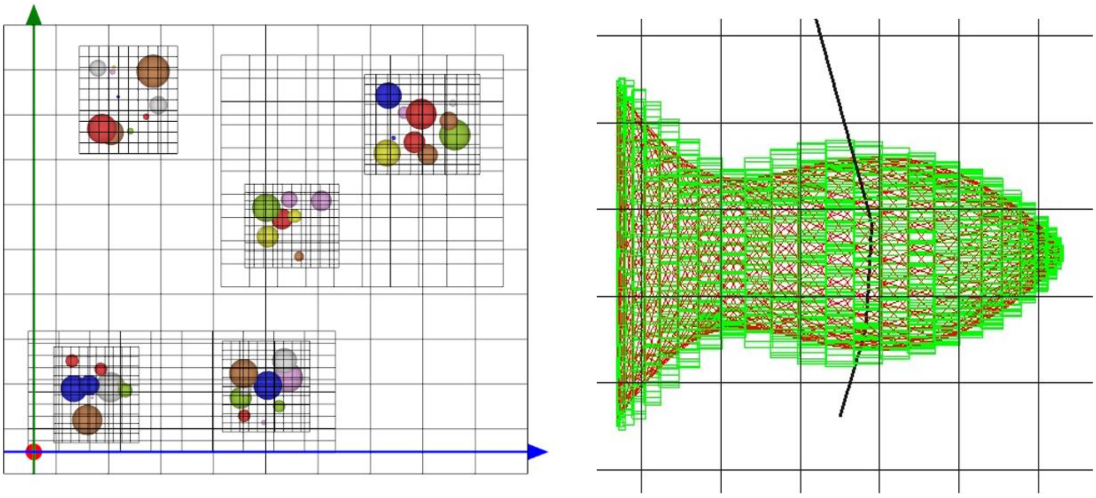

Figure 2: Advanced geometry modelling based on voxel tracing. Left picture: the simulation space is decomposed into a regular voxel grid. Clusters of objects can be endowed with a local voxel structure. This scheme reduces the number of ray object intersection tests very considerably. Furthermore, objects like the "fish" on the right side are covered by "starting boxes": when intersected by a ray they provide starting points for the ray object intersection calculation based on interval Newton methods. Any piecewise regular C2 continuous geometry can be traced with this method.

CAD files are imported into RayJack ONE using the external CAD Exchanger package [1], thus relying on a well-tested technology. CAD Exchanger allows access to all surface data, including non-geometrical information such as the object tree structure. Furthermore, standard surface types such as spheres or cylinders are automatically recognized, so that specialized highly efficient root solvers can be used for ray intersection calculations. Figure 3 shows an example for ray tracing at a CAD imported geometry.

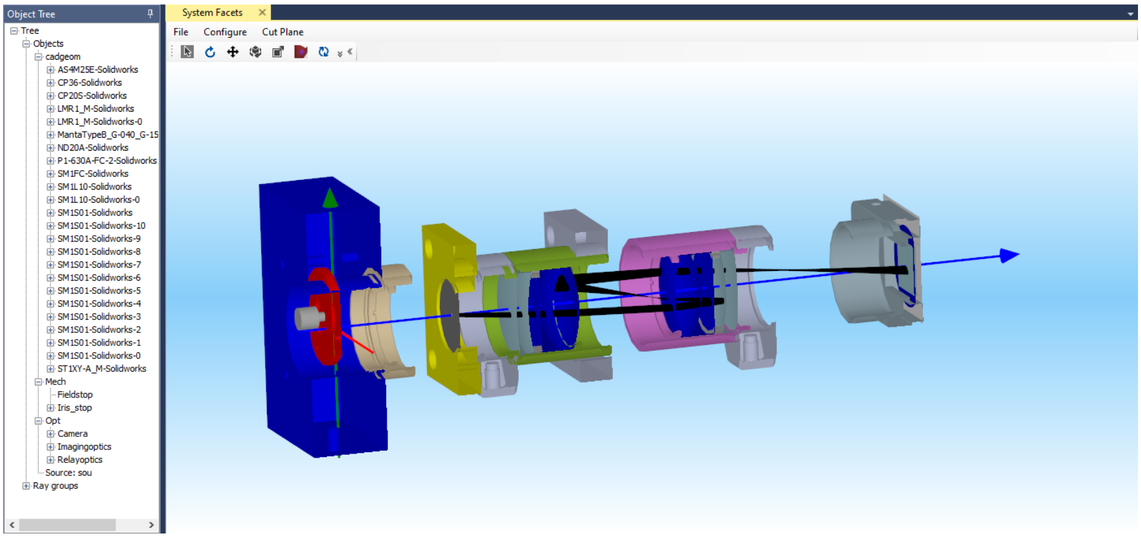

Figure 3: CAD import of a mechanical assembly. The object hierarchy in the CAD file is conserved when importing into RayJack ONE. The picture shows a ghost light simulation; the mechanical parts were imported from step-files downloaded from the online catalog of Thorlabs.

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 and bi-cubic splines can be used for interpolation of the data. A simple example of a surface imported from Nastran is shown in Figure 4.

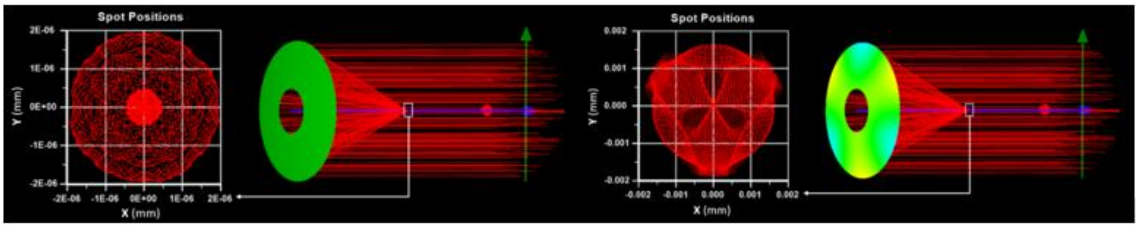

Figure 4: Ray-tracing from an ideal parabolic surface (left picture) and a deformed surface (right picture), along with the spot diagrams in the focal plane.

RayJack ONE supports practically all surfaces offered by OpticStudio and offers a (still growing) import filter for this software. The user can also define explicit and parametric surfaces directly in RayJack ONE by scripting. Examples for an imported geometry and a user-defined parametric surface are shown in Figure 5.

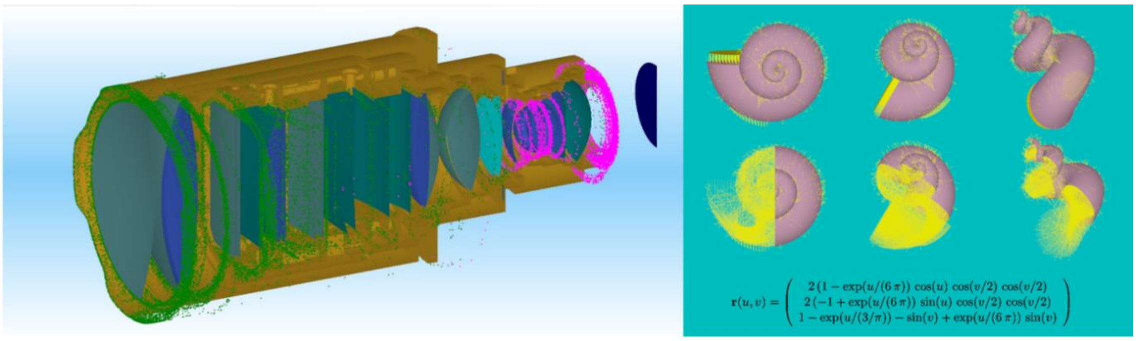

Figure 5: Left: Anamorphic cinema lens imported from OpticStudio (lenses) and CAD (mechanical parts) along with spots indicating critical and illuminated objects (data supplied by Glaswerk GmbH, Germany). Right: ray tracing on a sea-shell surface, defined by a mathematical formula in the Python script.

4 Light scattering and stray light analysis

One of the main tasks in optical analysis is stray light analysis, i.e. the analysis of unwanted light in an optical system. One main cause of stray light is scattering from optical-mechanical parts. RayJack ONE implements all standard scatter models, but also the capability to use measured scatter data tabulated in text files. One key-problem in stray light analysis is under-sampling. For radiometric analysis, ray tracers need a large number of rays to produce reliable results. However, in a well-designed optical instrument, most stray light paths are „unlikely” in a sense that only very few or no rays will follow them. The predictions of a stray light analysis will be inaccurate or completely useless in this case. One standard technique to improve ray statistics is importance sampling, which restricts the directions of scattered rays artificially, considering only rays pointing towards or away from certain target directions [2]. RayJack ONE offers a “TargetFinder” to find these target directions automatically as well as the capability to combine targets in a Boolean way, in order to substantially enhance the efficiency of importance sampling (Figure 6).

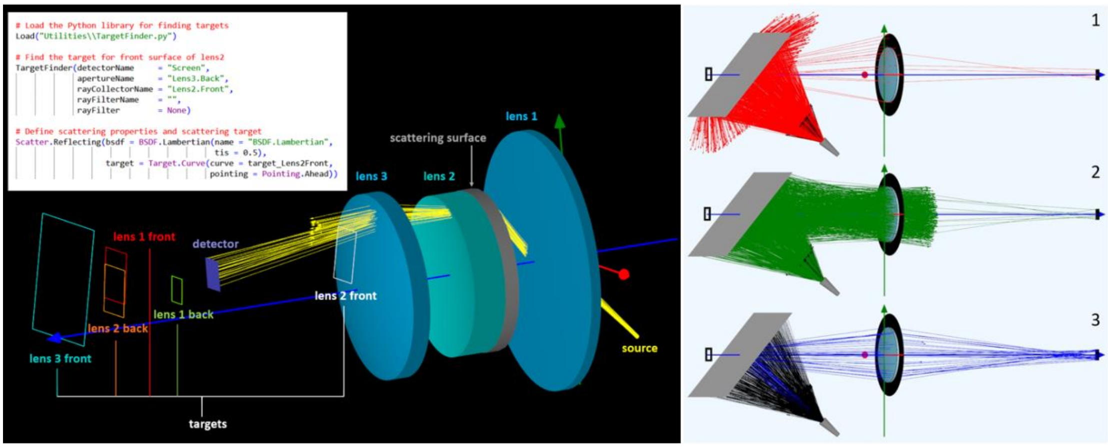

Figure 6: Left: RayJack ONE can store the intermediate state of rays propagating through the system. This capability is used to compute targets for importance sampling automatically and in one single simulation. Right: targets can be combined in a Boolean way, explained for the case of a light scattering object imaged through a lens onto a detector. Standard options for choosing the targets (1) and (2) are very inefficient, because most scattered rays do not hit the detector. A Boolean “AND” of both targets creates exactly the rays needed, with high efficiency.

When multiple scattering is relevant for stray light, standard simulation techniques are pushed to their limits or require excessively long computation times. RayJack ONE offers a novel and unique technique for multiple scattering. At each scattering event an “observation ray” is sent towards the detector. With this feature, simulation time can be reduced by orders of magnitude in many practically relevant cases (Figure 7).

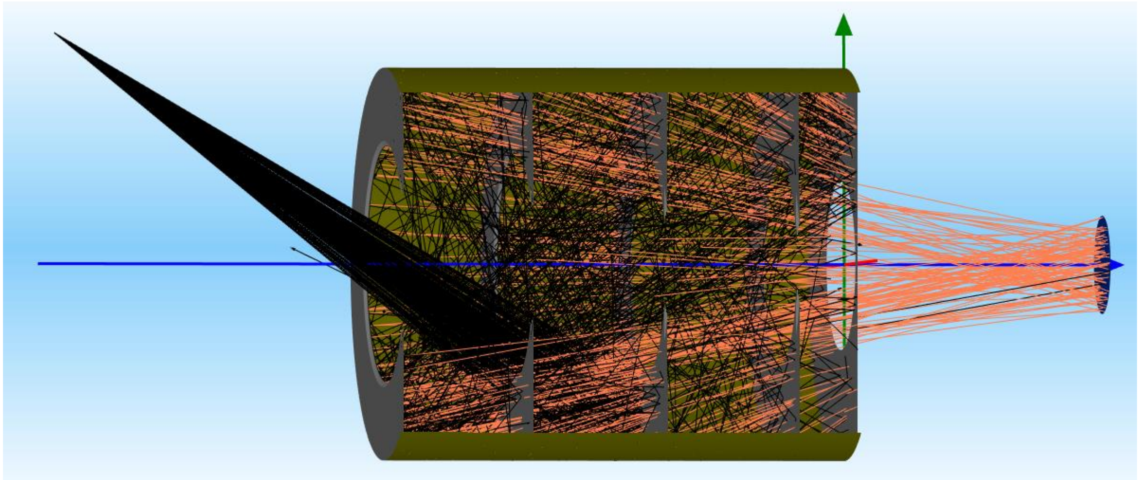

Figure 7: Principle of multiple scattering calculation for a baffle illuminated by a light source outside its exclusion angle. Many observation rays (shown in light orange) hit the detector; without using observation rays, just two rays would have arrived on the detector.

5 Advanced physical modeling

RayJack ONE models polarization from the light source to the detector, including polarization mechanisms such as birefringence, optical coatings or ideal polarizers, and it offers tools for analysis of the polarization state. The user may select between Jones and Stokes formalisms, but internally the software uses the so-called coherency matrix formalism. As a non-trivial example, Figure 8 shows polarized light propagation through a Fresnel rhomb.

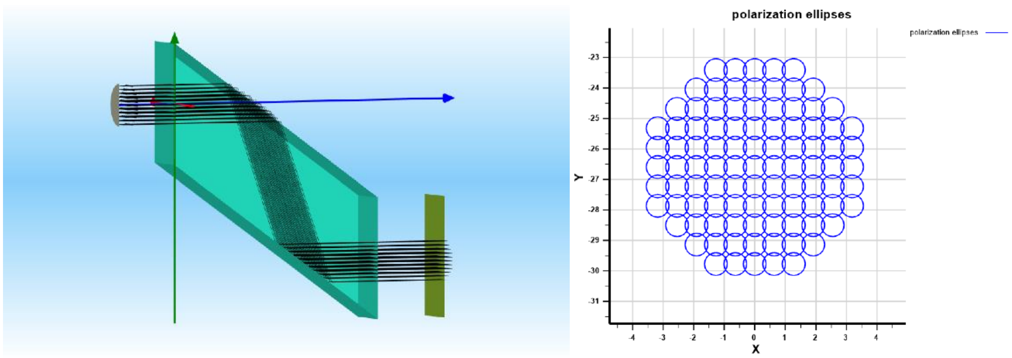

Figure 8: Fresnel rhomb to convert incident linearly polarized light into circularly polarized light by total internal reflection; the picture on the right side shows the polarization state of the rays after passing through the rhomb

Bright light sources outside the field of view of an optical instrument can diffract light into the system through wide angle diffraction which is often a substantial contribution to the stray light budget. A typical space-relevant example is sun light diffracted from the vanes of a baffle into the optical path of an optical instrument. RayJack ONE simulates wide angle diffraction from arbitrarily shaped planar apertures by ray-tracing, based on the stationary phase approximation to the so-called boundary diffraction wave [3].

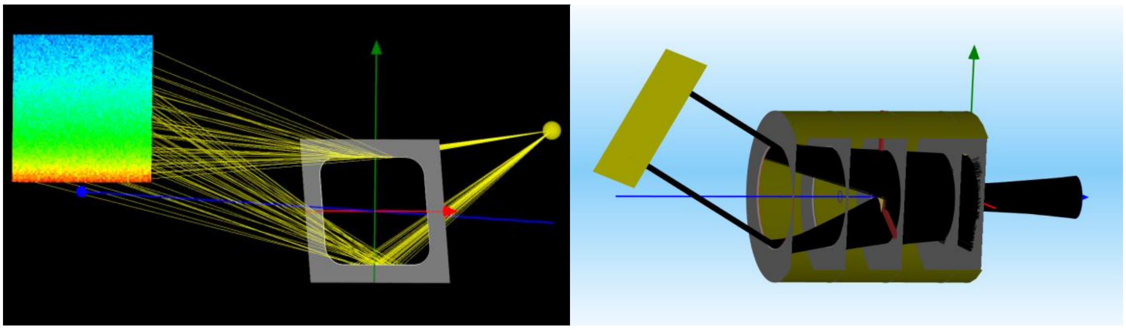

Figure 9: Wide angle diffraction from aperture. Left: light from a point source at finite or infinite distances is diffracted from the stationary phase points of an aperture. Right: Sunlight diffracted from the vanes of a Cassegrain telescope onto the primary mirror which is contaminated by particles. By scattering from these particles the diffracted light eventually reaches the image plane.

In differential ray tracing (DRT), infinitesimal ray bundles are traced through the system. This information can be used for highly accurate radiometric calculations [4]. In phase 2 of the project, the ray tracer was redesigned substantially to enable differential ray tracing for any geometry that can be represented in RayJack ONE. The method originally proposed in phase 1 of the project – so-called ray variation – turned out to be not reliable in certain cases where caustics are involved. We therefore developed an alternative method based on light source triangulation with an automatic mesh refinement. This method allows for robust and accurate radiometric calculations in non-sequential and sequential ray tracing. Differential ray tracing is about as fast as normal ray tracing. The differential information contained in the rays are beneficial also for other tasks, such as finding a ray path connecting two objects via several intermediate objects.

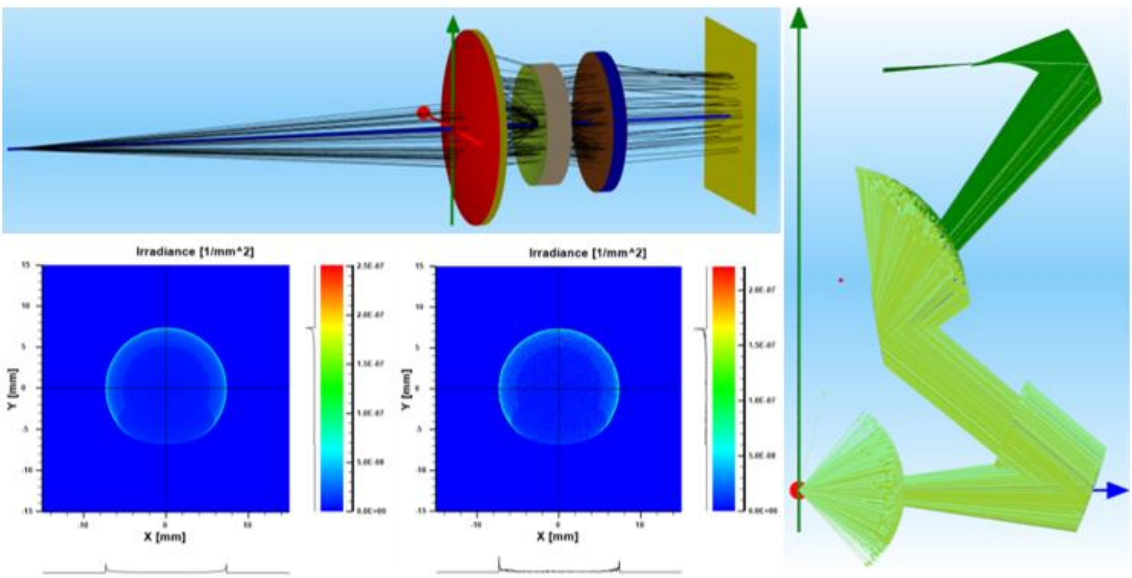

Figure 10: Left: Ghost analysis of a Cooke triplet with differential ray tracing (reflection at last and first surface). Differential ray tracing delivers smooth and crisp irradiance distributions (left) with only a few rays, whereas conventional ray tracing inherently suffers from shot noise and requires many rays. Right: Ray path finding in a mirror cabinet. Differential ray tracing is used to find a ray path from the point source in the bottom left corner to the small detector in the upper left corner for rays that are reflected at three curved mirrors.

6 Analysis capabilities

For a non-sequential ray tracing simulation, typically a large number of rays has to be traced – often many millions. Optical analysis means evaluation of rays with respect to their radiometric properties (irradiance, radiant intensity etc.), geometrical arrangement (spot diagrams) or history (path analysis). On the deepest level, each intersection of each ray can be reconstructed and analyzed numerically. Numerical data obtained from radiometric analysis can be post processed directly in RayJack ONE. Figure 11 shows some of the standard means used for optical analysis.

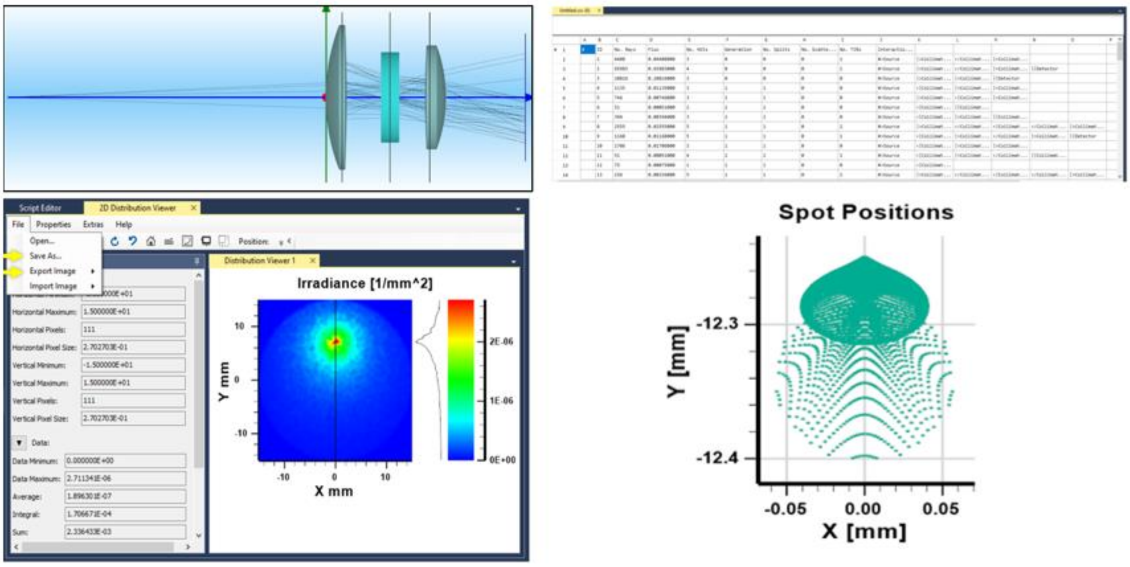

Figure 11: Potpourri of analysis features implemented in RayJack ONE. Uppermost picture: graphical display of a ghost path; picture in the middle: rays sorted according to their paths which are listed in an easy-to-interpret spreadsheet. Lower row of pictures: spot diagram of an imaging system with aberrations (left), distribution viewer showing irradiance on a detector.

7 Verification and Testing

At project start, software requirements and respective tests were formulated. These requirements specifications were adjusted during the project, ending up with a comprehensive and meaningful set of tests. These tests were performed on component, system, and application level and the user experience was evaluated too. All critical tests of the software functionality have been passed, including the quantitative correctness of the results. Regarding performance, RayJack ONE is always at least comparable with ASAP and often better. Some of the benchmarks specified in the requirements were maybe too ambitious and have not been reached.

Also, RayJack ONE’s predictions were compared with other software (mainly ASAP) and simple experiments. Although only a qualitative agreement with experiment could be expected, the experiments were valuable for testing the software as a whole and its fitness for real world problems.

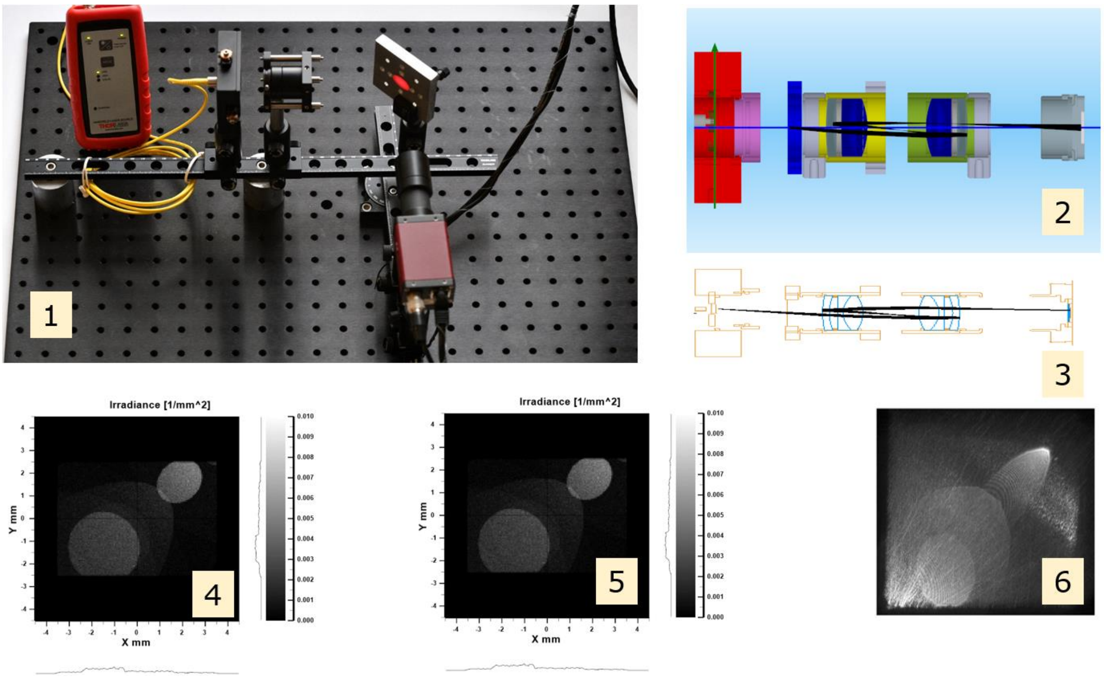

Figure 12: Experimental setup of ghost/stray light modelling (1); simulation models in RayJack ONE (2) and ASAP (3); Ghosts in RayJack ONE (4), ASAP (5, result imported into RayJack ONE) and experiment (6).

8 Conclusions and Outlook

In this project, a software for the analysis of space optical instruments was developed and tested. It offers many unique features that are useful for applications in space industry. Looking back to stray light analysis projects performed by Hembach Photonik in the past 10 years, which were exclusively done with ASAP, we can state that 100% of this work could have been done with the features now available in RayJack ONE with much less effort. Tasks as multiple scattering calculations for various space missions or the calculations of wide angle diffraction required many weeks for preparation and execution in ASAP and typically involved the use of external software for analysis.

Optical analysis software will never be able to model all physical phenomena relevant in practical applications and needs continuous enlargement and improvement. One part of the future development of RayJack ONE will therefore the inclusion of phenomena such as wave optics, light propagation through inhomogeneous (GRIN) media and many others. The other part will be the response to user feedback and improving user friendliness. Also there is quite some room for optimization of software performance.

9 Literature

[1] https://cadexchanger.com/, Web site of CadEx Company

[2] Eric C. Fest, “Stray Light – Analysis and Control”, SPIE Press, Bellingham 2013

[3] Max Born, Emil Wolf, "Principles of Optics", 7th Edition (Cambridge University Press, Cambridge 1999)

[4] David F. Rock , “Using differential ray tracing in stray light analysis, David F. Rock”, Reflection, Scattering and Diffraction from Surfaces III, Proc. of SPIE Vol. 8495, 2012