RAYTRACE3D BY FRAUNHOFER ISE

Accurate and Efficient Ray Tracing for Concentrator Optics

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1   Introduction

The Fraunhofer ISE in-house software suite *Raytrace3D* is targeted towards simulating the energy flow of solar radiation in *Concentrating Solar Power* (CSP) and *Concentrating Photovoltaics* (CPV) technologies, yet can be used for other applications as well. The first development of the software suite dates back more than ten years, when a first two-dimensional approach was implemented for line-focusing collectors (Mertins 2009). Later, the concept was extended to three dimensions and the program obtained its name *Raytrace3D*.

As opposed to rendering engines (*backward ray tracing*), Raytrace3D uses a *forward ray tracing* approach. This means that rays are started from a light source. Subsequently, they interact with geometries, until they are either absorbed or go towards *infinity* (in case they don't hit anything). To assess the optical efficiency of a concentrating system, the **ray energy absorbed on the solar receiver** is compared to **the ray energy from the sun that is incident on the primary aperture** (e.g. the heliostat field mirror area of a Solar Tower system).

To illustrate the basic principle, a mock-up ray tracing scene is depicted in Figure 1. A rectangular geometry carries a light source, where parallel rays with randomly distributed starting points are created and cast vertically downwards. A rectangle with a reflecting material changes the rays' direction to roughly horizontal, but also causes a statistically distributed scattering of the rays' directions (simulating surface defects) in the visualized example. Eventually, some rays are lost towards infinity, whereas others are terminated on the rectangular absorber. Due to the scattering effect of the reflector, the absorbed energy distribution is strongly inhomogeneous.
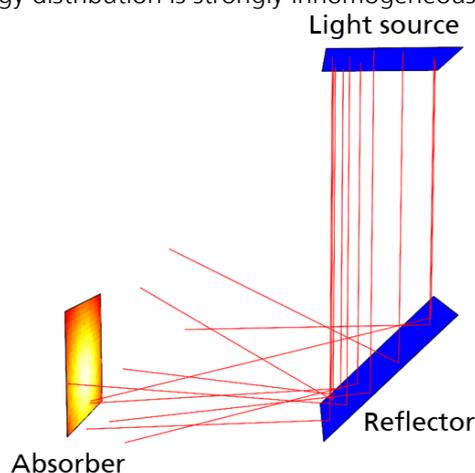
Figure 1: Visualization of mock-up ray tracing scene: a light source with parallel rays, a scattering reflector with slope deviations and a discretized absorber with a concentration map. While only ten ray paths are depicted as red lines, the actual number of traced rays in this simulation – to yield the depicted concentration map – was larger than one million.

In the following, implementation-specific features of Raytrace3D are highlighted. Furthermore, the modeling libraries and analysis routines are introduced. Finally, typical applications are presented.

2 Implementation-specific features and advanced modeling

2.1 Software stack

To achieve both high flexibility and high performance, Raytrace3D uses Python for the pre-/postprocessing and C++ for the fast and efficient numeric calculations in the computational core engine. Several established and well-tested libraries are utilized:

- Eigen (*eigen.tuxfamily.org*): linear algebra
- Boost (*boost.org*): advanced data types, date/time handling, file system operations, logging, CLI options, …
- Python Scientific Stack (Numpy, Scipy, Matplotlib, Pandas, multiprocessing): modeling, automatization, evaluation, visualization
- JSON (*json.org*) / YAML (*yaml.org*): interfacing

Raytrace3D fully follows the paradigm of object orientation, which is realized in both the C++ core and the Python preprocessing routines. Object orientation allows for:
- Straightforward extensibility of the modeling library by researchers, without the risk of breaking existing models or the computational core
- Simplified testing and debugging
- Easier comprehensibility for solar researchers without strong programming background
- Facilitated setup of simulation models, as the object-oriented implementation matches well with a component-wise way of model thinking (encapsulation) and allows for deriving specialized models from basic ones without redundant code (inheritance)
- Flexible, extensible and efficient combination of geometrical components with optical material properties

2.2 Ray handling

While the implementation primarily aims at modeling the interaction of rays with surfaces (see 3.3), volumetric effects can be considered as well (see 3.4).
Contrary to other ray tracing engines, rays interacting with a surface material can be handled energetically or statistically. This means that a refractory material might statistically decide if a ray should be transmitted or reflected, while a reflective material might reflect every ray yet reduce its energy (*intensity*). This dual approach allows for maximum flexibility.
During the tracing process, each ray can internally store its history of interactions, which allows for advanced evaluation techniques (see 4.1) and graphical visualization of the ray paths (Figure 1).

2.3 Parallelization

Raytrace3D supports parallelization on two levels:

1) Thread-based parallelization: an efficient multi-threading approach based on a pool of workers is implemented with the *Intel Threading Building Blocks (Intel)* library. In the C++ core engine, the rays are processed in parallel.

2) Process-based parallelization: for several applications, multiple ray tracing simulations are performed on a numeric grid (wavelengths in full spectrum simulations, nodes in a sky discretization, angular channels in a BRDF matrix). These simulations are parallelized with a multi-process approach.

In most cases, the second parallelization approach yields a larger speed-up, with accelerations close to linear with the number of CPU cores. These parallelization features of Raytrace3D are readily utilized on the Fraunhofer ISE in-house simulation servers.

2.4 Bounding box hierarchy

For a significant speed-up, a hierarchic structure of axis-aligned bounding boxes is automatically created at the beginning of each simulation. The bounding objects are organized in an R-Tree (https://en.wikipedia.org/wiki/R-tree), which makes the computational effort of the intersection detection for a single ray roughly logarithmic (instead of linear) with the number of objects in the scene. The bounding boxes on the deepest tree level are dimensioned such that they fully contain a single intersection object, with minimum volume.

Figure 2 depicts the tree structure applied to a Solar Tower simulation. Depending on the number of objects, simulations are accelerated by several orders of magnitude as compared to not using a hierarchy.
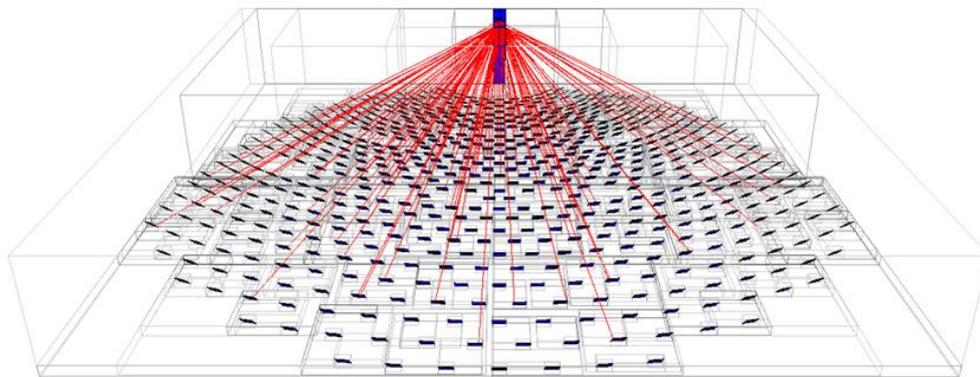
Figure 2: Visualization of polar heliostat field and cavity receiver, showing automatically created, axis-aligned bounding boxes (light grey lines).

3   Modeling libraries

Raytrace3D allows for detailed yet versatile modeling. A large variety of optical configurations can be represented, differing in number of objects, size, geometry types, surface/volumetric properties, number of optical stages and physical/semi-empirical interaction mechanics.

3.1   Geometries

Contrary to ray tracing implementations for rendering, Raytrace3D implements complex surfaces like quadrics directly instead of segmenting them with triangles. Commonly, the routines detecting an intersection with a ray contain three major steps (see also Figure 3):

1) Identifying zero, one or more intersection points of the ray vector with the (infinitely large) surface, which is e.g. described by a quadric formula
2) Sorting the intersection points by distance to the current ray origin, smallest distance first
3) Checking if the first intersection point in the sorted list is valid:
    - The intersection point lies in the positive ray direction, starting from the ray origin
    - The intersection point lies within the bounded geometry.
    - The distance to the ray origin is larger than a minimum value
    - The ray vector and the surface normal at the intersection point are not orthogonal

If an intersection point is not valid, the next possible intersection from the sorted list in 2) is checked. The ray will interact with the material at the first valid intersection point.
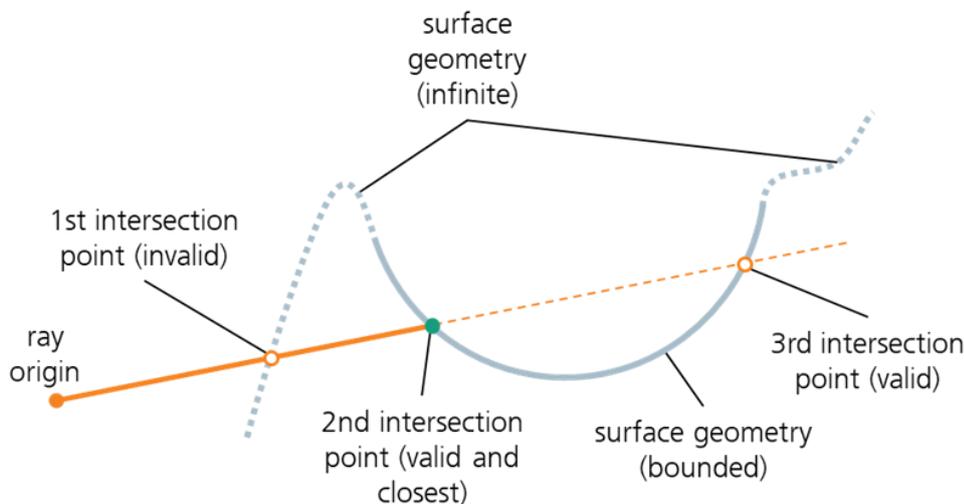

Figure 3: Intersection point identification of ray (orange) with complex surface geometry (grey). The first intersection point is outside the surface boundaries and thus invalid. The second and third intersection points are both valid, yet the second intersection point (green) is closer to the ray origin and therefore selected.

Light sources and/or materials can be assigned to geometries. Thus, a single geometry description interface allows for modeling both the intersection objects and the light sources in the scene. In addition to a direct implementation, geometries and surfaces may also be converted and imported from CAD formats or as triangulated surfaces.

3.2   Light sources

As the main applications for Raytrace3D are in the domain of solar concentrators, a variety of models for creating near-parallel rays is implemented to describe direct beam solar irradiance in different representations. They differ regarding the distribution of slight angular deviations from the parallel direction, due to the major application also referred to as *sunshape distribution*. Depending on the use case, the researcher can either choose from several parametrized models or define a custom angular distribution. Figure 4 shows a comparison of several ideal models typically found in literature and their equivalents simulated with a radial radiometer in Raytrace3D. The ideal profiles and the simulated counterparts agree very well. Slight differences in the low-angle domain can be attributed to statistical noise.
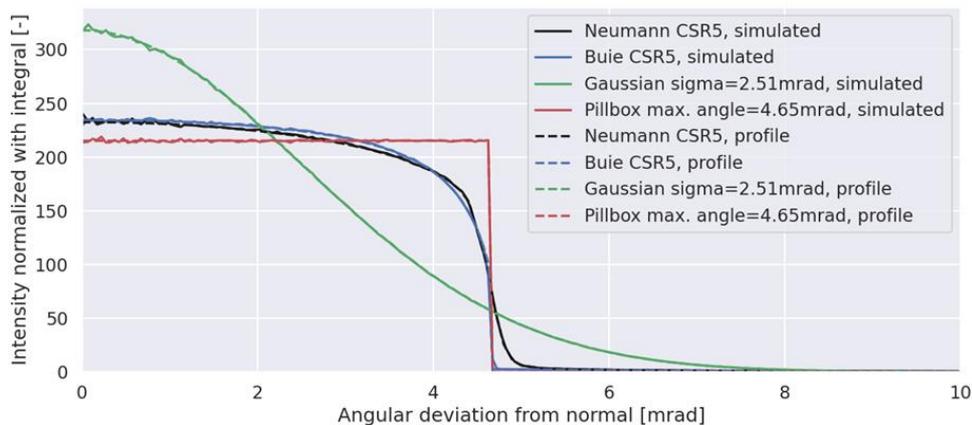
Figure 4: Comparison of different sunshape profiles to represent direct solar beam irradiance and their equivalents from a radiometric simulation.

With the very flexible user-defined angular distributions, other light sources, e.g. built in optical lab setups, can be readily simulated as well. Furthermore, Raytrace3D incorporates a diffuse light source mostly used for view factor assessment.
Besides angular spread, also polarization and spectral distributions are implemented. While polarization is carried by rays in their properties, a spectral distribution is usually implemented by simulating one single wavelength at a time (with all the material properties at this wavelength, see also 5.2).

3.3   Materials

The material library includes models with different levels of detail. While relatively simple parameter-based representations of specular/diffuse reflection, absorption and transmission exist, there are also more complex, physical models for a combination of reflection and refraction at a surface. Most of the implementations furthermore allow for specifying surface imperfections based on statistical distributions or a specified mapping (see 3.6).

Specialized models cover

- anti-reflective coatings
- soiled surfaces
- incidence angle-dependent material properties
- full BRDF surface representations

3.4 Volumetric materials

Volumetric extinction is calculated based on the path length covered by a ray between two intersections with the surfaces enclosing the volume. While this approach excludes directional changes of the rays by volumetric scattering, volumetric extinction as required for CSP and CPV applications can be sufficiently represented.

The volumetric material library includes basic exponential extinction, but also more complex models, e.g. for atmospheric attenuation in Solar Tower plants.

3.5 Teleport walls for periodic boundary conditions

For several applications, repeating geometric structures need to be modeled. So-called teleport walls allow for effectively creating periodic boundary conditions that can be used to model e.g. quadratic or hexagonal unit cells. This might be used to model the repeating pattern of an anti-reflecting surface coating (see 5.1) or the lens-cell units in a CPV array (see 5.2).

3.6 Mapping of local slope deviations

As an alternative to the statistical description of surface normal deviations, it is possible to map slope deviations directly to specific geometries. This might be used to simulate the characteristic behavior of a single CSP mirror whose surface structure was measured with deflectometry or photogrammetry.

Here, an important simplification is introduced: while the intersection point of a ray is determined with the ideal geometry, the interaction of the ray with the surface is modelled with the real, locally defined surface normal. For many applications with surface irregularities in the "mrad" domain, this approach is very accurate, yet fast, as angular slope deviations have a much stronger impact than deviations in the intersection point with the geometry.

4 Postprocessing and analysis tools

Raytrace3D features several powerful analysis tools specialized for tasks related to concentrating collectors.

4.1 Detailed loss evaluation

By storing the ray history throughout the tracing process, sophisticated evaluation routines within the C++ core engine allow for deep insight in the interaction of the radiation with multi-stage optics. As this functionality mostly describes the optical losses along the radiation transport, Sankey diagrams offer an intuitive means of visualization.

Notably, there is an evaluator routine for concentrators based on a primary (and optionally secondary) reflector array (Figure 5 left). While its development was mostly aimed at Solar Tower systems, it proved to be readily usable for Linear Fresnel collectors and other technologies as well.

Furthermore, a customizable evaluator routine for multi-stage CPV optics is available which allows for integrating both refractive lenses and reflective mirrors (Figure 5 right).
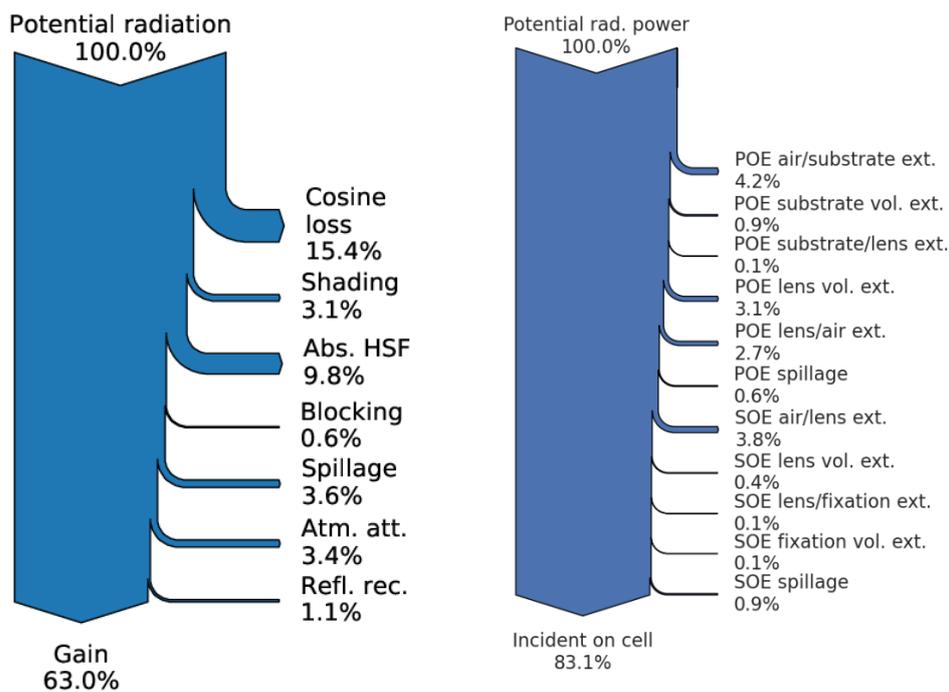

Figure 5: Detailed loss analysis based on evaluation of ray history. Left: exemplary annual analysis for a PS10-like polar heliostat field and cavity receiver (Abs. HSF=absorption on heliostat field, Atm. att.=atmospheric attenuation, Refl. rec.= Reflection from the receiver). Right: exemplary polychromatic analysis for a 2-stage (POE=primary optical element, SOE=secondary optical element) CPV system using refractory optics.

4.2 Concentration distributions on regions of interest

For most ray tracing studies, the integral (total or average) flux or concentration on a region of interest is most relevant. Beyond that, various applications also require de-

tailed knowledge about the spatially resolved concentration distribution on a specific surface. This can be relevant for the identification of potential hot spots or because flux inhomogeneities might incur strong subsequent losses (such as thermal radiation losses or circuitry losses in PV cells). Figure 6 exemplarily shows concentration maps on the absorber tube of a LFC and on the absorber panels of a Solar Tower receiver with secondary concentrators.
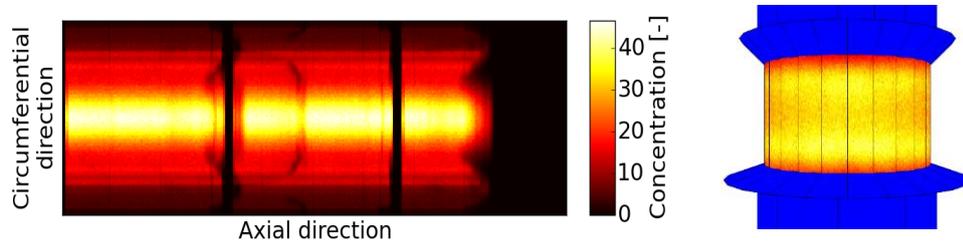
Figure 6: Concentration distributions on regions of interest. Left: Concentration map on the absorber tube in a linear Fresnel collector, with the interaction of a secondary concentrator and shading from structural elements. Right: flux maps on the absorber panels of a surrounding external Solar Tower receiver with a secondary concentrator above and below the panels.

Export of concentration maps is implemented for a variety of geometries. The maps can be exported either in textual or binary format for further post-processing or visualization. Notably, they are also input for a detailed Solar Tower receiver model implemented in the Fraunhofer ISE system simulation software *ColSim CSP* (Schöttl et al. 2020b; Rohani et al. 2018).

4.3 View factor assessment

The flexibility of Raytrace3D allows for applications beyond the direct simulation of solar concentrators. By mapping a diffuse light source to the surfaces such as a cavity receiver, the view factors (Teichel et al. 2012) to each cell of all other surfaces' discretization grid can be assessed. The capacity of geometries in Raytrace3D to carry both a light source (start rays) and a material (interact with/absorb rays) at the same time strongly facilitates this approach. The view factors are consequently applied in the calculation of the thermal radiation exchange of complex geometries, between the environment and adjacent surfaces.

A specific post-processing routine is built in Raytrace3D that allows for evaluating and exporting the view factors in matrix format, which can be directly loaded into the detailed thermal Solar Tower receiver model implemented in the Fraunhofer ISE in-house software *ColSim CSP*.

5   Applications

The following sections present several applications of the software Raytrace3D, without aiming to be a comprehensive compilation of its capabilities. The list is sorted by size of the applications, from small to large.

5.1   Micro-structured surfaces

Aside of the concentrator optics domain, Raytrace3D has been successfully applied for the optical characterization of micro-structured functional surfaces, e.g. to be used to reduce reflection from PV modules and to trap the light inside. Figure 7 shows a microscopic image of an artificially created pyramid structure and the respective unit cell simulation model with periodic boundary conditions.
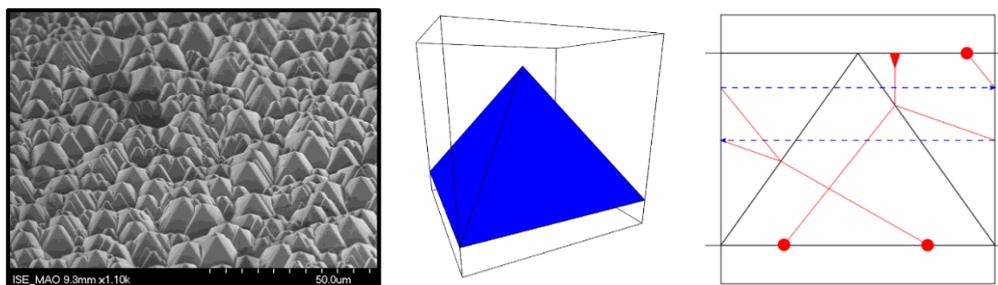

Figure 7: Micro-textured surface with pyramid structures. Left: Microscopic photograph. Center: Visualization of a unit cell model, with periodic boundary conditions/teleport walls including randomization approach to account for pyramids of different size. Right: Side view of the scene, with depiction of a single ray. The blue dashed lines show the teleport behavior from left to right and vice versa.

Notably, Raytrace3D contains a specific evaluator routine that provides the required input to describe a functional surface with the OPTOS (Tucher et al. 2015) formalism.

5.2   CPV optics

Raytrace3D is well suited for the simulation of Concentrator Photovoltaics (CPV) optics. The efficiency of a certain optical design, the impact of manufacturing tolerances or the effect of non-ideal angular alignment e.g. due to tracker behavior can be studied. Figure 8 depicts an exemplary application with a two-stage CPV system from the project MicroCPV (Wiesenfarth et al.).
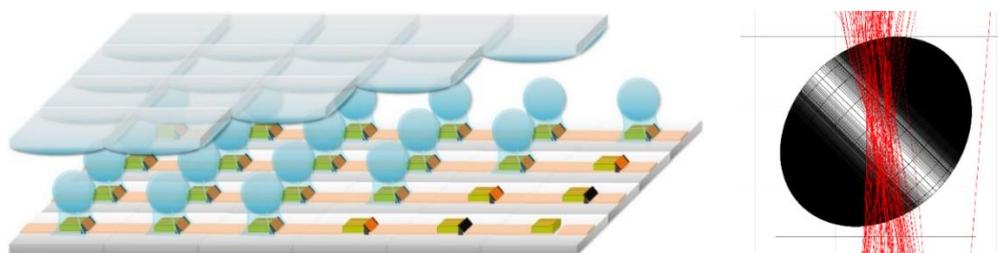
Figure 8: Concentrator optics developed in the MicroCPV project. Different options for a Primary Optical Element (POE) are studied that concentrates the solar radiation onto a ball lens (Secondary Optical Element, SOE). Left: sketch of the MicroCPV module array. Right: Detail visualization of the ray paths in the SOE, which is – in order to study manufacturing tolerances – slightly non-spherical and skewed.

As the optical properties of typical CPV materials (glass, silicone, PMMA) are strongly wavelength-dependent, full spectral analysis is required. Since discrete wavelengths can be simulated independently, this process is easily parallelizable on multi-CPU servers, for a (near-linear) speed-up.

Main results of the CPV analysis with ray tracing are the detailed optical loss analysis on the one hand (see 4.1) and the concentration distribution on the PV cell on the other hand (see 4.2). The latter can be further processed over a given solar spectrum and including the spectral response curves of the (multi-junction) PV cell to get the electrical current created by the CPV system.

5.3   Line-concentrating collectors

Ray tracing can be readily used for quantifying optical losses of line-concentrating collectors (Heimsath et al. 2014) and the application of Raytrace3D in this field has been successfully demonstrated as part of a simulation round-robin study (Osório et al. 2016).

Figure 9 shows an in-depth ray tracing model of a Linear Fresnel collector erected at the Fraunhofer ISE premises, including all relevant shading elements and details. Optical simulation results for the *Incidence Angle Modifier* (IAM) were used for a detailed identification of the collector's dynamic opto-thermohydraulic characteristics (Hofer et al. 2015).
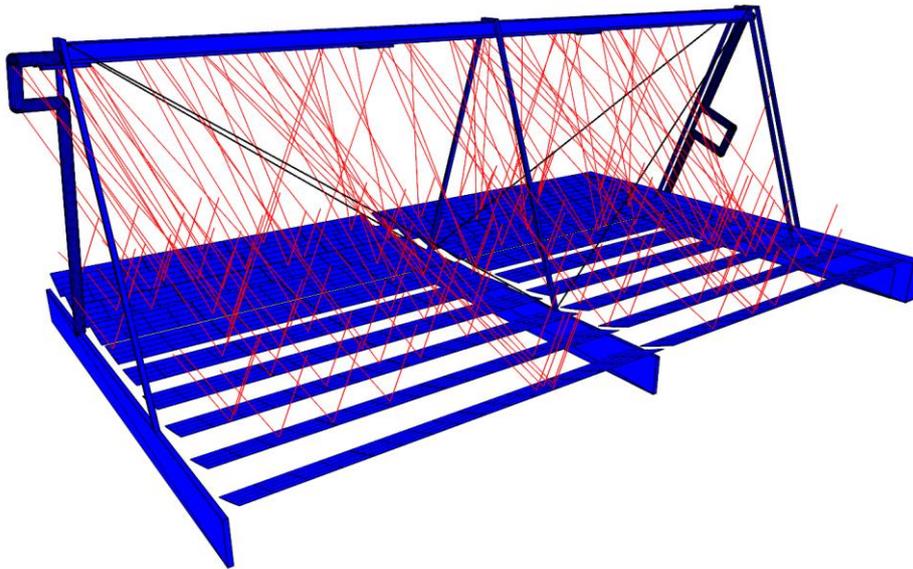
Figure 9: Visualization of detailed simulation model including ray traces for a Linear Fresnel collector constructed at the premises of Fraunhofer ISE

The optical behavior of *Parabolic Trough Collectors* (PTC) is less complex compared to LFC, which is why often more basic methods can be used for preliminary analysis. Nevertheless, Raytrace3D can be successfully applied for performing detailed studies on PTC, e.g. for gravity or wind-load induced deformations of the mirrors (see Figure 10).
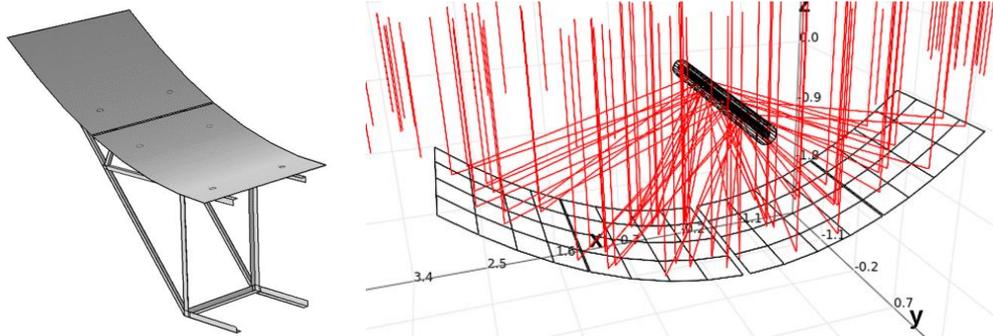
Figure 10: Simulating the impact of gravity or wind-load induced deformations on optical collector performance. The simulation model includes a multi-facetted parabolic mirrors, the receiver glass envelope and the absorber tube. Local slope deviations are mapped on the mirror geometries (see 3.6).

5.4 Solar Tower systems

Ray tracing is a very suitable tool for characterizing Solar Tower systems, since complex optical interactions like heliostat blocking and shading or radiation spillage can be analyzed with relative ease (Schöttl et al. 2020a).
Two aspects of the Raytrace3D software structure are particularly relevant for Solar Towers:

- Instead of creating a very large "sun" above the scene, light sources can be mapped directly onto heliostats. This approach avoids creating a large number of useless rays that never interact with the model and thus speeds up the simulation significantly.
- Due to the spatial structure of a heliostat field, simulations thereof profit strongly from the hierarchical bounding volume tree implemented in Raytrace3D (see 2.4). A speed-up of several orders of magnitude is achieved, depending on the number of heliostats.

Figure 11 shows a visualization for the Solar Two ray tracing model, including a detailed view on the receiver with the concentration distributions mapped onto the absorber panels.
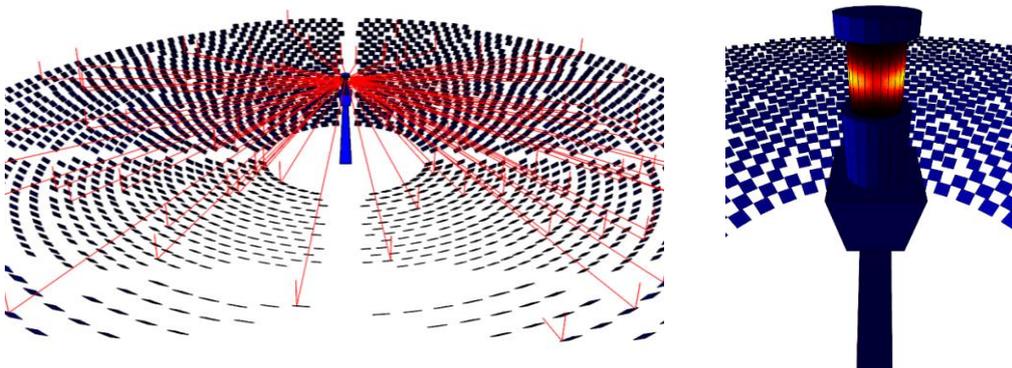
Figure 11: Visualization with selected ray traces for the Solar Two system (formerly placed in the Mojave Desert, USA), including heliostat field, tower structure and receiver.

Raytrace3D can also be applied to study more innovative concepts like the Solar Tower Beam-Down technology. An exemplary system based on surrounding "wedges" of

heliostats is visualized in <u>Figure 12</u> where a flat quadrilateral secondary mirror is assigned to each wedge.
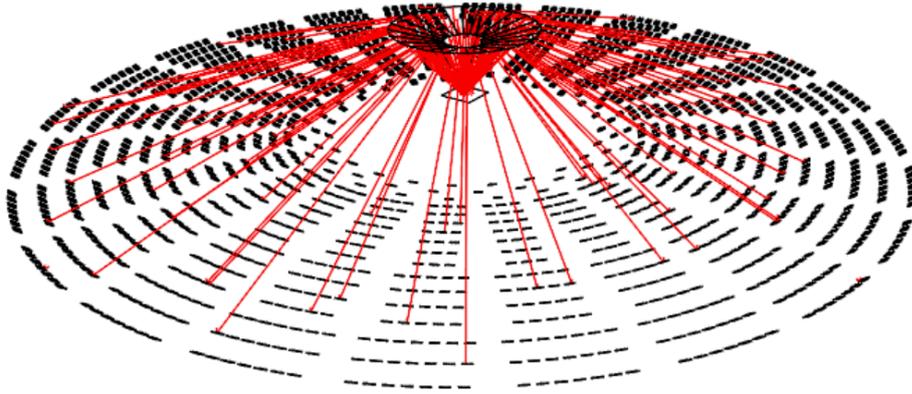
Figure 12: Exemplary visualization with selected ray traces of Solar Tower Beam-Down system with a surrounding heliostat field

To speed up the annual simulation of heliostat fields and central receivers, the concept of a *sky discretization* (Schöttl et al. 2016) has been developed, where ray tracing for discrete sun positions is carried out. Using this approach, large numbers of simulations for hourly or minute-by-minute time steps can be avoided. Conveniently, simulations on these sky nodes can be carried out in parallel, which allows for a near-linear speed-up on multi-CPU servers. While this concept has been originally developed for Solar Tower systems, it is applicable to other non-symmetric optics as well (For symmetric applications, usually Incidence Angle Modifiers (IAM) can be developed and applied).

6 Conclusion

Raytrace3D has proven to be usable for a variety of very diverse optical systems, most notably solar concentrators in the field of CSP and CPV. Several implementation concepts are specifically tailored to facilitate the simulation of concentrating collectors, either regarding ease of modeling or with regard to simulation speed. With its comprehensive model library and sophisticated evaluation routines, Raytrace3D is well suited to tackle industrial and scientific challenges related to the simulation of concentrator optics.

Being implemented as in-house software suite of Fraunhofer ISE, Raytrace3D allows to
- easily adapt the specifics of a simulation and the level of detail to the research or development question at hand and
- extend the tool and implement new features if required.

Are you dealing with a specific optical question? Do you require a characterization of conceptional or real concentrator optics? Do you need to optimize a collector design? Would you like to integrate a customized ray tracing solution in your own simulation software?

We are happy to support you!

Please contact
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- Dr.-Ing Gregor Bern (gregor.bern@ise.fraunhofer.de)

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