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OTSun Project: Development of a Computational Tool for High-resolution Optical Analysis of Solar Collectors

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Abstract

The OTSun project is a research project co-funded by the Spanish Ministry of Economy and Competitiveness, with the reference number ENE2015-68339-R, where the main goal is to develop a computational tool for high-resolution optical analysis of solar collectors. The project is runs from 2016 to 2018 and is composed of eight tasks. The main motivation of the project is to develop an open source code that serves as reference to simulate optical systems for solar energy applications where the most important optical effects are being considered. In order to achieve high-resolution results the radiation-matter interaction effects, the dependence of the incident angle on absorptive and anti-reflective surfaces, and also the dependence of the wavelength will be taken into account. The tool is based on the Monte Carlo ray-tracing method, and a useful software interface will be provided allowing the user to create, or import, the solar collector geometry. A data base of solar materials will be provided with the tool. Finally, the optical efficiency and the energy distribution on the receiver will be calculated by the program.

Keywords: *Ray-tracing, optical characterization, optical simulation, FreeCAD*

1. Introduction

Computational tools with the aim to simulate the optical performance of solar collectors are of utmost importance for optimization of a real system or during the design state of new systems. Moreover, the use of these tools produce economic savings in experimental validations, testing, and manufacturing (Osório et al., 2016); and also can be used to determine the optical behavior at different incidence angles (Hertel et al., 2016a, 2015). Nowadays there are many programs able to analyze the optical behavior of solar energy systems, such as STRAL, TieSol, ISOS, HFLCAL and HFLD. These programs are commercially available and are designed for the analysis of central tower plants with heliostats (Bode and Gauché, 2012). Programs that are available for free are SolTrace ("NREL," n.d.) and Tonatiuh (Blanco et al., 2009, 2005). Since OTSun is a project with the aim to develop an open source code with free availability, a briefly description of the specifications of the SolTrace and Tonatiuh softwares is exposed below.

SolTrace is a software tool developed at the National Renewable Energy Laboratory (NREL) to model concentrating solar power (CSP) systems and analyze their optical performance. Although ideally suited for solar applications, the code can also be used to model and characterize many general optical systems. SolTrace is free and can be downloaded from the NREL website. As for the ray-tracing methodology, the solar radiation distribution can be considered as a Gaussian, punctual or user defined models. For the optics of materials the "optical element definition" model is used to characterize any optic element of the system;

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this element is adjusted by parameters in order to consider mirrors or glasses, such as: the reflectivity (with incidence angle dependence), the transmissivity, the slope error, the specularity error, and the refractive index. In the case of refraction, the Fresnel equation is handling the reflection and refraction at interfaces (angular variation). SolTrace has a graphical user interface (GUI) for the visualization of the scene.

Tonatiuh is an open source code written in C++ and designed for the analysis of the optical behavior and energy distribution of radiation in concentrating solar power (CSP). Similar to SolTrace, Tonatiuh supports multiple geometric shapes and has a GUI. However, the analysis and the processing results should be treated with an external program such as Mathematica or R. Tonatiuh has a Universal GNU Public License, which allows free access to the code for any user and contribute to its development. About the ray-tracing methodology, the solar radiation distribution can be considered as a pillbox, or as the Buie model (Buie et al., 2003). As for the optics of materials, Tonatiuh considers refractive materials (e.g. glass covers) and specular materials (e.g. mirrors). The refractive materials are defined by the transmittance (a constant value), and the slope error. It should be noted that the electromagnetic Fresnel optics equations are not implemented. The reflective materials are defined by the reflectivity and the slope error.

Despite the variety of programs meant for optical simulation of solar systems, there is no open source software capable of taking into account the most relevant effects of the radiation-matter interaction that occur in solar energy systems, such as: electromagnetic Fresnel optics equations, the real behavior of dielectric materials, the wavelength dependence, the incidence angular dependence of selective and anti-reflective materials, the multivariate Gaussian function for the reflection direction, the volume scattering effects, among others. For this reason, the authors of this study are developing an open source code to simulate the optical behavior of solar collectors that takes into account the most relevant optical effects in optical solar systems.

To achieve the goals of the project, first a study of the most relevant effects related with the radiation-matter interaction of the common materials used to construct solar concentrating collectors has been conducted. Results are presented in another study at the EuroSun 2016 (Hertel et al., 2016b). All the interaction effects should be modeled by the Monte Carlo approach in order to consider the stochastic nature in the energy harvesting process of solar collectors.

On the other hand, a GUI will be provided with the tool to facilitate the visualization of the scene, and also be able to import the geometry of the solar collector from other formats. The interface software should allow working with open file formats such as STEP, STL, DXF, and OBJ.

An important part of the project is the availability under an open source license (GPL, freeBSD or similar). Finally it can be mentioned that the project is supported by the Plataforma Solar de Almería (PSA), the Spanish institute Instituto para la Diversificación y Ahorro de la Energía (IDAE), The solar Energy Research Center (CIESOL), TECNALIA Corporation, and SOLARUS Sunpower Sweden AB.

2. Previous results in ray-tracing analysis

The team of the project has a lot of experience in ray-tracing simulations. It can be noted that the first code developed was implemented in 2006 (Martínez Moll et al., 2006; Pujol et al., 2006) where the Fixed Mirror Solar Concentrator (FMSC) (Russell John L., 1977) was analyzed with simple optical models. The results showed the most interesting geometries of the FMSC based on two design parameters (the number of mirrors and the focus/width ratio). The simulations were conducted with simple models, such as a point source for the sun model, ideal specular reflectivity for mirror surfaces, a constant value for the transmittance of the cover, and a constant value for the absorptance of the receiver surface. As for the code, the geometry of the system only could be defined by triangles with ASCII files. Hence, only one algorithm was required to detect the intersection between a line and a triangle in 3D space. The algorithm used is the one exposed in the book (David H. Eberly, 2006). About the ray-tracing program developed at 2006, it can be concluded that the ray blocking effect was the most important phenomenon for the analysis of the optical efficiency of the solar collector. The code was implemented in FORTRAN.

It was not until 2012 when the first results with a more accurate ray-tracing model were presented by the authors (Pujol Nadal and Martínez Moll, 2012). The major improvements implemented at this stage were: the Fresnel equations for the electromagnetic waves (Hetch and Zajac, 1999), the Buie model for the solar radiation distribution (Buie et al., 2003), the incidence angle dependence for the absorptance surfaces according to the model exposed in (Tesfamichael and Wäckelgård, 2000), and a one-dimensional radial distribution for the normal deviations from an ideal specular reflection (Johnston, 1995). All the effects were modeled with the Monte Carlo methods. The tool was used to analyze the FMSC and its curved mirrors version, the Curved Slats Fixed Mirror Solar Concentrator (CSFMSC) (Pujol Nadal and Martínez Moll, 2013). The most promising geometries of both designs were identified for medium temperatures ranges in other works (Pujol-Nadal et al., 2013; R Pujol-Nadal and Martínez-Moll, 2014).

It can be noted that a difference of 25% was observed between the optical efficiency calculated by simple models (studies presented in 2006) and the one based on more accurate models (presented in 2012). Even though the more promising geometries were in both cases very similar. Hence, if it is true that simulations with simple optical models can be used to compare different designs of the same concept (the FMSC and the CSFMSC), the absolute value of the energy collected by the system can only be determined if the simulations take into account accurate models which are based on the most important effects in the energy harvesting process of the solar collectors.

In order to evaluate the importance of a high-resolution ray-tracing model with respect to a simple ray-tracing tool, an optical simulation of a parabolic through collector (PTC) has been conducted. The PTC chosen for the analysis was the NEP PolyTrough 1800 collector exposed in (Sallaberry et al., 2015). The simulations have been done using two different models: Model 1 and Model 2. The first one takes into account the Buie model for the Sun (Buie et al., 2003), one-dimensional radial distribution for the normal deviations from an ideal specular reflection (Johnston, 1995), Fresnel optics equations for electromagnetic waves, the extinction coefficient of the glass tube for the transmittance, and the angular dependence of the absorber surface (Tesfamichael and Wäckelgård, 2000). On the other hand, Model 2 considers a point source model for the sun, ideal specular reflectivity, a constant value for the transmittance of the glass tube, and a constant value for the absorptance of the receiver. The results are shown in Fig. 1, for transverse and longitudinal angles of incidence. It can be seen that if a simple model for the radiation-matter interaction is considered in a ray-tracing simulation, an overestimation of the optical efficiency is obtained.

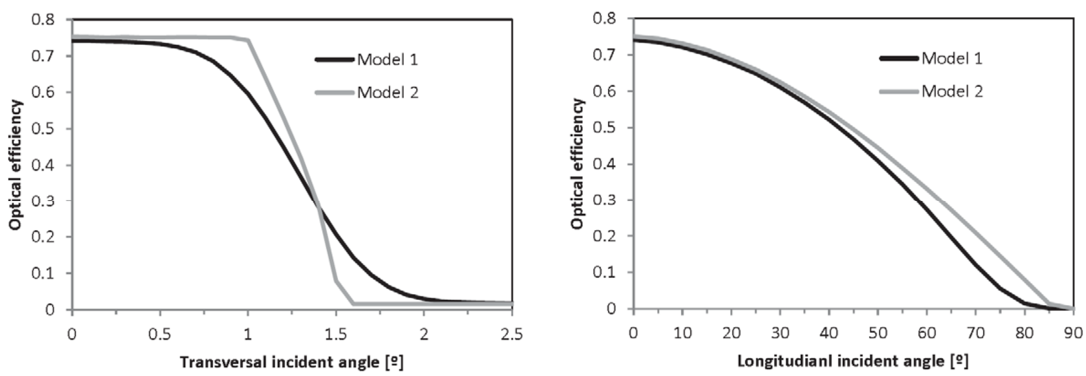


Fig. 1: Ray-tracing results of a PTC for transverse and longitudinal planes using simple and more accurate models

3. The ray-tracing code

The current code, written in FORTRAN, is under development. New models from 2012 are implemented in order to consider optical models based on the interaction of light and matter. The main description of the code in the actual state is described below.

In the current version the geometry has to be defined by surface objects. In a subsequent step different physical models with its respective parameters can then be assigned to each surface object.

For any type of model, the lay of energy conservation is always satisfied. There are consequently only three possible ways of interaction. The incident ray can be either reflected, transmitted, or absorbed according to Eq. 1.

$$R(\theta_i, \lambda) + T(\theta_i, \lambda) + A(\theta_i, \lambda) = 1 \quad (1)$$

All coefficients depend on the wavelength, the incidence angle and the polarization of the light. With Eq. 1 in mind it is possible to classify common materials of solar concentrating collectors into three different groups: Reflective (mirrors), transparent (envelope, covers etc.) and absorbing (receiver) materials. As illustrated in Fig. 2, the simplifying assumptions are zero transmittance for reflective and absorptive materials, and zero absorptance for transparent materials. The latter only goes for the surface itself, because in the medium (after passing through the interface) there will be absorptance of the propagating electromagnetic wave, see Fig. 3.

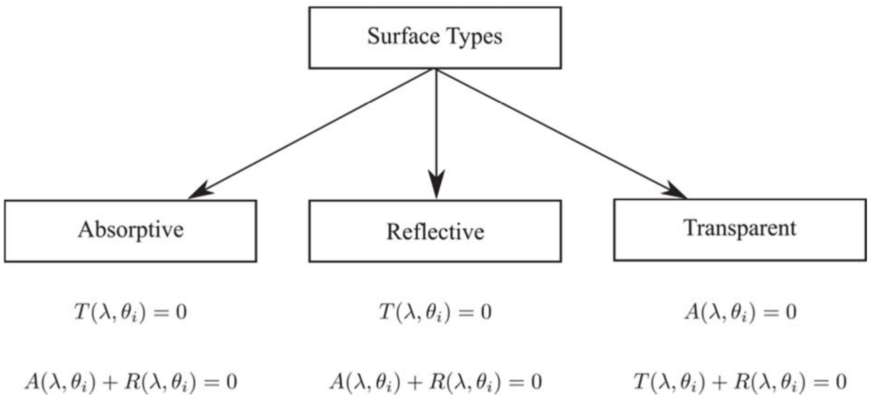
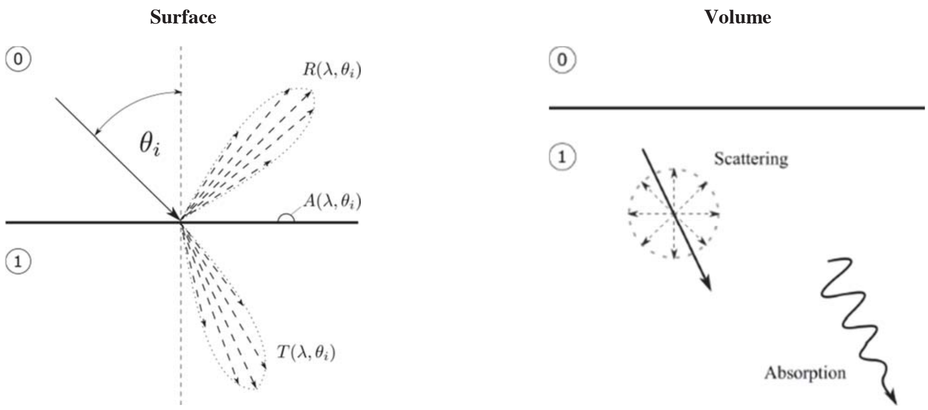


Fig. 2: Classification of typical solar thermal material: absorptive material (receiver), reflective material (mirrors) and transparent material (covers, envelopes)



a) b)

Fig. 3: Radiation-matter-interaction phenomena: a) Reflection, transmission and absorption on surfaces. b) Scattering and absorption within volume (Hertel et al., 2016b)

As far as conservation of energy goes, the interaction of an incident ray with a surface can be fully described by a surface reflectance model. What is then still missing for a more accurate description is the spatial dispersion of the reflected energy due to random microscopic surface textures. This phenomenon called scattering can be described by a scattering model.

In summary, all radiation-matter interaction models that our ray-tracing code contains can be categorized into:

- Surface effects
  - Reflectance models
  - Scattering models
- Volume effects (only transparent material):
  - Volume absorption.

3.1 Reflectance models

Fig. 4 shows all surface reflectance models, which are currently implemented in the OTSun ray-tracing code. For more details see (Hertel et al., 2016b). It is important to comment here on the accuracy of the reflectance model. As mentioned before, the surface reflectance is a function of the wavelength and the incidence angle of the ray, as shown in Eq. 1. Depending on the purpose of the study, the surface reflectance can also be defined as a constant value, only depending on the incident angle, or depending on both the incidence angle and the wavelength.

In any case, sufficient experimental data has to be available. As for selective materials, often manufacturers provide a constant value. If such a value is not available, (Tesfamichael and Wäckelgård, 2000) proposed an empirical model of $R(\theta_i)$. This model was derived from measurements of an Al2O3-Ni/Al2O3 and NiO3-Ni-composite selective surfaces. Unfortunately, there was no other data obtained apart from these two samples. The model of (Grena, 2010) is a good alternative to derive the incidence angle dependence if the absorption coefficient is known for normal incidence.

Alternatively, accurate information about reflectance can be obtained from refractive index data bases. Based on this information, the Fresnel equations for single interfaces or the Transfer-Matrix method for more complex multi-layers (coatings) are common approaches in other fields such as PV or optics design (Macleod, 2010).

3.2 Scattering models

At the moment there are three options for scattering implemented: no scattering, Lambertian (isotropic) or Gaussian scattering (Fig.). Isotropic dispersion is typical for matte surfaces, while a Gaussian curve describes the reflection pattern of specular surfaces such as mirrors. In reality, the result is often a combination of isotropic and specular reflection and is described by a bidirectional reflectance distribution function (BRDF).

In solar concentrating applications the Gaussian model was found to be sufficiently accurate to describe the reflection of mirrors. OTSun uses a more general superposition of two bivariate normal distributions (Eq. 2).

$$f = Ke^{\left(-\frac{\varphi^2}{2\sigma_{21}^2}-\frac{\varphi^2}{2\sigma_{22}^2}\right)} + (1-K)e^{\left(-\frac{\varphi^2}{2\sigma_{11}^2}-\frac{\varphi^2}{2\sigma_{12}^2}\right)} \quad (2)$$

with K the ratio between distributions, σ_{ij} the respective variances and φ the acceptance angle. Moreover, it is possible to define wavelength and incidence angle dependent data for the variances σ_{ij} such as defined e.g. by (Good et al., 2016).

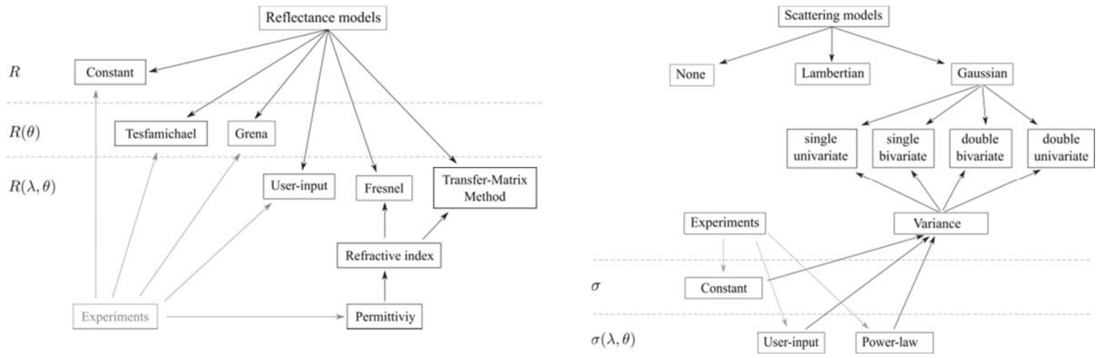


Fig. 4: Schematic of implemented reflectance (left) and scattering models (right) in the current version of the OTSun ray tracing code

4. Objectives and methodology

The improvement of the FORTRAN code is the first task of the OTSun project. The optical models are first proved and validated in the FORTRAN code, and then they will be implemented in the new version of the program.

The general objectives covered by the OTSun project are:

- Developing a computational tool for the high-resolution optical analysis of solar collectors.
- Validating the computational tool by comparison with theoretical and experimental results.
- Applying the computational tool in real cases.
- Distributing the tool as an open source code.

To achieve the general objectives, the next set of tasks will be developed during the project:

- Task 1: Current Status and improvements of the actual ray-tracing tool (FORTRAN).
- Task 2: Implementation of new algorithms of ray-intersection.
- Task 3: Implementation of a general algorithm for the energy distribution on the receiver.
- Task 4: Types of sources, spectrum and its implementation.
- Task 5: Models for specular reflective surfaces.
- Task 6: Radiation-matter interactions of materials.
- Task 7: Simulation of real cases.
- Task 8: Web and documentation platform.

General requirements for the simulation tool are a graphical interface for the visualization of the scene (GUI), and a programming language accessible to future improvements and developers. With this in mind, during the initial stage of the project we explored possible tools to start from; tools that were already developed with regard to these specifications. It should be clear that it is not beneficial to develop a visualization tool from scratch, but rather incorporate the physical models into an already existing visualization tool. Such a tool could be a computer aided design software (CAD), or any other 3D data visualization programs.

As discussed in previous sections, the geometry of the system only can be introduced by triangles in the actual FORTRAN code. It is possible to generate any geometry with the desired precision at the expense of an increasing number of triangles. Consequently, constructing curved surfaces with triangles has the disadvantage of requiring a large number of elements, which means increasing computation time. For this reason we explored new algorithms for ray-intersection with surfaces in task 2.

In view of the general specifications, and the need to reduce the CPU time, we explored the FreeCAD software ("FreeCAD," n.d.). FreeCAD is a parametric 3D modeler made primarily to design real-life objects of any size. Parametric modeling allows to easily modifying the design by going back into the model history and changing its parameters. FreeCAD is open source and highly customizable, scriptable and extensible, it runs on multiple platforms (Windows, Mac and Linux), and supports many open file formats such as STEP, IGES, STL, SVG, DXF, OBJ, IFC, DAE among others. It has the great advantage that almost all of FreeCAD's functionalities are accessible to Python, hence it is possible to easily extend these functionalities, automatize them with scripts, build self- made modules, or even embed FreeCAD in your own application.

Finally, it can be noted that Python is a widely used high-level, general-purpose, interpreted, and dynamic programming language, and that FreeCAD has implemented methods for the intersection between faces and lines (very useful for the ray-intersection problem mentioned above and to decrease the CPU time). For all of these reasons, we decided to develop the OTSun project as an extension of the FreeCAD software.

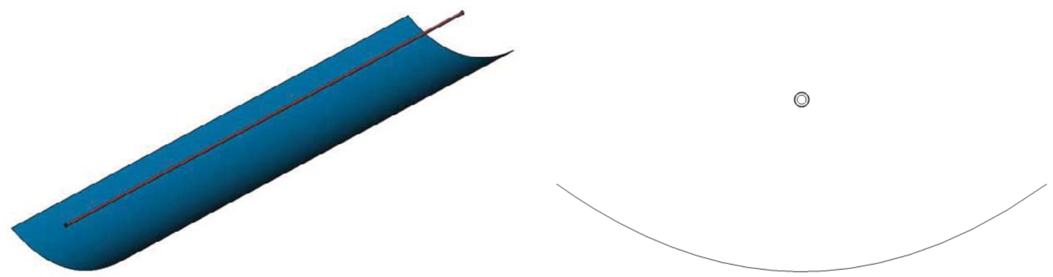
5. First results using the FreeCAD software

A ray-tracing simulation of a solar collector using the FreeCAD software has been conducted and validated. To do so, first the creation of the geometry of the NEP PolyTrough 1800 collector exposed in (Sallaberry et al., 2015) was modeled using the functions available in the *Part Module* of FreeCAD. Then, the skeleton of a simple ray-tracing procedure written in Python was implemented and executed. Only simple effects of optics have been implemented in this stage of the project. The main objective of this work was to evaluate the extensibility of FreeCAD software for ray-tracing simulations applied to solar collector systems.

5.1. Creating a PTC in FreeCAD

The *Part module* of FreeCAD allows accessing and using the OpenCasCade objects and functions. OpenCascade is a software development platform providing services for 3D surface and solid modeling, CAD data exchange, and visualization ("Open CASCADE Technology: Overview," n.d.). Most of its functionality is available as C++ libraries.

The *Part Module* has implemented tools for creating primitive objects, such as: box, cone, cylinder, torus, parabola and sphere among others. The ones that we used for creating the PTC were the parabola, the circle and the cylinder. Then, the *Part Module* has also implemented tools for modifying existing objects in the document, such as: booleans, union, common, extrude and cut among others. The extrude tool was used to create the parabolic mirror and the absorber tube from the primitives mentioned above. Since the glass tube has volume effects from the optical point of view, it was generated using the cut tool subtracting one cylinder from another. This way a solid object was obtained for the glass cover of the evacuated tube. A Python package with all the instructions mentioned above was written to create the geometry of the PTC in FreeCAD. Figs. 5 and 6 show the PTC created. Note that the parabolic mirror and the absorber cylinder are faces, but the glass tube is a solid.



(a) **(b)**

Fig. 5: (a) General view of the PTC. (b) Frontal view of the PTC

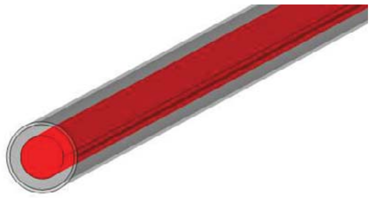


Fig. 6: Evacuated tube of the PTC

5.2. The ray-tracing procedure

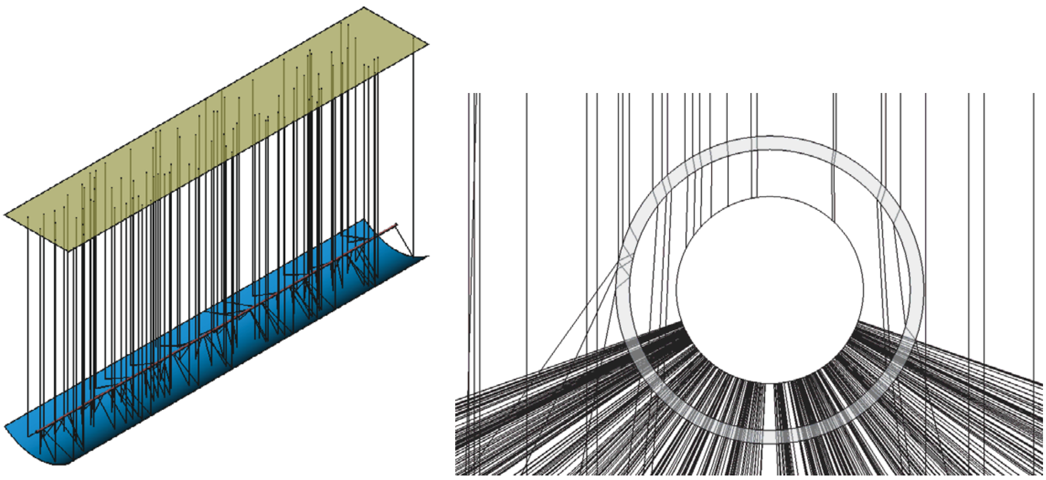
The program calculates ray trajectories originating from one source (called sun window) that emits rays to all surfaces of the system. We have created a Python package that uses the classes provided by FreeCAD and extends them in order to model scenes and implement the ray-tracing procedure.

At this stage of the project, the core of the computation is implemented via three main classes, Scene, Ray and SolarCollector. An object of the class Scene collects all the information related to the physical objects present in the active document (the solar collector constructed).The physical objects are represented using *Shapes* in FreeCAD with some extra information regarding their materials. At this stage of the project, only simple models for the optics are considered.

An object of the class Ray collects the path that a solar ray describes while it interacts with the objects present in its scene; it is initialized by giving its source and direction. For now, only a punctual source is considered. We have implemented algorithms to compute, step by step, the points that the object passes through while it is reflected, refracted or absorbed in the surfaces present in the scene. These two classes are used by the third; SolarCollector, that implements the overall computation of the optical efficiency of the scene as a solar collector, making an estimation of the overall energy that it gets absorbed when the scene is exposed to the source.

5.3. Ray-tracing simulations

Fig. 7(a) shows a visualization of a ray-tracing simulation of the NEP PolyTrough 1800 collector done with the package mentioned above. This simulation was done emitting 100 rays, and it can be see how the sun window emits rays to the solar collector system. In Fig. 7(b) a front projection of the same ray-tracing simulation is shown. Also visible are the path trajectories of the rays according to the refraction law. Another case is shown in Fig. 8, for the longitudinal angle equal to 45º.



(a) **(b)**

Fig. 7: Ray-tracing simulation with 100 rays emitted. (a) Total view of the concentrator, sun rays, and sun window. (b) Frontal projection of the same ray-tracing in the region of the receiver.

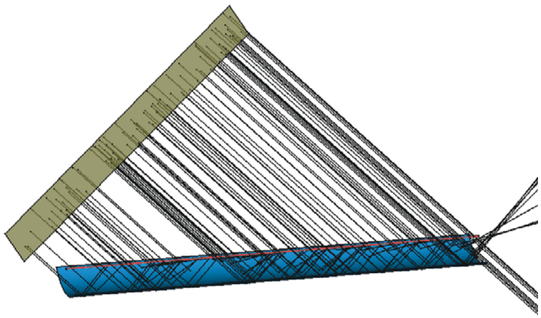


Fig. 8: Ray-tracing simulation with 100 rays emitted for the case of longitudinal angle equal to 45º

In order to validate the results of the new code generated, a simulation with 20000 rays has been conducted considering the same assumptions of Model 2 in Section 2. In Fig. 9 the optical efficiency obtained with the new code (OTSun_FreeCAD) and with the FORTRAN code (OTSun_FORTRAN) is shown. In view of the results, we can conclude that the new OTSun code calculates the optical efficiency with same accuracy as the FORTRAN version. Moreover, as the FORTRAN version was validated with experimental results in (Pujol-Nadal et al., 2015; Ramon Pujol-Nadal and Martínez-Moll, 2014), hence the code implemented in FreeCAD is also validated.

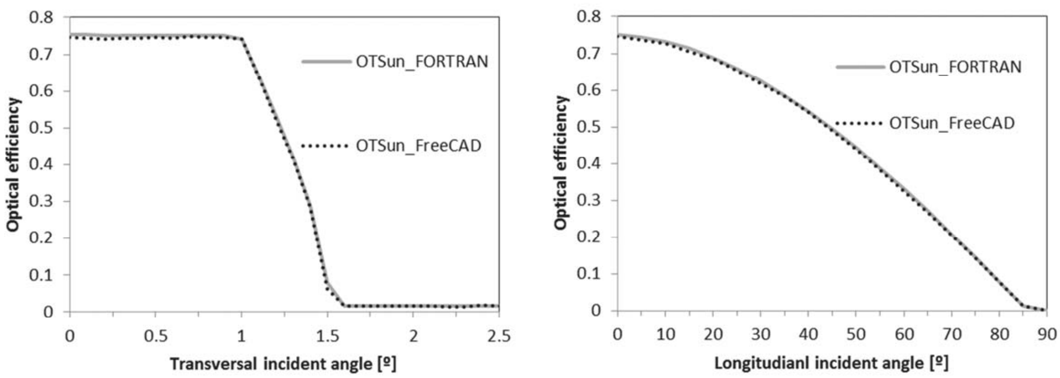


Fig. 9: Ray-tracing results of a PTC for transverse and longitudinal planes using simple models with FORTRAN and FreeCAD versions.

6. Conclusions

Ray-tracing simulations show great benefit for the optical analysis of solar collectors, and in order to achieve high-resolution results the consideration of the radiation-matter interaction is needed. In this contribution the authors describe the OTSun project, where the main goal is to develop a computational tool for high-resolution optical analysis of solar collectors. The tool will be developed under a free license (GPL, freeBSD or similar). Due to the general requirements for the tool, the authors decided to develop the OTSun project as an extension of the FreeCAD software which has the advantage that almost all of its functionalities are accessible to Python. A Python package has been written in order to explore the viability of making a ray-tracing simulation of a solar concentrating collector using the FreeCAD functions. In view of these experiences, it has been demonstrated that the FreeCAD program is suitable to extend its functionality and use it for a ray-tracing simulation of solar energy systems.

7. Acknowledgements

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