Efficient Ray-Tracing Program to Simulate the Optical Performance of Heliostats in Concentrated Solar Power Facilities

Iván Bravo Gonzalo[1], Alejandro Martinez Hernandez[1], Manuel Romero[1] and José Gonzalez Aguilar[1]

[1] IMDEA Energy Institute, Avda. Ramón de la Sagra 3, 28935 Móstoles (Spain)

Abstract

This paper presents a dedicated ray-tracing program developed in Matlab and specifically designed for assessing the heliostat optical performance of concentrated solar power facilities, in particular concentrated solar tower. To evaluate the performance of our program, we carry out a detailed comparison with a commercially available ray-tracing software (TracePro®) under various simulation conditions. As a test-case, we use the layout of the concentrated solar tower facility located at IMDEA Energy in Móstoles (Spain), although the program allows for simulations with different heliostat field layouts. We show that the simulations of flux distributions on the target given by our program agree very well with that of the commercial software, but the computation time is significantly reduced. In fact, much faster simulations are obtained not only for individual heliostats but also for the entire solar field, resulting in our program outperforming the commercial software in at least a factor of 10. It is also shown that in the case of using matrices of slope errors, with the aim to obtain more precise flux maps, our program is much more efficient than the commercial software. For instance, when the facet is divided into squares of 2.5 cm (matrix of slope errors with 4864 elements), our program is a factor of more than 5 orders of magnitude faster than the commercial software. To further validate our program, we show that the simulated flux maps of individual heliostats with both software show an excellent agreement with the corresponding experimental flux maps.

Keywords: Solar Power, Concentrated Solar Power, Ray-Tracing, Heliostats, Flux Maps

1. Introduction

Precise knowledge of the optical performance of the heliostat field is required in concentrated solar tower (CST) facilities in order to optimize its design, for instance, in order to obtain the maximum irradiance on the receiver (Iriarte-Cornejo et al., 2018) at minimum cost. For this purpose, commercially available ray-tracing software are typically used (Jafrancesco et al., 2018). However, commercial software are not usually dedicated only to CST simulations but are generic tools with a great variety of options that can be used for design of optical elements in many applications. This can result in limitations, e.g. extremely long computational times, when a very precise characterization of the heliostat field performance is needed (Jafrancesco et al., 2018). Therefore, the development of a dedicated software to simulate solar power facilities is important and of research interest in the concentrated solar power community. In fact, a great effort has been carried out during the years to develop specific software to simulate the optical performance of CST plants (Garcia, P., 2008, Cruz et al., 2017). This continuous effort has resulted in a wide variety of software with different characteristics, some of them even including an optimization tool for designing heliostat field's layouts. An example of it is the software developed by National Renewable Energy Laboratory (NREL), which offers not only analyses about the optical performance of a heliostat field with SolTrace (Wendelin, 2003), but also layout optimization with SolarPILOT (Wagner and Wendelin, 2018). However, there is still work to do in terms of speed in order to achieve precise and real-time simulations of the heliostat field. In this regard, for instance STRAL, a software developed by DLR (Belhomme et al., 2009), is able to perform precise and fast simulations. However, it is commercialized by DLR (Cruz et al., 2017) and thus there is no an open-source code to download, so that the availability is reduced compared to other tools. In this work, we propose a ray-tracing Matlab program specifically designed and optimized to precisely evaluate the optical performance of heliostats in CST facilities. Our program not only reproduces perfectly the results given by a commercial software (TracePro®) but also speeds up the simulations, which leads to a significant improvement in computation time. We believe that this is a step forward to achieve real-time and high precision optical simulations of heliostat fields in CST facilities.

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2. Ray-Tracing Program Description

This ray-tracing program works dividing the heliostat reflective surface into small elements and tracing rays from each one of these elements. The layout of the heliostat field under investigation is uploaded into the program as a file with the position (x, y and z coordinates) of each heliostat in the field. For each heliostat, the program solves a system of equations taking into account the position of the target, the geometry and tracking system of the heliostat, its position in the field, and the solar vector, which is given by the local time of the day, latitude and longitude. Once the system of equations has been solved, each element of the facet is oriented and its normal vector is statistically deviated a certain degree of milliradians to account for the optical error of the facet. If the deviations in x and y directions of the normal vectors to the reflective surface are known, also known as matrices of slope errors (MSE), the software allows importing them to obtain much more accurate simulations. After setting up the normal vectors, blocks and shadows are calculated in a similar way as done in (Belhomme et al., 2009). For those elements that are not blocked or shadowed, a bundle of sunrays is traced. Each sunray of the bundle is deflected from the main direction of the reflected sun vector according to the given sunshape distribution, and it has an associated weight in power depending on its deflection angle. In this version of the program, the sunshape is given by the limb-darkened distribution (Romero et al., 2016), in which the circumsolar ratio is discarded. Future versions will introduce different sunshapes with certain degree of circumsolar radiation for more precise simulations. Furthermore, as the rays have their origin on the heliostat facet (Belhomme, B., 2009), all of them reach the target if it is large enough. In contrast to this, many rays from the defined sun in TracePro® do not reach the heliostat and are therefore lost in the ground. This feature of our program results in an advantage in computational efficiency because TracePro® will need more initial rays than our program to obtain flux distributions on the target made of a desired number of rays. This will be investigated in the next sections. Finally, the number of elements in which the heliostat surface is divided, i.e., the grid, can be selected, modifying in this way the precision of the simulation. Another feature of the program it that its performance could be still greatly improved by parallelizing the process of ray-tracing by using GPUs (He et al., 2017). This feature is in progress and next versions of the program will include this parallelization.

3. Test-Case: IMDEA Energy Solar Tower Facility

To perform a more meaningful investigation, we choose a real test-case layout, the very high concentrating solar tower facility located in Mostoles (40.3399012, -3.8832431), Spain (Romero et al., 2017). The heliostat field layout consists of 169 single-facet heliostats distributed in 14 rows as shown in Fig. 1a. All the heliostats use a tilt-roll tracking mechanism to track the sun and spherical silvered-glass mirrors as reflective surface manufactured by RioGlass Solar. Each mirror has dimensions of 1.9 m x 1.6 m, which gives a total reflective surface of the solar field of around 514 m^2. To improve the peak flux, the heliostats in rows 1-8 have 20 m focal length (40 m curvature radius) while heliostats in rows 9-14 have 30 m focal length (60 m curvature radius). This configuration of the heliostat field results in high peak flux of about 3000 kW/m^2.

To further characterize the heliostat field, the reflective surface profile of some mirrors was measured by means of deflectometry (Ulmer et al., 2011). With this technique, the MSE were obtained every 2.5 mm. This is important because having the information about the specular surface profile of the mirrors, precise flux maps of individual heliostats can be obtained (Iriarte-Cornejo et al., 2018). In our investigation, some of the heliostats characterized with deflectometry have been simulated and then compared to the measured flux maps to assess the precision of our program.

Finally, a 15 m high central tower is shown in Fig. 1b, in which a Lambertian target is located at 13 m from the ground with dimensions of 1 m x 1 m. Flux maps of individual heliostats on the Lambertian target were measured with a CCD camera (Prosilica GT1930L) and a zoom lens using the flux map acquisition system (FMAS) developed by DLR (Thelen et al., 2017). However, in this case no detector was used, so measured maps have been normalized to the maximum intensity registered by the CCD camera. These experimental flux maps have been compared to the simulations by defining the same Lambertian target in our program. It is worth to note that our ray-tracing program is not only restricted to the IMDEA Energy solar tower facility, but other CST configurations could also be imported and studied with our program.

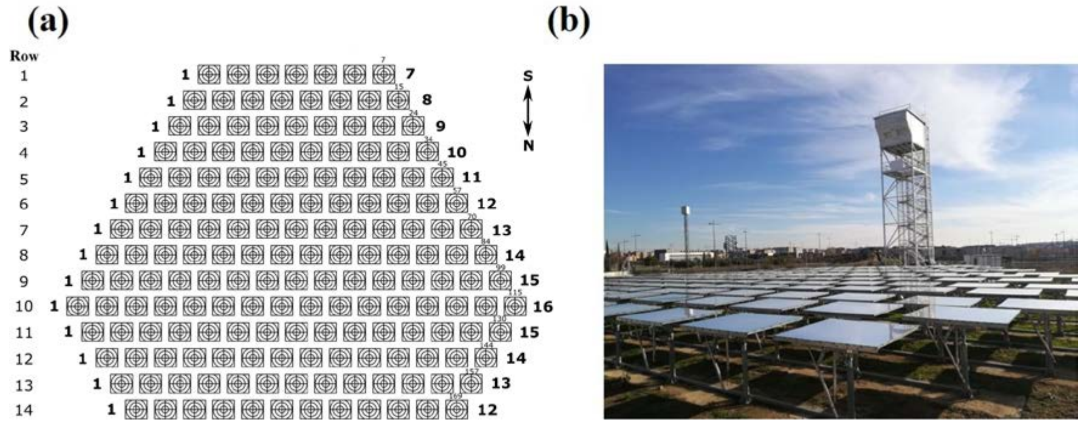

Fig. 1: a) Heliostat field layout consisting on 169 heliostats distributed in 14 rows. b) Picture of the heliostat field and tower located at IMDEA Energy.

4. Ray-Tracing Program Validation

All the simulations have been performed assuming a reflectivity of 90%, DNI (Direct Normal Irradiance) of 900 W/m^2 and same time of the day (15th of January 2019 at 12:56:08 local time). We also performed all the simulations using the same workstation for fair comparison between our Matlab program and TracePro® (Dell Precision T5500, Intel (R) Xeon(R) CPU E5620 at 2.4 GHz, Windows 7 Professional SP1 – 64 bits, 24 GB DDR3-RAM). The version of both software employed are Matlab R2019a and TracePro® 2018 Expert - 18.1.

4.1 Individual Heliostats

In order to validate our ray-tracing program, we carried out a detailed comparison with TracePro®, a commercially available software commonly used in the community. For the comparison between both simulation tools, different cases are investigated. First, we perform simulations of an individual heliostat (heliostat 5 on row 5 - see Fig. 1a) for which the MSE are known thanks to deflectometry. As the MSE were obtained with precision of 2.5 mm, the precision of the matrices can be resampled in order to investigate the effect on the computation time of the number of elements per facet, while having a fixed number of rays. For this first investigation, we perform simulations having the heliostat facet (dimensions: 1.6 m x 1.9 m) divided into squares of 10 cm, 5 cm and 2.5 cm, corresponding to have 304, 1216 and 4864 elements per facet. The number of initial rays traced is fixed to 121.6x10^5. For our program, this means that the bundle of rays associated to the sunshape for each grid element consists of 40000, 10000 and 2500 rays, respectively. On the other hand, even though the facet is divided into the same number of elements in TracePro®, the number of rays per element is not known. Table 1 summarizes the results and shows that for our program, the computation time is practically the same when increasing the number of elements per facet. In contrast, TracePro® needs much more computational time, drastically increasing with the number of elements. This is a great advantage of our program with respect to the commercial software because more precise simulations, i.e., using more elements per facet (more precision in the MSE), can be obtained with almost no penalty in computation time. For instance, when the facet is divided into squares of 5 cm, corresponding of dividing the facet into 1216 square elements, the computation time of our program is 6189 times faster than TracePro®. This factor increases with the number of elements per facet. We can therefore conclude that our Matlab program is much faster than TracePro® performing simulations with a large number of surface elements.

Tab. 1: Computational time vs number of elements per facet for simulations of an individual heliostat using the matrices of slope errors with precision of 10 cm (304 elements), 5 cm (1216 elements) and 2.5 cm (4864 elements). The simulation performed with TracePro® corresponding to 4864 elements was aborted after 1818000 s (21 days) because the simulation was already very long.

	Matlab program			*TracePro®*			*Speed Factor with respect to TracePro*		
Number of Elements per Facet	304	1216	4864	304	1216	4864	304	1216	4864
Computation Time [s]	10.8	12.5	18.2	5826	77361	>1818000	**539.4**	**6189**	**> 99890**

We can also take a look to the flux maps obtained with both software, which are shown in Fig. 2. The initial conditions are the same for both, that is, the same heliostat (5th of row 5), same time of the day, 304 square elements per facet and 121.6x10^5 of initial rays. As we can see in Fig. 2, not only the shape of the flux map obtained with our program is identical to the one obtained with the commercial software, but also the error of total power and peak flux values between both simulations are lower than 2%. These errors are maintained for the simulation performed with 1216 elements. For the simulation performed with 4864 elements, as it was aborted for TracePro®, we could not compare the total power and peak flux. Additionally, Fig. 2c shows both simulated flux maps overlapped in a single graph to clearly see the small differences between both simulations. Therefore, the results given by the commercial software for a single heliostat are completely reproduced with our program and it is thus validated. Finally, the normalized experimental flux map at the same time of the day is presented in Fig. 2d for comparison, showing a good agreement with the simulated ones, further validating our program.

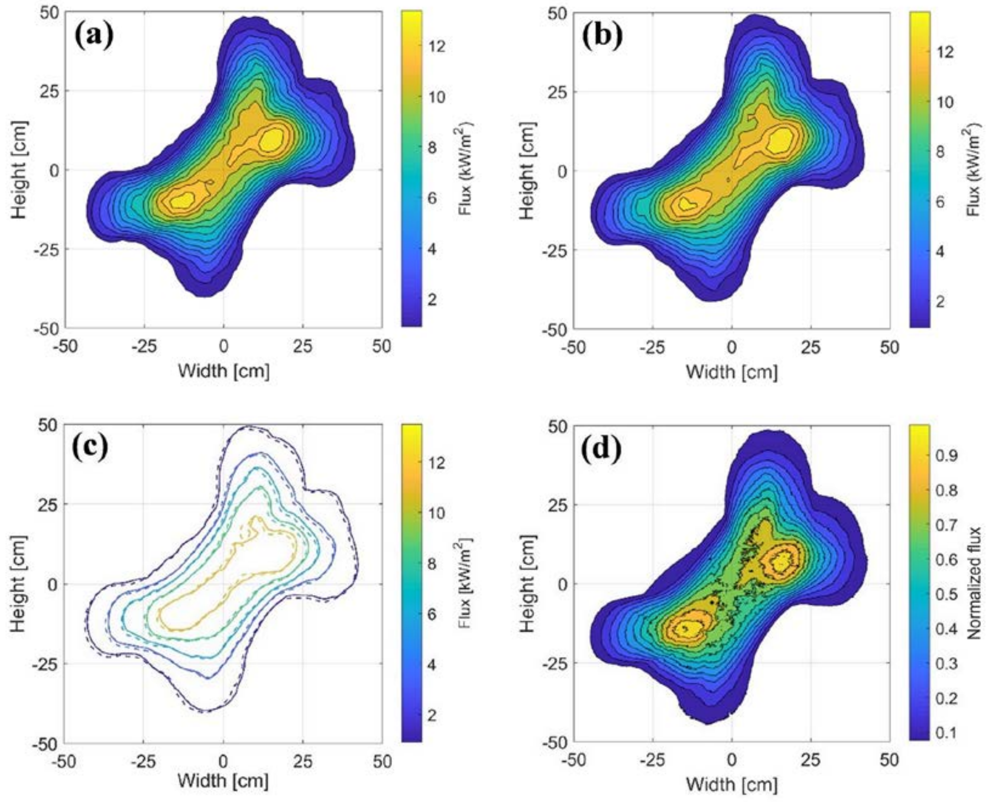

Fig. 2: Simulated flux maps with 121.6x10^5 rays of an individual heliostat using (a) Matlab and (b) TracePro®. The total power and peak flux obtained are: a) 2.1127 kW and 13.3589 kW/m^2, b) 2.1544 kW and 13.442 kW/m^2. c) Simulated flux maps overlapped in the same graph for better comparison. d) Normalized experimental flux map corresponding to the simulation.

Still with an individual heliostat, we can also assess the performance in computation time of both simulation tools as a function of the number of rays. Simulations were carried out with and without MSE to compare the computational performance with both settings. For TracePro®, when MSE were used, the facet was divided into 304 elements (10 cm square elements). In contrast to the previous case, when no MSE were used, the facet is composed of one single spherical surface element with the curvature radius given above and a statistically slope error of 1.25 mrad. For Matlab, 304 elements per facet were used in both cases, and the normal vector to each element was oriented as explained above, employing the same slope error when no MSE were used. Finally, the number of initial rays in each simulation was between 7.6x10^5 and 760x10^5. Figures 3a and 3b show the computation time when using (dark blue and orange bars) and not using MSE (light blue and yellow bars) as a function of the number of initial rays for Matlab and TracePro®, respectively. As we can see, our Matlab program outperforms again TracePro® in both configurations, especially when MSE are used. For instance, our Matlab program is 65 (977) times faster than TracePro® for the minimum (maximum) number of rays traced when MSE are used. Therefore, the relative difference in computation time of both software increases with the number of initial rays. Interestingly, Matlab is still faster when MSE are not used by a factor going from 9, for the minimum number of rays, to 154, for the maximum number of rays. Therefore, not only when completely precise simulations are needed but also for less demanding simulations, our Matlab program is faster than TracePro® in a factor of at least 9 for the same conditions. With these results, we see that our program can trace around 2x10^6 rays/s when 760x10^5 rays are traced, and this rate is the same using or not using MSE. In fact, for a lower number of initial rays, the ray-tracing rate is the same, but the computation time of the entire simulation is higher because of the time employed by Matlab in performing other actions, especially plotting the results of the simulations, i.e., the flux map. This explains why the computation time in Fig. 3a is approximately the same for the simulations performed with 30.4x10^5 or lower number of rays, because the time employed for performing such actions represents most of the computation time.

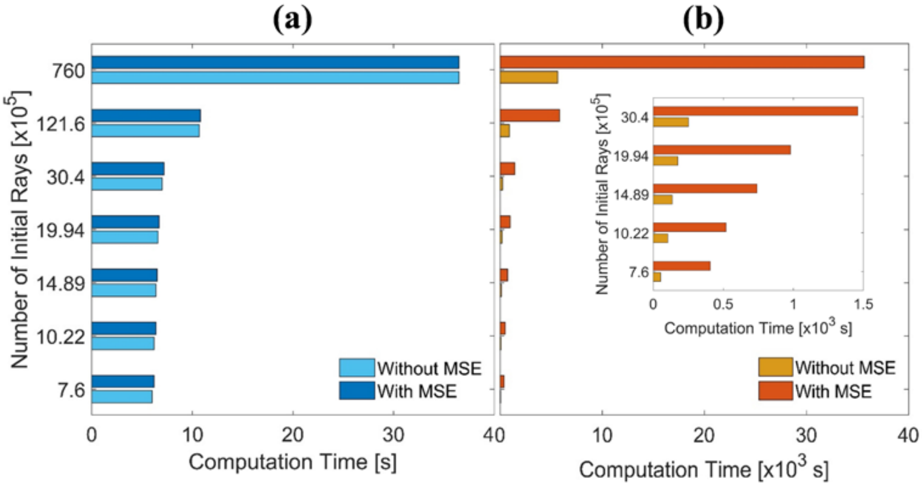

Fig. 3: Number of initial rays vs computation time for simulations with (a) Matlab and (b) TracePro®. Computation time when using and not using MSE is represented in (a) with dark blue and light blue and in (b) with orange and yellow, respectively.

4.2 Heliostat Field

For this second investigation, we simulate the entire heliostat field of IMDEA Energy. For the simulations with TracePro®, the facet of each heliostat is composed of one single spherical surface element with the curvature radius given above and a statistically slope error of 1.25 mrad. For the simulations with Matlab, the facet was divided into 304 square elements applying the same slope error. These simulations were carried out with the entire field, 169 heliostats, and 128.44x10^6 rays (7.6x10^5 rays per facet in Matlab). Similarly to the simulations of individual heliostats, we can see in Figs. 4a and 4b that both simulated flux maps of the entire heliostat field are identical. Furthermore, the error of total power and peak flux values between both simulations are lower than 2.5%. The computation time was longer for TracePro® (3301 s) than for Matlab (81 s) in a factor of 40. While not shown here, the trend is the same as with individual heliostats, the more initial rays traced, the more the relative difference in computation time between TracePro® and our Matlab program.

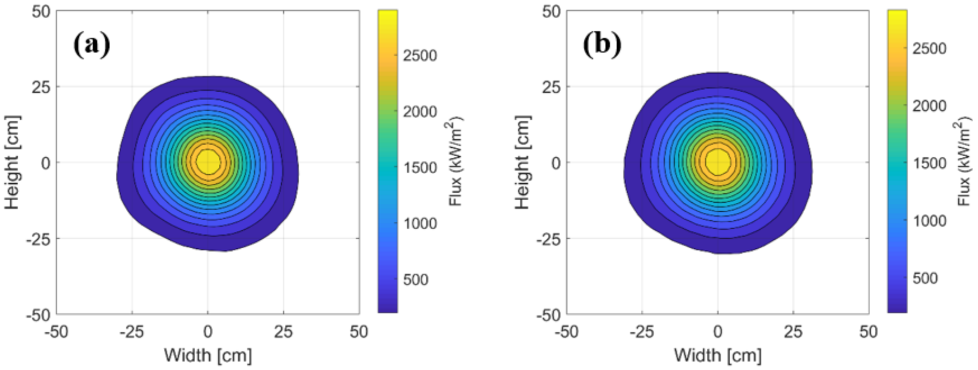

Fig. 4: Simulated flux maps with 128.44x10^6 rays of the entire field using (a) Matlab and (b) TracePro®. The total power and peak flux obtained are: a) 280.24 kW and 2897.8 kW/m^2, b) 280.75 kW and 2826.3 kW/m^2.

As already explained in Sec. 2, an interesting feature of our program is that the rays are generated and emerge from the heliostat's facet (Belhomme, B., 2009). This approach leads to an efficient way of tracing rays because all the rays will reach the target, when the target is sufficiently large. In contrast, software like TracePro® lose many rays in the ground. In order to investigate this effect, we performed simulations with both software having a number of initial rays resulting in the same number of rays reaching the target. As shown in Fig. 5, our Matlab program is very efficient tracing rays because all the initial rays except those corresponding to blocked or shadowed surface elements reach the target. In fact, for simulations of the entire field at the day and time given above, approximately 29% of the reflective surface area is being blocked or shadowed. However, it should be noted that rays corresponding to blocked and shadowed surface elements are not actually traced, so the program only takes time for calculating blocks and shadows. On the other hand, many of the rays traced by TracePro® misses the target not only because blocks and shadows, but also because those rays do not reach the heliostats. To give some numbers, the percentage of rays traced reaching the target is 71% (100% with no blocks and shadows) for our program and around 17% for TracePro®. Finally, we observe in Fig. 5 that to obtain flux maps with the same number of rays on the target, simulations with TracePro® take between 78 and 207 times longer than with Matlab. These numbers correspond to flux maps obtained with 20.17x10^6 and 114.31x10^6 rays on the target, respectively.

To summarize, our Matlab program is not only more efficient tracing rays but also much faster under the same conditions than the commercial software, either simulating individual heliostats or the entire field. Our Matlab program can simulate an entire field of 169 heliostats in 81 s, tracing 128.44x10^6 rays (0.76x10^6 rays per facet), which results in 1.59x10^6 rays per second. In addition, considering the conclusions drawn from Fig. 3a, we can estimate that approximately the same time, 81 s, will be needed by our program to simulate with high precision (using MSE) the entire field of IMDEA Energy (169 heliostats) tracing 128.44x10^6 rays.

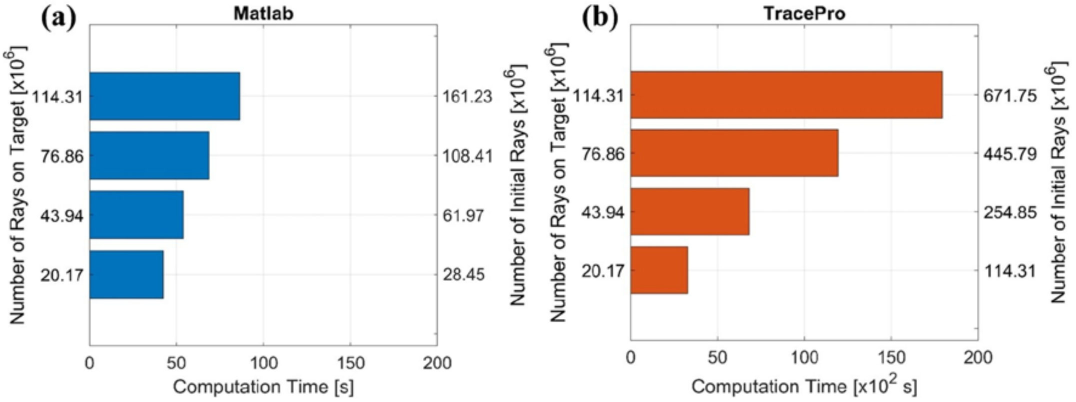

Fig. 5: Simulations with the same number of rays reaching the target vs computation time for (a) our Matlab program (blue bars) and (b) TracePro® (orange bars). For comparison, the number of initial rays for both software is also represented.

5. Conclusions

In conclusion, we reported the development and validation of a dedicated ray-tracing program in Matlab to simulate and assess the optical performance of heliostats in concentrated solar power facilities. In particular, we carried out simulations of the concentrated solar tower of IMDEA Energy in Móstoles (Spain). We performed a comparison with a commercially available software, TracePro®, in order to compare computation efforts and validate our program. Simulations showed that our ray-tracing program significantly outperforms the commercial software in computation time for all the conditions investigated here. We also showed that simulated flux maps with matrices of slope errors of an individual heliostat were almost identical with both software and very similar to the measured flux map, further validating our ray-tracing program. In terms of speed, our program can trace more than one million of rays per second and thus a simulation of the entire field of 169 heliostats using 7.6x10^5 rays per heliostat takes only 81 s. Most importantly, we can conclude that our Matlab program could be used to characterize a concentrated solar tower facility with high precision, using matrices of slope errors, with no penalty in computation time.

6. Acknowledgments

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