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Innovative Instrumentation and Methodology to Characterize Long Distance Heliostat Beam Quality in Commercial Solar Power Tower Plants

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Abstract. The characterization of the whole solar field of a solar tower power plant is a time consuming labor that has to be performed to know the optical quality of each heliostat in the field. This allows to correct some deviations of each heliostat, leading to an improvement in its individual performance, and thus, improving the final performance of the whole field. The current methodology to characterize the optical quality of a heliostat is based on using a lambertian target, in which the solar beam is focused and its reflected radiation is captured using cameras. This leads to important measurement inaccuracies due to the non-uniformity of the lambertian target and the behavior of the camera. But the fact that the sun beam can overflow the size of the target, and its power density can be almost in the order of the ambient light, implies that a huge part of the heliostats in a plant cannot be well-characterized by these systems. These issues are even more important taking into account that plant size tends to grow even larger, increasing the distance of the furthest heliostats, and that small heliostats begin to be introduced in solar fields, whose reflected power is lower than that of common heliostats. Those issues will be overcome thanks to a new measurement system based on a non-tracking way to scan the sun spot, using an array of optoelectronic detectors which can be installed in new plants and even in plants that are now in operation.

INTRODUCTION

Heliostat characterization in commercial solar tower power plants ensures keeping the heliostat beam quality within operating limits, which is crucial to have control over the flux distribution on the receiver, minimize losses by spillage and determine the economic and technical effectiveness of the plants. The most extended method [1][2] uses an auxiliary flat surface – a lambertian target – on top of the tower to individually aim the sun beam reflected by the heliostats, which is seen by a camera. The centre and shape of the spot is determined and analyzed for several incident angles of the Sun, their respective deviation calculated, the beam quality estimated, and thus, the errors can be corrected. Although this technique is very accurate and suitable for prototype evaluation at R&D centers or for small heliostat fields, its application in current commercial tower power plants, which contain several thousands of heliostats, most of them placed at long distances from any target, becomes almost impossible in practical terms, error-prone and not viable in most situations, both during commissioning and also in periodic characterizations along plant lifetime. These unbeatable difficulties rely on the following reasons:

- Non-linear response of the camera and non-uniform lambertian target, caused by dirtiness, peeling paint, edges and corners too highlighted, etc., resulting in poor quality images.
- The heliostat beam overflows the target mainly due to the high distance between the heliostat and the target, making impossible to capture the full heliostat image.

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- A large amount of noise is introduced in images of heliostat beam with low power flux-densities, due to its rivalry with ambient light. Low densities are achievable either by high distance between the heliostat and the target, by small-sized heliostat or both.

Nowadays, there is not a practical solution to accurately characterize beam quality on heliostat fields in commercial power plants under real working conditions. This lack of fast and accurate systems is evident and has been claimed by the concentrated solar industry on numerous occasions [3]. This technological shortcoming has become critical as the time being, highly influenced by many factors. Current trend in commercial solar power plants is to increase the nominal electric generation power and the thermal storage capacity; both aspects have direct impact on the total reflective surface needed, and thus, the number of heliostats, from 10 MWe and 74’880 m^2 in PS10 to 150 MWe and 1’300’000 m^2 in NOORo III. Correspondingly, the ground surface where the heliostat field is allocated has enlarged, resulting in a significant increase of the average distance from the heliostats to the receiver. Even more, considering that small and medium size heliostats turned up in the market with a very competitive cost per square meter during the last years [4], an increase in the amount of heliostats per plant would be expected for the same capacity. Assuming a 100 MWe plant, it is estimated that 80% of the heliostats are located at distances over 500 m and more of the 55% of them over 800 m, distance that, in a general assumption, is the practical limit of the state-of-the-art method, which leads that more than half of the heliostat field is not going to be adequately characterized.

The system herein presented overcomes these problems by means of a system of heliostat characterization independent of heliostat size and distance, and, more importantly, with a notable improvement in accuracy, making final evaluation much less sensitive to the density power of the reflected beam, and also less dependent on its size. The proposed methodology results in a portable and easy to install optical system. For commercial power plants, even those currently working, several systems can be installed, in order that many heliostats – one per system – can be characterized at the same time without interfering each other.

METHODOLOGY

State-of-the-Art Shortcomings

Non-linear Response of the Camera and Non-uniform Lambertian Target

The accuracy of the image based technique for reflected beam analysis is very sensible to lambertian target quality (it is assumed to be a homogeneous diffuse reflector, but it is heavily distorted by non-uniformity of paint, peeling and chipping, misalignment of borders, etc.), cleanliness and more importantly, by the non-linear response and low range of the camera, sensor shortcomings and lens distortions. This results in deformed images, loss of data and a generalized impoverishment of the heliostat beam image quality. Figure 1 shows a lambertian target, belonging to the Plataforma Solar of Almeria, in which highlighting borders and lack of uniformity are evident.

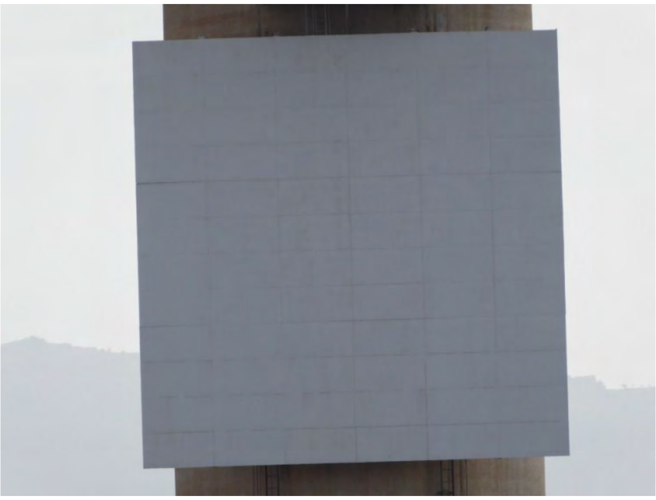


FIGURE 1. Lambertian target belonging to the Plataforma Solar of Almeria.

Heliostat Beam Size

Heliostat beam size depends on the heliostat optical quality, angular position, shape and mainly on its distance to the focus point. In a 100 MWe commercial power tower plant, heliostats allocated in the first row are placed at about a hundred meters far from the tower, while those allocated in the last row are placed at distances in the range of 1.5-1.7 km far from the tower. Figure 2 shows this effect, within a simulation environment, in the heliostat reflected beam size assuming a 120 m^2 squared heliostat perfectly adjusted for each distance (i.e. spherical shape with radius as two times the slant range and non-structural deformations) in one of the most favorable position, i.e. the heliostat is in the perpendicular plane to the target and both are coplanar with the Sun whose elevation is 60°. The simulated heliostats present an optical quality (sigma slope) of 2.0 mrad, which is a value quite good considering that the acceptance angle should not be above 2.6 mrad [5].

It is worth noting that the 95% of the energy in the furthest heliostat (1600 m) goes within a 34 m diameter circumference. For instance, that dimension is much larger than the receiver height of the Crescent Dunes Solar Plant [6] (around 30 m) and much larger than any lambertian target that may be built up there, and this is just a favorable case. In practice, at those distances and assuming an enough sized target, it is likely that the reflected beam drifts from the center overflowing the target and making impossible any kind of analysis based on the state-of-the-art method.

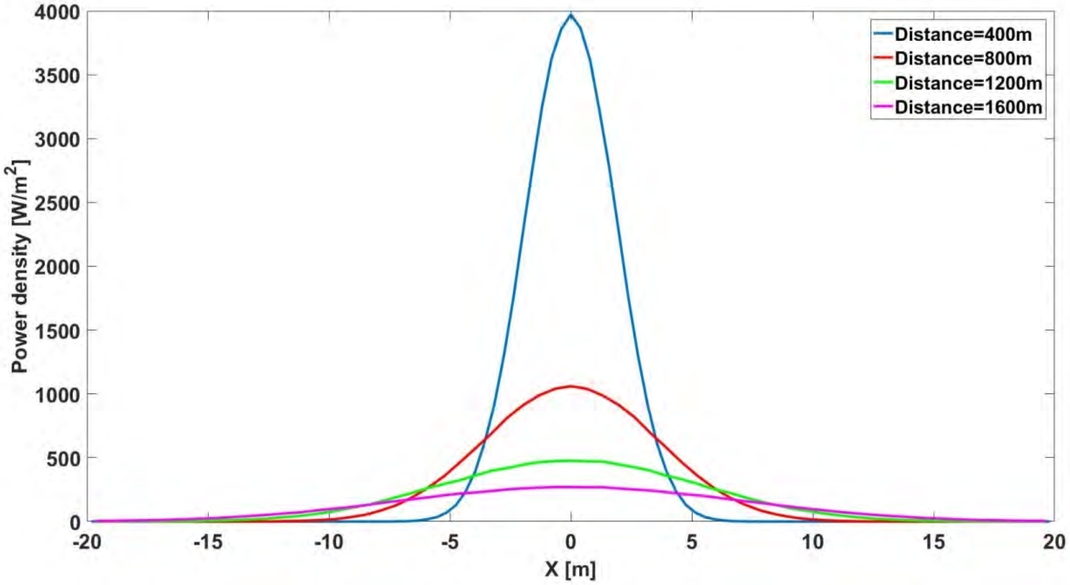


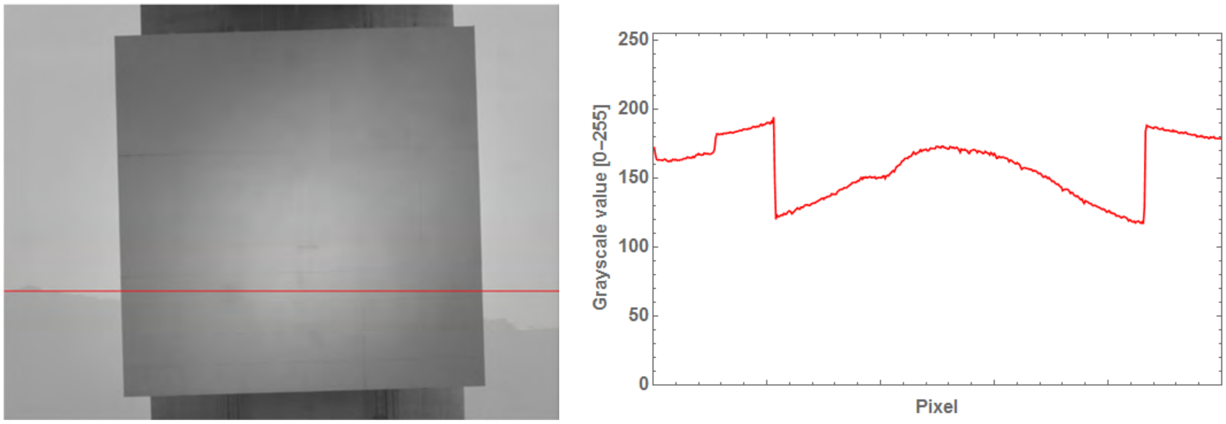
FIGURE 2. Maximum horizontal section of simulated power flux-densities for some heliostats.

Low Power Flux-Density

Values of power flux-density presents strong variations as function of the distance (see Fig. 2), but also, and more significantly, due to the heliostat size. Such curves were simulated with big heliostats (120 m^2) and a reasonably high (900 W/m^2) DNI – direct normal irradiance. Given small heliostats and less DNI would result in peak density power value around, or few times above, the albedo level, which is not sufficient to achieve enough contrast capturing the reflected beam, which all in all leads to lower the accuracy.

This issue is also of high interest in conjunction to the electronic noise due to the capture device resulting in low quality signal-noise ratio; the lower the density power, the poorer the signal-noise ratio. In fact, CENER's expertise estimates that camera noise and target shortcomings contribute to an uncertainty about 3-5% in pixel value.

Figure 3 shows an expected image collecting all previous weaknesses and a representative actual horizontal section.



(a) (b)

FIGURE 3. (a) Inappropriate capture for heliostat characterization. (b) Pixel values.

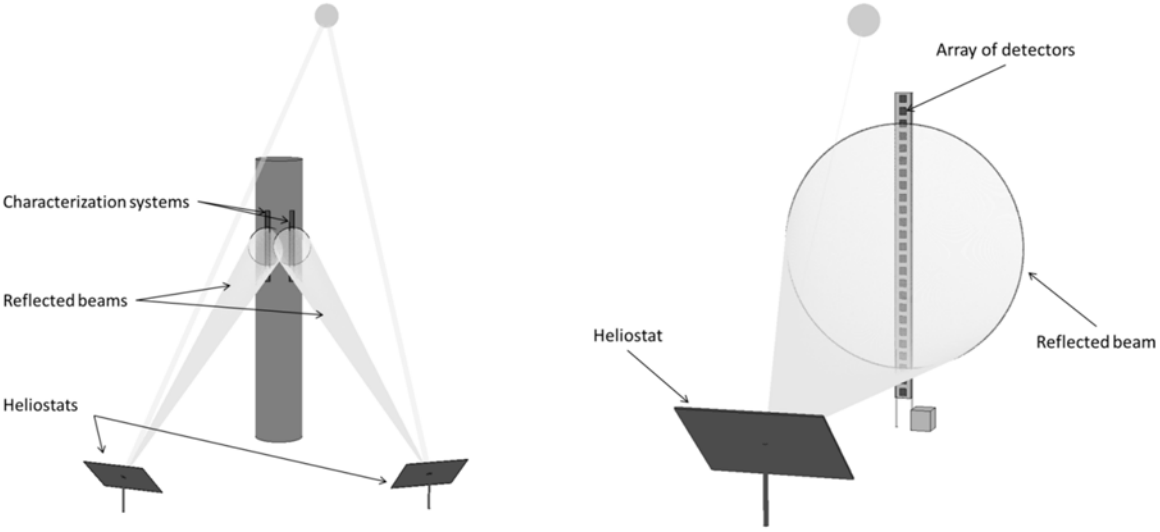
Innovative Approach

Applicability and final accuracy of current existing methods is limited by all abovementioned factors and error sources. Some others drawbacks exist, although less problematic, such the continuous drift-correction pattern of the reflected beam (caused by the tracking systems), the non-uniform movement of the heliostats drivers (due to their step-wise behavior) and the poor parallelization chances.

To address all these issues, a general purpose methodology for heliostat characterization has been developed based on a new measurement system and a new associated measurement procedure, as explained hereafter.

Equipment Description

The measurement system developed is an optoelectronic device whose configuration mainly consists of an array of sensors distributed along a vertical pole that can be as long as required, being its final longitude determined by a trade-off between the reflected beam sizes, the time per measurement and the cost. With this configuration, the system is portable, versatile and easy to integrate in the existing commercial power towers by attaching it to the tower structure (Fig. 4a) or being placed elsewhere (Fig. 4b), in order to be used as quality control system during heliostat manufacturing and assembling.



(a) (b)

FIGURE 4. Exemplary application of the characterization system in (a) solar tower power plant and (b) elsewhere.

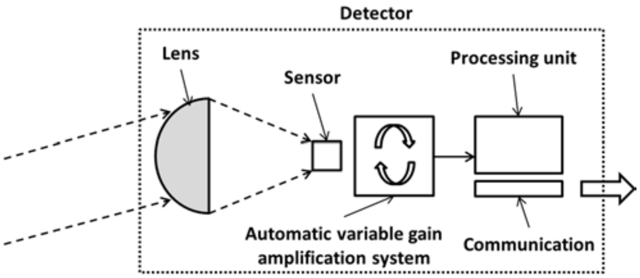


FIGURE 5. Exemplary application of the characterization system in (a) solar tower power plant and (b) elsewhere.

In particular, each sensor system in the array uses a lens that captures and concentrates the radiation coming from the heliostat into the optical sensor, thus increasing the power density of the signal and making the system capable of correctly measuring all heliostats, even long distance heliostats (Fig. 5). The use of a lens in each sensor system not only increases the power density of the signal, but also reduces the acceptance angle of the system. This fact means that it is possible to install, in the same tower, several of these systems in order to perform in parallel the characterization of several heliostats (as much as available systems), reducing in this way the time needed for characterizing the whole field. For example, a characterization system with an acceptance angle of 15° allows the installation of 24 independent systems along the 360° of the circular tower, considering similar systems placed at different tower levels (3 or 4) gives a total of 72-96 systems that are able to ideally process in parallel the same amount of heliostats. This idea is sketched in Fig. 4a.

The device has also been implemented with an automatic variable gain amplification system, associated with each detector, to automatically adjust the working range depending on the incident radiation. In this way, it is enabled a dynamic range wide enough to ensure the correct characterization of the entire field, independently of the variability of the power density-flux provided by all heliostats.

Initial calculations suggests that this system is able to achieve a signal-noise ratio improvement factors (signal is the reflected light coming from the heliostat and noise the ambient light) in the range of 20-100 for sensors acceptance angle of 20° and 10° respectively, in addition to avoid all sort of distortions that cameras and targets introduce in the final measurement, reaching, as described, a superior accuracy, so leading to a better heliostat characterization.

Measurement Procedure

The measurement procedure associated with this system is based on a non-tracking heliostat philosophy, in which the movement of the Sun actuates as the driver mechanism of a scanner-based measurement system.

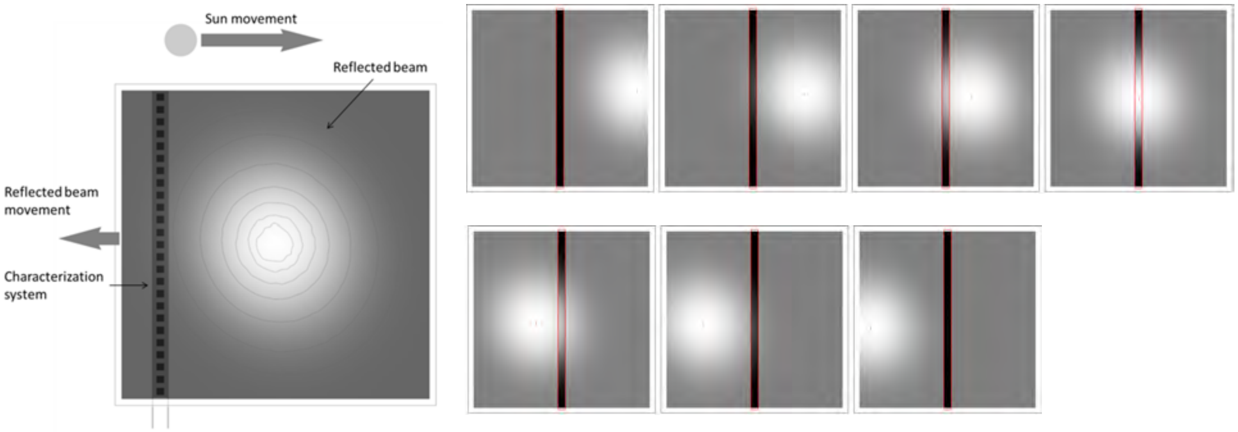
The process begins focusing the heliostat on a point just beside the pole. Due to the movement of the Sun across the sky, the reflected beam will almost horizontally move in the opposite sense across the pole too, so letting the array of detectors perform, in barely a few minutes, a scan of the whole beam. The fact that it is not being used any tracking system to move the reflected spot, owing to the use of the solar movement to scan the reflected beam, deletes its contribution to the error of the measurement, increasing in this way the accuracy of the system.

Once the reflected beam is focused on the desired point, the gain of each detector is individually adjusted taking into account the level of incident radiation on them. This differential treatment of each detector lets the system accurately measure sections of the reflected beam with huge differences in their level of incident radiation, due to the fact that both saturation of detectors and extremely low signal levels are avoided. So it results in an improved quality measurement of the flux in the whole area of the reflected beam.

When all gains are yet adjusted, the measurement is performed. The signals of all detectors are captured at the same time and the obtained data are normalized in gain, in order that storing a set of data that represents a vertical stripe of the reflected beam as it is just in that moment.

After that, the gain of the amplification system of each detector would be readjusted, if needed, to perform the next measurement. As this process takes some seconds in being completed, the Sun moves enough so as to capture a different, but adjacent, vertical stripe of the spot in the following measurement.

These previous steps are repeated while the light spot moves across the pole, as it is shown in Fig. 6, until the whole reflected beam has crossed it. So that the final result of this capturing process is a set of vertical stripes which represents sections of the reflected beam in different instants.



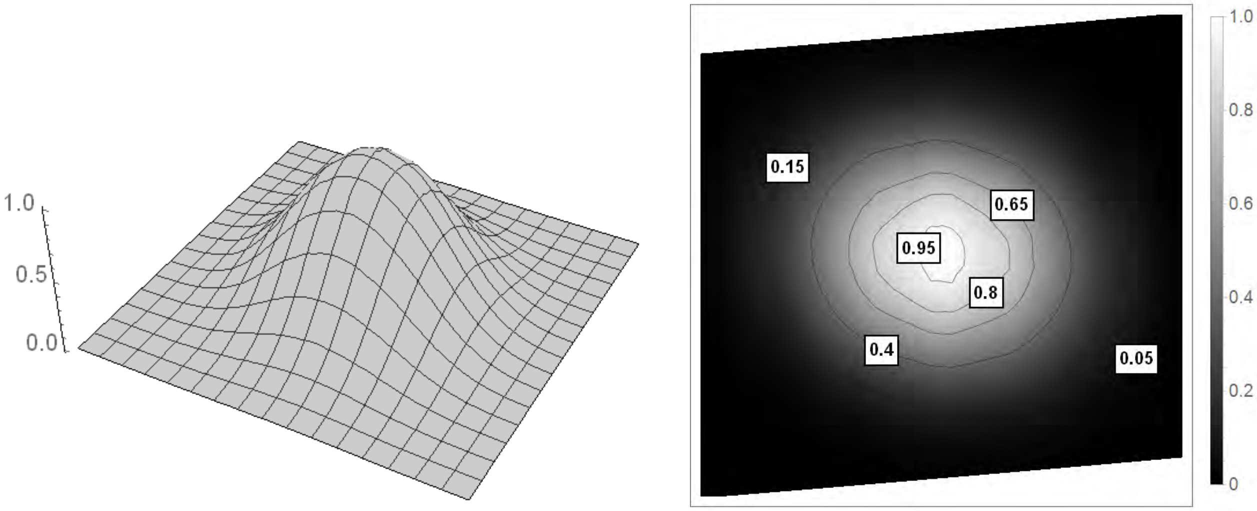
(a) (b)

FIGURE 6. (a) The measurement procedure. (b) Series of simulated measurements taken during the movement of the reflected beam over the pole.

Ideally, the reflected beam should move horizontally under the same conditions so that the reconstructed shape is just a simple concatenation of stripes. In practice, each captured vertical stripe is measured in different, but known, instants and conditions (e.g. variations in the DNI) that must be taken into account to normalize all measurement values. Besides and due to the actual sun movement, the reflected image simultaneously moves horizontally and drifts vertically. Corrections are needed to avoid distortions in the reconstructed image. Figure 7b shows a 2D simulated reconstructed shape in which the drift phenomena is clearly evident.

Having yet the whole reflected beam captured and reconstructed, its shape is analyzed to characterize the heliostat, which determines its focal length and the optical quality of the reflector.

This measurement procedure is limitless regarding the heliostat beam size. If the vertical dimension of the reflected beam, in the capture plane, is larger than the pole, applying several times the sweep concept, as much as needed, enables capturing the whole image. As explained before, the size of the pole should be a trade-off between the expected reflected beam sizes, the available time per measurement and the cost. Considering the curves displayed in Fig. 2, a 15 m length pole should be sufficient to characterize heliostats up to 1200 m in two sweeps as maximum.



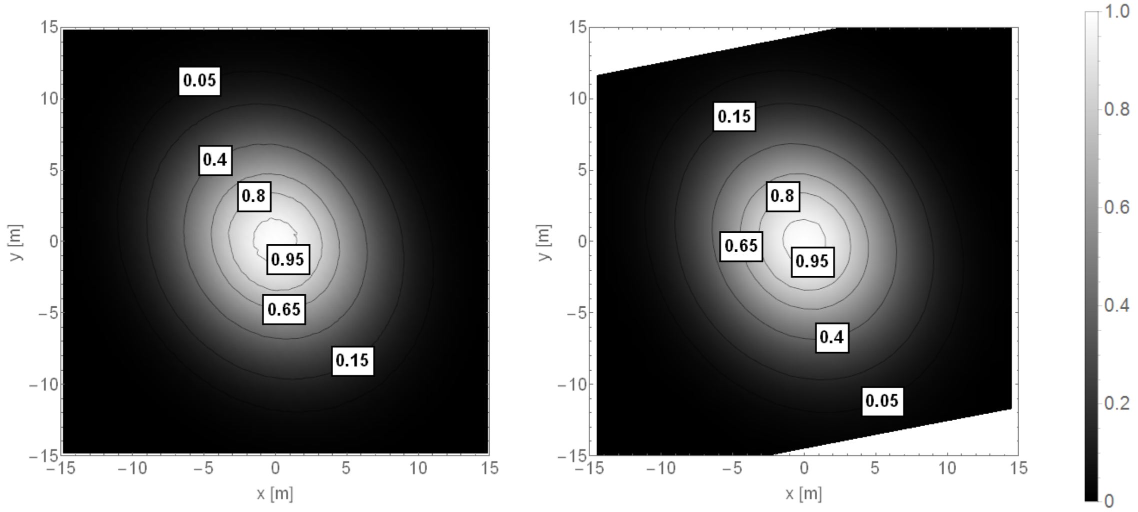
(a) (b)

FIGURE 7. Simulated final shape obtained after reconstructing the reflected beam. (a) 3D, (b) 2D.

APPLICATION

The methodology is demonstrated under a simulation environment. Thereby, several flux density distributions provided by different heliostats are performed with the ray tracing tool Tonatiuh [7]. In an initial case, assuming an ideal system able to continuously measure the reflected beam, the comparison between the reconstructed distribution and the actual one reveals that both shapes, for each case, perfectly fit each other. Slight and negligible distortions (differences below 0.1%) can be assigned to the inherent randomness of the Monte-Carlo method used.

Moving to a feasible scenario with a heliostat 1200 m far and a design of the system composed by 31 detectors along a 30 m pole with measurements every 12 seconds (making a total of 31 stripes and around 6 min time), the accuracy when analysing the reflected beam shape and characterizing the heliostat stays below 0.5% of error. If the pole changes to 15 m length and 21 detectors, two sweeps are required (twice of the time with the same 31 measurements per sweep). However, the error holds in the same level as the previous case. This case is depicted in Fig. 8.



(a) (b)

FIGURE 8. Simulated power flux-density distributions, (a) the actual shape, (b) the reconstructed one with the explained measurement procedure.

CONCLUSIONS

The innovative solution for heliostat characterization developed by CENER and UNIZAR (patent application P201830756) goes a step forward from the current state-of-the-art, proposing a valid system applicable to any heliostat, no matters the far they were in a heliostat field and maintaining high accuracy in all situations. With it, quality control of heliostats will improve, leading to a better control over the flux distribution, and finally, a better performance and cost-effectiveness of the solar tower power plant. Also, its additional advantage of being portable offers the chance to be installed in any commercial plant, including those that are already in operation.

The presented methodology takes advantage of the Sun movement to discretely scan the heliostat reflected beam while holding the heliostat motionless. The detector is composed by a lens that allows achieving a signal to noise ratio of, at least, 20-100 for the most common power densities in commercial power plants. Also, distortions and many drawbacks are avoided with the non-use of camera and lambertian target.

A discrete design solution for heliostats up to 1200 m is proposed, it is a system of 15 m length composed by 21 detectors able to characterize a heliostat every 6 minutes (12 minutes if two sweeps is needed) with in practical terms the same accuracy as the complete density power distribution was known.

Outlook

A prototype is now in the last stages of development. Later on, it will be tested in relevant environment and compared with the current methodology. Further work must be addressed to approach design solutions for specific real scenarios.

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