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Fast Optical Receiver Surface Characterization

Application on Cylindrical Solar Tower Receivers

Gregor Bern[1,*], Sara Zizzania[1,2], Moritz Bitterling[1], and Thomas Schmidt[1]

[1]Fraunhofer Institute for Solar Energy Systems ISE, Germany

[2]University of Naples Federico II, Italy

*Correspondence: Dr.-Ing. Gregor Bern, gregor.bern@ise.fraunhofer.de

Abstract. This paper presents an extension of the "Maximum Front Method" for assessing the spatially varying Bidirectional Reflectance Distribution Function on curved surfaces, specifically the receiver of a Solar Tower. The receiver, which links the solar field and the thermal cycle of a ST, operates under high solar concentrations and temperatures. This method is vital for efficient plant operations, enabling regular assessment of the receiver coating quality, early detection of degradation, and facilitating other measurement techniques. The paper discusses the challenges faced with the far field SVBRDF measurement when dealing with complex surfaces, including the trajectory of the light spot, and dealing with distance dependant reference intensity values. These challenges were addressed through a geometric approach and simulations were carried out using blender® to validate the method, showing its effectiveness on cylindrical and structured surfaces. However, accurately determining each component's spatial position was a persistent challenge for the practical demonstration. The paper suggests future research could consider line overlaps to maintain the evaluated area and develop methods to determine pipe positions directly from captured images. In conclusion, this method provides a foundation for solar tower receiver applications to monitor receiver state and improve robustness and efficiency in solar tower operation.

Keywords: Solar Towers, Receiver Monitoring, Bidirectional Reflectance Distribution Function

1. Introduction

The receiver, serving as the primary link between the solar field and the thermal cycle of a Solar Tower (ST), must endure high solar concentrations and temperatures. Keeping the receiver coating in top quality and ensuring good thermal properties are vital for efficient plant operation, while down time for maintenance is to be kept to a minimum. This motivates for the assessment of the coating quality in regular time intervals, allowing to identify the best time to recoat or to get early information about degradation before a failure. Furthermore, further measurement techniques under development for supporting the operation of ST, depend on the knowledge of the spatially varying Bidirectional Reflectance Distribution Function (svBRDF). Examples are flux mapping as described by Ho et al. [1], flux density estimation techniques as proposed by Raeder et al [2] or fast heliostat calibration and aim point correction during normal receiver operation [3,4]. Offergeld et al [5] have presented a technique to measure the relative reflectance of receiver surfaces following a scanning approach where a light spot created by a heliostat or an artificial light source is operated to follow a meandering path over the surface, while the directional reflexion is captured by a camera in a video. The maximum at each pixel over the whole time frame is regarded to relate to the maximum in the spot.

This maximum is assumed to be constant over the scanning time, thus serving as a reference for the relative reflectance map. In parallel, the Maximum Front Method (MF-BRDF) for measuring the spatially varying Bidirectional Reflectance Distribution Function (svBRDF) of ST system receivers was developed independently, motivated to improve heliostat calibration techniques [6, 7]. The long-distance BRDF measurement enables quick monitoring of the solar receiver's condition and performance, especially its directional absorbance. Similarly to Offergeld et al. [5], the MF-BRDF method uses video sequences of a light spot from a heliostat or an artificial source moving over the receiver to obtain a high-resolution spatially varying bidirectional reflectance map. The method requires a minimum of two intersecting light spot trajectories captured by the camera, with a few already allowing for a full characterization of the relative directional reflectance without imposing flux homogeneity requirements on the spot. Different camera-light-source configurations with respect to their positioning allow for the derivation of the svBRDF section of interest or the full svBRDF. This method was initially demonstrated on flat surfaces with sheets coated with Pyromark®2500 in the laboratory, and was validated against 3D photogoniometer measurements [6,8]. **Figure 1** shows the result of the validation for a central point of the evaluated sheet with the camera based measurements at various emergent angles and the extracted data from the 3D-photogoniometer measurement for normal light incidence. The measurements are perfectly inline, considering the measurement uncertainty, displayed as grey bars. This paper is aimed at demonstrating this method on a commercial ST plant receiver. The application on the non-flat surface of a downscaled lab demonstrator and its validation are also discussed.

This paper aims to extend the implementation and discuss the application to external receivers of commercial ST, presenting non-flat surfaces, such as pipe bundles arranged in a circular shape. The method is thus prepared for the experimental demonstration in a commercial scale Solar Tower plant, but also challenges and further improvements are discussed.

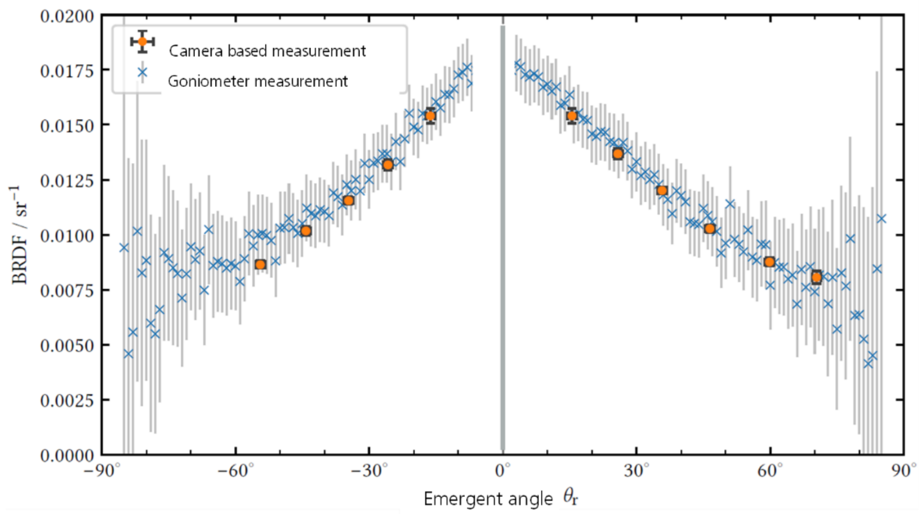

Figure 1. *Absolute bidirectional reflectance validation on Pyromark®2500. Blue crosses indicate photo-goniometer measurements with uncertainties, orange dots represent camera-based measurements. Measurements align within the uncertainty range.*

First, the basic MF-BRDF-method is quickly introduced and the further development for the application on structured surfaces, following the practical example of external receivers with pipe bundles is discussed. The feasibility and challenges are presented and validated with simulations conducted in blender® [9] and are then applied to a mock-up receiver model in the laboratory. Results and conclusions are finally discussed and an outlook is given.

2. The Maximum Front Method

The Maximum Front Method, designed to characterize the spatially varying bidirectional reflectance distribution function (SVBRDF) of surfaces, employs a camera and a light source such as a heliostat or spotlight. The light source generates a moving spot by rotating around an axis at its root, traversing a path of the spot over the entire visible receiver area. This movement is captured by the camera via a sequence of images depicting the evolving flux distribution.

In the previous implementation, the method assumes the integrity of the spot during the measurement, i.e., the shape of the relative flux distribution is constant. Any variation in absolute incident intensity can be corrected using parallel-measured Direct Normal Irradiance (DNI) values. The moving spot can be divided into slices along the direction of movement, each slice illuminating a group of points along a line. Each of these slices features a local maximum in irradiation, extracted through image sequence analysis. These local maxima move with equivalent speed throughout the sequence, forming a consistent front of local maxima. Evaluation of the local maximum at each camera pixel over the observation time allows for the computation of parallel paths of constant incident radiation, each originating from a different part of the inhomogeneous spot, as depicted in Figure 2a. The intersection of these paths with the paths obtained from a second, crossing movement and considering the integrity of reflectance at each crossing point, facilitates the evaluation of the full relative directional reflectance by solving a system of equations:

With knowledge of speed and direction, proportional relative reflectance values are calculated for each line in each sequence. In the overlapping area of two image sequences, these lines intersect at points with constant optical properties. At these points, an overdetermined system of equations is derived, which can be solved through minimization to provide factors for leveling all lines across all sequences to a common proportional reflectance map. A single reference point with known absolute reflectance enables the normalization of the map, resulting in a bidirectional reflectance values map. Multiple measurements with different camera perspectives and/or incidence flux allow for the derivation of the SVBRDF for all directions of interest. The Maximum Front Method is implemented in the Python programming language. Further details about the method can be found in Bern et. al 2020 [6].

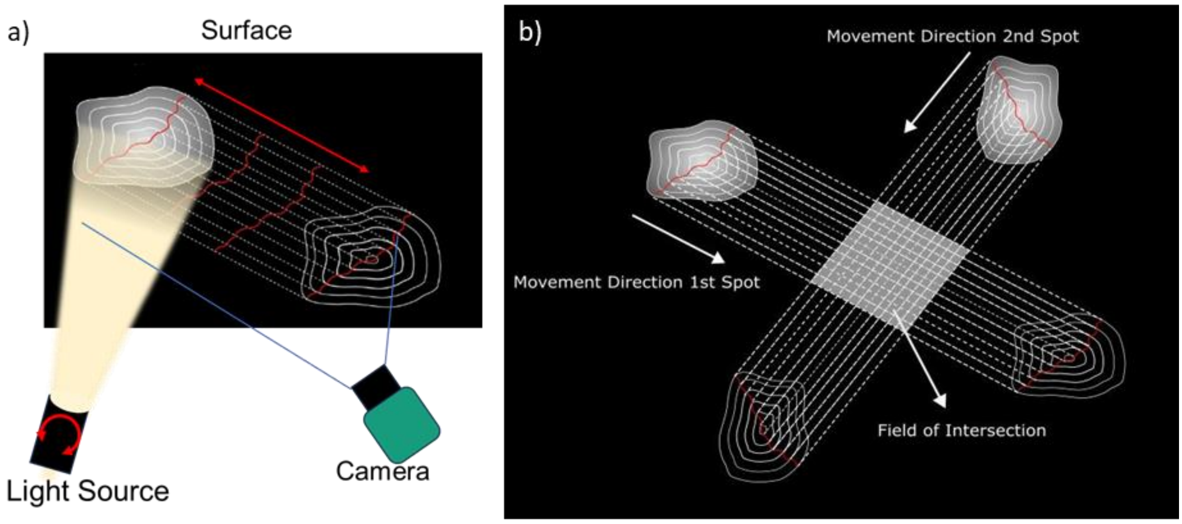

Figure 2. *Moving spot distributions and straight parallel lines describing the path*

The application of the method to shaped surfaces was first extended to a single cylindrical surface to identify necessary modifications. The trajectory of the projected spot and the discretized maximum front cannot be represented by straight parallel lines when projected onto a cylinder. The potential path of each light ray's direction at each point, as well as its incident angle, was calculated considering the position and dimensions of each component, such as camera resolution, cylinder dimensions, light source position, and rotational axes. The potential trajectory of an individual light ray emitted from the light source at a particular angle relative to its rotational axis was determined by intersecting the rotational cone with the cylinder, as illustrated in **Figure 3**a. The assumption was made that a point light source was reasonable, considering the application with an artificial light source. Utilizing the knowledge of camera position, orientation, and geometric calibration, the camera pixels were mapped onto the receiver area in the view, associating each pixel with a point on the receiver in 3D space. This correspondence allowed potential trajectories to be mapped to the pixels. Individual curves were defined by their angle relative to the light source and its rotational axis.

Figure 3b represents a section of an exemplary curve map, where each curve represents the same root point in the scanning light spot maximum front over a cylindrical surface. When mapped to camera pixels, it was found that lines may overlap or increase in thickness. For curved surfaces along the path, incident intensity values could not be considered constant, as they were subject to the inverse square law of distance for a point light source, and the cosine law for the projected irradiance on individual tubes and along their circumference. Thus, the integrity of the light source could no longer be assumed, however, the known relations were applied as correction to the measurement. By considering the relative position of each component and the receiver, the cosine and distance correction was mapped to the camera view to adjust each observation. However, this geometric approach for defining trajectories depends on accurately knowing the position of each component and the rotational axes. To a lesser extent, the correction maps also rely on precise knowledge of the component positioning.

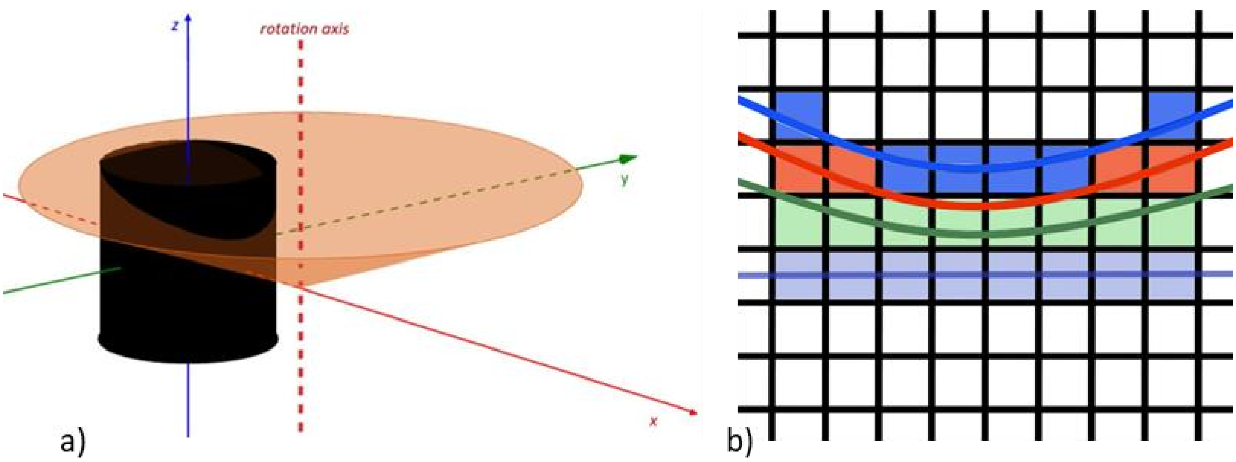

Figure 3. *Schematic of a light ray and its path over the cylinder*

3. Simulation and Experimental Test

This study involves a two-step investigation and theoretical validation of an approach under idealized conditions. Firstly, test data is simulated, followed by application to a mock-up receiver model in a laboratory setting. The open-source rendering and raytracing software, blender®, is utilized for ideal reference application simulations. The receiver is initially simplified as a single large tubular surface, before being discretized into individual panels. The digital model, created in Autodesk Inventor®, was imported into blender® for idealized evaluation and served as the basis for constructing the physical mock-up receiver for practical laboratory tests.

The model dimensions are approximately based on the Cerro Dominador receiver developed by John Cockerill, consisting of 16 panels downscaled by a factor of around 37. However, for practicality, the number of tubes per panel is reduced to 10. The laboratory setup consisted of half the receiver's circumference. **Figure 4** illustrates the Autodesk Inventor model used in the simulation, the mock-up laboratory model, and the future application—the receiver of the Solar Tower Plant Cerro Dominador in Chile.

blender® simulations provide an idealized assessment and analysis of uncertainties and errors. The software offers a realistic representation of the camera and optional surface properties that can be applied to the model. For idealized evaluation, perfectly Lambertian surfaces were applied to allow simplified validation. A point light source with a restricted cone and its rotational movement along a respective axis was implemented to generate artificial measurement data in the form of image sequences, which served as inputs to the MF-BRDF code.

Simulations of increasing complexity were conducted, including a homogeneous tubular surface over the entire receiver area with Lambertian surface and no interreflection, panel receiver surface with 16 segments each containing 10 pipes with and without interreflection between different pipes.

The laboratory setup replicated the simulation scale, but only for half the circumference. The pipes, coated with a black matte spray paint, had a diameter of 10 mm. The objective was to test the method, not the evaluation of a realistic absorber paint, hence conventional spray paint was deemed sufficient for the demonstration.

The light source was a LEDLENSER P7R LED-Spotlight with a luminous flux of 1000 lm. A PCO Edge 4.2 sCMOS camera equipped with a 25 mm fixed focus objective by Zeiss Optics was used. Image data was corrected using a dark frame and flat field correction, and a geometric correction of distortions based on the OpenCV pin-hole camera model. A Lambertian reference target from Sphere-Optics with a hemispherical reflectance of 10% in the visual spectrum was installed on the model top for reference. The light source was manually rotated to perform the scan after starting the video sequence capture, with the two movements performed around a vertical and a horizontal axis respectively for the assessment. The entire setup was scanned with a 3D-laser scanner to identify the relative positions of all components in the setup.

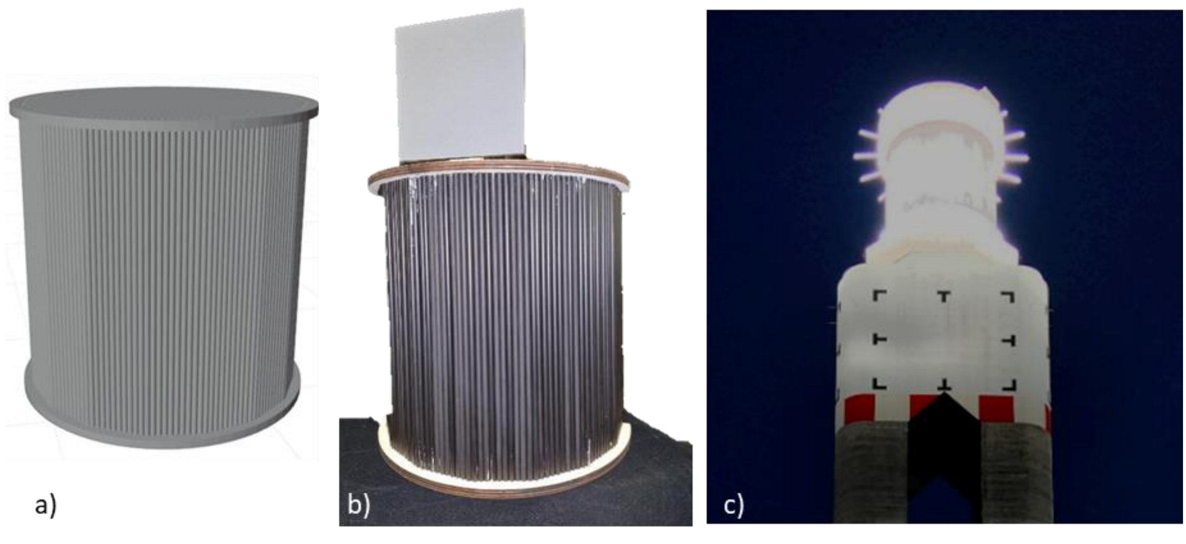

Figure 4. *Structured surface: a) Simulation model designed in Autodesk Inventor and evaluated in blender, b) mock up receiver model for lab demonstration with a flat Lambertian reference target c) The application outlook: receiver of the Cerro Dominador solar tower plant in Chile.*

4. Results and Conclusion

Exemplary results are presented in the following, starting with the idealized simulation models at reduced complexity. Fig 5a) shows the example of the receiver, not considering individual panels and tubes, with a homogeneous tubular surface for one extracted central cross section obtained from a line of camera pixels. The relative pixel intensity obtained in the first place is shown in blue. Applying the cosine correction (green) from the incident light and the relative distance correction (red) provides the expected result for a perfect Lambertian surface (orange), proving the general measurement and correction of the MF-BRDF method. It was identified that the definition of the thickness of the curved lines bundle considered may have relevant impact on the deviations from the ideal reference. On the other hand, the effect is influenced by the inhomogeneity of the considered light spot. In a worst case, standard deviations of 3% relative were observed with thicker lines. Higher discrimination allowed for deviations below 0.6%. Fig 5b shows the more realistic, but still idealized example, considering the panel receiver with individual tubes. The obtained relative pixel intensity shows the influence of the distance, but more prominently the impact of the cosine of the individual tube. The corrected relative pixel intensity, which would correspond to the corrected relative reflectance in a measurement, shows considerable artefacts, mainly stemming from the cosine correction one the one hand and averaging within the single pixels on the other hand. At the current state, deviations between 4-5% relative were reached, without cleaning of the artefacts. For an automized evaluation of receiver properties, further investigation is required to overcome these impacts. The third simulation, taking interreflection into account impose further challenges. Multiple reflexions in the small V-shaped cavities between the pipes can be assumed, but their impact remain unknown due to multiple possible roots and dependence on surface properties. An implementation of the models developed by Saint Pierre et al. [10] can be considered in further development. At the current stage simpler mitigation strategies were investigated, based on the reduction of the resolution with pixel-wise averaging, with limited success. The effect will be further analysed on real surfaces to identify the impact in real measurements.

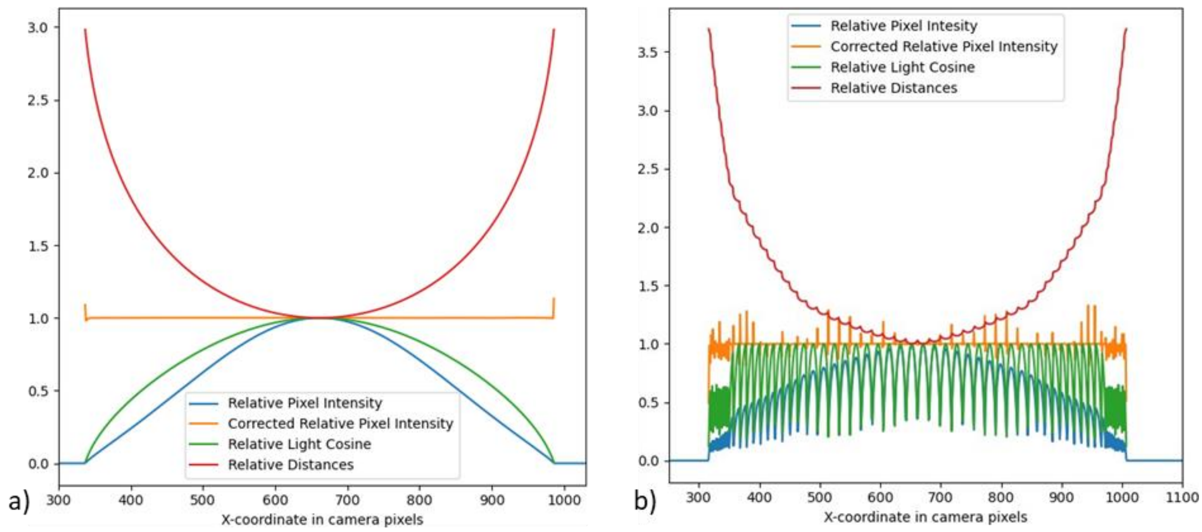

Figure 5. *Evaluation of simulated measurement - correction for the central horizontal line of the path for the idealized cylinder (left) and the composed tube panel receiver model (right)*

The practical demonstration of the method with the mock-up receiver was conduced successfully, however only providing qualitative results. The evaluation is based on two intersecting scanning movements of the light spot only. The evolution of the maximum front for the horizontal scan is shown in **Figure 6** a) as a colormap. The color code can be interpreted as an index relative to the time, that the maximum front in that cross cut reaches a certain point. Accordingly, the same color corresponds to the location of the maximum front at a point in time. The evaluation yielded in the relative reflectance map displayed in **Figure 6** b). The corrections were applied showing the expected effect. The true behaviour of the spray paint was not yet investigated and it presents an inhomogeneous reflectance as a result of the painting process. Furthermore, the pipes are not as straight and ideally placed as in the simulation model. Little deformations, that are also expected in real receivers, challenge the idealized geometric approach. Further development will investigate on the identification of geometric deformations from the measurement data in order to improve the quality of the measurement data. However, the result shows realistic results and qualitatively approve the theoretical approach tested in the idealized simulation environment.

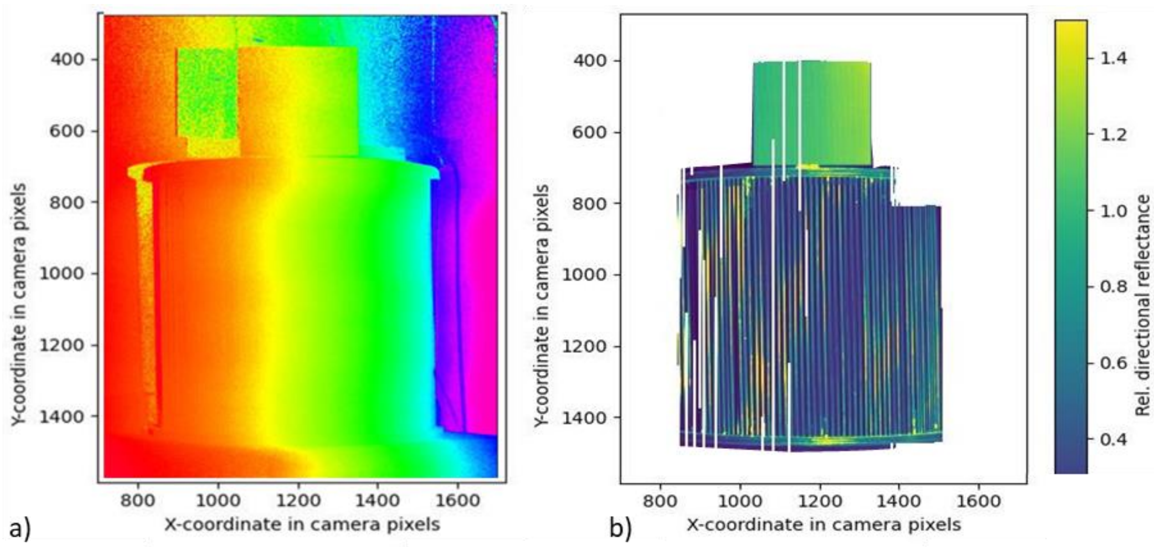

Figure 6. *Maximum front of an horizontal spot movement over the receiver*

5. Conclusion

This work expanded the "maximum front method" to measure spatial directional reflectance on curved solar tower receiver surfaces. Challenges like the path of a light spot on complex surfaces, intensity value correction based on cosine law and distances, and handling of interreflections were tackled. blender simulations validated these solutions, demonstrating the method's efficacy on cylindrical and structured surfaces.

A geometric approach effectively defined paths for constant incident flux lines on cylindrical surfaces. Corrective maps were constructed based on camera-captured intensity values to account for the cosine law and inverse square law. Persistent challenges include accurately determining each component's spatial position. Future research could consider line overlaps to maintain the evaluated area and develop methods to determine pipe positions from captured images directly.

In conclusion, a method for measuring reflectance over curved surfaces was developed, setting the stage for solar tower receiver applications to monitor receiver state and provide the basis for other imaging measurement techniques to improve robustness and efficiency in solar tower operation. The next step involves applying this method to the solar tower receiver at the Cerro Dominador power plant.

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Data availability statement

The experimental data can be made available on request by contacting the corresponding author Gregor Bern.

Author contributions

Gregor Bern: Conceptualization, Software, Resources, Supervision, Funding Acquisition, Methodology, Writing - Draft, Review and Editing. Sara Zizzania: Formal Analysis, Software, Validation, Visualization, Methodology, Writing – Review & Editing, Moritz Bitterling: Software, Writing – Review & Editing, Thomas Schmid: Supervision, Writing: Review and Editing.

Competing interests

The authors declare that they have no competing interests.

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