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Terrestrial Laser Scanning for Fast Spatially Resolved Cleanliness Assessment of Heliostat Fields

Maitane Ferreres Eceiza[1], Moritz Bitterling[1], Thomas Schmidt[1],Tobias Boehret[2], Denis Wohlfeld[2], and Gregor Bern[1]

[1] Fraunhofer Institute for Solar Energy Systems ISE. Heidenhofstr. 2, 79110 Freiburg, Germany

[2] FARO Technologies Inc. 250 Technology Park, Lake Mary, FL 32746, United States

Abstract. This paper presents a novel method for the assessment of cleanliness levels (i.e. specular relative reflectance) in the solar field by use of laser scanning. The detected backscattered laser intensity caused by soil and dust, on the otherwise specular mirror surfaces, can be used for determining the cleanliness of mirrors in the solar field with an excellent spatial resolution and acquisition speed. The backscatter behavior of soiled mirrors with distance and incident angle is analyzed and used for transferring the raw measurements values to a reference distance and incident angle. The experimental results of the novel laser scanning measurement technique as well as new insights on soiling behavior are presented. First, the calibration measurements with artificially soiled mirror samples are analyzed, followed by an extensive measurement campaign in a heliostat field. A correlation for the backscatter power and the cleanliness is found, and the first spatially resolved cleanliness measurement for a heliostat field is shown, successfully validating the measurement principle.

Keywords: Laser Scanning, LIDAR, Concentrated Solar Power, Heliostat Field, Soiling, Cleanliness

1. Introduction

Soiling causes reflectance losses in the solar field, compromising the energy production of Concentrating Solar Power (CSP) plants, as well as operation and maintenance costs. Permanently maintaining a high cleanliness of the mirrors is an important contribution to increasing the yield, performance, and revenue of the power plants, but it is to be balanced with the cost for cleaning. However, despite the cleanliness being of high interest in concentrating solar systems, it cannot yet automatically and continuously be determined with high resolution. State of the art measurements are conducted with handheld reflectometers at reflector regions reachable from the ground. In recent years, camera-based measurements have been proposed [1], with fixed camera position or partially drone-based [2], without reaching commercial level yet. To allow for an accurate monitoring of soiling levels to optimize overall economics, precise, replicable, and fully automated measuring methods are needed. In fact, the need of having a spatial systematic evaluation of soiling was pointed out as main gap for advancing in heliostat technologies in a recent report [3].

This paper proposes a novel method for the assessment of cleanliness levels (defined as specular reflectance of the soiled mirror with respect to a clean mirror [4]) in the solar field by use of terrestrial laser scanning (TLS), also known as LiDAR or 3D scanning. TLS is a ground-based, active imaging method that rapidly acquires accurate 3D point clouds of object surfaces by laser range determination. Currently, laser scanning measurements are used to determine geometries and positions of objects. In the recent years, laser scanning has been proposed as an alternative for performing shape assessment of heliostat mirrors [5] or to capture the relative canting angles between heliostat mirror surfaces [6]. However, the principle allows to extract more information. The information beyond range is primarily the backscatter of the object into the direction of the light source (sometimes also called retro-reflection or remittance) and detected by the TLS, defined as the ratio of backscattered to incident radiation at the wavelength of the laser at the instant angle of incidence. Applying physical transformations and calibration models, the backscatter which is caused by soil and dust on the otherwise specular mirror surfaces can be used for determining the cleanliness of mirrors in the solar field with an excellent spatial resolution and acquisition speed. Figure 1 shows a measured distribution of the detected backscattered laser intensity from a mirror, which is an indirect measure for the mirror's local specular reflectance. By performing the scan over many mirrors at once, a fast assessment of the spatially resolved cleanliness of the heliostat field is possible.

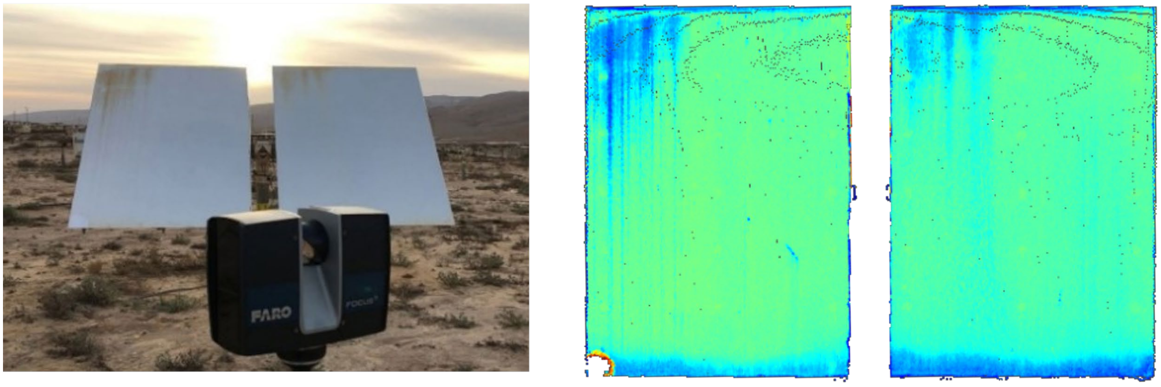

Figure 1. Left: Application of the terrestrial laser scanner measurement principle on a heliostat in the field. Right: Detected backscattered laser intensity over the surface of the heliostat. From this signal, the spatially resolved specular reflectance (cleanliness) of the mirrors is derived.

1.1 Methodology

Laser scanners provide a measure of the electronic signal strength obtained from the backscattered optical power, often referred to as "intensity" value. These intensity values are rarely used for technical evaluations in most laser scanning applications, and commonly their only purpose is to support the visual representation of a point cloud or the registration of markers.

For soiling assessment applications, first, this intensity measurement needs to be related with the detected backscattered power (Φ_{b}) of the mirror, which depends on the soiling level. For this, a mathematical description of the detector which models the behavior of the avalanche photodiode, and the logarithmic amplifier was found. The internal parameters of the scanner can be modelled with the following equation:

$$\Phi_{\mathrm{b}} = 10^{\frac{(Intensity - a_1)}{a_0}} \tag{1}$$

Data from calibration measurements with three different Lambertian samples (90%, 10% and 2% reflectance) was used for determining the constants a_0 and a_1 of this relation between the detected backscattered power and the intensity provided by the scanner (see Figure 2).

The backscatter power is dependent on the level of retroreflection of the target mirror, on the incident angle of the laser beam, and on the distance between the scanner and the heliostat mirror. Thus, the influence of the distance (d) and the incidence angle (θ) must be understood and modelled for isolating the retroreflection influence, for ultimately relating the detected power to the specular reflectance. For this purpose, the measurements can be transferred to a reference distance (d_{ref}) and incident angle (θ_{ref}) by cancelling their influence on the backscatter power:

$$\Phi_{\mathrm{b},\ d_{\mathrm{ref}},\theta_{\mathrm{ref}}}(d,\theta) = \Phi_{\mathrm{b}}\ \frac{f(d_{\mathrm{ref}})g(\theta_{\mathrm{ref}})}{f(d)g(\theta)}\ \eta_{\mathrm{ext}} \tag{2}$$

Additionally, the influence of the external factors (e.g., temperature) needs to be taken into account. For this, a normalization of the scan intensity must be performed (η_{ext}). The normalization was performed by means of the power of two fully characterized [7] reference samples (an aluminum sample coated with Pyromark 2500 and a Lambertian ceramic Promat Duratec-1000 sample) at a fixed and constant position.

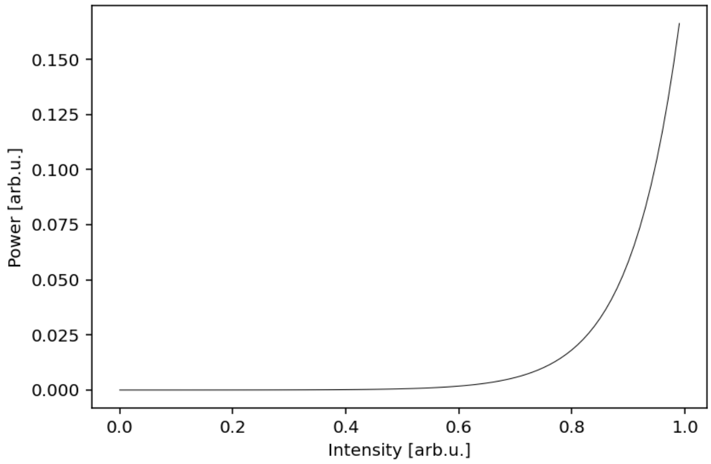

Figure 2. Incident power on the detector aperture of the laser scanner as a function of the scanner measurement signal (‘intensity’). This relation was identified in a calibration with Lambertian reference samples, and it is used as a first step in the conversion of the measurement signal of the scanner to cleanliness on the mirrors.

Numerous tests with the laser scanner have been conducted to prove the correlations, to derive empirical transfer functions and to calibrate the suitability for the measurement of mirror cleanliness. Several measurement campaigns with artificially soiled mirror samples with different cleanliness values were conducted in the lab (see Figure 3-Left), where the cleanliness values were determined with the pFLEX reflectometer [8]. During these measurements, the calibrations on the dependency on incidence angle and scanner-to-mirror distance, as well as on external factors, were conducted with the laser scanner. Dust from Plataforma Solar de Almeria, Spain, was used for the assessment in the laboratory.

Furthermore, the methodology was tested in a small-size heliostat field at IMDEA energy (see Figure 3-Right). The laser scanner was placed on the first floor of the tower to have a full view of the heliostat field comprising 155 heliostats. The effective range of the laser scanner during the tests was from 5-35 m. Each scan of the heliostat field was taken in 12 minutes, needing an average scan time of around 10 s per heliostat, containing 2000-100000 measurement points per mirror (both values depending on the position in the field).

During the two weeks stay, 23 mirrors were selected, and TLS scanner measurements were performed. Simultaneously to the TLS measurements, the cleanliness was monitor with the pFLEX reflectometer for comparison. During each TLS measurement campaign, a series of five scans was conducted, systematically varying the incident angles of the heliostat mirrors. The incident angles from the laser scanner to each mirror were determined by fitting a plane to each mirror's surface. The mirror position was changed only for experimental purposes of having several incident angles to analyse the backscatter behaviour. In the future, however, the cleanliness assessment will not interrupt normal field operation.

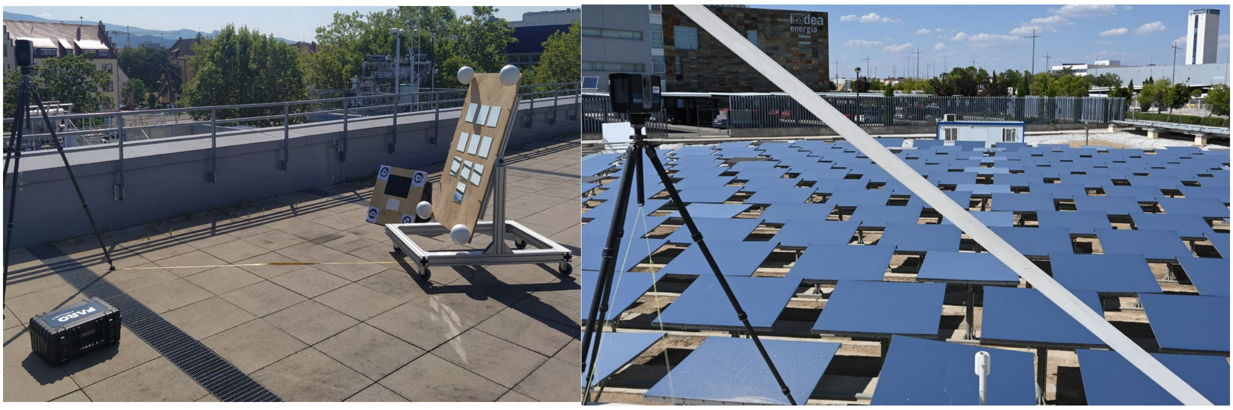

Figure 3. Left: Measurements with artificially soiled mirror samples for calibration on the dependency on incidence angle and scanner-to-mirror distance, as well as on external factors. The incident angles from the laser scanner to each mirror were calculated through automatic detection of the sphere located in the mirror plane. Right: Execution of the laser scanner measurement principle for heliostat cleanliness in the solar field at IMDEA energy. The effective range of the laser scanner during the tests was from 5-35 m, and the measurement of 155 heliostats (with 2000-100000 measurement points each) was performed in 12 minutes.

2. Results and discussions

2.1 Calibration of the measurement principle with artificial soiling in the lab

In this section, the results of the lab measurements conducted to prove the correlations and to derive empirical transfer functions are presented. Figure 4 represents the measurements conducted for variable distance at constant incidence angle, and Figure 5 the measurements for variable incidence angle at constant distance. Each point color corresponds to an artificially soiled mirror sample with a specific cleanliness value.

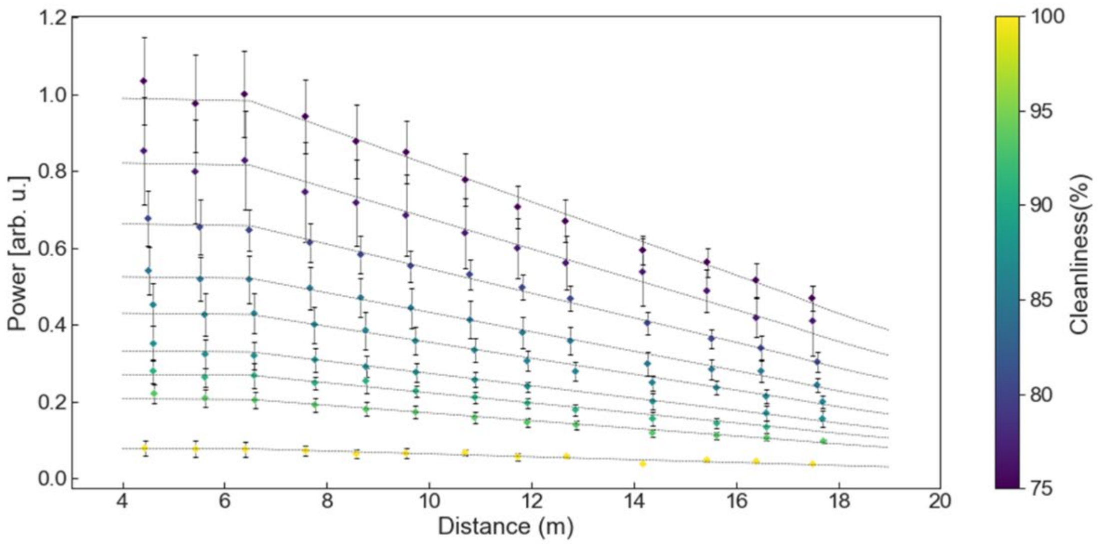

Figure 4. Measurement signal of the laser scanner for constant incidence angle and different mirror cleanliness values as a function of distance between scanner and mirror. For long distances, the detected intensity is proportional to r^{-2}. Due to geometrical measures, for short distances the signal is attenuated to a constant/linear behavior. The identified functional relationship is used for distance correction of the cleanliness measurements.

For long distances, the detected intensity is proportional to r^{-2}, thus the theoretical power law equation presents a good fit to model the data from a minimal distance. For shorter distances, additional intended optical effects aimed at protecting the detector from excessive intensity cannot be neglected, and the distance dependency of the backscattered power is modelled empirically with a constant/linear behavior (Figure 4). For the incidence angle, the backscatter power dependency was also modelled empirically (Figure 5) since an analytical model has not yet been developed to explain the backscatter behavior of soiled mirrors.

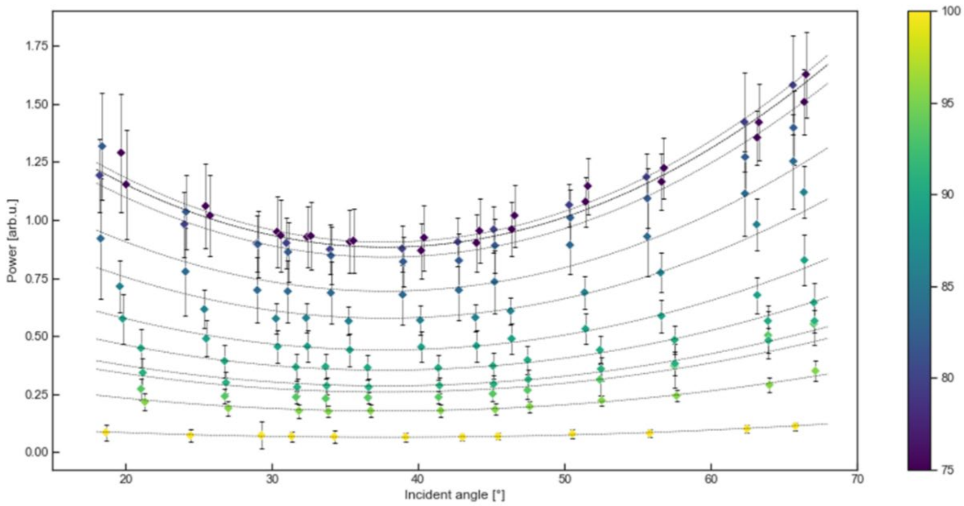

Figure 5. Influence of mirror inclination on the measurement signal: Detected power as a function of incidence angle for different cleanliness values. All measurements are taken at a constant distance. The influence of the mirror cleanliness is only a variable scaling in *y*-direction. The applied second order polynomial fits are used to correct the influence of mirror inclination in the evaluation the cleanliness measurements.

The power obtained from the measurements with artificially soiled mirrors were transferred to a reference distance and incidence angle. A clear functional relationship between TLS measurement corrected power and specular reflectance (cleanliness) is identified as shown in Figure 6. This finding suggests the potential applicability of the TLS method for cleanliness assessment.

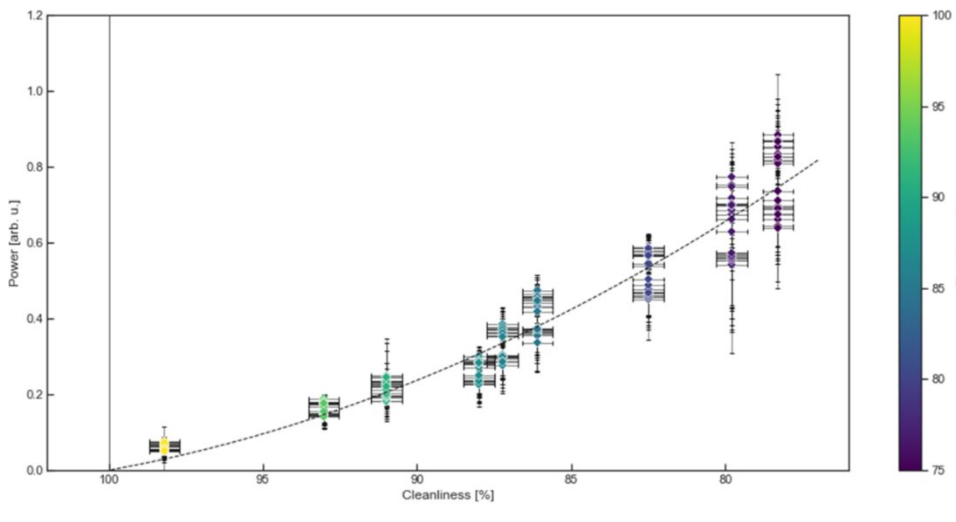

Figure 6. TLS detected power for different scanner-mirror distances and mirror inclinations after transformation to reference conditions as a function of cleanliness measured with the pFLEX reflectometer. Measurements were taken at an outside test field with artificially soiled samples.

2.2 Validation of the measurement principle in a heliostat field

This section presents the outcomes of a measurement campaign at the IMDEA energy solar field. Figure 7 shows the cleanliness values measured with the pFLEX reflectometer for the selected mirrors over the two-week period. Each cleanliness value was obtained averaging the nine spots of each mirror where the cleanliness was measured three times.

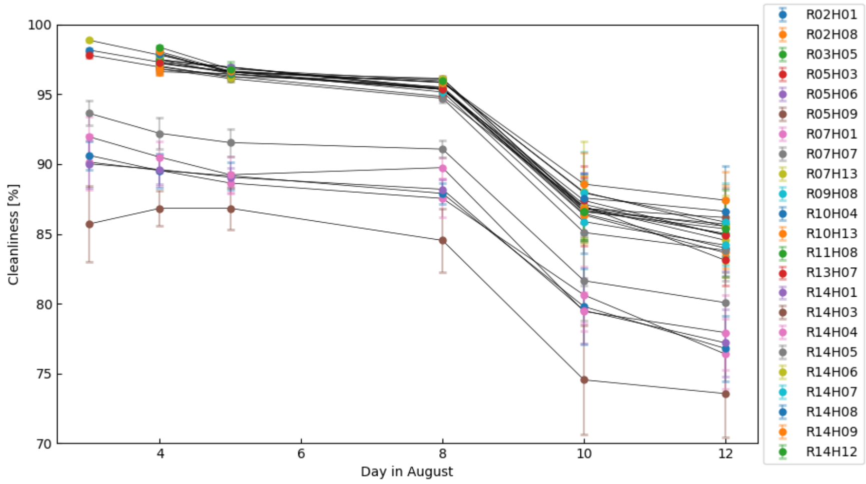

Figure 7. Mirror cleanliness measured with the pFLEX reflectometer during the measurement campaign at the IMDEA energy solar field. At the beginning of the measurement campaign, most of the mirrors were just cleaned, and only six mirrors were left in more soiled state. During the first days, a soiling rate of around 1%/d was observed, followed by a heavy rain soiling event around August 9.

From the scans performed during five different days over the measurement period, the median of the data points intensity of the whole mirror was obtained. This intensity was translated into power and normalized. Subsequently, the distance behavior was corrected with the model found in the calibrations performed in the lab. However, the incidence angle behavior had to be calibrated with the corrected data since the soil used in the lab for calibration was different from the one present at IMDEA energy solar field, and therefore presents another backscattering behavior. The resulting backscatter powers over the measured cleanliness value for the five days and different incidence angles can be seen in Figure 8.

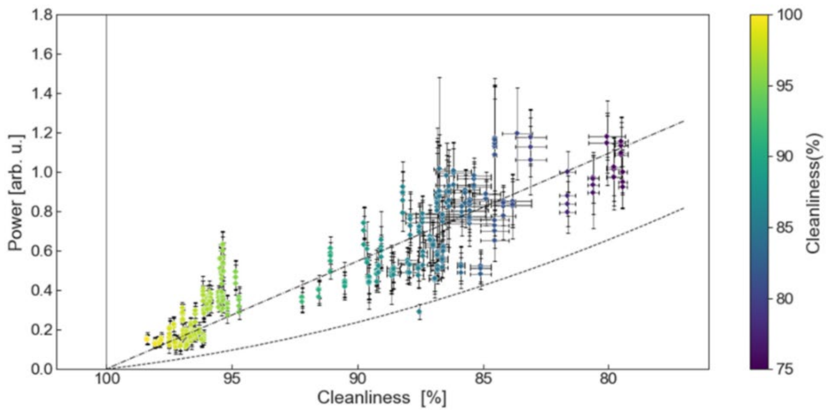

Figure 8. Results from IMDEA energy solar field: correlation between laser scanner power (transformed to distance and incidence angle reference conditions) and mirror cleanliness measured with the pFLEX reflectometer. Due to a different soiling type present in the field compared to the measurements conducted with artificially soiled samples, the correlation (dashed line) is different from the one found in the lab (dashed-dotted line). Although the field measurements exhibit higher uncertainties compared to the lab conditions, a visible correlation is observed, indicating that the TLS measurement signal has potential as a proxy for mirror cleanliness.

As expected, it is observed that the soil at IMDEA (the fit is represented with a dashed line) presents a different behavior than the one observed in the lab with artificially soiled mirror samples (dash-dotted line). The backscatter power is observed to be more intense for this type of dust for the wavelength of the scanner. Even though the uncertainty observed in the field is higher than in lab conditions, there is a clear correlation which shows that the TLS measurement signal yields a valid proxy for mirror cleanliness assessment. With the correlation between the power and the cleanliness, it is possible to represent the spatial distribution of the cleanliness from the intensity of the scans, as represented in Figure 9.

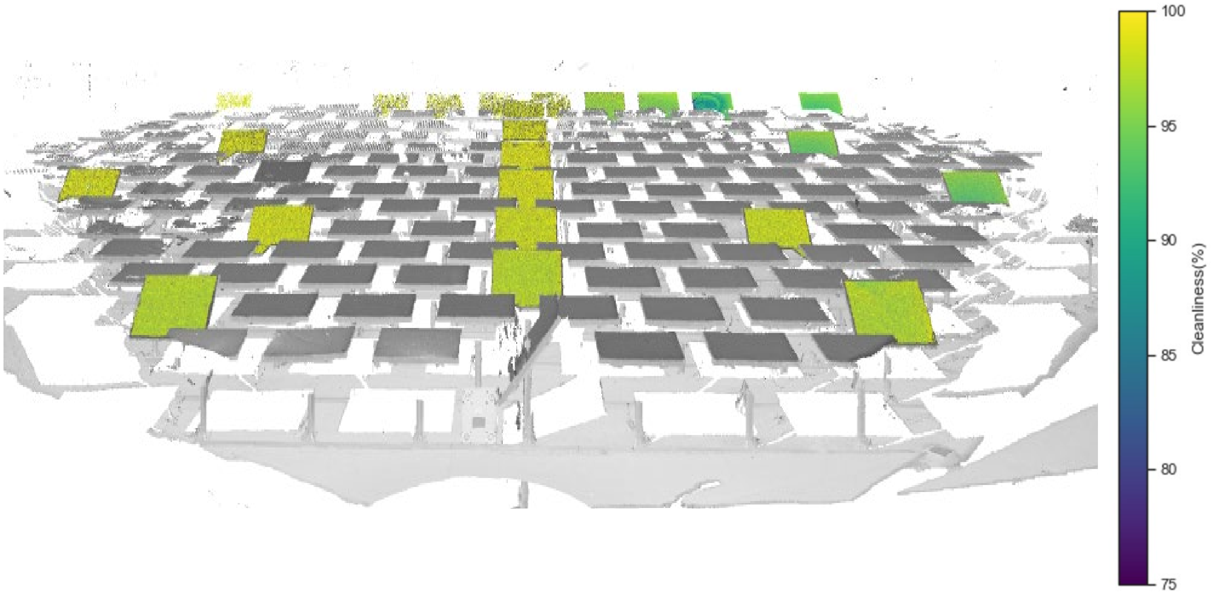

Figure 9. Digital representation of a 3D scan of the IMDEA energy solar field with the spatially resolved cleanliness of the heliostats shown as color map, where the uncleaned mirrors positioned in the bottom right of the field can be easily identified. Laser scanning offers a method for fast spatially resolved cleanliness assessment of a whole heliostat field, and thus it has the potential of replacing the manual procedure with handheld reflectometers.

3. Conclusions

Terrestrial laser scanning offers a fast and spatially resolved solution for heliostat field cleanliness assessment, showing the potential of replacing the manual procedure with handheld reflectometers. In this work, the measurement principle has been successfully developed and validated in the field. Moreover, an outlook on the digital representation of the soiling distribution in the solar field for optimization of the cleaning strategy and plant operation has been presented.

A correlation between the backscattered power and the cleanliness of the mirrors was found, during calibration in the lab and validation in the heliostat field. In each case, the incident angle behavior was calibrated with a different model, and a higher backscatter behavior was observed for the soil at IMDEA energy. In this direction, a better understanding of the scattering behavior of dust particles is needed. Gonio-photometer measurements will be analyzed for understanding the impact of the soiling on the BRDF of the mirrors. The objective of these measurements is to support with additional data the development of soiling models [9] and the laser scanning evaluation routines, for ultimately, calibrating the incident angle effect in the backscatter, and eventually, developing a physical model for relating the backscatter with the specular reflectance.

The further development of the principle will allow for new insights into increasing the efficiency of plant operation and maintenance based on a new measurement technique with existing and available hardware. Readily available UAV solutions will allow for the extension of the measurement range to full scale commercial heliostat fields with thousands of heliostats. A fast measurement of cleanliness with high spatial resolution on the heliostat field will allow for an optimized yield at reduced operational cost.

Competing interests

The authors declare no competing interests.

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