SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Measurement Systems, Devices, and Procedures
https://doi.org/10.52825/solarpaces.v1i.704

Published: 13 Mar. 2024

Study of Dust Particles on Solar Mirrors for Measurement of Soiling by Specular Reflectance and Imaging Assessment

Estelle Le Baron[1][https://orcid.org/0000-0001-7792-4648], Antoine Grosjean[2][https://orcid.org/0000-0003-4243-2306] and Angela Disdier[1]

[1] Univ. Grenoble Alpes, CEA, Liten, LITEN, DTCH, L2TS, F-38000 Grenoble, France

[2] Univ. Clermont-Ferrand, Institut Pascal, 4 Avenue Blaise Pascal, 63178 Aubière, France

Abstract. During the life time of Concentrated Solar Power plants (CSP), optical performances of solar mirrors are affected by soiling phenomena and surface degradations. In order to provide an adequate cleaning strategy, operators must determine the performance loss induced by soiling. Several commercial instruments already exist to measure optical reflectance, but they are dedicated to a single wavelength range or angle, contact and punctual measurements or to laboratory analyses. CEA has developed a new kind of sensor to measure separately the loss of specular reflectance thanks to a CCD camera and photodiodes. In this study, we compared the cleanliness factor calculated with the specular reflectance measured by commercial devices with the image processing performed with our equipment on different artificially soiled solar mirrors. The aim is to ensure that different levels of dirt on the mirrors can be easily assessed with a camera and image processing. We conclude that the level of soiling and the calculation of the percentage of dirty surface are similar to the measurement of the absolute reflectance for all the mirrors tested. These combinations of non-contact, automated, fast and precise measurement with image processing are reproducible for all levels of soiling.

Keywords: Solar Mirrors, Reflectance, Soiling

1. Introduction

Solar mirrors soiling of is one of the obstacles to high solar energy conversion of Solar Thermal Energy plants. As for receiver glasses and thermal absorbers, the optical performance of solar mirrors is affected by soiling phenomena and surface degradation, especially in desert and coastal environments. The objective for the industry is to minimize the maintenance cost and the environmental impact of solar materials 1. Plant O&M costs contribute about 14-17% to the LCOE, and mirrors washing and water costs contribute significantly to these costs 1 [2]. That is why solar mirrors must retain their optical properties during the life of the plant.

Therefore, understanding mirrors fouling and optimizing wash cycles is key to predicting O&M costs.

For clean glass silvered mirrors the solar weighted hemispherical reflectance measured at near-normal angles of incidence is an appropriate measure for performance description. When dust is deposited on the surface, optical losses due to scattering and absorption at increasing incidence angles considerably reduce reflected solar radiation. The theoretical measurement should operate in the solar spectrum domain from 320 to 2500 nm as specified in the actual SolarPACES Reflectance Guideline [3] and for a wide range of incidence angles. In fact, the spectral specular reflectance measurement for varying angles is not obvious, due to the difficulty of having a characterization instrument in the wall solar spectral wavelength range, for a reasonable cost, a high-resolution accuracy and a high operating speed. Different in-situ commercial reflectometers are described in the review [4]. This review explains the difficulties to compare results from an extended literature survey covering from 1942 to 2019, due to the high number of published papers in which the soiling effect is measured in different ways, manually and with different metrics, so difficulties may arise when comparing results.

For all these reasons, the development of new specular reflectometer laboratory prototypes is being supported in the SolarPACES task III by several research institutes e.g. SMQ2 by ENEA, S2R by DLR, VLABS by Fraunhofer-ISE and a custom spectrophotometer by the University of Zaragoza summarized in [5].

This paper aims to investigate how different dust levels and colors affect the reflectance value and to validate the performances of the laboratory automatized soiling sensor previously described in [6] developed in Wascop project [7] and patented [8] by comparison with various commercial equipment [9] [10]. The goal of this work is also to analyze dust with a simple and dual measurement sensor with “reflectance” and “image treatment” of soiled mirrors for two types of sand and six levels of soiling which differ significantly. Fraunhofer ISE also developed a camera method of soiling detection named FREDA [11] and DLR with Qfly measurement images uses an unmanned aerial vehicle (UAV) [12]. Image processing of particles with a microscope system is also developped by Atonometrics with the MARS™ Soiling Sensor [13] for PV market. This sensor includes a dust collection window configured to be in the same plane as the PV modules to be monitored and uses a microscopic imaging system to detect dust particles on the window coupled with image analysis which quantifies the fraction of light blocked by the dust particles.

2. Materials and methods

Six samples of monolithic silvered glass mirrors selected in this study are provided by one commercial manufacturer, anonymized in this paper and noted 1 to 6. The mirrors are artificially soiled by Fraunhofer ISE within the framework of the SFERA-III project of the European Union Horizon 2020.

Three samples 1 to 3 have been articially soiled with the same sand named “Yellow” from Israël Negev desert and three samples 4 to 6 named “Dark” sand from Almeria in Spain under defined conditions allowing a repeatable testing of coverage rates. The focus of this article lies on the applicability to solar reflector materials with a cleanliness of more than 60%. After being artificially soiled, the six mirrors are measured by our three specular reflectance measuring equipment described in Table 1. Specular reflectance is an optical property that measures the ability of the mirror to reflect incident sunlight in a single direction. The testing campaign comparison is performed to validate the performances of the laboratory soiling sensor, presented in 2019 [6], with two commercial specular reflectance equipments used by the community.

Table 1. Specular spectrophotometer instruments parameters.

Instrument	Reflectance parameter	Wavelength λ	Incidence angle θ_i	Half-acceptance angle φ
Devices & Services-D&S 15R-USB [9]	Near-specular	660 nm	15°	12.5 mrad
Perkin Elmer – spectrophotmeter Lambda 950 ARTA [10]	Specular	280-2500 nm	8°-85°	131 mrad
Soiling sensor prototype [6]	Specular	365-850 nm	15°-65°	20 mrad

3. Results

Specular reflectance values are measured at a monochromatic wavelength of 660 nm and 15° of incidence angle and different half acceptance angle as summarized in Table 1 with the portable reflectometer 15R-USB from Devices & Services D&S [9], the spectrophotometer Lambda 950 from Perkin Elmer with an ARTA tool [10] and the soiling sensor prototype [6].
Prior to soiling, the spectral reflectances of the mirror samples were measured by Fraunhofer ISE to select the most homogeneous from the population. Six soiled samples were selected for comparison with an identical clean sample. Three reflectance measurements were taken per sample at different locations (1 in the center, 1 cm on the left edge and 1 cm on the right edge). As the measuring instruments have different spot sizes, the measurements were carried out at the same location over larger or smaller areas.
The parameter of cleanliness factor, named CF, is the ratio of the actual reflectance of the mirror to its reflectance in the clean state and is calculated with the following equation defined in [3]:

$$CF = \zeta_{\lambda,\phi}(\lambda,\theta_i,\varphi) = \frac{\rho_{\lambda,\phi,soil}(\lambda,\theta_i,\varphi)}{\rho_{\lambda,\phi}(\lambda,\theta_i,\varphi)} \quad (1)$$

According to the definition in [3] it depends on the wavelength λ, the incidence angle θ_i and the acceptance angle φ.
For a comparison of different soiled reflectors, the cleanliness factor is used widely in the following analysis. For image processing, the cleanliness factor equation (1) was transformed by the ratio of soiled surface to cleaned surface.
Table 2 gives the average specular reflectance of three measurements (ρ_λ), the standard deviation (σ) and the average cleanliness factor (CF), for each sample with the three equipment. For the soiling sensor the cleanliness factor is calculated by reflectance and image treatment.

Table 2. Reflectance at 660 nm and cleanliness factor with the three equipment.

Samples	Sand	D&S			Lambda 950 ARTA			Soiling sensor			
		ρ_λ (%)	σ	CF (%)	ρ_λ (%)	σ	CF (%)	ρ_λ (%)	σ	CF (%) by ρ_λ	CF (%) by image
Clean		95.7	0.0		93.2	0.0		95.7	0.8		
1	Yellow	91.1	0.2	**95.2**	90.3	0.1	**96.9**	91.6	1.0	**95.8**	**94.5**
2	Yellow	80.5	0.7	**84.1**	83.9	1.0	**90.0**	80.3	4.3	**83.9**	**85.4**
3	Yellow	66.7	0.2	**69.7**	71.7	1.9	**76.9**	65.8	1.0	**68.7**	**73.9**
4	Dark	79.8	0.3	**83.4**	82.7	1.2	**88.8**	81.5	0.3	**85.2**	**79.6**
5	Dark	66.0	0.5	**69.0**	73.4	0.5	**78.7**	73.0	1.8	**76.3**	**71.9**
6	Dark	59.5	0.7	**62.2**	67.7	0.6	**72.6**	67.7	1.6	**70.8**	**66.7**

The soiling sensor reflectance shows a good correlation with the actual equipment (D&S and Lambda 950 ARTA).

The results obtained with our soiling sensor here present a good homogeneity with the results obtained with the other equipment with the exception of sample 2 which has a dispersion of the level of soiling (σ = 4.3%) certainly due to transportation. We note for samples 1, 2 and 3 our prototype gives similar specular reflectance results as D&S device with a maximum difference of 0.9 % for sample 3 ($\rho\lambda$ = 65.8% versus 66.7% for D&S).

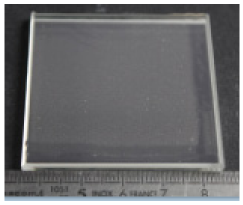
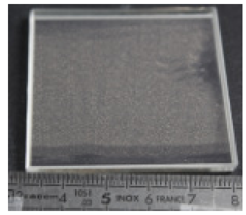
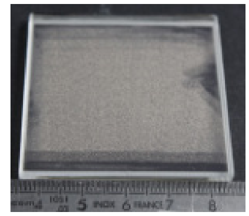
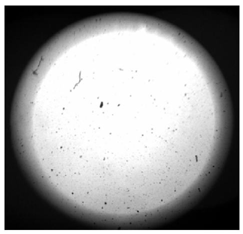
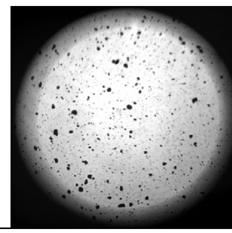
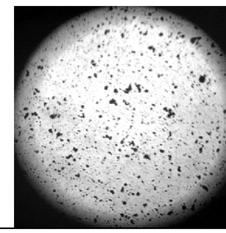
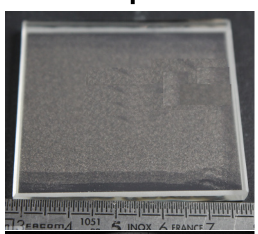
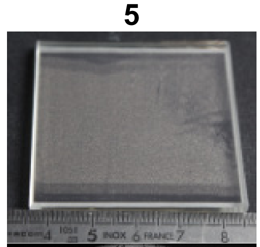
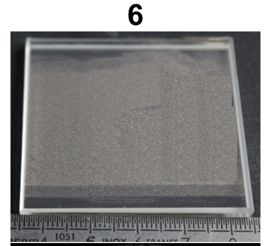
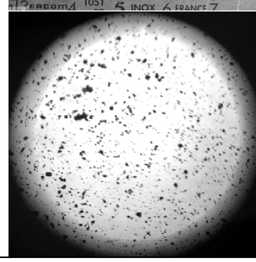
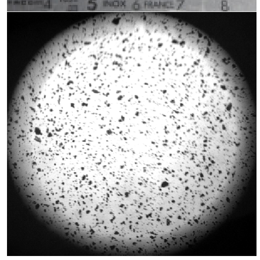
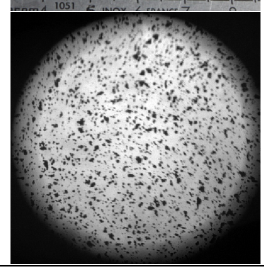
For samples 4, 5, and 6, the soiling sensor reflectance comparison is better with the Lambda 950 and ARTA tool with a maximum difference of 1.2% for sample 4 ($\rho\lambda$ = 81.5% versus 82.7% for ARTA). Sample 6, a really soiled mirror gives more dispersed reflectance results from D&S device (respectively $\rho\lambda$ = 67.7% versus 59.5 % for D&S). The small size of the spot makes the measurement with the D&S very variable depending on the light point on the glass contact surface compared with the spot size of the other devices [6], [10], [14].

Even using calibrated reflectometer, the achieved reflectance results differ for different instruments and acceptance angles due to particle scattering. The reflectance loss due to soiling is less pronounced according to the ARTA tool and the soiling sensor prototype with respect to the D&S. The larger acceptance angle allows the ARTA device and the soiling sensor prototype to collect a greated part of the scattered radiation. The detected reflectance values are correlated with the acceptance angle and the wavelength.

As previously described in [6], the main advantage of our soiling sensor prototype compared to the other commercial equipment is the presence of a CCD camera, which allows a complementary analysis by taking pictures of the sample surface. It also offers the capability to calculate the cleanliness factor CF by image treatment of the amount of dust deposited on the sample by area unit from a clean area.

For all the samples, our prototype gives in the last column of Table 2 the cleanliness factor CF results obtained by image treatment similar as D&S device with a maximum deviation of 4.5 % for sample 6 (66.7% versus 62.2% for D&S).

Table 3. Samples pictures and raw camera imagings.

	1	2	3
Samples pictures			
CCD camera images			
	4	**5**	**6**
Samples pictures			
CCD camera images			

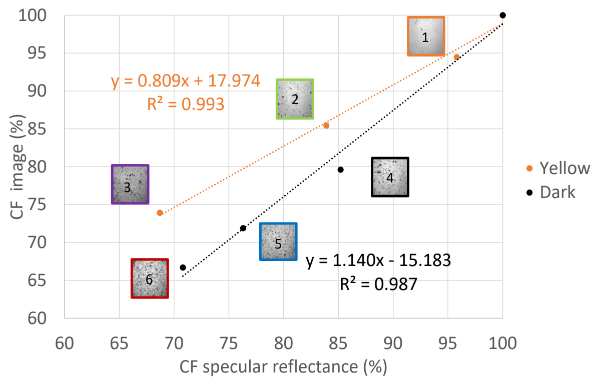
Our results and other papers show us that the impact of sand particles create a shadow on the mirror, the irradiation is blocked , either absorbed by the dust particle or scattered, creating a more diffuse reflectance and less reflective surface. As expected in Table 3, sample 1 with a high cleanliness factor (or low soiling rate) has few objects on its surface while sample 3 (highest dust level of "Yellow" samples) has many objects. The same conclusion is made for the "Dark" sands for samples 4 to 6.

Due to the heterogeneous level of the soiling, presented in Table 3, reliable reflectance measurements over the entire mirror surface were not possible with only spot measurements. As described previously in [14], the D&S reflectometer is recommended by the community, especially when measuring heavily soiled glass mirrors but for measurements taken at a few discrete moments in different timestamps by different operators may not be representative of the actual solar field performance and need statistical analysis procedures. The automated, non-contact measurement offered by our soiling sensor means there is no risk of cleaning the surface by changing the measurement point and contaminating the device, compared with the manual, contact-based D&S reflectometer.

At this point, we can conclude that this soiling equipment can perform a similar role to the D&S, but in an automatic way with various incidence angles and the possibility to take pictures of

the samples and process them as described in [6]. The large spot size gives more consistent results than D&S.
A greyscale, cropped and transformed camera imaging of the samples were processed. Using Scilab (5.5.2) with the Image Processing Design (IPD) toolbox (8.8.3) [15] with a method of edge detection filters, objects are detected on the sample and classified with different levels of dust. Image with pixels classified as heavily soiled is rendered as lightly shaded, and cleaner pixels in darker tones as shown in Figure 2.

The CCD camera with the image processing provides the capability to calculate the cleanliness factor (CF) for yellow and dark sands by image treatment and to calculate the correlation function with the CF by the reflectance of the same sensor as shown in Figure 1.a. To compare measurement results between two instruments measuring at similar wavelength and incidence angle but at different acceptance angles, we had achieved good results by applying a linear transfer function from the D&S results Figure 1.b.



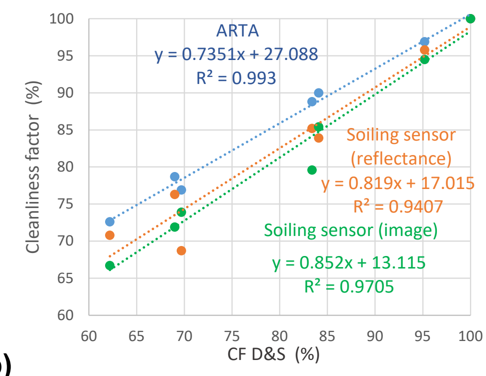


Figure 1. Correlation of cleanliness factor a) calculated by image treatment versus reflectance with the soiling sensor prototype and b) calculated by 3 methods versus D&S.

Overall, the image processing method gives a good correlation with optical reflectance losses, as show by Figure 1.a and 1.b. The image treatment is effective for yellow and dark sands, as indicated by the two high and homogeneous coefficients of determination (R^2=0.99) in Figure 1.a). The surface covered by the detected objects is directly related to the reflectance loss measurement, as described thank to Figure 1.b). Good agreement was achieved in terms of soiling estimation between our soiling sensor prototype and the commercial reflectometer D&S with maximum deviation for the most diffusive specimens. For example, for sample 6, the difference between the cleanliness factor CF obtained by image processing and that calculated from the reflectance of the D&S is 4.5%. On average for all the samples, the difference is 1.4%. It can be seen in figure 1.b, that a linear relationship between the cleanliness values measured with images of the soiling sensor prototype and the D&S device is given by y =0.852 x +13.115 with an acceptable coefficient of determination (R^2 = 0.97). The linear correlation with the ARTA tool differs due to the larger acceptance angle of the instruments.
Figure 2 illustrates an example of the possibility of particle analysis, by an edge-to-edge method for the six samples. As expected, the number of particles of sample 6 is greater than samples 3 and 5, also greater than samples 4 and 2, whatever their size expressed in pixels. This method makes it possible to easily and rapidly classify the level of soiling and the sizes of the particles deposited on the solar mirrors.

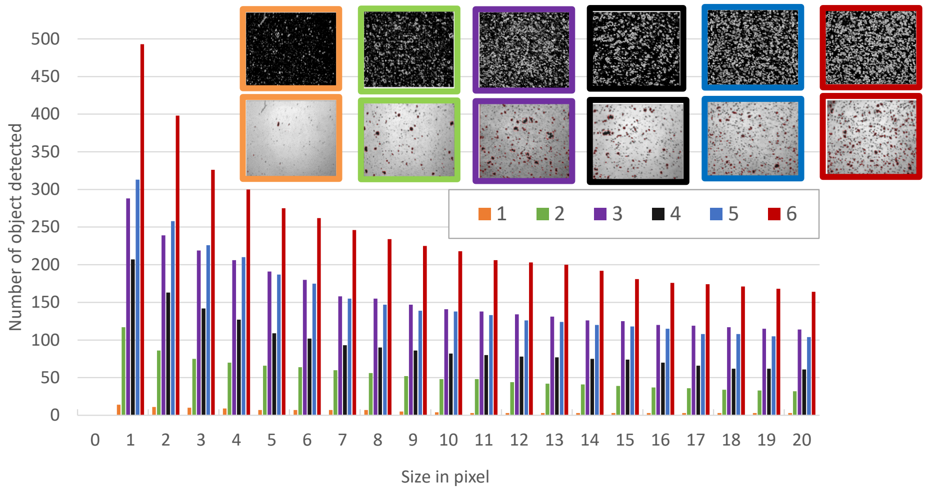


Figure 2. Number of soiling particles according to their size in pixel on samples 1 to 6.

Through image processing, we can obtain information about much or even all of the mirror surface. Using image processing to retrieve information about particle size distribution is also possible from a laboratory microscope using ImageJ® software of local point.

4. Conclusion

Artificially soiled laboratory data shows promising results for the fast, non-contact all-optical prototype soiling sensor. Image processing shows a good correlation with optical reflectance losses for different color of sands, any kind and level of soil, up to 40% optical loss. In red light (660 nm), this instrument measures the absolute specular reflectance and is able to calculate the cleanliness factor from the camera images assessment. The linear transfer function with a straight slope of 0.85 and a high correlation compared to the D&S reference device makes it possible to check the quality of imaging assessment for calculating the cleanliness factor. In particular, image processing does not require any calibration with another sensor or another reference cell or mirror, unlike reflectance measurement. By applying a calibration factor, the results can of course be improved. Overall the data clearly show the ability of this soiling sensor to track trends in soiling data and demonstrate good agreement between it and commercial instruments.

In summary, the development of this imaging soiling detection technique has the potential to increase the current coverage and spatial resolution of reflectance measurements. for the quantitative assessment of the dust of a CSP plant.

Full qualification of this instrument will require outdoor testing under real conditions with dirt and sunlight. Eventually it can be used to monitor soiling in CSP plants in operation in order to optimize cleaning for greater profitability. This image processing is also used for measurements of erosion and corrosion effects with a smartphone camera.

Data availability statement

The data supporting the results of this article can be accessed upon request to the authors.

Author contributions

Estelle Le Baron: Conceptualization, Investigation, Methodology, Visualization, Writing - review & editing. **Antoine Grosjean:** Investigation, Software, Writing – review & editing. **Angela Disdier:** Data curation.

Competing interests

The authors declare no competing interests.

Acknowledgments

The authors would like to acknowledge the financial support of the SFERA-III project from the European Union's Horizon 2020 research and innovation program under grant agreement No 823802.

References

1. IRENA, The power to change: Solar and wind cost reduction potential to 2025, tech. rep., International Renewable Energy Agency (IRENA), 2016.
2. R. Conceicao, H.G. Silva, M. Collares-Pereira, CSP mirror soiling characterization and modeling, Solar Energy Materials Solar Cells, 185 (2018) 233-239, doi: 10.1016/j.solmat.2018.05.035
3. SolarPACES Reflectance Guideline, Version 3.1. April 2020. https://www.solarpaces.org/wp-content/uploads/202004_SolarPACES-Reflectance-Guidelines-V3.1.pdf
4. R. Conceicao, J. Gonzalez-Aguilar, A. Alami Merrouni, M. Romero, Soiling effect in solar energy conversion systems: A review, Renewable and Sustainable Energy Reviews 162 (2022) doi: 10.1016/j.rser.2022.112434
5. F. Sutter and al., “Advanced Measurement Techniques to Characterize the Near-Specular Reflectance of Solar Mirrors”, SolarPACES Conference 2018, doi: 10.1063/1.5117618
6. E. Le Baron, A. Grosjean, D. Bourdon, A-C. Pescheux, F. Vidal, A. Disdier, New Equipment for Measurement of Soiling and Specular Reflectance on Solar Mirrors, , in 'Solar PACES 2019', doi: 10.1063/5.0028806
7. https://wascop.eu/
8. Patent EN 17 61041 O. Raccurt, C. Delord, P. Giraud, A-C. Pescheux, Système de surveillance de la dégradation et de l'encrassement d'un miroir, CEA.
9. Devices and Services Company, Devices and Services Portable Reflectometer Model 15R- USB. https://www.devicesandservices.com/prod02.htm
10. MT Solutions BV, ARTA – Technical Description, 2010.
11. G. Bern, T. Schmidt, N. Celentano, A. Heimsath, P. Nitz, FREDA - An Automated Field Reflectance and Degradation Assessment System for Central Receiver Systems, in AIP Conference Proceedings, Vol. 2033(AIP Publishing, 2018), doi: 10.1063/1.5067229

12. F.Wolfertstetter, R. Fonk, C. Prahl,; M. Röger, S. Wilbert; J. Fernández-Reche, Airborne soiling measurements of entire solar fields with Qfly. AIP Conf. Proc. 2020, doi: 10.1063/5.0028968
13. M. Gostein, B. Bourne, F. Farina and B. Stueve, "Field Testing of Mars™ Soiling Sensor," 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), Calgary, AB, Canada, 2020, pp. 0524-0527, doi: 10.1109/PVSC45281.2020.9300975
14. G. Zhu, D. Kearney, M. Mehos, "On characterization and measurement of average solar field mirror reflectance in utility-scale concentrating solar power plants", Solar Energy Vol 99, pp. 185-202, 2014, doi : 10.1016/j.solener.2013.11.009
15. Harald Galda, "Image processing with Scilab and Image processing Design Toolbox Copyright", 2011.