Guidelines

Recommendations for reflectance measurements on soiled solar mirrors

Version 0.1

July 2022

Authors: F. Wolfertstetter (DLR), F. Sutter (DLR), E. Lüpfert (DLR), M. Montecchi (ENEA), C. Pelayo (UNIZAR), C. Heras (UNIZAR), G. Bern (Fraunhofer ISE), M. Bitterling (Fraunhofer ISE), A. Heimsath (Fraunhofer ISE), A. Fernández-García (CIEMAT), J. Wette (CIEMAT), C.-A. Asselineau (IMDEA Energy, ANU), Guangdong Zhu (NREL)

Abstract

This document is a preliminary version of an extension to the existing SolarPACES reflectance measurement guideline [1]. Its intention is to specify best practices and recommendations on measurements of soiled reflectors in Concentrating Solar Power (CSP) solar fields (referred to as "soiling measurements" from now on). The methods and requirements for solar field soiling measurements differ from high precision (clean) reflector characterization.

This document summarizes the challenges in measuring soiling from an optical and spectral perspective. It provides an overview of available instruments and methods to determine soiling levels of solar fields and identify needs for further research in the field of soiling measurements.

The guideline is to be understood as a living document, open to regular updates as the state of the art of measurement instruments and procedures advances. Please send comments, amendments, suggestions to florian.sutter@dlr.de or arantxa.fernandez@psa.es.

1 Introduction

This guideline for characterization of soiled solar reflectors is published under the framework of the SolarPACES Task III: "Solar Technology and Advanced Applications". The project "Soiling Measurements of Solar Reflectors" was initiated because of the urgent demand to define best practice for soiling measurements in solar fields that deliver accurate results that are comparable within the solar community. The scope of this project was to collect field experiences [2], identify weak points in current practices and elaborate suggestions for best practices for solar field soiling measurements and reflectometer calibration procedures. In addition, the options to obtain practically relevant, comparable and well understood reflectance results (with the adequate parameters for the specific plant) from the limited reflectance values measured in the field with the portable equipment are investigated.

The guideline for reflectance measurements of solar mirrors covers definitions of parameters for soiling measurements. This document specifies in more detail the requirements and procedures for this application case.

Soiling measurements in a solar field differ from characterization of (clean) reflector materials in that:

1. Soiling reduces reflectance in a much broader range than typical for different but clean reflector types. Specular reflectance below 60% is not uncommon in operational solar fields.
2. Soiling is distributed differently over the reflector area of a solar field, and even over the area of each individual facet.
3. Dust types and the resulting optical properties of a soiling layer are potentially site and time dependent.

A useful parameter to quantify soiling is the cleanliness or soiling ratio, especially when comparing reflectance measurements from different mirror types or reflectometers. The cleanliness (or "soiling ratio") is the ratio of near-specular reflectance of the soiled and the clean mirror of the same type. The measurement device and its parameters such as wavelength, λ, acceptance angle, φ, and incidence angle, θ_i, should be the same for both measurements, clean and soiled. The cleanliness should be reported including the employed parameter set.

In solar applications, reflectance is best quantified in terms of solar-weighted reflectance. In CSP applications, mirrors are used to redirect solar radiation onto a receiver. The amount of intercepted radiation is proportional to the sun-conic reflectance, i.e. the ratio of solar radiation reflected into a specific acceptance angle. This clarifies why the performance of solar concentrators is strongly influenced by scattering, absorption and/or diffraction at a soiling layer deposited on the reflector surface. Hemispherical and near-specular reflectance depend on the incidence angle of the radiation [3], [4]. CSP collectors can operate at a broad range of incidence angles that depend on the solar field design and it should therefore be considered in a complete characterization [5].

Due to the lack of commercially available instrumentation to adequately characterize all reflectance properties of a reflector material in solar fields (see [1] and [2] for more details and references), a straightforward measurement procedure that obtains reliable results valid for all soiling types and densities is not possible at the current state of the art. Only in some cases with a very high number of measurements per collector, interpolations and approximations are suitable. A general, step-by-step measurement procedure does not meet the various needs of solar field operation strategies and research goals. This guideline is focused on illustrating the complexity and the challenges for a complete soiling characterization. It furthermore intends to give an overview and recommendation on possible measurement solutions. This includes recommendations about instrument selection, properties and considerations for calibration procedures and suggestions for practical simplifications where applicable. The parameters and values that should ideally be measured for a complete and adequate soiling characterization are described. Since the soiling distribution and type are very site dependent and no ideal measurement instrument is available, an overview of possibilities and their up- and downsides is given. The soiling measurement guideline focuses on the effect of a soiling layer, independent of the reflector material.

2 Terms and definitions

For the purposes of this document, the terms and definitions as given in the SolarPACES reflectance measurement guideline apply [1]. They are referred to without introduction in this document. It is recommended to read the reflectance measurement guideline before consulting the soiling measurement guideline. For quick reference, a selected list of definitions, abbreviations and symbols is given below:

CSP	Concentrated solar power
Collector	Element consisting of concentrator and receiver
Concentrator	Shaped reflector that focuses sunlight onto receiver
DNI	Direct normal irradiance
Reflector	Mirror that makes up the concentrator
Receiver	Element that absorbs the sunlight focused onto it to generate heat
ρ	Reflectance
λ	Wavelength
θ_i	Incidence angle
φ	Acceptance angle
$\rho_{\lambda,h}(\lambda,\theta_i,h)$	Spectral hemispherical reflectance
$\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	Solar-weighted hemispherical reflectance in the range between λ_a and λ_b
$\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Specular reflectance
$\rho_{\lambda,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$	Solar-weighted specular reflectance in the range between λ_a and λ_b
ξ	cleanliness factor or “soiling ratio”, i.e. ratio of soiled and clean reflectance of a sample
$\dot{\xi}$	soiling rate, i.e. variation of cleanliness over time

3 Reflectance measurements on soiled mirrors

The sun-conic specular reflectance of a concentrator will be referred to as solar near-specular reflectance from now on. More precisely it is:

- the solar-weighted value of the spectrum measured in the range of λ=[320, 2500] nm,
- with diverging incidence radiation φ_s~4.7 mrad,
- at the incidence angle θ_i representative of the plant (which depends on the technology and location),
- and collected in the acceptance angle φ of the receiver.

The direct experimental measurement of such a quantity is time-consuming, as well as quite difficult even for a specialized laboratory, and certainly it is unpractical in solar fields where only simple portable instruments can be used. Typically, a portable reflectometer allows to measure few values of near-specular reflectance taken at a certain θ_i and for one (or several) values of φ and λ.

Bearing in mind that the ultimate purpose of this document is to outline a reliable procedure for setting a *transfer function* between in-field reading and solar near-specular reflectance at θ_i and φ concerning of the specific plant and for a given typology of soiling, two other topics, important for in-field measurements must be considered:

1. the minimal requirements for the portable reflectometers;

2. the sampling strategy to get a representative value of cleanliness for the plant, considering the non-uniform distribution of soiling along the reflector surface.

The minimum list of recommended requirements for the measurement instrument is:

- Handheld reflectometer with specified λ, θ_i and φ
- "Near-normal" θ_i up to 15°
- φ up to 150 mrad
- Valid instrument calibration following manufacturer manual, mostly using a clean reference mirror sample
- Positioning adjustment possibility or high tolerance for mirror curvature and thickness
- High battery autonomy, compact, light, easy to handle, easy to use, etc.
- No external stray light, ambient temperature dependence or other environmental influences on measurement results
- Easy re-calibration procedure in the field
- No risk to human health during measurements

This list has been adapted to the findings from interviews with solar operators that have been conducted in the course of the SolarPACES project and that can be consulted as additional information [2]. The operators therein report experiences and issues with reflectance measurements in solar fields from a practical point of view.

Concerning the sampling strategy, the general recommendation is: i) select a limited number of SCEs/heliostats to be measured; ii) adopt a pattern of limited points on the reflector that are representative of soiling. These points shall be chosen in order to make the measurement easier and safe, considering the uncomfortable conditions in-field. As an example, for parabolic trough modules, a good option is to measure 5 points for each one of the outermost facets; that can be easily reached by a person on the ground without the need of a ladder, scaffolding, or platform. The topic will be taken up again in Sec. 5.

A soiling layer accumulated on a reflector surface scatters, diffracts and absorbs incident direct irradiance. As a consequence, the reflected beam is more disperse around the specular direction according to an angular radiance distribution depending on the soiling particle size distribution, composition and amount. Radiation scattered outside of the acceptance angle of the receiver is lost, and does not contribute to the power generation.

At the time of this preliminary report, experimental data on natural soiled specimens coming from CSP power plant locations is scarce. The current consensus is that relevant particle size distributions are thought to be mostly in the Mie scattering regime (see [6] and [7]), where the particle size is in the same order of magnitude as the solar spectrum. Forward scattering dominates there. CSP collectors only accept irradiance falling into a small acceptance angle range around the point of direct reflection that has been described and specified in the reflectance measurement guideline. Light scattered outside of this region misses the receiver and is lost for power generation.

End-users typically wish to correlate reflectance measurements obtained in field with their chosen portable reflectometers with the solar near-specular reflectance degradation induced by soiling, which affects the optical efficiency of their CSP plants. To achieve this goal, a soiling model was developed within this project [8].

This preliminary version of the guideline warns users by summarizing the actual knowledge on the topic with the following statements:

- Soiling degrades reflectance by absorption, scattering and diffraction.
- The soiling characteristics (particle size, particle absorption, etc.) depend on the specific site and time in question
- Regardless of the extent of degradation, normalized spectral decrements[1] and scattering behave differently from site to site, depending on the kind of soiling and its optical characteristics.
- At present, in-field measurements can only be achieved by portable reflectometers operating at just one or few λ, and at one or few θ_i and φ.
- The solar yield of CSP depends on solar near-specular reflectance at the average or the distribution of φ and weighted for the θ_i for the considered solar field layout over the course of a year.

Because of the above statements, we must conclude that unfortunately, it is not possible to outline a general correlation between single wavelength measurements, obtained in field with a portable reflectometer, and the solar-weighted reflectance of interest for the considered plant without further knowledge from laboratory measurements. This correlation must be defined for the specific type of soiling that can be site dependent and subject to seasonal changes.

Reflectometer readings taken with different φ therefore ignore different amounts of scattered solar irradiance. It has been demonstrated that even using well-calibrated reflectometers, soiling measurements differ substantially for different instruments because their measurement parameters (incidence and acceptance angle and wavelength) vary significantly, see [9] and Figure 1 as example. Another reason is that the current recommendation on calibration of reflectometers with a single specular calibration mirror does not account for different instrument acceptance angles φ as the highly specular calibration mirror shows only negligible beam spread. When measuring soiled mirrors, the range of reflectance values and the beam dispersion, as well as its spectral distribution, are influenced substantially by the presence of a soiling layer. The following sections serve to better understand, interpret and apply soiling measurements to solar field use cases. Each end-user should determine his/her own estimation method, which will strictly depend on the above parameters and the available measurement instrumentation.

1The *normalized spectral decrement* is the ratio $\left[\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)_{clean} - \rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)_{soiled}\right]/\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)_{clean}$. It represents the reflectance degradation induced by soiling unbiased for spectral features of the specific reflector.

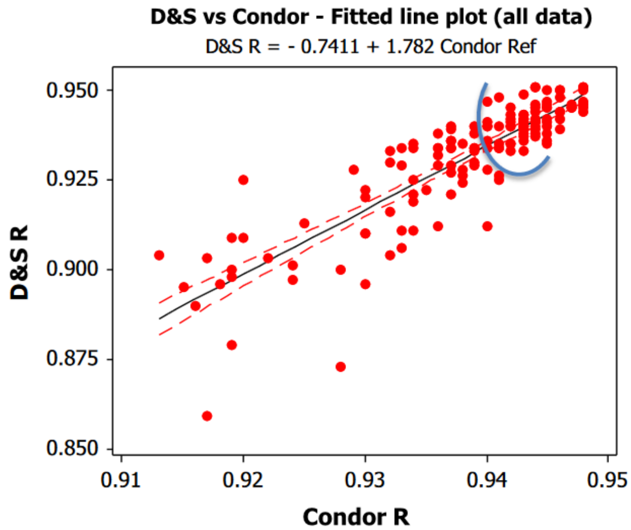


Figure 1. Direct comparison of reflectance measurements on soiled samples with two different reflectometers [9].

4 Measurement devices

After discussing the optical effects of soiling on the reflected irradiance and the precautions raised for interpreting and evaluating the instrument readings, this section presents the most commonly used instruments for solar field applications with exemplary pros and cons. Laboratory measurement equipment is not included in this list as it is not practicable in application in solar fields. Laboratory instruments usually require small samples to be exposed in the solar field and manually transported to the lab for investigation. Such solutions are usually much too costly in solar field operations.

The list below will also introduce measurement principles for soiling evaluation that are not yet employed in commercial power plants. Soiling evaluation can be performed using high precision reflectance measurement methods as those specified in the SolarPACES reflectance measurement guideline, but there are also novel methods to quantify dust amounts without directly measuring reflectance. More detailed analysis on many of the reflectance measurement devices are given in [10].

4.1 Handheld reflectometers

Handheld reflectometers that fulfill the requirements specified in the reflectance measurement guideline can be employed to measure the cleanliness or soiling ratio of solar reflectors. For this purpose, the reflectance has to be measured on a clean reflector of the same type, as a reference. Knowing the clean mirror's reflectance, the soiled reflectance can be compared to this reference in order to obtain the soiling ratio or cleanliness according to the equation given in the reflectance guideline. Handheld reflectometers use a range of optical arrangements and sensor technologies and are not automatically calibrated. A consequence of this is that reflectometers calibrated using the method prescribed by the manufacturer will provide reliable soiling ratios according to the optical setup but these need to be adapted according to the specific device arrangement to be a) translated into an absolute reflectance loss for a specific application and b) compared with measurements obtained with other devices.

The main advantages of the use of handheld portable reflectometers are:

– They are robust devices, proper for in-field usage

- Medium spatial resolution, in the sense that the measurement area is very small but the device can be transported to several locations

While the main disadvantages of their use are:

- Regular calibration is needed for repeatability
- The devices operate at one or a few narrow λ bands and not at full spectral resolution
- The φ is typically quite large in order to simplify the in-field adjustment of the optical path. Measurements at the relevant φ (7-20 mrad) require alignment of the device with respect to the mirror surface
- Correlation to laboratory measurement devices is needed in order to obtain solar-weighted reflectance loss at relevant angles
- No automatic measurements are done, that is, an operator is required

4.2 Irradiance based soiling sensors

There are methods to derive cleanliness and soiling rates from direct comparison between measurements of reflected and incident light on a reflector surface. The measurement principle of such an instrument is to compare direct normal irradiance (DNI) measured by a pyrheliometer to the DNI reflected off a mirror sample into a second pyrheliometer [10], [11]. These instruments use the natural sun as a light source, such that solar weighting is not necessary in data processing. Such devices provide an absolute cleanliness estimation when compared to the reflectance of a clean mirror.

Advantages of this kind of sensors are:

- They provide direct, absolute measurements
- High time resolution
- Automatic measurements can be programmed, no operator required

However, they also present some disadvantages:

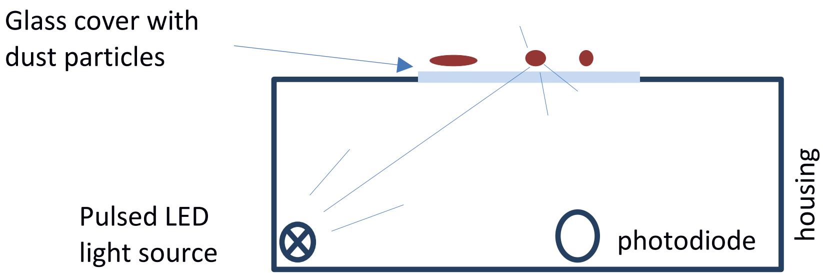
- non-portable device with pre-determined exposure arrangement
- Small spatial resolution
- Maintenance required
- Measurement only in sunny conditions

4.3 Scattering sensors

Another soiling sensor type are instruments that determine the scattered part of an incident beam and correlate that reading with actual reflectance losses caused by soiling. This means that these instruments do not measure the reflectance or cleanliness directly but rather detect the dust particle layer. This instrument type has been commercialized mainly for application in Photovoltaics [12] and also for CSP-application [13].

An example of a working principle of such a sensor can be seen in Figure 2 : dust accumulates on a transparent window integrated in the sensor housing. A pulsed LED light source illuminates the dust from below. Scattered light from the particles is detected in a photodiode. The device is calibrated using co-located reference measurements for each site for a limited period of time.

Figure 2 Measurement principle of scattering based soiling sensors.



Advantages are:

– High time resolution
– Automatic measurement
– Very low maintenance

Drawbacks of this measurement principle include the following:

- Dew formation and soiling accumulation can be different on a glass cover compared to a reflector
- Scattering is dependent on dust particles' optical properties. These can change over time due to different wind directions and long-range dust transport
- Absorption caused by soiling is not detected
- The single measurement spot is very small compared to the solar field aperture area
- Measurements are typically performed using only a small wavelength band

4.4 **Image-based methods**

A number of publications mention concepts of camera-based soiling detection methods [14]-[16]. They can be based on physical-optical principles and/or artificial intelligence. These methods have not yet reached commercialization, but their feasibility has been demonstrated.

Image-based methods use a similar principle to the scattering sensors described in section 4.3 in that they detect the soiling layer deposited on a surface by determining the amount of scattered light. The main differences are that the sun is used as a light source and CCD/CMOS camera sensors are used as the detector resulting in the potential coverage of the entire mirror surface, or multiple mirrors, appearing in an image. In an alternative implementation the attenuation due to soiling is measured at night with respect to an illuminated reference plane and reference probes in the field [16] . In the case of commercial CMOS cameras, a Color Filtering Array can provide some information about the spectral distribution of the reflected light. The main advantage of image-based methods can be their high coverage of the solar field. In addition, the cameras used are typically portable devices that can be used in several locations, increasing the spatial coverage of this technique further.

Advantages:

– Very high spatial resolution
– Portable device
– Potentially low labor requirement

Disadvantages:

- Scattering method: calibration is sensitive to dust properties
- Depending on the applied technique, the absorption caused by soiling is not detected
- Accuracy unclear
- Not yet commercially available

5 Measurement point selection and solar field averaging methods

The current version of the solar reflectance measurement guideline [1] specifies a procedure to determine average reflectance values for small samples, in the range of 12 x 12 cm^2, in laboratory condition. Five measurement points are recommended to determine a representative average reflectance. The application is the characterization of permanent degradation on samples that have been previously exposed to weathering conditions.

In the case of measurement of soiling on single samples for research purposes, this procedure is still valid and recommended. If the aim is to determine the average reflectance for an entire solar field with mirror areas of around 500,000 m^2 (example of an Andasol type power plant), more data points have to be taken. Procedures on how to determine a solar field average are given in [17], [19] and [18]. In general, the number and distribution of the measurement points depends on the solar field layout, the possible sources of soiling in the solar field (roads, cooling towers, etc.), the variation of the soiling layer and the desired accuracy of the resulting average solar field cleanliness. The referenced literature gives recommendations for specific cases and procedures on how to minimize the number of measurement points necessary to reach an acceptable accuracy for solar field average soiling values.

Solar field operators have to select and adapt the best suited procedure for their individual solar field layouts in order to reach a satisfying tradeoff between labor and accuracy.

6 Adaptation of solar field reflectometer readings to solar field optical properties

The optical properties of natural dust, that is found at CSP plants, differs especially in absorption, diffraction and scattering behaviors. Surface texture, particle size and color are some of the essential properties that influence their optical behavior. These dust properties are potentially dependent on site, weather and season. When measuring specular reflectance, the absorption by the particles leads to the same measurable effect almost independent of the measuring device. The scattering and diffraction of particles that cause a widening of the reflected beam, show influences in the measurement of the specular reflectance depending on the φ of the measuring device, as sketched in Figure 3.

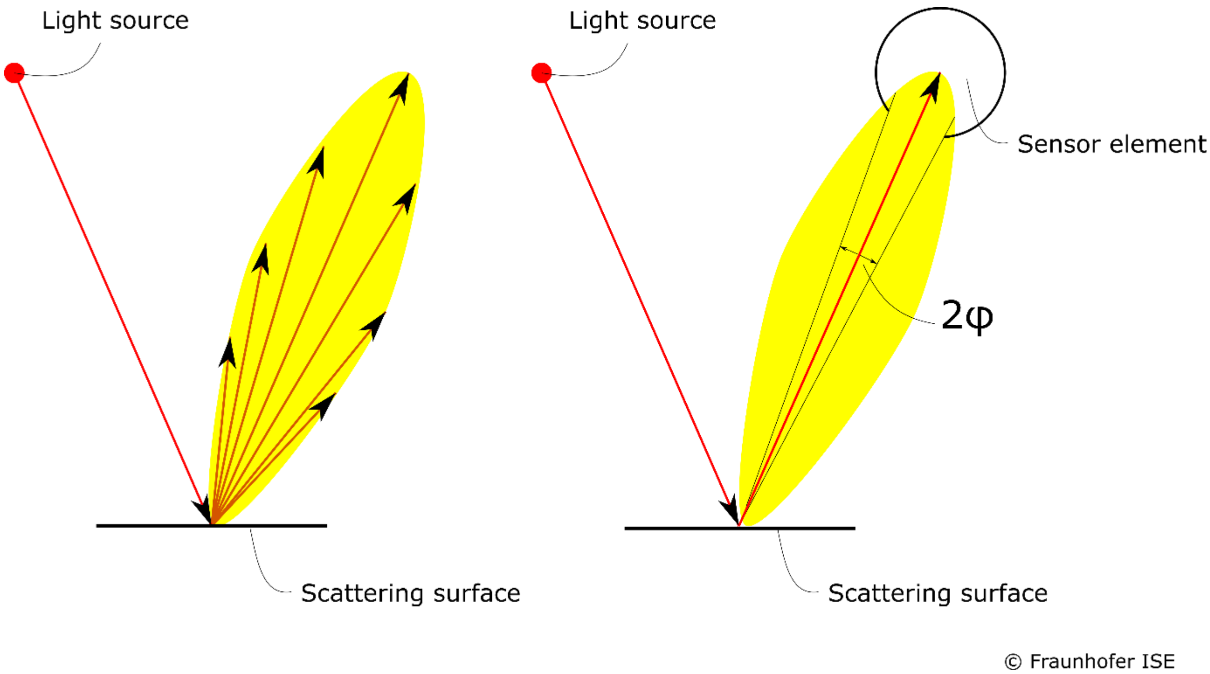


Figure 3: Left: The effect of the widening of the reflected beam due to soiling. Right: Only a share of the reflected radiation, subject to beam spread, is detected by the sensor element, restricted by the acceptance angle defined by the optical system.

As a consequence, a measurement device with a specific φ will measure a different value of reflectance, compared to a measurement device with a different φ, if the scattering behavior exhibits beam spread larger than the smaller φ. The influence is symbolically displayed in Figure 4 for a qualitative scattering profile representing different soiling levels and for three different φ. The dark orange surface represents the entire reflected light. The yellow share enclosed by the triangle representing the φ is the share that would be detected in the respective case.

The effect displayed in Figure 4 applies to both measurement devices and applications: depending on the size of an absorber and its distance to a reflecting surface element of a concentrating collector, different φ can be defined, which do not coincide necessarily with the φ of a device used for the measurement.

6.1 Transfer functions

Transfer functions based on a dust specific instrument to instrument/application correlation (as in the example of Figure 5) can be developed to:

a) compare measurements between different measurement devices,
b) understand and interpret reflectance measurements for the assessment of cleanliness and
c) identify, analyze and model the influence of soiling in the solar field of concentrating collectors

For obtaining such transfer functions considering the scattering behavior it is recommended to fix the point of 100%, representing the case of specular reflectance of the clean sample. Hence only the slope of the linear correlation must be determined. More research is needed to develop methods to adapt reflectometer readings of soiled mirrors to actual optical boundary conditions in solar power plants.

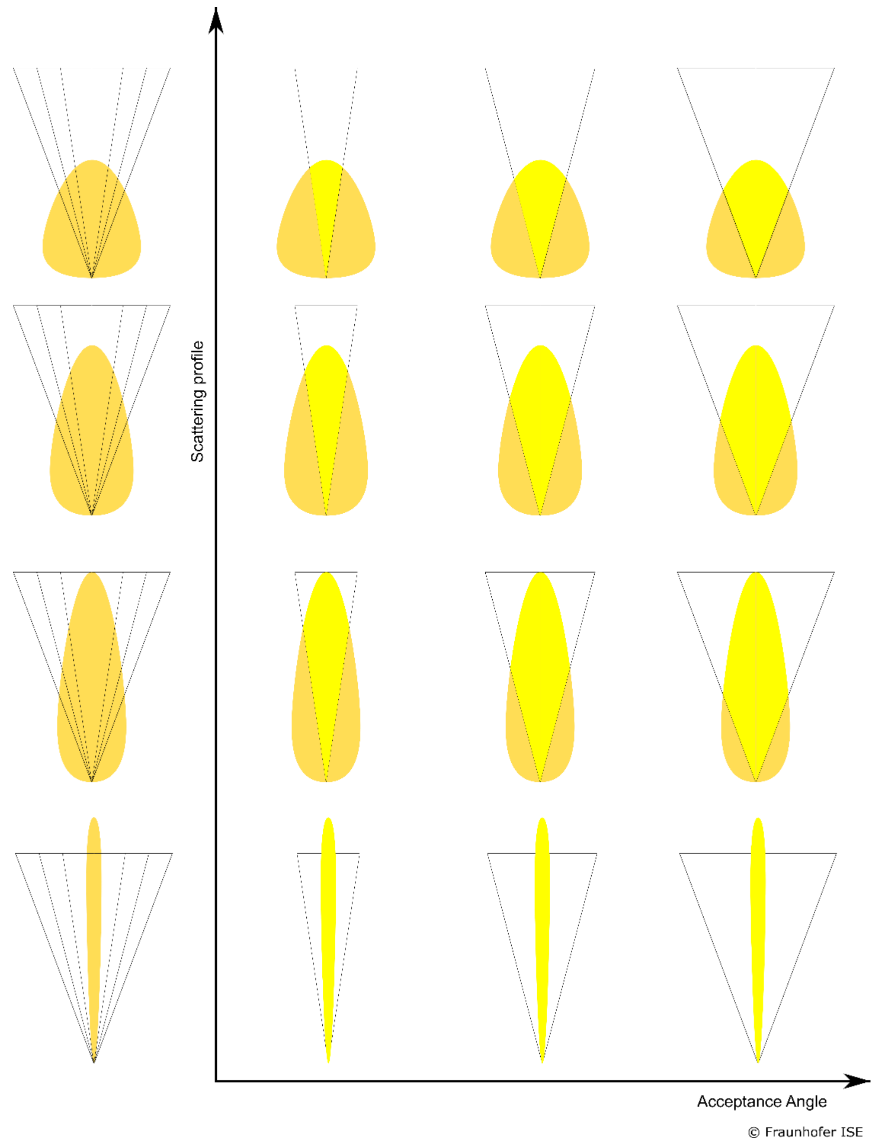


Figure 4: Qualitative representation of the effect of the widening of the reflected beam due to different soiling levels on instruments with different acceptance angles

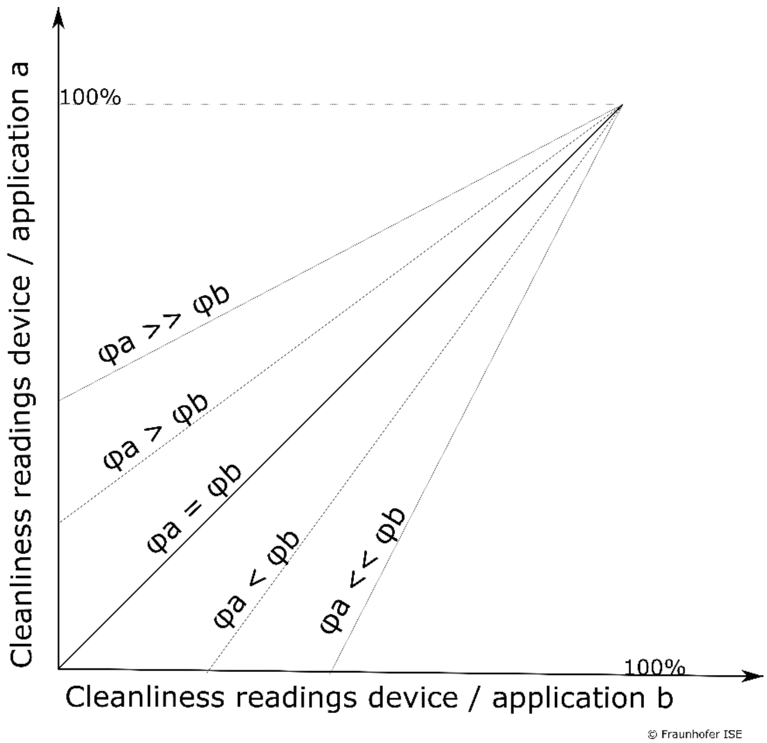


Figure 5: Qualitative representation of the transfer function for cleanliness between two devices / applications a and b with the acceptance angles φa and φb for one specific dust type.

Propositions have been made to develop transfer functions to adapt reflectometer readings to actual solar field optical properties. Due to the complexity of the task, no standardized method exists that accounts simultaneously for the effects of soiling on a spectral and optical level. An example procedure for setting the transfer function is given in the following:

1) Determine mean values or ranges of interest for both, θ_i and φ for the specific plant layout.

2) Expose flat mirror samples (about 5x5 cm^2, as many as practical) at the site of the plant for a period long enough to achieve a soiling level at which usually the mirror cleaning operation is planned; some of these specimens shall be collected at different periods of time, in order to soil with different amount or levels of the same soiling.

3) All these specimens shall be measured with the available portable reflectometer, and also a clean reference sample to determine the cleanliness of the specimens, noting the results with their corresponding λ, θ_i and φ for the specific equipment.

4) All specimens shall be sent to a specialized laboratory, equipped with a spectrophotometer such as [20], suitable to measure spectral near-specular reflectance at the typical (mean) θ_i and φ of the plant (option a), or in the range relevant for the plant (option b), as explained below:

a) If the end user is just interested in knowing the solar near-specular reflectance at the typical mean θ_i and φ of the plant, a unique transfer function will be given by the correlation of such solar near-specular reflectance measured with the lab spectrophotometer versus the readings obtained with the portable instrument (in step 3), each being related to the reflectance value of the clean sample.

b) If the end user requires detailed knowledge of the cleanliness behavior versus θ_i and φ, the near-specular reflectance of a cleaned mirror specimen should be modeled by EMA4SM [21] (which allows to predict the solar near-specular reflectance at any incidence angle), while the experimental spectra of soiled specimens obtained at the specialized laboratory should be analyzed on the basis of the Soiling Model developed in the framework of the SolarPACES project "Soiling Measurements of Solar Reflectors"[8] and the *SoilMirMod* software developed by ENEA and now made public as open-source software [22].

In any case, the plot of the solar-weighted near-specular reflectance (or the solar-weighted cleanliness, depending on the goal) versus the cleanliness readings obtained with the chosen reflectometer allows the end user to set his/her own transfer function.

In Annex A, part of the above procedure is used to predict the expected readings for several different portable reflectometers at the linear Fresnel plant of Brawley, California, where the naturally soiled specimens "California 8D" and "10D" were exposed. Annex A aims to explain the importance of establishing a custom transfer function to correlate the readings obtained in field with the chosen portable reflectometer, with the value of the solar reflectance calculated at the angle of incidence and acceptance of interest for the specific CSP plant. Please note that the transfer function is totally customized; as matter of fact it holds only for: i) a given CSP plant, ii) a specific type of soiling and iii) the chosen portable reflectometer.

6.2 Calibration coupons

Another option currently under investigation is the use of a set of calibration coupons with different known reflectance values for a large number of θ_i and φ, and solar spectra. These coupons should be durable and show similar beam dispersion behavior to naturally soiled reflectors. They should cover most of the range of dispersion characteristics occurring in natural dusts and thus consist of a larger number of samples. If such coupons can be produced and standardized they could replace the exposure and measurement of samples to natural soiling as proposed in steps 2 and 4 above. The rest of the procedure would be the same as in section 6.1.

Although the calibration using these coupons is not specific for the type of dust present at a site, it might increase measurement accuracy on a larger range of reflectance values than the standard calibration procedure for a single, clean and highly-specular calibration sample can provide only for clean mirrors. Further research and development is needed to fully develop this approach.

7 Outlook and needs for further research

Measurement of soiled reflectors in solar fields with high accuracy is a highly challenging task. Although very valuable knowledge has been gained during this project, within the working group of the authors, more open questions than answers have been identified that need to be addressed in future research tasks. This document is to be understood as a living document and interested readers are invited to contribute to this guideline in the future.

The most important steps in future research are listed in the following:

- Increase knowledge on optical behavior of different dust types and derive a typical range for parameters such as absorption, scattering, diffraction and spectral effects
- Develop optical models (such as transfer functions) to adapt limited reflectance measurements taken with available portable devices to solar near-specular reflectance for the specific plant layout and dust types
- Develop a calibration procedure for reflectometers using sets of fully characterized coupons covering a broad range of reflectance values with optical behavior similar to that of many natural dust types.

ANNEX A: Expected readings by portable reflectometers, compared with solar near-specular reflectance of interest for Brawley linear Fresnel plant

As discussed previously, it is impossible to outline a general correlation between single λ measurements, measured in field with a portable reflectometer, and the solar near-specular reflectance of interest for the considered plant. Instead, a custom transfer function must be defined in each case with the recommended procedure described in section 6.1. This annex aims to clarify, with a practical example, the fundamental concepts of such procedure. The case study is the Brawley plant, a linear Fresnel plant site in California, USA, where we have considered θ_i = 10° and φ = 12.3 mrad as the mean angles of interest (step 1 of the procedure). The naturally soiled specimens "California 8D" and "10D" were exposed in this CSP plant (step 2 of the procedure).

With respect to the step 3 of the procedure, the measurement with the portable equipment couldn't be directly accomplished because such instruments were not available at the moment of finishing this document. Therefore, S2R measurements of the soiled specimens were used to set up the soiling model by fitting its parameters. With the model, the expected readings of different reflectometers (listed in Table A1) were simulated. The solar near-specular reflectance of interest for the specific parameters of the plant were also simulated with the model (step 4.a of the procedure). Finally, the ratio between these is calculated to establish the necessary correction of the reflectometer readings.

Reflectometer	λ (nm)	φ (mrad)
D&S 15R-USB	660	3.5, 7.5, 12.5, 23.0
pFlex	470, 525, 625	67
Condor	435, 525, 650, 780, 940, 1050	145

Table A1 Characteristics of some commercial reflectometers.

Near-specular spectral reflectance of the California specimens 8D and 10D were measured with the S2R setup at θ_i = 10° and φ = {9.8, 12.3, 14.8, 20.2, 35.9, 107.4} mrad.

The normalized decrements (see the footnote at page 8) were analyzed with the *SoilMirMod* software [22] based on the Soiling Model [8] represented by the equation

$$f(\lambda, \theta, A, S, \sigma, D, k, L, E, B) =$$
$$\left\{1 - A - S\left[1 - \exp\left(-\left(\frac{4\pi\sigma}{\lambda}\right)^2\right)\right] - \frac{D}{1+\exp(-2K(\lambda - L))}\right\}\frac{1}{\cos^B\theta}$$

where: A is the experimental normalized absorptance decrement obtained by the hemispherical spectra measured with the specimen in clean and soiled status; the parameters listed in Table A2 are not depending on the acceptance angle and have the same value for the two specimens with the same kind of soiling; Scattering (S) and Diffraction (D) magnitude-parameters have a more complex behavior shown in Figure A1.

Parameter	California 8D & 10D
σ (nm)	69
1/K (nm)	340
L (nm)	900
B	0.35

Table A2 Common best fit parameters for the California specimens.

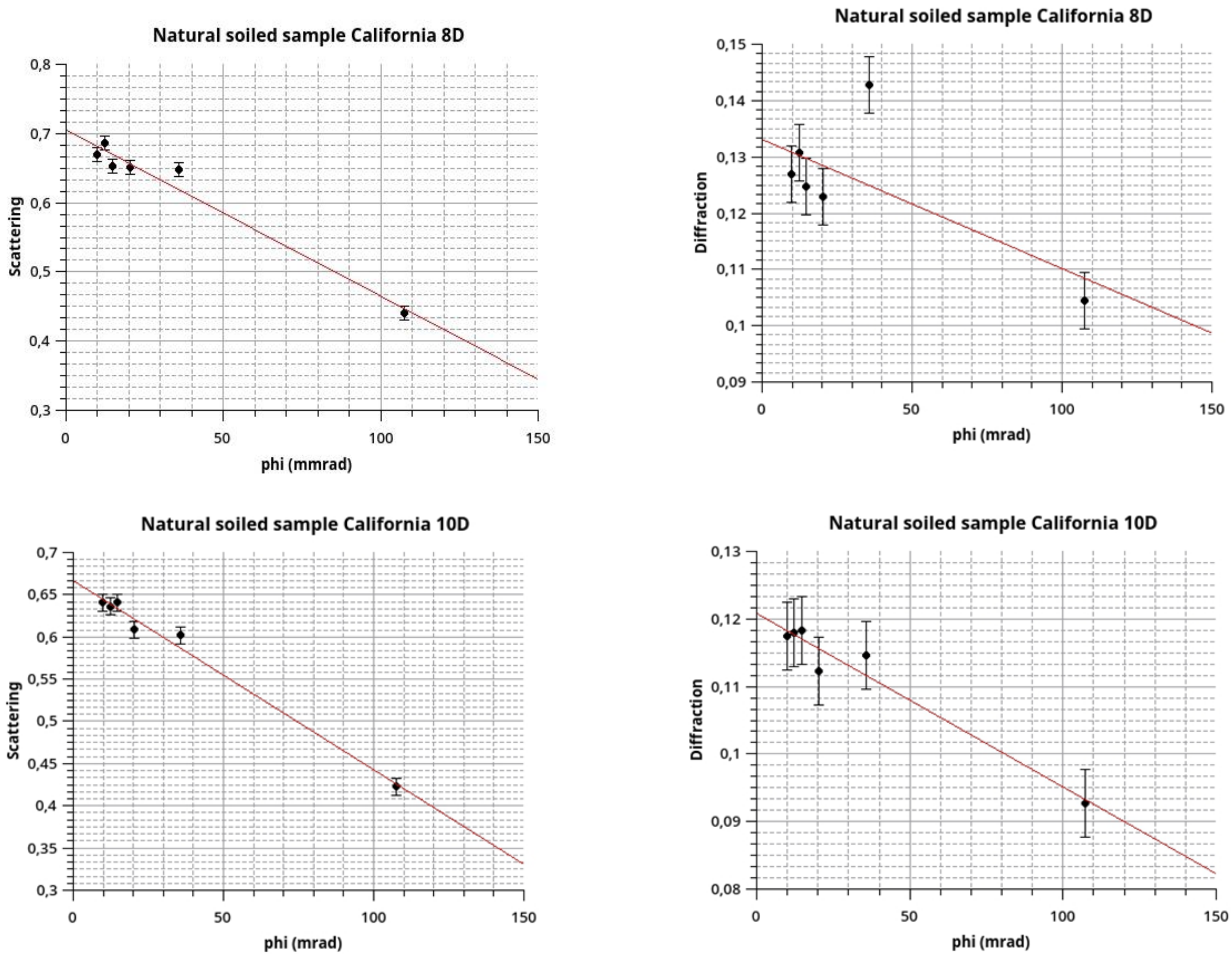


Figure A1 On the left (and on the right), plots of the the *SoilMirMod* best fit software Scattering (and Diffraction) coefficients versus the acceptance angle of the S2R measurements for both specimens.

From the above plots, one can infer Scattering and Diffraction coefficients at the acceptance angle of the pFlex and the Condor reflectometers (see Table A3); for the D&S 15R-USB reflectometer, let us assume we can use the closest value, i.e. φ = 12.3 mrad.

	pFlex: φ = 67 mrad	Condor: φ = 145 mrad
S_8D	0.54	0.36
D_8D	0.12	0.10
S_10D	0.52	0.34
D_10D	0.10	0.08

Table A3 Scattering and Diffraction coefficients for the *SoilMirMod* best fit software, expected at the acceptance angles of pFlex and Condor reflectometers.

On the basis of the parameters shown in Table A3, the simulated spectra shown in Figure A2 were computed; from those, one can get the expected cleanliness readings for the considered reflectometers (considering cleanliness = 1 + normalized_decrement). Those values are reported in Tables A4 and A5 demonstrating the strong dependence of the cleanliness value on type and configuration of the portable reflectometer.

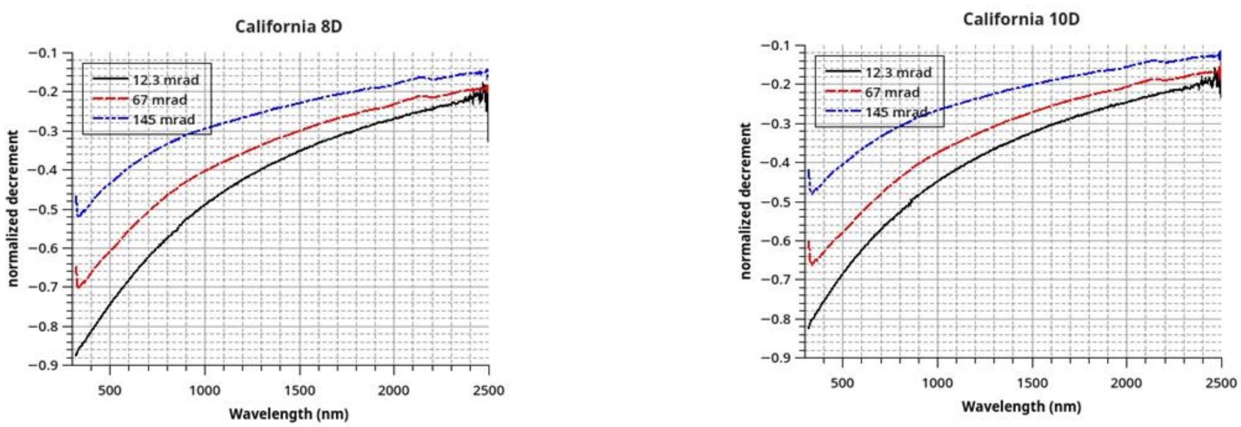


Figure A2 Experimental (12.3 mrad, black continuous line) and computed (67 and 145 mrad, red and blue dashed lines respectively) normalized decrement for California 8D (left plot) and California 10D (right plot) specimens. The computed spectra were obtained with the coefficients from Tables B2 and B3.

Reflectometer	λ (nm)	φ (mrad)	Cleanliness
D&S	660	12.5	0.356
pFlex	470	67	0.378
	525		0.406
	625		0.459
Condor	435	145	0.539
	525		0.577
	650		0.625
	780		0.662
	940		0.697
	1050		0.713

Table A4 Expected values of cleanliness for the California 8D specimen with three different reflectometers.

Reflectometer	λ (nm)	φ (mrad)	Cleanliness
D&S	660	12.5	0.414
pFlex	470	67	0.411
	525		0.435
	625		0.487
Condor	435	145	0.569
	525		0.607
	650		0.652
	780		0.688
	940		0.725
	1050		0.742

Table A5 Expected values of cleanliness for the California 10D specimen with three different reflectometers.

Finally, Figure A3 shows the mean ratio between the in-field cleanliness readings from the three considered reflectometers (simulated values presented in Tables A4 and A5), and the solar near-specular reflectance of interest for the Brawley plant, for the studied specimens (which is 0.520 for the 8D specimen and 0.560 for the 10D specimen).

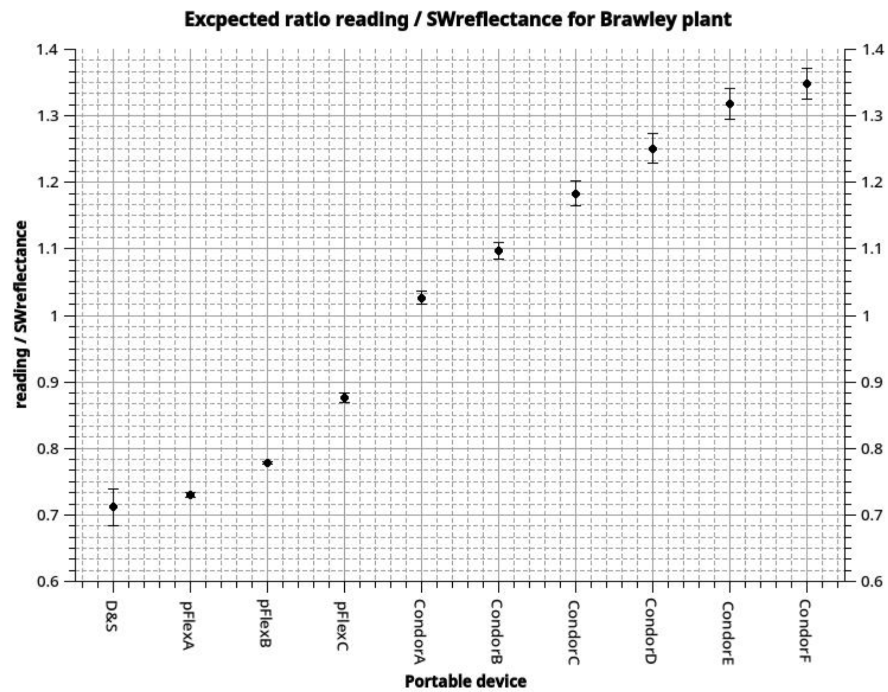


Figure A3 Expected ratio between in-field cleanliness readings and the solar near-specular reflectance of interest for Brawley plant.

On the basis of Figure A3, one can correct the readings obtained with one of the considered portable devices for evaluating the solar near-specular reflectance of interest for this plant; more precisely, the inverse of the plotted value is the custom transfer function for the considered devices at the Brawley plant.

Of course, for a different plant typology or for a different site, one has to repeat the procedure detailed here to update Figure A3 to the new situation.

Bibliography

[1] A. Fernández-García, F. Sutter, M. Montecchi, F. Sallaberry, A. Heimsath, C. Heras, E. Le Baron, A. Soum-Glaude. PARAMETERS AND METHOD TO EVALUATE THE REFLECTANCE PROPERTIES OF REFLECTOR MATERIALS FOR CONCENTRATING SOLAR POWER TECHNOLOGY. SolarPACES Guideline Version 3.1, April 2020. Almería.

[2] A. Fernández-García, F. Wolferststetter, M. Montecchi, G. Zhu, G. Bern, C. Pelayo, C. et al. Portable reflectometers to measure soiled reflectors in solar fields. SolarPACES Soiling Project. Deliverable 1. June 2021. Almería.

[3] F. Sutter, M. Montecchi, H. Von Dahlen, A. Fernández-García, M. Röger. The effect of incidence angle on the reflectance of solar mirrors. Sol Energy Mater Sol Cells. 2018;176:119-133. DOI: 10.1016/j.solmat.2017.11.029.

[4] A. Heimsath, P. Nitz. The effect of soiling on the reflectance of solar reflector materials - Model for prediction of incidence angle dependent reflectance and attenuation due to dust deposition. Sol Energy Mater Sol Cells. 2019;195:258-268. DOI: 10.1016/j.solmat.2019.03.015.

[5] M. Montecchi, F. Sutter, A. Fernández-García, A. Heimsath, F. Torres, C. Pelayo. Enhanced Equivalent Model Algorithm for Solar Mirrors. SolarPACES 2019. AIP Conference Proceedings 2020;2303:100005. DOI: 10.1063/5.0028768.

[6] C. Sansom, H. Almond, P. King, E. Endaya, S. Bouaichaoui. Airborne sand and dust soiling of solar collecting mirrors. SolarPACES 2016. AIP Conference Proceedings 2017;1850(1):130011. DOI: 10.1063/1.4984505.

[7] E.P. Roth, A.J. Anaya. The effect of natural soiling and cleaning on the size distribution of particles deposited on glass mirrors. Journal of Solar Energy Engineering 1980;102:248-256.

[8] M. Montecchi, F. Sutter. Soiling model for spectral reflectance of solar mirrors. Solar Energy. Under revision.

[9] Sansom, C., A. Fernández-García, P. King, F. Sutter, and A. Garcia Segura. Reflectometer Comparison for Assessment of Back-Silvered Glass Solar Mirrors. Sol Energy 2017;155: 496-505. DOI: 10.1016/j.solener.2017.06.053.

[10] A. Fernández-García, F. Sutter, L. Martínez-Arcos, C. Sansom, F. Wolfertstetter, C. Delord. Equipment and methods for measuring reflectance of concentrating solar reflector materials. Solar Energy Materials and Solar Cells 2017;167:28-52. DOI: 10.1016/j.solmat.2017.03.036.

[11] F. Wolfertstetter, K. Pottler, A. Alami-Merrouni, A. Mezrhab, R. Pitz-Paal. A Novel Method for Automatic Real-Time Monitoring of Mirror Soiling Rates. SolarPACES 2012, 11.-14. Sep. 2012, Marrakesch, Morocco.

[12] Javed, W., & Guo, B. (2022). Laboratory calibration of a light scattering soiling sensor. Solar Energy, 236, 569-575.

[13] R. Calvo, D. Argüelles-Arizcun, A. Fernández-García. Innovative low-cost sensor for continuous soiling monitoring of CSP plants. 24th SolarPACES International Conference on Concentrating Solar Power and Chemical Energy Systems. Casablanca, Morocco. October 2-5, 2018.

[14] F. Wolfertstetter, R. Fonk, C. Prahl, M. Röger, S. Wilbert, J. Fernández-Reche. Airborne soiling measurements of entire solar fields with Qfly. SolarPACES 2019. AIP Conference Proceedings 2020; 2303(1):100008. DOI: 10.1063/5.0028968.

[15] J. Coventry, C.A. Asselineau, E. Salahat, M.A. Raman, R. Mahony. A robotic vision system for inspection of soiling at CSP plants. SolarPACES 2019. AIP Conference Proceedings 2020;2303(1):100001. DOI: 10.1063/5.0029493.

[16] G. Bern, G., Schmidt, T., Celentano, N., Heimsath, A., & Nitz, P. (2018, November). Freda-an automated field reflectance and degradation assessment system for central receiver systems. SolarPACES 2017. AIP Conference Proceedings 2018;2033(1):230001. DOI: 10.1063/1.5067229.

[17] 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 2014;99: 185-202. DOI: 10.1016/j.solener.2013.11.009.

[18] J. Fernández-Reche. Reflectance measurement in solar tower heliostats fields. Solar Energy 2006;80(7):779-786. DOI: 10.1016/j.solener.2005.06.006.

[19] A.M. Bonanos, A.C. Montenon, M.J. Blanco. Estimation of mean field reflectance in CST applications. Solar Energy 2020;208:1031-1038. DOI: 10.1016/j.solener.2020.08.073.

[20] Sutter, Florian, et al. "Spectral characterization of specular reflectance of solar mirrors." *Solar Energy Materials and Solar Cells* 145 (2016): 248-254.

[21] M. Montecchi, F. Sutter, A. Fernández-García, A Heimsath, F. Torres, C. Pelayo. Enhanced Equivalent Model Algorithm for Solar Mirrors. SolarPACES 2019. AIP Conference Proceedings 2020;2303:100005. DOI: https://doi.org/10.1063/5.0028768.

[22] The open-source software SoilMirMod is freely downloadable at https://github.com/mmonty1960/SoilMirMod

