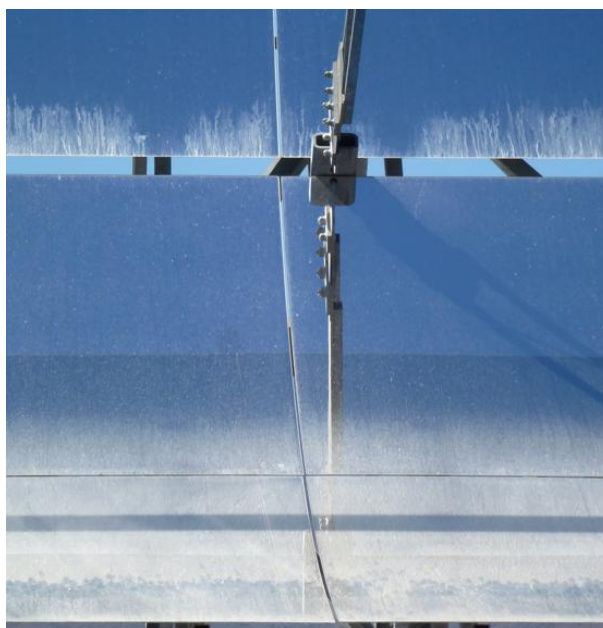




Guidelines

Recommendations for reflectance measurements on soiled solar mirrors



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Abstract

This document is 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 Thermal (CST) solar fields to quantify the impact of soiling on the reflectance (referred to as “soiling measurements” from now on). The methods and requirements for solar field soiling measurements differ from reflector characterization for clean mirrors.

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 johannes.wette@psa.es 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 in 2019 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 were investigated. In 2023, a project under the same framework was set up to continue the work in this field and to update and improve the significance of the guideline document to the current version.

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 mirror panel.
3. Soiling types and the resulting optical properties of a soiling layer are 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 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 CST 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]. CST 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 [6].

Due to the lack of commercially available instrumentation to adequately characterize all soiling and reflectance properties of a reflector material in solar fields (see [1] and [2] for more details and references), a straightforward measurement procedure that obtains highly accurate results valid for all soiling types and densities is not available at the current state of the art. Only in some cases with a high number of measurements per collector, interpolations and approximations are accurate. A general, step-by-step measurement procedure does not meet the various needs of all solar field operation strategies and research goals. This guideline focuses on illustrating the complexity and the challenges for a complete soiling characterization and gives an overview and recommendations on possible measurement solutions, including state-of-the-art reflectometer measurements and alternative methods under development. This includes recommendations for instrument selection, properties and considerations for calibration procedures and suggestions for practical simplifications where applicable. The parameters and values that are of interest for soiling characterization are described. Since the soiling distribution and type are very site dependent and no ideal measurement instrument is on the market, 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:

CST	Concentrated solar thermal
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 (half-)angle
$\rho_{\lambda,h}(\lambda, \theta_i, h)$	Spectral hemispherical reflectance for the wavelength λ of the incident radiation
$\rho_{s,h}([\lambda_a, \lambda_b], \theta_i, h)$	Solar-weighted hemispherical reflectance in the range between λ_a and λ_b
$\rho_{\lambda,\varphi}(\lambda, \theta_i, \varphi)$	Specular reflectance
$\rho_{s,\varphi}([\lambda_a, \lambda_b], \theta_i, \varphi)$	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
	$\xi = \rho_{\text{soiled}} / \rho_{\text{clean}}$
$\dot{\xi}$	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 $\lambda=[320, 2500]$ nm,
- with diverging incidence radiation $\varphi_s \sim 4.7$ mrad,
- at the incidence angle θ_i defined as standard condition or 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 specialized laboratories, making it certainly unpractical in solar fields. On the other hand, as discussed in the following, given the chosen soiling measurement method and the characteristic features of the plant of interest, one has to set a transfer function to obtain the solar near-specular reflectance from the method's results. The transfer function can be obtained by comparing the reading of the chosen method with the experimental value of the solar near-specular-reflectance for a number of differently soiled specimens. Nowadays, the state-of-the-art method for soiling measurements in the field is the use of portable reflectometers. In addition, a variety of alternative methods are under development addressing issues such as autonomy, covered area, and spatial resolution.

In order to make the solar near-specular reflectance measurement more accessible, a simplified laboratory set-up based as much as possible on commercial components has been investigated and details of setting it up and how to perform measurements can be found in [5]. It should be noted that the availability of a standard instrument for properly measuring the near-specular reflectance would also greatly simplify the characterization of clean mirrors with unperfect specularity, like thin solar mirrors offered as optical coatings or thin foils to be, respectively, deposited on or laminated to a rigid substrate which gives the desired shape to the facet.

Typically, a portable reflectometer allows to measure a 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 one main purpose of this document is to outline a reliable procedure for setting a *transfer function* between in-field readings 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 soiling measurement;
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 methods (state-of-the-art and alternative) is:

- Soiling data for specified λ , θ_i and φ
- Low external stray light, ambient temperature dependence or other environmental influences on measurement results
- Practical (re-)calibration procedure
- Uncertainty of data available and adequate uncertainty in relation to the application of the data
- No risk to human health during measurements

Additional requirements for the state-of-the-art handheld reflectometers are:

- “Near-normal” measurement, θ_i up to 20°
- φ up to 150 mrad

- Valid instrument calibration following manufacturer manual, mostly using a clean reference mirror sample
- High battery autonomy, compact, light, easy to handle, easy to use
- Positioning adjustment possibility or sufficient tolerance for mirror curvature and thickness

This list has been adapted to the findings from interviews with solar operators that were 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 measurement positions/solar collector elements/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 conditions in-field. As an example, for parabolic trough modules, a good option is to measure 5 points for each one of the outermost mirror panels; that can be easily reached by a person on the ground without the need of a ladder, scaffolding, or platform. The topic will be discussed 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 dispersed 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 publication of this guideline, experimental data on naturally soiled specimens coming from CST power plant locations are scarce. The relevant particle size distributions are thought to be mostly in the regime, where the particle size is in the same order of magnitude as the solar spectrum and forward scattering dominates there (see [7] and [8]). CST 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.

End-users typically wish to correlate reflectance measurements obtained in field with their chosen method with the solar near-specular reflectance degradation induced by soiling, which affects the optical efficiency of their CST plants. To achieve this goal, a model was presented in [9].

This guideline summarizes 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 decrements¹ and scattering behave differently from site to site, depending on the kind of soiling and its optical characteristics.
- At present, in-field measurements can be achieved e.g. by portable reflectometers operating at just one or few λ , and at one or few θ_i and φ .
- The solar yield of CST 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, exact 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

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

measurements and modelling. This correlation depends on the specific type of soiling that can be site-dependent and subject to temporal changes.

Reflectometer readings taken with different ϕ 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 [10] and Figure 1 as example. 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. The state of the art and alternative methods are presented in chapter 4. For the state-of-the-art reflectometer measurements in chapter 5 and 6 recommendations are given on measurement point selection and the development of transfer functions to the significant solar near-specular reflectance.

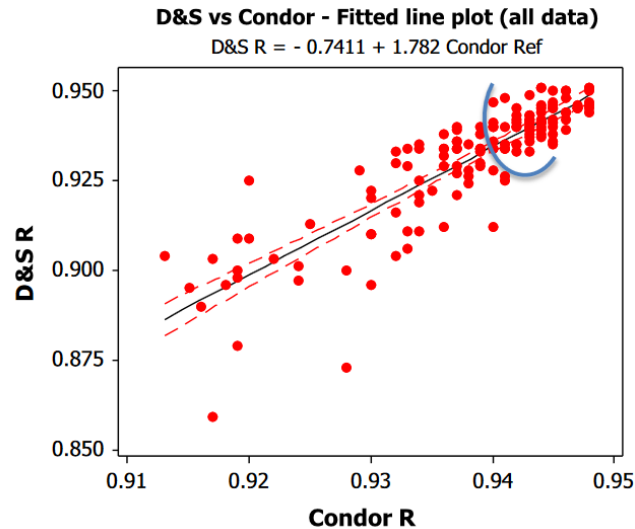


Figure 1. Direct comparison of reflectance measurements on soiled samples with two different reflectometers, D&S and Condor [10].

4 Measurement devices

This section presents the most commonly used instruments for solar field applications with exemplary pros and cons, starting with the state-of-the-art portable reflectometers. 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 complex and costly in solar field operations.

The list below will also introduce measurement principles for soiling evaluation that are not yet employed as a standard tool in commercial 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 analyses on many of the reflectance measurement devices are given in [11] and [12].

4.1 Handheld reflectometers (state-of-the-art)

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 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
- The devices are designed to be transported easily making them suitable to measure several locations of solar field.
- Instantaneous measurements (quick measurement process once correctly positioned)

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 actual surface coverage of each measurement is very small, a few mm², and several measurements are necessary to cover enough surface and obtain a useable reading for a given mirror in case of heterogeneous soiling.
- 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 Alternative devices and methods

Besides the handheld reflectometers several other methods to determine soiling have been derived. Many of those are still under development and not fully commercially available. These methods are presented in the following grouped in four categories:

1. Upgraded reflectometers
2. Camera-based methods
3. Other alternative measurement sensors
4. Multi-Parameters indirect methods

A detailed review of the methods presented in this section along with specific references to the literature is available in [12].

4.2.1 Upgraded Reflectometers

Methods in this category address some of the limitations of hand-held reflectometers by upgrading the devices and/or their packaging. Two examples of such devices are available. The Tracking Cleanliness Sensor (TraCS) quantifies soiling reflectance loss in conditions similar to field operation on a mirror sample. The device consists

of two tracking pyrheliometers and a sample mirror. One pyrheliometer measures the direct normal irradiance (DNI), while the other measures the DNI reflected by the sample mirror. Comparing both pyrheliometer readings, the reflectance of the sample mirror for its soiling condition can be derived. This design addresses several issues associated to handheld reflectometers:

- Representative incidence and acceptance angles for solar radiation
- Automated operation of the device leads to much higher time resolution
- The radiation used for the measurement is solar radiation (measurement is only possible during sunlight)

Another example of such systems is the AVUS device that incorporates a reflectometer within a protective housing facing a flap with a reference sample on the inner side, capable of opening to measure an exposed sample at the same position. By performing measurements on the protected and exposed samples regularly, it provides soiling estimations at regular intervals. The AVUS is specifically designed for remote locations leveraging a rain detector to automatically avoid altering measurement data. This design addresses several issues associated to handheld reflectometers:

- Extended automation for longer operations at remote sites without operator
- Automated operation of the device for higher temporal resolution
- Exposure inclination angle is variable allowing to estimate the impact of this parameter on soiling deposition

Both devices are stationary and lose the advantage of transportable devices, but they provide significantly better temporal resolution and improved measurements quality and representativeness, in different aspects. As with traditional handheld reflectometers, careful calibration and regular maintenance remains important to obtain good quality data.

4.2.2 Camera-based Methods

Camera-based methods enable data acquisition on mirrors from a distance. Cameras can be mounted on unmanned aerial vehicles (UAVs), making their transport, access to different parts of a solar field and automation much easier than for other devices. Cameras can reach high spatial resolutions and/or large coverage of a facility in each measurement. Camera-based methods have recently been the focus of numerous groups of researchers, with some already tested in field with heliostats, parabolic trough and linear Fresnel collectors. The fundamental principle of measurement followed by most groups is:

- Acquire an image containing a soiled mirror
- Isolate the mirror in the image via image processing
- Discriminate between the signal that corresponds to light scattered by the soiling and a background signal
- Calibrate the soiling signal to an absolute soiling ratio based on a reference

It is important to note that this conceptually simple task is very sensitive to many complex optical and signal processing aspects. First, the image needs to be of suitable quality and as close as possible to radiometric data. Correspondingly, the use of JPEG compression with commercial cameras brings along the need for further image processing as internal camera software performs many operations on such images to make them more aesthetically pleasing to the human eye, that have to be removed to make the data usable as radiometric information. RAW image formats can be used to avoid these additional steps, but they also require careful processing to remove artifacts. Second, soiling causes anisotropic reflections and scattering, causing the detected signal to depend on the viewing angle of the camera, an aspect that can significantly influence some methods. Third, the spectral distribution of the soiling reflections/scattering depends on the soiling composition and differs heavily depending on location and time of the year. This aspect should be considered in the development of soiling detection and

estimation methods. Finally, reported camera-based methods often rely on a reference image with no soiling and/or reference soiling measurement, generally performed with a handheld reflectometer. As such, camera-based methods cannot overcome the angular incidence, acceptance angle and spectral range limitations inherent to the calibrating device. Calibration is important as quantifying the scattering in a given direction is not enough by itself to retrieve the full soiling loss (absorption, angular variation, spectral effects, etc.).

The advantages of camera-based methods are:

- The measurement area covered is very high, allowing to measure large parts of the collector field
- Very high spatial resolution.
- Fast data acquisition leads to good temporal resolution.
- Low labor requirement, full automation is possible with commercial UAV solutions allowing also for frequent measurements.

Disadvantages:

- Reflection/scattering measurement: calibration is sensitive to dust spectral and directional properties
- Accuracy of measurements depends on complex model and calibration methods.

4.2.3 Alternative measurement sensors

Alternative devices have also been developed to measure the amount of light absorbed and/or scattered by soiling directly. In this category, 3 main sub-categories are found:

4.2.3.1 Paired PV devices

Pairs of PV devices such as reference cells or modules can be used to derive the soiling loss for PV systems. One of the devices must be clean while the soiling losses are measured on the second. The soiling ratio is derived by comparing their power or short circuit current. Typically, a pair of two devices of the same model is used, but it is also possible to compare different PV devices (e.g. reference cells and PV modules). These sensors require sunny conditions, and one of the two devices must be cleaned frequently. Incomplete cleaning can occur, if automatic cleaning methods are used, and can lead to measurement errors. The most important limitation of such devices with respect to CST soiling is that for PV soiling losses are much lower than for CST. This is because radiation that is scattered towards the PV cells is in great parts used by PV, but forward scattering outside of the small acceptance angle causes losses in CST. Also, the soiling layer has to be passed twice in CST, but only once in PV. Hence, a conversion of the PV to CST soiling losses is required. This conversion brings along significant additional uncertainty. The soiling loss measured by a PV device pair corresponds to the specific illumination condition, which is mainly defined by the solar incidence angle for sunny conditions. This incidence angle also affects the conversion to the specific CST technology.

Advantages of this kind of sensor are:

- High temporal resolution.
- Low cost.
- No operator needed to collect data in the field

However, they also present some disadvantages:

- Lack of optical representativeness: the soiling estimation does not reflect how soiling impacts CST performance. A conversion to CST soiling losses is required that increases the uncertainty.
- Cleaning is required for suitable operations; it can be automated, but requires monitoring.

- Low spatial resolution for stationary devices.
- Measurement only in sunny conditions (i.e. during operations) and sensitive to global irradiance levels (direct and diffuse).

4.2.3.2 LED-based sensors & microscopy

An artificial light source illuminates a soiled sample and a photodiode captures the back-scattered and/or the transmitted signal. This light source is usually a Light Emitting Diode (LED) for low energy, cost and durability considerations. The photodiode signal is altered depending on particle deposition, and interpreted to estimate soiling. An on-site calibration should be performed, with most devices using e.g. two photovoltaic (PV) cells that are included in the sensor under the same cover glass. The soiling ratio is the ratio of electrical power delivered by the integrated PV module when soiled, compared to the calibrated clean module electrical output, and this information is used for the calibration of the photodiode signal. A commercial device, originally developed for PV applications, is the DustIQ. Such devices are economical and require low or nearly no maintenance, but their measurement principles are not directly deriving CST soiling, in particular because of acceptance and incidence angles. If they are calibrated with a PV device pair the additional uncertainty due to the conversion of PV to CST soiling losses has to be considered, too. The representativeness of soiling measurements from LED-based sensors designed for CST is not currently established.

One commercial soiling sensor (MARS), also developed for PV applications, is based on microscopy instead of a simple photodiode. The device consists of a microscope system that focuses upwards on a glass panel upon which dust is collected. The grayscale intensity level of pixels corresponding to soiling particles deposited on the top surface of the glass is compared to the intensity level of black and white reference marks on the bottom surface of the glass, to estimate overall soiling level. The method is said to be insensitive to optical properties of the dust and can rely on natural sunlight and/or illumination from below by LEDs through a diffuser, similar to the previous paragraph. Other microscopy approaches have been developed for R&D purposes, but do not target monitoring of soiling for field operations.

All the devices in this category share the following advantages:

- Low maintenance.
- Good temporal resolution.

However, significant limitations for CST applications are:

- Lack of optical representativeness: the soiling estimation does not particularly reflect how soiling impacts CST performance. A conversion to CST soiling losses is required that increases the uncertainty.
- Stationary sensors offer low spatial resolution and surface coverage unless many sensors are used.
- Regular cleaning of part of the sensor tends to be required for good quality reference data.

4.2.3.3 Glossmeters

Glossmeters are used e.g. in the paint industry to characterize the “shininess” of paint and coating finishes. Glossmeters adopt a range of measurement setups (acceptance angles) depending on the expected/measured gloss value, in gloss units (GU), a measure of the intensity of the near-specular peak. According to the ASTM D523 – ISO 2813 standards, the gloss range (0-100) is based on a standard black glass with a refraction index of 1.567, with no specific constraints on the light source, usually a low-drift white LED. As such, these measurements are limited by the refraction index of the reference surface, which is not representative of CST mirror, and spectral distribution of the LED used. In addition, the use of acceptance angles far from those relevant in CST could lead to unrepresentative results, although this issue is shared with some portable reflectometers. Glossmeters have recommended measuring ranges and settings, depending on standards, which create more uncertainties when

comparing gloss measurements with reflectometer measurements. Glossmeters are used in commercial plants though and lately studies have shown similar behavior to specific CST reflectometers [25].

Advantages of glossmeters:

- A lower cost reflectometer-like device: robust and transportable with a reflecting optics arrangement.

Disadvantages:

- Glossmeters were not originally developed for this application, and they do not offer a direct quantitative soiling loss estimation.
- All limitations of handheld reflectometers apply; however, calibration may be less sensitive here.

4.2.3.4 Laser-scanners

The use of Terrestrial/3D Laser Scanning for spatial assessment of soiling was recently proposed. This method repurposes commercial 3D scanners: instead of measuring distances, the laser signal is further analyzed to interpret the backscatter intensity, providing valuable information on soiling. The measured feature is not the specular reflection, as observed with a reflectometer, but rather the backscatter, which needs to be well understood to assess the soiling impact on specular reflections. Hence, a conversion of the signal is needed, that increases the uncertainty as in the case of LED based methods. While the application of this method has been demonstrated in a small heliostat field, it is not yet commercially available.

This new technique offers potential advantages:

- Fast characterization of large areas of solar fields with high resolution.
- Side benefit of detailed shape characterization of heliostat facets.
- A technique that can operate day and night.

Potential disadvantages include:

- Cost of the equipment. The benefits in spatial and temporal resolution may outweigh the costs.
- Need to transport the scanner between locations.
- Translation of measurements into absolute soiling loss is complex, and signal to soiling loss conversion increases uncertainty.

4.2.3 Multi-Parameter indirect methods

Multi-parameter indirect methods use atmospheric variables, such as atmospheric particulate matter mass concentration, wind speed/direction, rainfall, air temperature and barometric pressure to train models, often using AI and/or machine learning, to output reflectance/power loss. The models need to be calibrated, using handheld reflectometers or other sensors. At the core of these methods is access to system-relevant meteorological data. The data can be provided by weather model data or nearby meteorological stations but, as soiling is quite sensitive to local variations of weather patterns and atmospheric dust concentrations, local meteorological stations are at times installed to feed data into the model. As these methods are calibrated with other devices, they are limited by the accuracy of these devices. In addition, the input data uncertainty and their spatial representativeness must be considered. Meteorological stations are stationary devices with point measurements. One grid point of weather model data often represents dozens or hundreds of square kilometers. This imposes constraints on the representativity of such data for full solar fields in both cases. Finally, as these methods rely on correlations from multiple sensors, estimating their accuracy is very complex. Reported works highlight the key role of atmospheric particle counters to yield accurate predictions.

The main advantages of such methods are:

- Good temporal resolution
- Leverages on some existing equipment at solar fields
- Option to forecast soiling or to estimate soiling using weather model data without instrumentation on site

The disadvantages are:

- Accuracy is low and hard to quantify

5 Measurement point selection and solar field averaging methods

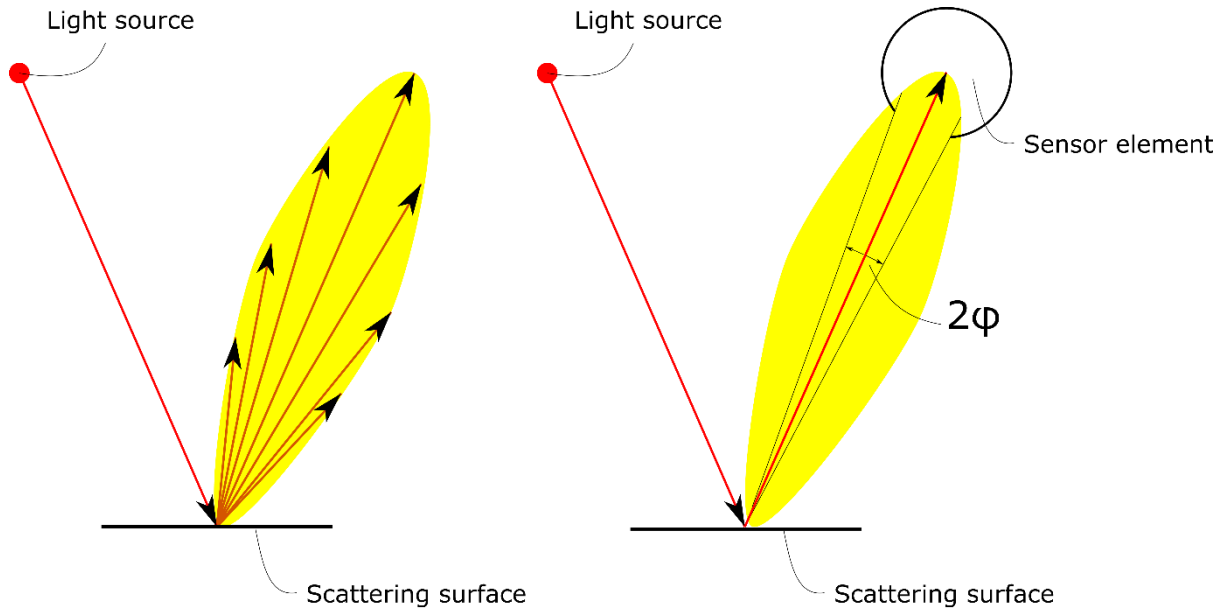
The current version of the solar reflectance measurement guideline [1] specifies a procedure to determine average reflectance values for small samples, in the range of $12 \times 12 \text{ cm}^2$, in laboratory condition. Five measurement points are recommended to determine a representative average reflectance. 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 $500,000 \text{ m}^2$ (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 [19], [20] and [21]. In general, the number and distribution of the measurement points depend 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. The number of mirror panels and measurement locations per panel will vary according to the needs of the site and the specific soiling, which may determine how heterogeneous the reflectance is.

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

The optical properties of natural soiling particles that are found at CST plants differ 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 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 reflectometer. 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 2.



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Figure 2: 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 3 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 3 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 4) can be developed to:

- compare measurements between different measurement devices
- understand and interpret reflectance measurements for the assessment of cleanliness and
- 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.

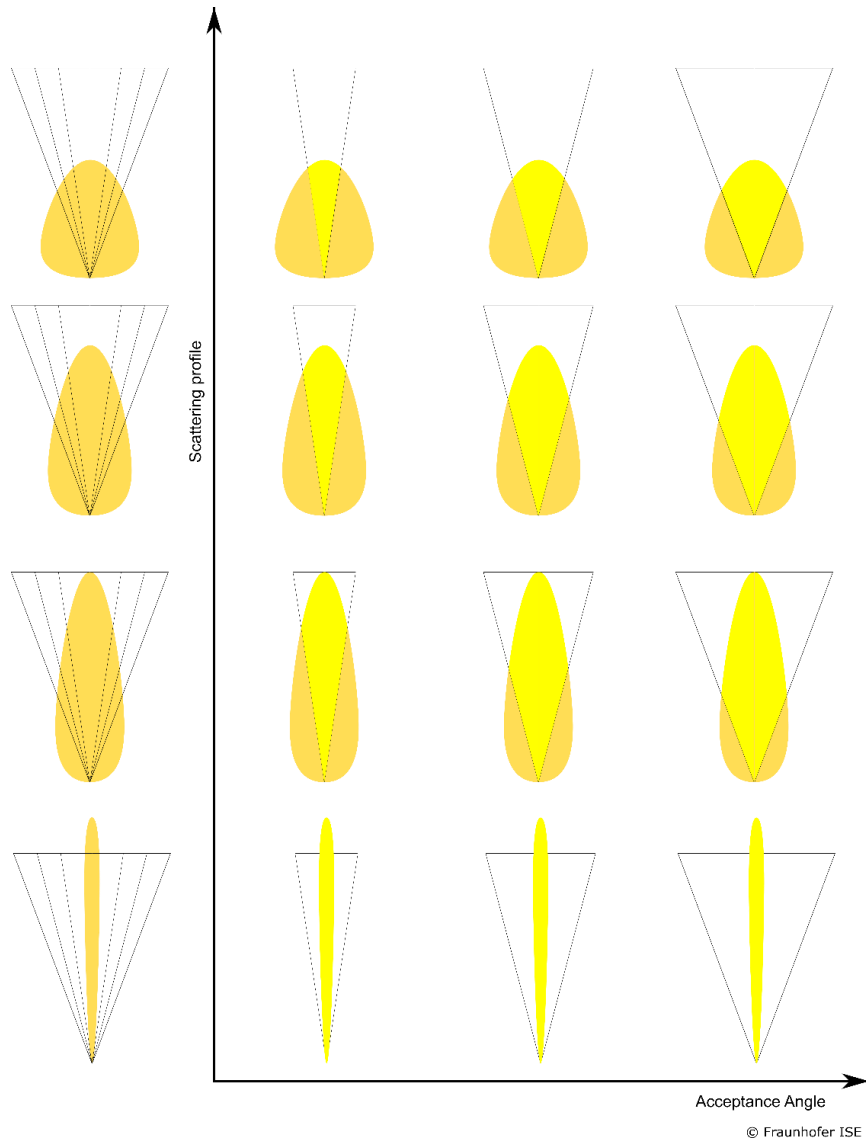


Figure 3: Qualitative representation of the effect of the widening of the reflected beam due to different soiling levels on instruments with different acceptance angles

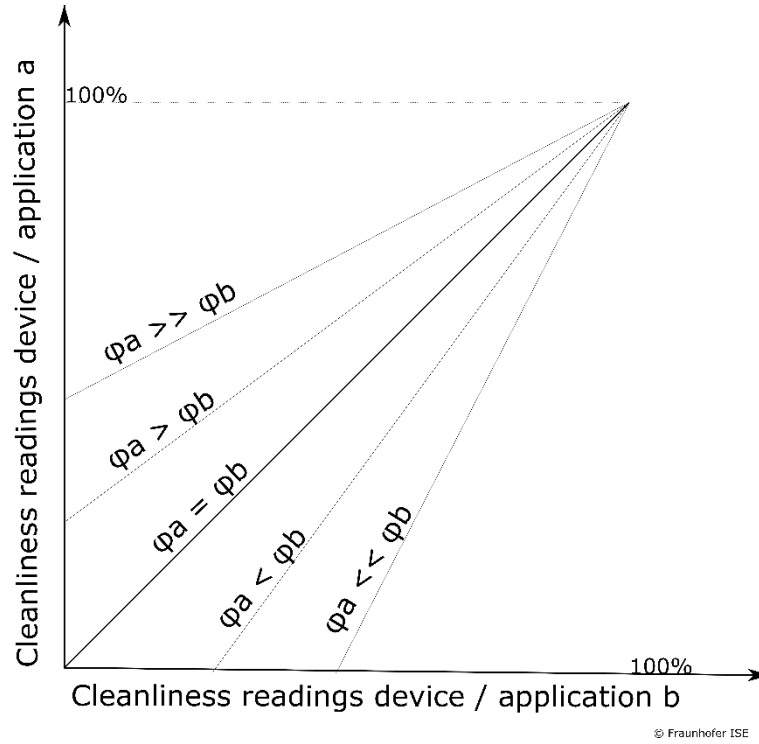


Figure 4: Qualitative representation of the transfer function for cleanliness between two devices / applications a and b with the acceptance angles φ_a and φ_b for one specific soiling type.

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 cm², 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 or different inclination angles, 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 [22], 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 [23] (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”[9] and the *SoilMirMod* software developed by ENEA and now made public as open-source software [24].

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 CST plant. Please note that the transfer function is totally customized; as matter of fact, it holds only for: i) a given CST plant, ii) a specific type of soiling and iii) the chosen portable reflectometer.

Annex B presents a practical example of a campaign to determine the transfer functions for one specific site (the Plataforma Solar de Almería) and all main commercial reflectometers. The methodology and the determined parameters of the transfer functions are given.

7 Outlook and needs for further research

Measurement of soiled reflectors in solar fields with high accuracy is a highly challenging task. Several methods exist and the advantages and disadvantages have been analysed and presented. These characteristics, including in particular the uncertainty, should be considered when selecting a soiling measurement option. Depending on the application and boundary conditions, different methods are the most suitable.

Although valuable knowledge has been gained during this project, within the working group of the authors, open questions 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 soiling 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 devices to solar near-specular reflectance for the specific plant layout and dust types
- Develop a calibration procedure for soiling measurement systems using sets of fully characterized coupons covering a broad range of reflectance values with optical behavior similar to that of many natural soiling 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 $\theta_i = 10^\circ$ and $\varphi = 12.3$ mrad as the mean angles of interest (step 1 of the procedure in section 6.1). The naturally soiled specimens “California 8D” and “10D” were exposed in this CST plant (step 2 of the procedure).

With respect to 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 was 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 [22] at $\theta_i = 10^\circ$ and $\varphi = \{9.8, 12.3, 14.8, 20.2, 35.9, 107.4\}$ 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.

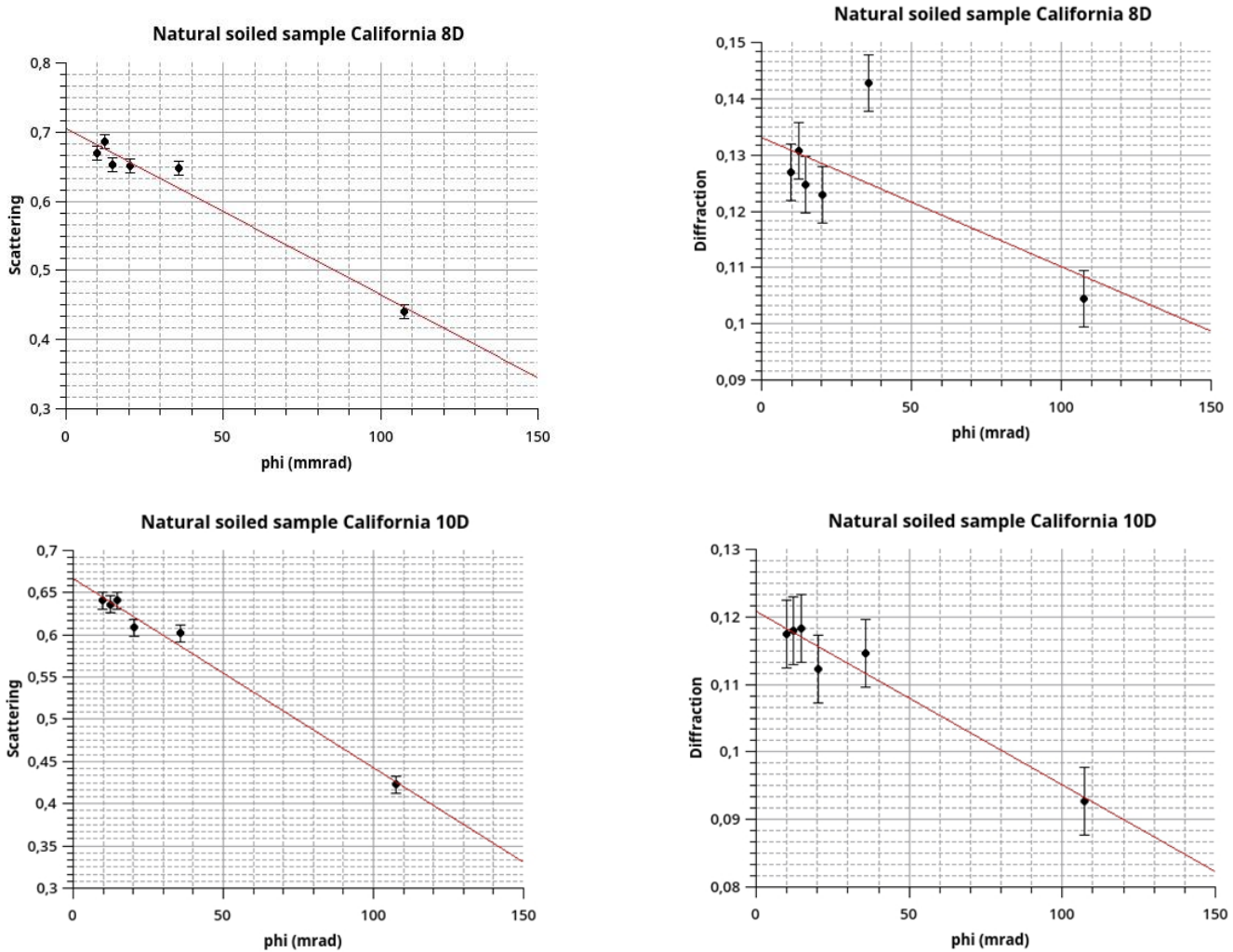


Figure A1 On the left (and on the right), plots of the *SoilMirMod* best fit software Scattering (and Diffraction) coefficients versus the acceptance angle of the S2R measurements for both specimens.

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. $\phi = 12.3$ mrad.

	pFlex: $\phi = 67$ mrad	Condor: $\phi = 145$ 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 = $1 + \text{normalized_decrement}$). 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.

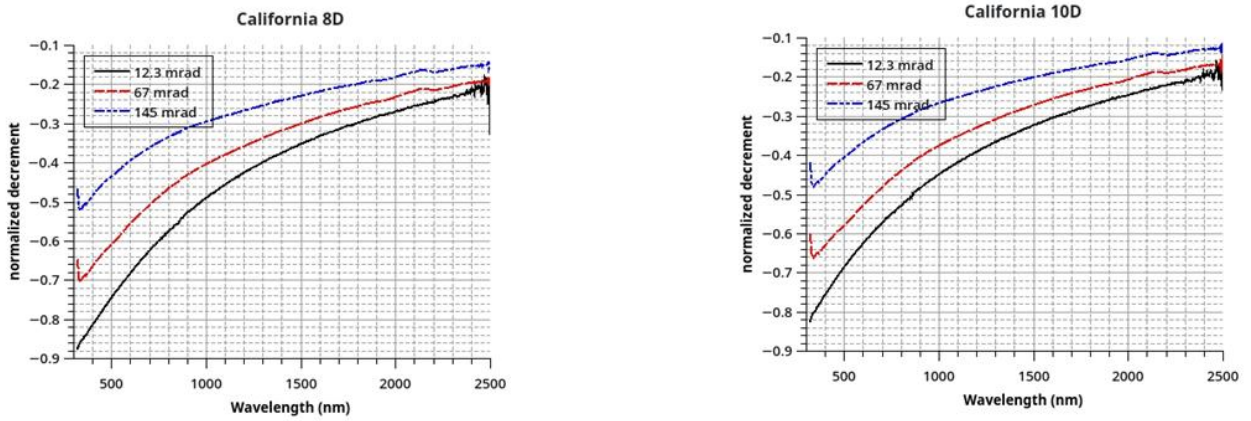


Figure A2 Experimental (12.3 mrad, black continuous line) and computed (67 and 145 mrad, red and blue dashed lines respectively) normalized decrement for California 8D (left plot) and California 10D (right plot) specimens. The computed spectra were obtained with the coefficients from Tables B2 and B3.

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).

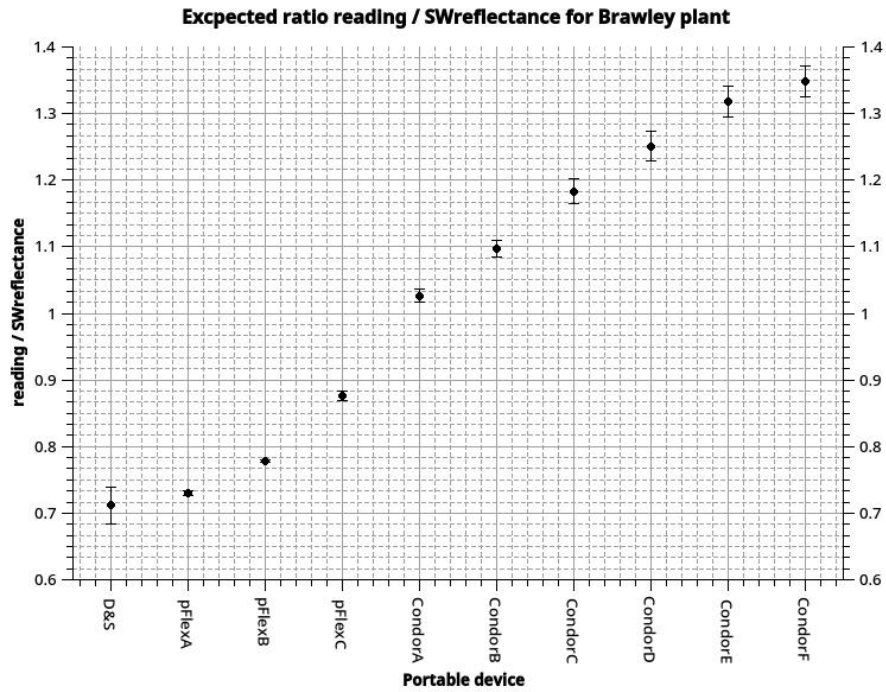


Figure A3 Expected ratio between in-field cleanliness readings and the solar near-specular reflectance of interest for Brawley plant.

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.

ANNEX B: Example development of transfer functions for main commercial reflectometers to solar near-specular reflectance at the PSA (Spain)

The purpose of this annex is to give an example of the determination process for the transfer functions between reflectometer readings and the solar specular reflectance, as proposed in section 6.1. The correlation parameters are presented together with the methodology to derive them for a site of interest. Here, the CIEMAT-PSA is chosen as a representative CST site and approximate representative values for incidence and acceptance angle are selected and seven of the main commercially important reflectometer models are included in the example. More detailed information on the methodology and results can be found in [25].

Methodology:

Measurements to determine the correlations are performed on naturally soiled reflector samples. A set of 21 samples of a commercial silvered-glass reflectometer material of 4 mm thickness in its pristine state are exposed for a period of around two weeks at the PSA site on a specifically designed exposure rack. Samples are tilted at different angles to the horizontal to provoke soiling of different levels of intensity to cover a wide range of cleanliness for the measurements. Alternatively, to create different soiling levels, samples can be collected after varying outdoor exposure durations at a fixed inclination angle.

The following seven commercial reflectometers, known to be used in CST plants for regular measurements, are used in this example: D&S-15R USB, D&S-15R RGB, pFlex, Condor, Konica Minolta CM700d, SOC-410 Solar, ZGM1130. For the devices which have the option to measure at various wavelengths, the value closer to 660 nm is used, to be comparable to the only available value of the D&S-15R USB device. For these devices, alternative wavelengths or the solar-weighted values can be used to determine the correlation coefficients.

Here, to determine the target value of the solar-weighted specular reflectance, the S2R [22] is used, measuring in the wavelength range of $\lambda = [320, 2500]$ nm, with an incidence angle of $\Theta_i = 30^\circ$ and an acceptance angle of $\varphi = 12.5$ mrad assumed as representative for the PSA case in [3]. To calculate the solar-weighted reflectance, the spectral data is weighted with the solar irradiance standard spectrum IEC 60904 [1].

Per sample, one measurement per equipment was performed and it is assured that approximately the same spot is selected for all devices to avoid uncertainties due to heterogeneous soiling patterns. Alternatively, several spots per facet could be selected and direct comparisons made or average values per sample used. Measurements on a clean sample of the same material are performed as well as a reference and to be able to calculate the cleanliness by dividing the reflectance in the soiled state by the value in the clean state. Values determined with the S2R are referred to as reflectance of interest (*ROI*) and cleanliness of interest (*COI*) from now on, as they represent the target values of this study.

Values for reflectance and cleanliness are then plotted for all reflectometers versus the respective *ROI/COI* value. Then, a linear approximation is performed with a least-square fit and the correlation coefficients (gradient *a* and y-axis cut *b*) are determined which directly allow the transformation of the reflectometer values. The ROI is determined according to:

$$ROI = a \rho_{\text{reflectometer}} + b \quad 1)$$

The COI is calculated according to:

$$COI = a \xi_{\text{reflectometer}} + b \quad 2)$$

All combinations of ROI/COI and $\rho_{\text{reflectometer}}/\xi_{\text{reflectometer}}$ have their specific parameters a and b .

Results

In Figure B1 the cleanliness data is displayed for all samples and reflectometers together with the linear approximations of all data sets. The higher the distance from the 1-1-diagonal the higher the differences to the COI values. All reflectometers show an excellent linear correlation to the COI values with coefficients of determination close to 1 ($R^2 > 0.985$). Two groups of behavior are detected in the data: three reflectometers show very similar values to COI due to similar acceptance angles; the rest of the reflectometers shows higher values than COI due to an overestimation of the cleanliness including more scattered light in the measurement than realistic caused by higher acceptance angles.

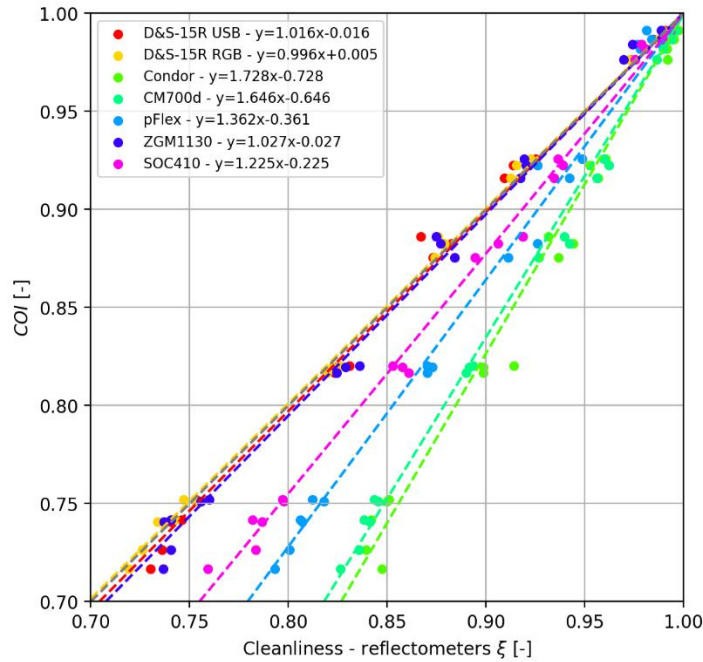


Figure B1: COI over ξ for all samples and reflectometers.

Table B1 displays the determined parameters for the linear correlations. These parameters allow to directly convert the reflectometer readings to COI using equation 2. The full dataset including ROI/COI , all incidence angles and reflectometer wavelengths can be found in [25].

Table B1: linear correlation coefficients for all reflectometers included to *COI* (30°, 12.5mrad)

Reflectometer	Wavelength	Linear equation		
	[nm]	a	b	R^2
D&S-15R USB	660	1.016	-0.016	0.996
D&S-15R RGB	650	0.996	0.005	0.998
Condor	650	1.728	-0.728	0.985
pFlex	630	1.362	-0.361	0.991
CM700d	660	1.646	-0.646	0.993
SOC410	620	1.225	-0.225	0.995
ZGM1130	White	1.027	-0.027	0.994

The use of the coefficients presented here for other sites than the PSA is strongly discouraged unless one can prove that the type of soiling at the site of interest is comparable to the one at the PSA.

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