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Cite as: AIP Conference Proceedings **2303**, 100007 (2020); https://doi.org/10.1063/5.0028749
Published Online: 11 December 2020

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Indirect Method to Determine Near-Normal Sun-Conic Reflectance

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Abstract. This paper presents an indirect method to estimate the near-normal sun-conic reflectance of solar mirrors, which is considered to be the relevant parameter to describe the reflectance characteristics of reflectors employed for CSP systems. The indirect method has been validated by direct measurements with the *Spectral Specular Reflectometer* measurement device reported in previous conferences. Good agreement between indirect and direct measurements was found for new and aged mirrors but not for soiled mirrors, where different phenomena seem to occur. The indirect method is thus only applicable for clean mirror surfaces in new and aged condition. The benefit of the indirect method is that it is simple and applicable with commercial equipment, providing a useful tool to determine near-normal sun-conic reflectance for all laboratories which do not own advanced reflectometers.

INTRODUCTION

The dependence of the reflectance, ρ, on wavelength, λ, incidence angle, θ_i, and acceptance angle, φ, has been broadly described in the SolarPACES reflectance guideline and in several research articles [1-4]. In the past years, the experts of the SolarPACES task III group have discussed to add another relevant parameter to the list, which influences the reflectance of a solar mirror: the beam deviation of the incident radiation, φ_i. Thus:

$$\rho = \rho(\lambda,\ \theta_i, \varphi_i, \varphi) \tag{1}$$

Specular reflectance is defined as the reflected energy of parallel light in the specular direction, meaning that φ_i and φ are equal to 0. Specular reflectance is thus a theoretical parameter, which can only be obtained by means of modelling, since the detector of every measurement device has a certain aperture and every light source exhibits a certain beam deviation.

If φ_i = 0 mrad and $\varphi > 0$, we speak of near-specular reflectance (see **FIGURE 1**a). This parameter also needs to be derived by optical models for the above mentioned reason. If φ_i = 4.7 mrad we speak of sun-conic reflectance, since the beam deviation of the incident radiation equals the angle of the sun-disc viewed from the earth at clear sky conditions (see **FIGURE 1**b). Sun-conic reflectance can easily be measured if the divergence of the light beam of the employed reflectometer is set to 4.7 mrad.

The optical model to derive near-specular from sun-conic reflectance is described in [5]. In case the effect of circumsolar radiation (CSR) is of importance ($\varphi_i \neq$ const.), it is advisable to feed the near-specular reflectance along with the varying CRS-values into system performance modeling tools. Otherwise, the sun-conic reflectance is the more appropriate parameter to use. The usage of sun-conic reflectance was first proposed by M. Montecchi in 2016 [6]. Due to the simplicity to determine this parameter by measurement and also due to the fact that it represents the

SolarPACES 2019
AIP Conf. Proc. 2303, 100007-1–100007-8; https://doi.org/10.1063/5.0028749
Published by AIP Publishing. 978-0-7354-4037-1/$30.00

CSP-application in a better way than the near-specular reflectance, it is intended to include sun-conic reflectance as the standard parameter to compare different reflector materials among each other in the next version of the SolarPACES reflectance guideline (v.4).

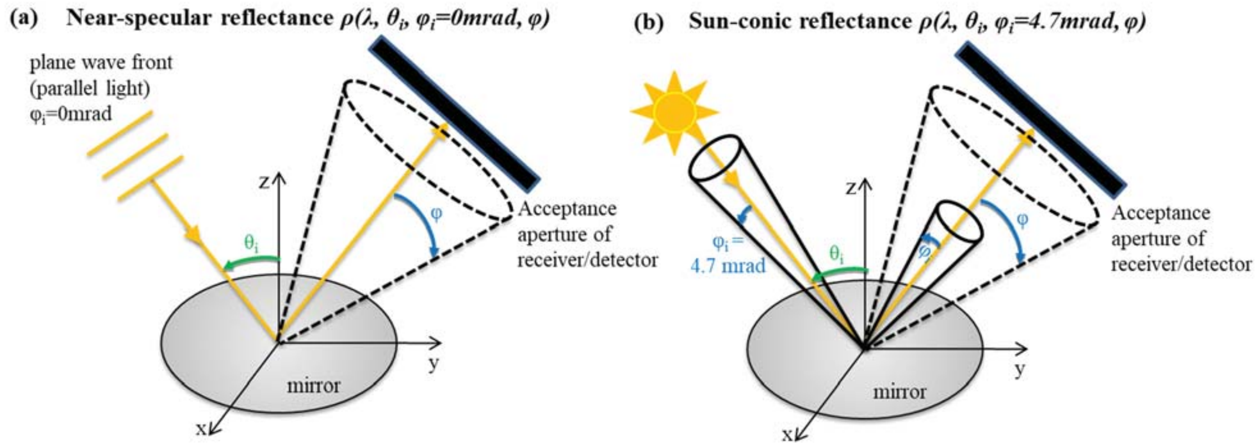


FIGURE 1 Illustration of reflectance parameters. The incidence angle is θ_i, the acceptance angle of the solar receiver or detector is φ. (a) Near-specular reflectance, the beam divergence of the impinging light source is $\varphi_i = 0$ mrad. (b) Sun-conic reflectance, the beam divergence of the solar disc is $\varphi_i = 4.7$ mrad.

Currently, four devices described in [7-10] are capable to determine the sun-conic reflectance spectrum. The measurement devices from DLR/CIEMAT and University of Zaragoza provide direct measurements, scanning the wavelength in 5 nm steps from 320 to 2500 nm and computing the solar-weighted sun-conic value from the obtained reflectance spectrum. The measurement devices from ENEA and Fraunhofer measure at few discrete wavelengths and obtain the solar-weighted value by means of the hemispherical reflectance spectrum and a model to account for optical scattering. In 2018, a Round Robin test was conducted among the four devices and good agreement was obtained for a 4 mm silvered-glass mirror sample. However, off-normal sun-conic reflectance of mirror types with higher scattering (e.g. aluminum or polymer based mirrors) lead to higher deviations. As result of this Round Robin test, the optical model of ENEA was improved and good agreement has been achieved now [5].

Unfortunately, the employed devices to measure sun-conic reflectance are lab-prototypes and they are not commercially available. This work presents a method to determine solar-weighted near-normal sun-conic reflectance using standard equipment and the relation between surface roughness and specular reflectance: the Total Integrated Scatter (TIS) relationship, firstly described by Davies in 1954 [11] and later rearranged to describe the scattering of metallic surfaces [12] is:

$$\frac{\rho(\lambda, \theta_i, \varphi_i, \varphi)}{\rho(\lambda, \theta_i, -, h)} = exp\left[-\left(\frac{4\pi\sigma_\varphi \cos\theta_i}{\lambda}\right)^2\right] \tag{2}$$

where σ_φ denominates the equivalent roughness, a non-physical parameter, which varies with the acceptance angle φ.

Equation 2 has already been applied to model the sun-conic reflectance spectrum of solar mirrors based on hemispherical reflectance measurements [13, 14, 15]. In fact, ENEA is already employing a more sophisticated model, which also describes oblique incidence [5]. This is especially relevant for multi-layered innovative mirror materials since equation 2 is conceived only for a metallic surface in air, but actually the metallic-layer is always protected by a transparent over-layer for any solar mirror. On the other and, silvered-glass mirrors showed to be almost independent from θ_i up to 60°. Therefore, near-normal analysis is expected to be sufficient for silvered-glass mirrors [2, 10]. In this paper, "near-normal" refers to incidence angles $\theta_i \leq 15°$.

The aim of this paper is to validate equation 2 at near-normal incidence for a set of different glass-mirror samples. Once validated, that equation allows one to predict the sun-conic reflectance spectrum from the hemispherical reflectance spectrum, using the equivalent roughness, which is evaluated at one or few wavelengths.

That is what is meant by *simplified indirect method*. It will be presented step by step, so it can be easily applied in different laboratories using commercial measurement equipment.

The simplified indirect method will be validated by comparing the evaluated sun-conic reflectance spectra with the ones directly measured with the Spectral Specular Reflectometer *S2R* [7]; the latter is what is meant by *direct method*. Such a validation of the applicability of the TIS model has not been carried out up to today since the measurement technique to directly measure spectral sun-conic reflectance is only available since 2014. The validation measurements are carried out at two different acceptance angles φ = 7 and 12.5 mrad, the smaller one being representative for solar tower application and the second one simulating parabolic troughs of Eurotrough geometry [2].

MATERIALS AND METHODS

The near-normal sun-conic reflectance of several silvered-glass mirror samples has been determined by means of the direct and indirect method. The obtained results of both methods are compared to determine their agreement.

In total, 27 commercial silvered-glass mirror samples have been analyzed. Five of them were in new state, as received from the factory. 17 samples were aged outdoors during 1 – 3.5 years at different exposure sites in Chile, Morocco and Spain. The new and aged samples were carefully cleaned before measurement to remove eventual dust particles. One additional sample has been measured in soiled state after exposure of 2 week in Tabernas, Spain. Additional 4 samples have been artificially soiled with dust samples from Morocco, India and Israel, in combination with humidity.

Direct Method to Determine Sun-Conic Reflectance

The direct measurement of *ρ([320-2500]nm, 10°, 4.7mrad, {7; 12.5}mrad)* is being carried out by measuring the near-normal sun-conic reflectance spectrum using DLR & CIEMAT's *S2R* [7] (see **FIGURE 2**a). The *S2R* has been validated with a calibrated first-surface silver reference mirror from National Research Council Canada (NRC). The good agreement with other lab-reflectometer prototypes shown in [10] confirmed the accuracy of the instrument.

Once the sun-conic reflectance spectrum is acquired in 5 nm steps, equation 3 is applied to compute the solar-weighted near-normal sun-conic reflectance as described in [1]:

$$\rho(SW, 10°, 4.7mrad, \varphi) = \frac{\sum \rho(\lambda, 10°, 4.7mrad, \varphi) \cdot G_b(\lambda)}{\sum G_b(\lambda)} \;,\; \lambda = 320, 325, \dots, 2500nm. \tag{3}$$

where, $G_b(\lambda)$ represents the spectral direct normal irradiance of the ASTM G173-03 reference spectrum.

Indirect Method to Determine Sun-Conic Reflectance

The indirect determination of *ρ(SW, 10°, 4.7mrad, {7; 12.5}mrad)* is conducted by the following steps:

1) Measuring spectral hemispherical reflectance spectrum *ρ([320-2500]nm, 8°,-, h)* using the *Perkin Elmer Lambda 1050* spectrophotometer with a 150 mm integrating sphere.

2) Measuring monochromatic near-normal sun-conic reflectance *ρ(660nm, 15°, 4.7mrad, {7; 12.5}mrad)* using the *Devices & Services (D&S) 15R-USB* portable specular reflectometer. Note that according to the manufacturer the incident beam divergence of the *D&S* reflectometer is $\varphi_i \approx$ 5mrad. Here it is assumed that φ_i = 4.7 mrad and the *D&S* measurements are denominated as sun-conic reflectance values.

3) Calculating the equivalent roughness σ_φ for φ={7, 12.5} mrad at the single wavelength of λ= 660 nm by rearranging equation 2:

$$\sigma_\varphi = \sqrt{-ln\left(\frac{\rho(\lambda, \theta_i, \varphi_i, \varphi)}{\rho(\lambda, \theta_i, -, h)}\right)} \cdot \frac{\lambda}{4\pi \cos\theta} = \sqrt{-ln\left(\frac{\rho(660nm, 15°, 4.7mrad, \varphi)}{\rho(660nm, 8°, -, h)}\right)} \cdot \frac{660nm}{4\pi \cos 10°} \tag{4}$$

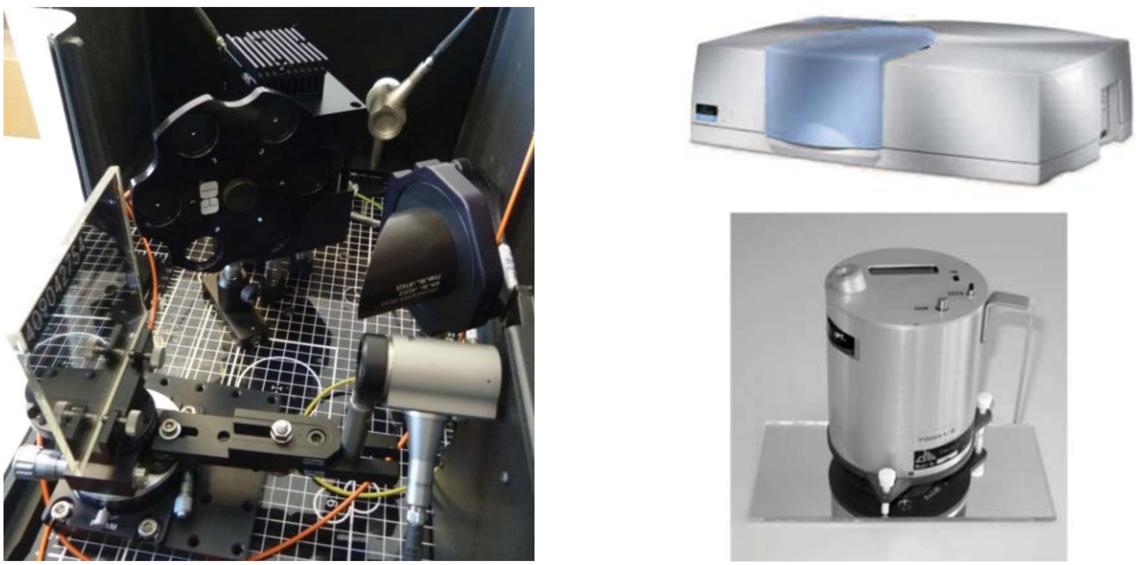
Note that measurements of different θ_i of 8° and 15° are fed into the model and that a fictive θ_i= 10° was used in equation 4. This is admissible since for silvered-glass mirrors the angular dependency is negligible as shown in [2, 10].

4) Calculating spectral sun-conic reflectance for each λ in the range 320 - 2500nm by rearranging equation 2. Spectra are computed for φ={7, 12.5} mrad:

$$\rho(\lambda, 10°, 4.7mrad, \varphi) = \rho(\lambda, 8°, -, h) \cdot exp\left[-\left(\frac{4\pi\ \sigma_{\varphi} \cdot \cos 10°}{\lambda}\right)^2\right] \tag{5}$$

5) Weighting of the sun-conic reflectance spectra $\rho(\lambda, 10°, 4.7mrad, \varphi)$ with the ASTM G173-03 reference spectrum according to equation 3.

The equipment used for the indirect method is shown in **FIGURE 2**b.



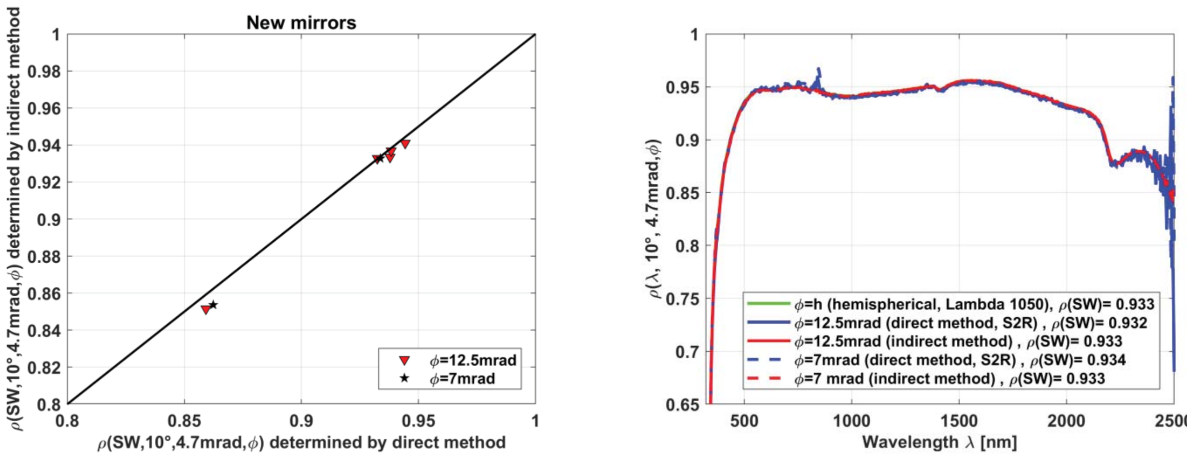
(a) (b)

FIGURE 2. Employed equipment to determine solar-weighted near-normal sun-conic reflectance at φ={7, 12.5} mrad. (a) Spectral Specular Reflectometer *S2R* used for the direct method, (b) *Perkin Elmer Lambda 1050* spectrophotometer and *D&S* 15R-USB reflectometer for the indirect method.

RESULTS

New Mirrors

The obtained solar-weighted near-normal sun-conic reflectance for both, the direct and indirect methods are shown in **FIGURE 3**a for the acceptance angles φ={7, 12.5} mrad. **FIGURE 3**b shows an exemplary comparison of the obtained spectra for the direct and indirect method. For comparison, also the hemispherical reflectance spectrum as obtained from the spectrophotometer measurement with integrating sphere is shown.

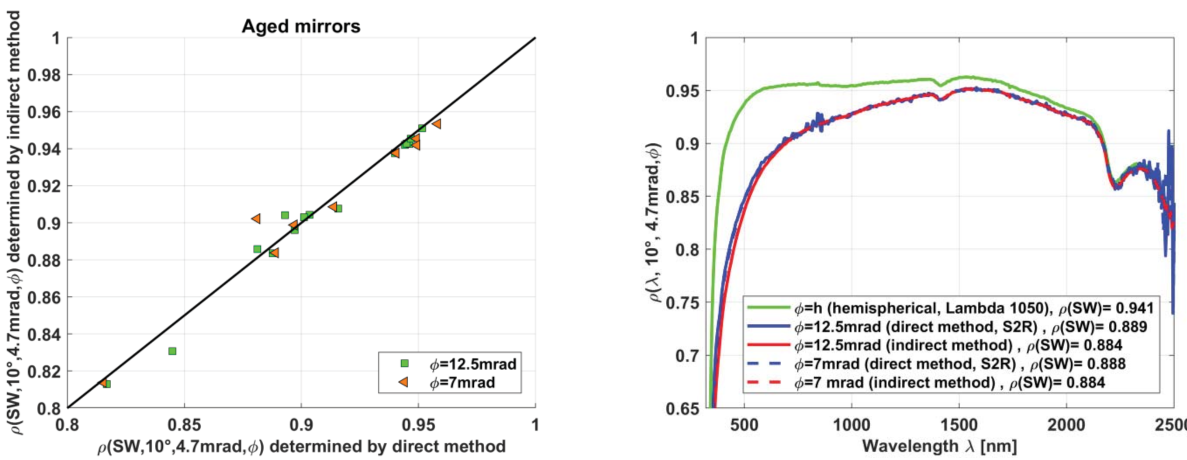


(a) (b)

FIGURE 3. Comparison of the direct and indirect methods for new mirror samples (a) Solar-weighted near-normal sun-conic reflectance at φ={7, 12.5} mrad of 5 new mirror samples. (b) Spectral near-normal sun-conic reflectance at φ={7, 12.5} mrad for one of the 5 measured mirror samples.

Aged Mirrors

The comparison of the direct and indirect methods for the solar-weighted and spectral sun-conic reflectance on outdoor aged mirrors is shown in **FIGURE 4**a and b, respectively. The spectra shown in **FIGURE 4**b correspond to a silvered-glass mirror sample, which was exposed during 24 months in Zagora (Morocco). The sample shows visible erosion damage on the glass surface as result of impacting sand particles during outdoor exposure. Zagora is known to be an aggressive site in terms of sand erosion (e.g. see Figures 10a,c in [16]). As can be noticed, good agreement was found.



(a) (b)

FIGURE 4. Comparison of the direct and indirect methods for outdoor aged mirror samples (a) Solar-weighted near-normal sun-conic reflectance at φ={7, 12.5} mrad of 17 mirror samples. (b) Spectral near-normal sun-conic reflectance at φ={7, 12.5} mrad for one of the 17 measured mirror samples.

Soiled Mirrors

FIGURE 5 shows the comparison of the direct and indirect methods to determine sun-conic reflectance on naturally and artificially soiled mirror samples with 5 different dust types. The spectra shown in **FIGURE 5**b correspond to an artificially soiled silvered-glass mirror sample with dust from Ashalim, Israel.

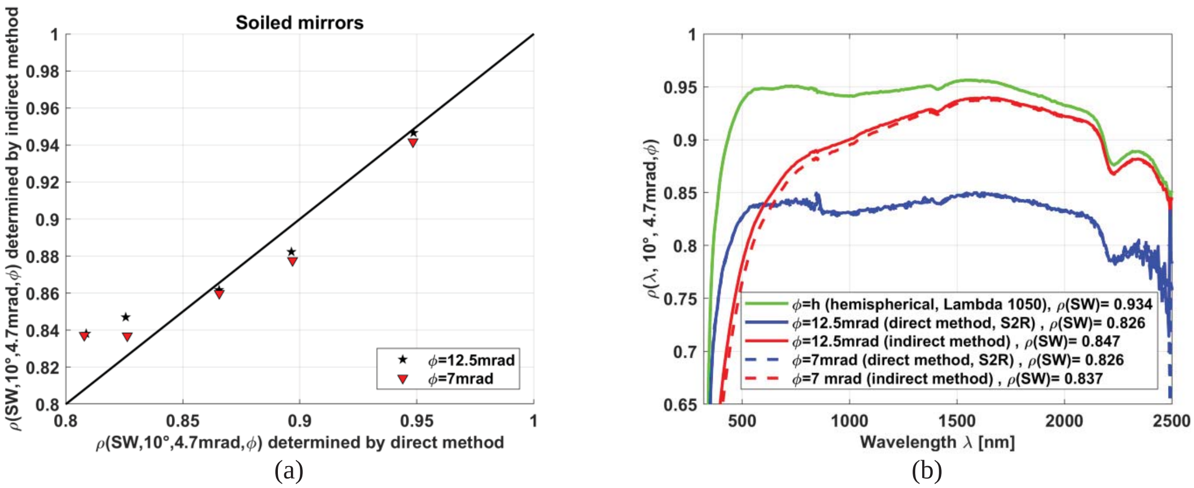


FIGURE 5. Comparison of the direct and indirect methods for soiled mirror samples (a) Solar-weighted near-normal sun-conic reflectance at φ={7, 12.5} mrad of 5 mirror samples. (b) Spectral near-normal sun-conic reflectance at φ={7, 12.5} mrad for one of the 5 measured mirror samples.

DISCUSSION

The analysis of the silvered-glass mirrors in new condition (see **FIGURE 3**) shows that the direct and indirect methods are equivalent: the standard deviation of the difference between both methods is only 0.4%-points (for solar-weighted near-normal sun-conic reflectance at φ= 7 mrad). The results also show that the hemispherical spectrum matches very well with the sun-conic spectra (see **FIGURE 3**b). It is thus sufficient to measure only the hemispherical reflectance spectrum to fully characterize new silvered-glass mirrors, since they are highly specular. This finding has already been published in [17] and was consequently included as simplified analysis in the current version of the SolarPACES reflectance guideline [1]. The conducted measurements in this paper confirm the validity of the simplified analysis from the SolarPACES guideline.

The analysis of the aged mirror samples also shows good agreement between the direct and indirect methods: the standard deviation of the difference between both methods is 0.8%-points (for solar-weighted near-normal sun-conic reflectance at φ= 7 mrad). On the one hand, the hemispherical spectrum showed to be not suited any more to characterize aged mirror samples due to the importance of scattering (see difference between the hemispherical and sun-conic spectra in **FIGURE 4**b). On the other hand, the indirect method proofed to be a useful tool to characterize the behavior of the full spectrum of aged samples based on only a single monochromatic sun-conic input to the model.

The indirect method did not succeed to predict spectral behavior of soiled mirror samples. **FIGURE 5**b shows substantial differences in the curve of the spectrum compared to the spectrum measured via the direct method. The soiling seems to cause the reduction of the reflectance spectrum for the same scale factor for the whole wavelength range. These differences were not only observed for the dust type from Israel, but also for the other 4 dust types analyzed. In addition, the standard deviation of the difference between both methods is 1.8%-points (for solar-weighted near-normal sun-conic reflectance at φ= 7 mrad). It is thus not recommended to use the indirect method to characterize soiled mirrors. Further research and refinement of the optical model is required in order to improve the prediction of the spectral behavior of soiled samples.

CONCLUSION

This paper presented a simple *TIS*-based indirect method to determine near-normal sun-conic reflectance of silvered-glass mirrors. Input parameters for the indirect method are: the near-normal hemispherical reflectance spectrum and the monochromatic near-normal sun-conic reflectance at certain acceptance angles. In this paper, the latter input parameter was measured with the commonly applied *D&S* reflectometer (λ=660 nm, θ_i=15°, φ_i=5 mrad, φ=7 and 12.5mrad). Output of the indirect method is the near-normal sun-conic reflectance spectrum, from which the solar-weighted near-normal sun-conic reflectance can be derived. This latter parameter is the relevant one to describe silvered-glass mirrors for CSP systems.

The indirect method has been validated by means of the Spectral Specular Reflectometer prototype *S2R* developed by DLR and CIEMAT. The indirect method showed to be applicable for new and aged silvered-glass mirror samples. The standard deviation of the difference between both methods was determined to be 0.4%-points for new mirrors and 0.8%-points for aged mirrors (for solar-weighted near-normal sun-conic reflectance at φ= 7 mrad). Conversely, the indirect method failed to predict spectral behavior of soiled silvered-glass mirror samples because the occurring driving phenomenon seems to be different than light scattering. Further research is required to properly describe the optical absorption and scattering effects of soiling particles.

Although the *S2R* is very well suited to fully characterize solar mirrors (also in soiled conditions), measurements are time consuming and the instrument is not commercially available. The indirect method is fast, simple and can be applied with standard commercial measurement equipment. It represents thus an attractive alternative to determine near-normal sun-conic reflectance of clean mirror samples.

NOMENCLATURE

CSP	Concentrated Solar Power
CSR	Circumsolar radiation
D&S	Devices and Services
$Gb(\lambda)$	spectral direct normal irradiance of the ASTM G173-03 reference spectrum, in W·m^{-2}·nm^{-1}.
h	hemispherical
S2R	Spectral Specular Reflectometer developed by DLR/CIEMAT
SW	solar-weighted
TIS	Total integrated scatter
θ_i	incidence angle, in °
λ	wavelength, in nm
$\rho(\lambda,\theta_i,\varphi_i,\varphi)$	reflectance
σ_φ	equivalent roughness
φ	acceptance half-angle of the solar receiver or detector of the measurement instrument, in mrad.
φ_i	beam divergence of sun or the light source in the reflectometer, in mrad. Here, φ_i = 4.7 mrad.

ACKNOWLEDGEMENTS

The research conducting to the results of this paper were funded by SolarPACES within the project "Measuring and modelling near-specular solar reflectance at different incidence angles" and the EU H2020 project RAISELIFE under Grant Agreement 686008.

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