Simplified Analysis of Solar-Weighted Specular Reflectance for Mirrors with High Specularity

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Abstract. The most relevant parameter to properly characterize solar mirrors is the solar-weighted near-specular reflectance. As this parameter cannot be directly measured with off-the-shelf instruments, a simplified procedure to be applied for highly specular solar mirrors is proposed in this paper. The approach, based on two criteria, was experimentally employed to check a wide variety of solar reflector materials. Only those mirrors with known high specularity passed the criteria, indicating that the proposed method is suitable.

INTRODUCTION

In Concentrating Solar Power (CSP) applications, mirrors are used to redirect solar radiation towards receivers where it is absorbed and transferred to a heat transfer medium which increases the enthalpy. This means that mirrors are one of the key components in CSP technologies. There is an urgent demand to standardize the qualification

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procedures of solar mirrors and to provide reliable performance analysis tools, whose results are comparable. Only the shared consensus on parameters and methods allows concurrent industrial products available on the market to be equitably qualified and compared. As a consequence, the solar community was called to work towards consensus of measurement procedures and to promote guidelines to be transformed into national and international standards. The most advance standardization committee in this topic is the Spanish one, AEN/CTN 206/SC 117 "Thermoelectric solar energy systems", which is also linked at international level with the IEC Technical Committee TC 117 "Solar thermal electric plants".

A group of experts in the field of optical mirror reflectance characterization has been working together as members of the SolarPACES Task III to create a reflectance measurement guideline. The SolarPACES project "Development of guidelines for standards for CSP components", was carried out during 2010 and 2011 to collect and prepare recommendations of procedures. This project funded a first reflectance round robin test, which was performed by DLR, CIEMAT and NREL [1]. Conclusions obtained during the experiments were shared with many other institutions and companies and a years-long debate was initiated. As a result, the first guideline for reflectance characterization of solar reflectors, titled "Parameters and method to evaluate the solar reflectance properties of reflector materials for concentrating solar power technology. Version 2.5", was published [2]. This guideline was accepted as official SolarPACES reflectance guideline and published on its website in June 2013.

A second round robin test, named SolarPACES reflectance round robin (SRRR), based on the procedures defined in the proposed guideline was launched at the beginning of 2013, under the coordination of ENEA. This test campaign consisted on evaluating 10 different reflector materials (including both conventional and innovative mirrors) by 6 independent laboratories (CEA, CENER, CIEMAT, DLR, ENEA and ISE Fraunhofer), named "evaluators". According to the results obtained, solar-weighted hemispherical reflectance values, $\rho_h(SW,\theta,h)$, measured by the evaluators with commercial instruments are in good agreement because the differences among the achieved values are within the typical measurement uncertainty of spectrophotometers [3]. This result demonstrated that the protocol included in the SolarPACES reflectance guideline to measure this parameter is appropriate. This protocol is mainly based on measuring the spectral hemispherical reflectance, $\rho_h(\lambda,\theta,h)$, at near-normal incidence (θ = [0, 10]º) with a high quality spectrophotometer equipped with an integrating sphere (with a diameter not lower than 150 mm) in the solar wavelength range (λ = [300, 2500] nm), and then averaging the experimental spectrum with the standard direct solar spectrum of ASTM G173-03 at Air Mass 1.5 [4].

It is widely accepted that the proper parameter to characterize a reflector material for solar concentrating applications is the solar-weighted near-specular reflectance, $\rho_s(SW,\theta,\varphi)$ [5]. In this case, a lack of commercial or validated instrumentation to adequately characterize it, according to the SolarPACES reflectance guideline, was noticed during the SRRR [3]. Some new instruments to properly measure the spectral near-specular reflectance, $\rho_s(\lambda,\theta,\varphi)$, of all type of reflector materials are under development or have been recently developed by some of the institutions, such as the SMQ by ENEA [6, 7], the MIRA by DLR [8, 9] and the VLABS by ISE Fraunhofer [10]. Additional research work to compare the results and to establish the measurement procedure is still required. Until these prototypes (or other similar ones) are validated and commercialized, simplifications and approximations to the procedure by means of commercially available instruments may be suitable in some cases, like high specular solar reflectors. Nevertheless, a consensus about the verifications to prove the specularity of a solar reflector material and the validity of the simplified procedures is still needed.

A new project to update the current SolarPACES reflectance guideline with an adequate simplified method for highly specular solar reflectors and to progress in the protocol to measure $\rho_s(SW,\theta,\varphi)$ of all kind of reflectors with the new advanced instruments was launched by SolarPACES in 2014, under the coordination of CIEMAT. Participating institutions are the SRRR evaluators and the University of Zaragoza (Spain), which is also working on this topic in cooperation with Abengoa Solar [11]. The first workshop, hosted by ISE Fraunhofer, took place in July 2015.

This work presents the results achieved concerning the first goal of this project, that is, a simplified method to analyse near-specular reflectance of highly specular solar mirrors by using commercial instruments. The research work to cover the second goal, a procedure to measure spectral specular reflectance of all types of reflector materials, is still underway.

METHODOLOGY

Current Procedure to Measure Specular Reflectance

The current version of the SolarPACES reflectance guideline specifies (among other characteristics) the following two requirements for instrumentation to measure specular reflectance [2]:

- Measurement at several (at least three) narrow wavelengths, λ, (line width similar to that of hemispherical measurements) appropriately spaced along the solar spectrum or at a specified λ range that accounts for differing wavelength dependent scattering properties.
- Measurement at several (at least three) precise and selectable acceptance apertures, φ, or an innovative approach that covers at least a range of φ from $\varphi \geq 0$ to $\varphi \leq 20$ mrad.

Current Simplified Procedure

This guideline also includes a simplified method to characterize reflectors with good specularity (section A4), the specularity defined as the ratio between specular and hemispherical reflectance [2]. The goal of this simplification is to permit the use of commercial instruments with limited properties and consists of relaxing the procedure abovementioned as follows:

- Measurement of specular reflectance is only necessary at one λ and one φ and one θ. This measurement is important as an indicator in the specularity properties of the material.
- The $\rho_s(SW,\theta,\varphi)$ can be assumed to be equal to the $\rho_h(SW,\theta,h)$, within the uncertainty boundaries.

To decide whether the simplified procedure can be applied to a particular mirror, its specularity must be determined, which implies the calculation of the specular to hemispherical ratio, $\rho_s(\lambda,\theta,\varphi)/\rho_h(\lambda,\theta,h)$, at several λ and φ. Three λ and three φ are proposed, involving nine values of $\rho_s(\lambda,\theta,\varphi)$. The mirror may be considered of good specularity if:

- The ratio is constant over the λ range under analysis for each φ.
- The results for $\rho_s(\lambda,\theta,\varphi)$ do not vary among each other and to $\rho_h(\lambda,\theta,h)$ more than the measurement uncertainty.

Another indicator mentioned for the quality of specularity is given by the angular distribution of the reflected beam, if equipment is available that allows to measure this. For a mirror material with good specularity, this distribution would be similar to a Gaussian distribution with a $\sigma \leq 0.5$ mrad.

New Proposal of Simplified Procedure

The diffuse reflectance, $\rho_d(SW,\theta,\varphi_d)$, is defined as the radiation scattered in the range of angle offsets from the specular direction [2]. Therefore, $\rho_s(SW,\theta,\varphi)$ can be written as in equation (1).

$$\rho_s(SW,\theta,\varphi) = \rho_h(SW,\theta,h) - \rho_d(SW,\theta,\varphi_d) \quad (1)$$

The new simplified approach proposed in this work is based on the following assumption: "when the $\rho_d(SW,\theta,\varphi_d)$ beyond φ = 7.5 mrad is less than the experimental error of the reflectance measurement, it is negligible and the $\rho_s(SW,\theta,\varphi)$ of a solar mirror can be approximated by $\rho_h(SW,\theta,h)$, as indicated in equation (2)".

$$\rho_s(SW,\theta,\varphi) \sim \rho_h(SW,\theta,h) \quad (2)$$

Solar mirrors fulfilling the above condition are named "highly specular solar mirrors", or equivalently "solar mirrors with high specularity". Compared to the previous method, the new one eliminates the measurement of the specular reflectance at one λ and one φ per θ and involves the solely measurement of the $\rho_h(SW,\theta,h)$.

Concerning the way to check if a certain solar mirror can be treated as highly specular, it is considered that the former method described in the previous section is not appropriate because it is based on the comparison of two parameters measured with two different commercial instruments ($\rho_s(\lambda,\theta,\varphi)$ measured with a specular reflectometer and $\rho_h(\lambda,\theta,h)$ measured with a spectrophotometer). These two measurement instruments have different θ (usually, θ = 8° for spectrophotometer and θ = 15° for reflectometer) and different spot sizes (typically, 12.0 x 4.5 mm^2 for spectrophotometer and 10 mm diameter for reflectometers) and might not be measured at exactly the same spot on the reflector.

A solar mirror can be considered as highly specular and, consequently, can be treated with the new simplified procedure, only if the following experimental criterion, composed of two conditions, is passed:

- The difference between the experimental values of near-specular reflectance, $\rho_s(\lambda,\theta,\varphi)$, at a λ in the range λ=[400, 700] nm and $\theta \leq 15º$, measured for $\varphi \approx 7.5$ mrad and $\varphi \approx 25.0$ mrad must be less or equal than the experimental error (typically ±0.003). The two measurements must be accomplished in the same conditions (particularly with the same instrument and in the same point of the mirror surface), except for the φ angle. This test must be repeated at least at three different points of the mirror surface.
- The solar-weighted diffuse reflectance at $\theta \leq 15º$ and $\varphi > 50$ mrad, $\rho_d(SW,\theta \leq 15º,\varphi > 50mrad)$, measured with a high quality spectrophotometer equipped with an integrating sphere with diameter not less than 150 mm and configured to leave the specular beam escaping with a light-trap accessory, must be less or equal than the experimental error (typically ±0.003).

These two conditions were experimentally applied to different solar reflectors to analyze the effectiveness of the criterion in permitting that only reflectors without considerable scattering pass them, demonstrating to be good candidates for being treated with the simplified procedure. The same reflector materials were measured by different institutions with different instruments to check the validity of the proposed simplified method. It is important to emphasize that the reflectors not passing the above criterion might also be suitable candidate reflectors, but they should be characterized with the full procedure.

Materials

Twelve reflector materials were included in the study, covering all type of solar reflectors. Their main characteristics are mentioned in Table 1. The first ten samples correspond to the specimens already used in the SRRR [3]. Except the University of Zaragoza, all institutions participating in this research work were already involved as evaluators in the SRRR. Consequently, a sample kit including these ten samples was still available for measuring at the evaluator's laboratories. An extra sample kit, which was available because one institution finally did not participate as evaluator in the SRRR, was sent by ENEA to the University of Zaragoza. The last two reflector materials (numbers 11 and 12) are silvered-glass mirrors with high-iron glass. They were added to the study because although they are low-quality mirrors, they have been employed in some CSP systems, mainly in heliostats for solar towers.

TABLE 1. Main characteristics of the samples included in the study.

Sample number	Reflecting surface	Reflective material	Characteristics
1	Second	Silver	Low-iron glass 0.5 mm
2	Second	Silver	Low-iron glass 4.0 mm
3	Second	Silver	Low-iron glass 1.6 mm
4	Second	Silver	Low-iron glass 2.0 mm
5	Second	Silver	Low-iron glass 3.0 mm
6	First	Silver	Laminated on Aluminum
7	First	Silver	Laminated on Aluminum
8	First	Silver	Laminated on Aluminum
9	First	Aluminum	Deposited on Aluminum
10	First	Aluminum	Deposited on Aluminum
11	Second	Silver	High-iron glass 4.0 mm
12	Second	Silver	High-iron glass 3.0 mm

Measurement Instruments

To check the first condition of the criterion, $\rho_s(\lambda,\theta,\varphi)$ was measured with several different commercial instruments and also advanced prototypes, accomplishing the conditions previously specified. In particular, the following equipment was utilized:

- The Vlabs instrument developed by ISE Fraunhofer. It is a laboratory instrument and method for evaluation of absolute specular reflectance [10]. Its main characteristics are: LED irradiation at λ={455, 533, 631} nm, an adjustable light source with a beam divergence half-angle of 1 mrad, variable θ in the range 8° < θ < 80° and specular reflectance data for continuously variable φ up to a maximum of 33 mrad. Measurements were taken at one position on the sample at θ= 15° (for reasons of comparability), λ = {455, 533, 631} nm and φ = {7.5, 23.0} mrad. The differences at the two φ were calculated.
- The Solar Mirror Qualification (SMQ) set-up developed by ENEA. It is a simple but advanced laboratory instrument conceived to measure both the hemispherical and near-specular reflectance under the same conditions [6, 7]. Its main characteristics are: lasers beams with low divergence (< 1 mrad) and small diameter (< 1 mm), absence of collimating and focussing lenses, experimental error of ±0.001 and able to measure at φ=[0, 20] mrad. Measurements were taken at θ= 3°, λ={451.5, 532.5, 661.0} and φ = {6.0, 20.0} mrad. The differences at the two φ were calculated for each λ.
- Two portable specular reflectometers by Devices and Services, model 15R- USB, one belonging to CEA and the second one belonging to the OPAC laboratory and owned by CIEMAT and DLR. This instrument has a LED beam at θ= 15° and λ of 660 nm. Measurements were taken at φ = {7.5, 23.0} mrad and the differences were calculated.
- A portable specular reflectometer by Devices and Services, model 15R-RGB, belonging to the OPAC laboratory, owned by CIEMAT and DLR. This instrument has a beam at θ= 15° with several λ in the required range, that is λ = {460, 550, 650} nm. Measurements were taken at φ = {7.5, 23.0} mrad and the differences were calculated at each λ.
- A laboratory set-up developed by the University of Zaragoza. Its main characteristics are: the light source is a He-Ne laser with a spatial filter and a divergence less than 1 mrad, the light is modulated using a chopper in order to delete ambient light, part of the light is used as a reference to control laser fluctuations and φ can be modified thanks to an Iris diaphragm placed on the photodetector with a maximum of 22.4 mrad. Measurements were taken at θ = 10º, λ = 633 nm and φ = {5.7, 22.4} mrad and the differences were calculated.

In addition, to check the second condition of the criterion, $\rho_d(SW,\theta,\varphi)$ measurements were taken by using spectrophotometers with an integrating sphere which incorporates a specular open port to leave the specular beam escaping. The reflectance spectrum was measured in λ = [300, 2500] nm. The specific instruments employed are listed below:

- An Optronics Laboratory spectrophotometer, model 750, owned by CENER. This instrument measured at θ = 10º. The integrating sphere has a diameter of 152.4 mm and a specular opening port (or light-trap) of $\varphi \approx$ 84 mrad.
- A Perkin Elmer spectrophotometer, model lambda 1050, belonging to the OPAC laboratory, owned by CIEMAT and DLR. This instrument measured at θ = 8º. The integrating sphere has a diameter of 150.0 mm and a specular opening port (or light-trap) of $\varphi \approx$ 116 mrad.

RESULTS AND DISCUSSION

Table 2 shows the results obtained to study the accomplishment of the first proposed condition of the criterion. The numbers indicated in this table are the differences of the $\rho_s(\lambda,\theta,\varphi)$ measured at the same λ with two different φ, that is, $\varphi_1 - \varphi_2$. Values marked in bold are higher than the threshold established (0.003), involving that the sample does not pass the first condition of the criterion. Although results obtained by CEA are not included in this table, the measurements performed by this institution are entirely in accordance with the ones obtained by the other institutions.

As shown in table 2, all glass-based mirrors (1-5 and 11-12) pass the first condition of the criterion, with maximum differences of specular reflectance measured at the two selected φ of 0.001, that is, quite lower than the established threshold of 0.003. The rest of the studied reflector materials (6 to 10), corresponding to innovative reflectors, do not pass the criterion. This means that these innovative mirrors present scattering at least in the cone angle comprised between the maximum and minimum acceptance angle studied, that is, between φ_2 and φ_1. The only exception for innovative mirrors is sample number 7, which pass or not the criterion depending on the exact measurement. According to this result, it is recommended but not mandatory to measure the solar mirrors with more than one instrument and/or with more than one λ.

TABLE 2. Results of the specular reflectance differences at two φ for the twelve solar mirrors studied.

Institu-tion	**ISE Fraun-hofer**			**ENEA**			**CIEMAT/DLR**				**Univ. Zarago za**
Instru-ment	Vlabs			SMQ			15R-RGB, D&S			15R-USB, D&S	Scatero -meter
θ (º)	15	15	15	3	3	3	15	15	15	15	10
$\varphi_1 - \varphi_2$ (mrad)	23.0 - 7.5	23.0 - 7.5	23.0 - 7.5	20.0 - 6.0	20.0 - 6.0	20.0 - 6.0	23.0 - 7.5	23.0 - 7.5	23.0 - 7.5	23.0 - 7.5	22.4- 5.7
λ (nm)	455	533	631	451.5	532.5	661.0	460	550	650	660	633
1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.001	<0.001	<0.001	<0.001	<0.001
2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.001	<0.001	<0.001	<0.001	<0.001
3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.001	<0.001	<0.001	≤0.001	<0.001
4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.001	<0.001	<0.001	≤0.001	<0.001
5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.001	<0.001	<0.001	≤0.001	<0.001
6	**0.031**	**0.026**	**0.020**	**0.047**	**0.030**	**0.019**	**0.026**	**0.022**	**0.017**	**0.019**	**0.024**
7	**0.007**	**0.004**	**0.008**	**0.006**	0.003	0.002	**0.009**	0.001	--	**0.004**	**0.004**
8	**0.006**	**0.005**	**0.006**	**0.015**	**0.011**	**0.010**	**0.005**	**0.007**	--	**0.016**	**0.009**
9	**0.053**	**0.041**	**0.037**	**0.054**	**0.046**	**0.042**	**0.056**	**0.045**	**0.035**	**0.034**	**0.035**
10	**0.041**	**0.065**	**0.054**	**0.067**	**0.042**	**0.040**	**0.096**	**0.071**	**0.034**	**0.034**	**0.053**
11	--	--	--	--	--	--	<0.001	<0.001	<0.001	<0.001	--
12	--	--	--	--	--	--	≤0.001	<0.001	<0.001	<0.001	--

To calculate $\rho_d(SW,\theta,\varphi)$ the diffuse solar spectra of the twelve samples were measured. Results are represented in Figure 1.

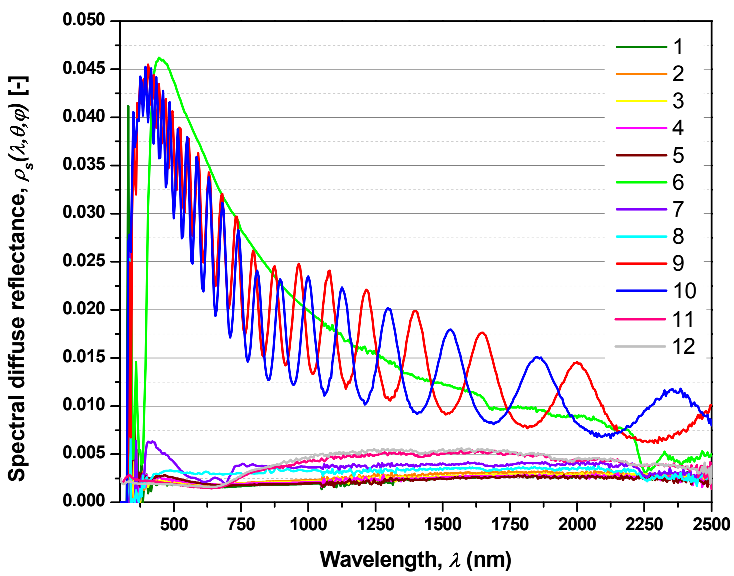

FIGURE 1. Diffuse spectra for the twelve solar mirrors studied.

As observed in Figure 1, the diffuse spectra for of the solar mirrors studied are quite small. The only exceptions are samples number 6, 9 and 10, which spectra are higher in the visible range. All spectral values were weighted with the solar spectrum from ASTM G173-03 [4]. Results are included in Table 3, for the application of the second condition of the experimental criterion. Values marked in bold are higher than the threshold established (0.003), involving that the sample does not pass the second condition of the criterion. This means that these samples present scattering in cone angles higher than the φ defined by the opening port of the spectrophotometers (φ_3).

TABLE 3. Results of the solar-weighted diffuse reflectance for the twelve solar mirrors studied.

Institution	**CENER**	**CIEMAT/DLR**
Instrument	Optronics Laboratory 750	Lambda 1050 Perkin Elmer
$\boldsymbol{\theta}$ **(º)**	10	8
$\boldsymbol{\varphi_3}$ **(mrad)**	84	116
$\boldsymbol{\lambda}$ **(nm)**	[300, 2500]	[300, 2500]
1	0.002	--
2	0.002	--
3	0.002	--
4	0.002	--
5	0.002	--
6	**0.028**	--
7	**0.004**	--
8	0.003	--
9	**0.025**	--
10	**0.024**	--
11	--	0.003
12	--	0.003

As can be observed in Table 3, the second condition of the experimental criterion is also passed by all the glass-based mirrors. In this case, a remarkable difference is observed between low-iron glass (1 to 5) and high-iron glass (11 and 12) because these two last present a higher value of $\rho_d(SW,\theta,\varphi)$, but still below the threshold. Concerning innovative mirrors, in this case only sample number 8 just passes the criterion. This sample does not pass the first condition of the criterion but do pass the second one because although it presents scattering in the cone angle comprised between φ_2 and φ_1 in the visible range, it does not present scattering at bigger angles (higher than φ_3) in the solar spectrum. That is, it cannot be consider as highly specular but the angles where it scatters are smaller than φ_3.

TABLE 4. Results of the solar-weighted diffuse reflectance for the twelve solar mirrors studied.

Sample number	**First condition of the criterion**	**Second condition of the criterion**	**Final result of the criterion**
1	✓	✓	✓
2	✓	✓	✓
3	✓	✓	✓
4	✓	✓	✓
5	✓	✓	✓
6	✗	✗	✗
7	Evaluator dependent	✗	✗
8	✗	✓	✗
9	✗	✗	✗
10	✗	✗	✗
11	✓	✓	✓
12	✓	✓	✓

A summary of the results obtained previously is comprised in Table 4. For the two conditions of the criterion, a green tick means that the sample passes it and a red cross is drawn when it does not pass it. The last column is the final result. According to the results presented in Table 4, all tested glass-based mirrors pass the experimental criterion and, consequently, they can be treated with the proposed simplified procedure. However, all tested innovative mirrors do not pass it, being excluded from the mentioned simplification.

CONCLUSIONS

The optical parameter to properly characterize the behaviour of a reflector material for CSP applications is the solar-weighted specular reflectance. As no commercial instruments and a proper protocol to measure this parameter is currently available, a new simplified procedure is proposed with the goal of providing a reliable method that can be performed with commercial instruments, until more research work is dedicated to validate and market some of the prototypes under development. This simplified approach is based on measuring uniquely the solar-weighted hemispherical reflectance and is only valid for those solar mirrors with a low fraction diffuse reflectance and high specularity. A procedure to check if a mirror candidate accomplishes this requirement, based on an experimental criterion composed of two conditions, is proposed. To verify the validity of the method proposed, the experimental criterion was applied by several research institutions to different reflectors samples, covering all available solar mirror types. According to the results obtained, glass-based mirrors pass the two conditions of the criterion and, consequently, can be measured by using the simplified method with commercial instruments. On the contrary, innovative mirrors do not pass the criterion and their specular reflectance measurement must be performed with advanced instruments or an appropriate method for the calculation of the solar-weighted specular reflectance, to be developed. Only sample 7 showed inconsistencies among the evaluators for one of the criteria. In general, very good agreement was obtained among the different research institutes, showing the applicability of the herein proposed method. The results presented in this paper will be added to the SolarPACES reflectance guideline [2].

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REFERENCES

1. S. Meyen, A. Fernández-García, C. Kennedy, E. Lüpfert, Standardization of Solar Mirror Reflectance Measurements Round Robin Test. SolarPACES Conference, Perpignan, 2010.
2. S. Meyen et al. Parameters and method to evaluate the solar reflectance properties of reflector materials for concentrating solar power technology. SolarPACES guideline V2.5. http://www.solarpaces.org/tasks/task-iii-solar-technology-and-advanced-applications/reflectance-measurement-guideline.
3. M. Montecchi, C. Delord, O. Raccurt, A. Disdier, F. Sallaberry, A. García de Jalón, A. Fernández-García, S. Meyen, C. Happich, A. Heimsath, W. Platzer, Hemispherical Reflectance Results of the SolarPACES Reflectance Round Robin. Energy Procedia **69**, 1904-1910 (2015).
4. ASTM G173-03. Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface. West Conshohocken: American Society for Testing and Materials (ASTM), 2003.
5. R. Gee, R. Brost, G. Zhu, G. Jorgensen, 2010. An improved method for characterizing reflector specularity for parabolic trough concentrators. SolarPACES Conference, Perpignan, 2010.
6. M. Montecchi, Approximated method for modelling hemispherical reflectance and evaluating near-specular reflectance of CSP mirrors. Solar Energy **92**, 280-287 (2013).
7. M. Montecchi, Upgrading of ENEA Solar Mirror Qualification Set-up, Energy Procedia **49**, 2154-2161 (2014).
8. S. Meyen, F. Sutter, P. Heller. Near specular scatter analysis method with a new goniophotometer. SPIE Optics and Photonics Technical Conference, San Diego, 2014.
9. S. Meyen, F. Sutter, P. Heller, A. Oschepkov, A New Instrument For Measuring The Reflectance Distribution Function Of Solar Reflector Materials, Energy Procedia **49**, 2145-2153 (2014).
10. A. Heimsath, T. Schmid, P. Nitz. Angle resolved specular reflectance measured with VLABS. Energy Procedia **69,** 1895-1903 (2015).
11. C. Alcañiz, N. Martínez, C. Heras, I. Salinas. Study of the influence of specularity on the efficiency of solar reflectors. Energy Procedia **69**, 14-23 (2015).