SolarPACES 2022, 28th International Conference on Concentrating Solar Power and Chemical Energy Systems
Measurement Systems, Devices, and Procedures
https://doi.org/10.52825/solarpaces.v1i.666

Published: 21 Dec. 2023

Comparison of Commercial Reflectometers for Solar Mirrors

Johannes Wette[1][https://orcid.org/0000-0003-1389-5176], Florian Sutter[2][https://orcid.org/0000-0002-2981-5807], Ricardo Sánchez-Moreno[1][https://orcid.org/0000-0001-5037-1385], and Aránzazu Fernández-García[1][https://orcid.org/0000-0001-6044-4306]

[1] CIEMAT-Plataforma Solar de Almería, Spain

[2] DLR, German Aerospace Center, Institute of Solar Research, Spain

Abstract. The important in-field characterization of solar mirror reflectance can be performed by a variety of commercial portable reflectometers. In this study the most common commercially available reflectometers are evaluated in a campaign comparing different reflector materials, covering a wide range of realistic reflectance and specularity values. Where possible, measurements are compared to reference values measured with laboratory equipment. In general, good agreement between measurements is detected for highly specular mirrors (average deviation 0.005±0.004) and methods for improvement are proposed when deviations are detected. Important differences between measurements are found for less specular reflectors, which are caused by the disparity of the measurement parameters of the devices. These differences confirm that detailed knowledge about the device characteristics is important, to be able to correctly interpret and utilize gained results, especially for soiled and degraded mirrors.

Keywords: Concentrating Solar Thermal Technology, Solar Reflector, Reflectometer, Near-Specular Reflectance, Optical Efficiency

1. Introduction

The reflectance of the reflectors of the solar field in concentrating solar thermal (CST, also named concentrated solar power, CSP) plants is one of the key parameters determining the field's optical efficiency. Reflector manufacturers optimize their material for high reflectance and long-term durability to maintain this high initial reflectance. Nonetheless, the reflectance of the mirrors usually decreases due to different factors during operation. The cause of this reduction can be permanent degradation (e.g. corrosion of the reflective silver layer, erosive attack of front surface) or removable soiling. The most significant parameter for the optical efficiency is the solar-weighted near-normal sun-conic reflectance [1]. This parameter is site and technology specific and depends on further parameters as, e.g. wavelength of the light, λ, the incidence angle, θ_i, the divergent angle of the light-source, φ_i and the acceptance angle, φ. The measurement of this reflectance parameter is not trivial and nowadays can only be performed by specialized laboratories [2, 3]. For practical reasons, different reflectance parameters that are easier to measure are used. Regular in-field measurements of the reflectance are necessary to evaluate degradation of the reflectors and especially the soiling, for the planning of cleaning tasks, as well as the determination of the overall optical yield. These in-field measurements are performed with commercially available reflectometers, which all measure with different values of the reflectance parameters above mentioned and which all have their particular advantages and shortcomings. Differences between these reflectometers include:

measurement principle, calibration process and materials, available incidence, divergent and acceptance angles, and wavelength of the light source, among others [4]. Due to these differences, also the results obtained with the different devices can vary. In the past, several campaigns comparing two or three of the reflectometers have been performed [5, 6]. Up until today, there is still a lack of data on the comparison of all the available reflectometers on the market to evaluate their suitability for significant measurements of reflectance. In this work, the six most commonly used reflectometers are tested in a laboratory measurement campaign on different types of solar reflector materials and their results are evaluated. Experiments were performed in the OPAC facilities, under a R&D cooperation between CIEMAT and DLR at the CIEMAT-Plataforma Solar de Almería.

2. Methodology

A variety of solar mirror materials was chosen and samples were prepared for the spectral near-specular reflectance, $\rho_{\lambda,\theta_i,\varphi}$, measurements with the different devices. The handheld reflectometers that were used for this study are displayed in Figure 1. In addition, measurement data was compared to readings of the spectral hemispherical reflectance, $\rho_{\lambda,\theta_i,h}$, measured with a Perkin Elmer (PE) Lambda 1050 spectrophotometer. $\rho_{\lambda,\theta_i,h}$ measurements were performed in the wavelength range of λ = [320, 2500] nm, using 5 nm intervals at θ_i = 8° with an integrating sphere of 150 mm diameter. The data was evaluated with a 2nd surface reference reflectance standard (calibrated in the range 300-2500 nm), traceable to NIST. Three measurements were taken on each sample, in different spots. Following ASTM Standard E903-82 (92) [7], the solar-weighted hemispherical reflectance, $\rho_{sw,\theta_i,h}$ can be calculated by weighting $\rho_{\lambda,\theta_i,h}$ with the solar direct irradiance G_b on the earth surface for each wavelength. For European and North American latitudes typical solar irradiance spectra are given by the current standard ASTM G173-03 [8] (direct irradiance) for air mass AM 1.5. For the reflectometer measurements, 3 to 5 measurements were taken per sample in different spots, depending on sample size and homogeneity of the material and the average values were used for the evaluation, as recommended in the actual SolarPACES reflectance measurement guideline [9].

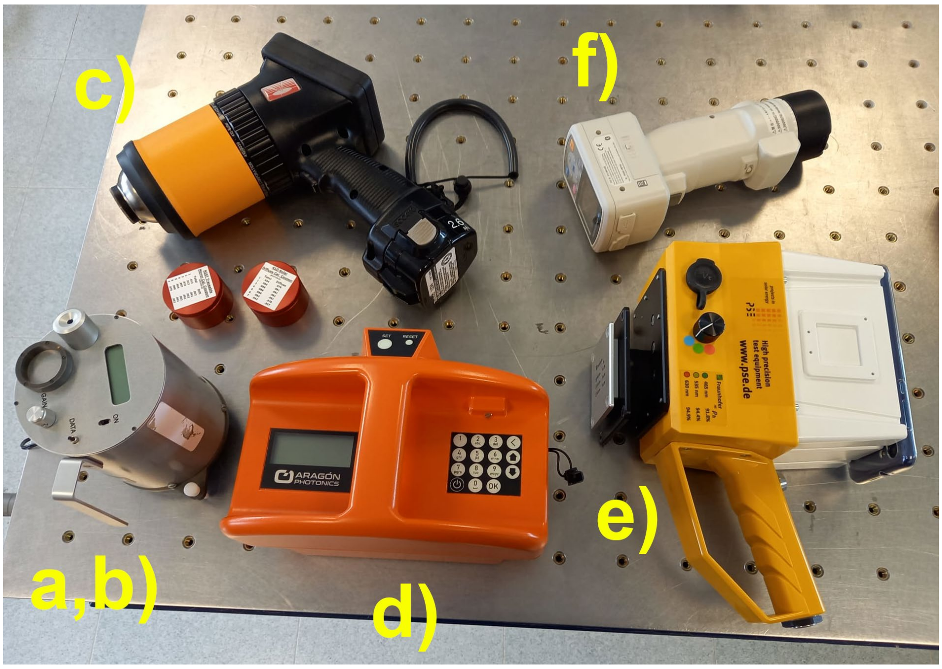


Figure 1. Handheld reflectometer models: a) 15R(-USB) (similar design as b) 15R-RGB) by D&S, c) 410-Solar by SOC, d) Condor by Aragon Photonics, e) pFlex by PSE, f) CM-700d by Konica Minolta.

Main characteristics of the reflectometers are presented in Table 1. All reflectometers are able to measure the near-specular reflectance with differences in θ_i and φ angles and λ of the used light.

- The 410-Solar and the CM-700d are equipped with integrating spheres and measure the hemispherical reflectance and diffuse reflectance, $\rho_{\lambda,\theta_i,d}$, to calculate the near-specular value.
- Most of the devices measure in one or several narrow λ bands with their respective peak values. The 410-Solar uses broader bands for the higher λ ranges, with bandwidths of up to 800 nm. The CM-700d measures in the spectral λ range from 400 to 700 nm, with steps of 10 nm.
- The D&S 15R models have the option to select different φ, all considerably lower than the rest of the devices. Due to these small φ, manual alignment of the reflectometer is required for measurements with the 15R models. An angle of φ=12.5 mrad is chosen for the measurements in this study. This manual alignment is not necessary for the other reflectometer types, which facilitates the measurement procedure.
- The reflectometers measure at relatively small θ_i, defined as near-normal (θ_i≤15º), with the 410-Solar angle being slightly higher (θ_i =20º).

Table 1. Reflectometer models and main parameters, *parameter not defined.

	Model	**Manufacturer**	**Reflectance parameter**	**θ_i [º]**	**φ [mrad]**	**λ [nm]**
a)	15R-USB	Devices and Services	$\rho_{\lambda,\theta_i,\varphi}$	15	3.5, 7.5, 12.5, 23	660
b)	15R-RGB	Devices and Services	$\rho_{\lambda,\theta_i,\varphi}$	15	2.3, 3.5, 7.5, 12.5, 23	460, 550, 650, 720
c)	410-Solar	Surface Optics	$\rho_{\lambda,\theta_i,\varphi}$ & $\rho_{\lambda,\theta_i,h}$	20	52.4	335-380, 400-540, 480-600, 590-720, 700-1100, 1000-1700, 1700-2500
d)	Condor	Aragon Photonics	$\rho_{\lambda,\theta_i,\varphi}$	12	145	435, 525, 650, 780, 940, 1050
e)	pFlex	PSE AG	$\rho_{\lambda,\theta_i,\varphi}$	8	67	470, 525, 625
f)	CM-700d	Konica Minolta	$\rho_{\lambda,\theta_i,\varphi}$ & $\rho_{\lambda,\theta_i,h}$	8	*	400-700 (10nm steps)

Mirror materials were selected to represent a variety of different mirror types with different optical characteristics concerning spectral behavior and specularity. Silvered-glass mirrors of different thickness were measured in the initial as well as degraded state. As an example of material of lower specularity, different aluminum reflectors were analyzed. Three samples were chosen to represent all of these characteristics and their results are presented in detail in the following section.

3. Results and discussion

Non-degraded silvered-glass mirror

In Figure 2, the reflectance values of the silvered-glass mirror in the clean and non-degraded state, measured with the different devices, are displayed over λ. In the case of PE Lambda, 410-Solar and CM-700d, the hemispherical values are chosen for comparison. The PE Lambda values are taken as the reference here, as laboratory devices usually show high precision and quality of the results were verified in the past [10]. The values for 410-Solar are displayed as horizontal lines covering the whole bandwidth of the respective λ ranges. As the mirrors are measured in the initial state, the specularity of the material is very high. This is confirmed by the fact that values of hemispherical and near-specular reflectance are in general in very good agreement. Especially the D&S models and the pFlex show only minimal spectral differences compared to PE Lambda ($\Delta\rho_\lambda$<0.004).

The Condor slightly overestimates the reflectance for the two lowest wavelengths ($\Delta\rho_\lambda$<0.014). After updating the reflectance values of the calibration coupon delivered for the Condor, based on measurements performed with the PE Lambda at OPAC, this overestimation could be strongly reduced ($\Delta\rho_\lambda$ <0.002; updated values not included in graph).

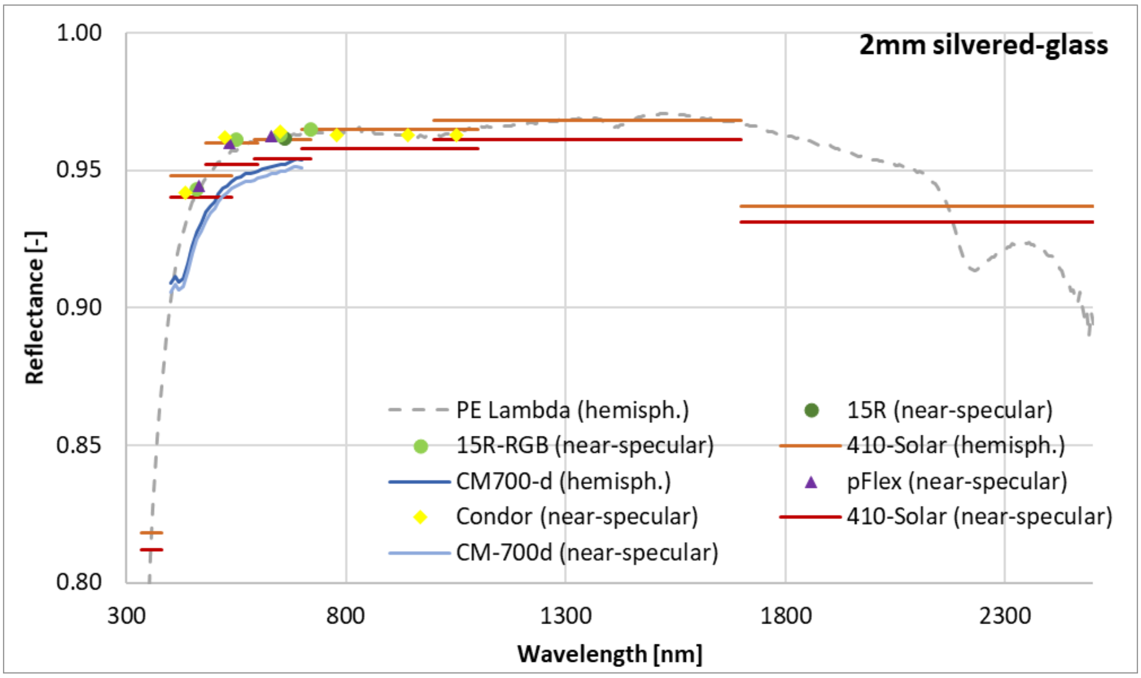
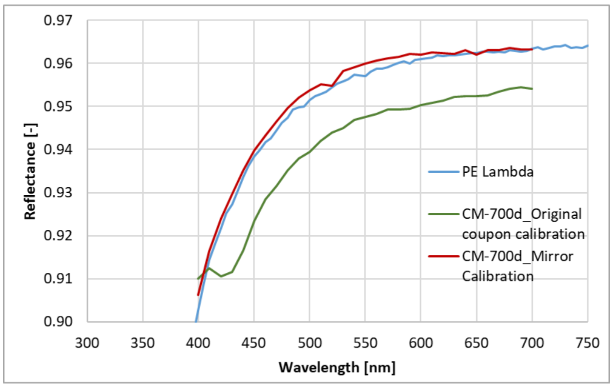


Figure 2. Reflectance (hemispherical and near-specular) spectra of a clean and non-degraded 2 mm silvered-glass mirror measured with all devices.

According to the results shown in Figure 2, lower values are detected for the CM-700d over the spectrum measured, compared to PE Lambda. It was found that this was related to the calibration of the equipment, which is performed with a white, highly diffuse, coupon. Using a well calibrated mirror as a calibration coupon, not provided with the equipment, these differences can be minimized (see Figure 3 left). Downside of this is, near-specular measurements are not possible with this calibration due to instrument restrictions.

For the 410-Solar, in addition to the hemispherical reflectance, the near-specular data are displayed in Figure 2. It can be seen that they lie considerably lower (average difference of 0.007) even though the mirror is highly specular. It was found that this is mainly due to a sensitivity of the equipment to the glass thickness of the measured reflector, which causes an underestimation of the near-specular reflectance. This can be seen in Figure 3 right, where

410-Solar measurements of the diffuse reflectance are presented for highly specular reflectors of different glass thicknesses (ranging from 0.2 to 2 mm). The thinner the glass, the lower is the diffuse part of the reflectance. The here used 410-Solar is aligned for first surface mirrors, but it is important to highlight that it can be realigned for other thicknesses by the manufacturer of the equipment, to avoid this issue.



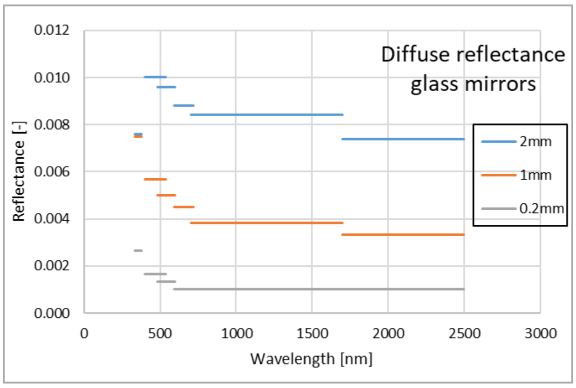


Figure 3. left: Comparison of measurements with different calibration coupons for the CM-700d, right: diffuse reflectance measured of mirrors with different glass thickness with 410-Solar.

In Table 2, the reflectance difference compared to the PE Lambda is displayed for all devices. The average of the whole respective spectral range, $\Delta\overline{\rho_\lambda}$, is taken, calculated as the absolute difference between reflectometer and PE Lambda per λ and averaged over all λ. This means the number of λ values taken into consideration to calculate the average, ranges from 1 for the D&S 15R to 31 for the CM-700d. Even the highest average difference is limited to 0.011 (for the CM-700d), which implies a very good agreement between devices. The average over all devices (with standard deviation) is 0.005±0.004. For the three devices with the highest deviation, specific methods for improvement are proposed and the results are included in the third column of the table as $\Delta\overline{\boldsymbol{\rho_\lambda}}^*$. When these improved values are considered, the average over all devices (with standard deviation) is 0.001±0.000.

Table 2. Absolute differences in reflectance measurements (2 mm silvered-glass initial) compared to PE Lambda: average over spectral values $\Delta\overline{\boldsymbol{\rho_\lambda}}$, with improved values for three devices $\Delta\overline{\boldsymbol{\rho_\lambda}}^*$, and if available solar-weighted $\Delta\boldsymbol{\rho_{SW}}$.

Reflectometers	$\Delta\overline{\boldsymbol{\rho_\lambda}}$	$\Delta\overline{\boldsymbol{\rho_\lambda}}^*$	$\Delta\boldsymbol{\rho_{SW}}$
D&S 15R	0.0010	---	---
D&S 15R-RGB	0.0017	---	---
Condor	0.0038	0.0011	0.0054
410-Solar	0.0087	0.0012	0.0013
pFlex	0.0018	---	0.0037
CM-700d	0.0110	0.0015	---

In addition, the difference of the solar-weighted value, $\Delta\rho_{SW}$, is displayed for the reflectometers which compute it. If the results of the individual instruments are analyzed, the $\Delta\overline{\rho_\lambda}$ is very low for the D&S 15R, the D&S-RGB and the pFlex (<0.002), and slightly higher for the Condor. The Condor value can be improved with the above mentioned update of the calibration values (from 0.0038 to 0.0011). The value for the 410-Solar is higher compared to the other equipment, which is only due to a higher difference at the lowest and highest wavelength, where only this reflectometer measures and where the reflectance curve of the mirror shows a steep gradient (see Figure 2). Anyhow, the solar-weighted value is in very good agreement. If the two extreme wavelength values are excluded in the averaging process, the result improves as well to 0.0012. Highest differences were detected for the CM-700d, which is again due to its white coupon calibration. The mirror calibration of the CM-700d described above decreases the $\Delta\overline{\rho_\lambda}^*$ to 0.0015.The pFlex and Condor showed slightly higher differences considering $\Delta\rho_{SW}$.

Eroded silvered-glass mirror

In Figure 4, the reflectance values are displayed for a 2 mm silvered-glass mirror, the same material as before, but after exposure at a desertic site with strong erosion of the glass surface. The erosion of the glass surface causes a decrease in reflectance, mainly in specularity. Therefore, for the two instruments which measure near-specular and hemispherical reflectance, both are displayed. For both the 410-Solar and the CM-700d, the difference between near-specular and hemispherical values is much bigger than for the reflector sample in the initial state (410-Solar: 0.063 compared to 0.007, CM-700d: 0.044 compared to 0.003), which indicates, that the instruments are properly detecting the decrease in specularity caused by the reflector degradation. The 15R models show the lowest reflectance values of all devices, which is in agreement with the fact that they have the smallest acceptance angle (φ=12.5 mrad) and therefore the measurements include less scattered light due to the erosion. For one band, 410-Solar shows lower values even than the 15R, which could be explained again by the underestimation of the near-specular reflectance due to the glass thickness. The near-specular values of the other reflectometers lie in between the hemispherical and the ones of the 15R-RGB, in accordance with their higher φ. The Condor has the highest near-specular reflectance values and acceptance angle (φ=145 mrad), followed by pFlex (φ=67 mrad) and CM-700d (φ not defined) and then 410-Solar (φ=52.4 mrad).

Hemispherical values of the 410-Solar lie slightly above the PE Lambda values but solar-weighted reflectance is in good agreement ($\Delta\rho_{SW}$=0.005). A comparison table similar to Table 2 is not included for this and the next presented reflector material. It is omitted because of the low specularity of the samples, which means a direct comparison to PE Lambda values is not possible. The differences between PE Lambda and reflectometers are desired and due to the measurements with smaller acceptance angles.

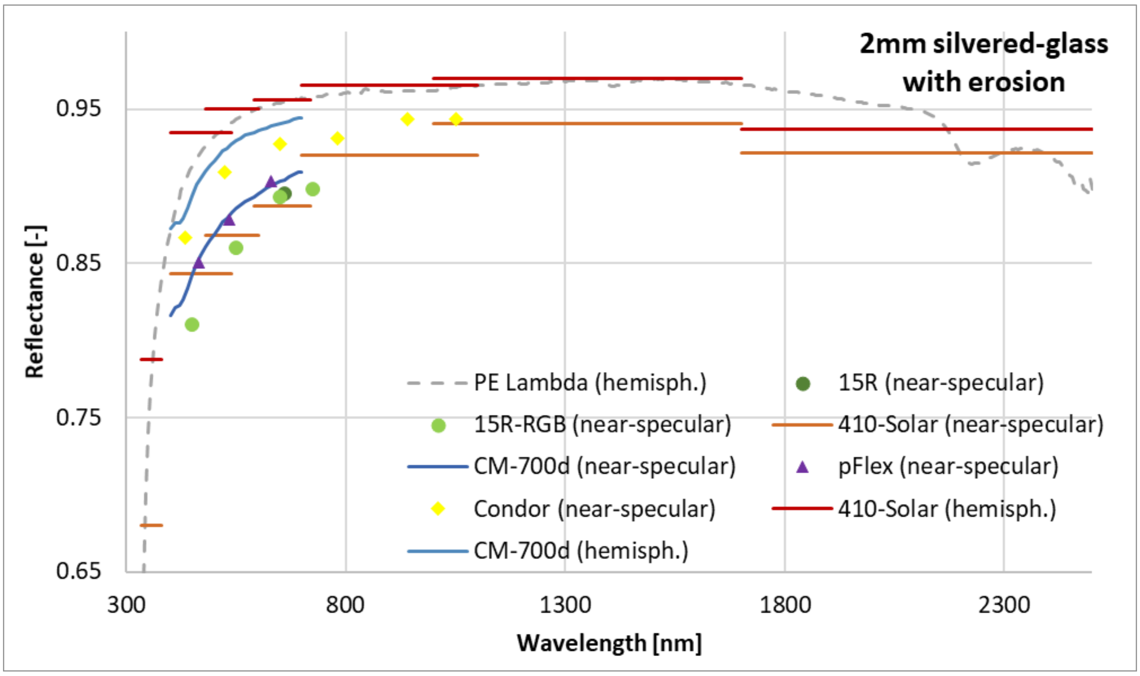


Figure 4. Reflectance spectra of 2 mm glass mirror after outdoor exposure, measured with all devices.

During the here presented campaign, high-quality spectral, near-specular reflectance data was not available for the materials as a reference. The comparison of reflectometer data with this kind of reference data, achieved with an advanced laboratory device (e.g. as in [2]), is planned for a future campaign and the agreement of data at comparable parameters (especially the φ) will be investigated. In addition, newly developed advanced optical models for soiled and degraded reflectors will be used to evaluate measurements with simulated results for comparison.

Aluminum sheet reflector

Another reflector included in the study was a first surface aluminum mirror. Results are displayed in Figure 5. The tendency here is the same as for the eroded glass mirror: most values lie in between the hemispherical value and the D&S values (with the lowest φ). The near-specular values of the 410-Solar lie much higher for this material, because the thickness is not influencing the measurements for this first surface mirror. The values are very close to the pFlex values, in accordance with the similar φ of the two devices. This result highlights the importance of a proper alignment of the 410-Solar by the manufacturer, depending on the glass (or any other front protective layer) thickness of the reflector sample to be measured. CM-700d values are lower for this case, a fact that is probably again connected to the calibration with the diffuse white coupon.

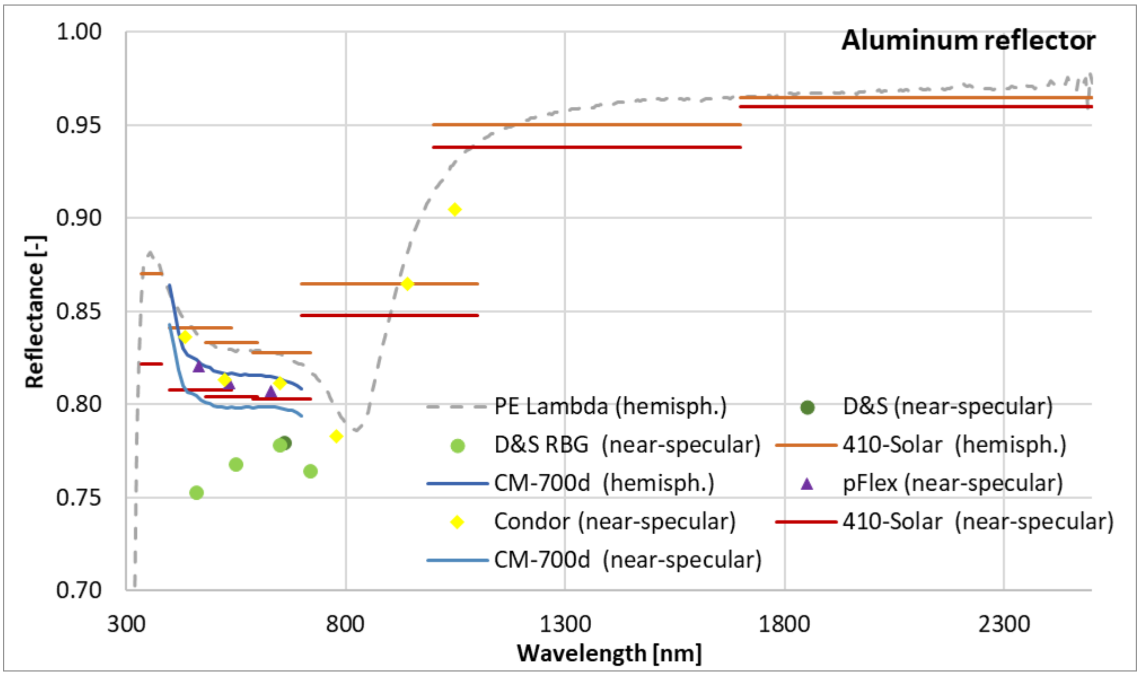


Figure 5. Reflectance spectra of aluminum mirror measured with all devices.

4. Conclusions

All commonly used commercial reflectometers were evaluated in the measurement campaign presented in this paper to compare the produced reflectance readings. Reflector materials of different reflectance and specularity values were used to cover a wide range of realistic materials. Good agreement with reference measurements was in general achieved for highly specular mirrors. Detectable differences were found for three devices and specific solutions to minimize these differences are proposed in this paper. Expected deviations due to the different φ were detected for less specular samples and the importance of the magnitude of these differences was confirmed. Because of these differences in measured parameters and reflectance values, the correct interpretation of measurements with the reflectometers is crucial, especially when comparing results from different devices or calculating optical yield of solar fields. This is even more important when less specular materials (e.g. non silvered-glass, degraded or soiled mirrors) are addressed. In a future campaign, the measurement of spectral, near-specular reflectance is foreseen to verify results for less specular samples. The knowledge of differences between the different reflectometers will help to select the proper devices, as models with lower, more realistic φ usually have a more complex handling, and even the use of transfer functions between results of different devices are possible.

Data availability statement

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

Author contributions

Johannes Wette: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft. Florian Sutter Investigation, Writing – review & editing. Ricardo Sánchez-Moreno: Investigation, Writing – review & editing. Aránzazu Fernández-García: Investigation, Writing – review & editing.

Competing interests

The authors declare no competing interests.

References

1. M. Montecchi, “Proposal of a new parameter for the comprehensive qualification of solar mirrors for CSP applications,” AIP Conference Proceedings, vol. 1734, no. 1, p. 130014, May 2016, doi: https://doi.org/10.1063/1.4949224.
2. F. Sutter, A. Fernández-García, A. Heimsath, M. Montecchi, and C. Pelayo, “Advanced measurement techniques to characterize the near-specular reflectance of solar mirrors,” AIP Conference Proceedings, vol. 2126, no. 1, p. 110003, Jul. 2019, doi: https://doi.org/10.1063/1.5117618.
3. F. Sutter, S. Meyen, A. Fernández-García, and P. Heller, “Spectral characterization of specular reflectance of solar mirrors,” Solar Energy Materials and Solar Cells, vol. 145, pp. 248–254, Feb. 2016, doi: https://doi.org/10.1016/j.solmat.2015.10.030.
4. A. Fernández-García, F. Sutter, L. Martínez-Arcos, C. Sansom, F. Wolfertstetter, and C. Delord, “Equipment and methods for measuring reflectance of concentrating solar reflector materials,” Solar Energy Materials and Solar Cells, vol. 167, pp. 28–52, 2017, doi: https://doi.org/10.1016/j.solmat.2017.03.036.
5. J.S. Crawford, J. Stewart, and J.A. Pérez-Ullivarri, „A Comparison of Three Portable Reflectometers for Use in Operations and Maintenance of CSP Plants”, SolarPACES conference proceedings, Marrakech, Morocco, 2012.
6. C. Sansom, A. Fernández-García, P. King, F. Sutter, and A. García-Segura, “Reflectometer comparison for assessment of back-silvered glass solar mirrors,” Solar Energy, vol. 155, pp. 496–505, Oct. 2017, doi: 10.1016/j.solener.2017.06.053.
7. ASTM E903-82. Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres, ASTM International, 2012.
8. ASTM G173-03. Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface, ASTM International, 2003.
9. Parameters and Method to Evaluate the Reflectance Properties of Reflector Materials for Concentrating Solar Power Technology Technology, SolarPACES Reflectance Guideline, v3.1, 2020.
10. M. Montecchi et al., “Hemispherical Reflectance Results of the SolarPACES Reflectance Round Robin,” Energy Procedia, vol. 69, pp. 1904–1910, May 2015, doi: https://doi.org/10.1016/j.egypro.2015.03.174.