STANDARDIZATION OF SOLAR MIRROR REFLECTANCE MEASUREMENTS – ROUND ROBIN TEST

Stephanie Meyen[1], Aránzazu Fernández-García[2], Cheryl Kennedy[3], Eckhard Lüpfert[4]

[1]Dipl.-Ing., Solar Researcher, DLR German Aerospace Center, Plataforma Solar de Almería (PSA), Ctra. Senés Km. 4, 04200 Tabernas, Spain, +34 950 611743, Stephanie.Meyen@dlr.de

[2]Master-Ing., Solar Researcher, CIEMAT, Plataforma Solar de Almería (PSA), +34 950387950

[3]Senior Scientist, National Renewable Energy Laboratory (NREL), +1 303 3846103

[4]Dr.-Ing., Solar Researcher, DLR German Aerospace Center, +49 22036014714

Abstract

Within the SolarPaces Task III standardization activities, DLR, CIEMAT, and NREL have concentrated on optimizing the procedure to measure the reflectance of solar mirrors. From this work, the laboratories have developed a clear definition of the method and requirements needed of commercial instruments for reliable reflectance results. A round robin test was performed between the three laboratories with samples that represent all of the commercial solar mirrors currently available for concentrating solar power (CSP) applications. The results show surprisingly large differences in hemispherical reflectance (σ_h) of 0.007 and specular reflectance (σ_s) of 0.004 between the laboratories. These differences indicate the importance of minimum instrument requirements and standardized procedures. Based on these results, the optimal procedure will be formulated and validated with a new round robin test in which a better accuracy is expected. Improved instruments and reference standards are needed to reach the necessary accuracy for cost and efficiency calculations.

Keywords: Reflectance measurement procedure, solar mirror characterization, round robin test, standardization, spectrophotometer, reflectometer

1. Introduction

Solar reflectors for concentrating solar power (CSP) applications can be characterized by the amount of sunlight reflected onto the receiver. This performance is influenced by the sun shape, reflector quality, tracking accuracy, and location of the CSP plant. Sun shape is the extent the incident rays from the sun are imperfectly collimated. Reflector quality is dependent on the solar-weighted reflectance and specularity of the mirror material in addition to the durability, cost, and deviations from the designed shape. Specular reflectance is the total reflectance minus the light scattered outside a specified acceptance half angle or, alternatively, the amount of light reflected into the acceptance half angle. Specularity is usually related to micro-imperfections of the mirror surface such as those caused by micro-roughness, soiling, dust accumulation, micro-cracks, haze, etc. Solar-weighted specular reflectance—the specular reflectance within a specified incidence and half-cone angle beam weighted across the solar spectrum—is the crucial parameter to characterize the quality and performance of solar mirrors. Frequently, the reflectance values cited in datasheets of commercial solar mirrors cannot be compared because of differences in measurement methods. Furthermore, no commercially available instrument can measure solar-weighted specular reflectance—the most significant metric.

CIEMAT-PSA (Almeria, Spain), NREL (Golden, Colorado, USA), and DLR-Quarz (Cologne, Germany) reviewed the reflectance measurement procedure presented in [1] to characterize solar mirrors. A round robin test that included the relevant solar reflector materials was performed at all three laboratories. The test results underline the importance of the instrument requirements and procedure discussed in Section 4. The

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proposed instrument requirements and procedures are meant to be a guideline for future instrument improvements and standards that is valid not only for glass mirrors but also for alternative mirror materials like silvered polymer, enhanced aluminum, and front surface mirrors that can provide challenges to accurate measurements.

2. Procedure and Instruments

2.1. General specifications

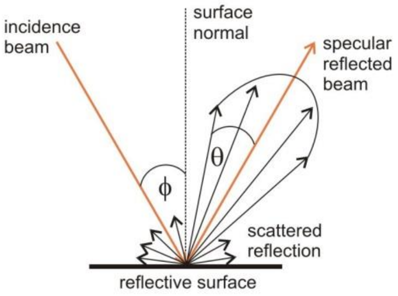

Figure 1. Definition of angles.

The solar-weighted specular reflectance $\rho_s(SW,\phi,\theta)$ at an incidence angle ϕ cannot be measured directly at a specific acceptance half angle θ (Figure 1) appropriate for solar applications. The acceptance half angle θ for the beam offset is determined by the collector design, size, and the acceptable total optical collector error [2]. The amount of sunlight concentrated onto the receiver by only the mirror material can be characterized by $\rho_s(SW,\phi,\theta)$, without considering other possible imperfections like shape, receiver alignment, and tracking errors. An acceptance half angle of θ = 7.5 – 12.5 mrad (primarily 12.5 mrad) is considered appropriate for typical parabolic trough designs [3].

There is no commercial instrument to quantify $\rho_s(SW,\phi,\theta)$, because the current instruments can only measure specular reflectance at a specified θ in narrow wavelength bands. Therefore $\rho_s(SW,\phi,\theta)$ must be approximated. Hemispherical reflectance $\rho_h(\lambda,\phi,h)$ is measured over a wavelength range representative of the terrestrial solar spectrum (λ = 250-2500 nm) with a UV-Vis-NIR spectrophotometer and an integrating sphere (typically, the incidence angle ϕ is 8°) relative to standards. The spectrum is then weighted by an appropriate standard terrestrial solar spectrum to compute a solar-weighted hemispherical reflectance, $\rho_h(\lambda$=250-2500 nm), as a meaningful single measure of optical performance. ASTM G173 at air mass 1.5 is recommended [4]. These techniques and measured data are directly comparable with DIN 5036-1, 3 [5,6]. The specular reflectance $\rho_s(\lambda,\phi,\theta)$ is measured with a specular reflectometer at θ = 3.5, 7.5, and 12.5 mrad with an incidence angle ϕ=15° for $\lambda \approx$ 660 nm. For highly specular glass or front surface reflectors, specular reflectance can be described by the ratio of specular reflectance $\rho_s(\lambda,\phi,\theta)$ to the hemispherical reflectance $\rho_h(\lambda,\phi,h)$ at the same wavelength is assumed to be constant and equals the ratio of the solar weighted values. The solar-weighted specular reflectance is then approximated by [7]:

$$\rho_s(SW,\phi,\theta) = \frac{\rho_s(\lambda = 660,\phi,\theta)}{\rho_h(\lambda = 660,\phi,\pi)} \rho_h(SW,\phi,\pi)$$

2.2. Requirements for reaching optimal results

Only measurements taken as a function of wavelength within a solar wavelength range of 250- 2500 nm or at representative discrete wavelength intervals in this range are suitable for the calculation of $\rho_s(SW,\phi,\theta)$. To realistically predict the reflected sunlight onto the absorber, instruments ideally allow the selection of specular reflectance measurements as a function of defined acceptance angles θ. Solar mirrors cover a wide range of materials and properties; namely, 1st and 2nd surface, glass mirrors of thickness ranging from 0.95 mm to 5 mm, silver and aluminum reflectance layers, and new reflector materials with surfaces that have complex specularity characteristics. Therefore, the instrument performance and procedure must be applicable for all such material characteristics. The greatest source of error lies in the accurate measurement of the specular reflected beam when portable instruments are used outdoors in a solar collector field, where the mirrors have a curvature due to their focal length and soiling particles can disrupt the smooth interface of the instrument to the mirror. The ability to visually check and adjust the beam alignment and ease of handling and also reduce the variability caused by different operators and ambient conditions (primarily temperature) is essential.

Reflectance measurements are usually taken in relation to calibrated reference standards; using the correct reference standard that is clean is essential. The best results can be achieved when the reference standard has similar reflective properties to the sample; that is, the type of mirror (1st surface or 2nd surface), the reflective material (silver or aluminum), the thickness, and its specularity. The reference standards and instruments must be calibrated regularly.

2.3. State of the art

Reflectance is measured in the laboratory with a UV-Vis-NIR spectrophotometer over the solar wavelength range and then weighted with the standard solar spectrum. Spectrophotometers can be equipped with an integrating sphere for hemispherical reflectance measurements and are usually very reliable for any kind of material when the correct reference standard is used [8]. Integrating spheres are also used in various portable reflectometers but are restricted to a small selection of discrete wavelength intervals. Instruments with integrating spheres usually offer openings in the sphere where the specular reflected beam can be excluded and an indirect acquisition of the specular reflectance is possible. The problem is that the acceptance angle of these "specular" parts is fixed and quite large so that useful ρ_s is not measured. Another option is the use of specular accessories [9] for spectrophotometers.

A variety of other portable reflectometers and glossmeters exist [7], which generally only measure specified wavelengths or a small wavelength range. In addition, gloss is not an optical property generally relatable to ρ_s so glossmeters should not be considered. All such devices suffer from major disadvantages:

- The acceptance angle cannot be selected; it is sometimes unknown or greater than θ = 7.5-12.5 mrad.
- The alignment cannot be checked and adjusted, which is necessary to measure mirrors with mirror surface micro-roughness or curvature.
- The restricted wavelength range does not allow a precise solar weighting.
- The design works reliably only for highly specular glass or front surface reflectors.
- Repeatability of measured values varied by several percentage points, giving unacceptable results [10].

The instrument selected for specular reflectance measurements can measure at three acceptance angles. The angle θ can be selected equal to 12.5 mrad and the beam alignment can be visually adjusted to allow representative and reproducible measurements on solar reflectors. The instrument measures at a wavelength interval of 635-685 nm with a peak at 660 nm and a repeatability of less than 0.005. The solar weighting is performed with the approximation explained above.

3. Round Robin Tests

3.1. Proceedings of round robin test

Using the same instruments with the same properties and the same measurement procedure should lead to similar results when a mirror is measured at different laboratories by different operators. On the basis of [1] and further discussions of how to measure $\rho_h(SW,\phi,\pi)$ and $\rho_s(SW,\phi,\theta)$, a round robin test was performed on a good representation of commercially available solar mirrors. Samples were measured at the three research laboratories. Each laboratory received a set of samples for the first round of measurements; the sets were then sent to the next laboratory, where they were measured and so on, resulting in three rounds.

For the measurement of $\rho_h(SW,8°,\pi)$, Perkin Elmer Lambda series (ϕ = 8°) spectrophotometers were used. CIEMAT used a new Lambda 1050 with a 150-mm integrating sphere, DLR used a Lambda 950 with a 150-mm sphere, and NREL used the older Lambda 9 and Lambda 900 equipped with 60-mm spheres. All laboratories used Devices & Services 15R reflectometers (λ = 660nm, ϕ = 15°) to measure $\rho_s(660nm,15°,\theta)$ with θ = 12.5 and 7.5 mrad. The 15R at CIEMAT is the new USB model purchased last year. DLR also purchased a new USB-15R reflectometer and made additional measurements with this ("DLR add" in section

4.3). The round robin test at NREL and DLR was performed with older models of the 15R. Last year, NREL's model was upgraded to USB and both were recalibrated by Devices & Services.

CIEMAT and DLR used 1st surface aluminumaluminum reference standards for the 1st surface samples (including the polymer film) and for the 2nd surface thin glass mirrors. They used 4-mm silvered-glass reference standards for 3-mm and 4-mm 2nd surface glass mirror samples. NREL used 2nd surface 1-mm silvered-glass reference standards for all 2nd surface glass samples and polymer film. Their 1st surface aluminum standards were used for 1st surface aluminum samples. During the test, NREL's instruments were recalibrated after the second round. CIEMAT samples were measured at NREL before and after the recalibration. NREL reference standards are older and were not recalibrated in time before the test started but are now being recalibrated. Samples will be remeasured with the recalibrated standards during the next round robin.

3.2 Samples

Nine different types of solar mirrors were provided by six different manufacturers for the test. Of each mirror type, five identical samples were provided; these were organized into three working sets of samples, each containing one mirror of each type plus two sets of control samples. Overall, there were 27 samples in the test, each measured three (hemispherical) to five (specular) times at each laboratory and sent in three rounds. Each laboratory started the measurements with a fresh set of samples identified as: CIEMAT1,...,CIEMAT9; NREL1,...,NREL9; and DLR1,...,DLR9. Mirror samples were:

- Type 1: 2nd surface silvered polymer film laminated to a 1-mm thick aluminum substrate from manufacturer A,
- Type 2: 0.95-mm thick 2nd surface silvered low-iron glass mirror laminated to a 1-mm thick glass substrate from manufacturer B,
- Type 3: 3-mm thick 2nd surface silvered low-iron glass mirror from manufacturer B,
- Type 4: 1.6-mm thick 2nd surface silvered low-iron glass mirror from manufacturer B,
- Type 5: 1st surface enhanced aluminum mirror applied to a 3-mm thick glass substrate from manufacturer C,
- Type 6: 0.95-mm thick 2nd surface silvered low-iron glass mirror from manufacturer D,
- Type 7: 1st surface aluminum mirror laminated to a metal-polymer-metal sandwich from manufacturer E,
- Type 8: 0.95-mm thick 2nd surface silvered low-iron glass mirror from manufacturer F, and
- Type 9: 4-mm thick 2nd surface silvered low-iron glass mirror from manufacturer F.

All samples had clean, smooth surfaces without scratches or soiling at the beginning of the test. Type 1 mirrors were supplied with thick edge protection. The overlapping edge protection on the corners prevented correct sample placement in the instruments. These corners were removed at the beginning of the test, which slightly warped the areas adjacent to the corners, making specular reflectance measurements in these areas significantly more difficult.

4. Measurement Results and Discussion

4.1. Hemispherical reflectance

The results of $\rho_h(SW,8°,\pi)$ are presented in Figures 2-4 together with the standard deviation (StDev) between the laboratories. To reduce the number of graphs, the results of polymer film are plotted together with aluminum mirrors in Figure 2, although the material types are not comparable. The same is the case in Figures 5-7.

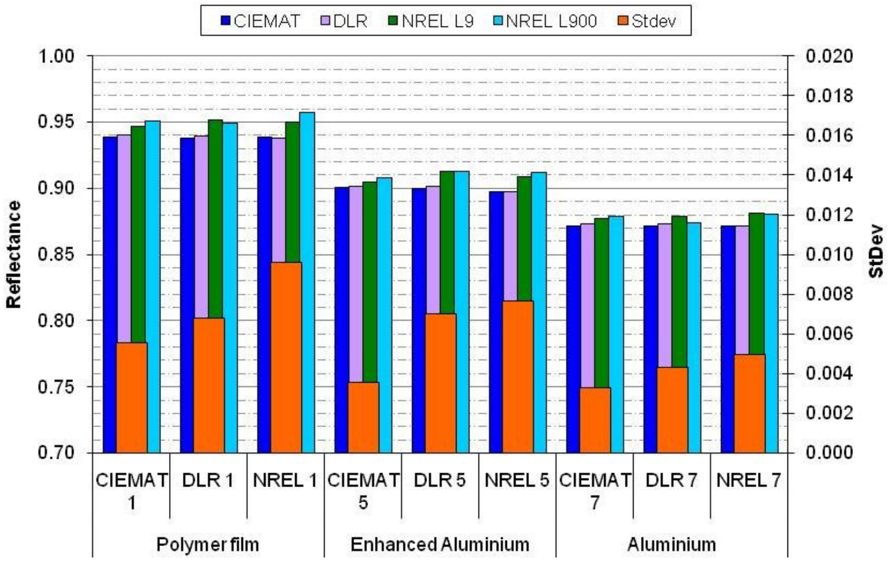

Figure 2. ρ_h**(SW,8°,** π**) ASTM G173 for silver polymer film and 1st surface aluminum mirror.**

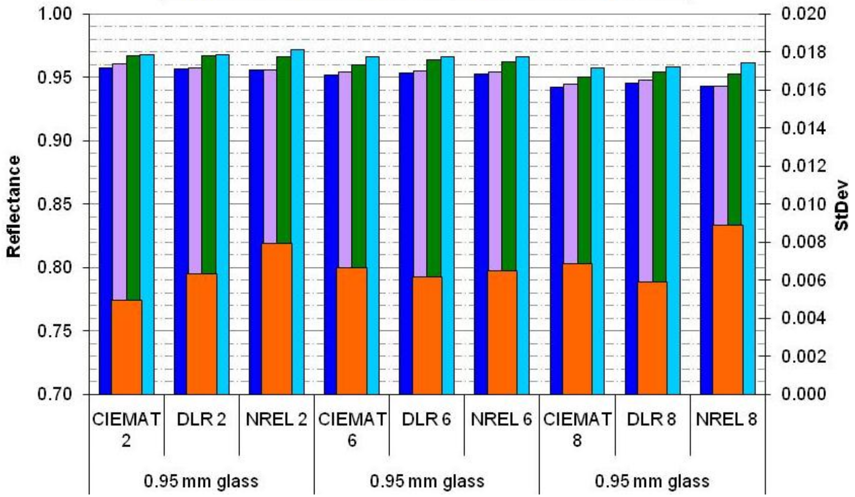

Figure 3. ρ_h**(SW,8°,** π**) ASTM G173 for 2nd surface thin-glass mirrors.**

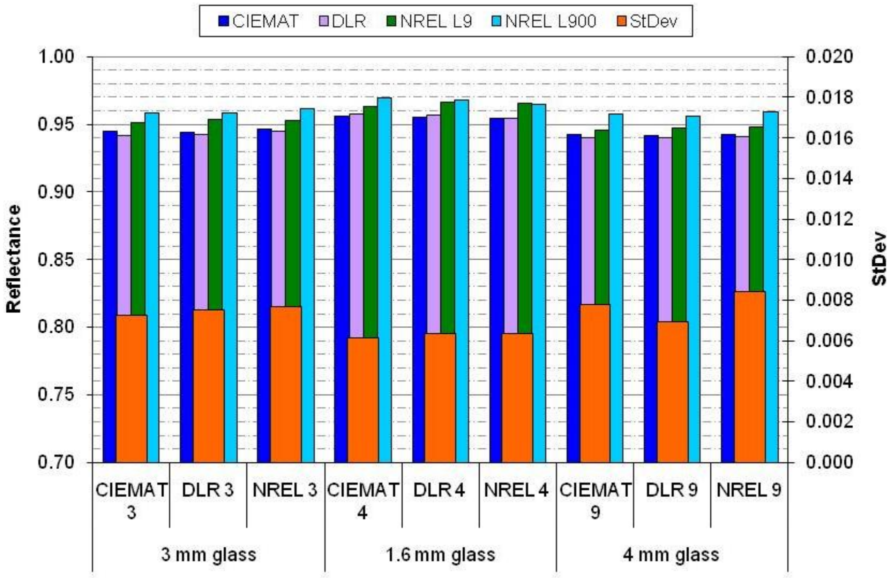

Figure 3. ρ_h**(SW,8°,** π**) ASTM G173 for 2nd surface glass mirrors.**

Surprisingly, the repeatability of the hemispherical measurements was not high between the laboratories, although the measurements within any one laboratory were very consistent. The deviation did not exceed 0.0020 for all material types when the CIEMAT and DLR measurements were compared, but the NREL results were higher. This can be explained by the NREL spectrophotometers' use of smaller integrating spheres—60 mm vs. 150 mm—and the age of the NREL reference mirrors. DLR and CIEMAT bought identical reference mirrors within the last two years from European laboratories, whereas NREL used significantly older reference standards that had not been recalibrated for a number of years because calibration services had been unavailable. This led to higher reflectance values; the same would be the case if dirty reference standards were used. In addition, the NREL spectrophotometers were overdue for their annual calibration for the first and second rounds and were recalibrated between the second and third rounds. The recalibration before the third round of CIEMAT samples reduced the deviation between laboratories, most significantly in the 1st surface aluminum and silvered polymer film.

The measurements of 2nd surface glass mirrors would be expected to have the best repeatability because of their homogeneity. The results reveal the opposite, indicating the importance of the correct reference standard. The 3-mm and 4-mm glass mirrors had the greatest deviation (StDev = 0.007) because NREL used 1-mm reference standards and DLR and CIEMAT used 4-mm standards. The thin-glass deviation is also high (StDev = 0.007) because only NREL had the 1-mm reference standards with similar properties to the samples, while DLR and CIEMAT used 1st surface aluminum standards. The aluminum samples measured against 1st surface aluminum reference standards thus show the smallest average divergence of StDevσ = 0.006. This results in a general averaged divergence of StDev = 0.007. The larger distributions of standard deviation in Figure 2 compared to Figures 3 and 4 is a result of the different material properties of aluminum and silvered polymer mirrors, which can have local variances.

4.2. Specular reflectance

The second measured value is ρ_s(660nm, 15°, 12.5mrad). At the end of the round robin test, DLR and NREL samples were measured at DLR with a fourth 15R reflectometer (plotted as "DLR add"). The results are plotted in Figures 5-7 together with the standard deviation (σ) between laboratories.

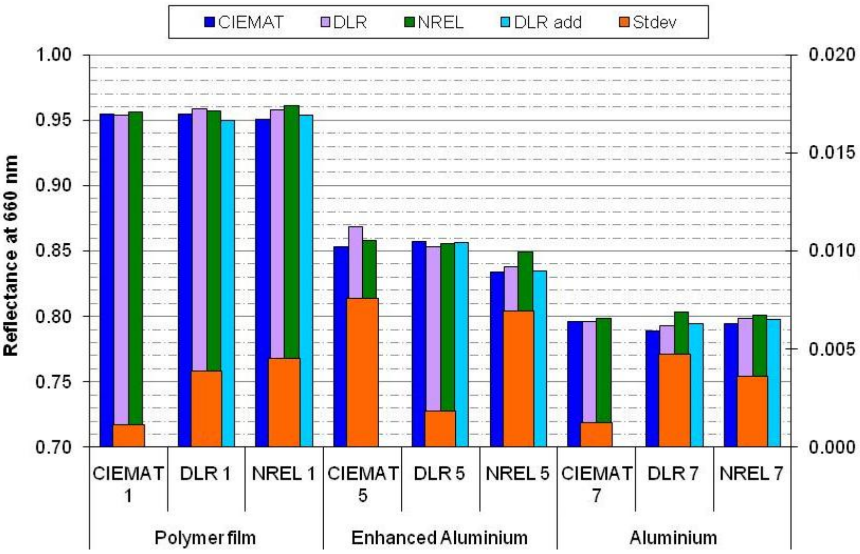

Figure 5. ρ_s(660nm,15°,12.5mrad) for polymer film and 1st surface aluminum mirror.

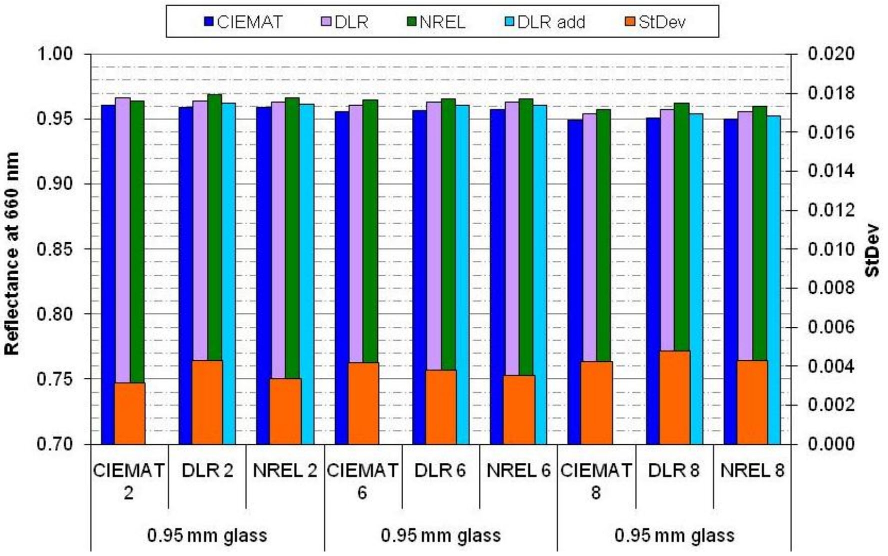

Figure 6. ρ_s**(660nm,15°,12.5mrad) for 2**nd **surface thin-glass mirrors.**

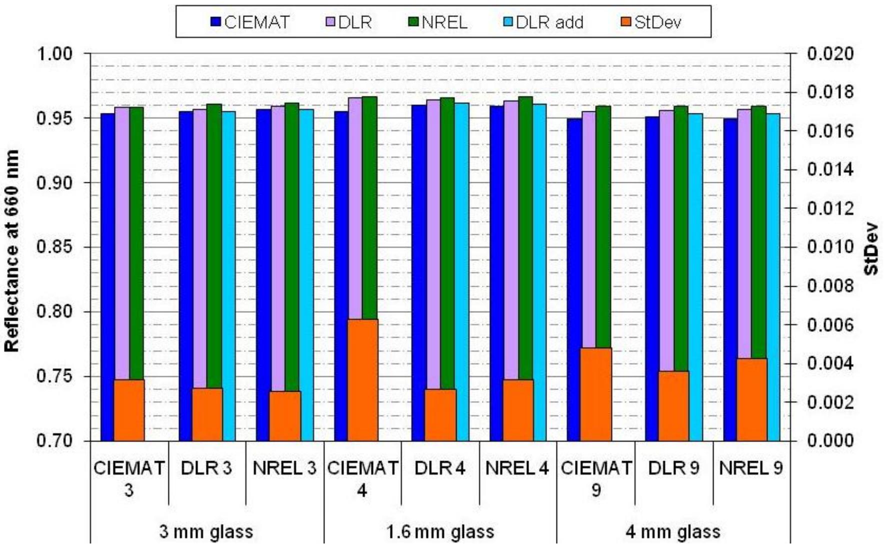

Figure 7. ρ_s**(660nm,15°,12.5mrad)for 2**nd **surface mirrors.**

The repeatability of specular reflectance for non-glass mirrors varies significantly at θ = 12.5 mrad (Figure 5) and even more at θ = 7.5 mrad. The aluminum and silvered polymer film mirrors have surfaces with microstructures and a complex reflected light distribution generally comprised of two Gaussians, one with a relatively high intensity that is highly specular (low θ) and the other having a relatively lower intensity and broader peak (high θ), which leads to local variation of reflectivity. The average deviation for all materials is StDev = 0.004.

Measurements on glass mirrors show that the difference between the four instruments is almost constant. The two new instruments of CIEMAT and DLR (“DLR add”) have more similar and lower results than the two older instruments of NREL and DLR.

5. Conclusion

The round robin test performed revealed important conclusions, about how measurement accuracy depends strongly on method, instrument, and reference standard calibration quality, selection of correct reference standard, operator experience, and sample homogeneity that will be used to further improve the measurement procedure for detailed reflectance measurements. The goal of the procedure is to optimize the capabilities of current instruments in a way that is valid for all solar mirror types on the market. The measurement accuracy achieved could be much higher than the StDev = 0.007 for $\rho_h(SW,8°,\pi)$ and StDev = 0.004 for ρ_s(660nm, 15°, 12.5mrad) measured in this round robin test.

A variation in reflectance values of 0.01 already has a significant impact on the efficiency and cost calculations for concentrating solar collectors; therefore, the reflectance measurement accuracy must be more precise than is currently possible. Improvements in commercial instruments and calibrated reference standards appropriate for the different CSP solar mirrors are critical. The work to develop a standard for solar-weighted reflectance measurements in accordance with the current state of the art will be continued. A new round robin test is planned with the improved and standardized method, and the accuracy of ρ_s(SW,15°,12.5mrad) will then be analyzed in greater detail.

Acknowledgements

The authors thank all of the mirror manufacturers who participated in the round robin test by providing samples, DKE for supporting the INS standardization project, Björn Schiricke from DLR, and Gary Jorgensen, Robert Tirawat, Marc Oddo, Christa Loux, Bryan Price, and Matthew Beach from NREL. NREL's part of this work was performed under DOE contract DE-AC36-99-GO10337.

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