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# Hemispherical Reflectance Results of the SolarPACES Reflectance Round Robin

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**Abstract**

Mirrors are the first link in the energy-conversion chain from Sun to electricity-delivery in the grid. Shape and solar reflectance are the key-parameters of mirrors, respectively affecting how solar radiation is concentrated around the focus, and how much of the impinging solar power is reflected. In SolarPACES Task III, an expert group is drafting the solar reflectance guidelines; in order to speed up the discussion the SRRR round robin was launched at the beginning of 2013. Identical kits, each one consisting of ten specimens collected from eight cooperating producers, were distributed and measured at six research institutes, acting as evaluators. The kit includes both traditional (glass based) and innovative (first-surface) solar mirrors. The paper only reports on the simplest task among those of SRRR: the solar hemispherical reflectance measurement. Near-specular solar reflectance was also measured and compared but the results are still under investigation and are not part of this paper. The measurements were accomplished according to the guidelines. The differences among the achieved results are within the typical accuracy of spectrophotometers, demonstrating the reliability of the reflectance guidelines. The statistic of the deviations from the true value is analysed separately for each evaluator, and allows us to infer information abut the gauging-status of the adopted reference mirror, as well as the measurement reproducibility.


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## 1. Introduction

A clear definition of the parameters needed to qualify components and systems for CSP applications, as well as suitable methods to measure them, are two very important goals among those set by SolarPACES TASK III - Solar Technology and Advanced Applications. Only the shared consensus on parameters and methods allows concurrent industrial products available on the market to be equitably qualified and compared.

Mirrors are of primary importance in CSP applications, being the first link in the energy-conversion chain from Sun to electricity-delivery in the grid. Shape and solar reflectance are the key-parameters of mirrors, respectively affecting how solar radiation is concentrated around the focus, and how much of the impinging solar power is reflected. The discussion on the experimental procedures for measuring shape and reflectance are going on in SolarPACES Task III, where two dedicated expert groups are drafting the guidelines.

The latest Reflectance Guidelines (version 2.5) is available for download from the SolarPACES web-page [1]. It is the result of a years-long debate, and based on a first reflectance round robin test [2]. The document establishes several important points. Among them, one of the most important concerns is the evaluation of solar-weighted hemispherical reflectance. The recommended procedure consists of measuring:

- at near-normal incidence,
- with a high quality spectrophotometer
- equipped with an integrating sphere with diameter not less than 150 mm,
- in the solar wavelength range (300-2500 nm).
- Finally, the experimental spectrum should be weighted according to the standard direct solar spectrum ASTM G173-03.

From a practical point of view, the range $0 - 10°$ is considered near-normal incidence because in this range, within experimental errors, reflectance (and transmittance) are not influenced by polarization and incidence angle of the light beam. This makes measurements more simple and reliable.

The first round robin test was performed in 2010 [2] with only three organizations participating. Main sources of error were detected. The measurement accuracy strongly depends on: method, instrument, reference-mirror, operator experience, and sample homogeneity. It revealed the necessity of standardized procedures and parameters.

In order to speed up the discussion around the guidelines, a second round robin test was launched at the beginning of 2013. Seven identical kits, each one consisting of ten specimens collected from eight cooperating producers, were distributed to seven research institutes, acting as evaluators: ENEA, CEA, CENER, CIEMAT, DLR, Fh-ISE, and NREL. Unfortunately, the latter has been unable to carry out the measurements for lack of funds.

The second round robin test, named SolarPACES Reflectance Round Robin (SRRR), has two goals: i) verify the reliability of the procedure for evaluating the solar-weighted hemispherical reflectance as suggested by the guidelines, and ii) stimulate each research institute to develop instrumentation and methods for evaluating off-normal near-specular solar reflectance. The first task has been accomplished quickly and with good results; the second is in stand-by, waiting for the completion of the two new instruments MIRA (DLR) [4] and VLABS (ISE) to verify the results achieved with the Solar Mirror Qualification developed by ENEA [5,6].

This paper reports only on the first goal, the solar-weighted hemispherical reflectance measurement; an oral report on the status of the second goal will be given at the next Task III meeting in Beijing.

**Nomenclature**

| | |
|---|---|
| SRRR | SolarPACES Reflectance Round Robin |
| $E_j$ | evaluator j-th |
| $\overline{x}$ | arithmetic mean |
| $s$ | corrected sample standard deviation |
| $x^*$ | robust average |
| $s^*$ | robust standard deviation |
| $\delta_{i,j}$ | deviation from the true value of the specimen i-th for the evaluator j-th |
| $\mu_j$ | arithmetic mean of the deviations of the evaluator j-th |
| $\sigma_j$ | corrected sample standard deviation of the deviations got from the evaluator j-th |

## 2. Solar-weighted hemispherical reflectance in SRRR

### *2.1. Round robin organization*

SRRR group is composed by two kinds of participants: producers and evaluators. The first are manufacturers, active in the solar-mirror market; the latter are scientists/technicians, highly experienced in reflectance measurements, working in one of the participating research institutes.

Producers sent a set of identical specimens of their products to the SRRR coordinator (ENEA) who in the end collected specimens of ten different solar-mirrors. Their main characteristics are shown in Tab. 1. The specimen homogeneity was initially checked at ENEA by measuring the hemispherical reflectance at 550 nm in several points close to the center of each sample. For traditional glass-based mirrors (sample 1-5) readings are almost independent on the measurement point, and the difference between two specimens is $\leq 0.005$. Samples 6-10 are innovative mirrors, characterized by using a substrate other than glass, and being *first surface mirrors*. Readings vary more depending on the spot position for those products whose reflectance spectrum is modulated by sharp interference fringes. In that case differences up to 0.02 were observed across the specimen surface, but on the other hand the spanned range does not differ more than 0.005 among the specimens of the same product. Because SRRR aims to compare the solar mean, the kit homogeneity was considered good enough to adopt the *parallel* procedure, where each participant evaluates an own set of specimens. This is time-saving and free of progressive reflectance alteration of the sample-kit that may occurs in the *circular* procedure, where the same sample kit is measured and sent to the next evaluator. Anyway, the option of still exchanging kits that show results with high divergence was held open for everybody.

Identical specimen-kits were suitably packaged to avoid surface damaging and environmental degradation: each specimen was individually wrapped in optical-quality paper-sheet; all together were sealed in a plastic bag. Evaluators were invited to measure each specimen as it is, without cleaning, in order to reduce the risk of alteration, averaging the results achieved for different position/orientation.

Table 1. Composition of the sample-kit used in SRRR.

| Sample No | reflecting surface | characteristics |
|---|---|---|
| 1 | 2nd | glass 0.95 mm |
| 2 | 2nd | glass 4 mm |
| 3 | 2nd | glass 1.6 mm |
| 4 | 2nd | glass 2 mm |
| 5 | 2nd | glass 3 mm |
| 6 | 1st | laminated on Aluminum |
| 7 | 1st | laminated on Aluminum |
| 8 | 1st | laminated on Aluminum |
| 9 | 1st | deposited on Aluminum |
| 10 | 1st | deposited on Aluminum |

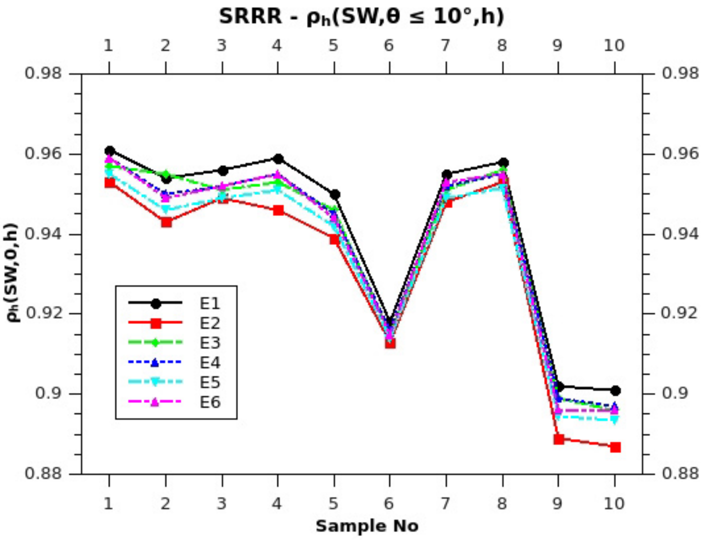


Fig. 1. Solar-weighted hemispherical reflectance (ASTM-G173) of SRRR samples (see Tab .1) measured by the six evaluators E1-E6 and evaluated according to the SolarPACES reflectance guidelines. The maximum difference among the results belonging to the same type of specimen is 0.014. This value is exactly the double of the uncertainty expected for a typical high quality spectrophotometer: the error on the reference mirror (±0.005) plus the baseline stability (±0.002). Thus the data agree within the experimental uncertainty even without including the differences among the specimens of the same type of product.

### *2.2. Results and discussion*

In accordance with the reflectance guidelines [1], each research institute used a high quality spectrophotometer, equipped with an integrating sphere with diameter not less than 150 mm. This limit is recommended in [3] and arises from the requirement that the ratio of port-area to diffusive-surface-area should be low enough (below 5%).

For each specimen, the reflectance spectrum was measured in the wavelength range 300-2500 nm, repeating the measurement on several different points of the surface, close to the center. Then, the solar reflectance was computed by applying the Standard ASTM G-173. The results obtained by the six evaluators, here anonymously codified as E1-E6, are shown in Fig. 1 and listed in Tab. 2. The maximum difference among the results belonging to the same type of specimen is 0.014. This value is exactly the double of the uncertainty expected for a typical high quality spectrophotometer: the error on the reference mirror (±0.005) plus the baseline stability (±0.002). Thus the data agree within the experimental uncertainty even without including the differences among the specimens of the same type of product.

Table 2. Solar hemispherical reflectance computed according to ASTM G173 measured by the six evaluators E1-E6.

| Sample No | E1 | E2 | E3 | E4 | E5 | E6 |
|---|---|---|---|---|---|---|
| 1 | 0.961 | 0.953 | 0.957 | 0.959 | 0.955 | 0.959 |
| 2 | 0.954 | 0.943 | 0.955 | 0.950 | 0.946 | 0.949 |
| 3 | 0.956 | 0.949 | 0.951 | 0.952 | 0.949 | 0.952 |
| 4 | 0.959 | 0.946 | 0.953 | 0.955 | 0.951 | 0.955 |
| 5 | 0.950 | 0.939 | 0.946 | 0.945 | 0.942 | 0.944 |
| 6 | 0.918 | 0.913 | 0.915 | 0.916 | 0.914 | 0.915 |
| 7 | 0.955 | 0.948 | 0.951 | 0.952 | 0.949 | 0.953 |
| 8 | 0.958 | 0.953 | 0.956 | 0.955 | 0.951 | 0.955 |
| 9 | 0.902 | 0.889 | 0.899 | 0.899 | 0.894 | 0.896 |
| 10 | 0.901 | 0.887 | 0.896 | 0.897 | 0.893 | 0.896 |

The statistical analysis of the data allows one to infer more information. According to the commonly used descriptive statistic, *arithmetic mean* ($\overline{x}$) and *corrected sample standard deviation* ($s$) are given by

$$\overline{x} = \frac{x_1 + x_2 + \ldots + x_N}{N} \qquad s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \tag{1}$$

However, the use of *robust statistic* is recommended in ISO 13528 [7], because outlier data may greatly affect those estimators. Therefore the values measured for each kind of sample have been analysed according to both methods and Tab. 3 shows the results: the agreement is better than 0.0007 and 0.0012 for mean and standard-deviation, respectively. Because these values are less than the typical spectrophotometer uncertainty, we can conclude that the solar-hemispherical-reflectance data achieved by the different evaluators are regularly distributed and none of them should be considered outlier. Therefore the usual descriptive statistics will be adopted in the following, as well as the assumption that $\overline{x}$ is the *true* value, because there is no other way to know it.

Table 3. Comparison between descriptive ($\overline{x}$ and $s$) and robust ($x^*$ and $s^*$) statistics. The agreement is better than 0.0007 and 0.0012 for mean and standard-deviation, respectively.

| Sample No | $\overline{x}$ | $s$ | $x^*$ | $s^*$ |
|---|---|---|---|---|
| 1 | 0.9573 | 0.0029 | 0.9574 | 0.0032 |
| 2 | 0.9495 | 0.0046 | 0.9495 | 0.0052 |
| 3 | 0.9515 | 0.0026 | 0.9513 | 0.0025 |
| 4 | 0.9532 | 0.0044 | 0.9537 | 0.0036 |
| 5 | 0.9443 | 0.0037 | 0.9443 | 0.0035 |
| 6 | 0.9152 | 0.0017 | 0.9150 | 0.0017 |
| 7 | 0.9513 | 0.0026 | 0.9513 | 0.0029 |
| 8 | 0.9547 | 0.0024 | 0.9548 | 0.0025 |
| 9 | 0.8965 | 0.0046 | 0.8970 | 0.0042 |
| 10 | 0.8950 | 0.0047 | 0.8957 | 0.0035 |

The analysis can be further carried on by considering the deviation of each result from its respective true value, i.e.

$$\delta_{i,j} = x_{i,j} - \overline{x}_i \tag{2}$$

where $i$ ($j$) is the sample (evaluator) index. Figure 2 shows the plot of $\delta_{i,j}$: the repeating order of the data per evaluator in respect to each other indicates a systematic source of the deviations. Here quality and gauging of the reference mirror play a mayor role and systematically affect all the reflectance values measured by the same evaluator, turning away the mean value of his deviations

$$\mu_j = \frac{1}{10}\sum_{i=1}^{10}\delta_{i,j} \tag{3}$$

from the true value

$$\overline{\mu} = \frac{1}{6}\sum_{i=1}^{6}\mu_j = \frac{1}{6}\frac{1}{10}\sum_{i=1}^{6}\sum_{i=1}^{10}(x_{i,j} - \overline{x}_i) = 0. \tag{4}$$

Other factors, like operator experience, age of light source, maintenance status of the instrument, as well as, the difference between specimens of the same type ($\leq 0.005$ @ $\lambda = 550$ nm) are sources of random errors, and affect the standard deviation

$$\sigma_j = \sqrt{\frac{1}{9}\sum_{i=1}^{10}(\delta_{i,j} - \mu_j)^2}. \tag{5}$$

As general rule, if $\mu_j - \sigma_j > 0$ ($\mu_j + \sigma_j < 0$) the reference used by $E_j$ may be over (under) evaluated; high value of $\sigma_j$ may be related to some weak points of the procedure adopted by $E_j$.

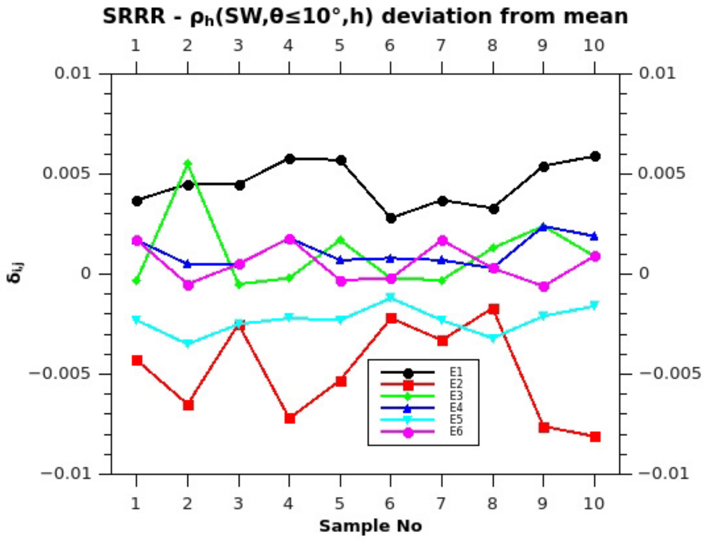


Fig. 2. Deviation $\delta_{i,j} = x_{i,j} - \overline{x}_i$ of the solar weighted hemispherical reflectance of the specimen i-th (with $i = 1, 2, \ldots, 10$) measured by the evaluators $E_j$ with $j = 1, 2, \ldots, 6$. The repeating order of the data per evaluator in respect to each other indicates a systematical source for the deviations.

On the basis of these argumentations, from Fig. 3, one can observe that the results obtained by evaluators E3, E4, E5 and E6 seem the closest to the true value; E5 is the evaluator with best reproducibility; E2 exhibits the worst reproducibility and results lower than the true value, which might be due to an under-evaluated reference mirror; E1 shows good reproducibility, but the results are higher than the true value, which might indicate an over-evaluated reference mirror. There might also be other influences that produce the differences. However, Fig. 3 demonstrates that the results from all evaluators do not deviate from the true value more than ±0.007. This also includes the observed difference between specimen of the same type, which is present even if small ($\leq 0.005$ @ $\lambda = 550$ nm). The agreement between all participants is thus very well, even for the innovative mirrors.

## 3. Conclusions

The SRRR round robin test was performed to verify the reliability of the SolarPACES reflectance guidelines [1]. It was concluded successfully for its first objective. The analysis of the solar hemispherical reflectance values using sets of 10 specimens that were provided by 8 manufacturers and were measured by 6 evaluators. The maximum difference among the results got from the different evaluators is 0.014. No outlier data were recognized. The deviation of the results got by each evaluator from the mean, which is assumed to be the true value, is smaller than ±0.007 and includes also the differences between specimen of the same type across the distributed sets which is up to $\leq 0.005$ @ $\lambda = 550$ nm. The data from all evaluators agree within the expected experiment uncertainty well.

Moreover, the statistic of the differences between result and true value, separately dealt for each evaluator, allows to infer information abut the gauging-status of the adopted reference mirror, as well as measurement reproducibility and other systematic problems.

The results of the SRRR demonstrate the reliability of the recommended procedure described in the SolarPACES reflectance guidelines in regard to the solar weighted hemispherical reflectance.

Near-specular reflectance measurements were also performed in this round robin test but not completed in time because new instruments were not ready. When these last measurements and their analysis are completed the results will be presented to the solar community.

## References

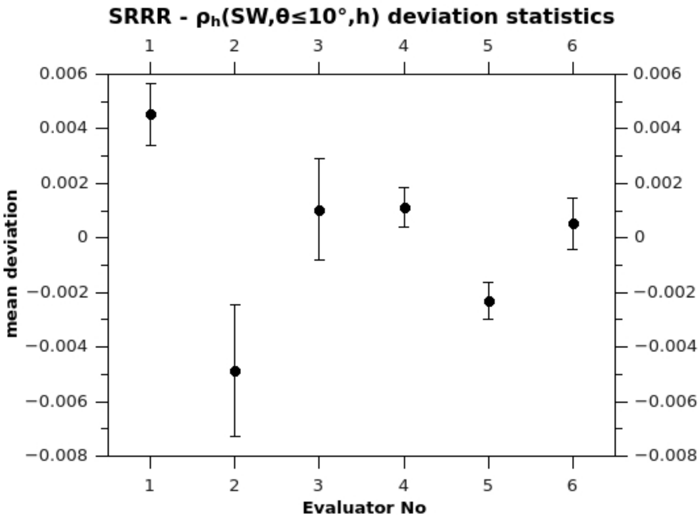


Fig. 3. Mean $\mu_j$ and standard deviation $\sigma_j$ of the deviation $\delta_{i,j} = x_{i,j} - \overline{x}_i$ of the evaluators $E_j$ with $j = 1, 2, \ldots, 6$. Evaluators E3, E4, E5 and E6 seem the closest to the true value; E5 is the evaluator with best reproducibility; E2 exhibits the worst reproducibility and results lower than the true value, which might be due to an under-evaluated reference mirror; E1 shows good reproducibility, but the results are higher than the true value, which might indicate an over-evaluated reference mirror.

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