

Simplified Set-Up for Near-Specular Solar Reflectance Measurement

M. Montecchi^{1,*} , F. Sutter² , and J. Wette³ 

¹ENEA, Italy

²DLR, Germany

³CIEMAT, Spain

*Correspondence: Marco Montecchi, marco.montecchi@enea.it

Abstract. In Concentrating Solar Power (CSP) plants, mirrors are used to redirect solar radiation onto a receiver. More precisely, the solar radiation, diverging with a half-angle of about 4.7 mrad, impinges off-normal on the mirror. Only the radiation reflected within the acceptance angle of the receiver is geometrically intercepted. Therefore, the kind of reflectance relevant for CSP applications can be defined as “near-specular”; it depends on three angles: solar-divergence, incidence on the mirror and detector-acceptance. Actually, the market is lacking of instruments to properly measure the near-specular reflectance. For that purpose only one custom instrument was set-up at a highly specialized laboratory to measure the spectral near-specular reflectance for both clean and soiled mirrors; in the latter more radiation is reflected beyond the acceptance angle. Now, the Work-Package 4 of the “Recommendations for reflectance measurements on soiled solar mirrors” Project funded by SolarPACES aims to cover that gap by outlining a Simplified Set-Up (SSUp) based on commercial components. It can be replicated by anyone having just basic skills in optics. The concept could even be taken by an industrial player to commercialize an engineered version of SSUp.

Keywords: Solar Reflectance, Mirrors, Soiling

1. Introduction

In Concentrating Solar Power (CSP) plants, mirrors are used to redirect solar radiation onto a receiver. Because from the Earth the Sun is not a point source, solar radiation is diverging; the typical (half) angle is about 4.7 mrad. As shown in Fig. 1, generally the solar radiation impinges on the mirror at the incidence angle θ , conveniently set to redirect the radiation towards the receiver. The size and distance of the receiver (or detector) determine the acceptance (half) angle φ_R within the reflected radiation is intercepted. In practical cases, the mirror surface is usually more or less soiled, thus diffraction and scattering enlarge the proportion of the reflected radiation outside the specular direction [1] – this radiation is lost to the energy conversion process. On the other hand, the part of reflected radiation travelling inside the (half) apex-angle φ_R cone is successfully intercepted by the receiver and can be exploited for CSP purposes. As a consequence, the most important mirror parameter to be evaluated is the so called near-specular solar-weighted reflectance, measured in the range 320-2500 nm, by means of a diverging light beam of 4.7 mrad (half angle), at the incidence angle θ and acceptance angle φ_R of interest for the specific plant [2]. A recently unpublished survey on several CSP plants showed that the yearly solar average of θ and φ_R are contained in [35, 45] deg and [6, 25] mrad intervals, respectively.

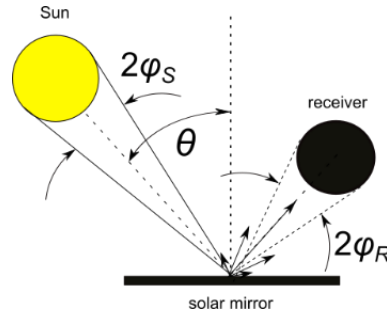


Figure 1. Schematic of relevant parameters for CSP applications

Unfortunately, the market lacks of suitable commercial instruments to measure the above described reflectance parameter. Only highly specialized optical laboratories developed several specialized set-ups [3], among them S2R [4] is certainly the most versatile and accurate even for soiled specimens.

Now the Work-Package 4 of the “Recommendations for reflectance measurements on soiled solar mirrors” Project funded by SolarPACES aims to cover that gap by outlining a Simplified Set-Up (SSUp) based on commercial components, which can be replicated by anyone having just basic skills in optics. The achieved results will be used to upgrade the SolarPACES reflectance guideline [5].

It would be even better if the concept here presented would be taken by an industrial player to produce and commercialize an engineered version of the SSUp.

2. The simplified set-up

Since the approval in March 2023 of the SolarPACES project *Update of guideline “Recommendations for reflectance measurements on soiled solar mirrors”*, ENEA has been developing the Simplified Set-Up (SSUp) at the Casaccia research centre.

The system design was driven by the following principles: simplicity, duplicability, and quick measurement. Therefore, as far as possible, the intention was to use easily available commercial components. To reduce measurement time as much as possible, the spectral analysis is entrusted to one or more spectrometers.

Due to lack of funding, the first demonstrative SSUp prototype was assembled on the basis of already available hardware components by adopting the optical scheme discussed in the following section. The results were very encouraging, but spectrally limited to 400-700 nm because of the old Ocean Optics USB2000 spectrometer.

Considering the importance of the topic, successively the set-up was implemented with two new spectrometers and a smaller integrating sphere (to increase the signal). The purchase of these new components was funded by the Italian Ministry of Environment and Energy Security through the “National Electric System Research” Programme – Project 1.9 “CST/CSP technology”, 2022-2024 implementation plan.

2.1 The optical scheme

The optical scheme of the SSUp is shown in Fig.2.

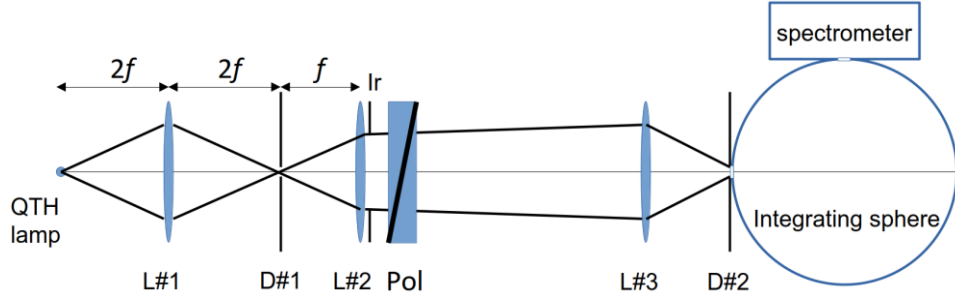


Figure 2. Optical sketch of the SSUp arranged in the baseline configuration performed without any mirror (see the text). To be measured, the specimen has to be inserted between Pol and L#3, requiring the proper realignment of the detector unit

Part of the radiation emitted by a Quartz Tungsten Halogen (QTH) lamp is focused by the lens L#1 on the diaphragm D#1 having the diameter ϕ_1 ; the transmitted radiation is collimated by the lens L#2 with focal length f_2 making a light beam diverging for the (half) angle

$$\varphi_s = \frac{1}{2} \frac{\phi_1}{f_2} \quad (1)$$

Before the beam impinges on the mirror surface (not displayed in Fig. 2) with an incidence angle greater than 15 deg, the beam is *s* or *p* polarized by Pol. The (reflected) beam is finally focused on the diaphragm D#2 (diameter ϕ_2) by the lens L#3 (focal length f_3), so that only the radiation diverging for less than the acceptance angle

$$\varphi = \frac{1}{2} \frac{\phi_2}{f_3} \quad (2)$$

enters into the integrating sphere and can be detected by the spectrometer. The spot-size of the beam impinging on the mirror surface can be adjusted by means of the iris diaphragm Ir, just placed at the exit of L#2.

It is noteworthy that in spectroscopic UV-VIS-NIR instrumentation, generally the light beam is manipulated by means of aluminium mirrors which exhibit achromatic focal length and high reflectance over a wide spectral range. Due to the limited budget, fused-silica lenses were used instead, which were already present at the lab. Transmittance and focal-length variation in the solar range 320-2500 nm resulted to be acceptable for our purposes.

2.2 The prototype

To obtain the collimated beam, advantage was taken of the lamp-housing already developed in early 2000s, in the framework of the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) of CERN, shown in Fig. 3.

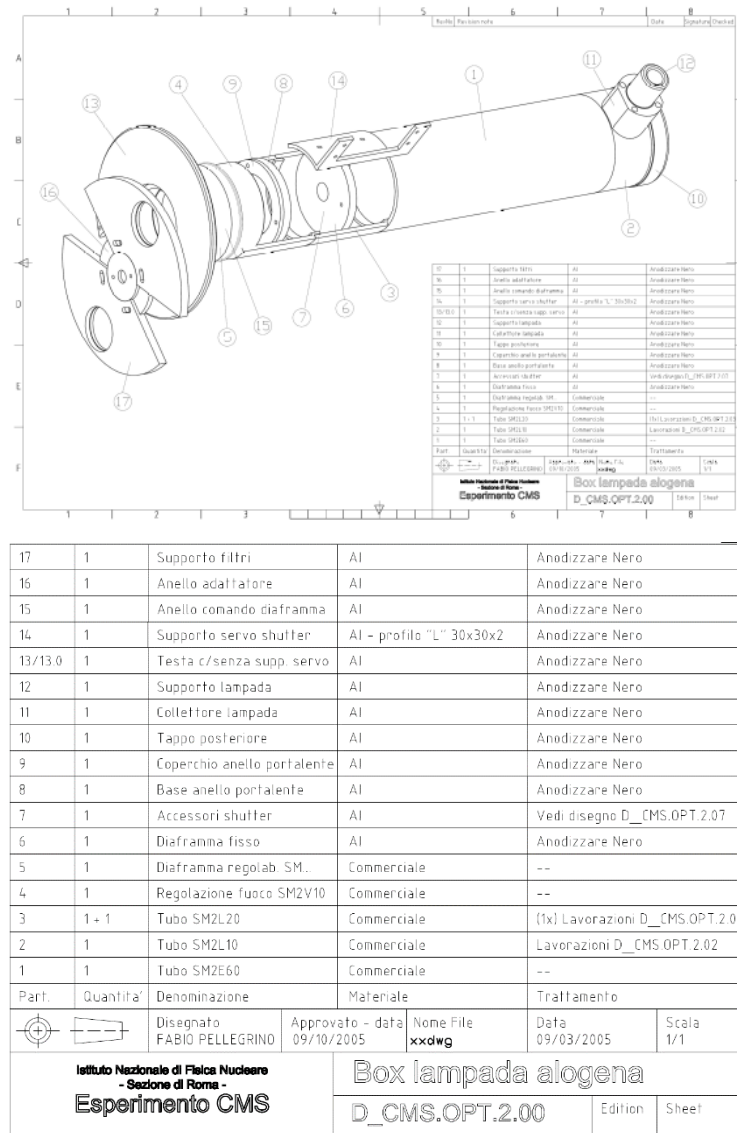


Figure 3. Schematic design of the lamp housing project with part list.

As specified in the legend, this lamp housing is mostly based on Thorlabs commercial components.

Referring to Fig. 2, the lamp housing includes the following components: QTH lamp (100 W), L#1 ($f_1 = 64$ mm), D#1, L#2 ($f_2 = 64$ mm) and Ir (ϕ adjustable in the range 1-25 mm). The distance QTH-L#1 and L#1-D#1 are set to $2f_1$ once for all, while D#1 was replaced with a new unit with diameter $\phi_1 = 0.6$ mm, values required by Eq. 1 to have a beam with divergence of 4.7 mrad.

The distance between L#2 and D#1 can be finely tuned by the adjustable lens tube (part of the housing); this distance was set to obtain the light beam increasing of 10 mm along a path of 1000 mm (divergence half-angle of 5 mrad).

The aperture of the iris Ir was adjusted to set to 12 mm the diameter of light beam hitting the specimen, similarly to the case of the S2R instrument [4] here used as reference.

As shown in Fig. 4, the remaining part of the instrument is installed on an optical top bench.

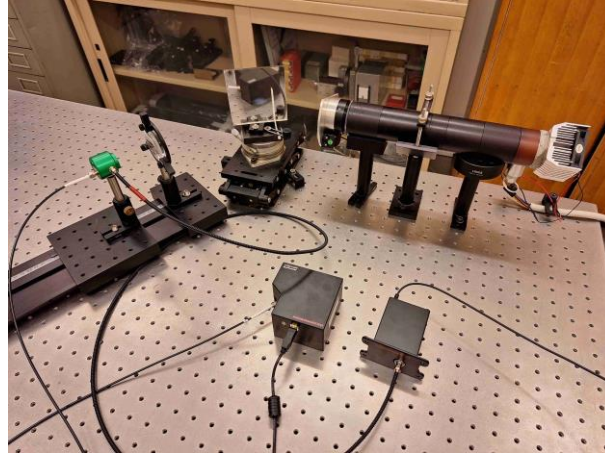


Figure 4. SSUp version August 2024, aligned for measuring at incidence angle of 60 deg

More precisely, the lamp housing (and the beam) is aligned horizontally. The specimen (the mirror) is installed on a goniometer rotation stage, equipped with an adjuster kinematic mirror mount; the latter allows the fine tilting of the mirror. In particular, the 0° of incidence and the orthogonality of the mirror surface to the beam are initially set by resending the reflected beam into the lamp-housing. Thanks to the beam enlargement occurring along the path, that alignment can be easily achieved by symmetrizing the bright annulus visible in the peripheral part of the adjustable iris diaphragm Ir.

As shown in Fig. 5, lens L#3, diaphragm D#2, and integrating sphere are firmly installed on an optical rail to make the so-called detector unit, which can be moved on the table surface as a whole. Please note that the diaphragm D#2 is installed on the entrance port of a 10 mm Artifex polymer integrating sphere, equipped with two SMA connectors to simultaneously inject the light signals into the optical fibres connected to the Hamamatsu spectrometers C10083MD (320-1000 nm) and C15511-01 (1100-2500 nm). The centres of L#3 and D#2 have been aligned centrally to the light beam by conveniently adjusting position and height of each component on the rail.

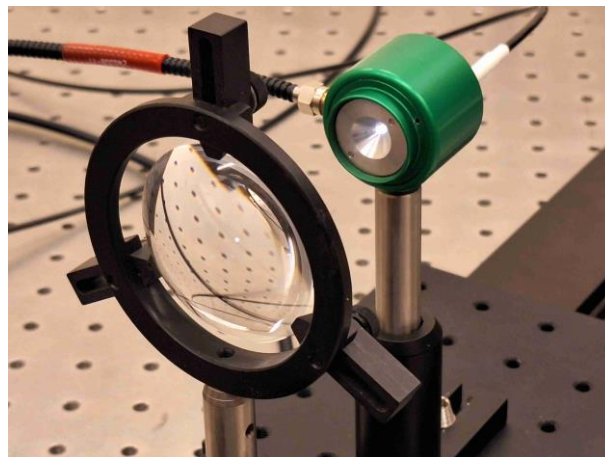


Figure 5. Detector unit, composed by the lens L#3, the diaphragm D#2 and the 10 mm integrating sphere. D#2 is placed at the entrance port of the integrating sphere

The distance between L#3 and D#2 has to be adjusted once for all according to the criterion of minimizing the diameter of the focused spot at the D#2 plane; the optimal distance between the lens flat side and D#2 resulted to be 63 mm. On the other side, according to the Oriel catalogue, the nominal back focal length from the lens flat side is 53.8 mm, while the nominal focal length is 65 mm. Therefore, the “principal point” is expected to be 11 mm far from the flat side (inside the lens). Therefore, at the optimized distance between L#3 and D#2,

the effective distance between the L#3 principal point and the diaphragm is $63+11=74$ mm. That value is 9 mm greater than the focal length of L#3, possibly for compensating the beam divergence.

In the end, after some preliminary tests, the D#2 diameter has been set to 1.82 mm to obtain $\varphi \approx 12.3$ mrad, according to Eq. 2. That is the chosen value for the initial comparison of SSUp with the reference instrument S2R.

Unfortunately at the present, no mechanical components are available, suitable to hang the detector unit to a rigid arm, pivoting around the vertical axis of the sample-holder goniometer; therefore the detector unit has to be carefully realigned on the reflected/transmitted beam the incidence angle is changed. Please note that this realignment just concerns the horizontal plane: thanks to the horizontality of the beam, the alignment in the vertical direction is maintained. Therefore, one has just to translate and rotate the detector unit to let the beam cross the L#3 centre, and at the same time the centre of D#2. This operation takes only few seconds; the reproducibility is very good.

3. Comparison with S2R – preliminary results

The validation of SSUp consists in comparing the reflectance spectra of a set of artificially soiled specimens with those previously measured with the reference instrument S2R. As a matter of fact, the measurement of soiled mirrors is the most challenging. The advantage of using artificially soiled mirrors, instead of naturally soiled ones, is that the latter are subject to the risk of modification during transport and handling due to the precarious adhesion between the dirt particles and the mirror surface.

Unfortunately, due to a temporary malfunctioning of S2R, the spectral range of the first set of specimens sent in ENEA-Casaccia was limited to the UV-VIS range (320-860 nm).

Successively, along the SSUp development, an unrecognised limit of S2R was pointed out: as shown in Fig. 6, the 90° off-axis parabolic mirror (carrying out the same task of L#3 in SSUp) actually used to focus the reflected beam on the diaphragm in S2R (which corresponds to D#2 in SSUp) does not allow to set uniquely the acceptance angle, because the length of the optical path between the reflecting surface and the diaphragm depends on the point of reflection, changing for more than 35%.

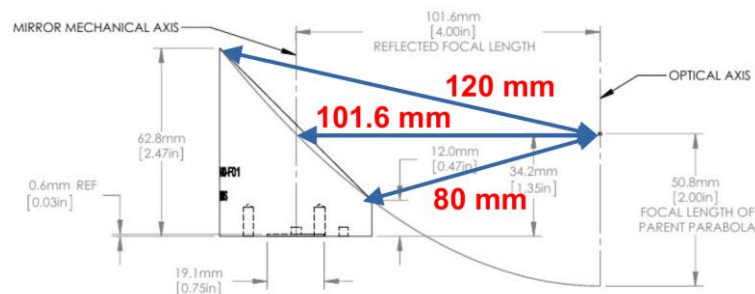


Figure 6. In off-axis parabolic mirrors the length of the optical path between point of reflection and focal point is different; that makes the acceptance angle not perfectly defined for this type of mirror.

Soon after the conclusion of a measurement campaign launched in 2024, the S2R instrument will be modified by replacing the 90° off-axis parabolic mirror with a standard spherical mirror; then a new set of artificially soiled specimens will be measured and sent to ENEA-Casaccia, allowing the definitive validation of SSUp.

At the present it was only possible to compare the SSUp spectra with those obtained with S2R in the range 320-860 nm keeping in mind that there the acceptance angle is not well defined: it ranges around the nominal value of 12.3 mrad.

The set consists of a clear (clean) mirror (Tgy1), and three artificially soiled labelled as S6 (sand-blasted), HO1 (hair-sprayed) and P2 (black paint sprayed); all these samples are flat.

To make the results more reliable and reduce the time of measurement, the baseline measurement is performed at the given incidence angle and polarization on the clean mirror Tgy1; then the other artificial soiled coupons are measured getting the ratio of their reflectance to the one of the clean coupon; that ratio is the *cleanliness* of the mirror. That method offers a second important advantage: the results are completely not depending on the reference used in S2R. In the case of samples with curved surface, that procedure (i.e. the baseline performed with the clean specimen at the given incidence angle and polarization) is mandatory because it properly compensate the effect of the not flat surface.

Figure 7 shows the comparison of the cleanliness measured with SSUp (black line) and S2R (blue points) for the three artificially soiled specimens.

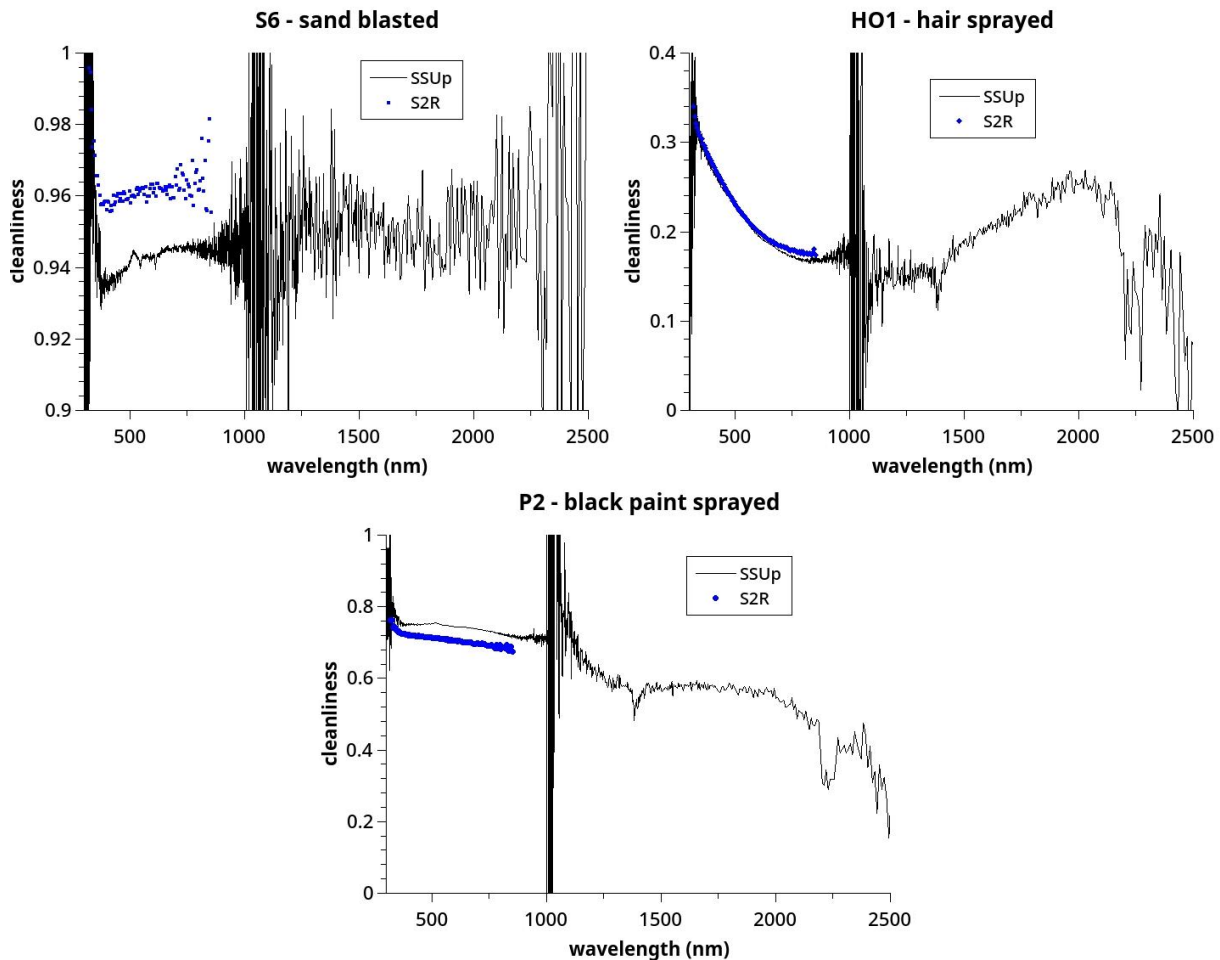


Figure 7. Comparison of the cleanliness spectra measured with SSUp and S2R for the artificially soiled specimens S6 (top left), HO1 (top right), and P2 (bottom)

Considering the temporary limits of S2R, the agreement is reasonably good, making the SSUp instrument very promising.

The definitive validation is expected by the end of 2024.

Data availability statement

Data can be distributed under request by sending an email to the contact author.

Underlying and related material

None at the present.

Author contributions

Montecchi: conceptualization, methodology, software, validation, investigation, supervision, original draft

All the other: validation, investigation, resource, review & editing

Competing interests

The authors declare that they have no competing interests.

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