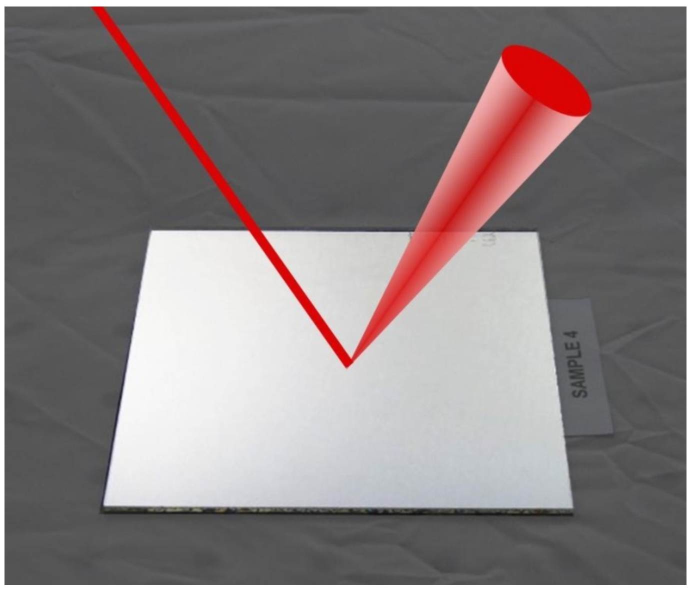
Guidelines

PARAMETERS AND METHOD TO EVALUATE THE REFLECTANCE PROPERTIES OF REFLECTOR MATERIALS FOR CONCENTRATING SOLAR POWER TECHNOLOGY



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SolarPACES is an international cooperative network bringing together teams of national experts from around the world to focus on the development and marketing of concentrating solar power (CSP) systems (also known as solar thermal power systems). It is one of a number of collaborative programs, called Implementing Agreements, managed under the umbrella of the International Energy Agency to help find solutions to worldwide energy problems. Within SolarPACES several international Task-activities coordinate the work.

The objectives of Task III "Solar Technology and Advances Applications" deal with the advancement of technical and economic viability of emerging solar thermal technologies and their validation with suitable tools by proper theoretical analyses and simulation codes as well as by experiments in special arrangements and adapted facilities. For this purpose, procedures and techniques are defined for the design, evaluation and use of the components and subsystems to optimize concentration, reception, transfer, storage and application of solar thermal energy. In essence, the goals are to investigate innovative multi-discipline advances needed for the further development of concentrating solar thermal systems. This also concerns, among others, process heat applications, the utilization of solar concentration for the development of improved materials, and the introduction of hybrid solar/fossil power plant concepts.

A group of experts in the field of optical mirror reflectance characterization has been working together as members of Task III to create this document of a reflectance measurement guideline. The solar community is called to work towards consensus of procedures and to promote the guidelines to be transformed into international IEC standards through the national organizations like UNE, IEC, DKE, ASME, ASTM, etc.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. SolarPACES shall not be held responsible for identifying any or all such patent rights.

The guideline is open to amendments and updating as the state of the art of measurement instruments and procedures advances. Please send comments, amendments, suggestions to arantxa.fernandez@psa.es (Ms. Aránzazu Fernández García, CIEMAT-PSA).

Introduction

This guideline for reflectance characterisation of solar reflectors is published under the framework of the SolarPACES Task III: “Solar Technology and Advanced Applications”. Within the SolarPaces Task III standardization activities, the project “Development of guidelines for standards for concentrating solar power (CSP) components” (2010-2011) was created by a small working group of researchers from DLR (*Deutsches Zentrum für Luft- und Raumfahrt*, Germany, acting as coordinator), CIEMAT (*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas*, Spain) and NREL (National Renewable Energy Laboratory, USA) because of the urgent demand to standardize the qualification procedures of solar mirrors and to provide reliable performance analysis tools, whose results are comparable within the solar community. Therefore, the scope of this project was to collect and prepare recommendations of procedures that can be presented to the standardization organizations (ISO, IEC, ASME, DIN, UNE, etc) and that can be formulated into international standards with respect to the following topics:

1. Guidelines for reflectance characterisation.
2. Guidelines for mirror panel and modules characterisation.
3. Guidelines for receiver performance measurements.

The milestones of this project are listed below:

- Develop draft standard procedures and distribute them among the SolarPACES Task III working group for discussion and iteration.
- Organize a round robin test campaign based on the procedures defined in the proposed standards and publish the results in a conference paper.
- Disperse the standards within the solar community through the SolarPACES website.

Focused on the first topic, a round robin test was performed between the three laboratories above mentioned with samples that represent all of the commercial solar mirrors currently available for CSP applications. The results obtained were presented in SolarPACES Conference 2010 [1]. In spring of 2011, a first interim guideline version on a specified measurement method to obtain solar weighted reflectance and monochromatic specular reflectance values with commercially available instrumentation was created by this small working group and published at the SolarPACES homepage [2].

On the basis of that document, a broader board of experts was formed with the incorporation of researchers from ENEA (*Agenzia Nazionale per le Nuove Tecnologie, l’Energia e lo Sviluppo Economico Sotenibile*, Italy), the Fraunhofer Institute for Solar Energy Systems (ISE, Germany) and CTAER (*Centro Tecnológico Avanzado de Energías Renovables*, Spain). These experts exchanged their knowledge and experience in comments and discussions that were implemented in the second version of a reflectance measurement guideline [3]. Thanks to these collaborations and also thanks to a strong involvement from the solar industry (Guardian Industries, Flabeg, AGC glass, 3M, Alanod, Constellium, Evonik, Abengoa Solar, Skyfuel etc.) the process towards reaching international consensus progressed very much. This second guideline was accepted as official SolarPACES reflectance guideline and published on its website in June 2013, replacing the first one.

In order to speed up the discussion around the guidelines, a small working group was created in 2013, developing an intense and fruitful cooperation since then. Within this group a second round robin test was launched with the coordination of ENEA. 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 (*Commissariat à l'Energie Atomique et aux Energies Alternatives*, France), CENER (*Centro Nacional de Energías Renovables*, Spain), CIEMAT, DLR, and Fraunhofer-ISE. The second round robin test, named SolarPACES Reflectance Round Robin (SRRR), had two goals:

1. Verify the reliability of the procedure for evaluating the solar-weighted hemispherical reflectance as suggested by the guidelines.
2. Stimulate each research institute to develop instrumentation and methods for evaluating off-normal near-specular solar reflectance.

According to the results obtained in the SRRR, which were published in SolarPACES Conference 2013 [4], the first task was properly accomplished. Solar-weighted hemispherical reflectance values measured by the evaluators with commercial instruments according to the protocol included in the SolarPACES Guideline V2.5 were in good agreement because the differences among the achieved values are within the typical measurement uncertainty of spectrophotometers. However, the second goal was not fulfilled because a lack of commercial instrumentation to adequately characterize the spectral near-specular reflectance of reflector materials was noticed. Only in some cases, like highly specular silvered-glass reflectors, simplifications and approximations to the procedure may be suitable. Nevertheless, a consensus about how to verify the specularity of a reflector material and the validity of the proposed simplified procedure was still needed.

The next step consisted on launching a new SolarPACES project titled “Reflectance Measurement Working Group under SolarPACES Task III” (2014-2017) to fund two workshops, under the coordination of CIEMAT and with the participation of the SRRR evaluators (ENEA, CEA, CENER, CIEMAT, DLR, and Fraunhofer-ISE), in addition to the University of Zaragoza (Spain) and PROMES (France). The goals of the workshops were as follow:

1. To modify the version 2.5 of the SolarPACES guideline to include a simplified procedure for highly specular mirrors.
2. Progress in the protocol to measure spectral near-specular reflectance of all kind of reflectors with the new advanced instruments.

The first workshop, hosted by ISE Fraunhofer, took place in July 2015, while the second one, hosted by CIEMAT-PSA, was hold in May 2017. As a result of the first workshop, a simplified procedure for highly specular mirrors was agreed and published in SolarPACES Conference 2015 [5]. During the second workshop, other aspects was addressed, such as the nomenclature, wavelength range for the solar reflectance, UV-weighted reflectance, measurement of aged or soiled mirrors, sample treatment and uncertainty calculation. All the agreements achieved during these two workshops are included in this current version of the SolarPACES Guideline (version 3.0), which substitute the previous version (version 2.5) and is available in the SolarPACEs website.

As the importance of measuring also the near-specular reflectance in a proper manner is now fully acknowledged by the SolarPACES Reflectance Group, but its experimental measurement is a hard task even for highly specialized optics laboratories, a new project SolarPACES project titled “Measuring and modelling near-specular solar reflectance at different incidence angles” was initiated (2017-2018). This project is coordinated by DLR, with the participation of ENEA, Fraunhofer ISE, CIEMAT and the University of Zaragoza. The project aims to take the current state of the art of reflectance measurements one step further, meaning that all three relevant parameters influencing the reflectance of a solar mirror will be considered: the entire solar wavelength range and the relevant incidence and acceptance angles for the CSP technology. The development and update of three new laboratory prototypes are being supported: SMQ by ENEA [6, 7], S2R by DLR [8], and VLABS by Fraunhofer-ISE [9-11].

1 Scope

The reflector quality in a CSP system directly influences the amount of solar radiation that can be converted into power. The efficiency of a CSP collector can be characterized by the solar flux that reaches the receiver, is absorbed and converted into heat, in relation to the solar incident flux at the aperture plane. The net solar flux intercepted by the receiver is influenced by the sun shape, the contour accuracy of the concentrator, the tracking system accuracy, the receiver position in relation to the ideal focal position, the incidence angle of the incoming sunlight relative to the concentrator, and the quality of the reflector [12-14]. This document is focused only on the last of these influences. The first characteristic demonstrating the quality of the reflector is its ability to reflect the majority of the incident sunlight. This can be quantified by the solar-weighted hemispherical reflectance, dependent on the incidence angle. Second, the reflected sunlight needs to be directed to the receiver with minimal loss; this is quantified through the specularity of the reflector (as well as its shape which is not part of this guideline).

Several types of solar mirrors are commercially available, including silvered glass of different thicknesses, metalized (primarily silver) polymer films, polished and anodized aluminum and other types that are expected to enter the market. The reflectance of these various reflector types can vary significantly, as does the amount of beam spread or wide angle scattering (i.e. the quality of specularity).

In solar applications, reflectance is best quantified in terms of solar-weighted reflectance, since not all parts of the solar spectrum have equal amounts of energy. So weighting a reflector's spectral reflectance according to the energy content of the solar spectrum is proper. Spectral reflectance is generally measured using an instrument that measures the hemispherical reflectance, that is, all reflected light is measured regardless its directionality. This is the solar-weighted hemispherical reflectance. Since the performance of solar concentrators also depends on the amount of beam spread and scattering that occurs at the reflector, specularity of the reflected light must also be characterized. The specularity profile of some reflectors, like silvered glass mirrors is very tight and can be adequately described by a tight, circular Gaussian distribution. Other reflectors provide a greater challenge for characterizing specularity because the reflected beam distribution is more complex and sometimes even anisotropic. Research regarding these various reflector behaviors was performed in the past [15, 17] and has been taken up again recently [18, 20]. The reflection properties can change depending on the incidence angle of the incident radiation. In CSP collectors, not only near normal incidence angles occur, but also greater angles up to 60° or even more (depending on system design). This has been mainly ignored in hitherto reflectance evaluations, where near normal incidence measurements are common, but it should be considered in a complete characterization [11, 21-22].

As observed in [4], the measurement of near-specular reflectance is difficult because the experimental reading is affected by the divergence of the measuring light beam itself. Unless the beam divergence is negligible with respect to the lower limit of the acceptance angle range one wants to investigate, the signal must be properly deconvoluted. In order to reduce such effect, and to make the experimental set-up simple, SMQ, MIRA, and VLABS adopt single wavelength or narrow band light sources, but that choice does not allow to continuously perform the measurement along the whole solar spectrum. Therefore, solar-weighted values can be obtained by means of a proper data modelling, as done in SMQ [7].

Recently the SolarPACES expert group is investigating a new approach: the inescapable divergence of collimated light beams obtained by not coherent sources makes the measurand a bit different from the canonical concept of reflectance, being it based on impinging plane waves. On the other hand, as recently proposed [20], when one assume a standard value for the divergence of solar radiation and set to that value the divergence of the impinging beam, the measurand, even if it is not exactly the canonic reflectance, certainly it represents something which is perfectly suitable for CSP applications: that is the "conic" reflectance. That is the preliminary theoretic assumption making the new instrument S2R [22] ready to use, without need of cumbersome data processing. Data comparison and discussion are still going on; as soon as possible the results will be reported in a next version of this document.

At the present, for the actual version of the guideline, we have to state that due to the lack of commercial available instrumentation to adequately characterize all reflectance properties of a reflector material [23], a straight forward measurement procedure that obtains reliable results valid for all materials is not possible at the current state of the art. Only in some cases, like highly specular glass reflectors, simplifications and approximations are suitable. In other cases a more thorough characterization is necessary, which might only be possible at specially equipped laboratories or even only with newly developed instrument prototypes. A general, step by step measurement procedure does not meet the different needs of the production industry, the application industry and the research sector. Therefore this guideline is focused on defining the parameters and values, that are necessary for a reliable reflectance characterization of a solar reflector material. This includes recommendations about instrument property requirements, proposals for simplifications and recommendations where these are applicable.

The goal of this document is to serve as guidance on the relevant parameters and measurement possibilities to reliably evaluate the reflectance quality of a solar reflector material, under laboratory conditions. It is a tool on how to obtain and provide the necessary data on reflectance properties, so that the material in question can be adequately evaluated for its destined application or be compared with other materials. It does not serve as guidance on how to use these data in simulations, ray-tracing, evaluation of efficiency in different collector systems etc. Commercial instruments or validated laboratory prototypes may be employed to measure the here defined parameters, as long as they fulfil the here mentioned requirements. This guideline describes on one hand the parameters and values that should ideally be measured for a complete and adequate reflector characterization. Since the technology to fulfil the ideal case is not yet available, the guideline defines on the other hand the minimum required parameters that are necessary for a useful evaluation and that can be acquired today.

One set of parameters shall serve to qualify all types of solar reflector materials. This set of parameters is described in chapter 4. Afterwards, the requirements for measurement instrumentation and the measurement procedure are discussed in chapters 5, 6 and 7. A first approximation of the methodology to monitor aged and/or soiled mirrors samples (which will be improved in further versions of this guideline) is included in chapter 8. The values to be reported and the accuracy that should be approached are described in chapter 9 and Annex B gives an evaluation example and a more detailed explanation of how to obtain solar weighting factors.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply, in part based on [24-27].

2.1 Basic definitions for reflectance

Reflectance
Light interacts with the matter it intercepts. The light can be absorbed, transmitted, or reflected according to the three corresponding ratios, depending on the wavelength of the light and the material properties. The material properties associated with these behaviours are absorptance, α, transmittance, τ, and reflectance, ρ. Usually a combination of these parameters takes place and they are subject to the law of conservation of energy, which states that $\alpha+\tau+\rho = 1$. The transmittance is considered to be zero for opaque objects. Reflectance is defined as the ratio of the radiant flux Φ_r reflected from a surface to that of the incident flux Φ_i, and thus

$$\rho = \frac{\Phi_r}{\Phi_i} \tag{1}$$

If two reflective surfaces are illuminated with the same incidence flux Φ_i, the ratio of their reflectance is proportional to the flux ratio:

$$\frac{\rho_1}{\rho_2} = \frac{\Phi_{r1}}{\Phi_i} \cdot \frac{\Phi_i}{\Phi_{r2}} = \frac{\Phi_{r1}}{\Phi_{r2}} \tag{2}$$

Reflectance is dependent on the wavelength, λ, the angle of incidence, θ_i, between the incoming light and the normal to the mirror surface, and light polarization. The amount of reflected radiance, ρ, is a material property and its angular distribution is a property of the microscopic surface flatness. Therefore, reflectance is distinguished into diffuse or specular reflectance as described below. Polarization can be neglected only at near normal incidence, i.e. $\theta_i < 15°$. Because sunlight is not polarised, for CSP applications one has to consider the unpolarized reflectance, given by the average value of *s* and *p* polarized reflectances. In the following, polarization will be omitted, and with “reflectance” it is referred to “unpolarized reflectance”. The reflectance at oblique incidence angles must be considered for *s* and *p* polarization separately and then the results averaged.

Law of reflection
The first law of reflection states that the incident ray, the reflected ray and the normal to the reflective surface at the point of incidence lie in the same plane. The second law of reflection states that the angle of incidence, θ_i, of a wave or stream of particles reflecting from a boundary, measured from the surface normal, is equal to the angle of reflection, θ_r, measured from the same surface normal.

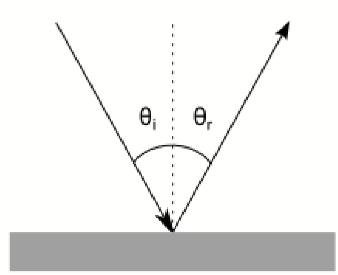


Figure 1: Law of reflection

Hemispherical reflectance

The spectral hemispherical reflectance, $\rho_{\lambda,h}(\lambda,\theta_i,h)$, describes the total amount of specular and diffuse radiation reflected into the hemisphere above the reflective surface of a material. It is a function of the wavelength, λ, and the incident angle, θ_i, of the incident light. It integrates the reflected intensity over the entire hemisphere of possible reflection.

Diffuse reflectance

Scattering theory requires the wave optics approach, which is beyond the purposes of this document. Here the phenomenon is illustrated with simplified geometric optics. If a parallel, extended bundle of light rays impinges on an object with a rough or microscopically structured surface of a size equal or greater than the wavelength, each individual ray encounters a different surface slope and therefore the law of reflection takes effect for a different angle θ_i to the surface normal at this point. As a result the bundle of light is diffusely scattered in all directions in the plane of incidence (Figure 2). The amount of diffuse scattering is dependent on the level of roughness or microscopic surface structuring. It is possible for oriented surfaces that the scattering will be anisotropic. The ideal diffuse reflector is a Lambert surface, where an equal amount of light is scattered in each direction of the hemisphere. The surface structure of certain materials (i.e. common in CSP application) leads to directional scattering, where the majority of the individual light rays are still oriented in the general specular direction related to the incidence angle of the light bundle, and only a small amount is scattered in a wide range of angle offsets from the specular direction. This leads to a reflectance distribution peaked in the specular direction and decreasing away from it [28].

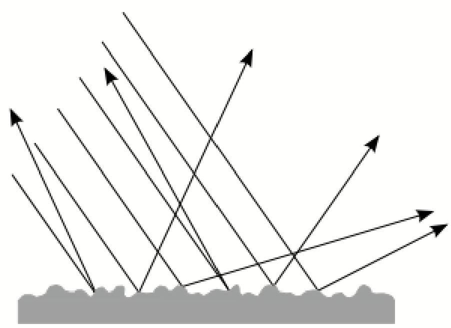


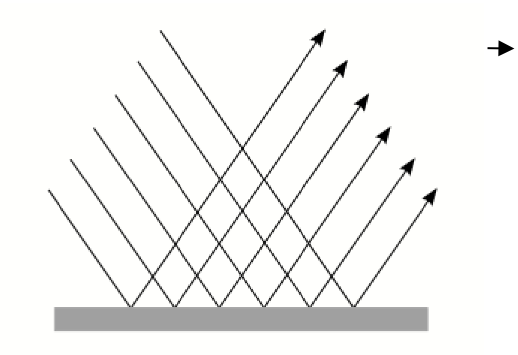
Figure 2: Diffuse reflection

Near-specular (or specular) reflectance and specularity

In CSP applications the hemispherical reflectance alone is not enough descriptive: mirrors are used to redirect solar radiation towards a receiver, and only the part reflected in the acceptance-angle 2φ of the receiver is intercepted, being φ the polar angle defined by the direction of the ideal specular reflected beam and the direction of the admissible maximum dispersion of reflection on the surface. Typically $\varphi \leq 20$ mrad, therefore the reflectance concerning CSP can be referred to as *near-specular*. Its value is generally less than the hemispherical one, and greater than the genuine *specular* reflectance, which strictly speaking refers to $\varphi = 0$. For the purpose of simplicity and usefulness, near-specular reflectance in this document is referred to as specular reflectance, always specified with the acceptance angle.

Its accurate measurement and evaluation is a challenging issue. As shown in **Figure 3a**, perfectly specular reflectance describes the case of reflection on a perfectly planar surface (i.e. with roughness much less than the radiation wavelength), where a parallel bundle of incident rays is reflected as a parallel bundle of rays according to the law of reflection. This is the ideal case where all light incident at θ_i is reflected at θ_r measured at any distance from the boundary. For real surfaces, the specular reflection is always mixed with a certain amount of scattering [12, 13, 15, 16, 29, 30].

The measured spectral specular reflectance for solar applications is written as $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$ where $\rho_{\lambda,\varphi}$ is dependent on the wavelength, λ, and is function of the incidence angle, θ_i, as well as the (half) acceptance angle, φ, associated with the detector aperture (Figure 3b). Alternately, the specular reflectance is the hemispherical reflectance minus the light scattered outside a specified φ.



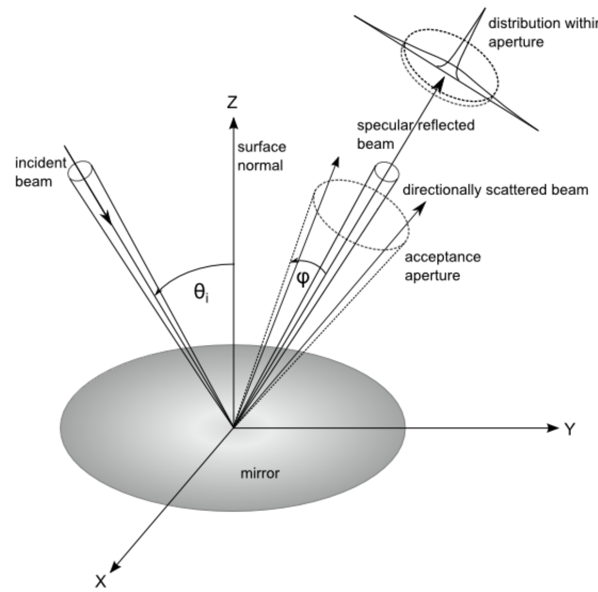


Figure 3a: Perfect specular reflection

Figure 3b: Specular reflection with offset

In practical application, the specular reflectance of a material is often inferred by the intensity measurement of the reflected beam collected through an aperture (**Figure 3b**) or measured within the field of view of the detector. The observed signal is given by:

$$\rho_{\text{detected}} = N \int_{\Omega} \int_{S_{\text{beam}}} \int_{S_{\text{detector}}} d\Omega_i \mathrm{ds}_{\text{beam}} \mathrm{ds}_{\text{detector}} I(A, \vec{\imath}) R\left(\frac{\overrightarrow{\mathrm{AB}} \times \vec{r}}{|\overrightarrow{\mathrm{AB}}|}\right) \tag{3}$$

where N is a normalization factor, $I(A, \vec{\imath})d\Omega_i$ is the beam intensity travelling in direction $\vec{\imath}$, inside the solid angle $d\Omega_i$ and hitting the point A on the mirror, B is the point on the detector surface capturing the light scattered along $\overrightarrow{\mathrm{AB}}$, which intensity is given by the scattering distribution function R. The unit vector, $\vec{r}$, indicates the direction of the specular reflection given by $\vec{\imath}$and the normal to the mirror surface. The integral is performed over Ω_i representing the divergence of the collimated light beam, the spot area on the mirror, S_{beam}, and the detector area, $S_{detector}$. Equation 3 represents the intensity profile of the light beam impinging on the mirror that is then convoluted with the function R, according to which the light is reflected and scattered by the mirror. A second convolution takes place with the function representing the detector aperture, that then captures the reflected light. Therefore, generally the measured signal itself is not a characteristic of the material, but the scattering distribution function R is. As discussed in [15] for example, the latter can be inferred only by the proper devolution of the experimental data. Additionally, R is also dependent on wavelength and incidence angle.

Once the reflectance distribution function R is known, the specular reflectance related to the acceptance angle, φ, is given by:

$$\rho_{\lambda,\phi}(\lambda, \theta_i, \phi) = \rho_{\lambda,h}(\lambda, \theta_i, h) \int_0^{2\pi} \int_0^{\phi} d\beta d\phi \sin(\phi) R(\lambda, \theta_i, \phi) \tag{4}$$

Where R is normalized to the integral over the acceptance angle $\pi/2$.

In some special cases it is appropriate to approximate R by a Gaussian distribution, as has been observed by [15, 19]. This changes equation 4 to:

$$\rho_{\lambda,\phi}(\lambda,\theta_i,\phi) = \rho_{\lambda,h}(\lambda,\theta_i,h) \cdot \left[1 - \sum_{j=1}^{M} K_j \exp\left[\frac{-\phi^2}{2\sigma_j^2(\lambda,\theta)}\right]\right] \quad (5)$$

Where $\sum_{i=1}^{M} K_j < 1$ if the scattering does not completely destroy the specular component.

In other cases, R might be approximated more adequately by adding an exponential term [9] or even by another different approach. Especially for materials with anisotropic scattering functions, the appropriate mathematical approximation of the same is being passionately discussed and has not been defined yet. A general approach that is valid for all materials does not exist.

Under certain circumstances it is possible to relate equation 4 directly to the intensity measurement for a circular acceptance aperture/detector aperture that is positioned in the exact specular direction. This applies when a highly collimated incidence beam is used and thus$I(A,\vec{\iota}) = I_0\delta(\vec{\iota})$. Or when the illuminated area on the mirror is much smaller than the detector aperture, so that it can be considered punctual. The convolution problem might also be avoided by relating the intensity measurement of a sample with unknown R to the intensity measurement of a reference mirror, of which it is known that all the reflected light enters the measurement aperture (thus it has perfect specular quality). Both intensity measurements imply the convolution of the same components, except for different R. This way, the specular reflectance value at this specific φ can also be estimated without knowing R of the sample.

Equations 4 and 5 relate the specular reflectance to specularity, which describes the beam spread caused by scattering according to R. A mirror with perfect specularity has no scattering or beam widening. In that case the beam spread is zero and $\rho_{\lambda,\phi}(\lambda,\theta_i,\phi) = \rho_{h,\lambda}(\lambda,\theta_i,h)$ regardless of φ. In other terms, the ratio of the two parameters is equal to 1. A differing ratio indicates not perfect specularity. This ratio must only be treated as an indicator, not for absolute values, because it tends to over-estimate the performance losses expected from a lower specularity reflector. In CSP applications, the actual impacts of reduced specularity must always be evaluated considering the other optical errors in the system. Consequently, this estimation should only be used to demonstrate reflectors with high specularity (scattering distribution with σ < 0.5mrad), as discussed in Appendix A.4. On reflectors with lower specularity, the only appropriate way to represent specularity is through scattering distribution functions, as discussed above.

Cleanliness factor (or soiling factor or soling ratio)

The cleanliness factor, $\zeta(\lambda,\theta_i,\varphi)$ is the ratio of the actual reflectance of the mirror to its reflectance in the clean state. It depends on the wavelength, λ, the incidence angle, θ_i, and the acceptance angle, φ.

$$\zeta_{\lambda,\phi}(\lambda,\theta_i,\varphi) = \frac{\rho_{\lambda,\phi,soil}(\lambda,\theta_i,\varphi)}{\rho_{\lambda,\phi}(\lambda,\theta_i,\varphi)} \quad (6)$$

Soiling rate

The soiling rate, $\dot{\xi}(\lambda,\theta i,\varphi,\Delta t)$, is the variation of the cleanliness factor over time, where Δt is the time interval between subsequent measured cleanliness factors.

$$\dot{\xi}_{\lambda,\phi}(\lambda,\varphi,\theta) = \frac{\Delta\zeta_{\lambda,\phi}}{\Delta t} \quad (7)$$

Collector: Element consisting of concentrator and receiver.

Concentrator: Shaped reflector that focuses sunlight onto receiver.

Reflector: Mirror that makes up the concentrator.

Receiver: Element that absorbs the sunlight focused onto it to generate heat.

2.2 Basic definitions for solar irradiance

Air Mass (AM)
Air mass, AM, is the optical path sunlight travels through the Earth's atmosphere. As sunlight passes through the atmosphere, it is attenuated by scattering and absorption; the thicker the atmosphere through which it passes, the greater the attenuation. The attenuation of solar radiation by the atmosphere is not the same for all wavelengths; consequently, passage through the atmosphere not only reduces intensity but also alters the spectral irradiance. The term "air mass" normally indicates the relative air mass, the path length relative to that at the zenith at sea level. Or the ratio of the mass of atmosphere in the observer-sun path relative to the mass that would exist if the observer were at sea level and the sun were directly overhead, at standard barometric pressure. By definition the sea-level air mass at zenith is 1. The value of the air mass is appended to the acronym AM, so an AM1 indicates an air mass of 1, AM1.5 indicates an air mass of 1.5, and AM2 indicates an air mass of 2. The region above the earth's atmosphere, where there is no atmospheric attenuation of sunlight is considered to have "air mass zero" (AM0).

3 Symbols (and abbreviated terms)

ξ	soiling rate
α	Absorptance
G_b	solar irradiance (W/m^2)
ρ	Reflectance
σ	Statistical standard deviation
τ	Transmittance
ζ	cleanliness factor
θ_i	Incidence angle
Φ	Radiance flux
φ	Acceptance angle
λ	Wavelength
$\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$	Specular reflectance
$\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$	Solar-weighted hemispherical reflectance in the range between λ_a and λ_b
$\rho_{\lambda,h}(\lambda,\theta_i,h)$	Spectral hemispherical reflectance
$\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$	Solar-weighted specular reflectance in the range between λ_a and λ_b

CEA	*Commissariat à l'Energie Atomique et aux Energies Alternatives* (Commission of Atomic Energy and Alternative Energies), France
CENER	*Centro Nacional de Energías Renovables* (National Center of Renewable Energies, Spain)
CIEMAT	*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Research Center of Energy, Environment and Technology),* Spain
CSP	Concentrating solar power
CTAER	*Centro Tecnológico Avanzado de Energías Renovables* (Advanced Technological Center of Renewable Energies), Spain
DLR	*Deutsches Zentrum für Luft- und Raumfahrt* (German Aerospace Center), Germany
ENEA	*Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sotenibile* (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), Italy
ISE	Fraunhofer Institute for Solar Energy Systems, Germany

4 Required set of reflectance parameters

In the Task III Reflectance group, it was decided that one set of parameters shall serve for the evaluation of all types of solar reflector materials. The parameters mentioned in the following sections define both, the parameters and values that should ideally be obtained for a complete and adequate reflector characterization and the minimum required parameters, that are necessary for a useful evaluation and that can be acquired today.

4.1. General

Most of the basic required parameters can be measured at the current state of the art with a combination of commercially available instruments, of which a deep revision can be found in [23]. Others can only be measured in specialized laboratories and still need improvement of measurement technology. A thorough characterization is necessary especially for the evaluation of mirror materials with complex surface and reflectance characteristics. On nearly perfectly specular reflector materials with stable surface characteristics, the minimum required parameters are sufficient for a reliable evaluation or even simplifications can be applied (see A.4).

4.2. Hemispherical reflectance

Various commercial laboratory instruments are available to measure spectral hemispherical reflectance, $\rho_{\lambda,h}(\lambda,\theta_i,h)$, usually by utilizing an integrating sphere, with good accuracy and spectrally resolved over the whole relevant solar spectrum of λ = [320, 2500] nm [31] (see section 4.4 for further explanations about the wavelength range). The hemispherical reflectance spectrum of a reflector material over this wavelength range is a first and very important measure for evaluating its ability to exploit the maximum amount of solar irradiation. Typically, $\rho_{\lambda,h}(\lambda,\theta_i,h)$ is measured at near normal angles of incidence (θ_i <= 15°), because experimental difficulties and errors increase dramatically at oblique angles. The incidence angle as well as the measurement wavelength or wavelength range must be indicated in the results. Measurements or theoretical models that have been experimentally validated may be applied to obtain $\rho_{\lambda,h}(\lambda,\theta_i,h)$at greater incidence angles. For CSP applications, incidence angles up to 50° or even more are relevant and should be part of the optical analysis.

- The spectrum of $\rho_{\lambda,h}(\lambda,\theta_i,h)$ for at least near normal incidence and in the solar wavelength range must be analyzed on a solar reflector material.

- Ideally this parameter is also obtained by measurement or by an experimentally validated theoretical model, as a function of θ_i or at least for several, greater angles of incidence as well (example of a model approach see [32]).

4.3. Specular reflectance

Due to the geometry of CSP concentrators, only the reflected radiation near the specular direction enters in the energy conversion chain, which is the measure of the specular reflectance, $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$. The range of relevant φ depends on the collector design. Typically it is 0-20 mrad. Beam spread and scattering is wavelength and incidence angle dependent and therefore the specularity or the approximated relationship $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)/\rho_{\lambda,h}(\lambda,\theta_i,h)$ can change over the spectrum and with angle of incidence. The specular reflectance spectrum should ideally be measured over the solar wavelength range or at least at several wavelengths, whose line-width is similar to that of the hemispherical spectrum measurement. The experimental apparatus must ensure that φ is kept constant over the spectral range of the measurement.

- The parameter $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$ must be measured at least at three wavelength bands or in the solar wavelength spectrum, at least at near normal incidence (θ_i <= 15°) and at least at three φ in the range of φ >= 0 to φ <= 20 mrad, except if the reflector material fulfills the criteria of high specularity described in Annex A.4. In that case the simplified procedure of A.4 may be applied.

- Ideally, the parameter $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$ is analyzed by measurement or by an experimentally validated theoretical model, as a function of λ, as a function of θ_i and as a function of φ (example of a model approach see [33]).

- The divergence of the beam of the equipment used to measure the specular reflectance should be equal or smaller than the mean solar disc angle (around ±4.7 mrad).

4.4. Solar-weighted reflectance

Solar weighting of the reflectance parameters is calculated with the currently valid standard solar spectrum ASTM G173 [31] for direct irradiance and the appropriate Air Mass (i.e. for Europe and USA it is AM 1.5). Solar weighting is performed according to the equations provided in chapter 7 and Annex B [34, 35]. The solar irradiation is provided in [31] in the wavelength range λ = [280, 4000] nm. In the far NIR the irradiated power is so scarce that the overall weight of the region 2500-4000 nm is only 0.0018 of the total. Because in the most common commercial spectrophotometers: i) λ is selected by gratings, ii) the measurable λ range is limited to 3300 nm, and iii) the acquisition time depends on the width of the wavelength range, the reduction of the upper limit of the λ range for solar weighting to 2500 nm is quite convenient. A symmetrical cut (0.0018 of the total) of the UV tail allows increasing the minimum wavelength to 320 nm, with the great economical advantage of make unnecessary the usage of the costly deuterium lamp and more relaxed the requirements on the suitable spectrophotometer. For the above explained practical reasons, the solar-weighting will be computed in the range λ = [320, 2500] nm.

The wavelength interval step of the measurement recommended is 5 nm (see Appendix B). If other wavelength interval step is selected for the measurements, the data have to be adapted to use the factors in Appendix B. In any case, the wavelength interval step must be lower or equal than 10 nm.

The solar-weighted specular reflectance, $\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$, is the relevant parameter to evaluate the CSP reflector material for both, the portion of solar irradiation reflected and the ability to redirect it towards the receiver. Actually, it is not possible to measure the specular reflectance spectrum at specified φ and then perform a solar weighting of the results. Therefore the solar-weighted hemispherical reflectance, $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$, is the relevant parameter to evaluate the portion of solar irradiance that is reflected by the reflector material. Still, it must be evaluated taking into account possible loss due to scattering, which can be revealed by comparing hemispherical reflectance to specular reflectance measured at the same wavelengths.

- As a minimum requirement, the parameter $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$, weighted according to the actually valid standard solar spectrum (currently [31]) for direct irradiance and the appropriate Air Mass (i.e. for Europe and USA it is AM 1.5) at least at θ_i <= 15°, must be acquired for a reliable analysis of the portion of the solar irradiance reflected by the reflector material.

- Ideally, the parameter $\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$, weighted according to the actually valid standard solar spectrum (currently [31]) for direct irradiance and the appropriate Air Mass (i.e. for Europe and USA it is AM 1.5) is acquired as a function of θ_i and φ, or at least at three θ_i and at three φ in the range of φ >= 0 mrad to φ <= 20 mrad.

The equations to be used in the calculation of the solar-weighted reflectance with the standard solar spectrum are explained in section 7.2.

4.5. UV-weighted reflectance

The UV region of the solar spectrum (that is, λ = [280, 320] nm) is very aggressive because it might cause human biological damage (DNA modification, skin cancer, etc.), materials degradation (polymers degradation, fused silica and glass solarization, etc.), bacterial inactivation by solar disinfection [36] and solar photocatalysis of organic compounds and microorganisms [37]. Therefore, it is greatly important to properly evaluate the UV reflectance of solar mirrors for some specific applications. However, as UV is just a small part of the terrestrial solar radiation (0.09%), the solar weighted formula including the whole solar wavelength range cannot be used to evaluate the UV reflectance to compare different commercial products for such applications. Table 1 shows the range and weight of the different UV classes.

Table 1. Range and weight of the different UV classes.

Class	Range (nm)	Absolute weight (%)	Relative UV weight (%)
UV	100-400	3.46	100.00
UVA	315-400	3.42	98.87
UVB	280-315	0.04	1.25
UVC	100-280	0.00	0.00

Depending on the range or class of interest, the proper λ range must be used to calculate the UV-weighted hemispherical reflectance, $\rho_{h,\varphi}([\lambda_a,\lambda_b],\theta_i,h)$, or the UV-weighted specular reflectance, $\rho_{UV,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$, according to the equations explained in section 7.2.

5 Requirements for instrumentation

The optimum instrument needed for precise measurements of the appropriate parameters to sufficiently evaluate all solar reflector materials does not exist currently. The properties that this ideal instrument should have are described in Section 5.1. This section is meant to guide the development of measurement technology towards satisfactory improvement, matched to the needs of CSP reflector material analysis. Section 5.2 discusses minimum requirements for selecting existing and future instruments, in order to best characterize the minimum relevant reflector parameters.

5.1. Ideal instrument properties

As mentioned before, it would be ideal to characterize a solar mirror material by accurately measuring specular reflectance over an appropriate range of λ, θ_i and φ to allow solar-weighted reflectance of a reflector and its specularity to be calculated. The instrument needed to perform this measurement should have the best combination of the following properties:

- Measurement wavelength range of 280 – 2500 nm at wavelength intervals which allow accurate solar weighted calculation (recommended wavelength interval of 5 nm, maximum 10 nm).

- Precise, selectable acceptance apertures or an innovative approach that covers a range of acceptance angles appropriate to measure the specular reflectance as a function of φ. It must be ensured that φ remains constant along the whole wavelength range of measurement.

- Measurement at various incidence angles ranging from near normal to at least 50° or an innovative approach to obtain the specular reflectance as a function of θ_i.

- Adjustment options to account for different mirror thicknesses and surface curvature.

- Absolute measurements, no reference mirror necessary.

- Measurement spot size as large as possible, with the option of reducing size in case of interest.

- All measurements included in the process of obtaining the desired result should be done at the same spot on the sample and with the same instrument (i.e. same light source, detector etc.).

- Non-contact measurement to avoid damaging the surface.

- Portable for field measurements, which implies high battery autonomy, battery status display, light-weight, small compact size, easy to handle, robust, and digital data storage.

- A coordinate system that is incorporated in the instrument to identify the position of defect points on a mirror and study their evolution over time would be a useful addition for monitoring quality.

- Stable concerning associated type-B[1] uncertainties. These type-B uncertainties should be kept to a minimum [38].

- No influence by external stray light.

- No risk to human health or environmental hazard involved.

5.2. Minimum required instrument properties

While research and development continues to improve the available instrumentation to fulfil most of the above mentioned qualities, the need for measurement results today requires the employment of existing technology, even if none exists that fully accomplishes the desired ideal measurement results. For the measurement of minimum required parameters as defined in chapter 4, not every available instrument is equally appropriate. To maintain a high accuracy and comparability of results, the following requirements should be fulfilled by the instrument that is to be employed.

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1 As explained in [41], type B uncertainties refer to instrument specific, systematic uncertainties (i.e. repeatability, calibration accuracy, ambient temperature dependency, stability of light source etc.) which, once determined, represent a constant value of measurement uncertainty. This value is added by means of sum of squares to the type A uncertainty, which represents the statistical variance between several measurements taken for each sample analysis.

5.2.1. Instrument properties for hemispherical reflectance

The measurement of hemispherical reflectance is a widely applied field and the available instrumentation is sophisticated to usually acquire results with high accuracy. For most reliable results, top class laboratory instruments like double beam spectrophotometers are recommended. For the instrument selection, the following should be considered:

- Measurement wavelength range of λ = [320, 2500] nm at wavelength intervals which allow accurate solar weighted calculation (maximum wavelength interval of 5 nm); in the case of interest in UV, the wavelength range to 280-2500 nm shall be used.

- Measurement at least at near normal incidence (θ_i <= 15°).

- Preferably absolute measurements, or measurement with a stable, calibrated reference mirror of the same material of the sample mirror studied (no diffuse reference coupon).

- If measurements at θ_i > 15° are possible, the calibration of the reference mirror must be available for the same incidence angles.

- If integrating sphere is part of the setup: sphere size needs to be adequate to minimize errors. A diameter not smaller than 150 mm is recommended [39]. Also, the port fraction must be between 2 and 4% of the surface of the sphere [40].

- Stable concerning associated type-B2 uncertainties. These type-B uncertainties should be kept to a minimum [38].

- No influence by external stray light.

- No risk to human health or environmental hazard involved.

5.2.2. Instrument properties for specular reflectance

The variation of solar mirror material types and their complex properties makes specular reflectance measurements more challenging. The result is very susceptible to differences in setup, beam alignment and acceptance aperture. Therefore the following requirements should be considered when selecting or developing a reflectometer:

- Measurement at several (at least three) narrow wavelengths (line width similar to that of hemispherical measurements) appropriately spaced along the solar spectrum or at a specified wavelength range that accounts for differing wavelength dependent scattering properties. If the reflector material is known to be of high specularity, the simplified procedure in Annex A.4 may be applied.

- Several precise and selectable acceptance apertures or an innovative approach that covers at least a range of acceptance angles from φ >= 0 mrad to φ <= 20 mrad. If the reflector material is known to be of high specularity, the simplified procedure in Annex A.4 may be applied.

- Measurement at least at near normal incidence (θ_i <= 15°), and preferably at two more angles of incidence.

- Preferably absolute measurements, or measurement with a stable, calibrated reference mirror (no diffuse reference coupon or coupon calibrated for gloss measurements).

- If measurements at θ_i > 15° are possible, the calibration of the reference mirror must be available for the same incidence angles.

- Adjustment options for correcting beam alignment, to account for different mirror thicknesses and surface curvature.

- If portable: high battery autonomy, battery status indicator, light-weight, small compact size, easy to handle, robust.

- Stable concerning associated type-B2 uncertainties. These type-B uncertainties should be kept to a minimum [38].

- No influence by external stray light.

- No risk to human health or environmental hazard involved.

5.2.3. Recommendations

The most common commercial instruments for measuring spectral reflectance are the dispersive spectrophotometers. In that case, among the settable parameters, scan speed v (nm /sec) and detector integration time τ (sec) are quite important because they determine the maximum detectable spectral slope of the measurement *M:*

$$\left.\frac{\mathrm{d}M}{\mathrm{d}\lambda}\right|_{max} \propto \frac{1}{v\tau} \tag{8}$$

Too high values of speed and integration time can bring to artificial spectra, like with peak-valley smoothing and λ-retarded behavior. Unfortunately it is not possible to indicate a setting having general validity, because the maximum slope strictly depends on the specific features of the spectra one has to measure: the more jagged the spectrum is, the slower speed with shorter integration times are required. As a rule of thumb, users should compare dynamical to stationary measurements at the wavelength where the spectrum shows the steeper slope; if the difference is larger than the experimental error, speed and integration time must be reduced.

2 As explained in [41], type B uncertainties refer to instrument specific, systematic uncertainties (i.e. repeatability, calibration accuracy, ambient temperature dependency, stability of light source etc.) which, once determined, represent a constant value of measurement uncertainty. This value is added by means of sum of squares to the type A uncertainty, which represents the statistical variance between several measurements taken for each sample analysis.

6 Preparation of measurement

The preparation of samples is an essential part of the measurement process. The important points to be considered for acquiring reliable measurement results are explained in the following.

6.1. General

- For laboratory measurements, the samples should be cut to a size that allows measurement on different points on the surface, but also fits into the instrument's sample holder. The sample must not be smaller than the sample port (opening hole). The reflector sample must be able to lie flat against the sample port of the instrument.

- To evaluate a commercial reflector product, samples should be taken out of the production line to be measured rather than prototype samples specifically made for the analysis. At least three replicate samples of one product batch should be analyzed, so that anomalies can be identified.

- Flexible samples should be applied to a stable, flat substrate before measurement. The substrate should have smooth surface properties, to avoid that roughness of the substrate influences the measured specularity of the sample.

- Regular recalibration and maintenance of instruments and reference standards at least every year are essential for a performance with constant high accuracy.

- At least 3 measurements on different local spots and different orientations (i.e. turns of 90°) should be performed per sample that are averaged for the result. To average anisotropic behaviour, it is especially advised to rotate the sample orientation on the sample support.

- Mirrors should be stored in a dry, dark local and protected to avoid the risk of scratches and degradation.

6.2. Cleaning

The mirror's front surface should be cleaned very carefully prior to measurement according to the manufacturer's recommendation or with compressed air (free of particles and oil). In case of remaining dust or soil after a visual inspection, a soft lens tissue and demineralized water will be employed. Abrasive or solvent agents that may change the properties of the sample shall never be employed. In addition, special care must be taken to avoid any contamination after the cleaning due to a negligent manipulation. The reflector surface may only be touched with gloves.

If the mirrors cannot be cleaned sufficiently with the normal cleaning procedure because of heavy soiling or because air-blown dirt has bonded and baked onto the mirror surface for samples exposed outdoors, slightly more aggressive methods may need to be used. Depending on the type of solar reflector, contact washing with a cotton swap and an extremely dilute solution of a mild detergent and demineralized water (1/100) followed by a copious rinse with demineralized water can be used. Careful utilization of ethyl alcohol can be used for glass, protected aluminium, and some front surface mirrors. Isopropanol is not advised because it leaves a residual coating which smears on the mirror. Many alcohols (e.g., toluene, acetone benzene) are not advised for use with silvered polymers because the alcohol can soften and damage the polymer surface. Commercial glass cleaner and chlorine- and ammonia-based cleaners are not recommended with sensitive metals like silver. If a smear is left on the mirror, it should be carefully removed with demineralized water.

The samples should be allowed sufficient time to dry (i.e., overnight), particularly if the mirror's surface can absorb water (i.e., silvered polymers) during cleaning. Any remaining dust should be removed with pressurized air. The sample should be free of grease and particles and perfectly dry before measurement.

6.3. Reference mirrors

If the measurement setup requires the use of a reference coupon, a mirror must be used for measurement of mirror material samples. Diffuse white coupons or black glass coupons used in glossmeters are not recommended [41]. If the results that are to be reported are acquired with different instruments, the same reference mirror should be used in all measurements. It is recommended to select a mirror of high specularity and reflectance that is stable to degradation as reference and have its calibration traceable to a certified calibration institute. The calibration of the reference mirror must be valid for the incidence angles in which the measurements are to be performed.

A set of at least two calibrated identical reference mirrors should be maintained. One of these mirrors should be kept in a protected clean place as a master standard. The second mirror can be used for daily measurements as a working standard. It is recommended to have more than one working standard and use them alternately to guarantee longer lifetimes. A mirror manufacturer may even use highly stable mirrors of the own production to be calibrated for use as working standards.

The working standards should be checked and recalibrated regularly (at least every year). The recalibration interval depends on the amount of daily usage. For recalibration, the master standard is used as reference mirror and the working standard is measured as a sample. Regular recalibration of both, working standards and, after a greater interval, also the master standard is necessary to maintain good accuracy. The reference mirrors should be replaced when they display visible degradation. Special care must be taken in managing the working standard if front surface mirrors are used.

The reference mirrors must be cleaned and without defects for measurements.

7 Weighting with standard solar spectrum

For evaluation of the quality of a mirror for application in concentrating solar power technology, the reflectance spectrum needs to be weighted with a standardized solar irradiance spectrum. This allows an averaged evaluation of the solar radiation that is reflected by the mirror material. The procedure is explained in the following.

7.1. General

The solar irradiance spectrum is taken from international standard tables which represent an average irradiance spectrum for the elevation of the concerned country, i.e. in the northern hemisphere at an elevation level typical for the United States or Europe the spectrum is calculated with Air Mass 1.5 (AM1.5) at normal incidence. Solar weighting of the reflectance results with different available solar norm spectra leads to a difference in the solar weighted values ranging from 0.3 up to 1.5 percentage points depending on the spectral properties of the material.

It is recommended to take the standardized solar irradiance spectrum from the most current accepted solar standard, which is actually ASTM G173 [31]. It should be avoided to apply tables for global solar irradiance. The relevant table, i.e. reported in Annex B represents direct + circumsolar solar irradiance.

7.2. Solar-weighted and UV-weighted reflectance

The calculation of solar weighting is explained extensively in the withdrawn standard ISO 9845 [34] and in the standard ISO 9050 [35], which only contains global irradiance tables. The solar-weighted reflectance, ρ_s, and the UV-weighted reflectance of a mirror represents the convolution of the spectral reflectance function, $\rho_\lambda(\lambda)$, with the solar irradiance function, $G_b(\lambda)$, in the proper λ range. Since these functions are generally only known with discrete values, the integration is performed as a summation. Therefore, the solar-weighted or UV-weighted hemispherical reflectance, $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$ or $\rho_{UV,h}([\lambda_a,\lambda_b],\theta_i,h)$, and the solar-weighted or UV-weighted specular reflectance, $\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$ or $\rho_{UV,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$, of a solar mirror is calculated using the values of the measured reflectance spectrum, $\rho_{\lambda,h}(\lambda,\theta,h)$, or $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$, and the direct solar irradiance spectrum, $G_b(\lambda)$, at wavelength intervals of $\Delta\lambda$ with equations 9.a and 9.b.

$$\rho_{\mathrm{Ss},h}([\lambda_a,\lambda_b],\theta_i,h) = \frac{\sum_{\lambda_{\min}}^{\lambda_{\max}} \rho_{\lambda,h}(\lambda,\theta_i,h)\cdot G_b(\lambda)\cdot\Delta\lambda}{\sum_{\lambda_{\min}}^{\lambda_{\max}} G_b(\lambda)\cdot\Delta\lambda} \text{for} \lambda = \{\lambda_{\min},\lambda_{\min}+5,\ldots\lambda_{\max}\} \quad (9.a)$$

$$\rho_{\mathrm{Ss},\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi) = \frac{\sum_{\lambda_{\min}}^{\lambda_{\max}} \rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)\cdot G_b(\lambda)\cdot\Delta\lambda}{\sum_{\lambda_{\min}}^{\lambda_{\max}} G_b(\lambda)\cdot\Delta\lambda} \text{for} \lambda = \{\lambda_{\min},\lambda_{\min}+5,\ldots\lambda_{\max}\} \quad (9.b)$$

where the λ_{min} and λ_{max} must be taken from Table 2, according to the type of desired average, and the subscript *Ss* properly set.

Table 2. Wavelength range, depending on the type of the desired average.

Class	Ss	λ_{min} (nm)	λ_{max} (nm)
solar	s	320	2500
UV	UV	280	400
UVA	UVA	315	400
UVB	UVB	280	315

Noteworthy, if $\Delta\lambda$ is constant, it can be suppressed in Equations 9.a and 9.b.

8 Measurement of aged and/or soiled mirror samples

This section presents a very preliminary draft of the methodology to monitor aged and/or soiled mirrors samples and will be improved in further versions of this guideline.

If mirrors are to be characterized which have been in-service outdoors or tested in accelerated aging or durability tests, several measurements need to be taken on the sample to ensure that the measured value is statistically meaningful. This is especially important when local degradation effect occur on the mirror surface.

If the time behavior of the reflectance during outdoor exposure is monitored, or if the reflectance decay during accelerated aging is to be measured, the samples shall be measured in the exact same positions for each analysis. A mask or stoppers may be used to easily find the same measurement position again after exposure.

To monitor the aging, it is sufficient to measure the specular reflectance at one defined wavelength in the range λ=[400, 700] nm, $\theta_i \leq 15°$ and a φ in the range of $\varphi >= 0$ to $\varphi <= 20$ mrad. The reflectance loss is computed by subtracting the initial value from the reflectance after exposure. The following parameters shall be reported after aging tests:

- Solar weighted hemispherical reflectance loss $\Delta\rho_{s,h}([320,2500],\theta_i,h)$
- Monochromatic hemispherical reflectance loss $\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$
- Monochromatic specular reflectance loss $\Delta\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$ (at the same wavelength as for $\Delta\rho_{\lambda,h}(\lambda,\theta_i,h)$)

For materials that may suffer from glass corrosion, it is recommended to test at least one additional sample with a protective tape on the glass surface, so that the reflectance measurement of the reflective layer is not influenced by glass corrosion. The sample should be placed with the protective paint side facing upwards in the chamber. Reflectance values of protected and unprotected samples shall be compared after the durability test.

As a minimum, 5 monochromatic specular measurements and 3 spectral hemispherical measurements shall be taken on a sample of around 100x100 mm². The 5 monochromatic measurements obtained with a reflectometer shall be taken in the center of the sample and close to the 4 corners of the sample. The measurement shall not be taken closer than 10 mm to the sample edge or areas that have not been exposed to the testing conditions (e.g. due to the sample holder). The spectral hemispherical measurements obtained with a spectrophotometer shall be taken in the center of the sample. The sample shall be rotated after each measurement by 90° (to obtain measurements at 0°, 90° and 180°on the same position on the sample).

Figure 4 shows an example of the measurements taken on a 120x120 mm² sample. The herein used reflectometer and spectrophotometer have a measurement spot of 10 mm diameter and 9 x 17 mm², respectively.

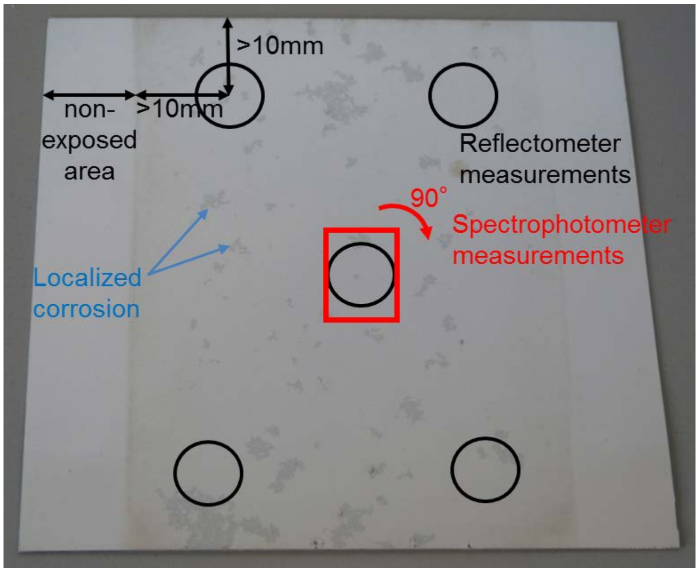

Figure 4: Exemplary measurements taken on a 120x120 mm² sample with localized corrosion spots.

9 Reporting and accuracy

The reported parameters and information need to be uniform and represent the measured reflectance parameters in a way, that the evaluator can distinguish the parameter characteristics. This ensures that reflectance data of products are comparable within the solar community and can be employed further in simulations and system analysis. The values that are to be reported are defined in the next Section. Sources of errors are discussed in Section 9.2.

9.1. Reporting

Reported values should always be exactly specified for hemispherical or specular reflectance including measurement wavelength spectrum, incidence angle and acceptance angle. For solar weighted values, the solar standard and its version that has been applied must be stated.

As a minimum requirement, the following results are to be reported:

- $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$ solar weighted hemispherical reflectance at near normal incidence.
- Hemispherical reflectance spectrum as a graph.
- $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$ specular reflectance at near normal incidence (optionally other angle of incidence), at least three λ and at least three φ in the range φ = 0-20 mrad (see chapter 4.3). If the reflector material is known to be of high specularity, the simplified procedure in Annex A.4 may be applied.
- $\rho_{\lambda,h}(\lambda,\theta_i,h)$ hemispherical reflectance values at the same wavelengths or range as $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$.
- Statistical standard deviation of measurements for all above listed values, $\sigma(\rho)$.
- Combined uncertainty including type A and type B uncertainties of measurement setup.

Furthermore, the typology and main characteristics of the used instruments should be reported. Also, the type of reference mirror with its calibration status and calibration uncertainty, as well as measurement spot size and the number and positions of measurements that have been averaged. Sample properties should also be reported, including material type, thickness, surface quality (clean, scratched, etc.), edge protection, possible curvature and other observations.

Reflectance values should be reported in dimensionless scientific format, i.e. $\rho_{s,h}([320,2500]nm,8^o,h)$ = 0.942.

If the measurement setup allows the determination of any of the above results as a function of θ_i and/or as a function of φ, then these functions should be reported additionally as graphs in a representative format.

9.2. Sources of error

Optical measurements are highly sensitive to error. Especially specular reflectance measurements are very susceptible to measurement errors and false handling of the instrument. To ensure reproducible and accurate measurements, the following points of importance need to be considered.

- For specular measurements, beam alignment is a highly important issue. If, due to displacement caused by mirror thickness or a bent/curved surface, the reflected beam does not enter the acceptance aperture or impinges onto the detector not correctly then the measurement result is affected.
- When specular measurements are performed at various acceptance angles and the setup requires a reference mirror, then the reference measurement with the reference mirror must be performed for each selected φ.

- When measurements are performed at various incidence angles using a calibrated reference mirror, the result might be afflicted with an error if the calibration of the reference mirror has not been performed at the same incidence angles.

- If the reference mirror is not clean, a lower flux intensity is associated with the reference reflectance value and therefore all sample measurements will be overestimated. The same is the case when the beam alignment with the reference mirror in place prevents the reflected beam to enter the acceptance aperture correctly or when the reference mirror has degraded.

The criteria and the procedures for calculating the uncertainty of solar reflectance are reported in Annex C.

Annex A
Practical application (informative)

A.1. General

This section is meant to provide a practical example for the procedure that can be applied to acquire the values that need to be reported according to section 9.1. The example assumes the measurement with common instruments but does not imply that the procedure is the only one applicable. It is possible to use simplified procedures for certain kinds of highly specular solar reflector materials. A suggestion on how the results can be evaluated and on how the procedure could be simplified, is part of this section.

A.2. Hemispherical reflectance

Spectral hemispherical reflectance might be obtained with a suitable, top class commercial spectrometer or spectrophotometer equipped with an integrating sphere of no less than 150 mm diameter. Typically, the incidence angle of such an instrument is near normal. As a reference mirror, a stable, 2nd surface silvered or aluminized glass mirror with a calibration traceable to a certified calibration institute, can be used. A dark current measurement (Zeroline) should always be subtracted from each measurement.

The sample measurement, $Measurement_{sample}$, is converted into a reflectance spectrum, $\rho_{\lambda,h}(\lambda,\theta_i,h)$, using the reference measurement, $Measurement_{reference}$, and the known reflectance spectrum of the reference mirror, $\rho_{\lambda,h,reference}(\lambda,\theta_i,h)$, as follows:

$$\rho_{\lambda,h,\text{sample}}(\lambda,\theta_i,h) = \frac{\text{Measurement}_{\text{sample}} - \text{Zeroline}}{\text{Measurement}_{\text{reference}} - \text{Zeroline}} \cdot \rho_{\lambda,h,\text{reference}}(\lambda,\theta_i,h) \qquad (10)$$

Several measurements on different surface areas are averaged. Then the solar weighting is performed as explained in chapter 7. The resulting parameters that can be reported are:

- $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$ solar weighted hemispherical reflectance at near normal incidence angle.
- Hemispherical reflectance spectrum as a graph.
- For non-specular reflectors, $\rho_{\lambda,h}(\lambda,\theta_i,h)$ at the relevant wavelength λ that is used in the specular measurement (following section), so that the two can be compared.
- The standard deviation of these measurements on different spots on the sample indicates its homogeneity and thus the confidence in the final result.

A.3. Specular reflectance

Any reflectometer that is adaptable to mirror thickness and surface curvature and is equipped with acceptance angle apertures in the correct range might be employed. Existing commercial instruments are either limited to only monochromatic, respectively only a few wavelengths for illumination, or otherwise do not have the possibility of selecting a defined acceptance angle in the relevant range. If the reflector material is known to be of high specularity, the simplified procedure explained in Annex A.4 may be applied.

One imagines for example measurement taken at near-normal incidence and φ = {3.3, 6.4, 9.6, 13.6, 16.4, 19.4} mrad or φ ={3, 7.5, 12.5, 23, 30} mrad and λ = {451.5, 532.5, 661} nm or λ = {455, 533, 660} nm.

It should be taken care that hemispherical and specular measurements are performed on the same surface spot of the sample and using the same measurement spot size. Several measurements on different surface areas are averaged. The standard deviation of the measurements on different spots on the sample indicates its homogeneity and thus the confidence in the final result

The resulting parameters that can be reported are a set of values for $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$ at near normal θ_i, that can conveniently be plotted as discrete data points per λ and φ with λ being the *x*-axis (Figure 5 left) or with φ being the *x*-axis (Figure 5 right).

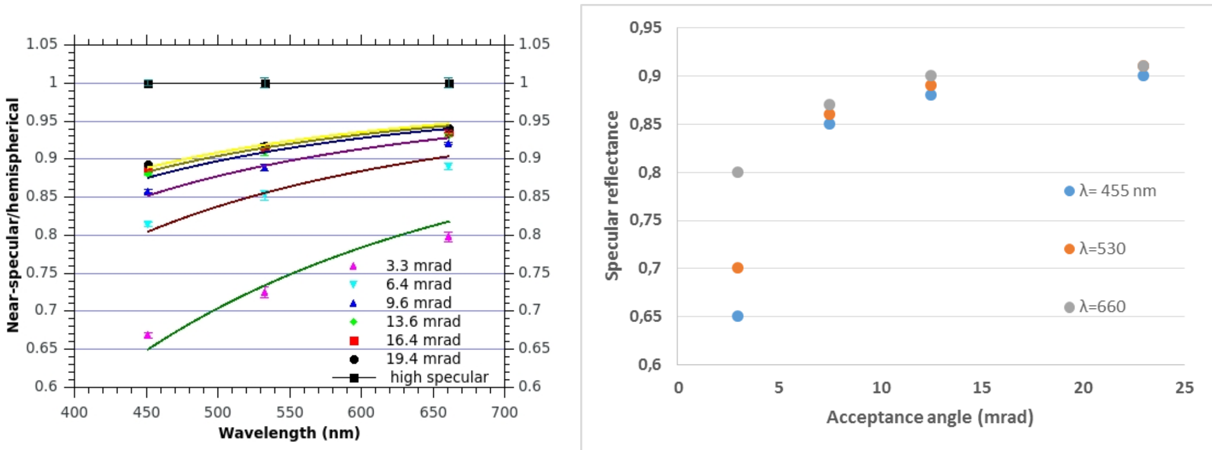

Figure 5: Example of plot for measured reflectance values representing a mirror with lower specularity in comparison to plotted values of a highly specular mirror. All values belong to real measurements. Left: λ in the *x*-axis. Right: φ in the *x*-axis.

A.4. Simplified procedure for reflectors with high specularity

The solar diffuse reflectance, $\rho_{s,d}([\lambda_a,\lambda_b],\theta_i,\varphi_d)$, is defined as the radiation scattered in the range of angle offsets from the specular direction [2]. Therefore, $\rho_{s,\varphi}(([\lambda_a,\lambda_b],\theta_i,\varphi)$ can be written as in equation (11).

$$\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi) = \rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h) - \rho_{s,d}([\lambda_a,\lambda_b],\theta_i,\varphi_d) \qquad (11)$$

The simplified approach is based on the following assumption: "when the $\rho_{s,d}([\lambda_a,\lambda_b],,\theta_i,\varphi_d)$ beyond φ=7.5 mrad is less than the experimental error of the reflectance measurement, it is negligible and the $\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi)$ of a solar mirror can be approximated by $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$, as indicated in equation (12)".

$$\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi) \approx \rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h) \qquad (12)$$

Solar mirrors fulfilling the above condition are named "highly specular solar mirrors", or equivalently "solar mirrors with high specularity". Compared to the previous method included in the version 2.5 of this guideline, the new one eliminates the measurement of the specular reflectance at one λ and one φ per θ_i and involves the solely measurement of the $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h)$.

Concerning the way to check if a certain solar mirror can be treated as highly specular, it is considered that the former method (included in the version 2.5 of this guideline) is not appropriate because it is based on the comparison of two parameters measured with two different commercial instruments ($\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$) measured with a specular reflectometer and $\rho_{\lambda,h}(\lambda,\theta_i,h)$ measured with a spectrophotometer). These two measurement instruments have different θ_i (usually, $\theta_i = 8°$ for spectrophotometer and $\theta_i = 15°$ 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 this simplified procedure, only if the following experimental criterion, composed of two conditions, is passed:

- The difference between the experimental values of near-specular reflectance, $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)$, at a λ in the range λ=[400, 700] nm and $\theta_i \leq 15°$, 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 $\theta_i \leq 15°$ and $\varphi > 50$ mrad, $\rho_{s,d}([\lambda_a,\lambda_b],\theta_i \leq 15°,\varphi > 50mrad)$, 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).

Annex B
Table for solar weighting of reflectance

B.1. General

The following table can be used to calculate the solar-weighted hemispherical or solar-weighted specular reflectance as explained in chapter 7. Column 1 represents the wavelength in regular intervals of $\Delta\lambda$ = 5 nm and column 2 gives the solar irradiance (direct + circumsolar) in $Wm^{-2}nm^{-1}$ extracted from the last column of ASTM G173-2003 [31].

B.2. Weighting table

If other wavelength interval step is selected for the measurements, the data have to be adapted to use these factors. In any case, the wavelength interval step must be lower or equal than 10 nm. The tabulated data differ from the original ones of ASTMG173 for the wavelength step which is made uniform in the guidelines for simplicity.

Table 3. Direct solar irradiance and weighting factors for solar-weighted reflectance, as a function of the wavelength.

Wavelength λ [nm]	Direct + Circumsolar G_b [W $m^{-2}nm^{-1}$]	Wavelength λ [nm]	Direct + Circumsolar G_b [W $m^{-2}nm^{-1}$]	Wavelength λ [nm]	Direct + Circumsolar G_b [W $m^{-2}nm^{-1}$]
280	2.54E-26	475	1.38E+00	635	1.31E+00
285	9.00E-17	480	1.38E+00	640	1.30E+00
290	5.15E-10	485	1.35E+00	645	1.32E+00
295	3.22E-06	490	1.40E+00	650	1.23E+00
300	4.56E-04	495	1.42E+00	655	1.22E+00
305	8.93E-03	500	1.34E+00	660	1.27E+00
310	2.78E-02	505	1.36E+00	665	1.29E+00
315	7.37E-02	510	1.35E+00	670	1.29E+00
355	3.91E-01	515	1.34E+00	675	1.26E+00
360	3.92E-01	520	1.33E+00	680	1.27E+00
365	4.18E-01	525	1.39E+00	685	1.25E+00
370	5.17E-01	530	1.36E+00	690	1.07E+00
375	4.11E-01	535	1.37E+00	695	1.15E+00
380	4.98E-01	540	1.31E+00	700	1.16E+00
385	4.86E-01	545	1.37E+00	705	1.20E+00
390	5.85E-01	550	1.36E+00	710	1.20E+00
395	6.01E-01	555	1.39E+00	715	1.14E+00
400	8.40E-01	560	1.31E+00	720	8.99E-01
405	8.78E-01	565	1.36E+00	725	9.47E-01
410	8.09E-01	570	1.32E+00	730	1.03E+00
415	9.56E-01	575	1.32E+00	735	1.11E+00
420	8.85E-01	580	1.35E+00	740	1.11E+00
425	9.93E-01	585	1.37E+00	745	1.14E+00
430	7.01E-01	590	1.23E+00	750	1.13E+00
435	1.01E+00	595	1.29E+00	755	1.13E+00
440	1.10E+00	600	1.33E+00	760	2.47E-01
445	1.20E+00	605	1.34E+00	765	6.34E-01
450	1.29E+00	610	1.32E+00	770	1.06E+00
455	1.27E+00	615	1.33E+00	775	1.08E+00
460	1.28E+00	620	1.33E+00	780	1.07E+00
465	1.29E+00	625	1.27E+00	785	1.06E+00
470	1.27E+00	630	1.26E+00	790	1.00E+00

Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]	Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]	Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]
795	1.01E+00	1040	6.34E-01	1290	3.95E-01
800	9.89E-01	1050	6.18E-01	1300	3.39E-01
805	9.73E-01	1055	6.12E-01	1305	3.68E-01
810	9.75E-01	1060	6.01E-01	1310	2.89E-01
815	8.29E-01	1065	5.95E-01	1315	2.74E-01
820	7.99E-01	1070	5.72E-01	1320	2.49E-01
825	8.98E-01	1075	5.61E-01	1325	3.09E-01
830	8.49E-01	1080	5.65E-01	1330	2.21E-01
835	9.29E-01	1085	5.62E-01	1335	2.22E-01
840	9.41E-01	1090	5.27E-01	1340	1.62E-01
845	9.42E-01	1095	4.94E-01	1345	1.05E-01
850	8.29E-01	1100	4.61E-01	1350	1.55E-02
855	8.47E-01	1105	4.81E-01	1355	3.48E-06
860	9.18E-01	1110	4.55E-01	1360	2.07E-06
865	8.95E-01	1115	2.38E-01	1365	8.78E-12
870	8.99E-01	1120	1.36E-01	1370	2.83E-07
875	8.62E-01	1125	1.38E-01	1375	3.13E-04
880	8.74E-01	1130	6.76E-02	1380	7.90E-05
885	8.79E-01	1135	1.48E-02	1385	2.03E-06
890	8.61E-01	1140	2.44E-01	1390	4.78E-04
895	7.60E-01	1145	1.40E-01	1395	6.51E-07
900	6.94E-01	1150	1.16E-01	1400	3.15E-09
905	7.63E-01	1155	2.99E-01	1405	3.54E-07
910	5.86E-01	1160	2.74E-01	1410	4.53E-04
915	6.36E-01	1165	3.71E-01	1415	1.79E-04
920	6.97E-01	1170	4.37E-01	1420	8.04E-03
925	6.66E-01	1175	4.31E-01	1425	2.51E-02
930	4.07E-01	1180	4.21E-01	1430	5.99E-02
935	2.37E-01	1185	3.89E-01	1435	2.08E-02
940	4.44E-01	1190	4.41E-01	1440	3.85E-02
945	3.47E-01	1195	4.27E-01	1445	4.84E-02
950	1.39E-01	1200	4.28E-01	1450	2.67E-02
955	3.22E-01	1205	4.17E-01	1455	6.44E-02
960	3.97E-01	1210	4.33E-01	1460	8.32E-02
965	4.75E-01	1215	4.09E-01	1465	9.09E-02
970	5.97E-01	1220	4.37E-01	1470	4.84E-02
975	5.55E-01	1225	4.41E-01	1475	1.80E-01
980	5.69E-01	1230	4.39E-01	1480	5.91E-02
985	6.47E-01	1235	4.44E-01	1485	1.22E-01
990	6.88E-01	1240	4.40E-01	1490	1.70E-01
995	7.07E-01	1245	4.36E-01	1495	1.77E-01
1000	6.92E-01	1250	4.37E-01	1500	2.43E-01
1005	6.41E-01	1255	4.31E-01	1505	1.79E-01
1010	6.77E-01	1260	4.12E-01	1510	2.63E-01
1015	6.67E-01	1265	3.79E-01	1515	2.58E-01
1020	6.58E-01	1270	3.71E-01	1520	2.57E-01
1025	6.57E-01	1275	3.95E-01	1525	2.51E-01
1030	6.51E-01	1280	4.04E-01	1530	2.48E-01
1035	6.43E-01	1285	4.06E-01	1535	2.59E-01

Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]	Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]	Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]
1540	2.57E-01	1790	8.68E-02	2040	8.83E-02
1550	2.62E-01	1800	3.11E-02	2050	6.69E-02
1555	2.60E-01	1805	1.45E-02	2055	5.41E-02
1560	2.58E-01	1810	9.48E-03	2060	6.82E-02
1565	2.60E-01	1815	3.21E-03	2065	6.10E-02
1570	2.35E-01	1820	9.66E-04	2070	6.47E-02
1575	2.33E-01	1825	1.25E-03	2075	7.63E-02
1580	2.38E-01	1830	5.09E-06	2080	8.55E-02
1585	2.51E-01	1835	6.28E-06	2085	8.38E-02
1590	2.35E-01	1840	6.13E-08	2090	8.78E-02
1595	2.51E-01	1845	6.13E-06	2095	8.84E-02
1600	2.31E-01	1850	2.93E-06	2100	8.49E-02
1605	2.30E-01	1855	2.78E-07	2105	9.18E-02
1610	2.11E-01	1860	1.09E-05	2110	8.83E-02
1615	2.34E-01	1865	1.66E-05	2115	9.03E-02
1620	2.28E-01	1870	2.61E-10	2120	8.63E-02
1625	2.31E-01	1875	4.43E-10	2125	8.73E-02
1630	2.30E-01	1880	7.61E-05	2130	8.84E-02
1635	2.27E-01	1885	4.31E-05	2135	8.87E-02
1640	2.09E-01	1890	2.20E-04	2140	8.94E-02
1645	2.12E-01	1895	1.27E-04	2145	8.81E-02
1650	2.19E-01	1900	8.49E-07	2150	8.34E-02
1655	2.16E-01	1905	5.58E-07	2155	8.36E-02
1660	2.17E-01	1910	2.27E-05	2160	8.29E-02
1665	2.06E-01	1915	1.97E-05	2165	7.52E-02
1670	2.16E-01	1920	4.45E-04	2170	8.08E-02
1675	2.08E-01	1925	9.23E-04	2175	7.93E-02
1680	2.00E-01	1930	5.45E-04	2180	8.06E-02
1685	2.08E-01	1935	3.54E-03	2185	7.35E-02
1690	2.00E-01	1940	3.24E-03	2190	7.79E-02
1695	2.04E-01	1945	1.07E-02	2195	7.78E-02
1700	1.95E-01	1950	1.65E-02	2200	7.02E-02
1705	1.93E-01	1955	9.89E-03	2205	7.29E-02
1710	1.83E-01	1960	2.16E-02	2210	7.82E-02
1715	1.85E-01	1965	2.81E-02	2215	7.52E-02
1720	1.82E-01	1970	4.81E-02	2220	7.66E-02
1725	1.74E-01	1975	6.67E-02	2225	7.44E-02
1730	1.70E-01	1980	7.42E-02	2230	7.47E-02
1735	1.58E-01	1985	8.16E-02	2235	7.33E-02
1740	1.64E-01	1990	8.41E-02	2240	7.21E-02
1745	1.51E-01	1995	7.98E-02	2245	6.99E-02
1750	1.62E-01	2000	3.75E-02	2250	7.10E-02
1755	1.49E-01	2005	1.47E-02	2255	6.69E-02
1760	1.56E-01	2010	3.91E-02	2260	6.61E-02
1765	1.30E-01	2015	2.62E-02	2265	6.74E-02
1770	1.38E-01	2020	4.42E-02	2270	6.41E-02
1775	1.12E-01	2025	7.28E-02	2275	6.33E-02
1780	9.81E-02	2030	8.35E-02	2280	6.56E-02
1785	7.52E-02	2035	9.48E-02	2285	6.24E-02

Wavelength λ [nm]	Direct + Circumsolar G_b [W m^{-2}nm^{-1}]				
2290	6.25E-02				
2300	5.82E-02				
2305	5.85E-02				
2310	6.32E-02				
2315	5.75E-02				
2320	5.15E-02				
2325	5.56E-02				
2330	5.62E-02				
2335	5.74E-02				
2340	4.54E-02				
2345	5.09E-02				
2350	4.11E-02				
2355	4.70E-02				
2360	4.97E-02				
2365	4.89E-02				
2370	3.05E-02				
2375	4.37E-02				
2380	4.21E-02				
2385	3.05E-02				
2390	3.67E-02				
2395	4.02E-02				
2400	4.37E-02				
2405	3.33E-02				
2410	3.35E-02				
2415	2.71E-02				
2420	2.64E-02				
2425	3.28E-02				
2430	4.47E-02				
2435	1.48E-02				
2440	4.29E-02				
2445	2.07E-02				
2450	1.35E-02				
2455	2.47E-02				
2460	3.32E-02				
2465	2.40E-02				
2470	1.66E-02				
2475	1.64E-02				
2480	8.00E-03				
2485	5.58E-03				
2490	3.50E-03				
2495	2.86E-03				
2500	7.03E-03				

Annex C
Calculation of the uncertainty of solar reflectance

This Annex defines the criteria and procedures for calculating the uncertainty in solar reflectance.

C.1. Short summary of ISO/IEC GUIDE 98-3

The ISO/IEC GUIDE 98-3 Standard (Guide to the Expression of Uncertainty in Measurement or GUM) [38] explains how to estimate the standard uncertainty of the measurand Y obtained by the measurement equation:

$$Y = f(X_1, X_2, \dots X_N) \tag{13}$$

where X_i are the input quantities. Given the set of input estimates $\{x_i\}$, the output estimate is

$$y = f(x_1, x_2, \dots x_N) \tag{14}$$

Reminding the reader to that document for the detailed exposition, here we just recall the evaluation of the standard uncertainty of each input quantity X_i, belongings to one of the two cases:

- **Type A: uncertainty is evaluated by the statistical analysis of series of observations -** as an example if the input quantity X_i is distributed like a Gaussian, its standard uncertainty is

$$u(X_i) = \sqrt{\frac{\sum_{k=1}^{N}\left(X_{i,k} - \overline{X_\iota}\right)^2}{n-1}} \tag{15}$$

  with

$$\overline{X_\iota} = \frac{1}{n}\sum_{k=1}^{N} X_{i,k} \tag{16}$$

- **Type B: uncertainty is evaluated by means other than the statistical analysis of a series of observations such as**, **manufacturers' specifications, calibration, and/or previous experience /literature estimates –** as an example if one can assume the uniform distribution in the range (a_-, a_+), the uncertainty is given by

$$u_j = \frac{(a_+ - a_-)}{2\sqrt{3}} \tag{17}$$

Once the uncertainties of the input quantities are suitably evaluated, the **combined standard uncertainty** of the measurement result y is given by

$$u_c^2(u) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, u_j) \tag{18}$$

where the partial derivatives $\frac{\partial f}{\partial x_i}$, referred as **sensitivity coefficients**, are evaluated at $\{xi\}$. The last term is null when the input quantities X_i are uncorrelated.

In the general case uncertainty is computed so that the range $\pm u$ has the confidence level of 68%, i.e. 1 standard deviation. Higher levels of confidence can be obtained by the **expanded uncertainty** which is calculated by multiplying the **combined uncertainty (u_c)** by a **coverage factor k.** For infinite degrees of freedom, *k*=2 and k= 3 define an interval of confidence of approximately 95% and 99%, respectively.

Summarizing, the procedure reported in the ISO/IEC GUIDE 98-3 consists of the steps reported in the following sketch

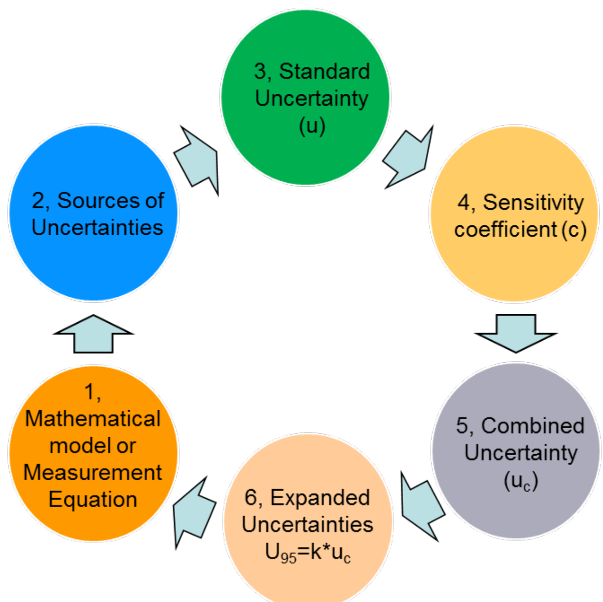

Figure 6: Summary of the procedure to calculate the uncertainty

C.2. Uncertainty of solar reflectance

In the most common case, reflectance is experimentally measured by means a relative device: at each wavelength two signals have to be acquired, M and B, respectively related to unknown and reference specimen; then reflectance is given by the measurement equation

$$\rho(\lambda) = \frac{M}{B}\rho_{ref}(\lambda) \tag{19}$$

where $\rho_{ref}(\lambda)$ is the reflectance of the reference. Here there are three input quantities which can be affected by a number of error sources. According to the CIE Technical report "practical methods for measurement of reflectance and transmittance" [42] they are:

- Calibration of the equipment (external calibrated standard)
- Repeatability
- Accuracy

- Wavelength deviation
- Mounting
- Maintenance
- Drift of the zero
- Sensibility to magnetic field
- Light source stability
- Data logger
- Temperature dependence
- Detector Non-linearity
- Aging
- Incorrect wavelength calibration
- Influence of slit-width on the wavelength calibration
- Bandwidth too wide
- Stray light impairing spectral purity
- Non-uniformity irradiance on the irradiated sample area

Anyway, in the case of high quality commercial spectrophotometers many of those sources can be neglected because leading to minor effects when the operator respects the recommendations reported in the user manual and the instrument is periodically checked by qualified technicians. Also we assume that the operator had already gained a good experience on the specific instrument so that the measurement parameters were optimized and the results are trustworthy. As an example, for dispersive instruments scan speed and time constant shall be rightly balanced to have good agreement between the signals acquired statically or dynamically, during the wavelength scan.

Usually the reference mirror is purchased from a certified vendor, thus the uncertainty of $\rho_{ref}(\lambda)$ belongs to the type B. The typical value is $\pm 0.005 = \pm 0.5\%$.

Concerning *M* and *B*, although the spectrophotometer gives their mean values along the selected time constant, commercial instruments does not return their standard deviation values. However, there is a much more important error source: the baseline drift occurring between the measurements of sample and reference whose are dealt at different time. Such a drift can be experimentally evaluated by repeating the acquisition of the reference spectrum several times along the typical lapse of validity the baseline. The baseline drift is the deviation by the expected value $1 = 100\%$. Except in the neighbourhood of the wavelengths where detector/grating/lamp are changed, the maximum typical value over 6 hours is $0.002 = 0.2\%$. Greater values are symptomatic of malfunctioning, like misalignment of the light beams or excessive variation of the environment conditions. Another important point is that along some hours the behaviour of the baseline drift is not random, but quite regular, likewise a thermal effect. Because in such a case standard deviation has not sense, we can use the maximum observed deviation as the conservative evaluation of the maximum error on B, attributing to M the only reading error due to the analogical to digital converter, which typical value is $0.0005 = 0.05\%$. By assuming the uniform distribution, for both the uncertainty is $\frac{1}{2\sqrt{3}}$ of their maximum error.

Under the above assumption, being the input quantities uncorrelated, the combined uncertainty of reflectance is

$$u_\rho^2 = \rho^2 \left[\left(\frac{\Delta M}{M} \right)^2 + \left(\frac{\Delta B}{B} \right)^2 + \left(\frac{\Delta \rho_{ref}}{\rho_{ref}} \right)^2 \right] \tag{20}$$

Finally the uncertainty of the solar reflectance is obtained by averaging u_ρ^2 similarly to ρ.

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