# Guidelines

PARAMETERS AND METHOD TO EVALUATE THE SOLAR REFLECTANCE PROPERTIES OF REFLECTOR MATERIALS FOR CONCENTRATING SOLAR POWER TECHNOLOGY
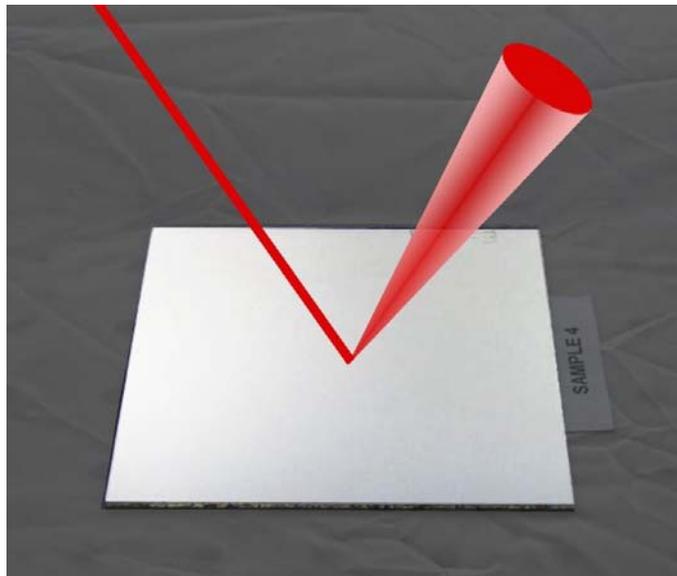
Official Reflectance Guideline Version 2.5

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Foreword

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 DKE, AENOR, 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 stephanie.meyen@dlr.de.

Introduction

This guideline for reflectance characterisation of solar reflectors is published under the framework of the SolarPACES Task III: "Solar Technology and Advanced Applications". The project "Development of guidelines for standards for concentrating solar power (CSP) components" had been created 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 organisations (ISO, IEC, ASME, DIN, AENOR, 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.

The presented work is focused on the first topic and was initiated and pushed forward mainly by the Solar Research Institute of the German Aerospace Center (DLR), working together with other research institutions like CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain) and NREL (National Renewable Energy Laboratory, USA) and also Enea (Agenzia Nazionale per le Nuove Tecnologie, I'energia e lo Sviluppo Economico Sotenibile, Italy), the Fraunhofer Institute for Solar Energy Systems (ISE, Germany) and CTAER (Centro Tecnológico Avanrado de Energías Renovables, Spain). 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 has progressed very much.

In spring of 2011, a first interim guideline version on a specified measurement method to obtain solar weighted reflectance values with commercial available instrumentation had been created from a very small group of authors and published at the SolarPACES homepage [1]. On the basis of that document, now the above mentioned broader board of experts has exchanged their knowledge and experience in comments and discussions that have been implemented in this second version of a reflectance measurement guideline. The content of this second version was mainly discussed and decided on during a technical meeting among the mentioned partners, that was held within the framework of the SolarPACES conference in September 2012 in Marrakech, Morocco. This second guideline version replaces the first one.

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). To properly characterize reflectors, both reflectance and specularity should be quantified.

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 reflectivity 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 [2][3][4] and has been taken up again recently [5][6][7]. 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 of up to 50° 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 [8].

Due to the lack of commercial available instrumentation to adequately characterize all reflectance properties of a reflector material, 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.

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 [9][10][11]. 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).

The goal of this document is to serve as a guidance on the relevant parameters and measurement possibilities to reliably evaluate the reflectance quality of a solar reflector material. 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 a 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. The values to be reported and the accuracy that should be approached is described in chapter 8. Annex A and Annex B give 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 [12][13][14].

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, 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). Thus $\theta_i = \theta_r = \theta$. Light follows the law of reflection.
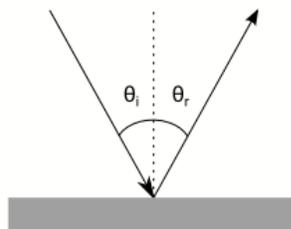

Figure 1: Law of reflection

Hemispherical reflectance

The hemispherical reflectance, $\rho_h(\lambda,\theta,h)$, 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, 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 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 [15].
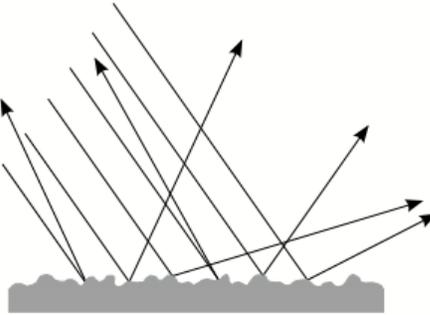
Figure 2: Diffuse reflection

Specular reflectance and specularity

For CSP application, specular reflectance is the most important parameter. However, 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 [2][3][9][10][16][17].

The measured specular reflectance for solar applications is written as $\rho_s(\lambda,\theta,\varphi)$ where ρ_s is dependent on the wavelength, λ, and is function of the incidence angle, θ, 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. Strictly speaking, the ideal specular reflectance is related to $\varphi = 0$, whereas the measurement at any small offset φ is more appropriately termed near specular reflectance. For the purpose of simplicity and usefulness, this parameter in this document is referred to as specular reflectance, always specified with the acceptance angle.

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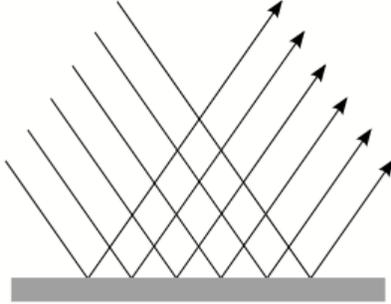
Figure 3a: Perfect specular reflection   Figure 3b: Specular reflection with offset
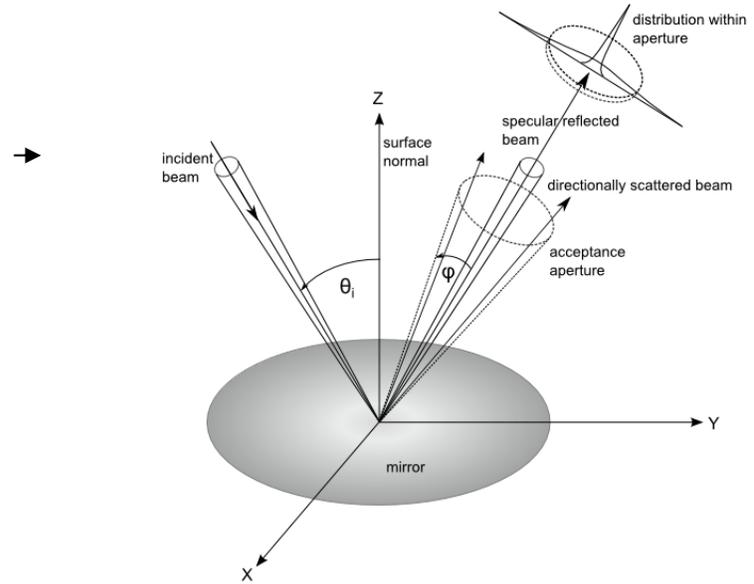
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In practical application, the specular reflectance of a material is often inferred by the intensity measurement of the reflected beam collected through an aperture (Figure 3b) or measured within the field of view of the detector. The observed signal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

$$\rho_{detected} = N\int_{\Omega}\int_{S_{beam}}\int_{S_{detector}} d\Omega_i ds_{beam}ds_{detector}I(A,\vec{i})R\left(\frac{\overrightarrow{AB}\times\vec{r}}{|\overrightarrow{AB}|}\right) \qquad (3.)$$

where N is a normalization factor, $I(A,\vec{i})d\Omega_i$ is the beam intensity travelling in direction $\vec{i}$, 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 $\overrightarrow{AB}$, which intensity is given by the scattering distribution function R. The unit vector, $\vec{r}$, indicates the direction of the specular reflection given by $\vec{i}$ 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 [2] 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:

$$\rho_s(\lambda,\theta,\varphi) = \rho_h(\lambda,\theta,h) \int_0^{2\pi}\int_0^{\varphi} d\beta\, d\varphi \sin(\varphi) R(\lambda,\theta,\varphi) \qquad (4.)$$

Where *R* is normalized to the integral over the acceptance angle π/2.

In some special cases it is appropriate to approximate *R* by a Gaussian distribution, as has been observed by [2][6]. This changes equation 4 to:

$$\rho_s(\lambda,\theta,\varphi) = \rho_h(\lambda,\theta,h) \cdot \left[1 - \sum_{j=1}^{M} K_j \exp\left[\frac{-\varphi^2}{2\sigma_j^2(\lambda,\theta)} \right] \right] \qquad (5.)$$

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 [7] 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 $I(A,\vec{i}) = I_0 \delta(\vec{i})$. 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 $\rho_s(\lambda,\theta,\varphi) = \rho_h(\lambda,\theta,h)$ 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.

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)

CSP   Concentrated solar power

Collector   Element consisting of concentrator and receiver

Concentrator Parabolic 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

ρ Reflectance

α Absorptance

τ Transmittance

Φ Radiance flux

λ Wavelength

θ Incidence angle

φ Acceptance angle

$\rho_h(\lambda,\theta,h)$ Hemispherical reflectance

$\rho_h(SW,\theta,h)$ Solar-weighted hemispherical reflectance

$\rho_s(\lambda,\theta,\varphi)$ Specular reflectance

$\rho_s(SW,\theta,\varphi)$ Solar-weighted specular reflectance

σ Statistical standard deviation

4 Required set of reflectance parameters

At the technical meeting in Marrakech in September 2012 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. 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 Annex A).

4.2 Hemispherical reflectance

Various commercial laboratory instruments are available to measure hemispherical reflectance, $\rho_h(\lambda,\theta,h)$, usually by utilizing an integrating sphere, with good accuracy and spectrally resolved over the whole relevant solar spectrum of 280^1 – 2500 nm [20]. 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, $\rho_h(\lambda,\theta,h)$ is measured at near normal angles of incidence ($\theta <= 15°$), 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 $\rho_h(\lambda,\theta,h)$ 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 $\rho_h(\lambda,\theta,h)$ 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 or at least for several, greater angles of incidence as well (example of a model approach see [21]).

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, $\rho_s(\lambda,\theta,\varphi)$. The range of relevant φ depends on the collector design. Typically it is 0-20 mrad. Beam spread and scattering is wavelength dependent and therefore the specularity or the approximated relationship $\rho_s(\lambda,\theta,\varphi)\big/\rho_h(\lambda,\theta,h)$ can change over the spectrum.

The specular reflectance spectrum should ideally be measured over the solar wavelength range or at least at

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[1] The standard solar spectrum ASTM G 173 starts at 280 nm. However, in some instruments a great amount of cost can be reduced by avoiding the use of an extra UV-lamp and starting the measurement at 300 nm. This is allowed since the UV and NIR tails have low impact on the final average value.

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 $\rho_s(\lambda,\theta,\varphi)$ must be measured at least at three wavelength bands or in the solar wavelength spectrum.

- As a minimum requirement, $\rho_s(\lambda,\theta,\varphi)$ must be measured at least at near normal incidence ($\theta <= 15°$) and at least at three φ in the range of $\varphi >= 0$ to $\varphi <= 20$ mrad.

- Ideally, the parameter $\rho_s(\lambda,\theta,\varphi)$ is analyzed by measurement or by an experimentally validated theoretical model, as a function of λ, as a function of θ and as a function of φ (example of a model approach see [22]).

4.4   Solar weighted reflectance

Solar weighting of the reflectance parameters is calculated with the currently valid standard solar spectrum ASTM G173 [20] 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 [23][24]. The solar irradiation is provided in [20] in the wavelength range $\lambda = 280 – 4000$ nm. Because the NIR range has low impact and it is practically more convenient for the measurement equipment, the relevant measurement range for reflectance evaluation can be resized to $\lambda = 280 – 2500$ nm or even to $\lambda = 300^2 – 2500$ nm.

The solar weighted specular reflectance, $\rho_s(SW,\theta,\varphi)$, 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, $\rho_h(SW,\theta,h)$, 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 $\rho_h(SW,\theta,h)$, weighted according to the actually valid standard solar spectrum (currently [20]) for direct irradiance and the appropriate Air Mass (i.e. for Europe and USA it is AM 1.5) at least at $\theta <= 15°$, must be acquired for a reliable analysis of the portion of the solar irradiance reflected by the reflector material.

- Ideally, the parameter $\rho_s(SW,\theta,\varphi)$, weighted according to the actually valid standard solar spectrum (currently [20]) 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 and φ, or at least at three incidence angles and at three φ in the range of $\varphi >= 0$ mrad to $\varphi <= 20$ mrad.

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

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[2] The standard solar spectrum ASTM G 173 starts at 280 nm. However, in some instruments a great amount of cost can be reduced by avoiding the use of an extra UV-lamp and starting the measurement at 300 nm. This is allowed since the UV and NIR tails have low impact on the final average value.

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 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 (maximum wavelength interval of 5 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.

- 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[3] uncertainties. These type-B uncertainties should be kept to a minimum [25].

- High precision and repeatability.

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[3] As explained in [25], 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.

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- 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.

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 $\lambda = 280^4 - 2500$ nm at wavelength intervals which allow accurate solar weighted calculation (maximum wavelength interval of 5 nm).

- Measurement at least at near normal incidence ($\theta <= 15°$).

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

- If measurements at $\theta > 15°$ 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 [26].

- Stable concerning associated type-B[2] uncertainties. These type-B uncertainties should be kept to a minimum [25].

- High precision and repeatability with a top class instrument.

- No influence by external stray light.

- No risk to human health or environmental hazard involved.

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[4] The standard solar spectrum ASTM G 173 starts at 280 nm. However, in some instruments a great amount of cost can be reduced by avoiding the use of an extra UV-lamp and starting the measurement at 300 nm. This is allowed since the UV and NIR tails have low impact on the final average value.

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.

- Several precise and selectable acceptance apertures or an innovative approach that covers at least a range of acceptance angles from $\varphi >= 0$ to $\varphi <= 20$ mrad.

- Measurement at least at near normal incidence ($\theta <= 15°$).

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

- If measurements at $\theta > 15°$ 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 display, light-weight, small compact size, easy to handle, robust.

- Stable concerning associated type-B[5] uncertainties. These type-B uncertainties should be kept to a minimum [25].

- High precision and repeatability.

- No influence by external stray light.

- No risk to human health or environmental hazard involved.

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[5] As explained in [25], 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. 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 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 are essential for a performance with constant high accuracy.

- At least 3 measurements on different local spots and different orientations (i.e. turns of 45°) 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.

6.2 Cleaning

The mirror's front surface should be cleaned very carefully with a soft lens tissue and deionised water or according to the manufacturer's recommendation prior to measurement.

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 deionised water (1/100) followed by a copious rinse of deionised 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 demineralised 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 [19]. If the results that are to be reported are acquired with different instruments, the same reference mirror should be used in all measurements [27]. 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. 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.

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

7 Weighting with standard solar norm 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 norm 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). 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 [27].

It is recommended to take the standardized solar irradiance spectrum from the most current accepted solar standard, which is actually ASTM G173 [20]. 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 hemispherical reflectance

The calculation of solar weighting is explained extensively in the withdrawn standard ISO 9845 [23] and in the standard ISO 9050 [24], which only contains global irradiance tables. The solar-weighted reflectance, $\rho(SW)$, of a mirror represents the convolution of the spectral reflectance function, $\rho(\lambda)$, with the solar irradiance function, $E(\lambda)$. Since these functions are generally only known with discrete values, the integration is performed as a summation. Therefore, the solar-weighted hemispherical reflectance, $\rho_h(SW,\theta,h)$, or the solar weighted specular reflectance, $\rho_s(SW,\theta,\varphi)$, here both represented by $\rho(SW)$, of a solar mirror is calculated using the values of the measured reflectance spectrum, $\rho_h(\lambda,\theta,h)$, or $\rho_s(\lambda,\theta,\varphi)$, here both represented by $\rho(\lambda_i)$, and the direct solar irradiance spectrum, E_λ, at wavelength intervals of $\Delta\lambda$ with equation 6.

$$\rho(SW) = \frac{\sum_{i=0}^{2500} \rho(\lambda_i) E_\lambda(\lambda_i) \Delta\lambda_i}{\sum_{i=0}^{2500} E_\lambda(\lambda_i) \Delta\lambda_i} \tag{6.}$$

The ratio of $E_\lambda(\lambda_i)\Delta\lambda_i \Big/ \sum_{i=0}^{i=2500} E_\lambda(\lambda_i)\Delta\lambda_i$ can be combined to a weighting factor $F(\lambda_i)$. Weighting factors $F(\lambda_i)$ for the interval of $\Delta\lambda = 5$ nm calculated from ASTM G 173 solar tables are given in Annex B.2. Using these weighting factors, the solar weighted reflectance is obtained by the sum of a simple multiplication:

$$\rho(SW) = \sum_{i=280}^{2500} \rho(\lambda_i) \cdot F(\lambda_i) \tag{7.}$$

The total sum of the weighting factors must be 1. Applying equation 7 together with the factors of Annex B.2 can lead to round off errors which can result in a sum not equal to 1. In that case equation 6 must be applied.

If it is necessary to use different wavelength intervals or a different wavelength range, the weighting factors given in Annex B.2 cannot be applied. New weighting factors should be created as explained in Annex B.1.

8 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 and accuracy are discussed in Sections 8.2 and 8.3.

8.1 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:

- $\rho_h(SW,\theta,h)$ solar weighted hemispherical reflectance at near normal incidence.

- Hemispherical reflectance spectrum as a graph.

- $\rho_s(\lambda,\theta,\varphi)$ specular reflectance at near normal incidence, at least three λ and at least three φ in the range $\varphi = 0$-20 mrad (see chapter 4.3).

- $\rho_h(\lambda,\theta,h)$ hemispherical reflectance values at the same wavelengths or range as $\rho_s(\lambda,\theta,\varphi)$.

- Statistical standard deviation of measurements for all above listed values, $\sigma(\rho_h)$ and $\sigma(\rho_s)$.

- 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 (if one has been used) 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. $\rho_h(SW,8°,h) = 0.942$.

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

8.2 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.

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- 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.

8.3   Accuracy

Optical measurements of solar mirrors require experienced operators taking special care to achieve highly accurate results. The uncertainty of a measurement contains type A and type B uncertainties [25]. Type A uncertainties only take into account measurement statistics (variance between several measurements on one sample). However, type B uncertainties depend on several factors, such as measurement instrument (which is affected by various sources of uncertainties like light source stability, reproducibility, detector sensitivity, maintenance status, etc.), sample quality, reference standard quality, calibration status and operator experience. In particular, the uncertainty of specular reflectance measurements increases for mirror samples with a low specular surface quality.

A combined measurement accuracy of $u = \pm 0.008$ to $u = \pm 0.014$ (with a factor of confidence k = 2) including type B and type A uncertainties is achievable [27][29] with state of the art commercially available instruments.

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Annex A
(informative)

Exemplary procedure

A.1 General

This section is meant to provide an example of a procedure that can be applied to acquire the values that need to be reported according to section 8.1. The example assumes the measurement with common instruments but does not imply that the procedure is the only one applicable. As has been discussed at the meeting in Marrakech, Morocco on September 2012, 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 is converted into a reflectance spectrum using the reference measurement and the known reflectance spectrum of the reference mirror, $\rho_{h,reference}(\lambda,\theta,h)$, as follows:

$$\rho_{h,sample}(\lambda,\theta,h) = \frac{Measurement_{sample} - Zeroline}{Measurement_{reference} - Zeroline} \cdot \rho_{h,reference}(\lambda,\theta,h) \qquad (8.)$$

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:

- $\rho_h(SW,\theta,h)$ solar weighted hemispherical reflectance at near normal incidence angle.

- Hemispherical reflectance spectrum as a graph.

- $\rho_h(\lambda_{meas},\theta,h)$ at the relevant wavelength λ_{meas} 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. Measurements are usually performed at near normal incidence.

One might imagine an exemplary measurement taken at φ = 3.5, 7.5, 12,5 and 23 mrad and λ = 450, 550, 660, 750 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 resulting parameters that can be reported are:

- Sixteen values for $\rho_s(\lambda,\theta,\varphi)$ at θ = near normal, that can conveniently be plotted as discrete data points per wavelength with φ being the x-axis.

- A decreasing manner in the values for $\rho_s(\lambda,\theta,\varphi)$ with decreasing φ indicates that surface roughness leads to a wider beam spread and scattering. In this case an adequate, verified model fit or more extensive measurements with a wider range of acceptance angles might be indicated to quantify specularity and the specular reflectance as a function of acceptance angle. This is convenient for the evaluation of the reflector in its destined application.

- If enough data can be obtained with the employed instrument (more acceptance angles especially in the small range nearing zero), a curve could be fitted into the plot approaching the hemispherical reflectance value at the measurement wavelength.

- The standard deviation of these measurements on different spots on the sample indicates its homogeneity and thus the confidence in the final result.

Other approaches might be to use the data in a TIS-model or to measure the complete reflectance distribution function with a goniometric setup, to calculate from these data the amount of radiation that would pass any virtual acceptance aperture.

A.4 Simplified procedure for reflectors with good specularity

One way of interpreting the above results might be to use the sixteen values for $\rho_s(\lambda,\theta,\varphi)$ and comparing them with $\rho_h(\lambda,\theta,h)$ at the same wavelength respectively, by using the ratio $\rho_s(\lambda,\theta,\varphi) / \rho_h(\lambda,\theta,h)$. The resulting sixteen ratio values can conveniently be plotted as discrete data points per acceptance angle with λ being the x-axis.

Note: If the standard deviation of $\rho_s(\lambda,\theta,\varphi)$ and/or $\rho_h(\lambda,\theta,h)$ measurements is high, this approach of evaluation gives no reliable information and is not appropriate.

Note: If the ratio plots are not constant over the wavelength range for each acceptance angle and/or if the results for $\rho_s(\lambda,\theta,\varphi)$ vary among each other or to $\rho_h(\lambda,\theta,h)$ more than the measurement uncertainty, then this approach of evaluation gives no reliable information and is not appropriate.

With a low standard deviation, however, the ratio values could be used to estimate the quality of specularity. The simplified approach consists of evaluating, if the ratio plots are constant over the wavelength range for each acceptance angle and if the results for $\rho_s(\lambda,\theta,\varphi)$ do not vary among each other and to $\rho_h(\lambda,\theta,h)$ more than the measurement uncertainty. Then it can be assumed that the reflector material in question has good specularity properties.

Another indicator for the quality of specularity is given by the distribution of the reflected beam into the hemisphere, if equipment is available that allows to evaluate this. For a mirror material with good specularity, this distribution would be similar to a Gaussian distribution with a $\sigma < 0.5$ mrad (see section 2.1). For reflectors with a wider scattering distribution, this simplified procedure is not appropriate because it tends to overestimate the impacts of specularity on applied CSP collectors.

If high specularity has been proven, for any subsequent sample measurements of the same reflector material, the following simplifications of procedure and reported parameters are allowed:

- Measurement of $\rho_s(\lambda,\theta,\varphi)$ is only necessary at one λ and one φ per incidence angle. This measurement is important as an indicator of changes in the specularity property of the material.

- The solar weighted specular reflectance $\rho_s(SW,\theta,\varphi)$ can be assumed to be equal to $\rho_h(SW,\theta,h)$ within the measurement uncertainty boundaries.

The resulting parameters that can be reported are:

- $\rho_h(SW,\theta,h)$ solar weighted hemispherical reflectance at least at near normal incidence.

- Hemispherical reflectance spectrum as a graph.

- $\rho_s(\lambda,\theta,\varphi)$ specular reflectance at least at near normal incidence, at one λ and one φ.

- $\rho_h(\lambda,\theta,h)$ hemispherical reflectance at the same wavelength as $\rho_s(\lambda,\theta,\varphi)$.

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Annex B
(informative)

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, column 2 gives the solar irradiance (direct + circumsolar) in $Wm^{-2}nm^{-1}$ extracted from the last column of ASTM G173-2003 [20], column 3 gives the solar irradiance integrated from $\lambda_0 = 0$ nm to λ_i calculated with the modified trapezoidal rule and column 4 presents the weighting factor $F(\lambda)$ used to calculate the solar weighted reflectance.

The values for $E_{0\rightarrow\lambda i}$ as the integral of irradiance from λ_0 to the actual λ_i were created using a modified trapezoidal integration technique [23][24] with $\Delta\lambda_i = 5$ nm:

$$E_{0\rightarrow\lambda i} = E_{0\rightarrow\lambda 1} + \sum_{j-1}^{i-1}\frac{E_{\lambda j+1} + E_{\lambda j}}{2}\Delta\lambda_i \qquad (9.)$$

The solar contribution prior to the first tabulated wavelength ($\lambda_1 = 280$ nm) was estimated as half of the first trapezoidal area and is therefore described by:

$$E_{0\rightarrow\lambda 1} = \frac{1}{2}\frac{E_{\lambda 1} + E_{\lambda 2}}{2}(\lambda_2 - \lambda_1) \qquad (10.)$$

($E_{0\rightarrow\lambda 1} = 1,125e^{-16}$ was used in the calculations for the values in chapter C.2.

The total integrated solar irradiance used for the calculation of the weighting factor $F(\lambda_i)$ was $E_{0\rightarrow 2500} = 893,4312$ Wm^{-2}. The values presented in the weighting table were extracted from the tables in ASTM G173 in intervals of $\Delta\lambda = 5$ nm. This has slightly smoothed the original solar curve, which has a higher wavelength resolution. The extracted data were used to create the integrated irradiance values and accordingly the weighting factors $F(\lambda_i)$ were calculated as follows:

$$F(\lambda_i) = \frac{E_\lambda(\lambda_i)\Delta\lambda_i}{\sum_{j=0}^{2500}E_\lambda(\lambda_j)\Delta\lambda_i} \quad \text{with} \quad \sum_{j=0}^{2500}E_\lambda(\lambda_j)\Delta\lambda_i = E_{0\rightarrow 2500} \qquad (11.)$$

The total sum of the weighting factors must be 1. Applying equation 7 can lead to round off errors which can result in a sum not equal to 1. In that case equation 6 must be applied.

B.2 Weighting table:

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\to\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
280	2,54E-26	0,0000	1,42E-28
285	9,00E-17	0,0000	5,04E-19
290	5,15E-10	0,0000	2,88E-12
295	3,22E-06	0,0012	1,80E-08
300	4,56E-04	0,0246	2,55E-06
305	8,93E-03	0,1165	5,00E-05
310	2,78E-02	0,3703	1,56E-04
315	7,37E-02	0,8365	4,12E-04
320	1,13E-01	1,5060	6,31E-04
325	1,55E-01	2,5484	8,68E-04
330	2,62E-01	3,8651	1,47E-03
335	2,65E-01	5,2685	1,48E-03
340	2,97E-01	6,7063	1,66E-03
345	2,79E-01	8,2255	1,56E-03
350	3,29E-01	10,0268	1,84E-03
355	3,91E-01	11,9863	2,19E-03
360	3,92E-01	14,0126	2,20E-03
365	4,18E-01	16,3495	2,34E-03
370	5,17E-01	18,6683	2,89E-03
375	4,11E-01	20,9393	2,30E-03
380	4,98E-01	23,3990	2,78E-03
385	4,86E-01	26,0764	2,72E-03
390	5,85E-01	29,0402	3,27E-03
395	6,01E-01	32,6423	3,36E-03
400	8,40E-01	36,9383	4,70E-03
405	8,78E-01	41,1572	4,92E-03
410	8,09E-01	45,5692	4,53E-03
415	9,56E-01	50,1701	5,35E-03
420	8,85E-01	54,8646	4,95E-03
425	9,93E-01	59,1007	5,56E-03
430	7,01E-01	63,3716	3,92E-03
435	1,01E+00	68,6373	5,64E-03
440	1,10E+00	74,3836	6,15E-03
445	1,20E+00	80,6018	6,71E-03
450	1,29E+00	86,9858	7,21E-03
455	1,27E+00	93,3473	7,08E-03
460	1,28E+00	99,7713	7,16E-03
465	1,29E+00	106,1848	7,22E-03
470	1,27E+00	112,8108	7,13E-03
475	1,38E+00	119,7058	7,70E-03
480	1,38E+00	126,5263	7,74E-03
485	1,35E+00	133,3826	7,53E-03
490	1,40E+00	140,4341	7,82E-03

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\rightarrow\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
495	1,42E+00	147,3413	7,97E-03
500	1,34E+00	154,0886	7,49E-03
505	1,36E+00	160,8623	7,61E-03
510	1,35E+00	167,5828	7,55E-03
515	1,34E+00	174,2663	7,49E-03
520	1,33E+00	181,0683	7,47E-03
525	1,39E+00	187,9326	7,76E-03
530	1,36E+00	194,7573	7,61E-03
535	1,37E+00	201,4566	7,67E-03
540	1,31E+00	208,1448	7,33E-03
545	1,37E+00	214,9711	7,64E-03
550	1,36E+00	221,8538	7,64E-03
555	1,39E+00	228,6041	7,77E-03
560	1,31E+00	235,2723	7,34E-03
565	1,36E+00	241,9711	7,59E-03
570	1,32E+00	248,5873	7,41E-03
575	1,32E+00	255,2573	7,40E-03
580	1,35E+00	262,0553	7,53E-03
585	1,37E+00	268,5686	7,69E-03
590	1,23E+00	274,8651	6,89E-03
595	1,29E+00	281,4021	7,20E-03
600	1,33E+00	288,0761	7,43E-03
605	1,34E+00	294,7398	7,51E-03
610	1,32E+00	301,3626	7,41E-03
615	1,33E+00	308,0008	7,42E-03
620	1,33E+00	314,4923	7,44E-03
625	1,27E+00	320,8063	7,09E-03
630	1,26E+00	327,2198	7,05E-03
635	1,31E+00	333,7266	7,31E-03
640	1,30E+00	340,2596	7,25E-03
645	1,32E+00	346,6268	7,37E-03
650	1,23E+00	352,7566	6,88E-03
655	1,22E+00	358,9786	6,84E-03
660	1,27E+00	365,3633	7,09E-03
665	1,29E+00	371,7943	7,20E-03
670	1,29E+00	378,1673	7,19E-03
675	1,26E+00	384,4896	7,07E-03
680	1,27E+00	390,7656	7,08E-03
685	1,25E+00	396,5656	6,97E-03
690	1,07E+00	402,1366	6,01E-03
695	1,15E+00	407,9301	6,46E-03
700	1,16E+00	413,8363	6,51E-03
705	1,20E+00	419,8221	6,71E-03
710	1,20E+00	425,6676	6,69E-03
715	1,14E+00	430,7731	6,40E-03
720	8,99E-01	435,3901	5,03E-03

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\to\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
725	9,47E-01	440,3321	5,30E-03
730	1,03E+00	445,6809	5,76E-03
735	1,11E+00	451,2359	6,21E-03
740	1,11E+00	456,8666	6,22E-03
745	1,14E+00	462,5359	6,38E-03
750	1,13E+00	468,1844	6,31E-03
755	1,13E+00	471,6325	6,34E-03
760	2,47E-01	473,8349	1,38E-03
765	6,34E-01	478,0808	3,55E-03
770	1,06E+00	483,4425	5,96E-03
775	1,08E+00	488,8145	6,04E-03
780	1,07E+00	494,1485	5,98E-03
785	1,06E+00	499,3220	5,96E-03
790	1,00E+00	504,3498	5,62E-03
795	1,01E+00	509,3378	5,63E-03
800	9,89E-01	514,2410	5,53E-03
805	9,73E-01	519,1099	5,44E-03
810	9,75E-01	523,6203	5,46E-03
815	8,29E-01	527,6910	4,64E-03
820	7,99E-01	531,9322	4,47E-03
825	8,98E-01	536,2993	5,02E-03
830	8,49E-01	540,7455	4,75E-03
835	9,29E-01	545,4215	5,20E-03
840	9,41E-01	550,1302	5,27E-03
845	9,42E-01	554,5584	5,27E-03
850	8,29E-01	558,7495	4,64E-03
855	8,47E-01	563,1623	4,74E-03
860	9,18E-01	567,6936	5,14E-03
865	8,95E-01	572,1791	5,01E-03
870	8,99E-01	576,5825	5,03E-03
875	8,62E-01	580,9234	4,82E-03
880	8,74E-01	585,3071	4,89E-03
885	8,79E-01	589,6569	4,92E-03
890	8,61E-01	593,7077	4,82E-03
895	7,60E-01	597,3424	4,25E-03
900	6,94E-01	600,9865	3,89E-03
905	7,63E-01	604,3588	4,27E-03
910	5,86E-01	607,4113	3,28E-03
915	6,36E-01	610,7415	3,56E-03
920	6,97E-01	614,1485	3,90E-03
925	6,66E-01	616,8310	3,73E-03
930	4,07E-01	618,4402	2,28E-03
935	2,37E-01	620,1427	1,33E-03
940	4,44E-01	622,1212	2,49E-03
945	3,47E-01	623,3380	1,94E-03
950	1,39E-01	624,4917	7,80E-04

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\to\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
955	3,22E-01	626,2890	1,80E-03
960	3,97E-01	628,4678	2,22E-03
965	4,75E-01	631,1468	2,66E-03
970	5,97E-01	634,0274	3,34E-03
975	5,55E-01	636,8393	3,11E-03
980	5,69E-01	639,8812	3,19E-03
985	6,47E-01	643,2206	3,62E-03
990	6,88E-01	646,7085	3,85E-03
995	7,07E-01	650,2043	3,96E-03
1000	6,92E-01	653,5368	3,87E-03
1005	6,41E-01	656,8327	3,59E-03
1010	6,77E-01	660,1919	3,79E-03
1015	6,67E-01	663,5048	3,73E-03
1020	6,58E-01	666,7940	3,68E-03
1025	6,57E-01	670,0644	3,68E-03
1030	6,51E-01	673,3004	3,64E-03
1035	6,43E-01	676,4933	3,60E-03
1040	6,34E-01	679,6452	3,55E-03
1045	6,27E-01	682,7581	3,51E-03
1050	6,18E-01	685,8342	3,46E-03
1055	6,12E-01	688,8671	3,43E-03
1060	6,01E-01	691,8554	3,36E-03
1065	5,95E-01	694,7714	3,33E-03
1070	5,72E-01	697,6022	3,20E-03
1075	5,61E-01	700,4165	3,14E-03
1080	5,65E-01	703,2336	3,16E-03
1085	5,62E-01	705,9540	3,14E-03
1090	5,27E-01	708,5045	2,95E-03
1095	4,94E-01	710,8914	2,76E-03
1100	4,61E-01	713,2459	2,58E-03
1105	4,81E-01	715,5849	2,69E-03
1110	4,55E-01	717,3181	2,55E-03
1115	2,38E-01	718,2530	1,33E-03
1120	1,36E-01	718,9369	7,59E-04
1125	1,38E-01	719,4506	7,72E-04
1130	6,76E-02	719,6566	3,78E-04
1135	1,48E-02	720,3048	8,29E-05
1140	2,44E-01	721,2654	1,37E-03
1145	1,40E-01	721,9060	7,82E-04
1150	1,16E-01	722,9448	6,52E-04
1155	2,99E-01	724,3766	1,67E-03
1160	2,74E-01	725,9879	1,53E-03
1165	3,71E-01	728,0082	2,08E-03
1170	4,37E-01	730,1800	2,45E-03
1175	4,31E-01	732,3099	2,41E-03
1180	4,21E-01	734,3339	2,35E-03

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0 \to \lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
1185	3,89E-01	736,4097	2,18E-03
1190	4,41E-01	738,5795	2,47E-03
1195	4,27E-01	740,7160	2,39E-03
1200	4,28E-01	742,8286	2,39E-03
1205	4,17E-01	744,9531	2,33E-03
1210	4,33E-01	747,0561	2,42E-03
1215	4,09E-01	749,1705	2,29E-03
1220	4,37E-01	751,3671	2,45E-03
1225	4,41E-01	753,5688	2,47E-03
1230	4,39E-01	755,7772	2,46E-03
1235	4,44E-01	757,9877	2,49E-03
1240	4,40E-01	760,1786	2,46E-03
1245	4,36E-01	762,3612	2,44E-03
1250	4,37E-01	764,5305	2,44E-03
1255	4,31E-01	766,6386	2,41E-03
1260	4,12E-01	768,6162	2,31E-03
1265	3,79E-01	770,4902	2,12E-03
1270	3,71E-01	772,4037	2,08E-03
1275	3,95E-01	774,3998	2,21E-03
1280	4,04E-01	776,4239	2,26E-03
1285	4,06E-01	778,4264	2,27E-03
1290	3,95E-01	780,3844	2,21E-03
1295	3,88E-01	782,2008	2,17E-03
1300	3,39E-01	783,9668	1,89E-03
1305	3,68E-01	785,6091	2,06E-03
1310	2,89E-01	787,0179	1,62E-03
1315	2,74E-01	788,3257	1,54E-03
1320	2,49E-01	789,7209	1,39E-03
1325	3,09E-01	791,0458	1,73E-03
1330	2,21E-01	792,1532	1,23E-03
1335	2,22E-01	793,1147	1,24E-03
1340	1,62E-01	793,7831	9,08E-04
1345	1,05E-01	794,0848	5,89E-04
1350	1,55E-02	794,1236	8,67E-05
1355	3,48E-06	794,1236	1,95E-08
1360	2,07E-06	794,1236	1,16E-08
1365	8,78E-12	794,1236	4,92E-14
1370	2,83E-07	794,1244	1,58E-09
1375	3,13E-04	794,1253	1,75E-06
1380	7,90E-05	794,1255	4,42E-07
1385	2,03E-06	794,1267	1,13E-08
1390	4,78E-04	794,1279	2,68E-06
1395	6,51E-07	794,1279	3,65E-09
1400	3,15E-09	794,1279	1,76E-11
1405	3,54E-07	794,1291	1,98E-09
1410	4,53E-04	794,1307	2,54E-06

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\to\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
1415	1,79E-04	794,1512	9,99E-07
1420	8,04E-03	794,2342	4,50E-05
1425	2,51E-02	794,4468	1,41E-04
1430	5,99E-02	794,6487	3,35E-04
1435	2,08E-02	794,7972	1,17E-04
1440	3,85E-02	795,0147	2,16E-04
1445	4,84E-02	795,2025	2,71E-04
1450	2,67E-02	795,4303	1,49E-04
1455	6,44E-02	795,7992	3,60E-04
1460	8,32E-02	796,2344	4,65E-04
1465	9,09E-02	796,5826	5,09E-04
1470	4,84E-02	797,1525	2,71E-04
1475	1,80E-01	797,7490	1,00E-03
1480	5,91E-02	798,2008	3,31E-04
1485	1,22E-01	798,9299	6,81E-04
1490	1,70E-01	799,7983	9,51E-04
1495	1,77E-01	800,8504	9,93E-04
1500	2,43E-01	801,9060	1,36E-03
1505	1,79E-01	803,0099	1,00E-03
1510	2,63E-01	804,3117	1,47E-03
1515	2,58E-01	805,5990	1,44E-03
1520	2,57E-01	806,8697	1,44E-03
1525	2,51E-01	808,1179	1,41E-03
1530	2,48E-01	809,3857	1,39E-03
1535	2,59E-01	810,6773	1,45E-03
1540	2,57E-01	811,9937	1,44E-03
1545	2,69E-01	813,3224	1,51E-03
1550	2,62E-01	814,6282	1,47E-03
1555	2,60E-01	815,9239	1,46E-03
1560	2,58E-01	817,2188	1,45E-03
1565	2,60E-01	818,4556	1,45E-03
1570	2,35E-01	819,6253	1,31E-03
1575	2,33E-01	820,8020	1,30E-03
1580	2,38E-01	822,0247	1,33E-03
1585	2,51E-01	823,2402	1,41E-03
1590	2,35E-01	824,4544	1,31E-03
1595	2,51E-01	825,6598	1,40E-03
1600	2,31E-01	826,8134	1,29E-03
1605	2,30E-01	827,9173	1,29E-03
1610	2,11E-01	829,0314	1,18E-03
1615	2,34E-01	830,1865	1,31E-03
1620	2,28E-01	831,3338	1,28E-03
1625	2,31E-01	832,4861	1,29E-03
1630	2,30E-01	833,6285	1,29E-03
1635	2,27E-01	834,7192	1,27E-03
1640	2,09E-01	835,7724	1,17E-03

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\rightarrow\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
1645	2,12E-01	836,8503	1,19E-03
1650	2,19E-01	837,9384	1,23E-03
1655	2,16E-01	839,0219	1,21E-03
1660	2,17E-01	840,0801	1,22E-03
1665	2,06E-01	841,1346	1,15E-03
1670	2,16E-01	842,1937	1,21E-03
1675	2,08E-01	843,2140	1,16E-03
1680	2,00E-01	844,2335	1,12E-03
1685	2,08E-01	845,2523	1,16E-03
1690	2,00E-01	846,2628	1,12E-03
1695	2,04E-01	847,2600	1,14E-03
1700	1,95E-01	848,2285	1,09E-03
1705	1,93E-01	849,1683	1,08E-03
1710	1,83E-01	850,0884	1,03E-03
1715	1,85E-01	851,0065	1,03E-03
1720	1,82E-01	851,8964	1,02E-03
1725	1,74E-01	852,7551	9,72E-04
1730	1,70E-01	853,5735	9,50E-04
1735	1,58E-01	854,3776	8,82E-04
1740	1,64E-01	855,1653	9,18E-04
1745	1,51E-01	855,9470	8,45E-04
1750	1,62E-01	856,7243	9,04E-04
1755	1,49E-01	857,4878	8,36E-04
1760	1,56E-01	858,2022	8,73E-04
1765	1,30E-01	858,8721	7,26E-04
1770	1,38E-01	859,4982	7,74E-04
1775	1,12E-01	860,0239	6,28E-04
1780	9,81E-02	860,4573	5,49E-04
1785	7,52E-02	860,8623	4,21E-04
1790	8,68E-02	861,1941	4,86E-04
1795	4,59E-02	861,3865	2,57E-04
1800	3,11E-02	861,5005	1,74E-04
1805	1,45E-02	861,5604	8,11E-05
1810	9,48E-03	861,5921	5,30E-05
1815	3,21E-03	861,6026	1,80E-05
1820	9,66E-04	861,6081	5,40E-06
1825	1,25E-03	861,6112	6,97E-06
1830	5,09E-06	861,6112	2,85E-08
1835	6,28E-06	861,6113	3,51E-08
1840	6,13E-08	861,6113	3,43E-10
1845	6,13E-06	861,6113	3,43E-08
1850	2,93E-06	861,6113	1,64E-08
1855	2,78E-07	861,6113	1,56E-09
1860	1,09E-05	861,6114	6,11E-08
1865	1,66E-05	861,6114	9,31E-08
1870	2,61E-10	861,6114	1,46E-12

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\to\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
1875	4,43E-10	861,6116	2,48E-12
1880	7,61E-05	861,6119	4,26E-07
1885	4,31E-05	861,6126	2,41E-07
1890	2,20E-04	861,6135	1,23E-06
1895	1,27E-04	861,6138	7,13E-07
1900	8,49E-07	861,6138	4,75E-09
1905	5,58E-07	861,6138	3,12E-09
1910	2,27E-05	861,6139	1,27E-07
1915	1,97E-05	861,6151	1,10E-07
1920	4,45E-04	861,6185	2,49E-06
1925	9,23E-04	861,6222	5,17E-06
1930	5,45E-04	861,6324	3,05E-06
1935	3,54E-03	861,6494	1,98E-05
1940	3,24E-03	861,6842	1,81E-05
1945	1,07E-02	861,7522	5,99E-05
1950	1,65E-02	861,8181	9,22E-05
1955	9,89E-03	861,8967	5,53E-05
1960	2,16E-02	862,0210	1,21E-04
1965	2,81E-02	862,2114	1,57E-04
1970	4,81E-02	862,4983	2,69E-04
1975	6,67E-02	862,8508	3,73E-04
1980	7,42E-02	863,2404	4,15E-04
1985	8,16E-02	863,6548	4,57E-04
1990	8,41E-02	864,0645	4,71E-04
1995	7,98E-02	864,3577	4,47E-04
2000	3,75E-02	864,4883	2,10E-04
2005	1,47E-02	864,6229	8,25E-05
2010	3,91E-02	864,7861	2,19E-04
2015	2,62E-02	864,9622	1,47E-04
2020	4,42E-02	865,2547	2,48E-04
2025	7,28E-02	865,6453	4,07E-04
2030	8,35E-02	866,0910	4,67E-04
2035	9,48E-02	866,5489	5,31E-04
2040	8,83E-02	866,9938	4,94E-04
2045	8,96E-02	867,3852	5,02E-04
2050	6,69E-02	867,6876	3,74E-04
2055	5,41E-02	867,9932	3,03E-04
2060	6,82E-02	868,3160	3,81E-04
2065	6,10E-02	868,6302	3,41E-04
2070	6,47E-02	868,9828	3,62E-04
2075	7,63E-02	869,3874	4,27E-04
2080	8,55E-02	869,8108	4,79E-04
2085	8,38E-02	870,2399	4,69E-04
2090	8,78E-02	870,6804	4,91E-04
2095	8,84E-02	871,1136	4,95E-04
2100	8,49E-02	871,5552	4,75E-04

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0 \to \lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
2105	9,18E-02	872,0054	5,14E-04
2110	8,83E-02	872,4520	4,94E-04
2115	9,03E-02	872,8935	5,05E-04
2120	8,63E-02	873,3274	4,83E-04
2125	8,73E-02	873,7667	4,89E-04
2130	8,84E-02	874,2095	4,95E-04
2135	8,87E-02	874,6547	4,96E-04
2140	8,94E-02	875,0985	5,00E-04
2145	8,81E-02	875,5272	4,93E-04
2150	8,34E-02	875,9445	4,67E-04
2155	8,36E-02	876,3607	4,68E-04
2160	8,29E-02	876,7560	4,64E-04
2165	7,52E-02	877,1458	4,21E-04
2170	8,08E-02	877,5459	4,52E-04
2175	7,93E-02	877,9456	4,44E-04
2180	8,06E-02	878,3307	4,51E-04
2185	7,35E-02	878,7091	4,11E-04
2190	7,79E-02	879,0984	4,36E-04
2195	7,78E-02	879,4685	4,36E-04
2200	7,02E-02	879,8263	3,93E-04
2205	7,29E-02	880,2041	4,08E-04
2210	7,82E-02	880,5875	4,37E-04
2215	7,52E-02	880,9670	4,21E-04
2220	7,66E-02	881,3446	4,29E-04
2225	7,44E-02	881,7174	4,16E-04
2230	7,47E-02	882,0875	4,18E-04
2235	7,33E-02	882,4510	4,10E-04
2240	7,21E-02	882,8062	4,04E-04
2245	6,99E-02	883,1585	3,91E-04
2250	7,10E-02	883,5033	3,98E-04
2255	6,69E-02	883,8358	3,74E-04
2260	6,61E-02	884,1695	3,70E-04
2265	6,74E-02	884,4983	3,77E-04
2270	6,41E-02	884,8169	3,59E-04
2275	6,33E-02	885,1390	3,54E-04
2280	6,56E-02	885,4589	3,67E-04
2285	6,24E-02	885,7712	3,49E-04
2290	6,25E-02	886,0790	3,50E-04
2295	6,06E-02	886,3760	3,39E-04
2300	5,82E-02	886,6679	3,26E-04
2305	5,85E-02	886,9722	3,28E-04
2310	6,32E-02	887,2740	3,54E-04
2315	5,75E-02	887,5465	3,22E-04
2320	5,15E-02	887,8143	2,88E-04
2325	5,56E-02	888,0940	3,11E-04
2330	5,62E-02	888,3780	3,15E-04

Wavelength λ [nm]	Direct + Circumsolar E_λ [W m^{-2}nm^{-1}]	Integrated Irradiance $E_{0\to\lambda i}$ [W m^{-2}]	Weighting Factor $F(\lambda_i)$
2335	5,74E-02	888,6348	3,21E-04
2340	4,54E-02	888,8754	2,54E-04
2345	5,09E-02	889,1053	2,85E-04
2350	4,11E-02	889,3256	2,30E-04
2355	4,70E-02	889,5674	2,63E-04
2360	4,97E-02	889,8139	2,78E-04
2365	4,89E-02	890,0125	2,74E-04
2370	3,05E-02	890,1980	1,71E-04
2375	4,37E-02	890,4126	2,45E-04
2380	4,21E-02	890,5943	2,36E-04
2385	3,05E-02	890,7624	1,71E-04
2390	3,67E-02	890,9548	2,06E-04
2395	4,02E-02	891,1646	2,25E-04
2400	4,37E-02	891,3572	2,45E-04
2405	3,33E-02	891,5241	1,86E-04
2410	3,35E-02	891,6755	1,88E-04
2415	2,71E-02	891,8091	1,51E-04
2420	2,64E-02	891,9570	1,48E-04
2425	3,28E-02	892,1508	1,84E-04
2430	4,47E-02	892,2995	2,50E-04
2435	1,48E-02	892,4437	8,26E-05
2440	4,29E-02	892,6027	2,40E-04
2445	2,07E-02	892,6881	1,16E-04
2450	1,35E-02	892,7837	7,57E-05
2455	2,47E-02	892,9283	1,38E-04
2460	3,32E-02	893,0712	1,86E-04
2465	2,40E-02	893,1728	1,34E-04
2470	1,66E-02	893,2554	9,31E-05
2475	1,64E-02	893,3163	9,16E-05
2480	8,00E-03	893,3502	4,48E-05
2485	5,58E-03	893,3729	3,13E-05
2490	3,50E-03	893,3888	1,96E-05
2495	2,86E-03	893,4136	1,60E-05
2500	7,03E-03	893,4312	3,94E-05

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