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Development of a spatially resolved reflectometer to monitor corrosion of solar reflectors

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ABSTRACT

Solar reflectors for Concentrating Solar Power (CSP) concentrators require a high reflectance and high specularity over the whole solar spectrum. During their lifetime of at least 20 years, the reflectors must withstand harsh outdoor conditions without loosing their reflective properties. Currently, there are not many devices available to measure the specular reflectance. In this work a prototype of a specular reflectometer with spatial resolution has been developed. The major advantage of the prototype compared to other reflectometers is the possibility of measuring the specular reflectance on an extended measuring spot of more than 5 cm in diameter with a spatial resolution of 37 pixel/mm. Additionally, measurements can be taken at three different acceptance half angles (φ = 3.5,6.0, and 12.5 mrad) and at three different wavelengths (λ = 410 nm, 500 nm, and 656 nm). This lab scale instrument can be employed to monitor degradation effects, such as corrosion spots, and evaluate their influence on the specular reflectance of solar mirror materials.

1. Introduction

The reflectance of a solar mirror is dependent on three parameters: (1) the wavelength λ of the incident light, (2) the incidence angle θ, and (3) the acceptance angle φ (see Fig. 1), which defines the angular area around the perfect specular reflection. It is important to indicate these parameters for any reflectance measurement [1]. The following nomenclature is used: $\rho(\lambda,\theta,\varphi)$.

The relevant wavelength rage for solar reflectors is the terrestrial solar spectrum (250–2500 nm). The maximum of the solar irradiation occurs at 470–660 nm with its peak at approximately 550 nm. Hence, for solar mirrors the reflectance in this range has the greatest relevance. In wavelength ranges outside of the solar spectrum the reflectance of the mirror is less important. A representative mean value of all reflectance values in the range of 250–2500 nm is obtained by performing a solar weighting with a standard solar spectrum (e.g. according to [2,3]):

$$\rho(SW,\theta,\varphi) = \frac{\sum_{i=250}^{2500} \rho(\lambda_i,\theta,\varphi) \cdot E_\lambda(\lambda_i)}{\sum_{i=250}^{2500} E_\lambda(\lambda_i)} \quad (1)$$

Solar weighted reflectance values are denoted by $\rho(SW,\theta,\varphi)$. The wavelength is measured in 5 nm intervals (λ_0 = 250 nm, λ_1 = 255 nm, ..., λ_{450} = 2500 nm) using an UV/VIS/NIR spectrophotometer from PerkinElmer. $E_\lambda(\lambda_i)$ denotes the spectral irradiance at the wavelengths λ_i, according to the standard solar spectrum.

For the PerkinElmer Lambda series spectrophotometers equipped with an integrating sphere the incidence angle is fixed at $\theta = 8°$ and the acceptance angle is the complete half space ($\varphi = 2\pi$). For $\varphi = 2\pi$, the reflectance value is also denoted as hemispherical reflectance. Hemispherical reflectance is composed of the specular and diffuse components.

For CSP collectors the specular reflectance of a mirror plays a more important role than the hemispherical reflectance. Specular reflectance is the amount of light reflected into the acceptance half angle φ shown in Fig. 1.

For example, in a parabolic trough collector with dimensions like the common Eurotrough, the radiation emitted by the sun is focused completely onto the absorber tube if the aperture angle of the reflected beam cone is less than 20 mradians (mrad) half-cone angle (Fig. 2). The image of the sun is spread wider by additional inaccuracies of the collector system introduced due to the absorber tube positioning, tracking imprecision, mirror slope errors and scattering on the mirror surface. It has been established that a specular reflectance measurement consisting of an acceptance angle of φ = 12.5 mrad is a reasonable measure for this kind of collector design [5–7]. However, it is preferred to have data available with additional angles in the range of φ = 3.5–20 mrad.

The specular reflectance is usually measured with a portable 15R specular reflectometer from Devices and Services Instruments

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Nomenclature

$a_{L3\text{-}R}$	distance lens 3 – reflector sample (mm)
$a_{R\text{-}A}$	distance reflector – acceptance aperture (mm)
D_A	diameter acceptance aperture (mm)
D_{EP}	diameter entrance pupil of the camera lens (mm)
D_{L2}	diameter lens 2 (mm)
D_{L3}	diameter lens 3 (mm)
D_R	diameter of illuminated reflector surface (mm)
E_λ	spectral irradiance of standard solar spectrum (W/m^3)
f_C	camera lens focal length (mm)
f_{L2}	focal length lens 2 (mm)
f_{L3}	focal length lens 3 (mm)
θ	incidence angle (°)
λ	wavelength (nm)
$\rho(\mathrm{SW},\theta,\varphi)$	solar weighted specular reflectance at incidence angle θ and acceptance angle φ (%)
$\rho(\lambda,\theta,\varphi)$	specular reflectance at wavelength λ, incidence angle θ and acceptance angle φ (%)
$\rho_R(\lambda,\theta,\varphi)$	specular reflectance at wavelength λ, incidence angle θ and acceptance angle φ of the reference mirror (%)
ρ_R	see $\rho_R(\lambda,\theta,\varphi)$ (%)
$\rho(i,k)$	specular reflectance at pixel i, k (%)
φ	acceptance angle (mrad)
φ^*	acceptance angle for rays close to the edge of the measuring spot (mrad)
φ_p^*	acceptance angle for rays close to the edge of the measuring spot for parallel incident light (mrad)
χ	f-number (–)
σ	standard deviation (–)
n	number of pixel (–)
n_h	horizontal number of pixel (–)
n_v	vertical number of pixel (–)
I	intensity of pixel (-)
I_R	intensity of pixel of original image of reference mirror (–)
$I_{avg,ref}$	average of all pixel of original image of reference mirror (–)
I'_R	intensity of pixel of reference image (–)
m	number of bit (–)
Ω	ratio to characterize camera noise (–)

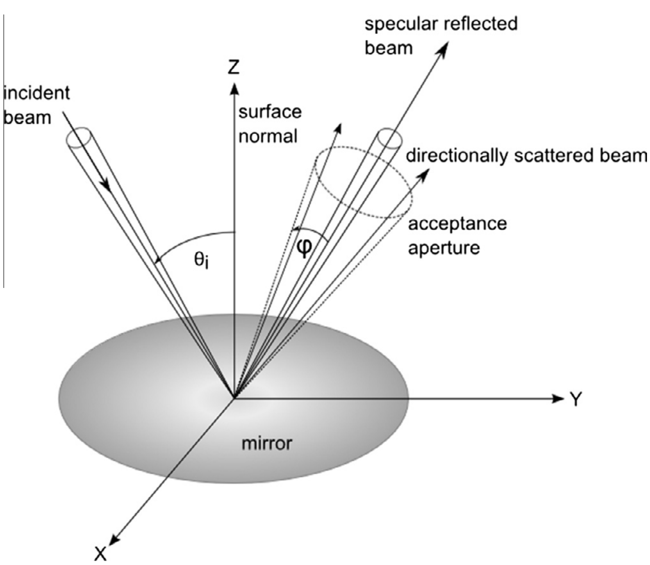

Fig. 1. Definition of parameters.

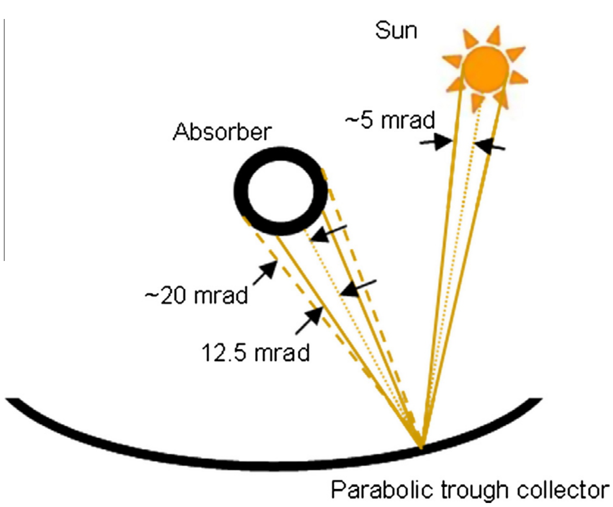

Fig. 2. Specular reflectance at a parabolic trough collector.

(D&S). Measurements can be taken at a single wavelength, $\lambda = 660$ nm, an incidence angle of $\theta = 15°$, and at three different acceptance angles ($\varphi = 3.5, 7.5, 12.5$ or 23 mrad). Alternative instruments to the D&S are described in [4].

Currently, there is no device available to measure the specular reflectance in the whole solar spectrum of 250–2500 nm with defined acceptance apertures, so that Eq. (1) cannot be used. The solar-weighted specular reflectance value can be approximated in some cases by making use of the solar weighted hemispherical reflectance $\varphi(\mathrm{SW},\theta,2\pi)$ according to Eq. (1) and then applying an approximation that was proposed first by Pettit [5]:

$$\rho(SW,\theta,\varphi) = \frac{\rho(660\ \mathrm{nm},\theta,\varphi)}{\rho(660\ \mathrm{nm},\theta,2\pi)}\rho(SW,\theta,2\pi) \quad (2)$$

As scattering is wavelength dependent, Eq. (2) is considered to be a rough estimate of $\rho(\mathrm{SW},\theta,\varphi)$ and only applicable for mirrors with highly specular surface properties. In addition to the problem that specular measurements can only be taken at a single wavelength, the existing instruments have the disadvantages that the measuring spot is usually very small (i.e. approximately 1 cm in diameter) and that the measurements integrate over the spot area and thus are not spatially resolved. This makes it hard to characterize locally degraded or soiled mirrors because several measurements are necessary to statistically evaluate the influence of degradation or soiling on the reflectance properties. Problems associated with the measurement of specular reflectance are also described in [8].

2. Materials and methods

In order to improve the existing specular reflectance measurement capabilities, a prototype of a reflectometer with the following characteristics has been designed:

Measuring spot size	5.35 cm in diameter
Light incidence angle θ	15°
Acceptance angle φ	3.5, 6.0 and 12.5 mrad
Wavelength λ	410, 500, 656 nm
Spatial resolution	37 pixel/mm