



The effect of incidence angle on the reflectance of solar mirrors

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ABSTRACT

Solar reflectors for Concentrating Solar Technologies require a high reflectance in the terrestrial solar spectrum (280–4000 nm). Besides the wavelength, the reflectance of solar mirror materials is also dependent on the incidence angle of the incoming sunlight. The commonly used measurement equipment measures the reflectance at fixed near-normal incidence angles, typically between 8° and 15°. In this work, the annual incidence angle frequency distribution has been calculated for a LS3/Eurotrough-type parabolic-trough collector located at different sites, and for the heliostat field of the solar tower system CESA-1 located at the Plataforma Solar de Almería in Tabernas, southern Spain. It was found that the most frequent incidence angles registered in the solar field are quite higher than the ones at which reflectance is measured with state of the art instruments, obtaining mean incidence angles in the range of 28–35° depending on the type and location of the solar field.

A methodology to predict the off-normal reflectance of silvered-glass mirrors based on near-normal reflectance and transmittance measurements of the uncoated glass is presented. The complex refractive index of 2, 4 and 5 mm thick solar glass and the deposited silver was determined and used to model the solar weighted reflectance of silvered-glass mirrors at different incidence angles. The model was compared to experimental measurements. For this purpose, the Spectral Specular Reflectometer (S2R) has been improved and updated with a polarizer crystal to measure reflectance at perpendicular (s-pol) and parallel (p-pol) polarizations up to incidence angles of $\theta = 70^\circ$.

Eight solar mirror materials (three silvered-glass mirrors of different glass thicknesses, two anti-soiling coated glass mirrors, two enhanced aluminum reflectors and a silvered polymer film) have been measured over a broad range of incidence angles and the results have been weighted with the annual incidence angle frequency distribution. The obtained incidence angle-weighted reflectance is a suited parameter to compare the efficiency of solar mirror materials taking into account their use in a specific collector type and location.

1. Introduction

In Concentrating Solar Technologies (CST), solar light is concentrated on a focal point or a focal line by using 2-axis or 1-axis tracking mirrors. A receiver, located in the focal point or line transforms the collected solar radiation either directly to electricity with concentrating photovoltaic (CPV) systems [1], to heat which can be used in a heat engine to produce electricity with concentrating solar power (CSP) systems [2] or for chemical [3] or thermal processes in industrial applications [4].

The reflectance, ρ , is defined as the ratio of the radiant flux reflected from a surface to that of the incident radiation [5]. The reflectance of tracking solar mirrors, $\rho_{\lambda,\varphi}(\lambda,\theta,\varphi,T_s)$, is dependent on the following four parameters: the wavelength λ and the incidence angle θ of the incident

light, the acceptance angle φ of the receiver, which defines the admissible angular area around the perfect specular reflection, and the surface temperature T_s [6,7].

The relevant wavelength range for solar reflectors is the terrestrial solar spectrum $\lambda = [280, 4000]$ nm. A representative mean value of all ρ in this range is obtained by performing a solar weighting with a standard solar spectrum (e.g. according to [8] (direct irradiance) for air mass AM 1.5 or [9]). Because the far-NIR and UV ranges have a low impact and it is practically more convenient for the measurement equipment, the relevant measurement range for reflectance evaluation can be resized to $\lambda = [320, 2500]$ nm. The absolute weight of solar radiation in the wavelength intervals [280, 320] and [2500, 4000] nm is less than 1% in total.

For the temperature range achieved during normal operation of

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Nomenclature			
CESA-1	central receiver power tower at PSA	R_f	reflectance $\rho_{s,h}([320, 2500]nm, 8^\circ, h)$ of front face of glass slab [-]
CPV	Concentrating Photovoltaics	T_s	surface temperature [°C]
CSP	Concentrating Solar Power	w_{col}	aperture width of PTC [m]
CST	Concentrating Solar Technologies	$y(x)$	parabolic mirror shape [m]
DNI	Direct Normal Irradiance	α	absorption coefficient of the solar glass [nm^{-1}]
EMA	Equivalent Model Algorithm	α_s	elevation angle of the sun [$-90^\circ; 90^\circ$] [°]
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	β	incidence angle after refraction [°]
NIR	Near infrared	$\gamma_{s,geo}$	azimut angle of the sun [$0^\circ; 360^\circ$] [°]
NIST	National Institute of Standards and Technology	ϵ_1, ϵ_2	dielectric constants to describe the refractive index and extinction coefficient [-]
PSA	Plataforma Solar de Almería, located in Tabernas, Spain	θ	incidence angle [°]
PTC	parabolic-trough collector	θ_{geom}	incidence angle of a PTC due to parabolic 2D-geometry [°]
S2R	Spectral Specular Reflectance Accessory	θ_{sun}	incidence angle between collector normal and sun [°]
ST	solar tower	λ	wavelength [nm]
TIS	Total Integrated Scattering	ρ	reflectance [-]
URA	Universal Reflectance Accessory	$\rho_{air glass}$	reflectance at the interface between air and glass [-]
B_1	constant of Sellmeier's equation [-]	$\rho_{air glass silver}$	reflectance of the Air Glass Silver model [-]
B_2	constant of Sellmeier's equation [-]	$\rho_{glass air}$	reflectance at the interface between glass and air [-]
B_3	constant of Sellmeier's equation [-]	$\rho_{glass silver}$	reflectance at the interface between glass and silver [-]
C_1	constant of Sellmeier's equation [μm^2]	ρ_i	see $\rho_i(\lambda, T, L, \varphi)$ [-]
C_2	constant of Sellmeier's equation [μm^2]	$\rho_i(\lambda, T, L, \varphi)$	incidence angle weighted specular reflectance for collector type T at a given location L [-]
C_3	constant of Sellmeier's equation [μm^2]	$\rho_{non-pol}$	reflectance of non-polarized light [-]
E_λ	Spectral irradiance of standard solar spectrum [W/m^3]	ρ_{p-pol}	reflectance of parallel polarized light [-]
f	Focal length of PTC [m]	$\rho_{s,h}$	solar-weighted hemispherical reflectance at $\theta=8^\circ$ and $[320,2500]nm$ [-]
h	thickness of glass slab [mm]	$\rho_{s,h}([\lambda_1, \lambda_2], \theta, h)$	solar-weighted hemispherical reflectance [-]
k_g	extinction coefficient of glass [-]	$\rho_{s,\varphi}$	solar-weighted specular reflectance at $\theta=8^\circ$ and $[320,2500]nm$ [-]
$k_{g,s}$	solar weighted extinction coefficient of glass in the range $[320,2500]nm$ [-]	$\rho_{s,\varphi}([\lambda_1, \lambda_2], \theta, \varphi)$	solar-weighted specular reflectance [-]
k_s	extinction coefficient of silver [-]	ρ_{s-pol}	reflectance of perpendicular polarized light [-]
\bar{n}_s	complex refractive index of silver [-]	ρ_λ	spectral reflectance [-]
n_1	refractive index of air [-]	$\rho_{\lambda,h}(\lambda, \theta, h)$	spectral hemispherical reflectance [-]
n_2	refractive index of medium 2 [-]	τ	see $\tau_{s,h}$ [-]
n_g	refractive index of glass [-]	$\tau(\lambda, \theta, h)$	spectral hemispherical transmittance [-]
$n_{g,s}$	solar-weighted refractive index of glass in the range 320-2500 nm [-]	τ_f	transmittance $\tau([320, 2500]nm, 8^\circ, h)$ of front face of glass slab [-]
n_s	refractive index of silver [-]	$\tau_{s,h}$	solar-weighted hemispherical transmittance at $\theta=8^\circ$ and $[320,2500 nm]$ [-]
θ_0	relative annual incidence angle distribution (whole year) [-]	φ	acceptance angle [mrad]
R	reflectance $\rho_{s,h}([320, 2500]nm, 8^\circ, h)$ of glass slab [-]		

primary solar mirrors in the field, the influence of T_s on ρ is not significant and may be neglected. Therefore, in the rest of this work, this parameter is omitted and the nomenclature used for reflectance is $\rho_{\lambda,\varphi}(\lambda, \theta, \varphi)$. The indices λ, φ denote specular monochromatic

reflectance. The indices s, h denote solar weighted hemispherical reflectance in the wavelength range $[320, 2500]nm$.

For CST the specular reflectance plays a significant role, since scattered light outside the acceptance angle cone is lost to the energy

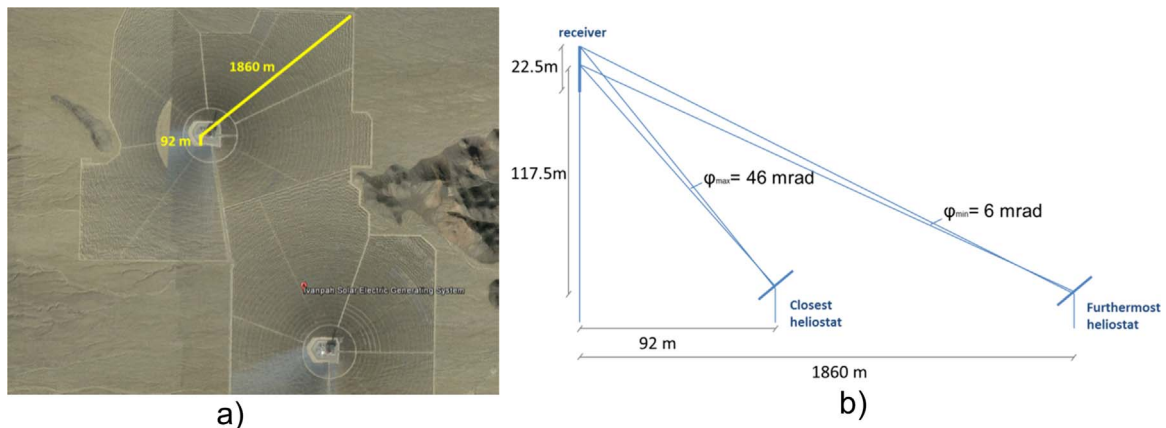


Fig. 1. a) Distance of closest and furthest heliostat from the receiver in the ST plant of Ivanpah, b) dimensions used to compute the acceptance angle φ .

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