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Portable Solar Spectrum Reflectometer for planar and parabolic mirrors in solar thermal energy plants

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ABSTRACT

This contribution presents a new field Solar Spectrum Reflectometer for solar-weighted specular reflectance characterization of planar, spherical or parabolic mirrors. This reflectometer is designed to provide fast and reliable field measurements and to be valid for any type of mirror currently installed in concentrated solar power systems, including parabolic trough, Stirling dish and central receiver power plants. The optical design of the Solar Spectrum Reflectometer, which includes 6 LEDs in the VIS–NIR band, is described, and its tolerance to variations in the geometrical parameters of the mirrors discussed and evaluated. The contribution of diffuse reflection and its impact on the measured reflectance is also calculated for different concentrated solar power systems.

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1. Introduction

Solar thermal energy (STE) power plants concentrate the solar light in high temperature receivers for generation of electrical power or process heat. Different mirror designs to concentrate solar light are used: flat plane mirrors, parabolic dishes and parabolic curved troughs are the most common designs.

The performance of these mirrors is dependent on their solar-weighted reflectance and the specularity of the mirror surface. Reflectance in STE is defined as the ratio of incident optical power reflected by the mirrors into the acceptance half angle of the solar plant receiver, and is usually affected by dirt accumulation and micro surface imperfections.

Thus, frequent measurement of the reflectance of the mirrors used in solar concentrators is needed in order to determine the effect of accumulated dust or to detect any permanent degradation of their surface. Solar-weighted reflectance, which is the reflectance within a specified incidence and half-cone angle beam weighted by the solar spectrum, is a key parameter to evaluate the quality and performance of solar mirrors (Levinson et al., 2010; Meyen et al., 2009, 2010; Sutter et al., 2016). Accordingly, field solar-weighted reflectance measurement of mirrors becomes of great interest as it has a direct impact on the assessment and prediction of STE plant global performance and efficiency. Accurate determination of this parameter is required in the most advanced daily maintenance protocols as a sensor of the central status (Levinson et al., 2010; Meyen et al., 2010, SolarPaces Round Robin).

Commercially available equipment intended for this purpose, described in general as Solar Spectrum Reflectometers (SSR), often provide incorrect field solar-weighted specular reflectance measurements, as they can only measure reflectance at certain design conditions. When the thickness or the curvature of the mirror does not match the specifications used for the optical design of the instrument, its low tolerance to the value of the optical system entrance angle generates non-negligible errors (Polato and Masetti, 1988).

Depending on the optical design strategies, we can classify SSR in two main categories: hemispherical SSR and specular SSR. The

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Abbreviations: STE, solar thermal energy; SSR, Solar Spectrum Reflectometer; LED, light emitting diode; φ_{max}, maximum aperture angle of the incident beam; α, angle of incidence on the glass; β, angle of incidence on the mirror; f, focal length; O, LED to lens distance; O', lens to detector distance; Φ, diameter; EP, entrance pupil; LE, entrance port; M0, mirror position; h, reflectometer to mirror relative displacement; R, effective reflectance for a receiver; RSSR, effective reflectance for a reflectometer; R_{spe}, specular reflectance; R_{dif}, diffuse reflectance captured by a receiver or a SSR; ΔR, reflectance measurement error; I, intensity of a light source; r, distance from mirror to a point on the receiver; D, shortest distance from mirror to receiver; d, width/diameter of the receiver; h, height of the location of a central receiver collector; l, height of a central receiver collector.

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former are equipped with an integrating sphere and are usually very reliable in laboratory scenarios when the correct reference standard is used (Fend et al., 2003; Montecchi, 2013; Roos, 1993); however, they require different configurations, including moving parts of the sphere for indirect acquisition of specular reflectance and large entrance ports to reduce the sensitivity of the instrument to mirror thickness (Polato and Masetti, 1988). In portable models, the adjustments necessary to measure mirrors with varied thicknesses and curvatures cannot be easily performed, so they are not usually suitable for plant surveying evaluations, which involve a large number of measurements that should be performed in a quick and simple way.

Specular SSR measure specular reflected light directly using an optical detector. Diffuse light is mainly discarded as its contribution is usually negligible, but obviously they show very low tolerance to changes in mirror design. Alignment and adjustment accessories can provide this tolerance (Sutter et al., 2016), but not without negatively impacting the SSR suitability for measurements performed in the field.

Usually, specular SSR are optically designed for planar mirrors in any soiling condition, but they underestimate specular reflectance on curved mirrors. On the other hand, portable hemispherical SSR achieve accurate specular reflectance values on any clean surface, but may overestimate specular reflectance when dirt accumulation is important, due to diffuse reflection not being discounted properly (Pettit and Freese, 1980).

This work proposes the use of collecting lenses in the detection system as an improvement on the specular SSR strategy. These lenses provide the necessary tolerance to changes in the geometrical dimensions of the mirrors, while helping to limit the impact of diffuse light on the measurement. This impact, though reduced, is not always negligible, so it will be necessary to establish a trade-off between the precision of the measurement and the adaptation of the reflectometer to fast and simple operation on the field.

According to these principles, we present a new optical design for a SSR, suitable for any planar, spherical or parabolic mirror currently installed in concentrated solar power thermo solar plants (Zhang et al., 2013), and which does not require moving parts or additional accessories. The advantages and limitations of this approach will be analyzed both theoretically and experimentally.

This design has been put to test in a portable device meeting all the requirements for plant surveying previously described, and commercialized as Condor (patent number WO2012010724).

The article is organized as follows. Section 2 describes the optical design of the instrument, with emphasis on the system aperture because of its impact on the final optical system tolerance. Section 3 includes theoretical and experimental studies of the tolerance of the device to variations in some geometrical parameters of the mirrors, as thickness and curvature radius. Section 4 explains the model used to evaluate the effect of the diffuse light in the reflectance measurements for different types of reflectometers and collectors. Section 5 uses that model to calculate the measurement errors due to diffuse light for the cases under study. Finally, conclusions are presented in Section 6.

2. Optical design

A suitable optical design is key for a field SSR instrument expected to work in any type of solar plant and measurement condition. In the new optical measurement device here described, the spectral reflectance is measured using 6 optical channels at different wavelengths, spanning from visible to near infrared, placed in line (Fig. 1(a)). Each channel includes a light emitting diode (LED) as the light source, a reference detector, a lens and a signal detector as shown in Fig. 1(b).

The main function of the lens is to provide the required tolerance to changes in the mirror geometrical parameters. As will be discussed in Section 3, this tolerance is determined by the dimension of the measurement light beam diameter on the lens relative to the diameter of that lens (tolerance will be higher the smaller the beam is compared to the lens). To achieve a good ratio between these two parameters, the aperture of the beam is limited to a φ_{max} of 39 mrad by using a fixed stop placed after the LED. This aperture determines the illuminated area on the lens surface and therefore the tolerance of the system.

The angle of incidence of the optical beam on the glass surface is $\alpha = 12°$, so, according to Snell's law, the angle of incidence on the mirror reflective surface is approximately $\beta = 8°$. Specularly reflected light is collected by a 12.5-mm diameter, 15-mm focal length (f) fused silica biconvex lens. As will be discussed in Section 4, this lens also collects a fraction of the diffusely reflected light, so its impact on the measured reflectance coefficient will be analyzed.

The LED is positioned at a distance O from the lens so that the beam diameter on its surface, $\phi_{beam\_lens} = 2O \cdot \tan \varphi_{max}$, is half its diameter. It focuses the reflected light on a 9 mm^2 effective area PIN photodiode detector (InGaAs or Si depending on the LED wavelength).

The paraxial optics diagram of one of the optical channels is shown in Fig. 2. In this figure, f is the focal length of the lens, placed at the origin. The detector is located at the image point O' of the LED located at point O. The entrance pupil (EP) of the optical system is defined by the stop diameter and is located at a distance D1 from the lens. M0 indicates the position of the mirror in the design on ideal conditions (26.5 mm from the lens). The image of the detector is located at O and works as the entrance port (LE), with a diameter given by the relationship:

$$\phi_{LE} = \frac{O}{O'}\phi_{det} \qquad (1)$$

with

$$O = \frac{O' \cdot f}{(O' - f)} \qquad (2)$$

In order to compensate variations on the LED optical power, backwards emitted light from the LED is also detected as a reference signal, as shown in Fig. 1(b).

The number and wavelengths of the LED can be easily modified to span over different spectral ranges, depending on the accuracy required for the solar-weighted specular reflectance value. The example described here uses 6 optical channels at wavelengths of 405 nm, 535 nm, 650 nm, 850 nm, 1100 nm and 1350 nm.

The existence of various measurement wavelengths is an important advantage when the reflectometer is used to test samples with a solar reflectance either unknown or needing validation, for example prior to the installation of new mirrors in a solar plant. Even when testing for mirror soiling due to accumulation of dirt, where the loss of reflectivity is mainly due to scattering, a spectral measurement is recommended (Heller, 2013).

A plastic body encloses the optical system in order to block nearly all external incident light on the detectors. However, a small fraction of this light could still reach the detection system, limiting the measurement dynamic range depending on weather conditions and position relative to the sun. This limitation is avoided using a synchronous detection scheme: the optical sources are modulated at a known frequency and the detected signals are then processed to retrieve only the part of the signal corresponding to that frequency, thus eliminating noise and external light which won't be modulated.

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