Solar Energy 155 (2017) 496–505

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Reflectometer comparison for assessment of back-silvered glass solar mirrors

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ARTICLE INFO

Article history:
Received 26 March 2017
Received in revised form 5 June 2017
Accepted 19 June 2017

Keywords:
Reflectometry
Optical instruments
Solar collector
Collector
Soiling

ABSTRACT

This paper compares the two most common reflectometers used to assess the specular reflectance of back-silvered glass mirrors for Concentrating Solar Power (CSP) applications, namely the Device and Services (D&S) 15R-USB and the Abengoa Condor SR-6.1 instruments. Comparisons are first made between the two instruments themselves using a Gage Repeatability and Reproducibility (R&R) study. Results are given for the as-cleaned collector mirrors and then as the mirrors become naturally soiled over a one month period. The results of the Gage R&R study show that for the D&S the gage itself contributes 40.97% of the variability, whilst 59.03% is due to part-to-part (location on the mirror under investigation) variability. For the Condor we show that the % Contribution from the gage is 62.18% of the total variability with only 37.82% of the contribution attributable to the location dependent reflectance. The Condor has a wider acceptance angle, and over the reflectance range of 0.91–0.95 the condor was found to measure higher than the D&S by an average of 1.53%. The differences between the soiling results obtained from the two instruments are explained, and the results are used to derive a predictive model for the soiling of solar collectors. In conclusion, both instruments have advantages and shortcomings, and the factors that influence which instrument to select are discussed.

1. Introduction

The performance of CSP plants (both with parabolic-trough collectors – PTC- and solar towers) is critically dependent on the optical efficiency of the solar field, particularly the specular solar reflectance of the solar concentrating mirrors. Generally made of back-silvered glass of up to 4 mm thickness, the mirrors and their tracking and supporting structures are also a significant capital cost (Pitz-Paal et al., 2007). Alternative reflecting materials are available (Bethea et al., 1981; DiGrazia et al., 2009; Sutter et al., 2012) but their robustness and durability has yet to be proven. Reflectance loss occurs most frequently by natural soiling with dust and sand, which is especially severe in the arid regions where CSP plants are preferentially located for reasons of high Direct Normal Irradiance (DNI) (Fernández-García et al., 2014a). Specular solar reflectance measurements on large solar collectors require specialist equipment, including purpose-built reflectometers. These mainly include the Abengoa Condor SR-6.1 (Martinez et al., 2012; Salinas et al., 2016), the D&S 15R-USB (Pettit, 1982; Ho et al., 2013), and the Surface Optics 410-Solar hand-held instrument (Crawford et al., 2012; Ho et al., 2013). The correct choice of instrument for on-field reflectance measurements must accomplish a set of requirements, comprising accuracy, high autonomy, easy to handle and operate, light weight, store system, with no influence from external light.

In this work a comparison is made between the two most commonly used reflectometers, namely the Abengoa Condor SR-6.1 and the D&S 15R-USB instruments. Following a statistical analysis of both instruments in laboratory conditions using a Gage R&R technique, we carried out a field study with measurements taken as natural soiling occurs on a representative solar collector located outdoors at the CIEMAT-PSA, in the desert region of Tabernas in Andalucía, Spain. The quality of the results from this two reflectometers are of particular interest because they are the most frequently used in existing commercial CSP plants and are also widely employed in research activities for both soiling characterization (Tahboub et al., 2012; Bouaddi et al., 2015) and durability assessment (Fernández-García et al., 2014b).

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http://dx.doi.org/10.1016/j.solener.2017.06.053
0038-092X/

Nomenclature

Acronyms

ANOVA	analysis of Variance
CSP	concentrating Solar Power
DNI	direct Normal Irradiance
D&S	device & Services
R&R	repeatability and Reproducibility
PSA	*plataforma Solar de Almería*
OPAC	optical Ageing Characterization (Laboratory)
PTC	parabolic-trough collector
LCL	lower statistical Control Limit
UCL	upper statistical Control Limit

Symbols

R	reflectance
ΔR	change in reflectance
σ^2_{total}	total variance in measurement of reflectance
σ^2_{refl}	variance in reflectance measurement attributable to the part
σ^2_{gage}	variance in reflectance measurement attributable to the reflectometer
$\sigma^2_{repeatability}$	variance in reflectance measurement attributable to instrument repeatability
$\sigma^2_{reproducibility}$	variance in reflectance measurement attributable to observer (reproducibility)
Xbar	facet average reflectance by location (on Minitab plots)
CI	confidence Interval
DF	degrees of freedom
P	Probability
R-Sq	percentage of data described by the best-fit line
S	standard deviation of how far the data values fall from the fitted values
SS	sum of squares

2. Methodology

This section includes a description of the two instruments included in the present research study and the methodology followed both in the Gage R&R study and in the soiling outdoor experiments. A Gage R&R study provides a means to assess the origin of the variability seen in a set of measurements. This variability can be due to the difference between the sites being measured, but can also be due to the operator of the instrument or the performance of the instrument itself. A Gage R&R study indicates whether the operators are consistent in their measurements of the same part (repeatability) and whether the variation between operators is consistent (reproducibility). Statistical software is a useful tool to perform this task, and for this work Minitab statistical software was selected.

2.1. Instrument description

The instruments under study are shown in Fig. 1, and their main features are listed in Table 1.

The Condor SR-6.1 Portable Reflectometer (named in the rest of this document as the Condor) was developed by Abengoa Solar New Technologies and the University of Zaragoza with a focus on usability and applications in operations and maintenance. Every measurement consists of six different beam sources of 435 nm, 525 nm, 650 nm, 780 nm, 940 nm and 1050 nm. Although results were collected at all six wavelengths, only the 650 nm results are reported here so as to compare with the single wavelength measurements of the D&S reflectometer. According to the manufacturer the Condor has a resolution of ±0.001, a repeatability of ±0.002 reflectance units, with 95% confidence, and an accuracy of ±0.002 reflectance units. The (half) acceptance aperture is 204 mrad. There are different versions of the D&S 15R-USB (named in the rest of this document as the D&S), with both 550 nm and 660 nm sources, but always with acceptance apertures less that the Condor (23 mrad, 12.5 mrad, 7.5 mrad, or 3.5 mrad). The D&S used in our experiments has a 660 nm source and the acceptance aperture selected was 12.5 mrad, that being the standard to study PTC technology (Meyen et al., 2010). According to the manufacturer the D&S-15R has a resolution of ±0.001 and repeatability of ±0.002 reflectance units. Each reflectometer has its own calibration reference piece, therefore it is expected that the reflectance measured on each will differ slightly, even on the just-cleaned mirrors. Note also the difference in acceptance aperture between the two instruments. The Condor has a wider acceptance aperture in order to assess mirrors possessing a wider range of curvatures and thicknesses. The penalty for this is an overestimate in the measurement of reflectance, which has been estimated in previous work to be less than 1.35% (Salinas et al., 2016).

2.2. Reflectometer Gage R&R

Any conclusions drawn from measurements made using either of the two reflectometers (the "gages") under investigation will depend on the accuracy of the data. If either the measuring instrument or the measurement method is not capable of making accurate or repeatable measurements, the data will contain an error. An analysis of the measurement system usually requires an investigation of repeatability, reproducibility, bias, stability, and linearity. In order to assess and compare the accuracy of reflectance measure-

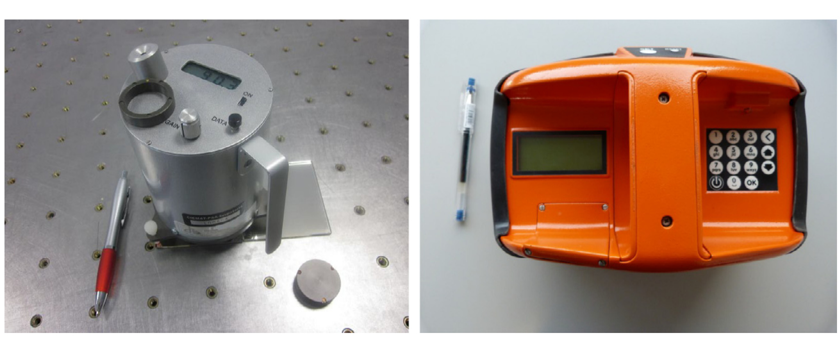

Fig. 1. D&S 15R-USB (left) and Abengoa Condor SR-6.1 reflectometer (right).