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Assessment of the impact of meteorological conditions on pyrheliometer calibration

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ABSTRACT

Pyrheliometer calibration must be done following strict procedures in order to ensure the required robustness and accuracy. These procedures are described in the ISO 9059:1990 and ASTM E 816 – 15 international standards. However, their application requires information that may not always be available or may be subjective, inaccurate or incomplete, as for example, the determination of "percent of cloud coverage" or "the existence of clouds 15° around the Sun". The irradiance measurements made by the reference and test instruments involved should also be collected over wide periods after, close to and before solar noon, which might not always be the case depending on the weather conditions during calibration. When those data are not available, the standard cannot be applied properly, and the experts have to decide which data can be used for the calibration. In this study, the abovementioned two main standards for pyrheliometer calibration were thoroughly reviewed, and a harmonized protocol is proposed that uses only the main data recorded. Nineteen field pyrheliometers were calibrated to verify the proposed procedure, and the results show its robustness. After calibration, we analyzed the variability in the calibration constant and the influence of some experimental conditions on the calibration results. As in previous references, the results show that variations in solar elevation and wind speed during the day still influenced the calibration constants of most of the test devices. On the contrary, neither the angle between the wind direction and the solar azimuth nor Linke turbidity seemed to influence the calibration constants calculated. The influence of the Linke turbidity is low as the viewing geometry of all involved pyrheliometers is very similar to each other and as low turbidity prevailed. The correlation between the solar elevation and the wind speed was analyzed and calibration constants were found to vary linearly with solar elevation and wind speed, respectively. Pyrheliometer calibration measurement testing was carried out in Summer 2014 at the Plataforma Solar de Almeria (PSA) in the context of the Solar Facilities for the European Research Area 2 Project (SFERA2).

1. Introduction

The accuracy of pyrheliometer measurements is important not only in scientific research, but in the solar power industry as well. Such diverse factors as a traceable calibration; pyrheliometer design performance characteristics; data acquisition system performance characteristics; proper installation, maintenance and operation procedures; contribute to the uncertainty of field measurements and calibration results (Sengupta et al., 2017; Thacher et al., 2000). In the past few years, efforts have been made to study, characterize and minimize those sources of uncertainty. The biggest contribution to the uncertainty of a well maintained field pyrheliometer is comes from the calibration. The most accurate calibrations can be achieved by outdoor calibrations against absolute cavity radiometers (Wilbert et al., 2010). The remaining uncertainty of the calibration is partly related to the meteorological conditions present during the calibration. For instance, the solar elevation influences the tilt error of pyrheliometers and wind can affect the field and reference instrument in a different way. Also, Wilbert et al. (2010) pointed out the importance of using reference and test pyrheliometers with the same aperture angle for calibration, because circumsolar radiation influences calibration accuracy. Thus, Linke turbidity should be less than 6 (ISO, 1990, Section 5.2.2), because

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Nomenclature

PSA	Plataforma Solar de Almería
DNI	Direct Normal Irradiance
BHI	Direct Horizontal Irradiance
GHI	Global Horizontal Irradiance
SFERA2	Solar Facilities for the European Research Area 2
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
WRC	World Radiation Center
BSRN	Baseline Surface Radiation Network
NREL	National Renewable Energy Laboratory
IRD	Integrated Recorded Data
FOV	Field Of View

direct irradiance scattering by aerosols and water vapor contribute to circumsolar radiation.

Calibration procedures have to be traceable and accurate. The calibration method must be standardized and reproducible at any location. Therefore, it has to include guidelines that produce similar results regardless of where the calibration takes place. In other words, the calibration method has to take into account all the factors involved in solar radiation measurement, so results can be reproduced and verified. The ISO 9059:1990 and the ASTM E 816 – 15 International standards have therefore been developed.

The aim of this study is to propose a harmonized pyrheliometer outdoor calibration protocol for the procedures described in the ISO and ASTM standards when access to information such as the cloud coverage or the distance from clouds to Sun is not available. Moreover, we also addressed the influence of some experimental (astronomical and meteorological) conditions on the calibration result. The experimental conditions tested were the solar elevation angle, wind speed, the angle between the wind direction and the solar azimuth and Linke turbidity (T_L).

These experimental conditions have been analyzed by other authors before. Several conditions that affect pyrheliometer calibration were addressed by Thacher et al. (2000), who reported negligible effect of wind speed on the CH1 pyrheliometers tested, but an effect of −0.15% on NIP pyrheliometer calibration constants. However, they also mentioned that the effect is not clear due to variability in wind speed and wind direction. Michalsky et al. (2011) found differences in irradiance measurements between *"clear-calm"* conditions (clear sky and wind speed below 2 ms^{-1}) and *"clear-windy"* conditions (clear sky and wind speed above 5 ms^{-1}). They also reported some dependence on solar zenith angle, but no temperature dependence below 15 °C in one of the groups of pyrheliometers. The influence of the solar zenith angle on pyrheliometer measurements was addressed by Habte et al. (2016b). These authors found differences in Direct Normal Irradiance (DNI) measurements depending on solar zenith angle that were even larger under cloudy conditions. In Habte et al. (2016a) differences were found in irradiance measurements of the same device due to the use of the different calibration constants in different calibration methodologies. As in the case of Dooraghi et al. (2014), they found better results when responsivity was considered a function of solar elevation.

The dataset used to test the proposed procedure was measured in Summer 2014 at the "Plataforma Solar de Almeria" (Spain) in the context of the – Solar Facilities for the European Research Area 2 Project (SFERA2).

This paper is structured as follows. First the framework and the main ISO and ASTM standard guidelines are described. The proposed calibration procedure is also described, as well as calculation of uncertainties and Linke turbidity. Then the calibration campaign including general conditions, references and test devices, are described. The calibration results, starting with data filtering, and finally, the results of the calibration constant, variability and the impact of some experimental conditions are shown in the last section.

2. Framework of the pyrheliometer calibration standard

The ISO 9059:1990 (ISO, 1990) and ASTM E 816 – 15 (ASTM, 2015) Standard guidelines for the pyrheliometer versus pyrheliometer calibration are described below. The review of these methodologies does not argue for or against the original criteria. That is outside the scope of this study. We do defend, however, the reasons or motivation for selecting the harmonized criteria fulfilling both standards.

2.1. The ISO standard for pyrheliometer calibration

The ISO 9059:1990 standard makes recommendations for calibrating field pyrheliometers by comparison to a reference pyrheliometer.

Among the meteorological variables recommended is **irradiance,** which values should be *"not less than 300 W m^{-2}, but irradiance values exceeding 700 W m^{-2} are preferred"*. Under recommended **sky conditions**, it states that *"clouds should have an angular distance from the Sun greater than 15°. Generally, good calibrations conditions exist when the cloud cover is less than 12.5%",* and Linke turbidity should be below 6. It does not give a maximum **wind speed**, but states that *"wind speed should be low, particularly when the wind is blowing in the direction of the Sun's azimuth ± 30°"*. Regarding temperature during calibration, *"The **temperature range** which is typical for the field application"*.

ISO standards for measuring equipment recommend that "Primary standard pyrheliometers be used as reference for the calibration of secondary standard pyrheliometers and may be used for the calibration of first or second class pyrheliometers." "The reference for calibration of any pyrheliometer in first or second class categories shall be a pyrheliometer in the same or higher category". Admissible tracker misalignment should be less than the slope angle minus 0.25°. The slope angle is the smallest angle between the instrument optical axis and a line connecting the outer borders of the sensor element and the aperture. The WMO recommendation for the slope angle is 1° (WMO, 2014). The datalogger resolution must be "at least 0.05% of the maximum pyrheliometer reading", and its "accuracy, stable over at least one year and including temperature-generated drift, better than ± 0.1%". "The datalogger system should have at least four channels". "The read-out the pyrheliometer signal shall be synchronous within 1 s, and the rate of instantaneous measurement should be between 1 per 30 s and 1 per 120 s". Finally, "…the distance between separately mounted instruments is less than 20 m."

The ISO standard establishes the following measurement procedure, which must be carried out in at least 10 (but preferably 20) series of measurements. Each series has to cover a time period of 10–20 min, including at least 10 instantaneous readings or 10 integrated records.

For the determination of the calibration factor, the ISO standard uses Eqs. (1)–(3),

$$F(j) = \sum_{i=1}^{n} \frac{E_{ref}(i,j)}{V_{test}(i,j)} \tag{1}$$

where i is the reading index within a series, j is the series index, E_{ref} is the irradiance measured by the reference pyrheliometer, V_{test} is the voltage registered by the field pyrheliometer, is the number of series carried out and n is the number of readings taken in each series.

The calibration factor $F(i)$ is estimated for each reading. After that, all the calibration factors from each single measurement $F(i,j)$ in a series are averaged into one $F(j)$ calibration factor for that series. And finally, all the series calibration factors are averaged for the final calibration factor F.