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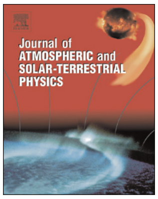

A method to measure the broadband longwave irradiance in the terrestrial direct solar beam

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ABSTRACT

Shortwave radiometers such as pyranometers, pyrheliometers, photovoltaic cells, and longwave radiometers such as pyrgeometers are calibrated with traceability to consensus References, which are maintained by Absolute Cavity Radiometers (ACRs) and the World InfraRed Standard Group (WISG), respectively. Since the ACR is an open cavity with no window, and was developed to measure the extended broadband spectrum of the terrestrial direct solar beam irradiance, then there would be discrepancy in calibrating the shortwave radiometers because of their limited spectral band. On the other hand, pyrgeometers are calibrated during the nighttime only, because no consensus reference has yet been established for the daytime longwave irradiance. This article describes a method to measure the broadband longwave irradiance in the terrestrial direct solar beam from 3 μm to 50 μm. The method might be used in developing calibration methods to address the mismatch between the broadband ACR and shortwave radiometers, and the lack of a daytime reference for pyrgeometer calibration. We used the described method to measure the irradiance from sunrise to sunset; the irradiance varied from approximately 1 W m^{-2} to 16 W m^{-2} with an estimated uncertainty of 1.46 W m^{-2}, for a solar zenith angle range from 80° to 16°, respectively.

1. Introduction

Solar and atmospheric science radiometers such as pyranometers, pyrheliometers, and photovoltaic cells are calibrated with traceability to the World Radiometric Reference (WRR) (ISO, 1990). The WRR is maintained by Absolute Cavity Radiometers (ACRs) (WRC/PMOD, 2011). An ACR is an open cavity with no windows, and was developed to measure the extended broadband spectrum of the terrestrial direct solar beam irradiance that extends beyond the ultraviolet and infrared bands; i.e., below 0.2 μm and above 50 μm, respectively. On the other hand, the pyranometers and pyrheliometers are developed to measure the broadband shortwave irradiance from approximately 0.3 μm to 3 μm, while the present photovoltaic cells are limited to the spectral range of approximately 0.3–1 μm. The broadband mismatch of the ACR versus the radiometers would cause a discrepancy in the radiometers' calibration methods that has not been discussed or addressed in solar and atmospheric science literature.

As will be shown in later sections, the measured longwave irradiance in the solar beam (from 3 μm to 50 μm), varies from 1 W m^{-2} to 16 W m^{-2} for solar zenith angle from 80° to solar noon, respectively. During the calibration of shortwave radiometers using an ACR the responsivity of the test radiometer (RS) is calculated by dividing the thermopile output voltage from the radiometer (V_{tp}) by the broadband reference irradiance (I) measured by the ACR, i.e. $RS = V_{tp}/I$. Since the longwave irradiance is sensed by the ACR but not sensed by the shortwave radiometer, then the broadband reference irradiance measured by the ACR is larger than the irradiance that would be sensed by the shortwave radiometer. Therefore, the resultant RS of the test radiometer would be lower than its actual responsivity. When the test radiometer is deployed in the field, the outdoor irradiance is calculated as $I = V_{tp}/RS$; since the RS is underestimated during the calibration, then the calculated irradiance in field measurement would be overestimated, e.g. overestimated from 1 W m^{-2} to 16 W m^{-2} for solar zenith angle from 80° to solar noon. This overestimated irradiance might have implications on solar and atmospheric science applications.

Pyrgeometers are also used for solar and atmospheric science applications. Pyrgeometers are calibrated with traceability to the World InfraRed Standard Group (WISG), yet they are calibrated during the nighttime only, because no reference has yet been

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established for the daytime longwave irradiance. The difficulty of measuring daytime longwave radiation is due to the unknown longwave irradiance from the sun, dome heating offsets in pyrgeometers that do not compensate for the dome heating using dome thermistors, and shortwave leakage through the dome in some older design pyrgeometers. These effects are seen as differences between measurements with pyrgeometers that are shaded from the sun and pyrgeometers that are unshaded (Meloni et al., 2012). Effects up to 15 W m^{-2} have been observed (Gröbner, 2010). This difference is relevant to daytime measurements of longwave radiation in larger networks.

This article describes a method to measure the broadband longwave irradiance in the terrestrial direct solar beam from 3 μm to 50 μm, as a first step that might be used to help develop calibration methods to address the mismatch between the broadband ACR and shortwave radiometers and the lack of a daytime reference for pyrgeometers. Since daytime measured data by pyrgeometers is used in many applications, then the broadband longwave measurement in the terrestrial direct solar beam might be essential in developing methods for characterizing pyrgeometers to evaluate their uncertainty during the daytime and to quantify the effect of dome heating on some pyrgeometers, without the need to install thermistors in their domes.

We used the described method to measure the irradiance from sunrise to sunset at the National Renewable Energy Laboratory's (NREL) Solar Radiation Research Laboratory (SRRL) (elevation = 1828.8 m above sea level); the irradiance varied from approximately 1 W m^{-2} to 16 W m^{-2} from z = 80 to solar noon, respectively, with an estimated uncertainty of 1.46 W m^{-2}. This irradiance magnitude changes, based on the solar zenith angle and the daily atmospheric content changes at SRRL.

2. Setup and measurement equation

The setup for the described method required two spectrally matched pyrgeometers, installed on solar tracker model Brusag-Intra with pointing errors $< 0.1°$, with one shading mechanism so that one of the two pyrgeometers was shaded. In this method, the two pyrgeometers were Eppley-precision infrared radiometers (PIRs) because they are fitted with dome thermistors to account for dome heating, and are widely used in many networks; e.g., the Baseline Surface Radiation Network (McArthur, 2004), and the U.S. Department of Energy's Atmospheric Radiation Measurement Program (Voils, 2010); yet other matched radiometer models might be used. The two PIRs were installed outdoors, horizontally on the solar tracker. The two pyrgeometers were calibrated with traceability to the WISG. One PIR was installed shaded from the sun disk using an Eppley-precision spectral pyranometer (PSP) dome, which transmits the broadband shortwave irradiance from approximately 0.3 μm to 3 μm (see Fig. 1). The PSP's shading dome was set up to shade the sun disk from the shaded PIR with a subtended angle of 5°, which is much larger than the solar tracker's pointing error of 0.1° to minimize effect of pointing errors on the measured irradiance. The subtended angle is also set up to equal the ACR's field of view for consistency with the shortwave radiometers' calibration method (Ohmura et al., 1998). The other PIR was not shaded. The thermopile output voltage, case temperature, and dome temperature of the two PIRs were measured simultaneously every five minutes. The solar zenith angle was calculated at each data point using the Solar Position Algorithm (Reda and Andreas, 2004). With this setup, the incoming irradiance, measured by the unshaded and shaded PIRs, was calculated using the following equation (Reda et al., 2002):

$$W = K_0 + K_1{*}V_{tp} + K_2{*}\, W_r + K_3{*}(W_d - W_r) \tag{1}$$

where,

W is the calculated atmospheric longwave irradiance, in Wm^{-2}
K_0, K_1, K_2, and K_3 are the calibration coefficients
V_{tp} is the thermopile output voltage, in μV
W_r is the receiver irradiance, in $\mathrm{W\,m^{-2}} = \sigma \times (T_c + 0.0007074 \times V_{tp})^4$, where T_c is the case temperature, in Kelvin, and σ is Stefan–Boltzmann constant $= 5.6704 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
W_d is the dome irradiance, in $\mathrm{W\,m^{-2}} = \sigma \times T_d{}^4$, where T_d is the dome temperature, in Kelvin.

Based on the setup in Fig. 1, the measured irradiance using the shaded and unshaded pyrgeometers included the following components:

2. The unshaded pyrgeometer components:
   1. Longwave irradiance from the hemispherical sky, without the longwave irradiance from the sun disk. This irradiance will be called LW-Diffuse irradiance ($W_{\mathrm{u,\ LW,\ D}}$); spectral range is 3–50 μm.
   2. Longwave irradiance from the sun disk ($W_{\mathrm{u,\ LW,\ Sun}}$); spectral range is 3–50 μm.
   3. Shortwave cutoff leakage through the unshaded pyrgeometer's dome ($W_{\mathrm{u,\ SW}}$); spectral range is 0.3–3 μm.
3. The shaded pyrgeometer components:
   1. LW-Diffuse irradiance measured by the shaded pyrgeometer ($W_{\mathrm{s,\ LW,\ D}}$); spectral range is 3–50 μm.
   2. Shortwave leakage through the pyrgeometer's dome ($W_{\mathrm{s,\ SW}}$);

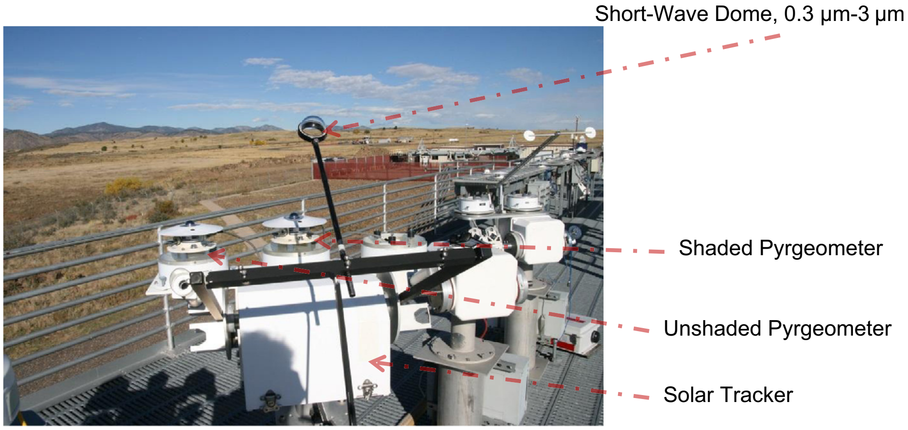

Fig. 1. Unshaded and shaded pyrgeometers at NREL/SRRL.