A Method to Measure the Broadband Longwave Irradiance in the Terrestrial Direct Solar Beam

By

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Abstract

Shortwave radiometers such as pyranometers, pyrhemometers, 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 Wm^{-2} to 16 Wm^{-2} with an estimated uncertainty of 1.46 Wm^{-2} , for a solar zenith angle range from 80° to 16° , respectively.

1. Introduction

Solar and atmospheric science radiometers such as pyranometers, pyrhemimeters, 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 $0.2 \mu\text{m}$ and above $50 \mu\text{m}$, respectively. On the other hand, the pyranometers and pyrhemimeters are developed to measure the broadband shortwave irradiance from approximately $0.3 \mu\text{m}$ to $3 \mu\text{m}$, while the present photovoltaic cells are limited to the spectral range of approximately $0.3 \mu\text{m}$ to $1 \mu\text{m}$. 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 $3 \mu\text{m}$ to $50 \mu\text{m}$), varies from 1 Wm^{-2} to 16 Wm^{-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. $\text{RS} = V_{\text{tp}}/I$. 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 $I = V_{\text{tp}}/\text{RS}$; since the RS is

underestimated during the calibration, then the calculated irradiance in field measurement would be overestimated, e.g. overestimated from 1 Wm^{-2} to 16 Wm^{-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 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 Wm^{-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 $3 \mu\text{m}$ to $50 \mu\text{m}$, 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 meters above sea level); the irradiance varied from approximately 1 Wm^{-2} to 16 Wm^{-2} from $z = 80$ to solar noon, respectively, with an estimated uncertainty of 1.46 Wm^{-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 $< 0.1^\circ$, 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 $0.3 \mu\text{m}$ to $3 \mu\text{m}$ (see Figure 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):

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

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 $W m^{-2} = \sigma * (T_c + 0.0007074 * V_{tp})^4$, where T_c is the case temperature, in Kelvin, and σ is Stefan-Boltzmann constant = $5.6704 * 10^{-8} W m^{-2} K^{-4}$

W_d is the dome irradiance, in $Wm^{-2} = \sigma * T_d^4$, where T_d is the dome temperature, in Kelvin.

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

2.1. The unshaded pyrgeometer components:

2.1.1. Longwave irradiance from the hemispherical sky, without the longwave irradiance from the sun disk. This irradiance will be called *LW-Diffuse irradiance* ($W_{u, LW, D}$); spectral range is $3 \mu m$ to $50 \mu m$

2.1.2. Longwave irradiance from the sun disk ($W_{u, LW, Sun}$); spectral range is $3 \mu m$ to $50 \mu m$.

2.1.3. Shortwave cutoff leakage through the unshaded pyrgeometer's dome ($W_{u, SW}$); spectral range is $0.3 \mu m$ to $3 \mu m$.

2.2. The shaded pyrgeometer components:

2.2.1. LW-Diffuse irradiance measured by the shaded pyrgeometer ($W_{s, LW, D}$); spectral range is 3 μm to 50 μm .

2.2.2. Shortwave leakage through the pyrgeometer's dome ($W_{s, SW}$); spectral range is 0.3 μm to 3 μm .

Therefore, the measured irradiance using the unshaded and shaded pyrgeometers (W_u and W_s) equals,

$$W_u = W_{u, LW, D} + W_{u, LW, Sun} + W_{u, SW} \quad (2)$$

$$W_s = W_{s, LW, D} + W_{s, SW} \quad (3)$$

The data were collected instantaneously from the two pyrgeometers; therefore, $W_{u, LW, D} = W_{s, LW, D}$. The longwave irradiance from the sun disk (W_{LW}) was calculated by subtracting Equation 3 from Equation 2,

$$W_{LW} = W_{u, LW, Sun} = W_u - W_s - (W_{u, SW} - W_{s, SW}) \quad (4)$$

The unshaded and shaded pyrgeometers are chosen to have minimum spectral difference; therefore, the term ($W_{u, SW} - W_{s, SW}$) in Equation 4 will be minimum. This is verified to be less than 0.73 Wm^{-2} , one standard deviation, by deploying the two pyrgeometers unshaded and under clear sky conditions, when clouds are at least 15° away from the sun disk, and the shortwave solar irradiance is larger than 400 Wm^{-2} (see Section 3.1). Therefore, the term ($W_{u, SW} - W_{s, SW}$) is considered zero, and the 0.73 Wm^{-2} might be added to the measurement uncertainty. Equation 4 will then yield the measured longwave irradiance from the sun, W_{LW} ,

$$W_{LW} = W_u - W_s, \quad (5)$$

where the irradiances W_u and W_s are calculated using Equation 1 for the unshaded and shaded pyrgeometers. Equation 6 can then be used to calculate the Direct-Normal-Longwave-Irradiance from the sun, W_{DNLW} ,

$$W_{DNLW} = \frac{W_{LW}}{\cos \theta}, \quad (6)$$

where θ is the solar zenith angle.

3. Outdoor Measured Data

3.1. Validating the matched spectral response

We deployed the two pyrgeometers from May 1 to August 3, 2014 with the shading disk removed to verify their matched spectral response. Therefore, both pyrgeometers were exposed to the same longwave and shortwave irradiances during the daytime. Only daytime and clear sky conditions were selected from the dataset. Figure 2 shows that the standard deviation of the difference between the measured irradiance by PIR1 from that of PIR2 is less than 0.73 Wm^{-2} . The differences can then be added to the overall uncertainty, as will be shown.

3.2. Outdoor measurement

Data were collected from June 17 to July 24, 2014 where one pyrgeometer was shaded with a PSP dome and the other was not shaded. Equation 1 was used to calculate W_u and W_s ,

$$W_u = 0.45 + 0.242 * V_{tp,u} + 1.004 * W_{r,u} - 2.61 * (W_{d,u} - W_{r,u}) \quad (7)$$

$$W_s = 0 + 0.225 * V_{tp,s} + 0.994 * W_{r,s} - 3 * (W_{d,s} - W_{r,s}) \quad (8)$$

Where the subscripts u and s imply unshaded and shaded, and the constants are the calibration coefficients of the unshaded and shaded pyrgeometers, with traceability to WISG.

Figure 3 shows the calculated longwave irradiance from the sun (W_{LW} and W_{DNLW}), using Equations 5 and 6. Figure 4 shows W_{LW} and W_{DNLW} versus the solar zenith angle.

The two figures illustrate that the longwave irradiance from the sun, W_{LW} , is at a maximum of 15.5 Wm^{-2} at solar noon ($\theta = 16.5^\circ$) and a minimum of 1 Wm^{-2} at zenith angle $= 80^\circ$. Meanwhile, the Direct-Normal-Longwave-Irradiance from the sun, W_{DNLW} , changes from 16 Wm^{-2} to 4 Wm^{-2} from solar noon to $\theta = 80^\circ$. Also, for zenith angles larger than 65° the magnitudes of spikes are larger for the W_{DNLW} plots than those of the W_{LW} ; this is attributed to the $\cos \theta$ term (denominator) in Equation 6; e.g., at $\theta = 65^\circ$ a change in atmospheric condition that might result in a 1 Wm^{-2} in W_{LW} change, might result in $1/\cos 65 = 2.4 \text{ Wm}^{-2}$ in W_{DNLW} .

3.3. Uncertainty discussion

A calibrated data acquisition was used to measure the output signals from the two PIRs simultaneously; thus, any errors were algebraically canceled by using Equation 5. Because the two pyrgeometers are Eppley PIRs and have the same design, therefore the difference in the magnitude of their output signals would result in a negligible uncertainty when using Equation 5. Meanwhile, the two pyrgeometers were calibrated with traceability to the interim WISG, then any bias in the reference would also algebraically cancel (see Equation 5 and Figure 2 for validating errors cancelation). Therefore, the estimated expanded uncertainty of measuring the longwave irradiance from the sun, W_{LW} equals two times the standard deviation derived in step 2.2.2; i.e., $2 * 0.73 = 1.46 \text{ Wm}^{-2}$.

For the Direct-Normal-Longwave-Irradiance from the sun (W_{DNLW}) in Equation 6, the expanded uncertainty with 95% confidence level (U_{95}) is estimated by calculating the sensitivity coefficients of W_{LW} and $\cos \theta$ in the right hand side of Equation 6, using the Guide to the Expression of Uncertainty (GUM) described step by step in Reda et al., 2008. Figure 5 shows U_{95} of measuring W_{LW} and W_{DNLW} versus the solar zenith angle. From the figure, note that the uncertainty of measuring W_{LW} is 1.46 Wm^{-2} ,

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4 while the uncertainty of measuring W_{DNLW} increases from 1.46 Wm^{-2} to 8 Wm^{-2} from solar noon to solar
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6 zenith angle 80° . Since the uncertainty of the solar zenith angle is $\pm 0.0003^\circ$ (Reda and Andreas, 2004),
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8 the increasing trend at the larger zenith angles is dominated by the magnitude of the cosine term in the
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10 denominator as discussed in Section 3.2, not from the uncertainty of the solar zenith angle. This is a
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12 limitation to using the method to measure W_{DNLW} . Future development of InfraRed Pyrhemometers (IRP)
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14 that measure the W_{DNLW} might be used to develop methods with lower uncertainties. Meanwhile, the
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16 method might be used in zenith angle range from 45° to solar noon with uncertainty less than 2 Wm^{-2} .
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23 **4. Model Comparison**

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25 The measured irradiances can be simulated by radiative transfer models with measurements or pre-
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27 given assumptions of atmospheric conditions. Precise computation of irradiance in the Earth's
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29 atmosphere is known to be extremely difficult because of the uncertainties in the inputs of atmospheric
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31 properties; e.g., the optical thickness of aerosol and the concentrations of water vapor and other
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33 absorbing gases. However, the simulations from a state-of-the-art radiative transfer model can provide a
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35 reasonable range of surface radiations under various atmospheric conditions and a reliable estimation
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37 of the typical values that are likely to be measured by the instruments. Thus, the model simulation and
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39 the comparison to onsite measurements provide an invaluable procedure to evaluate the performance
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41 of the algorithm introduced above, which might be used to explore any instrument uncertainties.
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48 In the current study, the surface irradiances from direct solar radiation and thermal emission by the
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50 atmosphere were computed using libRadtran, developed by Mayer and Kylling (2005). The libRadtran
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52 provides users a wide choice of available radiative transfer models to solve the radiative transfer
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54 problems at the wavelengths from ultraviolet through far infrared.
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The measured broadband direct normal irradiances (DNIs) by the surface instruments corresponded to two sources: the direct solar radiation transmitted through the atmosphere and longwave thermal emission from the atmosphere that arrived within the scope of the measured direct radiation. Thus, the measured W_{LW} can be given by,

$$W_{LW} = DNI_{solar} + F_{thermal} \quad (9)$$

where DNI_{solar} and $F_{thermal}$ are the contribution from solar radiance and the thermal emission from the atmosphere, respectively.

DNI_{solar} can be derived as follows:

$$DNI_{solar} = \frac{F_{solar}}{\cos \theta_0} \quad (10)$$

where θ_0 is solar zenith angle and F_{solar} is the downwelling solar irradiance simulated by libRadtran. For solar radiation, we selected the Discrete Ordinates Radiative Transfer (DISORT) model (Stamnes et al., 1988), provided by libRadtran, to compute the spectral transmittances through aerosol and absorbing gases in the atmosphere at the wavelengths of 3 μm to 50 μm . The clear atmosphere is represented by the 1976 US Standard Atmosphere, because it follows a median optical thickness of the atmosphere among all standard atmosphere profiles. The broadband irradiance is then given from an integral of the spectral irradiances at the land surface using the simulated spectral transmittances and a distribution of solar spectral irradiance at the top of the atmosphere. The libRadtran and DISORT models are not restated here because they have been discussed extensively in the literature (Mayer and Kylling, 2005; Stamnes et al., 1988).

$F_{thermal}$ in Equation (7) can be given as an integral of longwave radiances within the hemisphere:

$$F_{thermal} = \frac{1}{\cos \theta_0} \int_{\varphi_1}^{\varphi_2} \int_{\mu_1}^{\mu_2} I \mu d\mu d\varphi \quad (11)$$

where I is the radiance at the thermal wavelengths, and μ and φ are the cosine of zenith and azimuth angles, respectively. μ_1 , μ_2 , φ_1 , and φ_2 are related to the opening angle of the instruments. Because thermal emission by the atmosphere can be approximated as isotropic, I can be given by

$$I = \frac{F_{thermal}^{\downarrow}}{\pi} \quad (12)$$

where $F_{thermal}^{\downarrow}$ is the downwelling thermal flux that can be simulated by DISORT. Assuming the opening angle of the instrument is 5° , the coefficients used by Equation (11) can be given by

$$\mu_1 = \cos(\theta_0 - 2.5) \quad (13a)$$

$$\mu_2 = \cos(\theta_0 + 2.5) \quad (13b)$$

$$\varphi_2 - \varphi_1 = \frac{5\pi}{180} \quad (13c)$$

Figure 6 shows the difference between the measured irradiance and the calculated irradiance using the mathematical model. The measured precipitable water and Aerosol Optical Depth at 500 nm (AOD) are used as input parameters to the model when the data is available; data was only available during the second through the fourth clear days, see Figure 7. In Figure 6, the irradiance is shown when only the precipitable water is used, the precipitable water and AOD are used, and when the US standard atmosphere is used. From the figure it is noted that there is no significant difference between the three calculations, and that many of the differences between the measured irradiance and the calculated irradiance using the model are larger than the measurement estimated uncertainty of 1.465 Wm^{-2} . The

larger differences might be a result of the difference between the actual atmospheric content and the input variables to the mathematical model, specially the absorbing gases, which were not available at our site. Future research and model improvement based on actual measurement might then be used to validate the improved model.

5. Conclusion

The longwave irradiance from the sun was measured using the described method above, with an expanded uncertainty of approximately 1.46 Wm^{-2} . When the measured irradiance was compared to the model calculation, the differences varied from 0 Wm^{-2} to $\pm 4 \text{ Wm}^{-2}$, which was not within the estimated uncertainty of the measured irradiance of 1.46 W/m^2 (see Figure 6). The larger differences might be attributed to the difference between the actual atmospheric contents during the measurement and the standard parameters used in the mathematical model. Further investigation and model improvement might be needed to minimize the difference between the measurement and the model calculation.

This method is a preliminary step that might contribute to establishing a consensus world reference for the direct-beam longwave irradiance that might be used to calibrate future radiometers dedicated to such measurement; e.g., an InfraRed pyr heliometer, IRP, fitted with solar blind coated silicon windows has been proposed to measure direct-beam longwave irradiance from the sun. Its initial results were presented at the 14th BSRN Scientific Review and Workshop (Konings, 2014). Once the IRP is calibrated, it might then be used simultaneously with the ACR, as a transfer reference during the calibration of shortwave radiometers. It might also be used to characterize the performance of pyrgeometers during daytime, which would help in assessing the pyrgeometers' uncertainty budget during the daytime.

Once this method is refined and a consensus reference is established, it might also be used to correct for the spectral mismatch that results from calibrating shortwave radiometers using an unwindowed

absolute cavity radiometer, develop a calibration method to calibrate pyrgeometers during daylight time, instead of the present nighttime only calibration, and validate mathematical models.

6. Future Work

As next steps, develop calibration procedures to address the spectral mismatch between the ACR and shortwave radiometers and the lack of longwave reference during daytime, and replicate this setup using matched pairs of other commercially available pyrgeometer models. As different models have slightly different spectral transmission characteristics, the spectral distribution of direct-beam longwave irradiance can be studied in more detail. Also, we propose to perform this measurement at other geographical locations.

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Figure 1. Unshaded and shaded pyrgeometers at NREL/SRRL

Figure 2. Irradiance difference when both pyrometers are unshaded during the daytime at NREL/SRRL, spectral match validation

Figure 3. Calculated longwave irradiance from the sun versus Mountain Standard Time for five clear sky days at NREL/SRRL

Figure 4. Calculated longwave irradiance from the sun versus zenith angle for five clear sky days at NREL/SRRL

Figure 5. Uncertainty with 95% confidence level of the measured irradiance versus solar zenith angle

Figure 6. Differences between the measured and model irradiance

Figure 7. The measured precipitable water and AOD during the outdoor longwave measurement