Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error during Outdoor Calibration Using the Component Sum Method

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ABSTRACT

Thermopile pyranometers' thermal offset has been recognized since the pyranometer's inception. This offset is often overlooked or ignored because its magnitude is small compared to the overall solar signal at higher irradiance. With the demand of smaller uncertainty in measuring solar radiation, recent publications have described a renewed interest in this offset, its magnitude, and its effect on solar measurement networks for atmospheric science and solar energy applications. Recently, it was suggested that the magnitude of the pyranometer thermal offset is the same if the pyranometer is shaded or unshaded. Therefore, calibrating a pyranometer using a method known as the shade/unshade method would result in accurate responsivity calculations because the thermal offset error is canceled. When using the component sum method for the pyranometer calibration, the thermal offset error, which is typically negative when the sky is cloudless, does not cancel, resulting in an underestimated shortwave responsivity. Most operational pyranometers that are in use for solar radiation measuring networks are calibrated using the component sum method since it is possible to calibrate many pyranometers simultaneously. From this arises the importance of correcting the component sum method results to account for the thermal offset error.

In this article a method of using a blackbody system to calculate the net longwave responsivity of pyranometers, which is largely responsible for the offset error, is described. This longwave responsivity is then used to correct the pyranometer's shortwave responsivity during the component sum method calibrations and thereby substantially reduces the effect of the offset error on the final pyranometer responsivity. Practical procedures for performing this calibration procedure along with its limitations and remaining uncertainties are given.

1. Introduction

The thermal offset of thermopile pyranometers is a result of the temperature gradient between the pyranometer dome and its thermopile (Gulbrandsen 1978; Bush et al. 2000; Haeffelin et al. 2001; Dutton et al. 2001; Philipona 2002; Reda et al. 2003). This offset has often been overlooked or ignored in the past, but recently, with the demand for smaller uncertainty in measuring solar radiation, there have been many publications describing the offset, its magnitude, and its effect on solar measuring networks for atmospheric science

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and solar energy applications. All publications (e.g., Dutten et al. 2001; Haeffelin et al. 2001; Philipona 2002) show a strong correlation between the thermal offset error and the net longwave radiation (NET-IR), measured by a collocated pyrgeometer. This is expected since the offset is caused by the temperature difference between the dome and detector, which is driven by the NET-IR. Philipona (2002) suggests that the magnitude of the thermal offset is the same if the pyranometer is shaded or unshaded. Therefore, calibrating a pyranometer using the shade/unshade method would result in accurate responsivity calculations. The reason is that the thermal offset error is canceled using the shade/unshade equation since the shaded thermopile voltage is subtracted from the unshaded voltage in the equation numerator [see section 3, Eq. (6)]. When using the component sum method for the calibration [see section 3, Eq. (4)], the thermal offset error causes the thermopile output voltage to be too small; consequently, the resultant responsivity is underestimated. This is because, when calibrating a pyranometer under cloudless clear-sky conditions, the effective sky temperature is lower than the ambient temperature where the pyranometer is installed. This causes the pyranometer dome temperature (T_d) to be lower than its case temperature (T_c); consequently, the dome IR radiation would be smaller than that of the case. Because the resultant NET-IR sensed by the pyranometer thermopile equals the dome radiation minus the case radiation, the NET-IR is negative, causing a negative thermal offset error at the thermopile. The smaller the thermal conductivity between the pyranometer dome and its case, the greater the effect of the sky temperature on T_d; consequently, the thermal offset error would be more negative.

Most pyranometers that are deployed in the solar radiation measuring networks are calibrated using the component sum method since it enables many pyranometers to be calibrated simultaneously. From this arises the importance of correcting the component sum method results to account for the thermal offset error. This would allow consistent calibrations that account for the NET-IR during the calibration event and enable users to correct their historical data when corresponding NET-IR data are available.

In this article, we describe a method of using a blackbody system to calculate the NET-IR responsivity of pyranometers and use it to correct the shortwave responsivity for the thermal offset error during the component sum method calibrations. In section 2, we describe the calibration of 21 pyranometers in a blackbody system and calculate their NET-IR responsivity. Then, in section 3, we show how the correction is applied to the shortwave responsivity during the outdoor calibration. In section 4, we describe two methods to validate the correction method.

2. Blackbody calibration to calculate the NET-IR responsivity of pyranometers

Figure 1 is a simplified diagram for the blackbody system (BBS) that is used for the pyranometer calibration. In use since 2001, this system was developed by The Eppley Laboratory, Inc. (EPLAB), and the National Renewable Energy Laboratory (NREL) to calibrate pyrgeometers (Reda et al. 2002). The system consists of a blackbody cavity (BB) and aluminum plate that are connected to two independent temperature baths. The system is enclosed in a container that is purged with dry air to maintain the relative humidity at less than 10% to prevent water condensation at temperatures below the dewpoint.

We calibrated 21 pyranometers, of different types and manufacturers, in the BBS. The sample consisted of 3 EPLAB 8-48s (BW), 1 Kipp & Zonen CM22, 16 EPLAB PSPs, and 1 Spectrosun SR-75. The sample choice was based on availability of different models and on the fact that the model PSP is widely used.

Each pyranometer was placed on the BBS aluminum plate in an upright position with its dome inside the BB sphere, where there is no visible light. The plate temperature is considered the pyranometer case temperature (T_c) and measured using a thermistor that is installed in the plate.

The calibration was performed at five temperature plateaus that are listed in Table 1. Each plateau has a BB temperature (i.e., sky) that is different from the plate temperature (i.e., pyranometer case) to simulate the atmospheric conditions that are similar to what a pyranometer encounters when deployed outdoors. During the calibration, the difference between the blackbody and case radiations is considered the net longwave radiation and it ranged from -131.6 to -60.3 W m^{-2}, as shown in Table 1.

In Fig. 2, we show the correlation between the thermopile output voltage (V_{TP}) and the NET-IR for 14 pyranometers. From the figure, one can notice that the output voltage is linear with respect to the NET-IR for all pyranometers. This implies that there is a strong correlation between the V_{TP} and the NET-IR, and that the error in calculating the NET-IR using the aluminum plate radiation, rather than the pyranometer case radiation, is negligible. Also in the figure, the slope of the straight-line fit is the BB responsivity of the pyranometer, $\mathrm{RS}_{\mathrm{bb}}$:

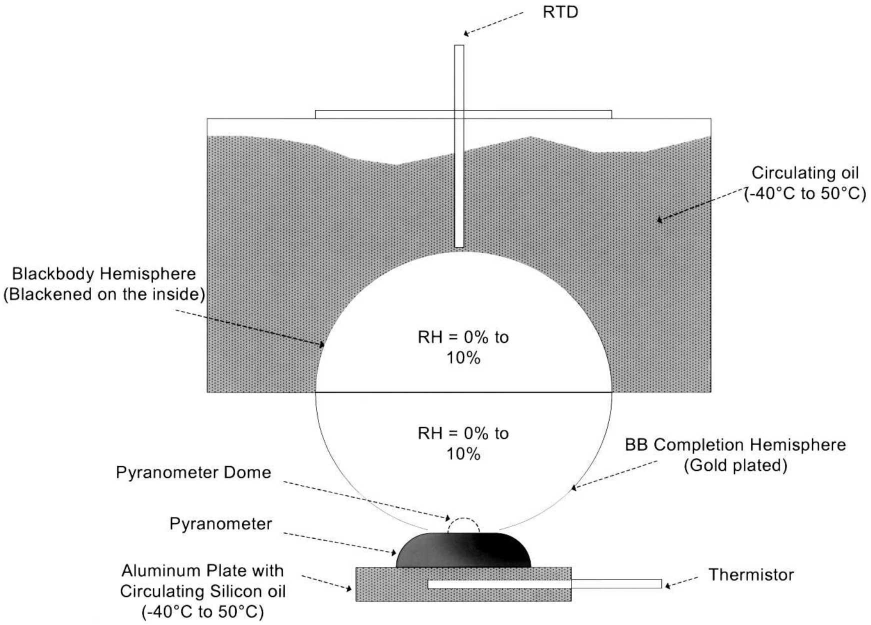

FIG. 1. The blackbody system (BBS) with a pyranometer in place.

$$\mathrm{RS_{bb}} = \frac{V_{\mathrm{TP}}}{W_{\mathrm{LW}}} = \frac{V_{\mathrm{TP}}}{W_{\mathrm{bb}} - W_c}, \quad (1)$$

where V_{TP} = thermopile output voltage of the pyranometer (in μV), W_{LW} = NET-IR (in W m^{-2}), W_{bb} = BB radiation [in W m^{-2} = $\sigma{*}T_{\mathrm{bb}}^4$, where $\sigma = 5.6697 \times 10^{-8}$ W m^{-2} K^{-4} and T_{bb} is the BB temperature (in K)], W_c = pyranometer case radiation [in W m^{-2} = $\sigma{*}T_{\mathrm{c}}^4$, where T_c is the pyranometer case temperature (in K)]. This temperature is measured by either a thermistor that is fitted in the pyranometer case or a thermistor inside the BBS aluminum plate.

When a pyranometer is used outdoors to measure the shortwave radiation (SW), its output thermopile signal (V_{TP}) is divided by the shortwave responsivity ($\mathrm{RS_{SW}}$) to calculate the global shortwave irradiance. Since the NET-IR error signal is algebraically added to the V_{TP}, it is divided by $\mathrm{RS_{SW}}$. Because the pyranometer thermopile error signal is developed as a result of the NET-IR (W_{LW}) and is treated as if it were a net shortwave (W_{SW}), W_{LW} must be accounted for as an equivalent W_{SW} during the BBS calibration. Therefore, we introduce the term shortwave/longwave equivalence, E, in Eq. (2), which is calculated from the BB calibration data:

$$E = \frac{W_{\mathrm{SW}}}{W_{\mathrm{LW}}} = \frac{V_{\mathrm{TP}}/\mathrm{RS_{mfr}}}{V_{\mathrm{TP}}/\mathrm{RS_{bb}}} = \frac{\mathrm{RS_{bb}}}{\mathrm{RS_{mfr}}}, \quad (2)$$

where W_{SW} is shortwave net radiation (in W m^{-2}), W_{LW} longwave net radiation (in W m^{-2}), and $\mathrm{RS_{mfr}}$ the manufacturer shortwave responsivity of the pyranometer (if not available, then an estimated responsivity from any present or historical calibration can be used).

Note that the $\mathrm{RS_{mfr}}$ does not have to be accurate (within 3%–5% is adequate) because the thermopile error signal, resulting from the pyranometer thermal offset, is a small fraction of the total SW thermopile signal. Therefore, the error resulting from using $\mathrm{RS_{mfr}}$ instead of the correct responsivity is negligible.

Pyrgeometers are often used to measure the NET-IR, then used to correct for the thermal offset error of a pyranometer (Bush et al. 2000; Haeffelin et al. 2001; Dutton et al. 2001). To calculate the pyranometer thermopile thermal offset signal error, ΔV, during the outdoor calibration, the NET-IR is measured using a pyrgeometer. We then multiply the NET-IR (W_{LW}) by E to calculate the shortwave equivalent irradiance (W_{SW}), $W_{\mathrm{SW}} = W_{\mathrm{LW}}E$. Next we multiply W_{SW} by $\mathrm{RS_{bb}}$ to calculate ΔV, as shown in Eq. (3); W_{SW} is multiplied by

TABLE 1. Temperature plateaus for the pyranometer calibration in the blackbody system.

Blackbody temperature (°C)	Case temperature (°C)	$T_{\mathrm{bb}} - T_{\mathrm{c}}$ (°C)	$W_{\mathrm{NET}} = W_{\mathrm{bb}} - W_c$ (W m^{-2})
−35	−5	−30	−110.8
−20	−5	−15	−60.3
−20	10	−30	−131.6
−5	10	−15	−71.3
10	25	−15	−83.6

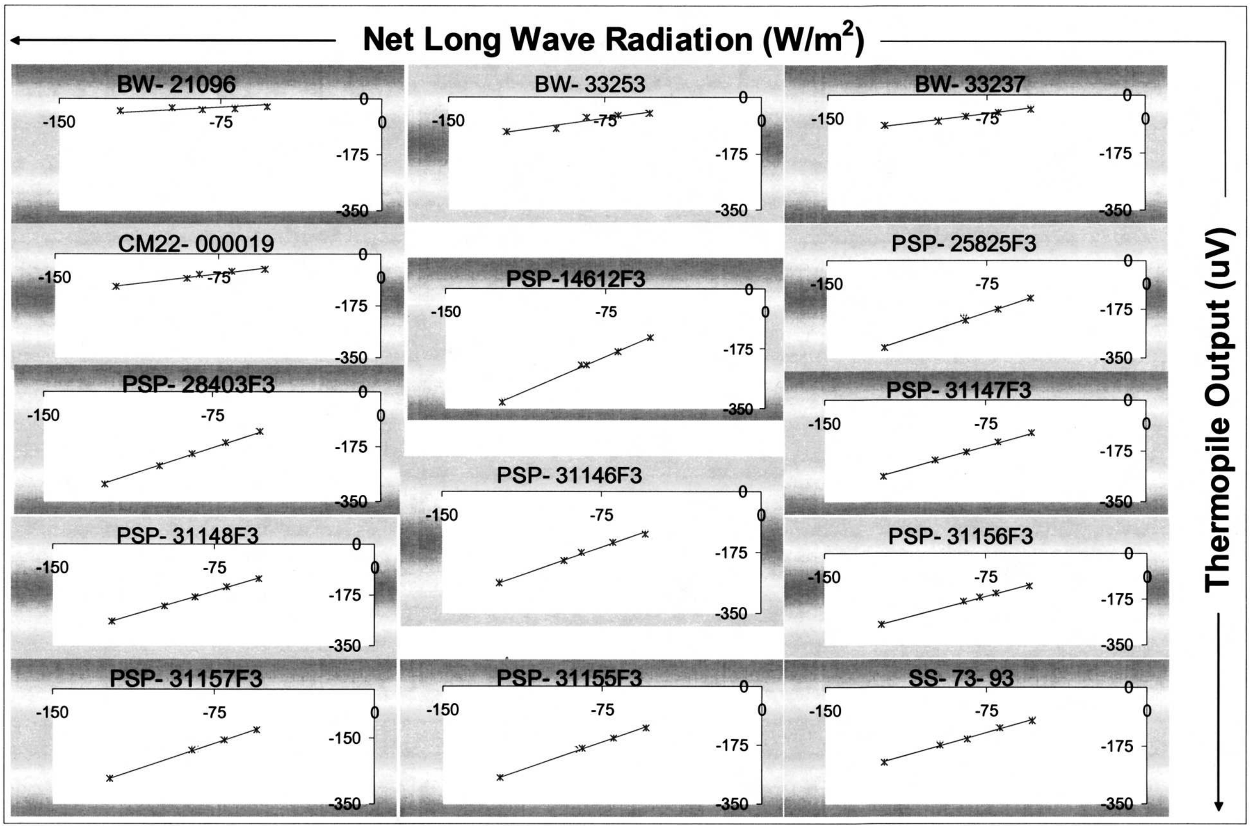

FIG. 2. Thermopile voltage vs NET-IR during the BBS calibration.

$\mathrm{RS_{bb}}$ rather than $\mathrm{RS_{SW}}$ because ΔV is the result of the pyranometer response to W_{LW} rather than W_{SW}:

$$\Delta V = W_{\mathrm{LW}} E \mathrm{RS_{bb}} = W_{\mathrm{LW}} \mathrm{RS_{NET}}, \tag{3}$$

where $\mathrm{RS_{NET}}$ is defined as the NET-IR responsivity of a pyranometer and equals $E\mathrm{RS_{bb}}$.

Table 2 is a list of the results of all pyranometers that were calibrated in the BBS. Table 2 shows that $\mathrm{RS_{NET}}$ for the 13 PSPs with the highest serial numbers (30000 series) is almost the same (average is 0.56 with a percentage standard deviation of 2%), while for lower serial numbers $\mathrm{RS_{NET}}$ is larger. This implies that, in the absence of a BBS, one might be able to use a fixed $\mathrm{RS_{NET}}$ for a pyranometer that has a serial number that is in the range of these serial numbers. This requires further evaluation for different manufacturers, models, and serial numbers. Also, $\mathrm{RS_{NET}}$ for models 8-48 and CM22 is less than 0.1 μV/(W m^{-2}), which is <1/6 that of models PSP and SR-75. This implies that the 8-48 and CM22 have approximately one-sixth the thermal offset error of a PSP or one-fourth the thermal offset error of the SR-75 (i.e., if the PSP had 12 W m^{-2} error, the 8-48 and CM22 would have less than 2 W m^{-2} error).

From the PSP sample in Table 2, there is a PSP, serial number 33852F3, that is fitted with a case thermistor. This pyranometer $\mathrm{RS_{NET}}$ is 0.608, which is 8.6% larger than the average of the 13 PSPs with the highest serial numbers. This error might be attributed to the case temperature being measured at the aluminum plate for the 12 other pyranometers. The thermal offset error for a PSP at NREL site can reach -20 W m^{-2} during the calibration conditions; thus an error of 8.6% in $\mathrm{RS_{NET}}$ would result in -1.7 W m^{-2} error. For an irradiance level of 1000 W m^{-2} during calibration, the -1.7 W m^{-2} error might result in 0.17% error in calculating the responsivity. From this and from what will be shown in section 4a (that the average error that resulted from correcting the component sum = 0.18% for PSPs), we demonstrate that using the aluminum plate temperature instead of the PSP case temperature contributes a small error during the pyranometer calibration.

3. Using $\mathrm{RS_{NET}}$ to correct for the thermal offset error during the outdoor pyranometer calibration

As mentioned in the introduction, pyranometers can be calibrated outdoor using two popular methods, the

TABLE 2. The blackbody system calibration results. Average RS_{NET} for the 13 PSPs with highest S/N = 0.56 and standard deviation = 2%.

Model-serial number	RS_{bb}	$*R^2$	SW/net equiv. (E)	$RS_{NET} = RS_{bb}E$	RS_{mfr}
BW-21096	0.363	0.9109	0.033	0.012	12.05
BW-33253	0.8894	0.8834	0.097	0.087	9.13
BW-33273	0.7734	0.9872	0.079	0.061	9.80
M22-000019	0.8872	0.972	0.096	0.085	9.30
PSP-14612F3	2.6591	0.9975	0.267	0.710	9.93
PSP-25825F3	2.5076	0.9951	0.256	0.642	9.75
PSP-28403F3	2.3824	0.9992	0.265	0.630	8.97
PSP-31146F3	2.1232	0.9946	0.262	0.557	8.13
PSP-31147F3	2.1278	0.9988	0.258	0.548	8.22
PSP-31148F3	2.1707	0.9992	0.263	0.572	8.24
PSP-31149F3	2.1804	0.9971	0.250	0.545	8.72
PSP-31150F3	2.2126	0.9997	0.259	0.573	8.54
PSP-31151F3	2.1726	0.9995	0.261	0.566	8.34
PSP-31155F3	2.2002	0.9966	0.261	0.574	8.47
PSP-31156F3	2.188	0.9974	0.262	0.573	8.37
PSP-31157F3	2.2046	0.9980	0.258	0.568	8.56
PSP-31158F3	2.1800	0.9996	0.252	0.549	8.66
PSP-31159F3	2.1433	0.9971	0.253	0.543	8.46
PSP-31160F3	2.2045	0.9923	0.251	0.554	8.77
PSP-33852F3**	2.2183	0.999	0.274	0.608	8.1
SS-73–93	1.8151	0.9962	0.209	0.379	8.69

* Goodness of the fit.

** Fitted with a case thermistor to measure body temperature T_c.

component sum and the shade/unshade. The two methods with their corresponding thermal offset correction are described as follows.

a. Component sum method

In the component sum method, the pyranometer is calibrated unshaded during clear-sky conditions. The responsivity RS_{SW} during the calibration is calculated as (ASTM 1993, section 14; ISO 1993),

$$RS_{SW} = \frac{U}{G_{ref}} = \frac{U}{N\cos z + D}, \tag{4}$$

where U is thermopile output during the component sum (unshaded) calibration (in μV), G_{ref} the reference SW global irradiance (in W m^{-2}) calculated from the beam and diffuse irradiance, N the beam irradiance (in W m^{-2}) measured by an absolute cavity radiometer, z the solar zenith angle (in °), and D the reference diffuse irradiance (in W m^{-2}) measured by a shaded pyranometer that has negligible thermal offset error.

To correct for the thermal offset error during the component sum method calibration, ΔU is calculated using Eq. (3); thus Eq. (4) yields

$$RS_{SW} = \frac{U - \Delta U}{N\cos z + D}. \tag{5}$$

b. Shade/unshade method

In the shade/unshade method, the pyranometer is unshaded, then shaded for a specific period of time, then the RS_{SW}, in [μV (W m^{-2})$^{-1}$] is calculated as

$$RS_{SW} = \frac{U - S}{N\cos z}, \tag{6}$$

where S is the thermopile output (in μV) during the shade period (Reda et al. 2003).

To account for the thermal offset error Eq. (6) is rewritten as

$$RS_{SW} = \frac{(U - \Delta U) - (S - \Delta S)}{N\cos z}, \tag{7}$$

where ΔU and ΔS are the thermopile thermal offset error during the unshade and shade periods, consecutively. From the time when the pyranometer is unshaded to the time when it is shaded, the NET-IR change would be negligible because the calibration is usually performed during stable clear-sky conditions. Thus ΔU would be approximately equal to ΔS, so they cancel in the numerator of Eq. (7) (Philipona 2002).

4. Correction method validation

To validate this correction, we used two validation methods. First, we compared RS_{SW} calculated from the shade/unshade method to the one calculated from the corrected component sum method. Second, we compared the calculated daytime net responsivity (DT-RS_{NET}) from the global irradiance thermal offset error to the BBS responsivity (BBS-RS_{NET}). As described below, we show from the first method that the calculated RS_{SW} using the corrected component sum method is consistent and comparable to the responsivity calculated using the shade/unshade method. And from the second method, we show that the DT-RS_{NET} is comparable to the BBS-RS_{NET}.

a. Comparing RS_{SW} from the shade/unshade method to the uncorrected and corrected component sum method

We calibrated 11 unventilated radiometers outdoors using the shade/unshade and the component sum methods. The sample consisted of three different models that were calibrated in the BBS: 7 EPLAB PSPs, 3 EPLAB 8-48s, and 1 Kipp & Zonen CM22. During the calibration we measured the NET-IR using a collocated shaded EPLAB pyrgeometer model Precision Infrared Radiometer (PIR). From the NET-IR we calculated the thermal offset error (ΔU) for each pyranometer using Eq. (3) and its RS_{NET} from Table 2. We then

TABLE 3. Responsivity using the shade/unshade and uncorrected and corrected component sum methods.

						Percent error	
Model-serial number	z (°)	NET-IR (W m^{-2})	RS_{SU}	RS_{UCS}	RS_{CCS}	$RS_{SU} - RS_{UCS}$	$RS_{SU} - RS_{CCS}$
B&W-21096	36.1	−177.9	11.500	11.552	11.554	−0.45	−0.47
B&W-33253	36.1	−177.9	8.736	8.758	8.777	−0.25	−0.46
B&W-33273	36.1	−177.9	9.379	9.381	9.394	−0.01	−0.16
Percent rmse for the B&W sample						0.09	0.15
CM22-000019	31.2	−168.1	9.350	9.311	9.326	0.42	0.25
PSP-28403F3	36.1	−177.9	8.722	8.589	8.725	1.52	−0.04
PSP-31146F3	31.2	−168.1	7.975	7.861	7.966	1.43	0.11
PSP-31147F3	36.1	−177.9	7.920	7.807	7.927	1.42	−0.09
PSP-31148F3	31.2	−168.1	7.971	7.860	7.970	1.39	0.01
PSP-31155F3	31.2	−168.1	8.203	8.095	8.205	1.31	−0.03
PSP-31156F3	31.2	−168.1	8.102	7.956	8.066	1.81	0.45
PSP-31157F3	31.2	−168.1	8.169	8.060	8.171	1.33	−0.03
Percent rmse for the PSPs sample						1.47	0.18

calculated the responsivity using the component sum method with ΔU correction using Eq. (5).

In Table 3, we list the calculated responsivity of each pyranometer, using the shade/unshade (SU), and uncorrected and corrected component sum methods (UCS and CCS). To eliminate the zenith angle response error, we calculated the responsivities at specific zenith angles that are listed, for each pyranometer, in the second column of Table 3. Each zenith angle was calculated as the average of the last three 1-s readings of the unshaded period of each pyranometer (Reda et al. 2003). The table is an example of the difference between different calibration methods at a specific z. From the table, one can notice that for the PSP sample, the root-mean-square error (rmse) of the calculated responsivity has decreased from 1.47% to 0.18% by applying the thermal offset correction to the responsivity that is calculated using the component sum method. The rmse, for all results, is calculated taking the shade/unshade method as the correct responsivity. Also, the rmse for the model 8-48 sample has changed, insignificantly, from 0.09% to 0.15%, and for model CM22 the error decreased from 0.42% to 0.25%.

Although small, the difference between the calculated responsivity using the shade/unshade method and those from the corrected component sum method might be attributed to the following.

1) The shade/unshade method may not be ideal because it is assumed that the shaded and unshaded responsivities are equal (Reda et al. 2003). In reality, the responsivity during the shade period is dependent on the diffuse sky energy distribution, while it will depend mostly on the sun's zenith and azimuth angles during the unshade period (Reda et al. 2003). This will contribute some error in the shade/unshade method.
2) There may be a correction to the thermal offset error resulting from the NET-IR difference during the unshade and shade periods. The NET-IR difference might be attributed to the following.
    - The fact that the NET-IR must be calculated at the pyranometer detector surface (Detector NET-IR) and would equal the difference between the sky radiation (i.e., dome) and the detector surface radiation, rather than the pyranometer case (body) radiation (Reda et al. 2002). During the unshade period the thermopile output is much greater than that during the shade period; thus the detector surface temperature is greater than that during the shade period. Because the sky is cold during clear sky conditions (e.g., approximately −10° to −30°C for NREL location), the Detector NET-IR would be greater (i.e., more negative) during the unshade period than during the shade period. The Detector NET-IR difference during the unshade and the shade periods would result in ΔU being greater, in absolute value, than ΔS; how much greater is not evaluated thoroughly and requires further research for different types of thermopile. Preliminary results show that the responsivity of PSPs would increase by approximately 0.2%.
    - The effect of the sun disc longwave radiation being shaded and unshaded during the shade/unshade calibration. The longwave radiation (2.8–50 μm) in the sun disc equals 1.5 W m^{-2}, at Solar Radiation Research Laboratory (SRRL) location at zenith angle 37° on 14 April 2004, using

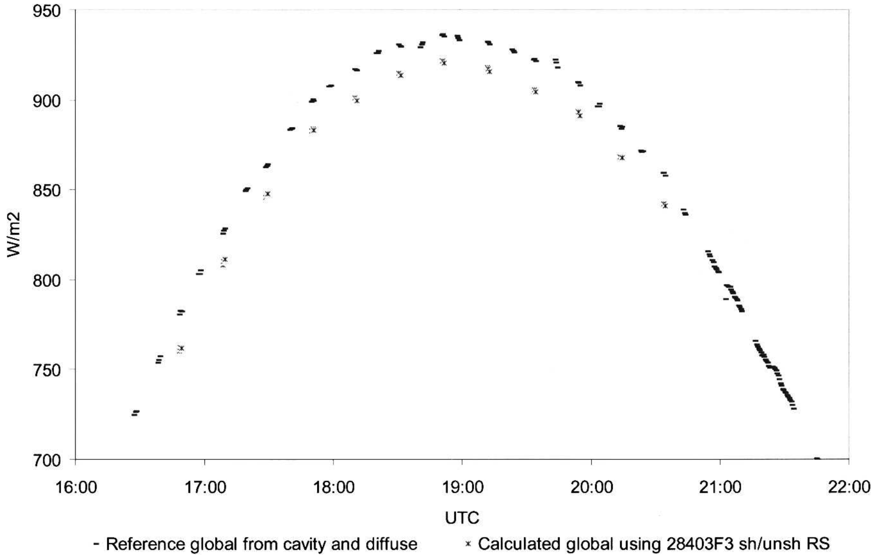

FIG. 3. The reference global irradiance vs the global calculated using 28403F3 shade/unshade RS.

MODTRAN4 (Anderson et al. 1999). For an RS_{NET} of 0.5 μV (W m^{-2})$^{-1}$, the 1.5 W m^{-2} error in IR causes an error of $0.5 \times 1.5 = 0.75$ W m^{-2} shortwave error. This might cause a 0.08% error in the calculated responsivity (for a 1000 W m^{-2} irradiance level).

3) For the EPLAB model 8-48, there might be minor errors resulting from the quality, consistency, and spectral response of the black and white paint.
4) There may be small errors in the blackbody calibration of pyranometers resulting from the fact that their case temperature is not exact. Because typical pyranometers do not have case thermistors, their case temperature is measured at the aluminum plate rather than the case during the BBS calibration.
5) There may be small errors resulting from the nonideal cutoff wavelength (2.8 μm) of the pyranometers quartz dome, which might allow some longwave radiation, with wavelength greater than 2.8 μm, to be transmitted to the detector.
6) There may be small errors resulting from the effect of the environmental conditions, for example, wind speed, wind direction, temperature, humidity, pressure, etc.

b. *Comparing the daytime and blackbody system net responsivities (DT-RS_{NET} and BBS-RS_{NET})*

We calibrated one PSP (serial number 28403F3) using the shade/unshade method. In this method the sampling rate was one reading per second, the zenith angle and the shade and unshade voltages were calculated as the average of three readings at the end of the unshade period. The shade voltage, of the pyranometer being calibrated, was calculated at the end of the unshade period using a control pyranometer that was shaded during the shade and unshade periods. This method is described in detail in Reda et al. (2003), where the shade voltage at the end of the unshade period is calculated using the voltage ratio of the control pyranometer to the pyranometer being calibrated. We then used the resultant RS_{SW} at each individual zenith angle to calculate the global solar irradiance (G). To eliminate the cosine response error of the radiometer we, simultaneously, measured the reference global irradiance (G_{ref}) with an absolute cavity radiometer and a shaded pyranometer, and applied the component sum equation, $G_{ref} = N \cos z + D$, where N was measured by the cavity and D was measured using a shaded 8-48 that has a negligible thermal offset error. The cavity was traceable to the World Radiometric Reference (WRR), and the 8-48 was calibrated using the shade/unshade method with traceability to WRR (Reda et al. 2003). During data collection we also measured the NET-IR (W_{LW}) using a collocated shaded pyrgeometer, EPLAB model PIR.

In Fig. 3, we show that G_{ref} is always greater than G from sunrise to sunset for all zenith angles. Because G is calculated by using the correct RS_{SW} (from the shade/unshade calibration), the difference between G_{ref} and G must be attributed to the thermal offset error signal. Therefore, we calculated the daytime RS_{NET} of the pyranometer as follows:

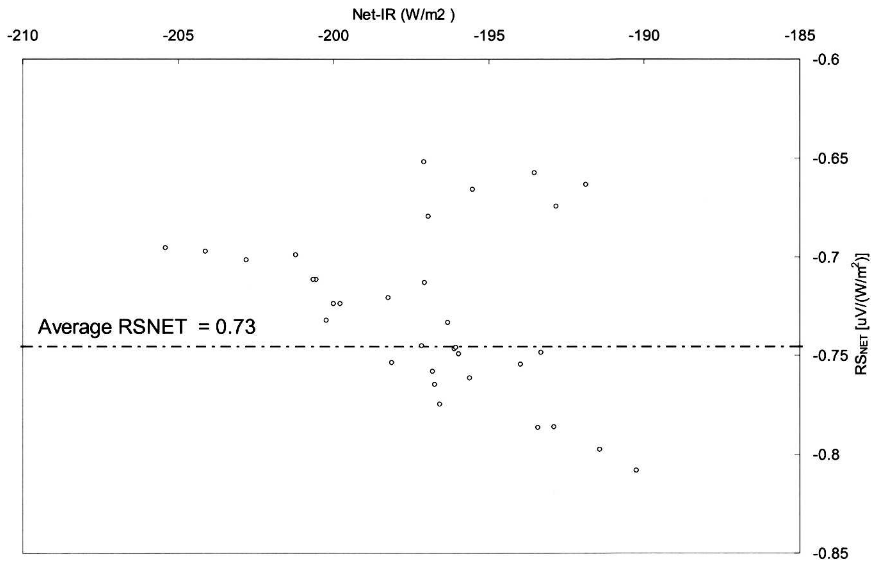

FIG. 4. Calculated $\mathrm{RS}_{\mathrm{NET}}$ from reference global irradiance minus calculated global using 28403F3 shade/unshade RS.

$$\Delta G = G_{\mathrm{ref}} - G. \tag{8}$$

Then

$$\Delta U = \Delta G \mathrm{RS}_{\mathrm{SW}}. \tag{9}$$

Then

$$\text{daytime } \mathrm{RS}_{\mathrm{NET}} = \frac{\Delta U}{W_{\mathrm{LW}}}, \tag{10}$$

where W_{LW} is measured by the pyrgeometer during the data collection.

From Fig. 4, note that the average daytime $\mathrm{RS}_{\mathrm{NET}} = 0.73$ with a range between 0.65 and 0.80. This implies that using the blackbody system $\mathrm{RS}_{\mathrm{NET}}$ (0.63 for PSP-28403F3, from Table 2) would result in a comparable value to the daytime $\mathrm{RS}_{\mathrm{NET}}$. The difference between daytime $\mathrm{RS}_{\mathrm{NET}}$ and the blackbody system $\mathrm{RS}_{\mathrm{NET}}$ may be due to other environmental conditions that can af-

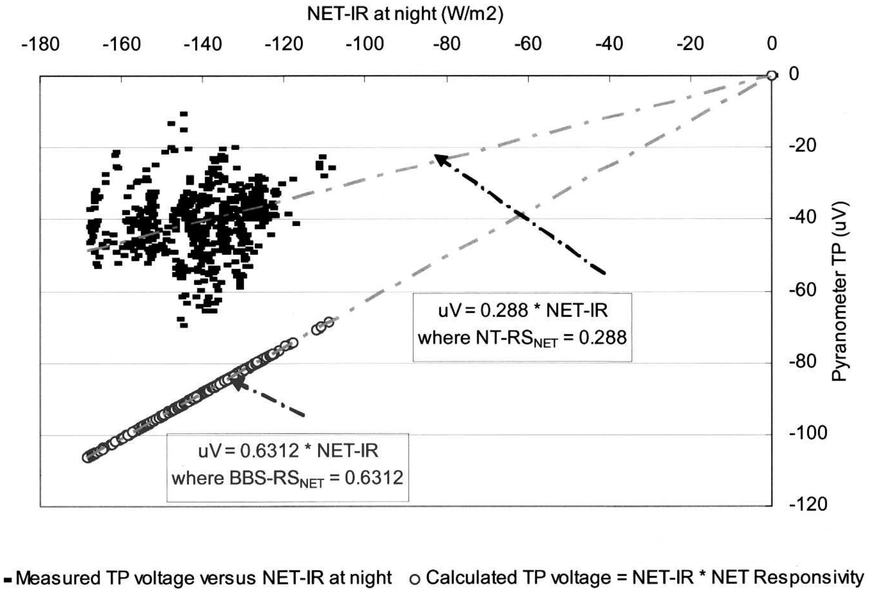

FIG. 5. The $\mathrm{RS}_{\mathrm{NET}}$ calculated from the nighttime and from the BBS calibration.

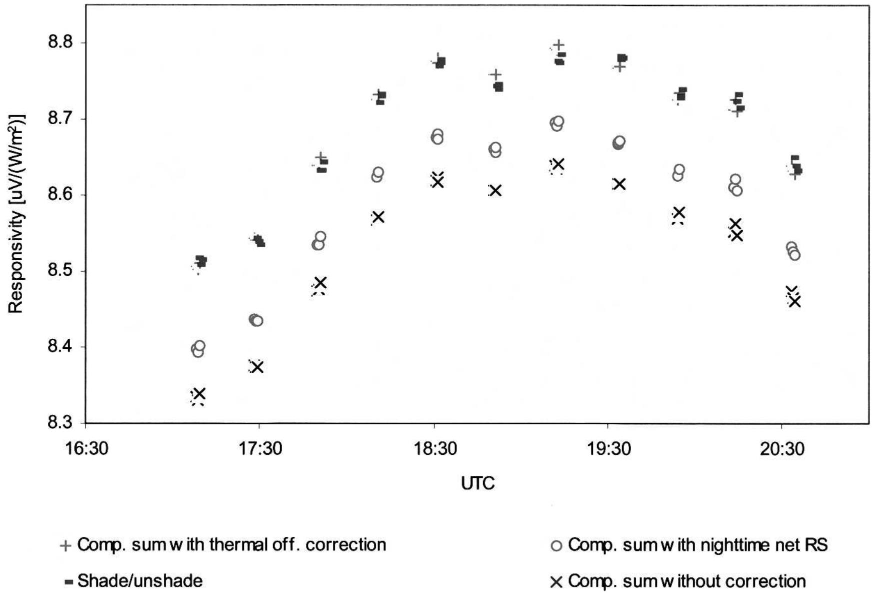

FIG. 6. The RS_{SW} for PSP-28403F3 using different calibration methods.

fect the pyranometer dome temperature outdoor (i.e., wind speed, humidity, pressure, etc.), or to the issue discussed in section 4a(2), where the Detector NET-IR is calculated using the temperature of the detector surface instead of the case for the outgoing radiation calculation.

It is noteworthy at this point to mention that pyranometer users have been using the correlation between nighttime pyranometer thermopile signal and the NET-IR, which results in a nighttime net responsivity that is applied during the day to correct for the thermal offset error (Dutton et al. 2001). This method does not fully correct that error (Dutton et al. 2001; Younkin and Long 2004). From Fig. 5, it is shown that the blackbody system RS_{NET} is almost double the magnitude of the nighttime RS_{NET} for the pyranometer, which suggests that there is a difference between the daytime and nighttime pyranometer response to the NET-IR, possibly due to the effect of the solar radiation on the atmospheric constituents during the daytime. This requires further research beyond the scope of this article.

In Fig. 6, we show the results of calibrating PSP-28403F3 using the shade/unshade, the uncorrected component sum, the corrected component sum using the BBS-RS_{NET}, and the corrected component sum using the NT-RS_{NET}. The calibration was performed for 3 h around solar noon on 14 April 2004. We show in the figure, at each zenith angle, that using the BBS-RS_{NET} to correct for the thermal offset error makes the component sum responsivity agree with the shade/unshade responsivity, while using the NT-RS_{NET} results in $<60\%$ of the correction.

5. Conclusions

The results demonstrate that correcting the component sum method to calculate the pyranometer responsivity, using the blackbody net responsivity to correct for the thermal offset error, gave a comparable responsivity to that using the shade/unshade method. The illustrated correction method resulted in reducing the difference between the component sum and shade/unshade methods from 1.47% to 0.18% for model PSP and 0.42% to 0.25% for CM22. The 8-48 difference increased from 0.09% to 0.15%, but this is negligible. Even though these differences are small after the correction, they might be attributed to calculating the NET-IR as the difference between the sky and pyranometer case radiation, rather than the difference between the sky and detector surface radiation.

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