A New Method for Calibrating Reference and Field Pyranometers

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ABSTRACT

A simple method for calibrating reference pyranometers is described. Called the alternate method, it requires monitoring of direct irradiance and diffuse and global irradiance voltages without the need for a calibrated diffuse pyranometer. The method involves alternately using each of the pyranometers for monitoring diffuse and global irradiance voltages and then solving pairs of simultaneous equations for each available zenith angle, where the only unknowns are the directional responses of the pyranometers being calibrated. Results from models and field calibrations show that the uncertainties of the alternate method are less than 1% for solar zenith angles less than 75° and are equal to or better than those determined from the composite method under identical conditions. The new method calibrations are also in good agreement with sun-disk method calibrations. It is argued that by using the alternate method for on-site field calibrations the uncertainties in network measurements can be reduced.

1. Introduction

The need for high quality solar irradiance and exposure observations in the Global Atmosphere Watch [World Meteorological Organization (WMO) 1991a] and the Baseline Surface Radiation Network (BSRN) (WMO 1991b) has promoted further examination of the methods used to calibrate pyranometers. For routine high quality and accurate irradiance data within the BSRN program, measurements of diffuse, direct, and global irradiance are mandatory, as these three measurements provide closure of the measurement system. Field calibrations of the instruments are also preferred to reduce data uncertainties.

This paper describes a simple technique for the pyranometer calibration either in the field or at a calibration center and removes the need for a reference diffuse pyranometer. The new method requires typical field measurements of global, diffuse (both from pyranometers), and direct (pyrheliometer) sensor voltages in clear sun conditions, and the pyrheliometer irradiances having traceability to the World Radiometric Reference (WRR). It will be shown that the new method, called the alternate method because it alternates the type of measurements of the two pyranometers, can provide uncertainties equal to or less than the composite method for the determination of the directional response (WMO 1995). By using sufficient care during its implementation, the new method has little impact on routine monitoring of solar irradiance components.

Calibrations of pyranometers are currently performed by either using a duplicate set of well-calibrated instrumentation and applying the composite method, or disrupting pyranometer measurements by using the sun-disk technique (WMO 1995). The former requires significant investment in additional instrumentation and careful instrument setup, while the latter can be labor intensive and a costly disturbance to the measurements. Both require an investment in time to ensure that an appropriate number of calibration points are obtained.

The composite method is WMO's preferred technique for calibrating field pyranometers (WMO 1995); it entails radiometer measurements during clear sky conditions of the direct solar irradiance E_{dir} with a reference pyrheliometer and the diffuse irradiance E_{sky} with a reference pyranometer, and then determining the ratio of the horizontal components to the voltage from the global pyranometer (V) being calibrated. That is, the irradiance-weighted response R [μV (W m^{-2})$^{-1}$] of the pyranometer at solar zenith angle ϑ_0 is given by

$$R(\vartheta_0) = \frac{V}{E_{\mathrm{dir}} \cos\vartheta_0 + E_{\mathrm{sky}}} \qquad (1)$$

and is an approximation of the directional response. In the composite method, the pyranometer is exposed to normal clear-sky operating conditions with no significant radiative transients and can be readily automated by using a shaded pyranometer and pyrheliometer with an appropriate solar tracking mount. However, it is impossible to use this technique without a calibrated pyra-

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nometer for measuring diffuse irradiance. A question then arises: How does one calibrate the first reference pyranometer for the measurement of diffuse or global irradiance?

The sun-disk technique is the method most cited for the calibration of reference pyranometers. This method requires the pyranometer to be shaded by a small disk and then exposed to global irradiance, while the direct beam irradiance is measured with a pyrheliometer. While simple in theory, this method has some difficulties: namely,

(i) the thermal shocks to the pyranometer as it is rapidly and frequently subjected alternately to global and then diffuse solar irradiance, and

(ii) the need for either an automated system or a labor intensive manually operated shading system.

Difficulty (i) can impact the uncertainty of the derived calibration coefficient for a number of reasons. First, the zero irradiance signal can fluctuate because of the thermal stresses and imbalances between dome and body heating. Second, the multiple time constants of the pyranometer can result in incorrect voltages (Kuhn 1973). Third, the rate of change of irradiances during the exposure and shading process can complicate the extrapolation and interpolation of appropriate signals and irradiances (Forgan 1979, 1984).

The difficulties associated with (ii) can severely limit the frequency and number of calibration points. Automatic systems typically require two tracking systems and complex algorithms, while manual systems are time consuming and increase the uncertainty through inherent repeatability problems. Laboratory methods, using nonsolar sources could also be used, but these methods introduce other problems associated with relating a source to a detector based solar radiation standard (the WRR). It will be shown that the new method provides a useful calibration without either complexity or the need for an array of additional equipment.

2. Alternate method

a. *Theory—For an ideal pyranometer*

On a clear-sky day the irradiance signal V from a pyranometer subjected to a 2π-sr field of view (having zenith angle ϑ, and azimuth φ) with radiance distribution $L(\vartheta, \varphi)$ and having directional response function $R(\vartheta, \varphi)$ is given by

$$V = \iint R(\vartheta, \varphi) L(\vartheta, \varphi) \cos(\vartheta) \sin(\vartheta) d\vartheta d\varphi, \quad (2)$$

which in turn can be separated into two components, namely, the intense horizontal direct beam (V_{dir}) and diffuse sky (V_{sky}) irradiance signal components given by

$$V_{\mathrm{dir}} = \cos(\vartheta_0) E_{\mathrm{dir}} R(\vartheta_0, \varphi_0) \quad (3)$$

and

$$V_{\mathrm{sky}} = \iint_{\mathrm{sky}} R(\vartheta, \varphi) L(\vartheta, \varphi) \cos(\vartheta) \sin(\vartheta) d\vartheta d\varphi. \quad (4)$$

The sky (or diffuse) irradiance is given by

$$E_{\mathrm{sky}} = \iint_{\mathrm{sky}} L(\vartheta, \varphi) \cos(\vartheta) \sin(\vartheta) d\vartheta d\varphi \quad (5)$$

and can also be expressed as

$$E_{\mathrm{sky}} = \frac{V_{\mathrm{sky}}}{R_{\mathrm{sky}}}, \quad (6)$$

where R_{sky} is the diffuse irradiance response. For an ideal pyranometer, R is constant for all directions, and hence, R_{sky} is equal to R for all sky radiance distributions.

The direct irradiance is measured for two periods: A and B. In period A, pyranometer 1 is shaded and produces a diffuse sky signal and pyranometer 2 is exposed to global irradiance. In period B, pyranometer 1 is exposed to global irradiance and pyranometer 2 is exposed to diffuse sky irradiance. The global irradiance for period A at solar zenith angle $\vartheta_{0\mathrm{A}}$ can be expressed as

$$\frac{V_{\mathrm{A2}}(\vartheta_{0\mathrm{A}})}{R_2} = E_{\mathrm{dirA}} \cos(\vartheta_{0\mathrm{A}}) + \frac{V_{\mathrm{A1}}(\vartheta_{0\mathrm{A}})}{R_1}, \quad (7)$$

where $V_{\mathrm{A2}}(\vartheta_{0\mathrm{A}})$ is the global irradiance signal from pyranometer 2 and $V_{\mathrm{A1}}(\vartheta_{0\mathrm{A}})$ is the diffuse irradiance signal from pyranometer 1. A similar equation can be written for period B: namely,

$$\frac{V_{\mathrm{B1}}(\vartheta_{0\mathrm{B}})}{R_1} = E_{\mathrm{dirB}} \cos(\vartheta_{0\mathrm{B}}) + \frac{V_{\mathrm{B2}}(\vartheta_{0\mathrm{B}})}{R_2}. \quad (8)$$

Hence, there are pairs of simultaneous equations with the two unknowns R_1 and R_2, which are the responsivities for pyranometers 1 and 2, respectively. If period A was composed of a set of observations at m solar zenith angles for the three required parameters, and if during period B there were a set of observations at n solar zenith angles, it would be possible to solve for $m \times n$ pairs of simultaneous equations and therefore be able to produce significant statistics.

b. *The method for nonideal pyranometers*

Unfortunately, pyranometers do not have ideal directional response, and it is unlikely that $R(\vartheta, \varphi)$ is equivalent to R_{sky} for all but a few special cases. Hence, (7) and (8) are no longer valid. In this case the response terms in (7) and (8) are replaced with irradiance-weighted responses for both the global and diffuse components. The practical implementation of the alter-

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nate method is to substitute the R_i terms with weighted directional responses such that

$$\frac{V_{A2}(\vartheta_{0A})}{R_2'(\vartheta_{0A})} = E_{dirA}\cos(\vartheta_{0A}) + \frac{V_{A1}(\vartheta_{0A})}{R_1'(\vartheta_{0B})} \qquad (9)$$

and

$$\frac{V_{B1}(\vartheta_{0B})}{R_1'(\vartheta_{0B})} = E_{dirB}\cos(\vartheta_{0B}) + \frac{V_{B2}(\vartheta_{0B})}{R_2'(\vartheta_{0A})}, \qquad (10)$$

where $R_2'(\vartheta_{0A})$ is the weighted directional response for pyranometer 2 for solar zenith distance θ_{0A} in period A and $R_1'(\vartheta_{0B})$ is the weighted directional response for pyranometer 1 for solar zenith distance θ_{0B} in period B. In clear-sky conditions, the two global signals V_{A2} and V_{B1} will be dominated by large direct irradiances for the majority of zenith angles. It will be shown that the impact of the approximations for diffuse responsivities in (9) and (10) is minimal for a wide range of zenith angles, and pyranometer types and the derived responses are good approximations of the true directional responses.

A further restriction was imposed on the practical implementation of the method to fix the representativeness of the solution, reduce the impact of irradiance ratios, and enable long-term monitoring of the stability of pyranometer pairs. As with the example of using ideal pyranometers, it is possible to generate $m \times n$ pairs of simultaneous equations, with the range in derived responses for a particular zenith distance and pyranometer dependent on the irradiance ratios, radiance distributions, and the true pyranometer directional responses. The restriction was to choose one pair of equations for each solar zenith distance, such that the pair gave the minimum $|\vartheta_{0A} - \vartheta_{0B}|$. This restriction was imposed on the analyses presented below.

The measurements required to implement the new method could be carried out over a single day of relatively clear skies, or on multiple days. For the case of a single clear-sky day, the clear-sky direct irradiance is measured continuously with a well-calibrated pyrheliometer. Pyranometer 2 would be exposed to global irradiance and pyranometer 1 to diffuse sky irradiance from dawn to solar noon; then the instruments would be alternated in function so that pyranometer 1 is exposed to global irradiance and pyranometer 2 to diffuse sky irradiance for the remainder of the day. In the case of multiple days, pyranometers 1 and 2 could be exposed for one day in one configuration and on another day in the alternate configuration (and if swapped after sunset will cause little disruption to solar irradiance data collection).

3. Results

To test the practical implementation of the alternate method, field measurements and modeling experiments were performed. Given the type of data required for the alternate method, it was possible to use the same data to calibrate each pyranometer by the composite method after the initial calibration. This was done both for the model and field experiments by using the mean responses derived from the alternate method in the zenith range of 35°–55° to represent the diffuse response in composite method analysis.

a. Modeling

The modeling experiments were performed by first calculating the irradiance components for several clear-sky periods from dawn to solar noon and then using these data with parameterizations of different pyranometer directional responses to calculate voltages. For simplicity, the sky radiance distribution was assumed to be isotropic when deriving the relevant model pyranometer voltages.

Given the nature of the alternate method, a very simple model for the magnitudes of the solar irradiance components was required. For period A, the direct beam to diffuse irradiance ratio was assumed to be 15 (as in a very clean atmosphere) and for period B it was assumed to be 9 (as in a moderately turbid atmosphere) for solar zenith angles up to 85°. The direct beam irradiance at a solar zenith angle of 5° was set at 1000 W m^{-2} and at 85° was 750 W m^{-2}; log-linear interpolation with air mass was used for determining the direct solar irradiance between the solar zenith angles of 5° and 85°.

Very simple models were used as analogs of pyranometer directional responses, and results from three modeled pyranometer responses (Pyr 1, Pyr 2, and Pyr 3) were used for the discussion below. The shapes of two pyranometer responses were based on simple approximations of the form

$$R(\vartheta) = 100\exp\left(\frac{\vartheta^3}{F}\right), \qquad (11)$$

where ϑ is zenith angle in degrees and F is a constant. For Pyr 2, $F = 5.5 \times 10^{+6}$, and for Pyr 3 $F = 11.5 \times 10^{+6}$. Pyr 3 approximated the relative directional response of a WMO (1995) first-class pyranometer. Pyr 1 was derived from response equations given by Nelson and Dutton (1994) for a typical National Oceanic and Atmospheric Administration network pyranometer.

The directional responses for the three pyranometer models are shown in Fig. 1. The percentage differences between the true and derived responses for the three possible combinations of model pyranometers using both the alternate and composite methods are shown in Figs. 2, 3, and 4. Figure 2 shows the calibration results for Pyr 1 using Pyr 2 (or Pyr 3) as the alternate pyranometer or the pyranometer used for diffuse irradiance in the composite method. Figures 3 and 4 show similar results for Pyr 2 and Pyr 3, respectively.

The alternate method gives results well within 1.5% for all zenith angles modeled and exceeds only 1.0%

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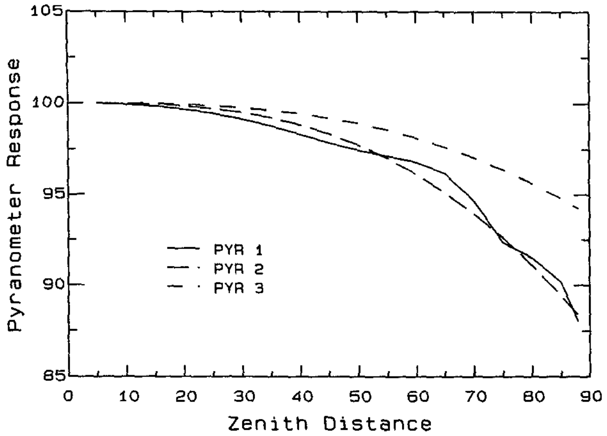

FIG. 1. The true relative directional responses of the three nonideal pyranometers (Pyr 1, Pyr 2, and Pyr 3) used in modeling the alternate method. Pyr 1 is derived from Nelson and Dutton (1994); details of the other responses are provided in the text.

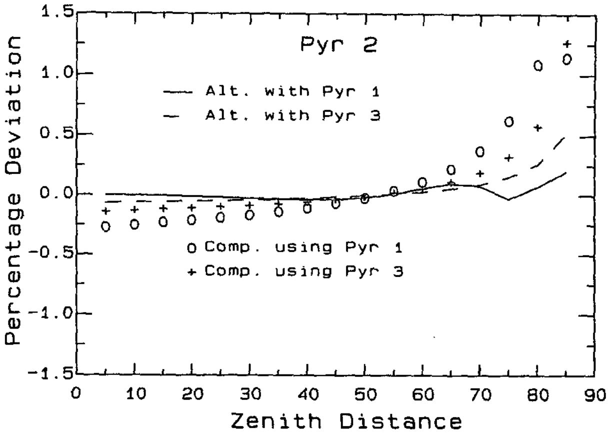

FIG. 3. Percentage deviations from the true directional response of alternate and composite method calibrations for the model pyranometer Pyr 2, using Pyr 1 or Pyr 3.

for the Pyr 3 and Pyr 2 combination at 85°. For all combinations of model pyranometer pairs, the percentage deviation is within 0.20% for zenith angles less than 75°. This is not surprising given that the solution for both coefficients at solar zenith angles less than 75° is dominated by the horizontal direct irradiance component. For higher and increasing solar zenith angles the diffuse sky calibration response contribution to the signal increases steadily as the ratio of diffuse sky irradiance to the horizontal direct component increases. Under turbid sky conditions this ratio can be greater than unity for solar zenith angles less than 80°.

In Table 1, statistics for the mean difference for the alternate and composite methods using model pyranometers and irradiances at 17 zenith angles between 5° and 85° (at 5° intervals) are given. The statistics are generated from the percentage differences between the true and resultant responses for both methods. The alternate and composite method statistics are similar only in the case of using Pyr 2 to calibrate Pyr 3. In all other cases the alternate method statistics have the smaller mean differences and sample standard deviations. For all six combinations, the alternate method mean differences are less than 0.09%, two of which are negative and four positive, and four out of six pairs are less than 0.05%. For the composite method, the mean differences are always positive and greater than 0.07%, with the highest mean difference of 0.18% for Pyr 2 calibrated with diffuse irradiances from Pyr 1. For five pyranometer pairs, the sample standard deviation from the composite method is higher than that from the alternate method.

The results indicate that the derived responses from a variety of pyranometer types produced excellent

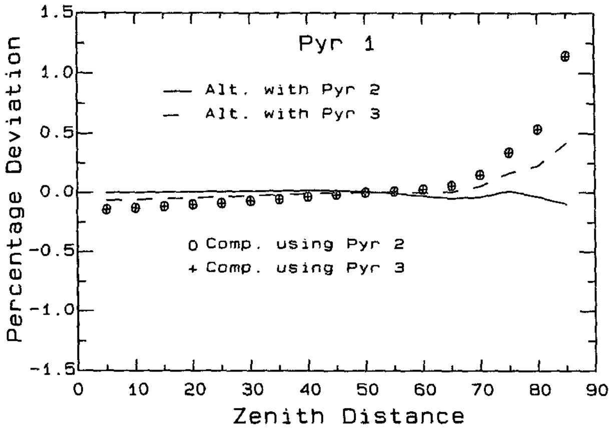

FIG. 2. Percentage deviations from the true directional response of alternate and composite method calibrations for the model pyranometer pair of Pyr 1, using Pyr 2 or Pyr 3.

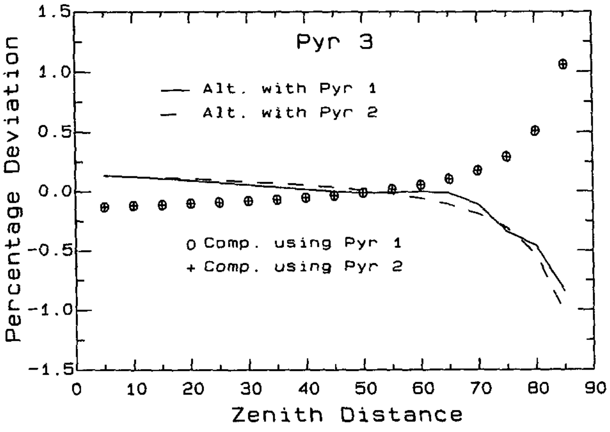

FIG. 4. Percentage deviations from the true directional response of alternate and composite method calibrations for the model pyranometer Pyr 3, using Pyr 1 or Pyr 2.

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TABLE 1. Comparison on differences between the true model responsivities derived from the alternate and composite method for model pyranometer pairs; also shown are the associated sample standard deviations (σ). All statistics are derived from percentage deviations from the true value. For the alternate method the column labeled "diffuse pyranometer" is the other pyranometer of the pair, while for the composite method it is the pyranometer supplying the reference diffuse irradiance.

		Alternate method		Composite method	
Pyranometer calibrated	Diffuse pyranometer	Mean (%)	σ (%)	Mean (%)	σ (%)
Pyr 1	Pyr 2	−0.01	0.03	+0.09	0.32
Pyr 1	Pyr 3	+0.03	0.13	+0.09	0.32
Pyr 2	Pyr 1	+0.02	0.06	+0.18	0.65
Pyr 2	Pyr 3	+0.04	0.15	+0.10	0.36
Pyr 3	Pyr 1	−0.07	0.26	+0.08	0.31
Pyr 3	Pyr 2	−0.08	0.30	+0.08	0.30

agreement between true and derived responses for zenith angles less than 75°, with uncertainties increasing at larger zenith angles when the pyranometer responses varied significantly at those zenith angles.

The results show that there were consistent trends in any errors versus direction. The reason for these trends is a result of the assumption that the diffuse sensitivity is equal to the angular sensitivity when solving the simultaneous equations. If $\partial R_{\mathrm{dir}}/\partial\theta$ for both pyranometers were negative but of different magnitude, the pyranometer with the highest $\partial R_{\mathrm{dir}}/\partial\theta$ overestimated R_{dir} for large zenith angles and underestimated for small zenith angles. The pyranometer with the smallest magnitude in $\partial R_{\mathrm{dir}}/\partial\theta$ showed opposite trends. Similarly if both pyranometers had positive $\partial R_{\mathrm{dir}}/\partial\theta$, the reverse applied. For the alternate method, these trends or biases from the true responses were typically less than 0.05% for all angular directions less than 75° for all the realistic model responses studied. Pyranometers with a greater absolute $\partial R_{\mathrm{dir}}/\partial\theta$ in directional response will typically have diffuse calibration coefficients (under isotropic radiance conditions) significantly different from the directional coefficients at zenith angles greater than 65°. Pyranometers with identical relative directional response, gave negligible (<0.001%) differences to the true values for all conditions. This is not surprising given that the impact of different magnitudes of directional response translates into a single constant.

In summary, the modeling results indicate that the alternate method will produce very good estimates of the pyranometer sensitivity over a wide range of zenith angles. Most importantly, the method's uncertainty is not affected to any significant degree by the variation of sensitivity with direction of the pyranometers' used, and therefore, the method can be used with the wide variety of pyranometer types. Hence, operational networks using pyranometers with moderate to poor directional responses should achieve similar sensitivity uncertainties to those using pyranometers with good to ideal directional responses.

b. Field calibrations

The calibration of pyranometers in the environment is impacted by a number of factors. The resolution of the data system, the instruments, and other environmental impacts (including nonisotropic radiance distributions) increase the uncertainties. To gauge the impact of these factors the method was tested in Melbourne, Australia (37°S), at the Bureau of Meteorology (BoM) ozone and radiation facility in March 1994, during relatively cloud-free sky conditions.

Two Kipp and Zonen CM11 pyranometers were set up for calibration by the alternate method over a period of 2 days (1 and 2 March 1994). The direct irradiance was measured by a Kipp and Zonen CH1 FT001 pyrheliometer on the BoM active solar tracking system, which also accommodated the shading disk for diffuse irradiance signal measurements used in the alternate method calibrations. Pyranometer CM11 882383 was mounted on the tracker in diffuse mode and CM11 882378 in global mode for the first afternoon and second morning's observations, and their modes were swapped at solar noon on the second day. A third pyranometer CM11 882380 that has a long history of sun-disk calibrations was also available, measuring diffuse irradiance for the majority of the observations but also global irradiance on two occasions to enable alternate method calibrations with the other two pyranometers. CM11 882380 acts as the reference diffuse pyranometer for the composite method calibrations of pyranometers by the BoM.

Unfortunately, it was not possible to provide both the diffuse and global pyranometers with the same field of view; the diffuse pyranometer was mounted on a tracking unit some 2 m below and 5 m north of the global pyranometer. The difference in the field of view affected the diffuse signals by amplifying them on average by 2%; this was corrected in the following analysis but was estimated to have impacted the results by less than ±0.3%.

Data were collected every 30 s using a digital voltmeter with 10-nV resolution, and 100-nV accuracy. Instrument zeros were determined at the beginning and end of the data collection periods as well as during the hours of darkness between 1 and 2 March 1994. For all pyranometers, the zeros were approximately −0.013 mV with a standard deviation of 0.002 mV; for the pyrheliometer the mean zero was −0.005 mV with a standard deviation of 0.001 mV. The sky conditions were not always (water droplet) cloud-free and, being in the center of an industrial and urban environment, were influenced by aerosol pollution clouds from midmorning. There was, however, no significant short-term variability in the attenuation of the direct solar beam during the period of the tests.

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The use of 1.5 days of data meant that both afternoon (day 1)–afternoon (day 2), and morning (day 2)–afternoon (day 2) data series could be used for the analysis, over a zenith range of between 30° and 77°. In addition, the composite method was used to calibrate the sensors by combining irradiances from the pyrheliometer and CM11 882380 in diffuse mode; over the zenith range of 30°–75°. The derived directional responses [μV (W m^{-2})$^{-1}$] using the alternate and composite methods for CM11 882383 are presented in Fig. 5 and for CM11 882378 in Fig. 6.

The alternate calibration results for CM11 882383 shown in Fig. 5 indicate minor absolute variation in response with zenith angle with a mean of 4.505 μV (W m^{-2})$^{-1}$ and a sample standard deviation of 0.13% of the mean. The responsivity of CM11 882383 increases with zenith angle, with the maximum deviation from the mean of about +1% for 77°, and for zenith angles less than 75°, the deviations from the mean are less than 0.5%. As expected from the theory, there are differences between the composite method results and those from the alternate method, with the largest equivalent to approximately 0.3% for a zenith angle of about 45°. For the same zenith angle, the alternate and composite method means differ by less than 0.1%.

In Fig. 6 the alternate and composite method results show a diurnal range in the directional response of CM11 882378 that is most likely the result of either poor correspondence between the radiometric (or true) level and that assumed from the leveling bubble on the instrument, or an azimuthal response. The maximum diurnal range for the alternate method of less than 1.7% occurs at a zenith angle of approximately 50°. The mean sensitivity is 4.418 μV (W m^{-2})$^{-1}$ with a sample standard deviation of 0.3%. As with CM11 882383, the results suggest that the sensitivity of CM11 882378 increases with zenith angle. There are systematic differences between the composite and alternate method results for CM11 882378, with the composite method results showing lower sensitivities by approximately 0.2%, with a maximum absolute differences between the two methods of 0.9% for zenith angles greater than 65°.

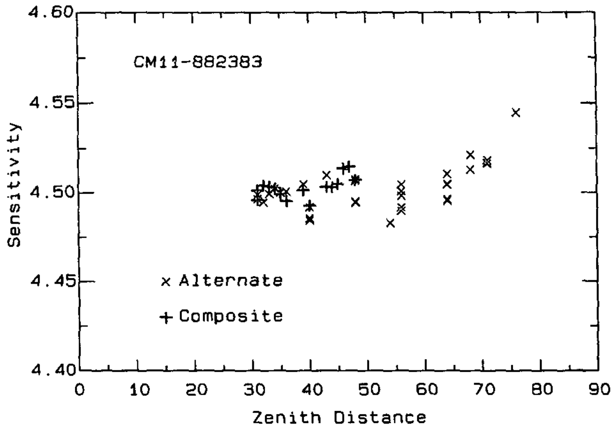

FIG. 5. Alternate and composite method calibration results [μV (W m^{-2})$^{-1}$] for Kipp and Zonen CM11 882383 based on data from 1 and 2 March 1994.

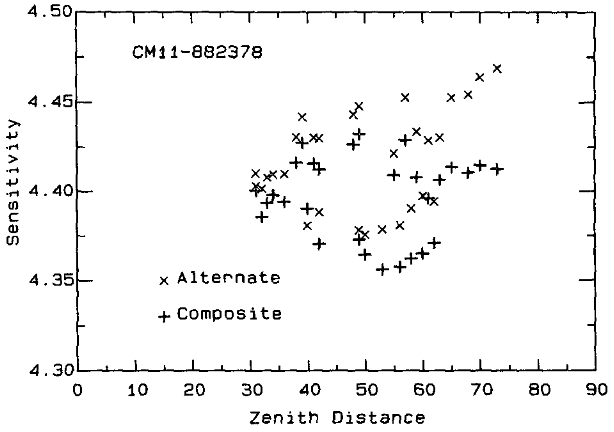

FIG. 6. Alternate and composite method calibration results [μV (W m^{-2})$^{-1}$] for Kipp and Zonen CM11 882378 based on data from 2 March 1994.

Such differences are not surprising since both the composite and alternate methods produce an irradiance-weighted directional response, not the true directional response. The alternate method uses a different diffuse calibration coefficient for each zenith angle, while the composite method uses a reference pyranometer with a fixed calibration coefficient for diffuse irradiance. Contributing to the differences are biases introduced by both methods.

The difference between the diffuse exposure for the global and diffuse pyranometers during the measurements is also responsible for some of differences in derived sensitivities, as the diffuse irradiances measured by CM11 882380 were essentially identical to that measured by the alternate method global pyranometer but different to those measured by the alternate method diffuse pyranometer. These errors are estimated to be less than ±0.3%.

Comparisons of the sun disk (for 3 days in 1992–93) and the alternate method results for CM11 882380 are given in Fig. 7. The total range of all the calibrations over a zenith range of 26°–73° is less than about 2%. The assumed mean sun-disk calibration for CM11 882380 is 4.46 μV (W m^{-2})$^{-1}$ and is biased to zenith angles in the range of 25°–50°. Only five zenith angles were available for this instrument's calibration by the alternate method because of the lack of data. The range of points shown at the five alternate method zenith angles represent multiple usage of the same zenith angles for a series of zenith angles available for the CM11 882378 and 882383 (ranging between 30° and 77°). Despite the wide (and inappropriate) zenith bounds used for the second pyranometer, the spread at 54° is

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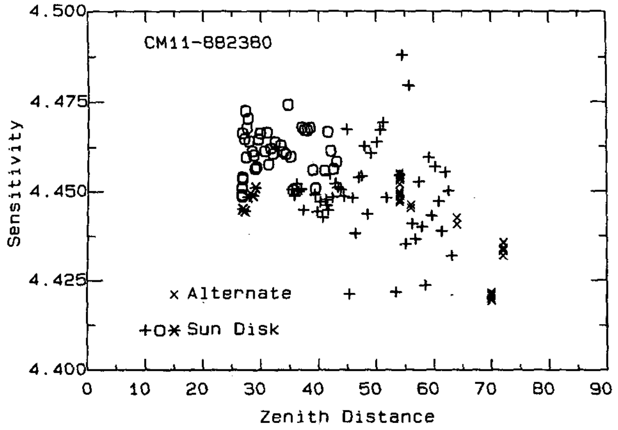

FIG. 7. Comparison of sun-disk and alternate-method-derived responses [μV (W m^{-2})$^{-1}$] for pyranometer Kipp and Zonen CM11 882380 at different zenith angles. Sun-disk results for 27 February 1992 (+), 22 October 1992 (O), and 11 November 1993 (*) are displayed with alternate method results for 2 February 1994 at zenith distances of 54°, 56°, 64°, 70°, and 73° (×).

less than 0.2%. The alternate method results (for 54°, 56°, and 64°) show good agreement with the sun-disk results, being centered in the 1.9% range of sun-disk results but with less variance. Considering that all the sun-disk calibrations were achieved using an active cavity radiometer well referenced to the WRR, while the alternate method used a less accurate thermopile radiometer, the agreement is excellent. Also evident is the similar trend of declining response with zenith angles greater than 55° in the results from both the sun-disk and the alternate methods.

The alternate method results were also compared to the original calibrations for the three pyranometers as supplied by the manufacturer, which included estimates of cosine response. The results were encouraging as the maximum deviation from the alternate method results was less than 0.2% for all zenith angles listed by the manufacturer.

4. Discussion

The modeling results and the practical examples show that the alternate method provides excellent estimates of directional response for zenith angles less than about 75° and show acceptable results for higher zenith angles. As noted in the alternate method modeling results, the variances and biases resulting from the alternate method are very low if the two pyranometers have similar relative directional sensitivity. This is not the case for the composite method as the highest mean difference and sample standard deviation resulted from the calibration of Pyr 2 using Pyr 1, with both pyranometer models approximating the responses of pyranometers used in radiation networks (Nelson and Dutton 1994; and Flowers 1981). The results presented in Table 1 also suggest that the alternate method would be an appropriate method for the calibration of two pyranometers with similar but moderate to poor relative directional responses.

The simplicity of the alternate method and its ease of operation make it ideal for the calibration of reference pyranometers. The initial focus of the development of the alternate method was to calibrate a reference pyranometer for use in composite method calibrations and remove any requirement for calibration by the sun-disk method. The alternate method has been shown to produce excellent agreement with independent sun-disk calibration results even when the limits of practical application are breached. At a site where the three components (global, diffuse, and direct beam) are monitored independently at a frequency of better than or equal to a minute mean, the calibration of the field pyranometers could be accomplished with little disturbance of the continuous record. After calibration of the data collection systems, a typical calibration process for a field site would be the following.

(i) Mount a traveling standard pyrheliometer(s) to the direct pyrheliometer mounting and take measurements from it in parallel with field pyrheliometer measurements.

(ii) Swap the diffuse for the global pyranometer either before sunrise or after sundown.

(iii) After a suitable period of comparison (ISO 1990, hereafter ISO 9059), remove the traveling standard pyrheliometer(s) from the field pyrheliometer mount.

Suitable clear-sky data, collected from the field instruments some days (or months) prior to and after the pyranometers are swapped, would provide the information required to use the alternate method and reference the pyranometers to the field pyrheliometer. The ISO 9059 field calibration of the pyrheliometer in the period when the pyranometers are swapped would provide the reference for all field instruments to the WRR.

Confidence in the range of directional responses for most observed zenith angles at the field site would increase if the swap of the pyranometers at the field location occurred at the time of the local summer solstice, when the diurnal range of zenith angles is greatest. The necessity for such timing of the pyranometer swap is critical if the pyranometers' cosine responses are poor.

The alternate method has been used to calibrate a 14-station Australian network during October–December 1994. Each station monitors global, diffuse, and direct irradiance with Kipp and Zonen radiometers, and the pyranometers were swapped during a routine station visit for the calibration of the data system and pyrheliometer. The station pyrheliometers were calibrated on site with a set of two traveling standard pyrheliometers that had maintained their calibrations to within ±0.1%. The resulting calibrations were within 0.5% of the original calibrations performed in 1993 for all pyr-

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heliometers and within 0.6% for all pyranometers with the majority deviating by less than 0.2%.

Removing instruments for calibration must increase the uncertainty as the calibration process will not duplicate the conditions during routine operation. The total uncertainty in the routine measurements is reduced by in situ field calibration using the alternate method.

5. Conclusions

The alternate method provides a very simple and robust means to calibrate a pyranometer, without the need of a previously well characterized and calibrated pyranometer. The accuracies obtained from the method are dependent on the angular response of the pyranometer pair being calibrated but are likely to be well within 1% of the radiometric reference supplied by the pyrheliometer for zenith angles less than 70° and of similar or better accuracy to that obtained by a well characterized composite method calibration. For a set of pyranometers with roughly identical relative directional responses, the accuracies are significantly better than those obtained from a composite method calibration using the same pyranometers.

Agreement between the sun-disk and alternate method calibrations of a working pyranometer was excellent, with the alternate method results showing the least variance and range for set zenith angles. A comparison of composite and alternate method results for two working pyranometers also showed excellent agreement, with the mean of both types of calibrations agreeing to better than 0.1%.

With suitable planning the method can provide the means for easy in situ field calibration. Such field calibration can eliminate either the need for regular return of pyranometers to a central facility or duplication of instrumentation at the field site. Therefore, use of the alternate method for field calibration is likely to reduce capital and ongoing costs, as well as reduce the total uncertainty in the measurements.

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