A proposed working standard for the measurement of diffuse horizontal shortwave irradiance

J. J. Michalsky,[1] C. Gueymard,[2] P. Kiedron,[3] L. J. B. McArthur,[4] R. Philipona,[5] and T. Stoffel[6]

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[1] Atmospheric radiative transfer model estimates of diffuse horizontal broadband shortwave (solar) irradiance have historically been larger than measurements from a shaded pyranometer. A reference standard for the diffuse horizontal shortwave irradiance does not exist. There are no current efforts to develop an absolute standard that are known to the authors. This paper presents the case for a working standard for this measurement. Four well-behaved pyranometers from two previous intensive observation periods (IOP) were chosen for this study. The instruments were characterized for spectral and angular response before the IOP and calibrated during the IOP using a shade/unshade technique with reference direct irradiance from an absolute cavity radiometer. The results of the comparison and detailed analyses to explain the differences suggest selecting three of the four for the working standard. The 95% confidence uncertainty in this standard is estimated at 2.2% of reading + 0.2 W/m^2. In lieu of a comparison to this trio, a procedure for obtaining low-uncertainty diffuse horizontal shortwave irradiance is suggested.

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1. Introduction

[2] The motivation for improving the measurement of diffuse horizontal broadband shortwave irradiance (hereafter, diffuse or diffuse irradiance) was discussed thoroughly by *Michalsky et al.* [2003], which describes the first diffuse intensive observation period (IOP), and in *Michalsky et al.* [2005], which describes the second diffuse IOP; consequently, the motivation for this effort will be brief. Clear-sky radiative transfer models of diffuse irradiance are persistently higher than measurements, especially for modest aerosol loads. Recently, *Michalsky et al.* [2006] compared six radiative transfer models with clear-sky measurements for a wide range of aerosol loads and solar angles. This study demonstrated that better diffuse measurements with a better specification of the surface albedo and better aerosol optical property specifications, especially asymmetry parameter, narrowed the average bias to under 2% or about 2 W/m^2 for the 30 cases investigated.

[3] The purpose of this third diffuse IOP, conducted between 10 and 19 October 2006, was to select from among the best pyranometers in the first and second diffuse IOPs. Elimination of pyranometers to be included in the standard is based on one or more of the following: noisy signals, instability with respect to the other instruments within the overall group, and poor offset corrections. The pyranometers chosen for the standard were characterized for individual spectral and angular responses in order to explain any discrepancies that might arise during the comparisons. The goal was to develop a reliable, diffuse-irradiance working standard that will minimize the likelihood that the discrepancy with models can be attributed to diffuse measurement uncertainty.

[4] In the next section the instrumentation is highlighted including a discussion of the calibration of the pyranometers and the thermal offset (zero) corrections. Section 3 illustrates the results from a few days that indicate cloudy-sky and clear-sky behavior of the group of pyranometers before recalibration and offset correction and after these corrections are applied. Section 4 describes the characterization of the pyranometers for spectral response including reflectivity of the receiver surfaces. Calculations are presented that model how the spectral character of the instruments could cause differences in response. The angular responses of the pyranometers are shown, with some results regarding the changes that could arise because of angular response differences under cloudy and clear skies. Completely independent methods to measure diffuse that can be used to decide among dissident measurements are described in section 5.

[1] Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.
[2] Solar Consulting Services, Colebrook, New Hampshire, USA.
[3] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, Colorado, USA.
[4] Meteorological Service of Canada, Downsview, Ontario, Canada.
[5] Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center, Davos, Switzerland.
[6] National Renewable Energy Laboratory, Golden, Colorado, USA.

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Table 1. Pyranometers Used for the IOP, Response Measurements, Standard Deviation of New Responses, and Offsets

Instrument	Serial Number	Response (Old), μV/W/m^2	Response (New), μV/W/m^2	Standard Deviation of 30-Point Sample	Predicted Offset, W/m^2	Capped Offset, W/m^2
cm22rp[a]	990010	11.46	11.46 μv/W/m^2	0.03 μv/W/m^2	−0.7	−0.9
cm22[b]	010047	9.6027	9.76	0.03	−1.6	−1.2
cm11[c]	069059	8.43	8.31	0.02	−2.5	−2.3
8-48[d]	34580	9.62	9.66	0.03	+0.1	+0.7

[a]Kipp & Zonen, Inc. CM 22; provided by Rolf Philipona with a custom VHS ventilator with heating.
[b]Kipp & Zonen, Inc. CM 22; Kipp & Zonen CV2 ventilator with no heating.
[c]Kipp & Zonen, Inc. CM 11B; Kipp & Zonen CV2 ventilator with no heating.
[d]Eppley Laboratory, Inc. 8-48; Eppley Laboratory, Inc. VEN ventilator with no heating.

Section 6 summarizes these discussions. Section 7 suggests a triad of pyranometers as a diffuse working standard with their estimated uncertainty. A method to use for diffuse measurements if a comparison to this triad is not possible is suggested.

2. Pyranometers, Calibrations, and Offset Corrections

[5] In this third diffuse IOP four pyranometers were used to measure diffuse irradiance simultaneously, and a pyrgeometer was used to measure the net infrared for use in correcting the offsets of the pyranometers. Table 1 contains four well-behaved instruments from the second IOP [*Michalsky et al.*, 2005] that are used for this study. The third column contains the responses supplied by the owner or manufacturer of the pyranometer. The fourth and fifth columns contain the responses and standard deviations obtained from a shade/unshade calibration during the IOP that will be discussed below. The sixth column contains the predicted offsets, which will be discussed below, for the time the day when conditions are expected to produce the highest offsets, followed in column seven by the results of a capping experiment to measure the offsets.

[6] A shade/unshade calibration was performed for all four pyranometers centered near solar noon on 11 October 2006 and then again on 13 October 2006 for the 8–48 only. The IOP dates were selected anticipating this calibration since the preferred solar angle for calibrating is 45° and the Sun remains within ±1° of this angle for about two hours around solar noon at the Department of Energy's Atmospheric Radiation Measurement (ARM) Climate Research Facility's (ACRF) Southern Great Plains (SGP) central site (36.607°N, 97.496°W). The four pyranometers were mounted on a tracker, thus maintaining their same orientation in azimuth relative to the Sun. The level of the instruments was checked before the calibration. All pyranometers are alternately shaded and unshaded manually in the same order within 10–15 s and left in that condition for the remaining 2 or 3 min (see below) to permit the instrument to stabilize at its full-shade or full-Sun value. Since instruments have different time constants this stabilization time varies. In Figure 1a the shade and unshade periods were 3 min long, and a stable value was slowly approached because of the rather long time constant of the 8–48 pyranometer. Each dot is a 10-s average of 1-s samples. In Figure 1b the shade or unshade period is 2 min for the cm11 pyranometer and the instrument quickly settles to a stable value, as was true for all of the Kipp and Zonen instruments. The ratio of the difference in voltage readings ($V_{unshade} - V_{shade}$) to the product of the direct irradiance, measured with an absolute cavity radiometer, and the cosine of the solar-zenith angle, *sza*, is the responsivity of the pyranometer:

$$\text{Response} = \frac{(V_{unshade} - V_{shade})}{\text{Direct Irradiance} \cdot \cos(sza)} \quad (1)$$

[7] Comparing columns three and four in Table 1, the calibration of the CM 22 from the World Radiation Center (cm22rp) had not changed from the shade/unshade calibration performed during the second diffuse IOP [*Michalsky et al.*, 2005]. The other cm22 shade/unshade calibration yielded a 1.6% higher response than the calibration provided by the National Renewable Energy Laboratory (NREL), which did not use a shade/unshade technique for their calibration. The change in response for the cm11 was 1.4% lower than the indoor calibration provided by the manufacturer. The 8–48 response was 0.4% higher than the manufacturer's indoor calibration.

[8] The thermal offset correction used nighttime pyranometer measurements as a function of the net infrared (net-IR) signal from a colocated pyrgeometer. This technique for correcting offsets in pyranometers was explained by *Dutton et al.* [2001]. Figure 2 illustrates this process for the cm11, which has the largest offset of the four pyranometers. Using only nighttime data with the Sun below the horizon (more than 7° below), the pyranometer reading is plotted versus the net-IR reading for nine nights of 10-s data, or over 36,800 points. Each dot in Figure 2 is a 10-s average of 1-s samples. The linear least squares fit to all the data in Figure 2 is the black line. The green (dashed) line is a robust fit to the data, which de-emphasizes outliers. The source of the outliers that occurred during the IOP is uncertain, but they are associated with a disruption of the thermal balance of the pyranometers. The green (dashed) line is used to predict the offset for all conditions, both night and day. A stringent test of the offset correction is to estimate offsets in the early afternoon on a clear day. This produces a large, negative, net-IR irradiance (approximately −150 W/m^2), outside the bounds of the nighttime signals. Higher net-IR irradiance occurs during the day than at night because the direct Sun heats the body of the pyranometer, which does not occur at night, while the dome that is blocked from direct sunlight radiates to space leading to an exacerbated difference in dome and case temperatures, thus causing a high net-IR

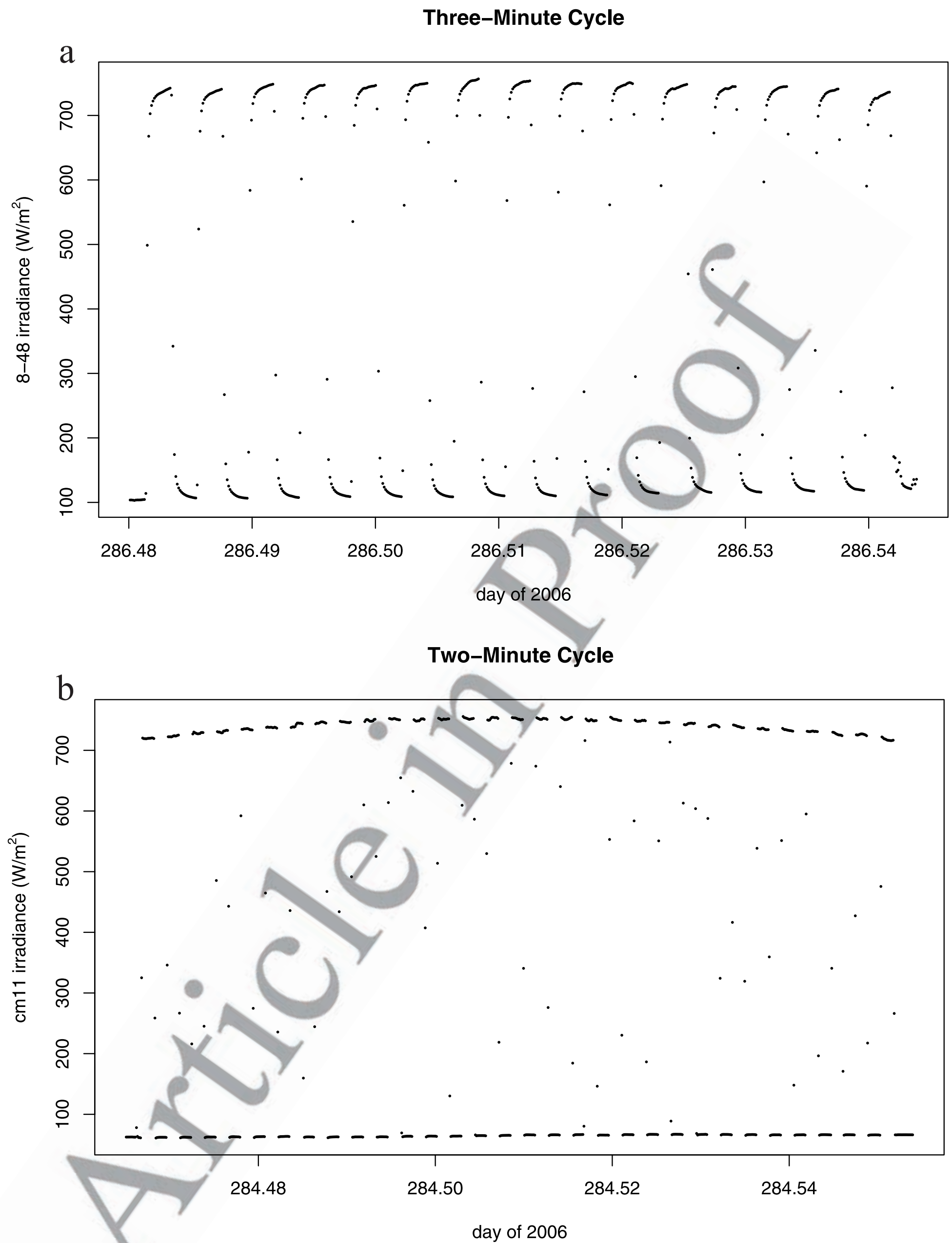

Figure 1. (a) For a shade-unshade calibration the 8–48 pyranometer is alternately shaded and unshaded (3 min each) and the difference is compared to the direct beam irradiance measured with an absolute cavity radiometer and multiplied by the cosine of the solar-zenith angle. (b) The same sequence of shading and unshading is repeated for the cm11 pyranometer with a 2_min cycle. Note the difference of the time responses of the two instruments; the 1/e 8–48 time response (5 s) is three times that of the cm11 (1.66 s).

signal. To assess the offset, the instrument dome is capped to block all incoming solar radiation. The best assessment of the offset occurs when the time constant of the detector is 1–2 s, or shorter, so that the dome temperature experiences a minimal change because of the heat-trapping cap. As may be expected from Figure 1a, the 8–48 with its slow time constant may not satisfy this criterion, while the others respond very quickly to the blocked radiation and yield a reasonable estimate of the daytime offset. The last two columns of Table 1 indicate that the predicted and measured offsets are within 0.4 W/m^2 except for the 8–48, as expected since the 8–48's slow response does not permit a true offset determination by this method.

[9] Using nighttime data to correct daytime measurements cannot account for the fact that during the daytime solar radiation heats the detector. The difference between the dome and detector temperatures causes the offset, and the proxy method to estimate the offset using the net-IR

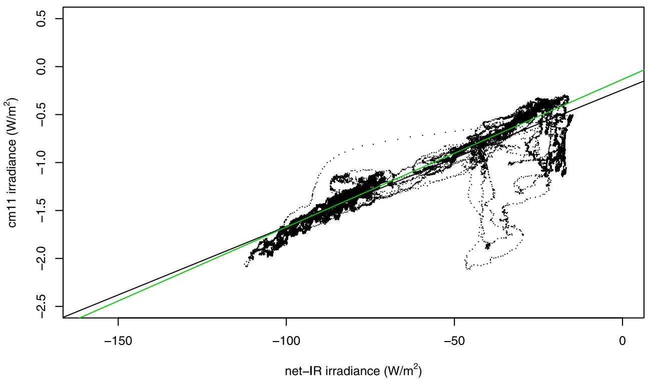

Figure 2. The offset prediction is determined by regressing offset at night versus the simultaneous thermopile net-IR from a colocated pyrgeometer. The outliers are caused by thermal imbalances associated with rainfall on the instruments. The black line is a linear least squares fit and the green (dashed) line is a robust fit that deweights outliers.

irradiance, which emulates the difference in dome and receiver temperature difference, may not hold if the detector is irradiated. One way to test whether the offset estimate based on the robust fit to the nighttime data is correct is to ratio the 8–48, an instrument which has almost no thermal offset, to the offset-corrected instruments, and then to plot this ratio as a function of incoming diffuse radiation. If the offset correction is inadequate, this ratio should increase with higher irradiance as the temperature difference between the dome and detector exceeds that estimated by the proxy measurement provided by the net-IR irradiance. Figure 3 is a plot of the ratio of the 8–48 to each of the three offset-corrected pyranometers as a function of diffuse irradiance. The data are screened to allow only diffuse irradiances that exceed 50 W/m^2 and for overcast conditions; the last requirement is to avoid confusing this effect with the clear versus cloudy sky effects that will be discussed in a later section. There is no significant increase in the ratio with irradiance. Although it increases slightly at low irradiances, the ratio is smaller at the highest irradiances. The 8–48/cm11 ratio has the largest change in the top of Figure 3, but the maximum effect is only slightly larger than 1% suggesting that the offset correction scheme is adequate. Since we have chosen cloudy conditions for this plot, the dome and case difference caused by cooling to space is small in the pyrgeometer, but if the detector heating in the pyranometer causes a detector-dome temperature difference in this instrument, then the effect of inadequate offset corrections should be detected in these plots, but is not.

[10] Note that the ratios in Figure 3 are consistently greater that one: this suggests that the 8–48 irradiances are too high relative to the other instruments. This could be the result of what Figure 1a illustrates. The shaded and unshaded values do not quite arrive at asymptotic values suggesting that the numerator of equation (1) should be larger. A larger response would result in a smaller calibration constant (the inverse of the response) and, therefore, lower irradiances.

[11] As in the second IOP [*Michalsky et al.*, 2005], the shading and receiver geometry is the same for all pyranometers, thus eliminating different receiver views of the solar aureole as a source of differences.

3. Comparisons of the Diffuse Irradiances

[12] Figure 4 contains three plots. The pyranometers and the pyrgeometer were mounted on trackers that provided shading for the instruments all day. The top plot is the diffuse irradiance from each of the four pyranometers. In this plot the offsets are not corrected and the original calibrations from Table 1, column 3 are used. In the middle plot the offsets are corrected and the shade-unshade calibrations from Table 1, column 4, are applied. The 8–48 has an additional multiplicative factor of 0.98 applied to the data to correct for the underestimate of responsivity as discussed in the last section. This correction was based on forced agreement with the other three instruments when totally overcast conditions prevailed. In the bottom plot the ratio of each corrected output to the corrected output of pyranometer cm22rp is plotted. The diffuse signal is also plotted with the values in W/m^2 labeled on the right-hand side. This day

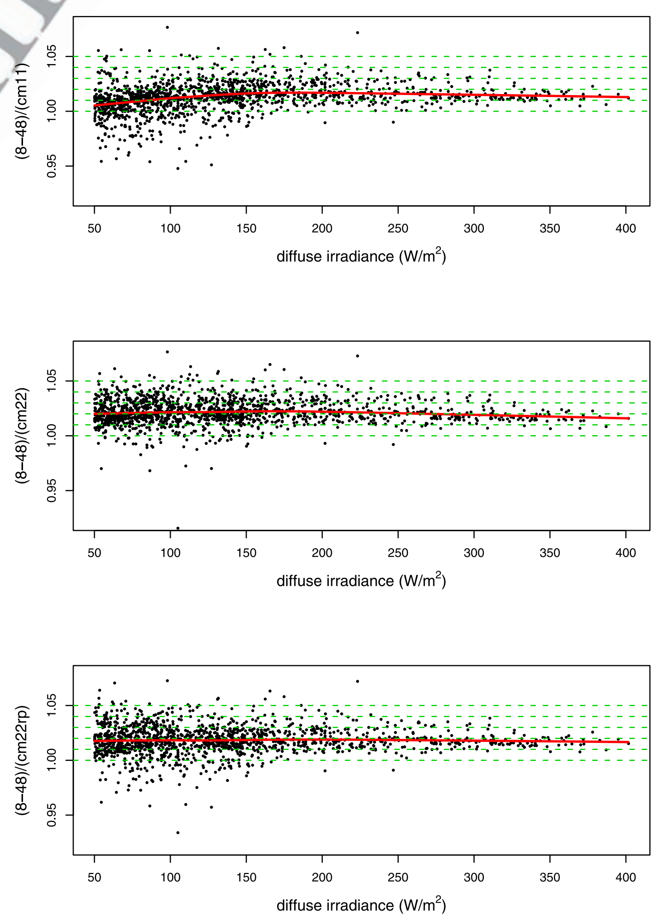

Figure 3. These are plots of the ratio of the 8–48 to each of the Kipp and Zonen pyranometers as a function of the cloudy-sky irradiance. Points are screened to select overcast skies with diffuse exceeding 50 W/m^2. There is no obvious dependence of the offset correction on the heating of the sensor by solar flux.

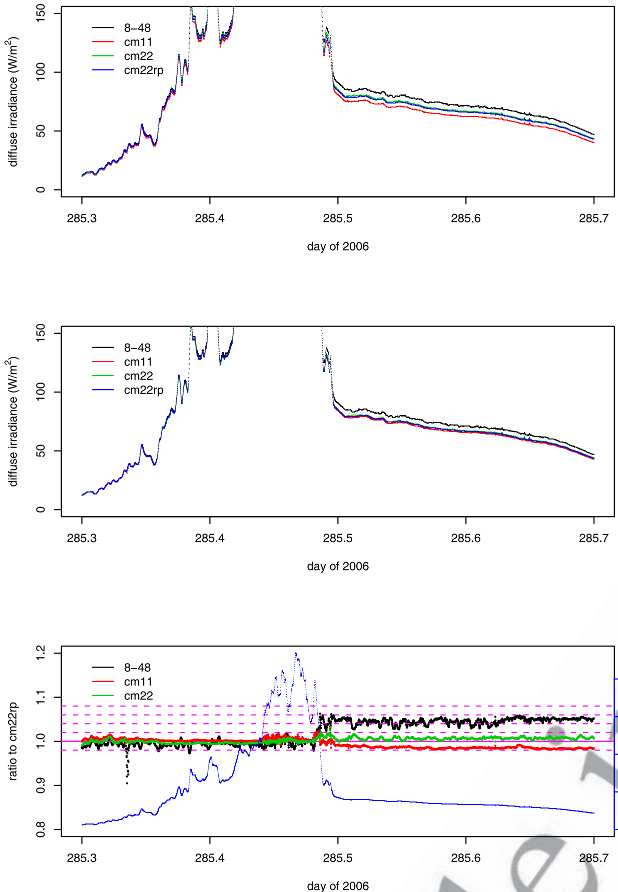

Figure 4. (top) Diffuse irradiance for the four instruments with original calibrations and no offset corrections for a day that was overcast in the morning and completely clear in the afternoon. (middle) The data are offset_corrected and have the shade-unshade calibrations applied. The 8_48 has an additional adjustment of 2% as discussed in the text. (bottom) A ratio of each pyranometer to the cm22rp.

was completely overcast in the morning, and completely clear after solar noon with a rapid transition between these two conditions. The difference between the top and middle plots indicates slightly improved agreement in the morning among all pyranometers (the overplot looks like a single instrument). In the afternoon the cmxx pyranometers of Kipp and Zonen indicate modest separation, but the 8–48 reads notably higher relative to these. The bottom plot clearly shows the abrupt change in the ratio of the 8–48 to cm22rp associated with clearing skies.

[13] Figure 5 is similar to Figure 4, but the sky is covered by cirrus during most of this day. The bottom plot's right-hand axis is direct normal irradiance. This plot shows that the direct beam passes through transparent cirrus clouds whose thicknesses are insufficient to completely extinguish the solar beam. The 8–48 irradiance is higher throughout the day, but the ratio to the cm22rp is smaller than it was in the clear portion of Figure 4. An examination of all similar plots for the IOP reveals that clear skies produce ratios of the 8–48 to the cm22rp that are in the range of 1.04 to 1.05 for the clearest skies, about 1.00 for the cloudiest, with intermediate values for conditions such as in Figure 5. Attempts to explain these differences follow.

4. Spectral and Angular Response Differences

[14] The agreement among all four pyranometers when there is complete overcast is near 1% for irradiances above 50 W/m^2 to ensure that the instrumental signal-to-noise ratio is not an issue. For clear conditions the three Kipp and Zonen instruments (designated collectively as cmxx) agree within 2% even though there are differences in how the instruments are constructed (different dome glasses) or operated (different ventilation). The 8–48 disagreement is highest for clear conditions and somewhat less for cirrus-covered skies.

[15] An obvious difference, as suggested by *Michalsky et al.* [2005] for the second diffuse IOP, is the spectral distribution of scattered radiation from these different skies [e.g., see *Michalsky et al.*, 2005, Figure 10]. The cloudy sky has a spectral distribution similar to the Sun, but the clear-sky distribution is shifted well to the blue relative to the solar spectrum because of the predominance of Rayleigh scattering. It is possible to model the relative responses of

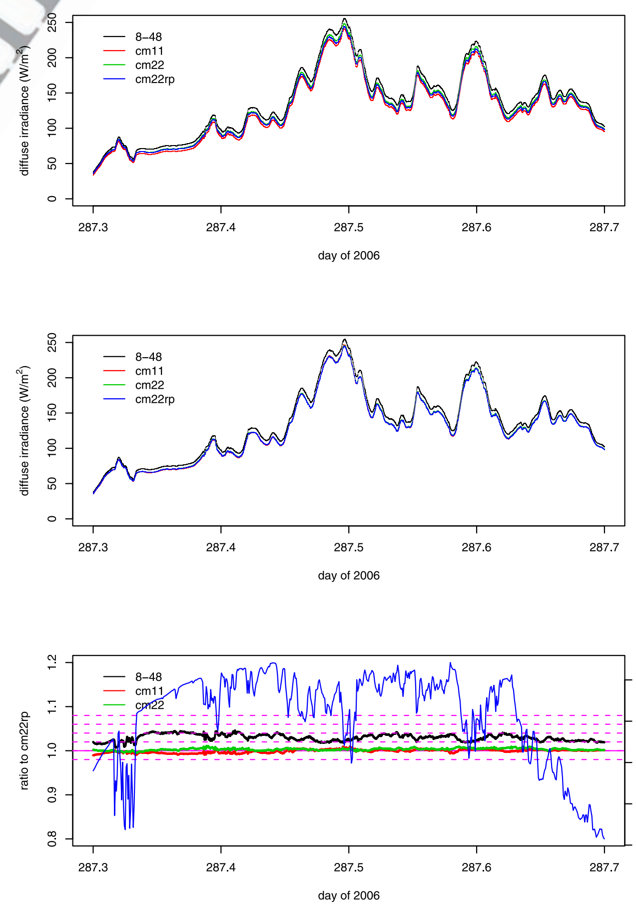

Figure 5. The same plot sequence as in Figure 4 is shown except the bottom plot's right-hand side is direct irradiance rather than diffuse. This direct beam plot indicates when cirrus clouds are present and demonstrates that cirrus produces a smaller 8–48 to cm22rp ratio than in Figure 4, which depends on the extent of the cirrus cover.

Table 2. Difference in Clear-Sky Diffuse Irradiance Responses if Calibrated by Shade-Unshade

Pyranometer	Dome Glass (T)	Sensor Absorber (A)	$I_{diffuse\text{-}measured}/I_{diffuse\text{-}model}$
Eppley 8–48	Schott WG295	NRC-measured white NRC-measured black	1.011
Kipp&Zonen CM11	Schott N-K5	Kipp&Zonen data	0.988
Kipp&Zonen CM22	Tydex KS-4V(quartz)	Kipp&Zonen data	0.996

the different instruments if we have the transmissions of the glasses, the spectral absorptions of the receivers, and the spectral distribution of the incident irradiances. In the work by *Michalsky et al.* [2005], generic absorptions and transmissions were used to posit a plausible explanation for why the instruments disagree. In preparation for this IOP, spectral measurements of the reflection from coupons, which are similar to the receiver surfaces in a new Eppley 8–48 black and white pyranometer, were made by the National Research Council of Canada from 250 to 2200 nm. The Kipp and Zonen pyranometers all use the same black paint for their receivers. Kipp and Zonen provided the spectral absorption for their receivers. Both manufacturers also provided transmission curves for the types of glasses used. We used the SMARTS model [*Gueymard*, 2001] to produce plausible spectra for conditions during the IOP.

[16] As discussed by *Michalsky et al.* [2005] the signal from a single black thermopile detector instrument depends on the absorption of the paint *A*, the transmission through the dome or domes *T*, and the spectral distribution of the incoming solar radiation *I*, all as a function of wavelength λ. A pseudo-calibration of the instruments is performed using modeled direct solar radiation on a horizontal surface as in our shade-unshade field calibration. Therefore the pyranometer "signal" is represented as follows

$$S_{direct-horizontal} = K \cdot \int_{\lambda} I_{direct-horizontal}(\lambda) A(\lambda) T(\lambda) d\lambda. \qquad (2)$$

[17] The irradiance received from the direct beam falling on the horizontal is $\int I_{direct\ -\ horizontal}(\lambda) d\lambda$. The pseudo-calibration of the pyranometer is this last term divided by equation (2), or

$$\frac{\int_{\lambda} I_{direct-horizontal}(\lambda) d\lambda}{K \cdot \int_{\lambda} I_{direct-horizontal}(\lambda) A(\lambda) T(\lambda) d\lambda}. \qquad (3)$$

[18] The pyranometer "signal" from the diffuse irradiance is similar to equation (2)

$$S_{diffuse} = K \cdot \int_{\lambda} I_{diffuse}(\lambda) A(\lambda) T(\lambda) d\lambda. \qquad (4)$$

[19] The product of equations (3) and (4) produces the pseudo-diffuse irradiance that would be measured by a pyranometer calibrated with the shade-unshade method. The constant of proportionality K in equations (3) and (4) cancels. This irradiance can then be compared with $\int_{\lambda} I_{diffuse}(\lambda) d\lambda$.

[20] For the case of an 8–48 we substitute the difference in black and white surface absorption for the single black surface absorption. Table 2 contains the ratios of the pyranometer "diffuse measurements" (products of equations (3) and (4)) to the diffuse obtained by integration of the modeled clear-sky diffuse irradiances.

[21] The Kipp and Zonen cm22 has the closest response to the modeled irradiance, but is low by about 0.4%. The 8–48 is high by about 1.1% and the cm11 is low by about 1.2%. Consequently, the 8–48 for clear skies should read about 1.5% high relative to the cm22. The spectral effect is, therefore, in the direction indicated in Figures 4 and 5, but the difference is about a third of the difference that needs to be explained. The bottom of Figure 4 indicates that the cm11 shifts from agreeing with the cm22rp during the cloudy part of the day to reading low relative to the cm22rp during the clear afternoon, which is the observed direction and roughly the magnitude of the shift expected from Table 2 if all of the shift is caused by spectral response.

[22] A further difference between clear skies and overcast skies is the spatial distribution of the diffuse radiation. This was also discussed in the second IOP paper [*Michalsky et al.*, 2005]. In that paper plausible arguments were made for why the 8–48 could measure higher relative to other instruments in a clear versus cloudy sky. Generic angular responses were used to calculate the differences. For this study the angular responses of the four pyranometers were measured in four cardinal directions at the National Atmospheric Radiation Centre (Canada). The results of those measurements for the four instruments in the IOP are plotted in Figure 6. The 8–48 has a super cosine response in three of the directions plotted, i.e., as the elevation angle gets lower the response is higher than a true cosine response for three directions. The cm11 has a tendency to fall off slightly and then rise to be nearer to true cosine at the largest angle measured. The cm22 and cm22rp behave similarly for the most part. All instruments have what generally would be considered good angular responses, deviating less than 5% from true cosine, except at the largest angle measured of 80°.

[23] To estimate the effects of cosine response on the level of agreement among measurements, two models of skylight distribution were used. Although these are distributions for luminance, they are approximately correct for radiance. The *Moon and Spencer* [1942] model was adopted for cloudy-sky calculations. In this model there is symmetry in luminance about the zenith direction. The zenith luminance is three times greater than the luminance near the horizon. For the clear-sky model the formulation of *Kittler* [1967], which was subsequently adopted by the International Commission on Illumination [*Commission Internationale de l'Eclairage*, 1973], was used. The model is not for a pure Rayleigh sky, but includes realistic aerosol scattering that

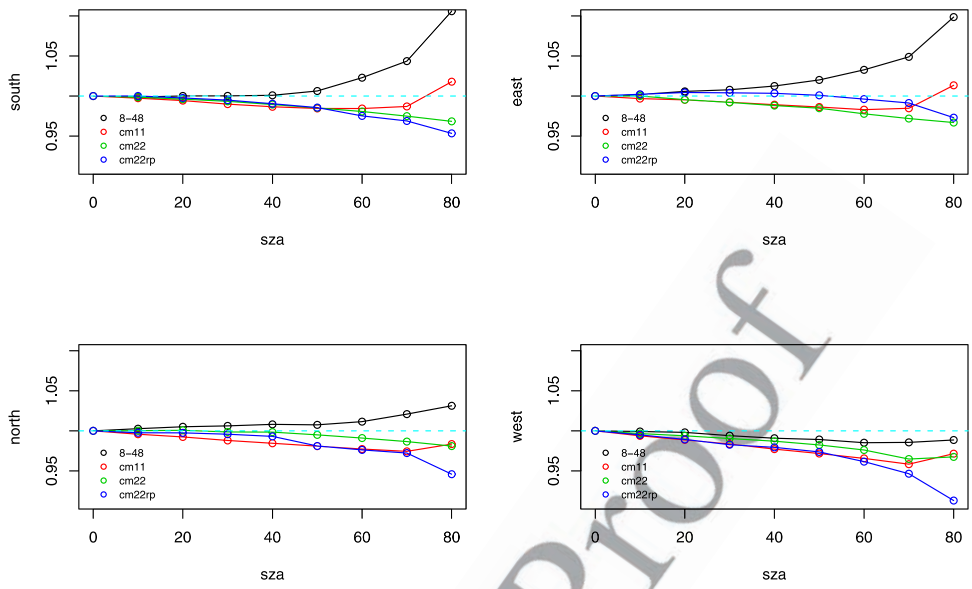

Figure 6. Angular responses in four cardinal directions (signal cable north) for the four pyranometers in the IOP.

produces circumsolar brightening and enhanced luminance near the horizon.

[24] The calculations were performed for pyranometers calibrated at a solar zenith angle of 45° and placed on trackers that always orient the pyranometers in the same direction relative to the Sun as in this study. Corrections for these two skies and these four pyranometers were performed. Table 3 contains the required correction factors for skylight with the Sun at 45° using the cosine responses from Figure 6. For example, the 8–48 for a cloudy sky (Moon-Spencer) has to be divided by 1.0004, while the cm22 has to be divided by 0.9999, to correct for the deviations from a true cosine response. For a clear sky (CIE-Clear) the correction for the 8–48 is division by 1.0044 and the correction for the cm22rp is division by 0.9949. By comparing the ratio of 1.0004/0.9999 in cloudy skies to 1.0044/0.9949 in clear skies, the 8–48 shows a relative shift of 0.9% up with respect to the cm22rp as the sky changes from cloudy to clear. Through the same reasoning the cm11 shifts up by 0.3% relative to the cm22rp from cloudy to clear skies, and the cm22 shifts up by 0.4%. The corrections for the Sun at 30° elevation are about half that at 45°.

[25] The spectral and angular response effects, combined, result in a 0.4% shift up in changing from cloudy to clear for the cm22 relative to the cm22rp. The combined effects for the cm11 relative to the cm22rp yield a net shift down by about 0.9% from cloudy to clear since the spectral shift down is partially canceled by the angular response shift up. The 8–48 spectral and angular shifts in changing from cloudy to clear conditions are in the same direction relative to the cm22rp and are 2.4% up. Examination of Figure 4 qualitatively agrees with these calculations. There is fair quantitative agreement in shifts for the cm11 and cm22 relative to the cm22rp. The 8–48, indeed, reads higher than the cm22rp when it is clear, but only about half of the increase (2.4% versus 5.2%) is explained by the spectral and angular corrections.

5. Other Measurements of Diffuse Compared to IOP Pyranometers

[26] Two 8–48 pyranometers are included as part of the permanent instrument array at the ARM SGP site. These SGP 8–48s are separated by about 450 m from the radiation calibration facility (RCF) where the IOP measurements were made. Cloudy skies produce noisier comparisons because of the distance separation than clear skies. On average these two station 8–48s compared to the cm22rp are 5.3% and 3.1% higher when it is clear than when it is cloudy. The differences among the three 8–48s suggest that the spectral and cosine effects differ among instruments. Whether the differences are primarily angular or spectral for a particular instrument is impossible to assign without detailed characterizations. Calibration of the pyranometer at a solar-zenith angle of 45° minimizes the effects of angular response on the diffuse irradiance for all pyranometers with angular responses similar to those measured. This can be qualitatively understood because the diffuse signal is nearly proportional to $\sin(\theta) \bullet \cos(\theta) = \sin(2\theta)\backslash 2$, which peaks at 45°. For this reason most of the difference can be attributed to the spectral response of the 8–48. In the current IOP the actual reflection from the black and white sectors was not measured, but coupons made of the same substrates coated in a similar way to the sectors of the 8–48

Table 3. Corrections (Divisors) to Diffuse for Imperfect Angular Response for Sun at 45°

Model Sky	cm22rp	8–48	cm11	cm22
Moon-Spencer	0.9999	1.0004	1.0030	0.9920
CIE-Clear	0.9949	1.0044	1.0012	0.9912

Table 4. Integrated RSS Data Plus Added Modeled Spectra Compared to Measured Diffuse/Direct

Date 2006	LT	Measured Direct	Diffuse cmxx/8-48	RSS+ Diffuse	SMARTS Direct	SMARTS Diffuse
11 Oct	0900	874.8 nip	54.4/56.7	53.0	871.3	60.3
11 Oct	1100	962.5 cav.	64.7/67.4	64.7	957.8	69.2
12 Oct	1433	914.8 nip	66.6/68.8	65.1	909.7	69.0
13 Oct	1200	897.1 cav.	100.7/105.9	100.4	902.4	102.0

were used as proxies for the actual reflectivities. Coupon differences from the actual 8–48 surfaces may account for why only about one half of the increase could be explained.

[27] An entirely different measurement of diffuse that may help point to the true diffuse irradiance is the spectral diffuse irradiance measurement of the rotating shadowband spectroradiometer (RSS) [*Harrison et al.*, 1999]. The RSS data using a Langley-plot calibration technique to determine spectral sensitivity [*Kiedron et al.*, 2002] give an integrated diffuse value at 1433 local time (LT) on 12 October 2006 that totals 54.8 W/m^2 between 361.5 and 1074 nm. The corresponding uncertainty in integrated RSS diffuse measurement is estimated at about 3%. To estimate the unmeasured spectral irradiance we used the SMARTS radiative transfer model [*Gueymard*, 2001] with inputs of measured aerosol properties (column aerosol optical depth at five wavelengths, ground-level measurements of aerosol properties to estimate single scattering albedo and asymmetry parameter), water vapor column, ozone column, and estimated spectral surface albedos. Integrating model output between 280 and 361.5 nm yields 8.2 W/m^2 and between 1074 and 4000 nm another 2.1 W/m^2 for a total of 65.1 W/m^2. The measured diffuse for that same time for the cm11 is 66.4 W/m^2; for the cm22 is 66.9 W/m^2; for the cm22rp is 66.6 W/m^2; and for the 8–48 is 68.8 W/m^2. The RSS measured diffuse was added to the model runs (designated RSS+) on three other occasions for the total of four cases that are summarized in Table 4. All four skies were cloudless. The measured direct with the Eppley NIP or the Eppley HF cavity radiometer are given in the third column to be compared with the SMARTS model results in the sixth column. All direct results show excellent agreement to within about 5 W/m^2. The fourth column lists two measured diffuse values; the first is the average of three cmxx instruments, which are within 0.6 W/m^2 of each other in all four cases, and the second entry is the 8–48 reading. The summed spectral diffuse in column five is closer to the average of three cmxx pyranometers with the largest difference 1.5 W/m^2. The difference between the summed spectral diffuse and the 8–48 varies between 2.7 and 5.5 W/m^2. Note that the summed SMARTS modeled spectral diffuse between 280 and 4000 nm is higher than the measurement for low aerosol cases, but agrees rather well for the higher aerosol case on 13 October.

[28] A point that can be made is that all Kipp and Zonen instruments are constructed similarly, and, therefore, would be expected to agree. Of course, each cmxx instrument in this study is different in some detail; the cm11 has a different glass dome than the cm22s, and cm22rp has a heater and a different ventilator that the cm22. An instrument that is different than the Kipp and Zonen pyranometers and different than the Eppley 8–48 is the Eppley PSP. The ventilated Eppley PSP has one of the largest offsets known for a ventilated pyranometer [see, e.g., *Michalsky et al.*, 2003, Figure 10]. *Philipona* [2002], however, demonstrated that with proper heating and ventilation of the PSP this offset could be eliminated. A PSP that was shade/unshade calibrated at NREL was operated in the same type of ventilator as in the *Philipona* [2002] study in a follow-on experiment to the October 2006 IOP. This instrument/ventilator combination was colocated in Boulder, Colorado, with the cm22 and the 8–48 used in the earlier IOP. Figure 7 is a plot of diffuse irradiance from two clear days as identified by the direct irradiance, scaled and overplotted in gray. The offset for the PSP, while noisy, oscillates about zero irradiance. An analysis of the nighttime data for eight nights for the PSP yields a probability distribution that is symmetric and peaks at zero irradiance. From Figure 7 it is clear that the PSP agrees better with the cm22 than the 8–48. Although not conclusive, since this PSP's angular and spectral responses were not measured, this lends additional support to the proposition that cmxx instruments are making better diffuse measurements than the 8–48.

6. Summary

[29] *Reda et al.* [2003] have estimated the uncertainty of diffuse irradiance measurements made with Eppley 8–48s. They concluded that the Eppley 8–48 could be used to measure diffuse with an uncertainty of ±(3% of reading + 1 W/m^2). The current study suggests that there is agreement at least at this level or even better when overcast conditions prevail among all four pyranometers. However, when the sky is clear, five of six 8–48s have a high bias, which ranges between 2–5%, with respect to the other three measurements of diffuse irradiance in the IOP. Comparisons during the IOP suggest that the cm22rp and cm22 are usually in agreement at the 0.5% level, or better, for cloudy or clear conditions. When either of these instruments is compared to the 8–48 in the IOP, the results range between agreeing when it is cloudy to over 5% disparity when it is clear, with the 8–48 higher. Repeating this comparison (cloudy ratio of pyranometers to clear ratio) using the two permanent central facility 8–48s at the ACRF during the IOP resulted in 8–48s reading higher by 3.1% and 5.3% relative to the trio of Kipp and Zonen pyranometers in this IOP. A follow-on study comparing three Boulder station 8–48s with the cm22 from the IOP produced 8–48/cm22 ratios between cloudy and clear skies that were −0.2%, 1.9%, and 3.9% for three pyranometers. This expands the range of variability that is seen among 8–48 responses and further weakens the case for their use in establishing a diffuse irradiance standard.

[30] Integrated RSS spectral irradiance measurements over most of the clear diffuse spectrum that were calibrated by the Langley method were made and then augmented with

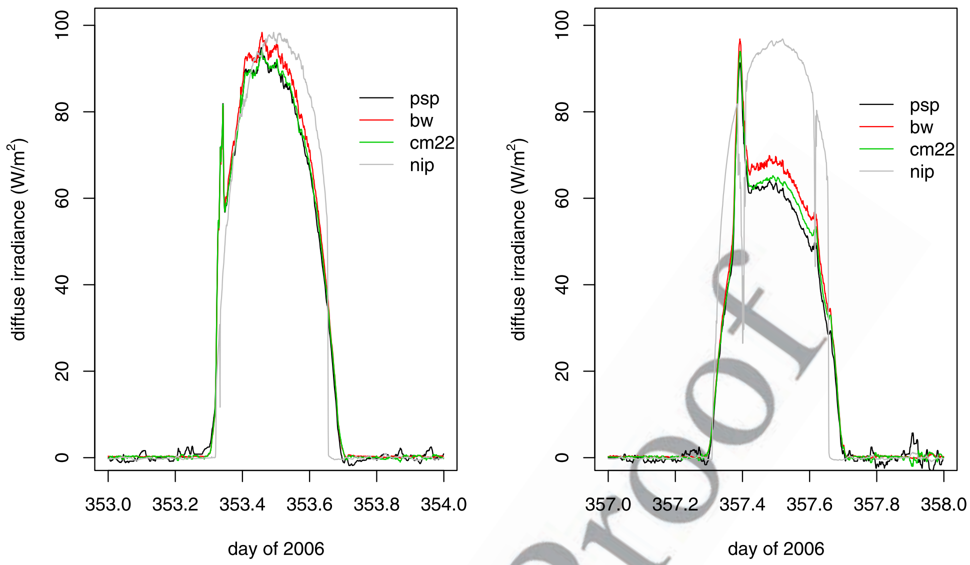

Figure 7. Diffuse irradiance from two clear days in Boulder, Colorado, in 2006 with two pyranometers from this IOP and a PSP operated in a *Philipona* [2002]–style ventilator and heater system that eliminates zero offsets. The scaled direct irradiance is in gray to confirm the clarity of the atmosphere. The diffuse measured by the cm22 and the PSP are in close agreement.

a model for the missing ≈ 15% of the irradiance not measured. The additional modeled irradiance should affect the integrated spectral irradiance uncertainty by no more than 1 W/m^2. The four cases studied suggested closer agreement with the cmxx instruments than with the 8–48. This independent result supports the proposition that the cmxx trio makes a more accurate diffuse measurement.

[31] A different instrument, the PSP by the same manufacturer of the Eppley 8–48, was operated in a heated ventilator that eliminated its typically large offset. Although not corrected for angular and spectral responses, this shade/unshade calibrated PSP agreed better with the cmxx trio than the 8–48 in side-by-side measurements providing additional support for the cmxx standard.

7. Conclusions

[32] Using the cm11, cm22, and cm22rp average as the standard for diffuse irradiance, an uncertainty at the 95% confidence level is estimated at ±(2.2% of reading + 0.2 W/m^2). That this is a reasonable estimate is illustrated in the bottom of Figures 4 and 5 where the departures from unity among the ratios are within the bounds of the ±2% lines. For this uncertainty determination guidance provided by *Cook* [1999] was used. The statistical component of the uncertainty (Type A uncertainty) came from adding, in quadrature, the 95% cavity uncertainty (0.45%) and twice the standard deviation of the mean (0.10%) from the 30 measurements used to obtain calibration constants from the shade/unshade calibration sequence. The largest uncertainties are of the B type (those not based on a statistical calculation). These came predominantly from the angular responses, the spectral responses, and the temperature dependences. The largest deviations from the "perfect" response as modeled in Table 2 for spectral response (1.2%) and Table 3 for angular response (0.88%), and for temperature response (1.0%) based on manufacturer specifications were used as the half-widths of rectangular distributions. Other type B errors, for example, the resolution of the data acquisition system, were found to be much smaller and negligible relative to these. The three standard uncertainties were added in quadrature to obtain the type B uncertainty estimate. This type B uncertainty was doubled and squared and added to the type A uncertainty (as given above) squared. The square root is the 2.2% stated uncertainty. The added 0.2 W/m^2 reflects the estimated ability to correct the zero offset for these three instruments.

[33] Similar results should be possible by following the steps outlined in this paper. Specifically, it is assumed that one uses shaded and ventilated pyranometers and a shaded and ventilated pyrgeometer. The pyrgeometer is used to derive a nighttime relationship between pyranometer offset and pyrgeometer reading that is used to correct all pyranometer offsets, day or night. Further, this assumes that the pyranometers are calibrated using a shade/unshade method as outlined in this paper with simultaneous measurements of direct beam irradiance using an absolute cavity radiometer with the Sun within 1–2° of 45° solar-zenith angle. Note that the shading of the pyranometers uses tracking shading disks, not fixed shadowbands, which would block much more of the sky than the area around the solar disk. Some assurance that the angular response is no worse than the instruments in this paper, based on measurements provided by the manufacturer or made in one's own laboratory, should be obtained. The requirement for data acquisition with a resolution of 0.05 W/m^2 can usually be met with modern field data loggers.

[34] This approach should minimize the uncertainty in diffuse irradiance measurements, if side-by-side calibrations of shaded pyranometers using the cmxx trio cannot be made.

[35] **Acknowledgments.** The authors thank Afshin Andreas for programming the data loggers and performing the data collection during

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C. Gueymard, Solar Consulting Services, P.O. Box 392, Colebrook, NH 03576, USA.

P. Kiedron, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, USA.

L. J. B. McArthur, Meteorological Service of Canada, Downsview, ON, Canada M3H 5T4.

J. J. Michalsky, Earth System Research Laboratory, NOAA, Boulder, CO 80305, USA. (joseph.michalsky@noaa.gov)

R. Philipona, Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, CH-7260 Davos, Switzerland.

T. Stoffel, National Renewable Energy Laboratory, Golden, CO 80401, USA.