Establishing the Clear-Sky Diffuse Reference for BORCAL Using EPLAB Model 8-48 Pyranometers at the National Renewable Energy Laboratory

I. Reda, T. L. Stoffel, and D. Myers
National Renewable Energy Laboratory
Golden, Colorado

Abstract

Precision pyranometer calibrations are important to the quality of Atmospheric Radiation Measurement's (ARM's) shortwave solar irradiance measurements. Calibrations at the National Renewable Energy Laboratory (NREL) and Southern Great Plains (SGP) are under clear-sky conditions. G = I * COS(2) + D, is used to establish the reference global during the calibration. The references for the beam irradiance, I, and the solar zenith angle, 2, are internationally recognized. There is no recognized reference for the diffuse irradiance, D. Our research goal is to establish a consistent diffuse reference in the absence of internationally recognized reference to produce consistent calibration results. We describe a method to establish a Clear-Sky Diffuse Reference (CSDR) using The Eppley Laboratory, Inc. (EPLAB) model 8-48 pyranometer because it has small thermal offset error (< ± 1 W/m2). The standard shading method, ASTM E-913, described in the Annual Book of ASTM Standards, section 14, volume 14.02, is used to calculate the shade (diffuse) responsivity (RS) for the pyranometer. The method is modified, slightly, to account for the pyranometers time constant, zenith, and azimuth responses. A control pyranometer (CP) monitors the diffuse ratio between the test pyranometer (TP) and the CP during the shade periods. The basic assumption is that the diffuse RS, under clear-sky conditions, will change in the solar zenith angle range from 30° to 60°, depending on the sky conditions and the average zenith/azimuth angle of the unblocked circumsolar around the shading disk. The clear-sky diffuse RS is computed as the RS at 45° zenith. Half the RS range from 30° to 60° is added as uncertainty to the total calibration uncertainty. To reduce the errors resulting from the azimuth response, the RS at 45° zenith is calculated using the shade/unshade method at three horizontal positions that are separated by 120° degrees. The average of these three responsivities is then considered the clear-sky diffuse RS at 45° zenith.

Two pyranometers, model 8-48, were chosen to establish NREL-CSDR, and then were calibrated using the described shade/unshade method. The two pyranometers were used as reference pyranometers to calibrate six TPs, model 8-48. All pyranometers were installed, outdoor, on sun trackers under shading disks. The six pyranometers were calibrated, unshaded, during the 2001-BORCAL event at NREL and SGP. We will compare the results of calibrating the TPs using NREL-CSDR against their results from the 2001-BORCAL event, and show the consistency of NREL-CSDR and the difference between calibrating the pyranometers when shaded and when unshaded.

The Diffuse RS of a Pyranometer

$$RS_d = \frac{\int_0^{2\pi} \int_0^{\pi/2} RS(\theta, \phi) * D(\theta, \phi) * \mathrm{Sin}(2\theta) \cdot d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi/2} D(\phi) * \mathrm{Sin}(2\theta) \cdot d\theta \quad d\phi}$$

where,

RS_d	=	the diffuse RS,
θ and ϕ	=	the zenith and azimuth angles, respectively,
$D(\theta, \phi)$	=	the diffuse irradiance distribution, and
$RS(\theta, \phi)$	=	the pyranometer RS.

The Diffuse RS for All and Clear-Sky Conditions

All-Sky Conditions

RS_d will change in value with the change of the diffuse irradiance distribution, $D(\theta, \phi)$ although its value will always lie between the extreme values of $RS(\theta, \phi)$. Thus, for all-sky conditions, RS_d can be considered as,

$$RS_d = \frac{RS_{max} \ (\theta, \phi) + RS_{\ min} \ (\theta, \phi)}{2}$$

and, its percentage uncertainty, u_d, can be considered as,

$$u_d = \pm \frac{\left[RS_{max} \ (\theta, \phi) - RS_{min} \ (\theta, \phi)\right] * 100}{2 \ RS_d}$$

where, RS_{max} (θ, ϕ) are the maximum and minimum responsivities of the pyranometer.

Clear-Sky Conditions

A reasonable assumption is that RS_d will equal the RS at $\theta = 45°$ and that it will change in the range from $RS(30°, \phi)$ to $RS(60°, \phi)$, depending on the sky conditions and the average zenith/azimuth angle of the unblocked circumsolar around the shading disk. The reponsivity change in the range from θ equals 30° to 60° is then added to the total uncertainty of RS.

Thus, for the clear-sky condition,

$$RS_d = \int_0^{2\pi} RS(45, \phi) \cdot d\phi$$

Procedure

Shade/Unshade Timing and Sequence (see Figure 1)

From the ASTM standard:

- the shaded period = 30 * τ
- the unshaded period = 60 * τ

where τ is the pyranometer time constant. For the 8-48s pyranometers τ = 5 seconds. Thus, the shaded period = 150 seconds, and the unshaded period = 300 seconds.

The shade/unshade sequence is repeated at four azimuthal positions: 0°, 120°, 240°, and 0°, clockwise, from the original position where the signal connector is at a reference marked position.

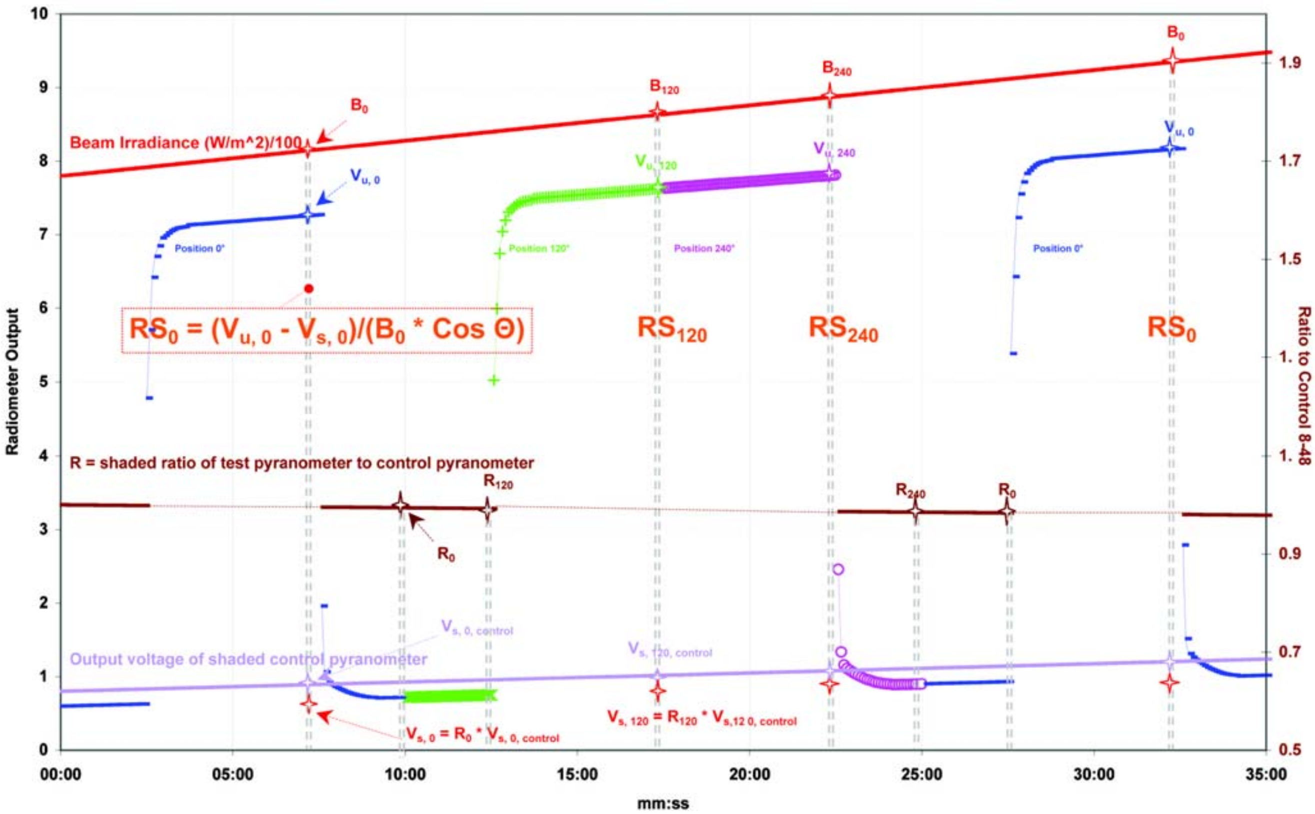


Figure 1. Timing diagram for the shade/unshade method to calibrate EPLAB Model 8-48.

Data Collection

The data are collected every 5 seconds from the TP and a continuously shaded CP, and an absolute cavity radiometer, simultaneously. The test and control pyranometers, EPLAB model 8-48, are installed shaded and on trackers. The shade/unshade sequences are performed on the TP only.

The data are collected in the zenith angle range from 40° to 50°.

Timed so that $\theta = 45°$ would occur at the middle of the procedure period (i.e., at the end of the unshaded period during position 120°).

The ratios of the shaded output voltages from the test and control pyranometers are calculated for a minimum period of 5 minutes, before and after position 0°. The ratios are then fitted to a function of θ.

RS Calculation

For the TP:

$$RS_{test,\,d} = \left(\sum_{i=0}^{n} RS_i\right) / n,$$

where n is the number of positions.

For the CP:

$$RS_{control,\,d} = RS_{test,\,d} \,/\, R_{sh,\,45},$$

where $R_{sh,45}$ is the shaded ratio at zenith angle = 45° from the ratio equation in Figure 2.

The RS Equation at Each Position

$$RS_{test,u,i} = \frac{U_{test,i} - S_{test,u,i}}{B_{u,i} * \mathrm{Cos}\,\theta_{u,i}}$$

where all the reported values are the average of the last three readings during the shade or unshaded periods, and,

i	=	the i[th] horizontal position where I = 0°, 120°, or 240°,
$RS_{test,\,u,\,i}$	=	the unshaded RS of the TP, ($\mu V/(W.m^2)$),
$U_{test,\,i}$	=	the unshaded output voltage of the TP, (μVDC), and
$S_{test,\,u,\,i}$	=	the calculated shaded output voltage of the TP, during the unshaded period, (μVDC)

$$S_{test,\,u,\,i} = R_{sh,\,i} * S_{control,\,u,\,i}$$

where,

$R_{sh,\,i}$ = the shaded ration ($S_{test,\,s,\,i}$ /$S_{control,\,s,\,i}$), where $S_{test,\,s,\,i}$ is the shaded output voltage of the TP, during the shaded period, and

$S_{control,\,u,\,i}$ = the shaded output voltage of the CP, during the unshaded period.

Note: $R_{sh,\,i}$ can also be substituted by the R_{sh} equation in Figure 2 at each θ. TP may stay unshaded during the shade/unshade period!

$B_{u,\,i}$ = the beam irradiance, during the unshaded period, (W/m^2).

$\theta_{u,\,i}$ = the solar zenith angle, during the unshaded period.

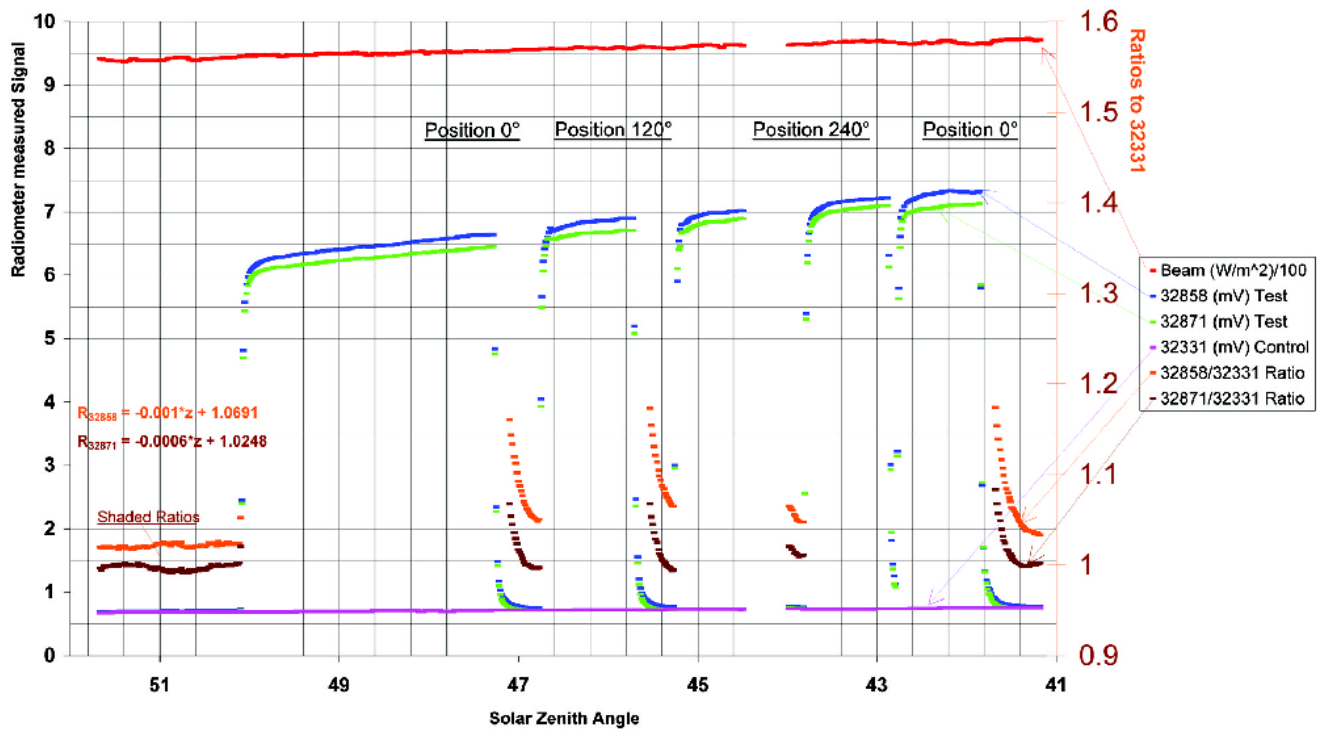


Figure 2. Raw data for the shade/unshade on May 8, 2001.

The Calibration Uncertainty

$$u_{95} = \pm \sqrt{(u_{acr})^2 + (u_{DAQ})^2 + (u_{\theta})^2 + (u_{RS,\Delta\theta})^2 + (K * u_R)^2}$$

where the uncertainties are

u_{acr} = absolute cavity radiometer; (~0.4% Rdg),
u_{DAQ} = data acquisition system: (~0.05% Rdg),
u_{θ} = zenith angle calculation; (~0.02% Rdg),
$u_{RS,\Delta\theta}$ = effective RS resulting from its change in the zenith angle range from 30° to 60°; (~1.5 to 2.5% Rdg),

$$u_{RS,\Delta\theta} = \frac{RS_{max} - RS_{min}}{2 * RS_d} * 100$$

where RS_{max} and RS_{min} are the maximum and minimum responsivities in the zenith angle range from 30° to 60°.

$u_{RS,equiv}$ = nonequivalence of the shaded and unshaded responsivities; because the RS equation assumes that the shaded and unshaded responsivities are equal; ($U_{RS,equiv}$ ~0.5% Rdg),

$$u_{RS,equiv} = \frac{MAX\{RS_i\} - MIN\{RS_i\}}{2 * RS_d} * 100$$

u_R = shaded ration, R_{sh}, resulting from fitting the ratios to a function of θ; (from Figure 2, u_R ~0.6% Rdg); K is the shade/unshade fraction (S/U), where S and U are the shaded and unshaded output voltages of the TP at any position; (K ~0.1 thus, K * U_R ~0.06%).

The total uncertainty for the TP: $U_{test, 95} = \pm \{(u_{test, 95}$ % Rdg + $u_{off}\}$, where u_{off} is the uncertainty resulting from the thermal effect (±1 W/m^2 for model 8-48); ($U_{test, 95}$ ~25% Rdg).

The total uncertainty for the control instrument: $U_{control, 95} = \pm \{[(u_{test, 95})^2 + (u_R)^2]^{1/2}$ % Rdg + $u_{off}\}$; (~2.6% Rdg).

Results of the Shade/Unshade for the Clear-Sky Diffuse RS

Table 1 shows the results of the shade/unshade performed on May 8, 2001, and the results of using the actual ratios at each position (0°, 120°, and 240°) versus the results of using the ratios function in Figure 2. The RS of the CP, Serial Number 32331, is calculated using each of the TPs responsivities and their ratios to 32331. The results show the consistency of the results and that the ratios function can produce comparable results if used during the shade/unshade period.

Table 1. Results from the Shade/Unshade on 5/8/2001.

Serial Number	32858 Shade/Unshade Test	32871 Shade/Unshade Test	32331 Shaded Control	
			Using 32858 Ratio	Using 32871 Ratio
RS_d Using $R_{sh,i}$ Ratios $\mu V/(W.m^2)$	9.128	8.922	8.916	8.943
RS_d Using R_{sh} Function $\mu V/(W.m^2)$	9.154	8.924	8.942	8.943
$\pm U_{95}$	2.5 % + 1 W/m²	2.6 % + 1 W/m²	2.6 % + 1 W/m²	2.7 % + 1 W/m²

Figure 3 shows the historical results of the three pyranometers. On May 1, 2000, Serial Number 32858 was calibrated using the shade/unshade; then was used as a reference for BORCAL00-01 (May 16, 2000), in which Serial Numbers 32871 and 32331 were calibrated unshaded. During the April 24, 26,

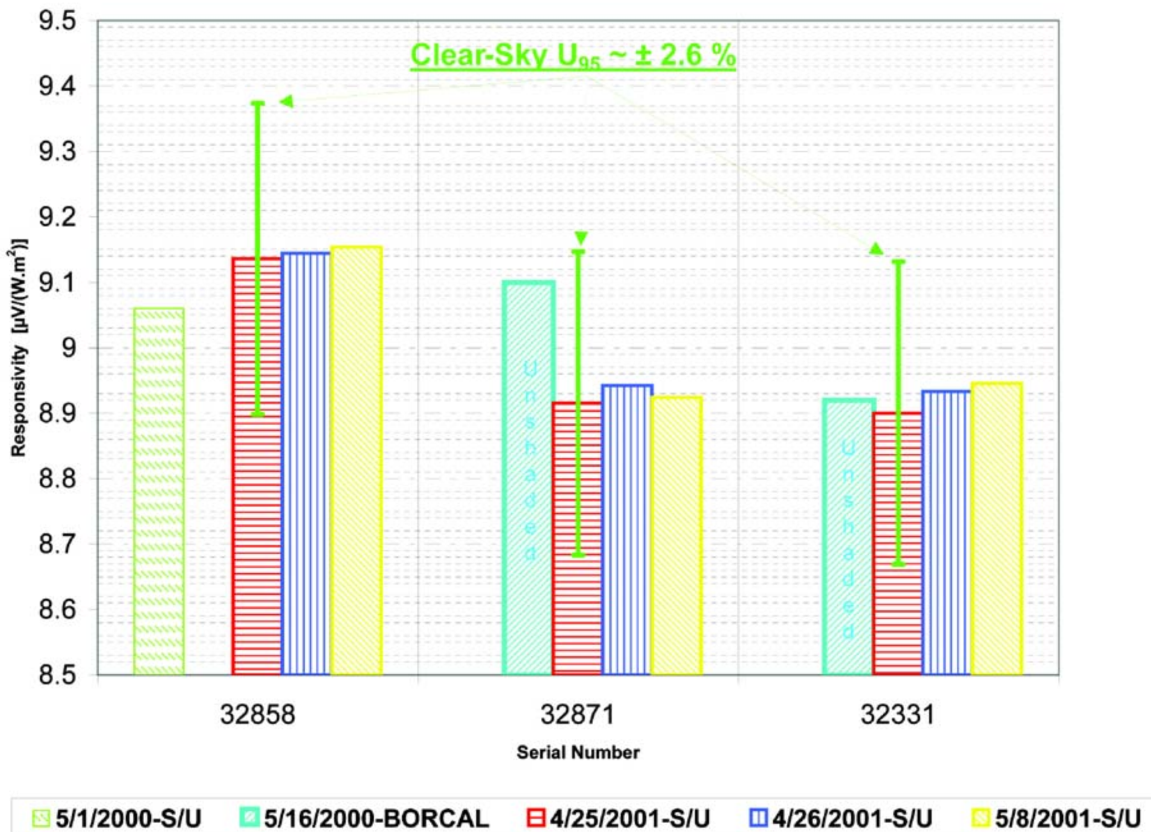


Figure 3. Shade/Unshade/BORCAL historical results.

and May 8, 2001, events, the pyranometers were calibrated using the shade/unshade procedure, with 32331 being the CP. The historical results show that all responsivities are within the stated uncertainties.

Transferring NREL Clear-Sky Diffuse Reference to Other EPLAB 8-48s

The two-reference pyranometers, Serial Numbers 32858 and 32871, and six TPs, model 8-48, were installed outdoor, shaded, and on sun trackers.

The reference diffuse irradiance was calculated as the average reading of Serial Numbers 32858 and 32871.

Results of calibrating the six TPs are shown on the following pages.

Calibration Results from Clear-Sky Conditions

	15187	33253	33273	32872	32873	32331
RS $(uV/W/m^2)_{BORCAL2001}$	10.46 unsh @ 45°	8.76 unsh @ 45°	9.35 unsh @ 45°	9.44 unsh @ 45°	8.57 unsh @ 45°	8.96 shad
RS $(uV/W/m^2)_{March2002}$	10.25 shad	8.78 shad	8.97 shad	9.45 shad	8.73 shad	9.08 shad
SD $(uV/W/m^2)$	0.17	0.60	0.14	0.08	0.09	0.12
U_{95} (%)	3.39	13.62	3.21	1.74	2.12	2.63

Errors from reference diffuse irradiance during Clear-Sky conditions

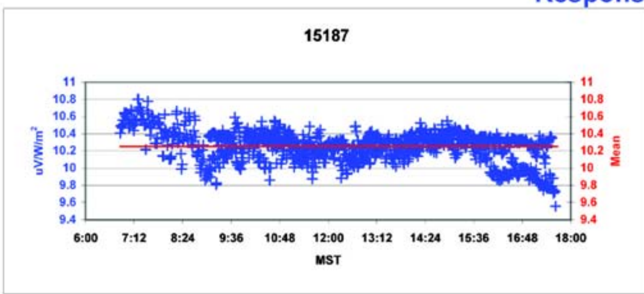
9&19 March,2002	15187	33253	33273	32872	32873	32331
MSE (W/m^2)	0.99	10.18	0.85	0.39	0.57	0.93
StDev (W/m^2)	1.21	14.29	1.04	0.65	0.60	1.27
$U_{95}(W/m^2)$	1.62	5.51	1.50	1.16	1.15	1.65
MSE (%)	2.88	46.35	2.57	0.73	1.12	1.72
StDev (%)	4.72	136.05	4.43	0.95	1.44	2.27
U_{95} (%)	3.14	16.60	3.04	1.43	1.76	2.20

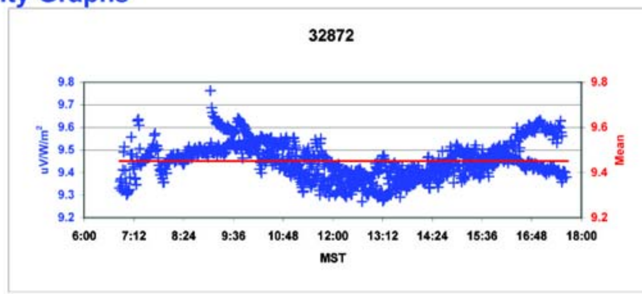
Errors from reference diffuse irradiance during All-Sky conditions

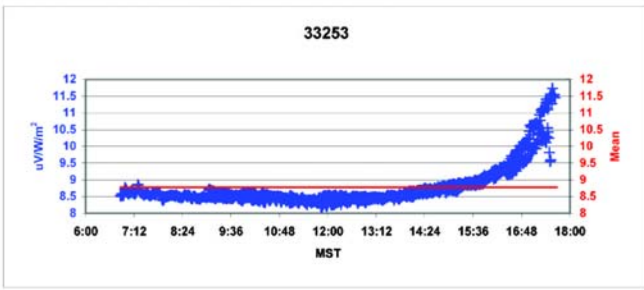
1 to 22 March, 2002	15187	33253	33273	32872	32873	32331
MSE (W/m^2)	19.95	9.07	47.99	3.95	5.66	26.34
StDev (W/m^2)	48.47	18.03	90.45	9.50	13.64	55.33
$U_{95}(W/m^2)$	9.95	6.10	13.68	4.40	5.28	10.67
MSE (%)	4.07	10.92	9.93	1.37	1.41	4.03
StDev (%)	4.77	28.00	17.54	2.62	1.87	4.65
U_{95} (%)	3.22	7.55	6.04	2.33	2.00	3.18

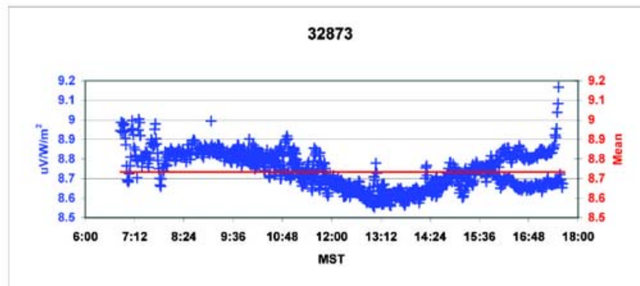
Calibration Results from March 2002 Comparison

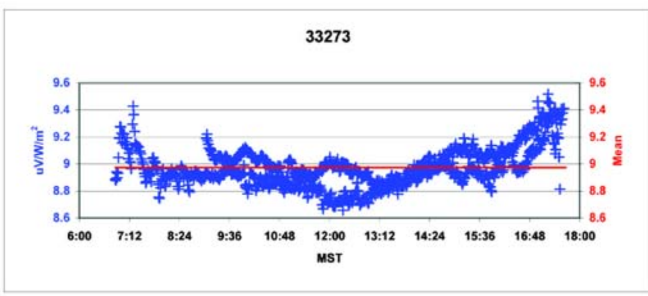
Responsivity Graphs

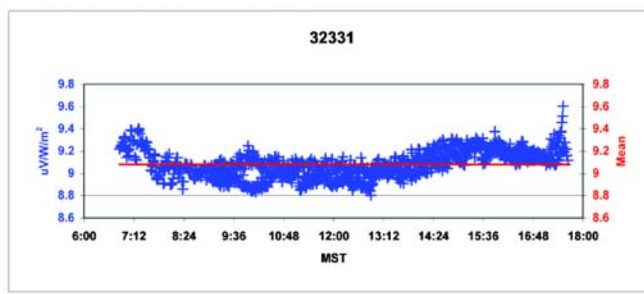




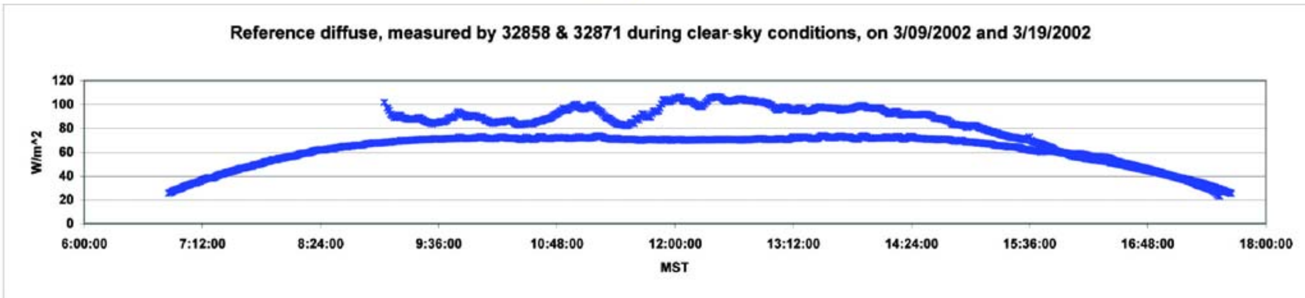




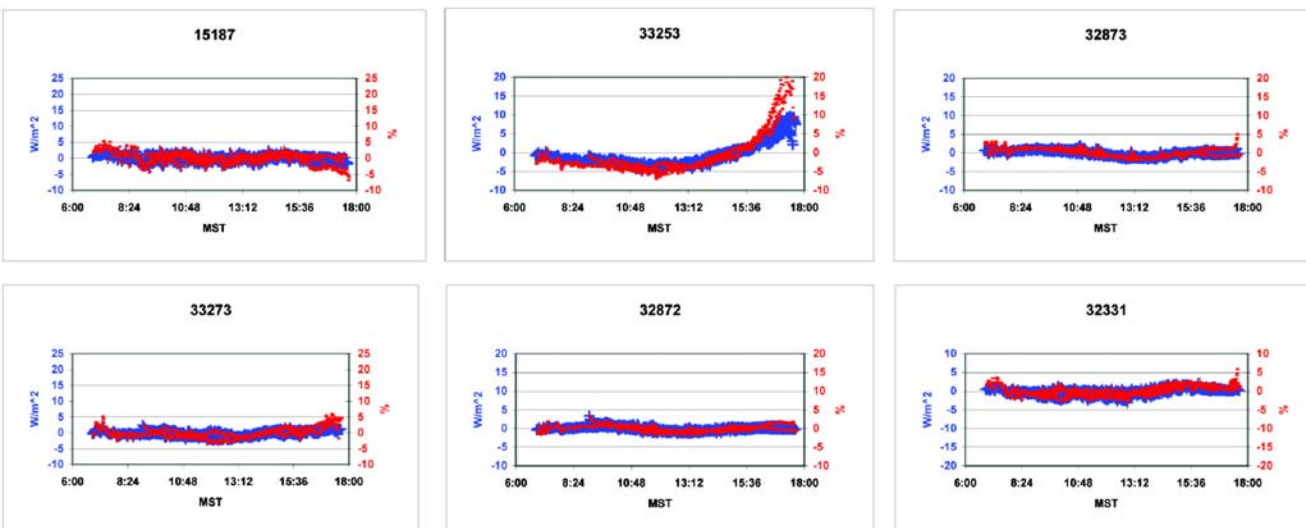




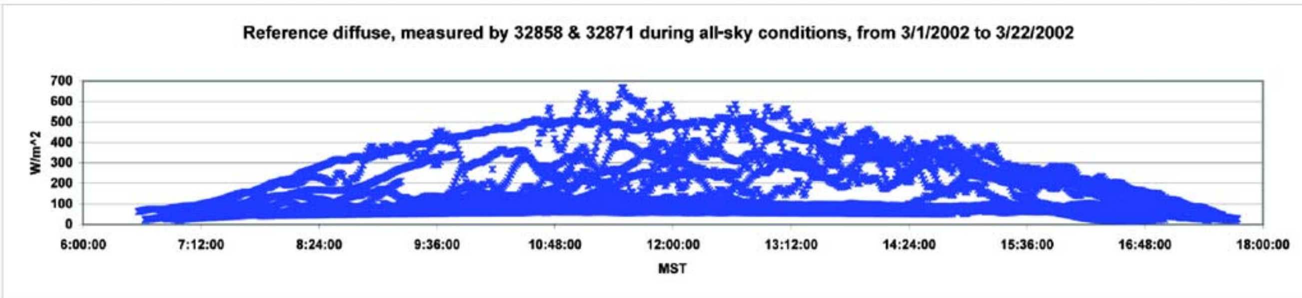
Clear-Sky Conditions



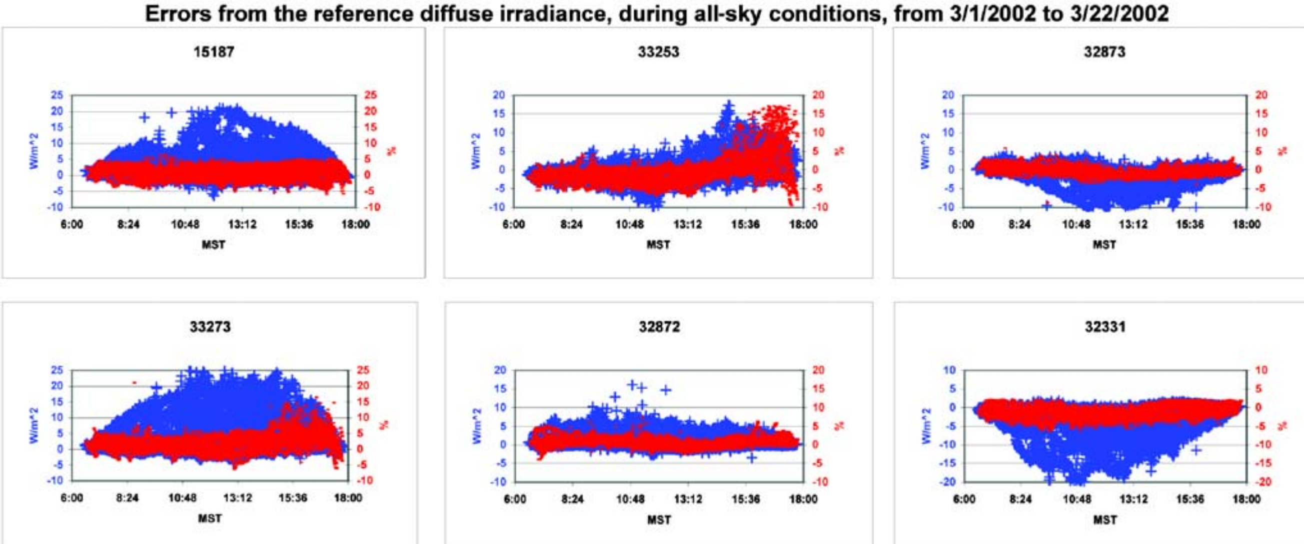
Errors from the reference diffuse irradiance, during clear-sky conditions, on 3/09/2002 and 3/19/2002



All-Sky Conditions



Errors from the reference diffuse irradiance, during all-sky conditions, from 3/1/2002 to 3/22/2002



Conclusions

The shade/unshade method, using a CP, is consistent from calibration to calibration. Using the CP we reduced and quantified the errors resulting from the sky instability and the pyranometer time constant, during the shade/unshade periods: (0.06%).

The diffuse RS is best calculated when the TPs are shaded; (from the six TPs, the agreements between the shaded and unshaded calibrations ranged from 0% to 2.5%.

The reference diffuse irradiance can be transferred to shaded TPs with the following precision:

- For clear-sky conditions – 1.2 W/m^w to 1.6 W/m^2 for five pyranometers and 5.5 W/m^2 for Serial Number 33253.

- For all-sky conditions – 4.4 W/m^2 to 10.7 W/m^2 for the six pyranometers (~3% for 4-pyranometers and ~7% for 2-pyranometers.

Future Work

Using the ratio of the TP to the CP, can reduce the number of times the pyranometer is shaded or unshaded; consequently, the waiting time for instrument stability would be reduced. The shade/unshade sequence can then be modified to the following sequence:

1. Shade the TP, then calculate its ratio to the shaded CP.

2. Unshaded the TP then rotated to six positions instead of three (0°, 60°, 120°, 180°,…, and 270°), to account for azimuth response.

3. Shade the TP, then calculate its ratio to the CP. Then establish the ratios function and calculate the RS for each position as described.

4. Repeat steps 1 through 3. This will result in two RSs for each of the six positions at two respective zenith angles (z). Then calculate the RS at z = 45° by linear interpolation/extrapolation of the two RSs.

5. The average of the six Rss at Z = 45° will equal the diffuse RS of the TP.

Investigate the behavior of Serial Numbers 32253 and 33273.

Corresponding Author

Ibrahim Reda, ibrahim_reda@nrel.gov, (303) 384-6385