Improving the Accuracy of Using Pyranometers to Measure the Clear Sky Global Solar Irradiance

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Abstract

Pyranometer users have customarily applied one responsivity value when calculating the global solar irradiance. Usually, the responsivity value is reported by either the manufacturer or a calibration facility. Many pyranometer calibrations, made at the National Renewable Energy Laboratory (NREL) and elsewhere, have shown that the responsivity of a pyranometer changes with the change in solar zenith and azimuth angles. Depending on how well the pyranometer sensor is radiometrically leveled, these changes can exceed ±5% of the reported responsivity, which means that errors in the calculated global solar irradiance can exceed ±5% from the nominal values. This is a method to decrease the errors resulting from the change of the solar zenith angle under clear-sky conditions. Two responsivity functions, morning and afternoon, were used instead of one responsivity value. The two functions have been chosen because of asymmetry of the morning and afternoon cosine responses demonstrated by some pyranometers.

RCC BORCAL Results

The procedure NREL uses to calibrate radiometers is called Broadband Outdoor Radiometer Calibration (BORCAL). The software used to acquire the data, calculate responsivities, and print the final BORCAL report is called Radiometer Calibration and Characterization (RCC). The responsivity of each pyranometer is reported as responsivity versus solar zenith angle bin, each bin is 10° from 0° to 90°. The responsivity of the 45° to 55° range is also reported. Pyranometer users have customarily applied the responsivity for the range from 45° to 55° to calculate the global solar irradiance.

$$G_i = \frac{V_i}{RS_{45-55}} \tag{1}$$

where: G_i = i^{th} calculated global solar irradiance in W/m^2
V_I = i^{th} output voltage of the pyranometer in microvolts (µV)
RS_{45-55} = responsivity at solar zenith angle range from 45° to 55° in $\mu V/W/m^2$.

Figure 1 shows the responsivity versus zenith angle for PSP 25825F3. From the figure, one can note that the responsivity of the pyranometer changes with zenith angle. Thus, using one responsivity, RS_{45-55}, can introduce errors into the global irradiance calculation.

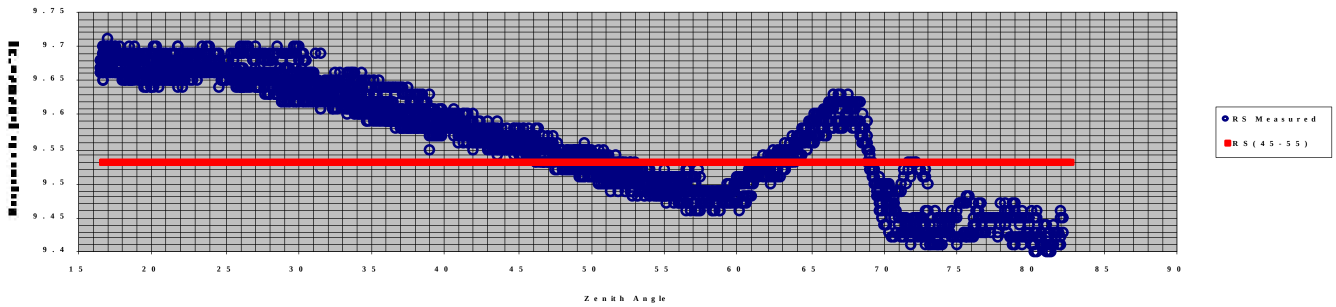

Figure 1. Responsivity versus solar zenith angle for 25825F3, from BORCAL9702.

The change of responsivity versus zenith angle is called the cosine response. The cosine response is unique for each pyranometer. It depends on how well the sensor is leveled during assembly, the resolution of the spirit bubble level in the base of the pyranometer, and the surface roughness of the sensor. Figure 2 shows an example of a pyranometer with an unleveled sensor. In this case, if one responsivity value were used, the resulting errors are from -5% to 1.7% in global irradiance measurements.

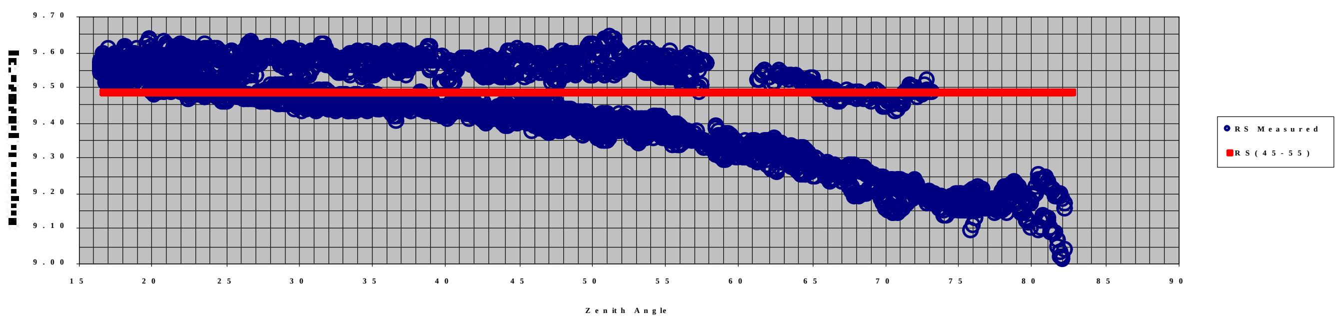

Figure 2. Responsivity versus zenith angle for 73-38, from BORCAL9702.

Proposed Method

This method can reduce the errors in global solar irradiance measurements, using pyranometers, by using a function of responsivity versus zenith angle. Because of the asymmetry between the morning and afternoon cosine response for a pyranometer, two functions, $RS_{am}(\theta)$ and $RS_{pm}(\theta)$, were chosen to fit the morning and the afternoon responsivity versus zenith angle. Then, the global solar irradiance is calculated in the morning, using the following equation:

$$G_i = \frac{V_i}{RS_{am}}(\theta_i) \qquad (2)$$

where: G_i = i^{th} global solar irradiance reading in W/m^2
V_i = i^{th} output voltage of the pyranometer in microvolts (μV)

$RS_{am}(\theta_i)$ = pyranometer's responsivity calculated by substituting the i[th] zenith angle, θ, in the morning function $RS_{am}(\theta)$.

In the afternoon, the irradiance is calculated using Eq. (1) and substituting $RS_{am}(\theta_i)$ by $RS_{pm}(\theta_j)$.

In order to calculate the coefficients of each fitting function, a number of data points are chosen at a 5° zenith angle increment. The data points are then substituted in the function. This will form a set of (n+1) equations with (n+1) unknown coefficients. Matrices are then used to solve the (n+1) equations. The following two cosine functions were chosen to:

$$RS_{sm}(\theta) = \sum_{i=0}^{n} a_i * \cos^i \theta_{i,am} \tag{3}$$

$$RS_{pm}(\theta) = \sum_{j=0}^{m} p_j * \cos^j \theta_{j,pm} \tag{4}$$

where: $RS_{am}(\theta)$ and $RS_{pm}(\theta)$ = morning and afternoon responsivity functions of a pyranometer, respectively

n and m = number of morning and afternoon data points used to solve the $(n+1)^{th}$ and $(m+1)^{th}$ order equations, respectively

a_i and p_j = i^{th} morning and j^{th} afternoon coefficients, respectively

$\theta_{i,am}$ and $\theta_{j,pm}$ = i^{th} morning and j^{th} afternoon zenith angles, respectively.

A detailed procedure to solve the matrices is described in a June 1998 NREL report NREL/TP-560-24833.

Results for EPLAB PSP, Serial Number 25825F3

Table 1 shows the resultant morning and afternoon coefficients.

Table 1. Morning and afternoon coefficients for 25825F3.

Index	Morning Coefficients (ai)	Afternoon Coefficients (pi)	Index	Morning Coefficients (ai)	Afternoon Coefficients (pi)
0	322.0557	-177040.6421	9	-10051108841	6218266505.218
1	-15340.3639	4380869.3172	10	10234305726	8230850516.817
2	335132.3279	-49189047.4696	11	-4157036370.6	-16754266146.5
3	-4316594.1507	331183115.551	12	-5383059629.6	14738556229.14
4	36609827.5220	-1486510847.19	13	11400268630	-7542415882.63
5	-216280857.64	4666092359.57	14	-10312974037	2180603495.788
6	917533664.659	-10398110383.6	15	5409879832.5	-277477554.087
7	-2833288139.8	16154549290.1	16	-1599620089.6	
8	6351005967.98	-16016335476.3	17	207760813.39	

For pyranometer PSP 25825F3, Figure 3 shows the responsivity versus true solar time, using BORCAL9702 and the two fitting responsivity functions, $RS_{am}(\theta)$ and $RS_{pm}(\theta)$. Figure 4 shows the percentage error in the global solar irradiance measurements, if one responsivity (e.g., responsivity at zenith angle range from 45° to 55°) is used, and the percentage error if the two fitting responsivity functions, $RS_{am}(\theta)$ and $RS_{am}(\theta)$, are used. The percentage errors are calculated as follows:

$$E_{i,RS} = \frac{\left[\dfrac{V_i}{RS_{45-55}} - G_{i,ref}\right]*100}{G_{i,ref}} \tag{5}$$

where: $E_{i,RS}$ = error of the i^{th} data point using one responsivity, RS_{45-55}
$G_{i,ref}$ = i^{th} reference global solar irradiance
V_I = i^{th} output voltage from the pyranometer, in microvolts
RS_{45-55} = responsivity of the pyranometer at 45° to 55° zenith angle bin

and,

$$E_{i,am,RS(\theta)} = \frac{\left[\dfrac{V_i}{RS_{am}(\theta_1)} - G_{i,ref}\right]*100}{G_{i,ref}} \tag{6}$$

where: $E_{i,am,RS}(\theta)$ = error of the i^{th} data point using the morning responsivity function
$RS_{am}(\theta_i)$ = morning responsivity calculated by substituting θ by θ_i in the morning responsivity function, $RS_{am}(\theta)$, where θ_i is the i^{th} zenith angle.

The errors resulting from using the afternoon responsivity function, $E_{j,pm,RS(\theta)}$, are calculated using Eq. (6) by substituting V_i and $RS_{am}(\theta_i)$ by V_j and $RS_{pm}(\theta_j)$.

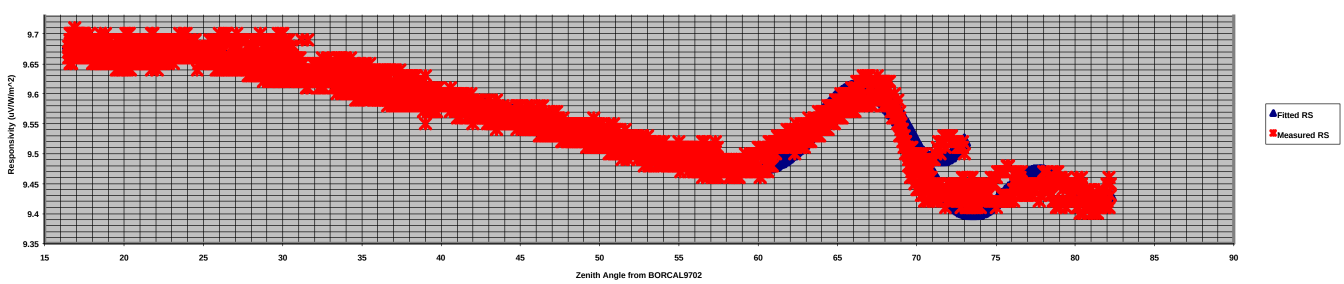

Figure 3. Measured and fitted responsivities versus solar zenith angle for 25825F3, from BORCAL9702.

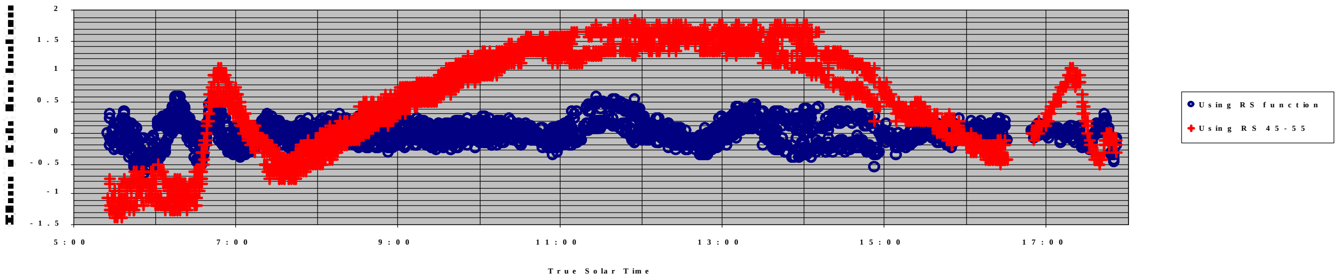

Figure 4. Percentage errors resulting from using RS (45-55) and RS functions versus true solar time for 25825F3.

Table 2 shows the maximum and minimum percentage errors at zenith angle ranges 16.5° to 45° and 55° to 82°.

Table 2. Percentage errors resulting from using $RS_{45\text{-}55}$ and functions RS() for 25825F3.

Zenith Angle Range	**Using $RS_{45\text{-}55}$**		**Using $RS_{am}(\theta)$ and $RS_{pm}\theta)$**	
	Maximum Error	**Minimum Error**	**Maximum Error**	**Minimum Error**
16.5° to 45°	1.85	0.3	0.5	-0.5
55° to 82°	1.05	-1.4	0.6	-0.65

Conclusions

Figure 4 and Table 2 show that the values of percentage errors resulting from using $RS_{45\text{-}55}$ are larger than the percentage errors that result from using the two responsivity functions, $RS_{am}(\theta)$ and $RS_{pm}(\theta)$. The table and figure also show that the errors are increasing outside the zenith angle range from 45° to 55° when $RS_{45\text{-}55}$ is used, but the errors stayed about the same using the two responsivity functions, $RS_{am}(\theta)$ and $RS_{pm}(\theta)$.The two responsivity functions, $RS_{am}(\theta)$ and $RS_{pm}(\theta)$, are only valid between and at the boundary conditions. For this reason, it is important to calibrate the pyranometer from sunrise to sunset in order to cover the zenith angle range from 0° to 90°. If zenith angle at solar noon does not reach 0° on the day of calibration or if calibration was stopped before 90° is reached, extreme care should be taken in estimating data points outside the boundary condition to cover the range 0° to 90°. These estimated data points can then be included in the data set used to calculate the morning and afternoon coefficients of the functions $RS_{am}(\theta)$ and $RS_{pm}(\theta)$.

This method describes the first step toward improving the uncertainty of measuring the clear-sky global solar irradiance. The second step is to develop two responsivity functions, $RS_{am}(\theta, \phi)$ and $RS_{pm}(\theta, \phi)$, where ϕ is the solar azimuth angle, to include the azimuthal response of a pyranometer. This was not discussed in this paper because of the complexity of the functions and the lack of calibration data from different days of the year. More calibrations from different days of the year are recommended to describe the zenith and azimuthal responses more accurately for a pyranometer.