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THE IMPACT OF INDOOR AND OUTDOOR RADIOMETER CALIBRATION ON SOLAR MEASUREMENTS

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ABSTRACT: Accurate solar radiation data sets are critical to reducing the expenses associated with mitigating performance risk for solar energy conversion systems, and they help utility planners and grid system operators understand the impacts of solar resource variability. The accuracy of solar radiation measured by radiometers depends on the instrument performance specification, installation method, calibration procedure, measurement conditions, maintenance practices, location, and environmental conditions. This study addresses the effect of calibration methodologies and the resulting calibration responsivities provided by radiometric calibration service providers such as the National Renewable Energy Laboratory (NREL) and manufacturers of radiometers. Some of these radiometers are calibrated indoors, and some are calibrated outdoors. To establish or understand the differences in calibration methodology, we processed and analyzed field-measured data from these radiometers. This study investigates calibration responsivities provided by NREL's broadband outdoor radiometer calibration (BORCAL) and a few prominent manufacturers. The BORCAL method provides outdoor calibration responsivity of pyranometers and pyrheliometers at a 45° solar zenith angle and responsivity as a function of solar zenith angle determined by clear-sky comparisons to reference irradiance. The BORCAL method also employs a thermal offset correction to the calibration responsivity of single-black thermopile detectors used in pyranometers. Indoor calibrations of radiometers by their manufacturers are performed using a stable artificial light source in a side-by-side comparison of the test radiometer under calibration to a reference radiometer of the same type. In both methods, the reference radiometer calibrations are traceable to the World Radiometric Reference. These different methods of calibration demonstrated 1% to 2% differences in solar irradiance measurement. Analyzing these values will ultimately assist in determining the uncertainties of the radiometer data and will assist in developing consensus on a standard for calibration.

Keywords: Radiometer calibration, thermopile, photodiode, pyranometer, pyrheliometers, global horizontal irradiance, direct normal irradiance, diffuse global irradiance, responsivity, measurement uncertainty

1 INTRODUCTION

One of the critical components for a successful solar energy project is access to accurate solar resource data. Pyranometer and pyrheliometer radiometers are used to measure global horizontal, diffuse, plain-of-array, and direct normal solar irradiances. To acquire accurate solar resource information from these radiometers, the tools used to design, manufacture, calibrate, deploy, and maintain them must continuously improve to provide necessary assurances to solar system financiers, developers, and operators. Investors must understand the quantitative terms of the risks of their investments based on the knowledge of the solar resource inputs, and they need to be assured that system operators can operate and maintain their solar energy conversion system assets with maximum efficiency and value.

This study assesses multiple radiometer calibration methodologies and the resulting variations of irradiance measurements. Calibration is one source of uncertainty in radiometric data. Addressing the irradiance differences in data resulting from the myriad calibration methodologies helps quantify the radiometric measurement uncertainties. Further, the study serves to open a dialogue among radiometer manufacturers and calibration service providers to develop a consensus on a standard approach to calibration that will alleviate, reduce, or explain the differences in irradiance measurements due to the differing calibration methodologies.

2 METHOD

The radiometric data used in the study is traceable to the System Internationale, or SI, units through the World Radiometric Reference scale [1]. Data was collected for two months through the Measurement Instrumentation Data Center at the National Renewable Energy Laboratory (NREL). Clear-sky data were selected for the analysis based on a clearness index (Kt) greater than 0.6 (Eq.1).

$$Kt = \frac{GHI}{ETRN * \text{Cos (SZA)}} \qquad (1)$$

where:
GHI = global horizontal irradiance (W/m^2)
ETRN = extraterrestrial direct normal radiation (W/m^2)
SZA = solar zenith angle (degree).

The 1-minute data from the unit under test (UUT) radiometers were compared to reference GHI or direct normal irradiance (DNI) data. The reference irradiance data were obtained using a Kipp and Zonen model CHP1 pyrheliometer (serial number 140108), and reference diffuse horizontal irradiance (DHI) measurements were made by a shaded Kipp and Zonen model CM22 pyranometer (serial number 010047). These two reference radiometers provide the lowest measurement uncertainty for GHI [2], [3], [4]. A component sum method (Eq. 2) was used to obtain reference GHI data using measured data from the above reference radiometers.

$$GHI = DNI * Cos(SZA) + DHI \qquad (2)$$

The DNI UUT radiometer data were directly compared to the reference DNI. All of the radiometers included in the study were calibrated by NREL's BORCAL process and the radiometer manufacturers using indoor calibration methods. The radiometers were deployed soon after calibration by the two methods.

TABLE I

RESPONSIVITY VALUE CASES APPLIED IN THE STUDY. WHEN THERMAL OFFSET CORRECTION IS APPLICABLE (YES), EQUATION (3) IS USED. IF NOT APPLICABLE (NO), EQUATION (4) IS USED.

Cases	Calibration Method	Thermal Offset Correction Applicability		
		Thermopile Pyranometer	**Thermopile Pyrheliometer**	**Silicon Photodiode Pyranometer**
Case 1	BORCAL responsivity as a function of SZA	Yes	No	No
Case 2	Manufacturer calibration responsivity at manufacturer-specified SZA in degrees	N/A	N/A	N/A
Case 3	BORCAL responsivity at 45°	Yes	N/A	N/A
Case 4	BORCAL responsivity at 45°	No	N/A	N/A
Case 5	Manufacturer calibration responsivity at manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation	N/A	Yes	N/A

Measurement degradation and/or sensitivity drift were not considered to affect the responsivity of the radiometers. Further, our analyses were well within the recommended calibration cycle of one to two years [5]. The two months of data in this study were collected from June 23, 2015, through July 19, 2015. The analyses are based on measurements under clear skies.

2.1 Background on Calibration Methodology

NREL provides the following calibration services through the BORCAL process;

1. Calibration responsivity at a 45° SZA with thermal offset correction (using Eq. 3) for thermopile pyranometers and no thermal offset correction for thermopile pyrheliometers and photodiode.
2. Calibration responsivity as a function of SZA with thermal offset correction (using Eq. 3) for thermopile radiometers and no thermal offset correction for thermopile pyrheliometers and photodiode.

$$R = \frac{(V - R_{net} * W_{net})}{GHI} \quad (3)$$
$$GHI = DNI * Cos(SZA) + DHI$$

where:
R = the pyranometer's responsivity, in µV/ (Wm^{-2})
V = the pyranometer's sensor output voltage, in µV
DNI = the direct normal irradiance measured by a primary or standard reference pyrheliometer, measuring the beam irradiance directly from the sun's disk, in Wm^{-2}
SZA = the solar zenith angle, in degrees
DHI = the diffuse sky irradiance, without the beam irradiance from the sun's disk, measured by a shaded pyranometer, in Wm^{-2}
R_{net} = the pyranometer's net infrared responsivity, in µV/(Wm^{-2})
$Wnet$ = the effective net infrared irradiance measured by a collocated pyrgeometer, in Wm^{-2}.

Indoor calibration methods by manufacturers provide single calibration responsivity, typically at approximately normal incidence. In most cases, the indoor calibration method uses Eq. 4:

$$R_{UUT} = \frac{V_{test}}{V_{ref}} R_{ref} \quad (4)$$

where:
R_{test} = responsivity of the radiometer under calibration, µV/(Wm^{-2})
V_{ref} and Vtest = the voltages (µV), measured using the reference and the field radiometers, respectively
R_{ref} = responsivity, µV/(Wm^{-2}) of the reference radiometer.

2.2 Measurement Analysis Method

To analyze the measured data, the radiometric data from the UUT radiometers were back-calculated to determine the raw voltage readings using Eq. 5 This equation excludes the thermal offset correction applied by NREL to the solar irradiance data used in the study. Then the different responsivity values were applied to the voltage readings to generate irradiances based on each responsivity.

The measurement equation for generating raw voltages is:

$$V_{raw} = G_m * R + R_{net} * W_{net} \quad (5)$$

where:
V_{raw} = raw voltage readings, in µV
G_m = measured irradiance, in W/m^2
R = the responsivity, in µV/Wm^{-2} used to produce the initial GHI values (from BORCAL).
Note: G_m applies to both pyranometers and pyrheliometers UUT.

Five responsivity value cases (Table 1) were applied to the raw voltage readings. These values were obtained from the BORCAL and manufacturers' indoor calibration methods—that is, users of the radiometric data obtain calibration responsivity from one of the cases below either from NREL or manufacturers.

For thermal offset correction cases, the thermally corrected voltage reading was obtained using Eq. 6:

$$V_{cor} = V_{raw} - W_{net} * R_{net} \quad (6)$$

where:
V_{cor} = corrected voltage, in μV

The thermal offset correction was applied using net long-wave responsivity (R_{net}) estimated or determined by blackbody characterization of the pyranometer [6] and a collocated pyrgeometer of a body type similar to the thermopile radiometer under test for determining W_{net}, using Eq.7 & 8 [7].

$$W_{net} = W_{in} - W_{out} \quad (7)$$

$$W_{out} = \sigma * T_c^{\ 4} \quad (8)$$

where:
W_{in} = incoming infrared from the pyrgeometer, in W/m^2
W_{out} = outgoing infrared from the pyrgeometer, in W/m^2
T_c = case temperature of the pyrgeometer, in Kelvin (K)
Σ = 5.6704x10^{-8} W/(m^{2}K^4) (Stephan-Boltzmann's Constant).

The measured irradiance can now be determined for each case of responsivity under consideration:

$$G_{new} = \frac{V_{cor}}{R_{case_i}} \text{ or } G_{new} = \frac{V_{raw}}{R_{case_i}} \quad (9)$$

G_{new} is the new GHI and DNI irradiance values obtained through implementing the various calibration cases. R_{case} is the responsivity value for each case. Eq. 9 (left) was applicable for Case 1 and Case 3, and Eq. 9 (right) was used for Case 2 and Case 4; and for photodiodes and thermopile pyrheliometers, the thermal offset corrections (R_{net} and W_{net}) were not applicable.

BORCAL provides responsivity at 2° bins of SZA. For this case, irradiance values are calculated using a high-resolution responsivity and SZA. The high-resolution function is obtained by linearly interpolating the morning and afternoon averaged 2° responsivity data [8]. The authors of [9] confirmed that the responsivity as a function of SZA significantly reduces the cosine response error and ultimately the overall uncertainty of the radiometric data.

Note: The reference DNI and the DNI measured by the UUT were corrected for cosine response using the responsivity as a function of SZA method.

A percentage difference calculation was applied to assess the performance of each UUT relative to the reference instruments (Eq. 10):

$$Difference(\%) = \left(\frac{(G_{new} - G_{Ref})}{G_{Ref}}\right) * 100 \quad (10)$$

where G_{Ref} are the irradiance values for the reference instrument in W/m^2.

3 RESULTS AND DISCUSSION

Multiple radiometers were included in the study. Fig. 1 and Fig. 3–5 show the results of the comparison of the UUT to the reference GHI and DNI data. To better understand the differences due to calibration methodology, the results of the comparison were partitioned into 10° bins of SZA in which the center of the bin represented the midpoint of each 10° SZA bin. The information in the figures below is derived from 1-minute irradiance data.

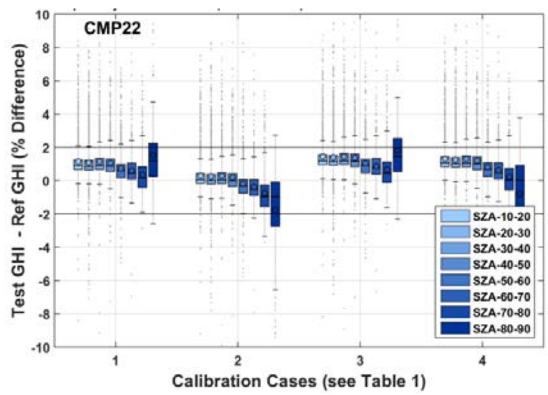

Figure 1: Indoor and outdoor calibration comparison of the reference GHI irradiance to the CMP22 test radiometer irradiance.
Note: Each blue box represents a 10° bin as well as the upper quartile and the lower quartile (also called the interquartile range) of the data in each bin. The circle in each blue box is the mean, and the black line signifies the median value. Ninety-nine percent of the data set is within the whiskers; data beyond the whiskers are plotted with a symbol (dots).

The four calibration cases in Fig.1 show differences up to 2% in GHI measurement. However, the NREL responsivity as a function of SZA (Case 3) and the manufacturer calibration responsivity (Case 4) provide least differences compared to the NREL 45° SZA responsivity with and without thermal offset. One hypothetical explanation for the better agreement of the manufacturer calibration responsivity result relative to the NREL methods is that the reference DHI used in the study is from the same manufacturer and same model as the UUT (CMP22). This condition could favor the CMP22 comparison to the reference data; however, this needs further investigation.

Overall, the NREL responsivity as a function of SZA performed relatively better compared to the GHI UUT (Fig. 3 and Fig. 4). However, this method demonstrated poor performance in higher SZA (Bin 80° to 90° SZA). The reason is that the NREL 2° responsivity bins extend only up to a maximum of 80° during the BORCAL, and the same maximum responsivity number gets repeated beyond the SZA limits (circled in red in Fig. 2) on the day of calibration.

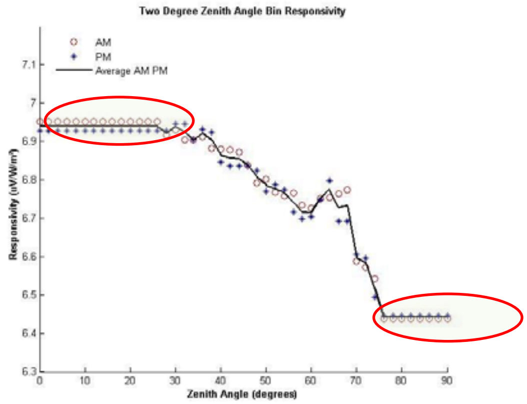

Figure 2: Example of responsivity as a function of SZA for Eppley Laboratory, Inc.'s Standard Precision Pyranometer (Model PSP) after averaging the a.m./p.m. 2° bins and interpolating among each set of bins. Responsivities for less than 26° SZA have the same value as the 26° SZA. The same is true for responsivities greater than 76° SZA, wherein they have the same value as the 76° SZA (modified from [8]).

However, the effect is minimal for the smaller SZA bin (Bin 10° to 20° SZA, Fig. 2—red circle) for three reasons. First, the lowest SZA observed for the study location was approximately 17°; therefore, the bin range had an approximate 18.5° center point lowest SZA for this bin, which is on the higher end of Bin 10° to 20°. Second, the number of occasions when the SZA falls between 17° and 20° SZA during the study period is relatively small compared to Bin 80° to 90° SZA. Third, responsivity at a smaller SZA has much lower dependence on zenith angle compared to a high SZA

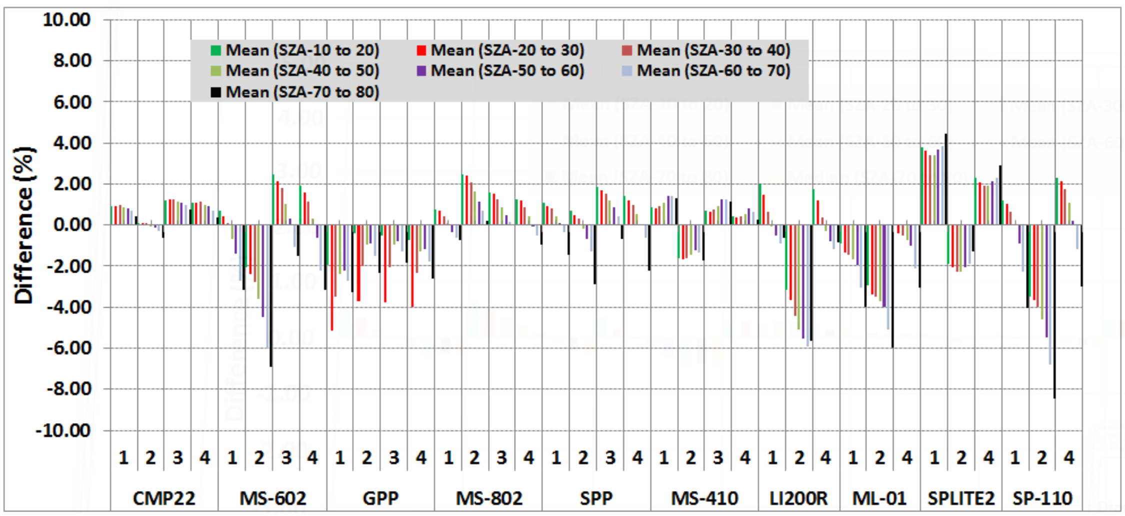

Figure 3: Mean percent differences for six thermopile pyranometers (first six) and four photodiode pyranometers (last four).

As shown in Fig. 3, some of the radiometers—such as MS-802, SPP, L200R, SP-110—in Case 1, which is NREL's BORCAL responsivity as a function of SZA, appear to perform better than they do in the rest of the cases. Overall, comparing the calibration methodologies would provide a better understanding of the performance of the radiometers in relation to SZA.

DNI UUT radiometers were also compared. Fig. 3 shows a comparison of the EKO Instruments model MS-56 to the Hukseflux model DR02.

As stated in Case 5 of Table 1, the comparisons of the MS-56 and DR02 were carried out using manufacturer-supplied equations (11 and 12, respectively).

$$G_{man_{MS-56}} = \frac{V_{raw} + k * V^2{}_{raw}}{R_{test}} \qquad (11)$$

where:

G_{man}= DNI irradiance derived using manufacturer supplied equation, in W/m^2.

k = a multiplier coefficient supplied by the manufacturer, (1/ µV).

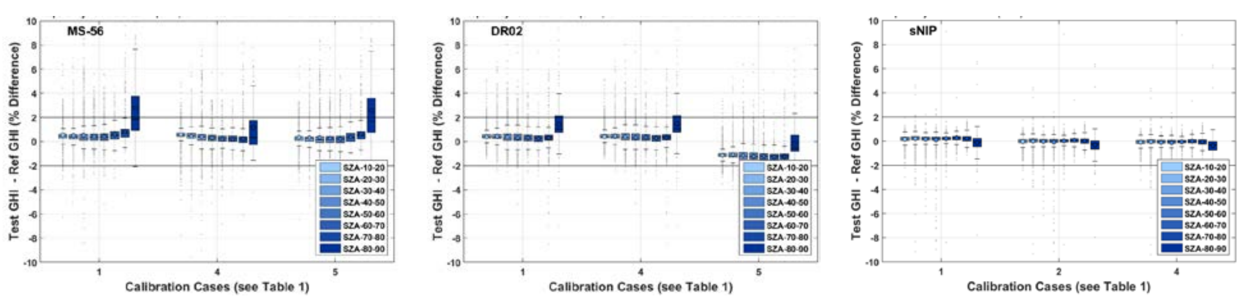

Figure 4: Mean percent differences for three thermopile pyrheliometers.

$$G_{man_{DR02}} = \frac{V_{raw}}{R_{test} * (a * Temp^2 + b * Temp + C)} \quad (12)$$

where a, b, and c are the coefficients supplied by the manufacturer, and $Temp$ (degrees Celsius) is the measured ambient temperature from a collocated temperature sensor.

For MS-56 in Fig. 4, for SZA greater than 30° and lower than 60°, the NREL 45° responsivity (Case 4) method provided a better comparison to the reference data than that of the manufacturer calibration responsivity (Fig. 4); however, the manufacturer calibration responsivity performed better than the NREL responsivity as a function of SZA in most SZA bins. This could be related to no SZA dependence of pyrheliometers.

For DR02, NREL's BORCAL calibration responsivity provided a better result than that of the manufacturer-supplied responsivity; however, for the SPP, the manufacturer-supplied responsivity demonstrated relatively a better result than NREL's BORCAL methods.

4 SUMMARY AND RECOMMENDATION

The accuracy of solar radiation measurements depends on the radiometer calibration procedure. This study addressed the calibration methodology and the resulting calibration responsivity provided by the manufacturers and radiometric calibration service provider. Differences among the values from indoor manufacturers' irradiance compared to outdoor NREL's BORCAL irradiance values are observed to be on the order of 1% to 2% (Fig. 1 and Fig. 3) for pyranometers. Differences for pyrheliometers are less than 1% (Fig. 4). The study is important for quantifying the overall radiometric data uncertainty estimation and to apprise radiometric data users and calibration service providers of the variations in solar resource measurements due to calibration. The results of our study suggest a need to develop a consensus on a standard approach to calibration that will alleviate such differences in irradiance measurements due to the differing calibration methodologies. Guidance from radiometer manufacturers and calibration service providers to the users of these specialized instruments will also aid in understanding the accuracy limitations (e.g., when and where to use the calibration responsivity). For example, radiometers used indoors, such as in accelerated weathering chambers, should be calibrated indoors.

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