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THE IMPACT OF INDOOR AND OUTDOOR RADIOMETER CALIBRATION ON SOLAR MEASUREMENTS

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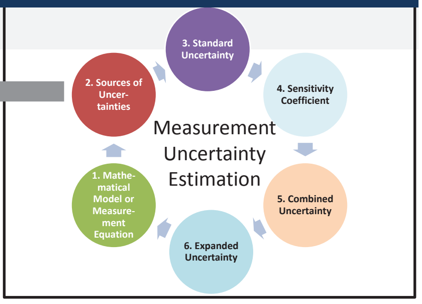
Abstract

This study addresses the effect of calibration methodologies on calibration responsivities and the resulting impact on radiometric measurements. The calibration responsivities used in this study are 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. These different methods of calibration demonstrated 1% to 2% differences in solar irradiance measurement. Analyzing these values will ultimately enable a reduction in radiometric measurement uncertainties and assist in developing a consensus on a standard for calibration.

Method

Some Sources of Measurement Uncertainty

- Calibration
- Spectral Response
- Zenith Angle
- Maintenance—Soiling
- Data logger uncertainty
- Temperature dependence
- Nonlinearity
- Aging



Five different cases are possible for evaluating the impact of calibrations on measurements, as shown in Table 1. All cases are not applicable to every instrument based on their type and available calibration information from the manufacturer.

TABLE 1. RESPONSIVITY VALUE CASES APPLIED IN THE STUDY. THERMAL OFFSET CORRECTION IS APPLICABLE (YES). IF NOT APPLICABLE (NO).

Cases	Calibration Method	Thermal Offset Correction Applicability		
		Thermopile Pyranometer	Thermopile Pyrheliometer	Silicon Photodiode Pyranometer
Case 1	BORCAL responsivity as a function of solar zenith angle (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	No	No
Case 4	BORCAL responsivity at 45°	No	No	No
Case 5	Manufacturer calibration responsivity at specified SZA with supplied measurement equation	N/A	N/A	N/A

Calibration and Measurement Equations applied to Cases 1–5:

NREL's Broadband Outdoor Radiometer Calibration method

$$R = \frac{(V - R_{net} * W_{net})}{GHI}$$

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

R = the pyranometer's responsivity, μV/(Wm^{-2})
V = the pyranometer's sensor output voltage, in μV
DNI = the beam irradiance in Wm^{-2}
SZA = the solar zenith angle, in degrees
DHI = the diffuse irradiance in Wm^{-2}
R_{net} = the pyranometer's net infrared responsivity, in μV/(Wm^{-2})
W_{net} = the effective measured net infrared irradiance in Wm^{-2}.

General method for indoor/manufacturer radiometer calibration

$$R_{UUT} = \frac{V_{test}}{V_{ref}} R_{ref}$$

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

Convert irradiance measurement to raw voltage:

$$V_{raw} = G_m * R + R_{net} * W_{net}$$

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).

Recalculate Irradiance from voltage Cases 1–4

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

G_{new} represents the new GHI and DNI irradiance values obtained through implementing the various calibration cases. R_{case} is the responsivity value for each case.

For thermal offset correction (Cases 1 & 3), the thermally corrected voltage is:

$$V_{cor} = V_{raw} - W_{net} * R_{net}$$

V_{cor} = corrected voltage, in μV

$$W_{net} = W_{in} - W_{out}$$
$$W_{out} = \sigma * {T_c}^4$$

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).

Compute irradiance from voltage Case 5

MS-56 Pyrheliometer

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

G_{man}= DNI irradiance derived using manufacturer supplied equation, in W/m^2.
k = a multiplier coefficient supplied by the manufacturer, (1/ μV).

DR-02 Pyrheliometer

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

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.

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Results

TABLE 2. INSTRUMENT LIST (DEPLOYED FROM 6/23/2015–7/19/2015)

Instrument Type	Model	Type of Measurement	Factory Calibration date	NREL Calibration Date	Manufacturer	Calibration Cases Applied	Manufacturer	Comment
Thermopile	CMP22	GHI	5/5/2014	6/4/2015	Kipp & Zonen	1,2,3,4	Kipp & Zonen	Clear glass domes
Thermopile	MS-802	GHI	5/23/2014	6/4/2015	EKO Instruments, Inc.	1,2,3,4	EKO Instruments, Inc.	Clear glass dome
Thermopile	MS-602	GHI	4/21/2014	6/4/2015	EKO Instruments, Inc.	1,2,3,4	EKO Instruments, Inc.	Clear glass dome
Thermopile	MS-410	GHI	10/20/2014	6/4/2015	EKO Instruments, Inc.	1,2,3,4	EKO Instruments, Inc.	Clear glass dome
Thermopile	SPP	GHI	7/10/2014	6/4/2015	Eppley Laboratory, Inc.	1,2,3,4	Eppley Laboratory, Inc.	Clear glass dome
Thermopile	GPP	GHI	6/24/2014	6/4/2015	Eppley Laboratory, Inc.	1,2,3,4	Eppley Laboratory, Inc.	Clear glass dome
Semiconductor	LI-200R	GHI	4/1/2015	6/4/2015	LICOR	1,2,4	LICOR	Diffuser
Semiconductor	ML-01	GHI	4/17/2014	6/4/2015	EKO Instruments, Inc.	1,2,4	EKO Instruments, Inc.	Diffuser
Semiconductor	SP-110	GHI	12/22/2014	6/4/2015	Apogee - Diffuser	1,2,4	Apogee - Diffuser	Diffuser
Thermopile	MS-56	DNI	7/12/2012	6/4/2015	EKO Instruments, Inc.	1,4,5	EKO Instruments, Inc.	Glass window
Thermopile	sNIP	DNI	7/29/2014	6/4/2015	Eppley Laboratory, Inc.	1,2,5	Eppley Laboratory, Inc.	Glass window
Thermopile	DR02	DNI	4/18/2015	6/20/2015	Hukseflux	1,4,5	Hukseflux	Glass window

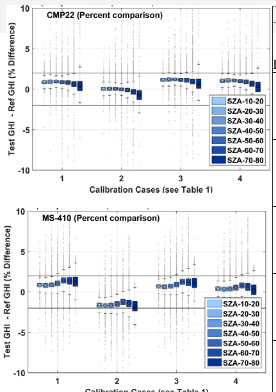

Fig. 1: Results from comparison of two of the 6 thermopile pyranometer instruments shown in Table 3.

Table 3: Thermopile Pyranometer

Inst.#	Cases	Solar Zenith Angle, deg. (10 to 20) (%)	(20 to 30) (%)	(30 to 40) (%)	(40 to 50) (%)	(50 to 60) (%)	(60 to 70) (%)	(70 to 80) (%)
CMP22	1	0.9	0.9	1	0.9	0.8	0.7	0.5
	2	0.1	0.1	0.1	0	-0.1	-0.3	-0.6
	3	1.2	1.2	1.3	1.2	1.1	1	0.7
	4	1.1	1.1	1.1	1	0.9	0.7	0.4
MS-602	1	0.7	0.4	0.1	-0.7	-1.4	-2.7	-3.2
	2	-2.1	-2.4	-2.8	-3.6	-4.5	-6	-6.9
	3	2.5	2.2	1.8	1	0.3	-1.1	-1.5
	4	1.9	1.6	1.2	0.3	-0.6	-2.2	-3.2
GPP	1	-1.9	-5.2	-3.5	-2.4	-2.2	-2.7	-3.3
	2	-0.4	-3.7	-2	-1	-0.9	-1.5	-2.3
	3	-0.5	-3.8	-2	-0.9	-0.8	-1.3	-1.9
	4	-0.7	-4	-2.3	-1.3	-1.2	-1.8	-2.6
MS-802	1	0.8	0.7	0.4	0.1	-0.3	-0.6	-0.7
	2	2.5	2.4	2.1	1.6	1.1	0.7	0.2
	3	1.6	1.5	1.2	0.9	0.5	0.2	0.1
	4	1.3	1.2	0.9	0.4	-0.1	-0.5	-1
SPP	1	1.1	0.9	0.8	0.4	0.1	-0.3	-1.4
	2	0.7	0.5	0.3	-0.2	-0.7	-1.3	-2.9
	3	1.9	1.7	1.5	1.2	0.8	0.4	-0.7
	4	1.4	1.2	1	0.5	0	-0.6	-2.2
MS-410	1	0.9	0.8	0.9	1.1	1.4	1.4	1.3
	2	-1.6	-1.7	-1.6	-1.5	-1.2	-1.4	-1.7
	3	0.7	0.6	0.7	0.9	1.3	1.2	1.1
	4	0.4	0.4	0.4	0.6	0.8	0.7	0.3

Table 4: Photodiode Pyranometer

Inst.#	Cases	Solar Zenith Angle, deg. (10 to 20) (%)	(20 to 30) (%)	(30 to 40) (%)	(40 to 50) (%)	(50 to 60) (%)	(60 to 70) (%)	(70 to 80) (%)
LI200R	1	2	1.5	0.6	0	-0.5	-0.9	-0.6
	2	-3.1	-3.7	-4.5	-5.1	-5.6	-5.9	-5.6
	4	1.7	1.2	0.4	-0.3	-0.8	-1.2	-0.9
ML-01	1	-0.9	-1.3	-1.4	-1.7	-1.9	-3	-4
	2	-2.9	-3.4	-3.5	-3.7	-4	-5.1	-6
	4	0.1	-0.4	-0.5	-0.8	-1	-2.1	-3.1
SP-110	1	1.2	1	0.7	0	-0.9	-2.3	-4
	2	-3.5	-3.6	-4	-4.6	-5.5	-6.8	-8.5
	4	2.3	2.1	1.8	1.1	0.2	-1.2	-3

Fig. 1 and Table 3 show the differences arising from applying different calibration cases for the thermopile pyranometers. Table 4 shows the results from comparing the photodiode pyranometers, and Fig. 2 and Table 4 show the comparison for the pyrheliometers. Differences more than 2% are shown in yellow. Note that pyrheliometers are not influenced by angle-of-incidence effects and therefore have better agreement.

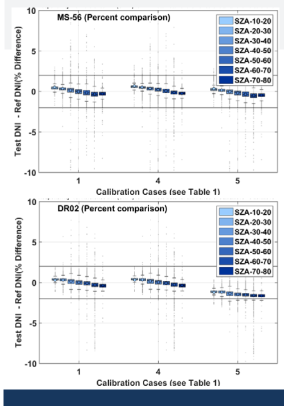

Table 5: Thermopile Pyrheliometer

Inst.#	Cases	Solar Zenith Angle, deg. (10 to 20) (%)	(20 to 30) (%)	(30 to 40) (%)	(40 to 50) (%)	(50 to 60) (%)	(60 to 70) (%)	(70 to 80) (%)
MS-56	1	0.5	0.3	0.1	0	-0.2	-0.3	-0.3
	4	0.7	0.5	0.3	0.2	0.1	-0.1	-0.2
	5	0.3	0.2	0	-0.2	-0.3	-0.5	-0.5
sNIP	1	0.2	0.3	0.2	0.3	0.3	0.2	0.1
	2	0	0.1	0	0.1	0.1	0	-0.1
	4	0	0	0	0	0	-0.1	-0.1
DR02	1	0.3	0.3	0.2	0	-0.1	-0.3	-0.4
	4	0.3	0.3	0.2	0.1	-0.1	-0.3	-0.3
	5	-1.2	-1.2	-1.3	-1.5	-1.5	-1.6	-1.6

Fig. 2: Results from comparison of two of the 3 thermopile pyrheliometer instruments shown in Table 5.

Summary

- Radiometers presented here are not necessarily representative units.
- Differences between manufacturer's irradiance and outdoor NREL BORCAL irradiance values are observed to be on the order of 1% to 2% for pyranometers.
- Differences for pyrheliometers are less than 1% .
- Understanding and quantifying the difference between the different calibration methodologies will ultimately improve measurement accuracy.
- Both methods are traceable to World Radiation Reference.
- Outdoor calibrations are useful for cosine response correction, which ultimately assists in reducing measurement uncertainty.

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