Calibration Procedure of a Modified Hukseflux SR25 as an Example to Establish the Diffuse Reference for the Outdoor Broadband Radiometer Calibration

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List of Acronyms

ACR	Absolute Cavity Radiometer
BORCAL	Broadband Outdoor Radiometer Calibration
NREL	National Renewable Energy Laboratory
SRRL	Solar Radiation Research Laboratory
WRR	World Radiometric Reference

Executive Summary

Accurate pyranometer calibrations, traceable to internationally recognized standards, are critical for solar irradiance measurements. One calibration method is the component summation method, where the pyranometers are calibrated outdoors under clear sky conditions, and the reference global solar irradiance is calculated as the sum of two reference components, the diffuse horizontal and subtended beam solar irradiances. The beam component is measured with pyrheliometers traceable to the World Radiometric Reference, while there is no internationally recognized reference for the diffuse component. In the absence of such a reference, we present a method to consistently calibrate pyranometers for measuring the diffuse component. The method is based on using a modified shade/unshade method and a pyranometer with less than 0.5 W/m^2 thermal offset. The calibration result shows that the responsivity of Hukseflux SR25 pyranometer equals 10.98 $\mu V/(W/m^2)$ with ±0.86% uncertainty.

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1 Introduction

Accurate short wave solar irradiance measurements are important to renewable energy resource assessments and atmospheric science research. The National Renewable Energy Laboratory (NREL), located in the United States of America, has been involved in solar resource assessment and radiometry since 1977, working to improve the calibration and characterization of pyrheliometers, pyranometers, and pyrgeometers. The Broadband Outdoor Radiometer Calibration (BORCAL) process was developed at NREL to automate the calibration of radiometers for field measurements supporting renewable energy and atmospheric science applications [1]. NREL uses the BORCAL process to calibrate and characterize up to 100 pyrheliometers, pyranometers, and pyrgeometers in one event using the Radiometer Calibration and Characterization software [2].

To calibrate pyranometers, the BORCAL process uses the summation technique [3], where the responsivity of the pyranometer (RS) equals:

$$RS = \frac{V - RS_{IR,Net} * W_{IR,Net}}{N * COS\ \Theta + D} \qquad (1)$$

where,

- V = Thermopile output voltage (µV)
- $RS_{IR,\,NET}$ = Infrared Net responsivity of pyranometer under test [µV/(W/m^2)]
- $W_{IR,\,NET}$ = Infrared net irradiance measured by collocated pyrgeometer (W/m^2)
- N = Direct beam irradiance (W/m^2)
- Θ = Solar zenith angle (°)
- D = Diffuse irradiance (W/m^2).

The Infrared Net responsivity and Infrared Net irradiance ($RS_{IR,\,NET}$ and $W_{IR,\,NET}$) are used to correct for the thermal offset error of the pyranometer [4]. The direct beam irradiance (N) is measured using an absolute cavity radiometer that is traceable to the World Radiometric Reference (WRR) which is the internationally recognized standard for direct beam solar irradiance [5]. The solar zenith angle (Θ) is calculated using the Solar Position Algorithm, SPA [6]. However, there is no such standard for diffuse irradiance (D) measurement. In the absence of such a standard, this calibration procedure is to establish a diffuse reference to produce consistent pyranometer calibration results using BORCAL. In this procedure we use pyranometer model SR25, manufactured by Hukseflux, which by design has thermal offset in the order of 0.5 W/m^2 under clear sky conditions. This SR25 has been modified with an SR30 thermopile detector.

2 Procedure

The following steps are used to calculate the diffuse responsivity based on the detailed method described in [7 and 8]:

1. Mount the test pyranometer, a control pyranometer (same model as test), and a calibrated Absolute Cavity Radiometer (ACR) on sun trackers. The pyranometers are mounted horizontally and shaded with shading disks that subtend an angle of 5°, which equals the ACR field of view.

2. Collect simultaneous data every 10 seconds from the test and control pyranometers, and the ACR.

3. Start the shade/unshade sequence using the following protocol:

   3.1. The azimuth rotation sequence must be 0° to 120°, 240°, and then back to 0°.

   3.2. The test radiometer must be shaded at position 0° for at least 120 seconds before starting the sequence.

   3.3. Start the sequence at solar zenith angle Θ = 62° AM.

   3.4. At position 0°, record $\Theta_{s, 0, 0}$, the irradiance measured by the ACR ($N_{s, 0, 0}$), and the output voltage from the shaded test and control radiometers ($V_{t, s, 0, 0}$ and $V_{c, s, 0, 0}$), in µV. Note that the subscripts s, (0, 0), t, and c mean shaded, position 0° before unshading the test radiometer, test radiometer, and control radiometer, consecutively.

   3.5. Unshade the test radiometer at position 0° and then immediately start rotation to 120°, then wait 20 seconds and record $\Theta_{u, 120}$, $N_{u, 120}$, $V_{t, u, 120}$, and $V_{c, s, 120}$. Note that the subscript u means unshaded.

   3.6. Rotate to 240° and then wait for 20 seconds and record $\Theta_{u, 240}$, $N_{u, 240}$, $V_{t, u, 240}$, and $V_{c, s, 240}$.

   3.7. Rotate back to position 0° and then wait for 20 seconds and record $\Theta_{u, 0}$, $N_{u, 0}$, $V_{t, u, 0}$, and $V_{c, s, 0}$.

   3.8. At position 0°, shade for 90 seconds then record $\Theta_{s, 0, 1}$,$N_{s, 0, 1}$, $V_{t, s, 0, 1}$, and $V_{c, s, 0, 1}$. Note that the subscript (0, 1) means position 0° after shading the test radiometer.

   3.9. Repeat sequences 3.4 through 3.8 till Θ = 28°.

Figure 1 is a simplified illustration of one of the above sequences.

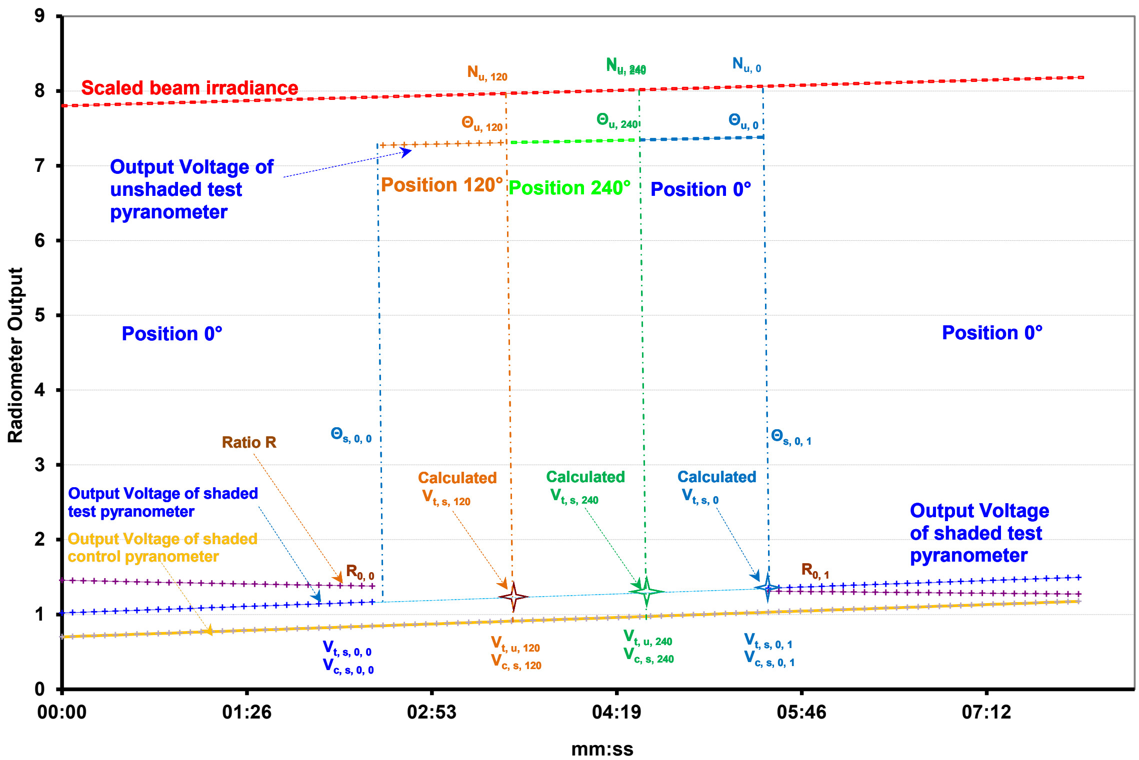

Figure 1. Simplified illustration of one of the above sequences

4. Calculate the ratio $R_{0,0}$ at the zenith angle $\Theta_{s,0,0}$:

$$R_{0,0} = \frac{V_{t,s,0,0}}{V_{c,s,0,0}} \tag{2}$$

5. Calculate the ratio $R_{0,1}$ at the zenith angle $\Theta_{s,0,1}$:

$$R_{0,1} = \frac{V_{t,s,0,1}}{V_{c,s,0,1}} \tag{3}$$

6. Fit $R_{0,0}$ and $R_{0,1}$ versus $\Theta_{s,0,0}$ and $\Theta_{s,0,1}$ to a straight line and calculate its slope, m:

$$m = \frac{R_{0,1} - R_{0,0}}{\Theta_{s,0,1} - \Theta_{s,0,0}} \tag{4}$$

7. Calculate the ratio R_{120}:

$$R_{120} = R_{0,0} + m * (\Theta_{u,120} - \Theta_{s,0,0}) \tag{5}$$

8. Calculate the ratio R_{240}:

$$R_{240} = R_{0,0} + m * (\Theta_{u,240} - \Theta_{s,0,0} \tag{6}$$

9. Calculate the ratio R_0:

$$R_0 = R_{0,0} + m * (\Theta_{u,0} - \Theta_{s,0,0} \tag{7}$$

10. Calculate the voltage of the test radiometer at position 120° as if it is shaded, $V_{t, s, 120}$:

$$V_{t,s,120} = V_{c,s,120} * R_{120} \tag{8}$$

11. Calculate the voltage of the test radiometer at position 240° as if it is shaded, $V_{t, s,240}$:

$$V_{t,s,240} = V_{c,s,240} * R_{240} \tag{9}$$

12. Calculate the voltage of the test radiometer at position 0° as if it is shaded, $V_{t, s, 0}$:

$$V_{t,s,0} = V_{c,s,0} * R_0 \tag{10}$$

13. Calculate the responsivity of the test radiometer at position 120°, RS_{120}:

$$RS_{120} = \frac{V_{t,u,120} - V_{t,s,120}}{N_{u,120} * COS\ \Theta_{u,120}} \tag{11}$$

14. Calculate the responsivity of the test radiometer at position 240°, RS_{240}:

$$RS_{240} = \frac{V_{t,u,240} - V_{t,s,240}}{N_{u,240} * COS\ \Theta_{u,240}} \tag{12}$$

15. Calculate the responsivity of the test radiometer at position 0°, RS_0:

$$RS_0 = \frac{V_{t,u,0} - V_{t,s,0}}{N_{u,0} * COS\ \Theta_{u,0}} \tag{13}$$

16. Calculate the average solar zenith angle Θ_{av}:

$$\Theta_{av} = \frac{\Theta_{u,120} + \Theta_{u,240} + \Theta_{u,0}}{3} \tag{14}$$

17. Calculate the average RS_{av} at Θ_{av}:

$$RS_{av} = \frac{R_{120} + R_{240} + R_0}{3} \tag{15}$$

18. Repeat steps 4 through 17 for all zenith angles from 62° to 28°

19. From equations 14 and 15, fit all calculated zenith angles and responsivities to straight line function, RS(Θ):

$$RS_{\Theta} = a + b * \Theta \tag{16}$$

20. Calculate the responsivity where the zenith angle equals 45°, RS_{45}:

$$RS_{45} = a + b * 45 \tag{17}$$

where *a* and *b* are the intercept and slope of the straight line function.

21. Calculate the responsivity where the zenith angle equals 30°, RS_{30}:

$$RS_{30} = a + b * 30 \tag{18}$$

22. Calculate the responsivity where the zenith angle equals 60°, RS_{60}:

$$RS_{60} = a + b * 60 \tag{19}$$

23. Calculate the ranges from RS_{30} to RS_{45} and from RS_{60} to RS_{45}, R_{30} and R_{60}:

$$R_{30} = |RS_{30} - RS_{45}| \tag{20}$$

$$R_{60} = |RS_{60} - RS_{45}| \tag{21}$$

3 Calibration Results

We collected data on July 10, 2017, in the zenith angle range 30° to 60° to calibrate Hukseflux pyranometer SR25-2530 using SR25-2529 as the control radiometer and ACR serial number AHF29219. Figure 2 shows the irradiance measured by AHF29219 and the calculated ratios versus the zenith angle. Figure 3 shows the calculated shade voltage for SR25-2530 versus the zenith angle. Figure 4 shows the average responsivity versus the zenith angle for SR25-2530.

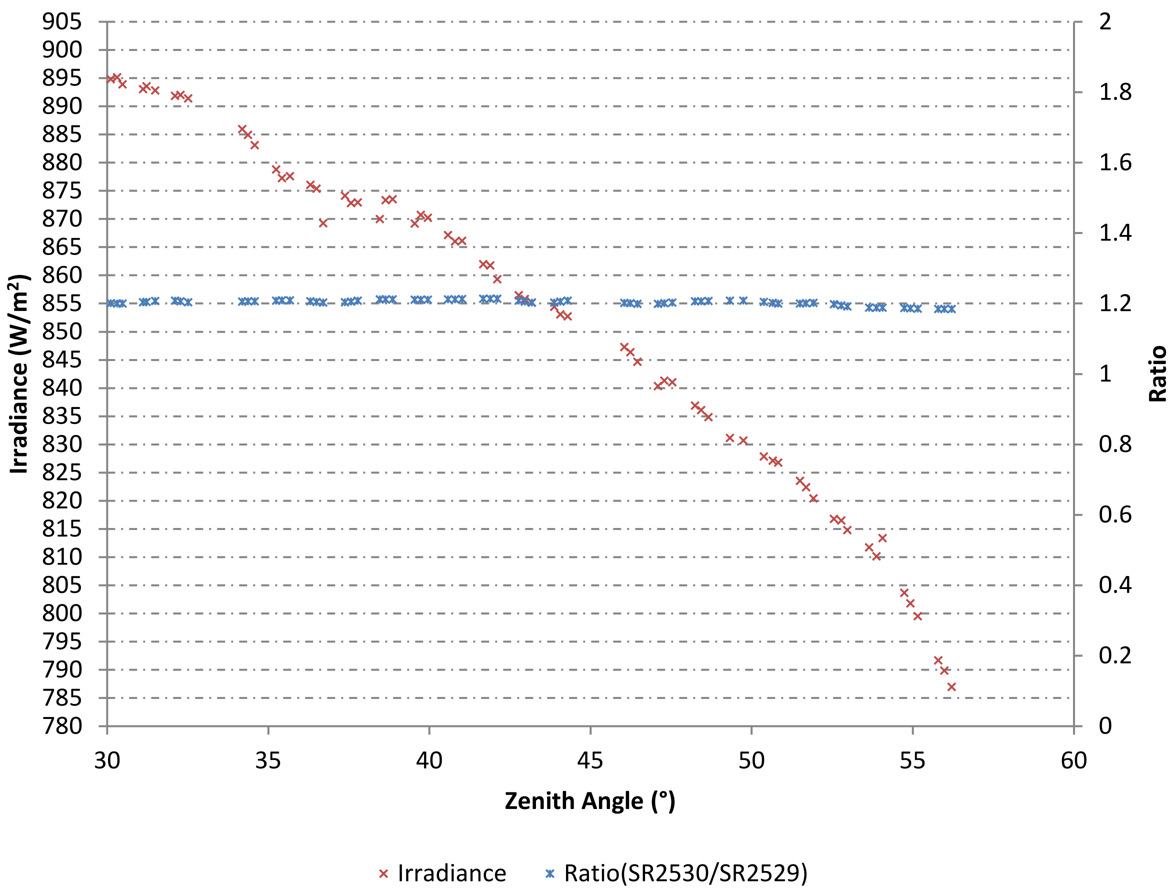

Figure 2. Irradiance and ratios versus zenith angle

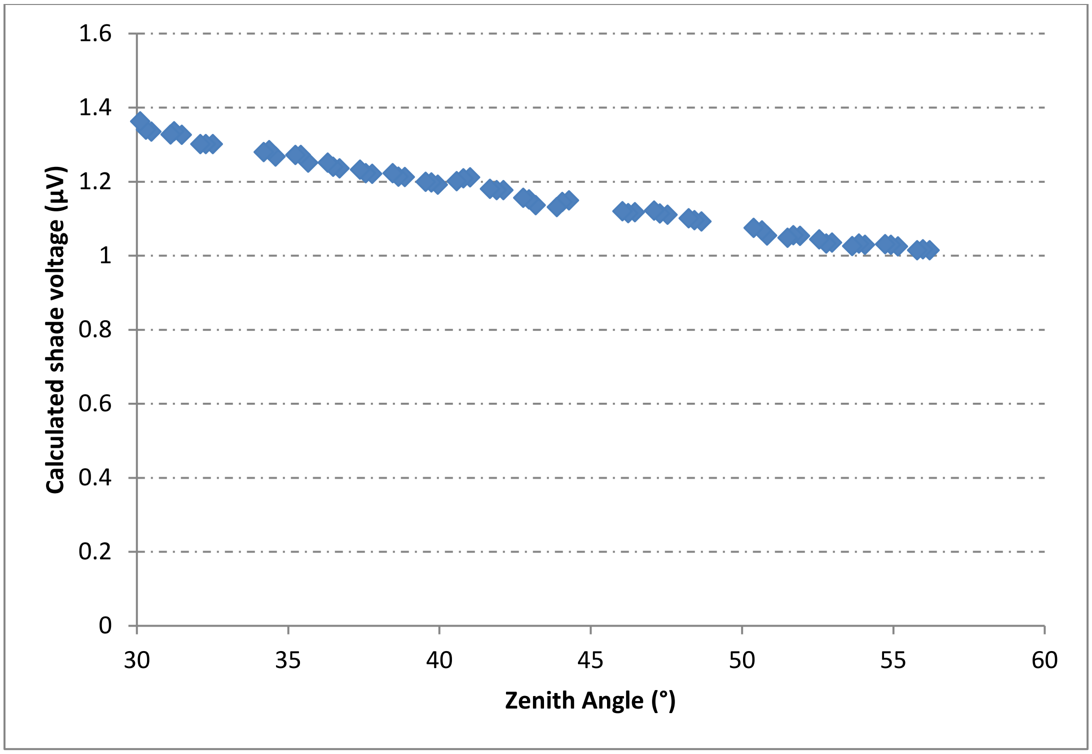

Figure 3. Calculated shade voltage for SR25-2530

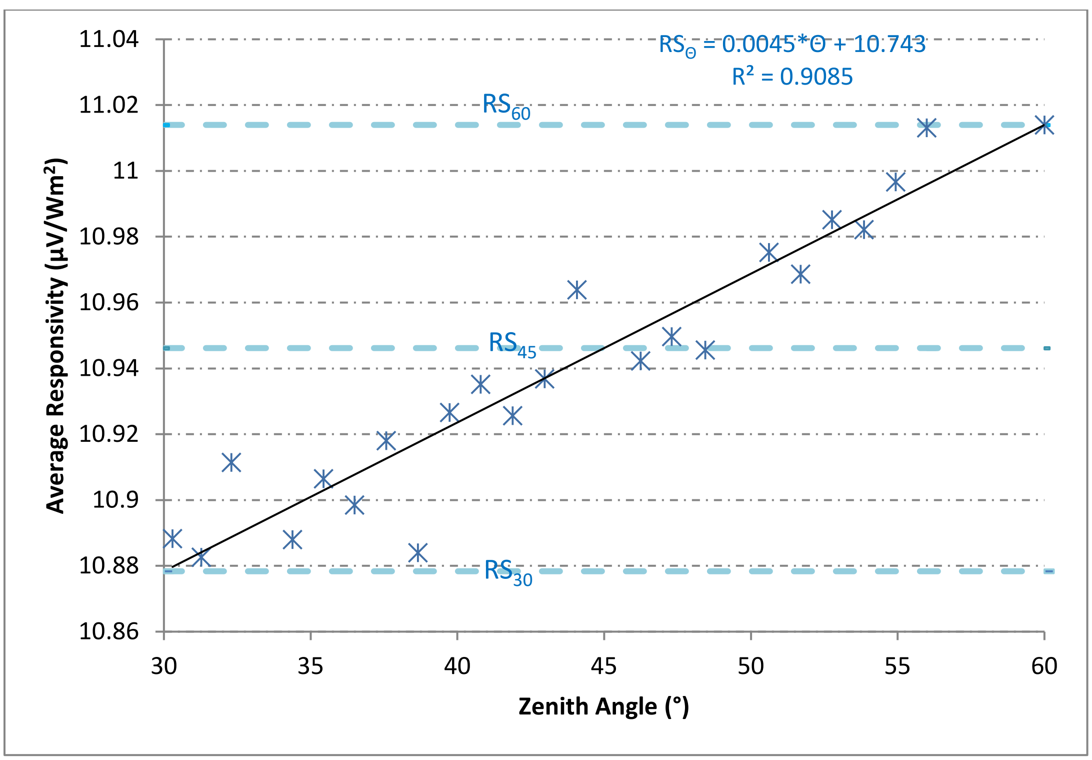

Figure 4. Average responsivity versus zenith angle

The calibration uncertainty is calculated using the *Guide to the Expression of Uncertainty in Measurement* method described in detail by Reda et al. 2008 as follows [3]:

1. Measurement Equation similar to Equation 13 above:

$$RS = \frac{V_u - V_s}{N * COS\ \Theta} \quad (22)$$

2. Calculate the sensitivity coefficients using partial derivatives of *RS* versus each variable:

$$c_{Vu} = \frac{1}{N * COS\ \Theta} \quad (23)$$

$$c_{Vs} = \frac{-1}{N * COS\ \Theta} \quad (24)$$

$$c_N = \frac{-(V_u - V_s)}{N^2 * COS\ \Theta} \quad (25)$$

$$c_\Theta = \frac{-(V_u - V_s) * N * SIN\ \Theta}{(N * COS\ \Theta)^2} \quad (26)$$

3. Calculate the standard uncertainty of each variable:

$$u_{Vu} = \frac{U_V}{\sqrt{3}} \quad (27)$$

$$u_{Vs} = \frac{U_V}{\sqrt{3}} \quad (28)$$

$$u_N = \frac{U_N}{\sqrt{3}} \quad (29)$$

$$u_\Theta = \frac{U_\Theta}{\sqrt{3}} \quad (30)$$

4. Calculate the Type-B combined standard uncertainty, u_B:

$$u_B = \sqrt{(c_{Vu} * u_{Vu})^2 + (c_{Vs} * u_{Vs})^2 + (c_{VN} * u_{Vu})^2 + (c_\Theta * u_\Theta)^2} \quad (31)$$

5. Over the zenith angle range of calibration, calculate the residuals of all measured responsivities from their calculated values using the straight line fitting Equation 16, r:

$$r = RS_{calculated} - RS_{measured} \quad (32)$$

6. Calculate the average and standard deviation of the residuals, r_{av} and s

7. Calculate the Type-A standard uncertainty, u_A:

$$u_A = \sqrt{r_{av}^2 + s^2} \quad (33)$$

8. Calculate the maximum of the two ranges R_{30} and R_{60}, R_{max}

9. Calculate the standard uncertainty of the range, u_R:

$$u_R = \frac{R_{max}}{\sqrt{3}} \tag{34}$$

10. Calculate the standard uncertainty of the sensor nonlinearity, u_{NL}:

$$u_{NL} = \frac{U_{NL}}{\sqrt{3}} \tag{35}$$

where U_{NL} is the manufacturer specification.

11. Calculate the combined standard uncertainty, u_c:

$$u_c = \sqrt{u_B^2 + u_A^2 + u_R^2 + u_{NL}^2} \tag{36}$$

12. Because some of the variables in the measurement equation have a rectangular distribution, the degrees of freedom is infinity; therefore, the coverage factor equals 1.96.

13. Calculate the Expanded Uncertainty, U_{95}:

$$U_{95} = \pm 1.96 * u_c \tag{37}$$

Table 1 shows the calibration result, including uncertainty.

Table 1. Calibration Result and Uncertainty

RS_{45} (μV/Wm^{2})	10.95
Combined Type-B standard uncertainty, u_B	0.23 %
Combined Type-A standard uncertainty, u_A	0.12%
Standard uncertainty of 30° to 60° range, u_R	0.36%
Standard Uncertainty of sensor Non Linearity, u_{NL}	0.12%
Effective degrees of freedom, $DF_{c\ eff}$	∞
Coverage factor, *k*, for 95% level of confidence	1.96
Expanded uncertainty, U_{95}	0.89 %
Thermal offset	0.5 W/m^{2}
Valid zenith angle range	30° to 60°

4 Conclusion and Future Work

Measuring the clear-sky diffuse irradiance with an uncertainty of ± (0.89% of reading + 0.5 W/m^2), with respect to the International System of Units (SI) through the WRR, is achieved using pyranometers model SR25 when calibrated using this shade/unshade method. This uncertainty is adequate for the purpose of calibrating unshaded pyranometers using the BORCAL method because, under clear skies, the ratio of the diffuse to the global irradiance is in the order of 1/10, which means the error in the reference global irradiance is in the order of ± (0.1 *0.89% + 0.5 W/m^2) = ± (0.09% + 0.5 W/m^2).

The SR25 pyranometers will be calibrated yearly to establish the diffuse reference before the BORCAL season starts. The resulting RS from each calibration will be tracked to evaluate the stability of the diffuse reference.

References

[1] NREL Broadband Outdoor Radiometer Calibration (BORCAL) Reports, National Renewable Energy Laboratory (NREL), Golden, CO, USA, annual.

[2] A. M. Andreas, S. M. Wilcox, "Radiometer Calibration and Characterization (RCC) User's Manual: Windows Version 4.0," NREL/TP-3B10-65844, 2016.

[3] I. Reda, D. Myers, T. Stoffel, "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective," Measure Vol. 3 (4) December pp. 58-66, 2008.

[4] I. Reda, J. Hickey, C. Long, D. Myers, T. Stoffel, S. Wilcox, J. J. Michalsky, E. G. Dutton, D. Nelson, "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method," Journal of Atmospheric and Oceanic Technology, pp. 1531-1540, 2005.

[5] PMOD/WRC, "International Pyrheliometer Comparison, IPC XII, 28 September – 16 October 2015, Final Report," June 2016.

[6] I. Reda and A. Andreas, "Solar position algorithm for solar radiation applications," J. of Solar Energy, Vol. 76, pp. 577-589, 2004.

[7] I. Reda, T. Stoffel, D. Myers, "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance," Solar Energy Vol. 74 (2), pp. 103-112, 2003.

[8] ASTM G167, "Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer".