

Using an Absolute Cavity Pyrgeometer to Validate the Calibration of a Secondary Standard Pyrgeometer Outdoors, Independent from the Reference Value of the Atmospheric Longwave Irradiance

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How to cite this paper: Reda, I., Andreas, A., Gotseff, P. and Kutchenreiter, M. (2020) Using an Absolute Cavity Pyrgeometer to Validate the Calibration of a Secondary Standard Pyrgeometer Outdoors, Independent from the Reference Value of the Atmospheric Longwave Irradiance. *Atmospheric and Climate Sciences*, 10, 530-537. <https://doi.org/10.4236/acs.2020.104027>

Received: September 11, 2020

Accepted: September 26, 2020

Published: September 29, 2020

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Abstract

Accurate measurements of broadband outdoor longwave irradiance are important for renewable energy applications and the study of the atmosphere and climate change. A unique method of pyrgeometer calibration has been developed to improve the measurement uncertainty [1]. The results of this method yielded irradiance values within ± 3 W/m² of those traceable to the World InfraRed Standard Group (WISG). This article describes a technique for validating this pyrgeometer calibration method using two Absolute Cavity Pyrgeometers (ACPs). The ACPs and pyrgeometer model PIR were deployed outdoors and the irradiance measured by the PIR was compared against the average irradiance measured by the two ACPs. The irradiance measured by the PIR was calculated using two equations, NREL equation and the Physikalisch Meteorologisches Observatorium Davos (PMOD) equation. The uncertainty with 95% confidence level (U_{95}) of the irradiance measured by the PIR using NREL equation equaled ± 3.51 W/m² with respect to SI and using PMOD equation U_{95} equaled ± 2.99 W/m² with respect to SI. These results suggest that the PIR calibration method might be useful in addressing the international need for a secondary standard pyrgeometer traceable to SI.

Keywords

Absolute Cavity Pyrgeometer, ACP, Pyrgeometer, WISG, Atmospheric Longwave Irradiance

1. Introduction

The pyrgeometer model PIR was installed outdoors on an aluminum plate that was connected to a temperature controller, see **Photo 1**. Adjusting the temperature controller to decrease the pyrgeometer's body temperature changed the pyrgeometer's thermopile output. If the incoming radiation was stable, then the slope of the change in the pyrgeometer's output irradiance (W_{out}) versus the change in the thermopile output voltage (V) would equal the pyrgeometer outdoors responsivity (RS), independent from the absolute value of the atmospheric longwave irradiance [1]. We then evaluated the results of the method using two Absolute Cavity Pyrgeometers (ACPs), ACP95F3 and ACP10F3. The ACPs were installed on temperature controllers and operated as described in [2]. The described method addressed the inherent problems related to the spectral difference between the blackbodies and the atmospheric irradiance by calculating RS from the clear sky outdoor calibration and using the actual atmospheric irradiance as the calibration source.

Section 2 describes the procedure, equations, and the mathematical representation of the rate of change of V versus W_{out} .

Section 3 shows the procedure results and the outdoor evaluation of this procedure. The evaluation compared the measured irradiance by the PIR against the average irradiance measured by ACP95F3 and ACP10F3.

Section 4 is the conclusion.

2. Procedure

The ACPs and PIR were deployed outdoors from July 20 to August 19, 2020. Two equations were used to calculate the atmospheric longwave irradiance measured by the PIR, as described below in NREL and PMOD equations.

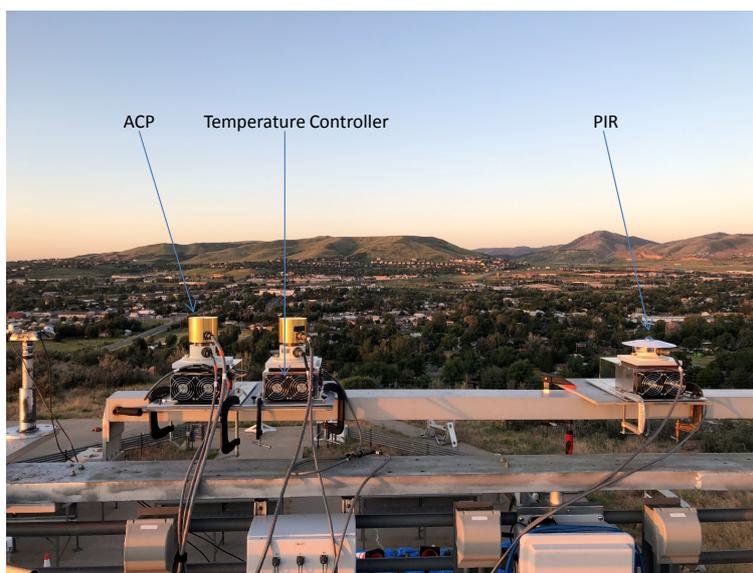


Photo 1. Outdoor set up from left to right of ACP95F3, ACP10F3, and PIR on top of temperature controllers.

NREL Equation [3]

$$W_{atm} = K_0 + K_1V + K_2W_r + K_3(W_d - W_r) \quad (1)$$

where:

W_{atm} is the atmospheric longwave radiation in W/m^2 .

K_0 , K_2 , and K_3 are the calibration coefficients of the pyrgeometer, calibrated at the PMOD [4].

K_1 is the reciprocal of the PIR's RS, calculated from the outdoor calibration described below.

V is the pyrgeometer thermopile output, in microvolts.

W_r is the pyrgeometer receiver radiation = $\sigma * T_r^4$, and $T_r = T_c + K_4 * V$,

where:

σ Stefan-Boltzman constant = $5.6704 \times 10^{-8} W/m^2/K^4$.

T_c pyrgeometer case temperature, in Kelvin.

S Seebeck coefficient = 39 V/K.

n number of thermopile junctions = 56 junctions.

E thermopile efficiency factor = 0.65 (manufacturer specification).

K_4 thermopile efficiency factor equal to $1/(S * n * E) = 0.0007044 K \cdot uV^{-1}$.

W_d is the pyrgeometer dome radiation = $\sigma * T_d^4$, where T_d is the dome temperature in Kelvin.

Equation (1) is rewritten in the following form:

$$W_{out} = W_{atm} - W_{net} = W_{atm} - K_1V \quad (2)$$

where:

W_{net} is the net irradiance measured by the pyrgeometer thermopile.

W_{out} is the outgoing irradiance from the pyrgeometer.

$$W_{out} = K_0 + K_2W_r + K_3(W_d - W_r) \quad (3)$$

A fundamental principle for this calibration procedure is to lower the outgoing irradiance while the atmospheric longwave irradiance (W_{atm}) is constant, *i.e.*, stable during clear sky conditions to within 1 W/m^2 from the start to end of the calibration, at least 7 minutes. Lowering W_{out} was achieved by cooling the pyrgeometer's case using the temperature controller. While lowering W_{out} , all signals from the pyrgeometer were measured every 10 seconds (*i.e.*, thermopile output voltage, T_c and T_r). Differentiating Equation (2) with respect to time then yields:

$$dW_{out}/dt = dW_{atm}/dt - K_1 dV/dt \quad (4)$$

If W_{atm} is assumed constant, Equation 4 then yields:

$$K_1 = -dW_{out}/dt \quad (5)$$

Equation (5) implies that the change of W_{out} versus the change of V yields K_1 , which is independent from the absolute value of W_{atm} .

Once K_1 was calculated using the above procedure, Equation (1) was used to calculate the measured atmospheric longwave irradiance for 2 hours, and then the procedure was repeated from a solar zenith angle of $>95^\circ$ (PM) to $<95^\circ$

(AM).

PMOD Equation [4]

$$W_{atm} = V/C(1 + K_1\sigma T_b^3) + K_2W_b + K_3(W_d - W_b) \quad (6)$$

where C is the pyrgeometer responsivity and T_b is the case temperature.

As in the NREL method described above, where W_{atm} is assumed to be constant, differentiating Equation 6 with respect to time yields:

$$d(V(1 + K_1\sigma T_b^3))/dt / C = -K_2 dW_b/dt - K_3 d(W_d - W_b)/dt \quad (7)$$

For simplicity, Equation (7) is rewritten as:

$$C = dF/dW_{out} \quad (8)$$

where $F = V(1 + K_1\sigma T_b^3)$ and $W_{out} = -K_2W_b - K_3(W_d - W_b)$.

Equation (8) implies that the change of F versus the change of W_{out} yields C , which is independent from the absolute value of W_{atm} .

The ACP's Measurement Equation [2]

To measure the atmospheric longwave irradiance:

$$W_{atm} = (K_1V + (2 - \varepsilon)K_2W_r - (1 + \varepsilon)W_c)/\tau \quad (9)$$

where:

W_{atm} is the atmospheric longwave irradiance (W/m^2).

K_1 is the reciprocal of the ACP's responsivity ($W/m^2/uV$).

V is the thermopile output voltage (uV).

ε is the gold emittance.

K_2 is the emittance of the black receiver surface.

W_r is the receiver irradiance (W/m^2).

W_c is the concentrator irradiance (W/m^2).

τ is the ACP's throughput.

3. Results

The measurement uncertainty was calculated using the following equation:

$$U_{95} = \text{SQRT}(U_{95ACP}^2 + U_{95PIR}^2) \quad (10)$$

where U_{95ACP} equals $\pm 2 W/m^2$ with respect to SI [2], using the NREL equation U_{95PIR} equals $\pm 2.88 W/m^2$ with respect to ACP; therefore, U_{95PIR} equals $\pm 3.51 W/m^2$ with respect to SI. Using the PMOD equation, U_{95PIR} equals $\pm 2.22 W/m^2$ with respect to ACP; therefore, U_{95PIR} equals $\pm 2.99 W/m^2$ with respect to SI.

Photo 1 shows the outdoor set up of ACP95F3, ACP10F3, and PIR. **Table 1** is a sample list of the calculated K_1 for the PIR (NREL), ACP95F3, ACP10F3, and C for PIR (PMOD). **Figure 1** and **Figure 2** show W_{net} versus V for ACP95F3 and ACP10F3. **Figure 3** shows W_{out} versus V for the PIR using the NREL equation. **Figure 4** shows W_{out} versus F for the PIR using the PMOD equation. **Figure 5** shows the average irradiance of the ACPs and the PIR using NREL and PMOD equations. **Figure 6** shows the difference between the ACPs average irradiance and the PIR irradiance using NREL and PMOD Equations. **Figure 7** shows the atmospheric water vapor content.

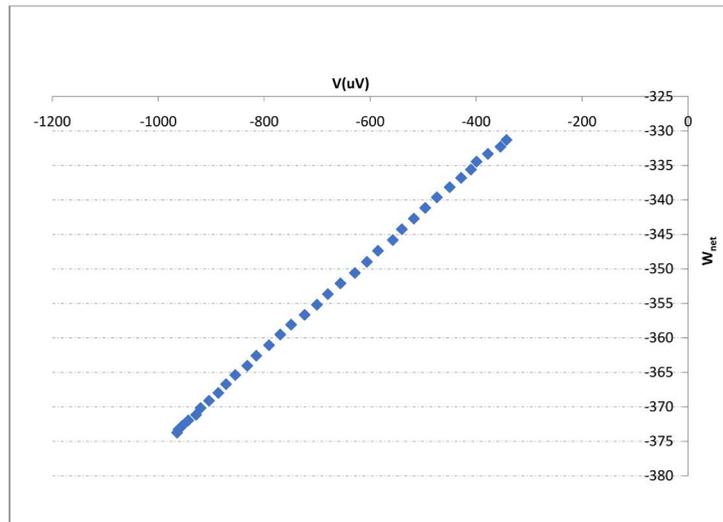


Figure 1. W_{net} versus thermopile output voltage during the calibration of ACP95F3.

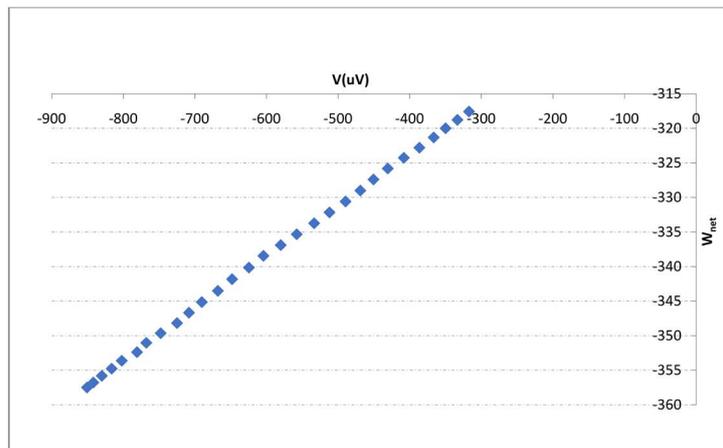


Figure 2. W_{net} versus thermopile output voltage during the calibration of ACP10F3.

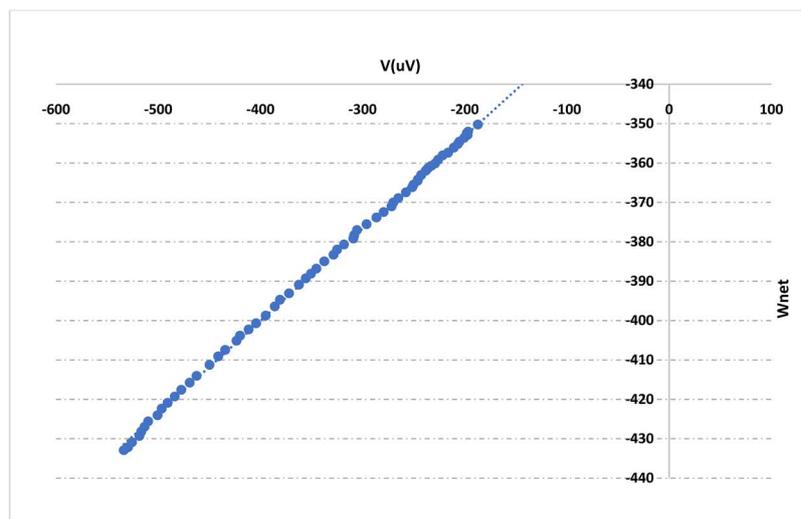


Figure 3. W_{out} versus thermopile output voltage during the calibration of PIR31197F3 using NREL equation.

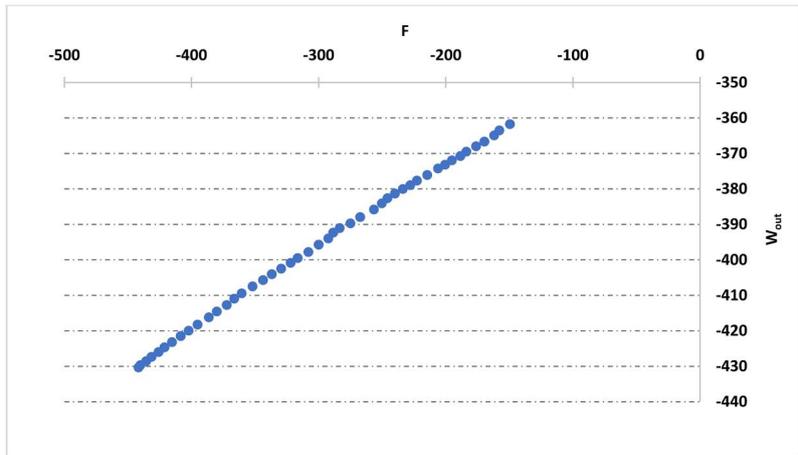


Figure 4. W_{out} versus F during the calibration of PIR31197F3 using PMOD equation.

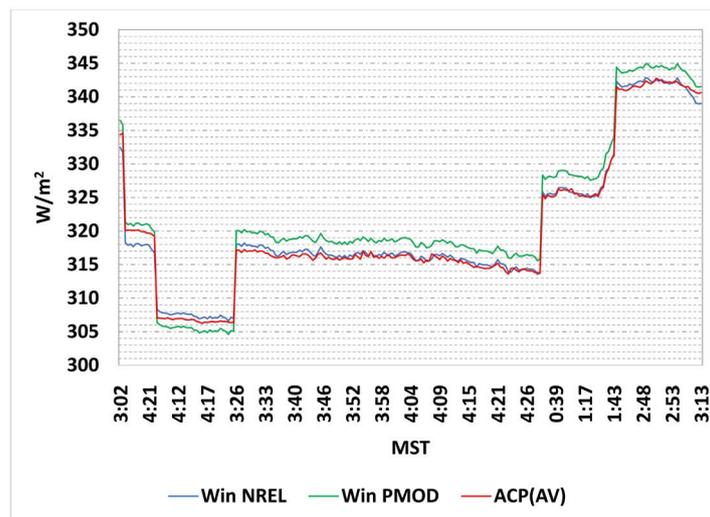


Figure 5. ACPs average irradiance and PIR31197F3 irradiance versus MST.

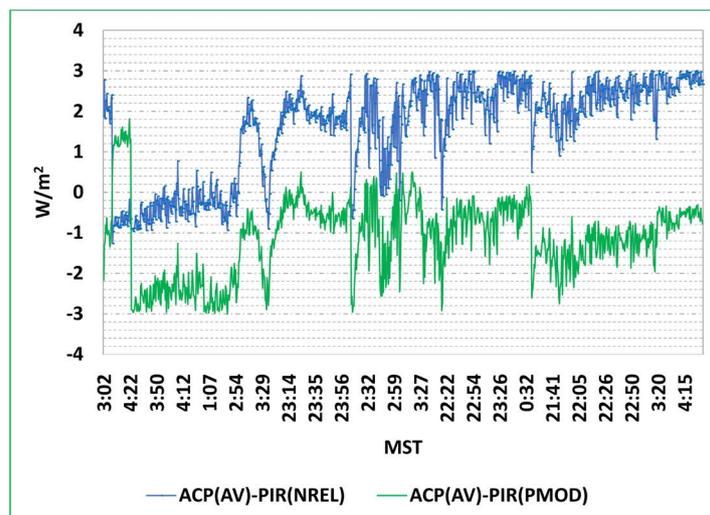


Figure 6. Difference between ACP's average irradiance and PIR31197F3 irradiance versus MST.

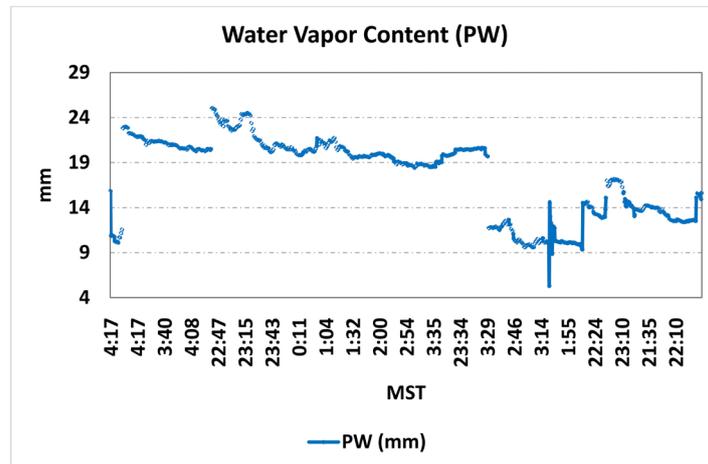


Figure 7. Water vapor content during data collection versus MST.

Table 1. Sample of the calculated K_1 for PIR (NREL), ACP95F3, ACP10F3, and C for PIR (PMOD).

Date	K_1			C
	PIR (NREL)	ACP95F3	ACP10F3	PIR (PMOD)
7/20/2020	0.2352	0.0697	0.0707	4.5283
7/21/2020	0.2480	0.0674	0.0751	4.3126
7/22/2020	0.2556	0.0655	0.0766	4.3075
7/29/2020	0.2297	0.0701	0.0791	4.4923
7/30/2020	0.2480	0.0807	0.0767	4.2560
8/11/2020	0.2561	0.0717	0.0791	4.1499
8/15/2020	0.2412	0.0672	0.0759	4.4200
8/16/2020	0.2395	0.0714	0.0757	4.4516
8/17/2020	0.2396	0.0684	0.0770	4.4476
8/19/2020	0.2488	0.0692	0.0783	4.2890

4. Conclusion

We conclude that using this procedure will result in calibration coefficients that are independent from the absolute value of the atmospheric longwave irradiance. Based on the results, it is possible to achieve an uncertainty of ± 3.51 W/m² using the NREL equation and an uncertainty of ± 2.99 W/m² using the PMOD equation with respect to SI. These results suggest that the PIR calibration method might be useful in addressing the international need for a secondary standard pyrogeometer traceable to SI.

Acknowledgements

The authors thank the Atmospheric Radiation Program, the NREL Metrology Laboratory, and the NREL Photovoltaic program for providing the funds for this article. The authors also thank Julian Gröbner of PMOD/WRC for calibrating

the pyrgeometer used in this article and for pre-reviewing the article before submitting it to the Journal. We strongly thank Martina Stoddard for her persistent administrative support.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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