

Pyrgometer Calibration for DOE-Atmospheric System Research program using NREL Method



Science Team Meeting

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Overview to address some ECR comments

Thermocouple/thermopile

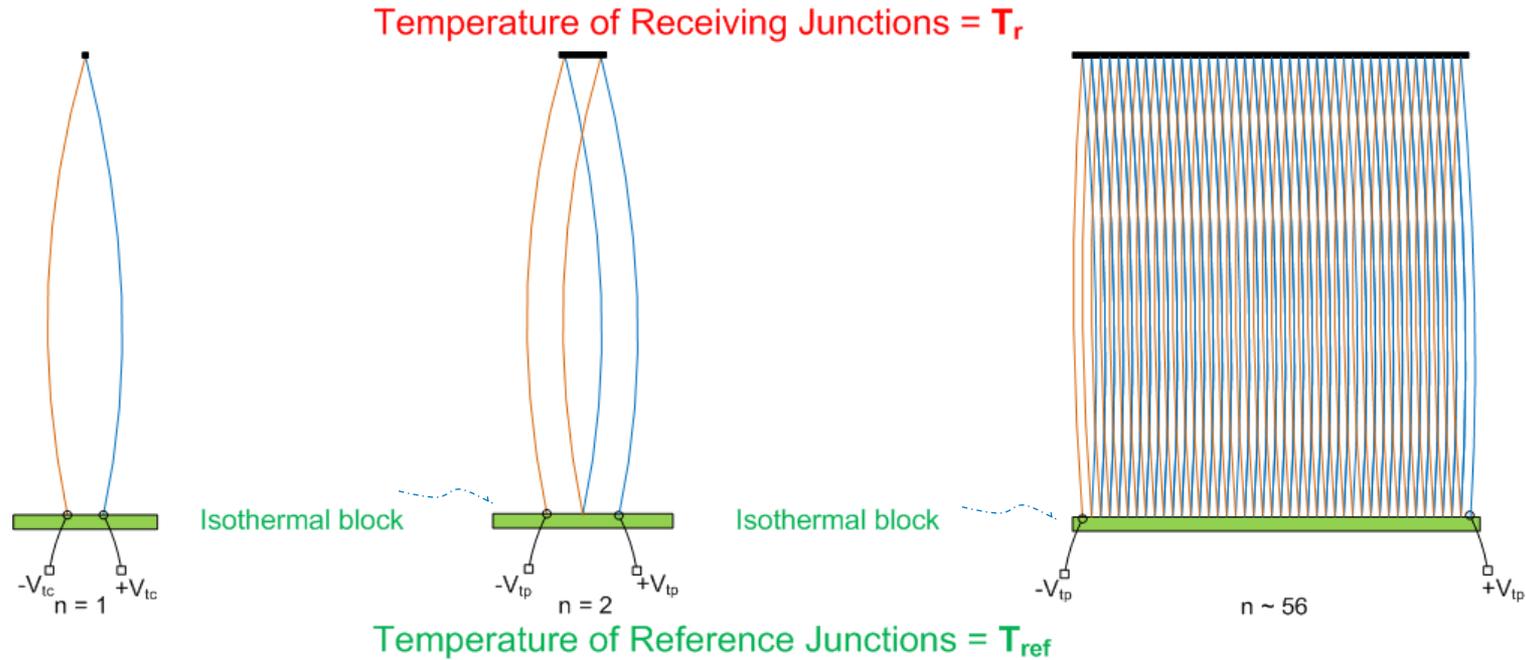
Pyrgeometer thermodynamics

NREL & PMOD equations

NREL calibration method

Conclusion.

Effect of increased junctions on thermopile



$$V_{tp} = n \cdot s \cdot e (T_r - T_{ref})$$

where,

n = number of junctions

s = Seebeck coefficient

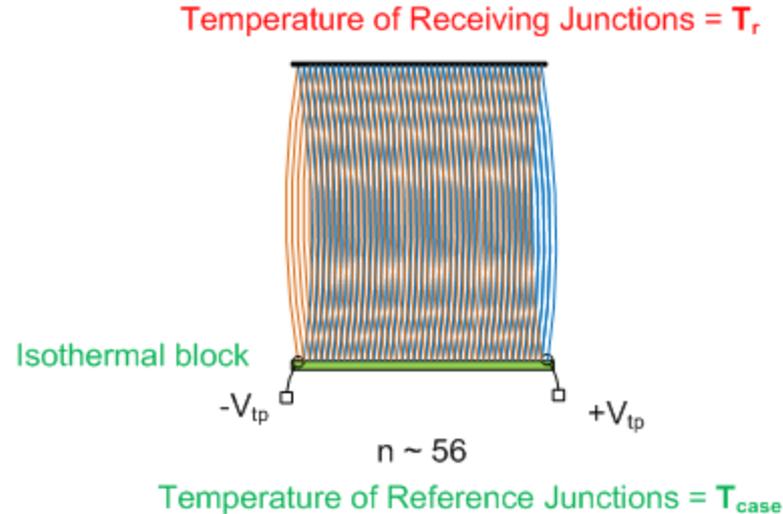
e = thermopile efficiency. $e=1$ for $n = 1, 2$, or small number

$n \uparrow$ to increase signal/noise ratio, thermal conductivity between receiving&reference junctions \uparrow , T_{ref} effect on $T_r \uparrow$, therefore $e \neq 1$

If n is not optimum $\rightarrow V_{tp} \downarrow$, n too large $V_{tp} \sim$ zero volt

Effect of increased thermal conductivity on PIRs

Not to scale



$$V_{tp} = n \cdot s \cdot e (T_r - T_{case})$$

where $e = 0.65$ for PIRs, measured by John Hickey for PIRs with $n \sim 56$ junctions and Seebeck coefficient $\sim 39 \mu\text{V/K}$, reported in:

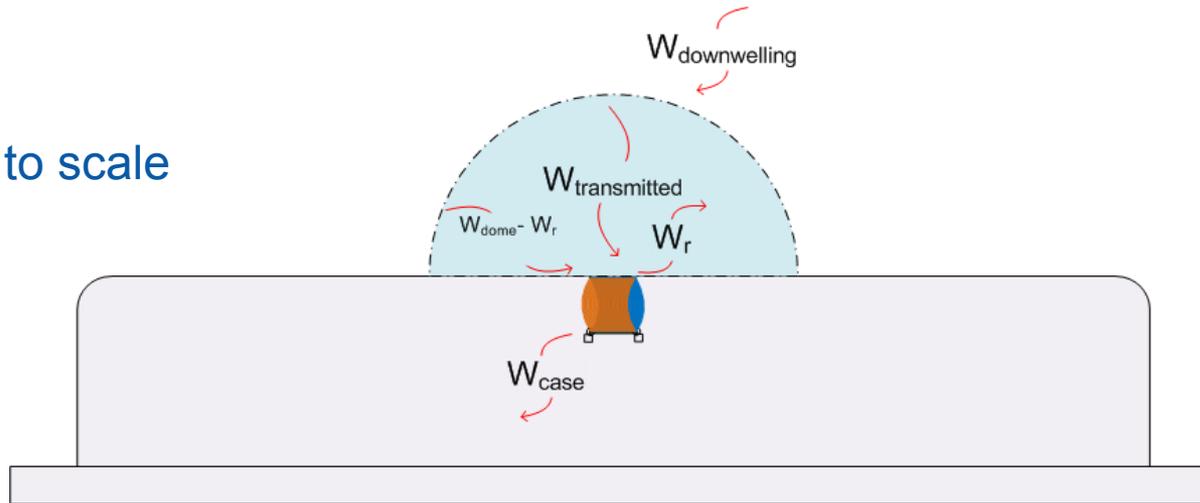
Reda et al., (2002). [Pyrgometer Calibration at the National Renewable Energy Laboratory \(NREL\)](#). Journal of Atmospheric and Solar-Terrestrial Physics. Vol. 64(15), 2002; pp. 1623-1629.

therefore,

$$T_r = T_{case} + 0.0007044 V_{tp}$$

Simplified pyrgemeter thermodynamics

Not to scale



- Net Irradiance = $W_{\text{net}} = K_1 \cdot V_{\text{tp}}$
 $= W_{\text{incoming}} - W_{\text{outgoing}} = W_{\text{transmitted}} + K_3 \cdot (W_{\text{dome}} - W_r) - K_2 \cdot W_r$
 where $W_{\text{transmitted}} = \tau \cdot W_{\text{downwelling}}$, and $\tau = \text{Dome+Filter transmittance}$.. assumed to be constant

Other equations are based on assumptions: $e = 1$ and $W_{\text{outgoing}} = W_{\text{case}}$ instead of W_r !?!

- Arrange the above equation and Re-name constants, therefore,

$$W_{\text{downwelling}} = K_1 \cdot V_{\text{tp}} + K_2 \cdot W_r - K_3 \cdot (W_{\text{dome}} - W_r)$$

This is NREL's equation without K_0 , Reda et al., (2002). *Pyrgemeter Calibration at the National Renewable Energy Laboratory (NREL)*. Journal of Atmospheric and Solar-Terrestrial Physics. Vol. 64(15), 2002; pp. 1623-1629.

K_0 is reserved for troubleshooting regressions & blackbody calibrations only

Comparing NREL and PMOD equations

NREL Equation:

$$W_{\text{downwelling}} = K_1 \cdot V_{\text{tp}} + K_2 \cdot W_r - K_3 (W_{\text{dome}} - W_r)$$

Expansion of NREL Equation to compare with PMOD equation:

1. $T_r = T_{\text{case}} + 0.0007044 V_{\text{tp}} \dots$ for PIRs

2. $W_{\text{downwelling}} = K_1 \cdot V_{\text{tp}} + K_2 \cdot \sigma (T_{\text{case}} + 0.0007044 V_{\text{tp}})^4 - K_3 [W_{\text{dome}} - \sigma (T_{\text{case}} + 0.0007044 V_{\text{tp}})^4]$
Expand $(T_{\text{case}} + 0.0007044 V_{\text{tp}})^4$ using $(a + b)^4 = a^4 + 4a^3b + 6a^2b^2 + 4ab^3 + b^4$

3. Arrange terms and re-name coefficients,

$$W_{\text{downwelling}} = K_1 \cdot V_{\text{tp}} + k'_1 \cdot T_{\text{case}}^3 \cdot V_{\text{tp}} + k_2 \cdot W_{\text{case}} - k_3 (W_{\text{dome}} - W_{\text{case}}) + k_4 \cdot T_{\text{case}}^2 \cdot V_{\text{tp}}^2 + k_5 \cdot T_{\text{case}} \cdot V_{\text{tp}}^3 + k_6 \cdot V_{\text{tp}}^4$$

PMOD Equation:

$$W_{\text{downwelling}} = V_{\text{tp}} (1 + k_1 \cdot \sigma \cdot T_{\text{case}}^3) / c + k_2 \cdot W_{\text{case}} - k_3 (W_{\text{dome}} - W_{\text{case}}) \\ = K_1 \cdot V_{\text{tp}} + k'_1 \cdot T_{\text{case}}^3 \cdot V_{\text{tp}} + k_2 \cdot W_{\text{case}} - k_3 (W_{\text{dome}} - W_{\text{case}})$$

! PMOD equation = NREL equation without k_4 , k_5 , and k_6 terms !

From many comparisons, U_{g5} using NREL or PMOD equation = (1 to 3) W/m^2 w.r.t. WISG

NREL Calibration Procedure

Procedure is developed after many comparisons/validations with PMOD/NOAA
Calibration is performed outdoor using a group of reference pyrgeometers with traceability to consensus reference, WISG

Recommended Measurement Equation:

$$W_{\text{downwelling}} = K_1 \cdot V_{\text{tp}} + K_2 \cdot W_r - K_3(W_{\text{dome}} - W_r)$$

Process:

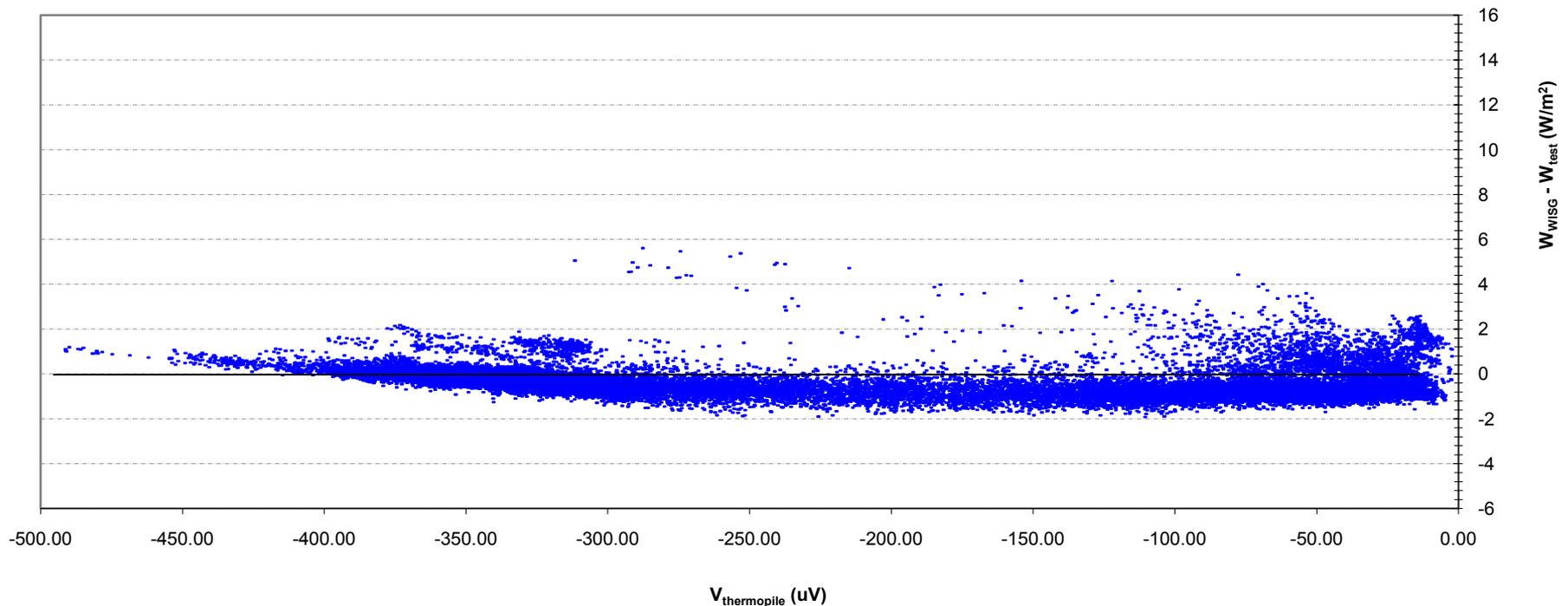
1. V = minimum negative magnitude (Cloudy sky), adjust K_2 to minimize the difference between pyrgeometer under test (PUT) irradiance and reference irradiance
2. V = maximum negative magnitude (Clear sky), adjust K_1 to minimize the difference between the PUT irradiance and reference irradiance
3. Adjust K_3 to minimize the scatter of the differences between PUT irradiance and reference irradiance.

Future software development might include/evaluate regression, with uniform sets of data!!, to calculate the calibration coefficients

NREL Calibration Method Validation

At least 40 pyrgeometers were calibrated using NREL method with uncertainty $U_{95} < 3 \text{ W/m}^2$ with respect to WISG, for all sky conditions, e.g.

Difference between the reference irradiance and the irradiance measured by 31197F3 using NREL method/equation



Conclusions

NREL method achieves uncertainty of $< 3 \text{ W/m}^2$ for all sky conditions

NREL equation accounts for the pyrgeometer thermodynamics

Since $T_r = T_{\text{case}} + 0.0007044 V_{\text{tp}}$, and response time of thermopile is faster than case temperature response, therefore, NREL equation reduces response time of measuring $W_{\text{downwelling}}$ needed for fast changes in sky conditions

At present, with the instruments/data-acquisition limitations, all equations might achieve $U_{95} = (1 \text{ to } 3) \text{ W/m}^2$ w.r.t. WISG

In the future, when U_{95} of measuring instruments and consensus reference is reduced, NREL equation might be a good candidate when uncertainty of fractions of W/m^2 is needed

Manufacturers specifications to include thermopile efficiency, e , for accurate K_2 and K_3 derivation.