NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Pyrgeometer 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

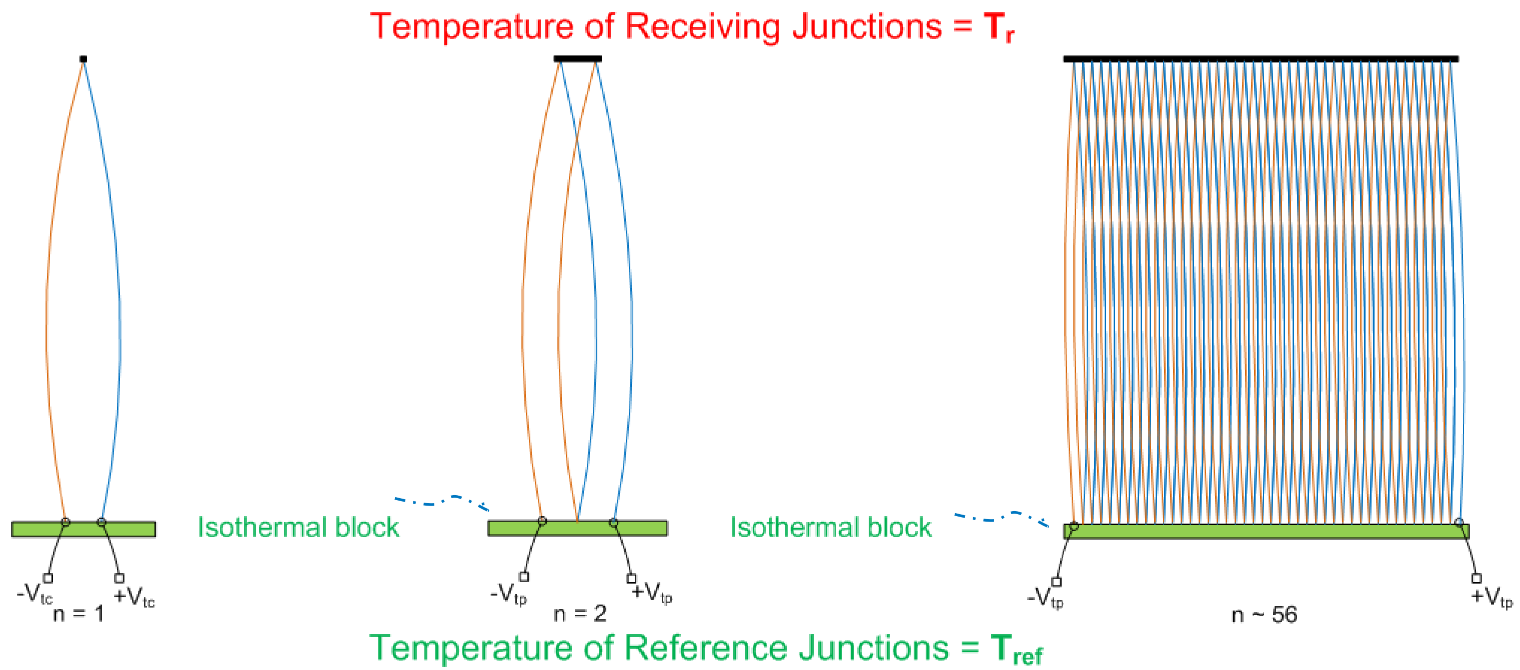
Pyrgeometer thermodynamics

NREL & PMOD equations

NREL calibration method

Conclusion.

Effect of increased junctions on thermopile



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

where,

n = number of junctions

s = Seebeck coefficient

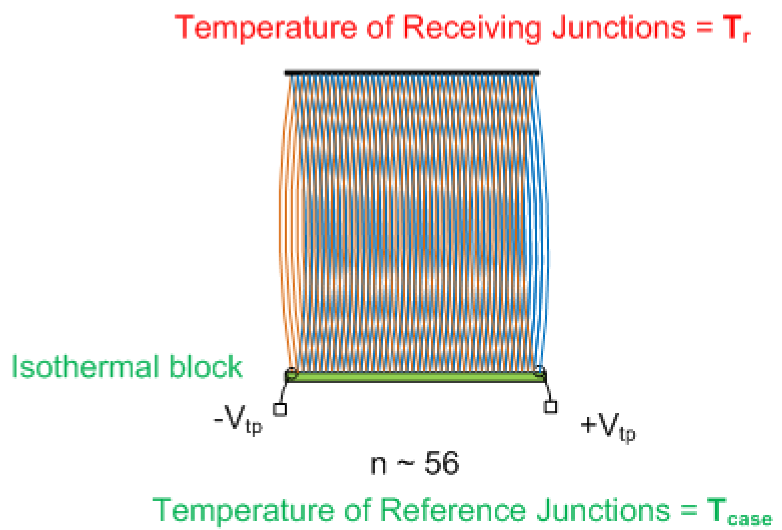
e = thermopile efficiency. e=1 for n = 1, 2, or small number

n↑ to increase signal/noise ratio, thermal conductivity between receiving&reference junctions ↑, T_{ref} effect on T_r ↑, therefore **e ≠ 1**

If n is not optimum → V_{tp} ↓ , n too large V_{tp} ~ zero volt

Effect of increased thermal conductivity on PIRs

Not to scale



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

where e = 0.65 for PIRs, measured by John Hickey for PIRs with n ~ 56 junctions and Seebeck coefficient ~39 µV/K, reported in:

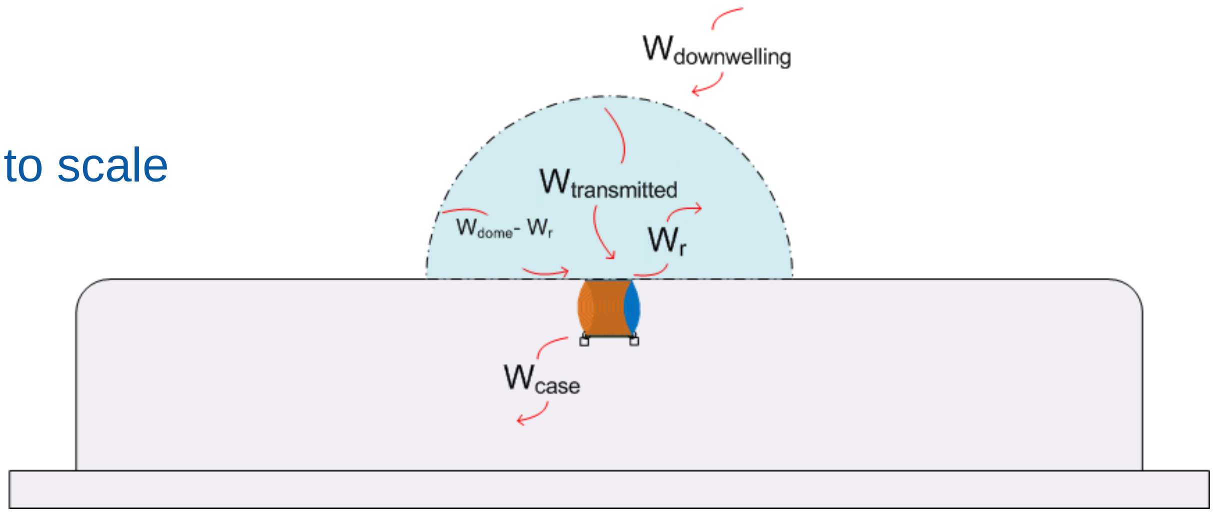
Reda et al., (2002). Pyrgeometer Calibration at the National Renewable Energy Laboratory (NREL). Journal of Atmospheric and Solar-Terrestrial Physics. Vol. 64(15), 2002; pp. 1623-1629.

therefore,

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

Simplified pyrgeometer thermodynamics

Not to scale



- Net Irradiance = W_{net}= K_1'.V_{tp}

  = $W_{incoming}$ - $W_{outgoing}$ = $W_{transmitted}$ + K_3'.(W_{dome} – W_r) – K_2'.W_r

  where $W_{transmitted}$ = τ . $W_{downwelling}$, and τ = Dome+Filter transmittance .. assumed to be constant

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

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

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

This is NREL's equation without K_0 , Reda et al., (2002). Pyrgeometer 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:

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

Expansion of NREL Equation to compare with PMOD equation:

1. $T_r = T_{case} + 0.0007044\ V_{tp}$ ….. for PIRs
2. $W_{downwelling} = K_1.V_{tp} + K_2.\sigma(T_{case} + 0.0007044\ V_{tp})^4 - K_3[W_{dome} - \sigma(T_{case} + 0.0007044 V_{tp})^4]$

   Expand $(T_{case} + 0.0007044\ V_{tp})^4$ using $(a + b)^4 = a^4 + 4a^3b + 6a^2b^2 + 4ab^3 + b^4$
3. Arrange terms and re-name coefficients,

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

PMOD Equation:

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

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

From many comparisons, U_{95} 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:

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

Process:

1. V = minimum negative magnitude (Cloudy sky), adjust K_2 to minimize the difference between pyrgeometer under test (PUT) irradiance and reference irradiance

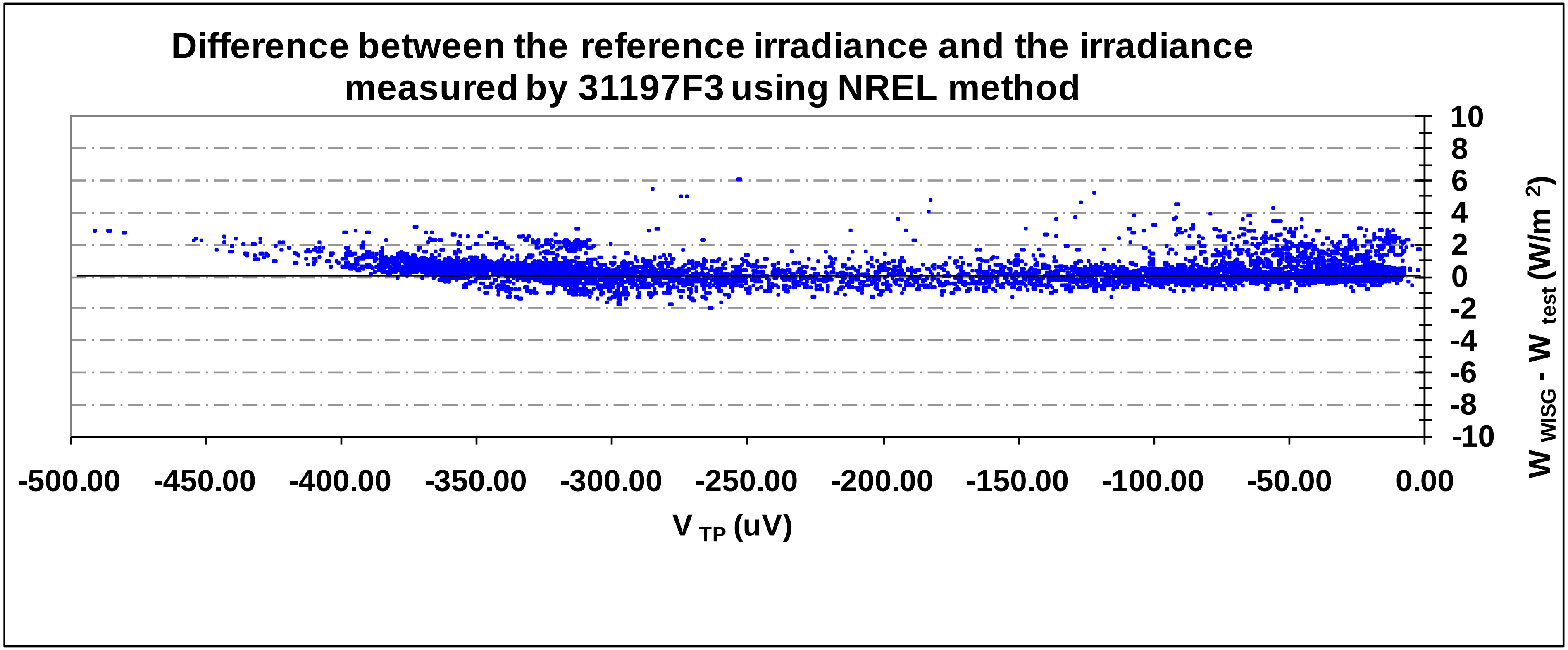
2. V = maximum negative magnitude (Clear sky), adjust K_1 to minimize the difference between the PUT irradiance and reference irradiance

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 $U_{95} < 3\ W/m^2$ with respect to WISG, for all sky conditions, e.g.



Conclusions

- NREL method achieves uncertainty of < 3 W/m^2 for all sky conditions
- NREL equation accounts for the pyrgeometer thermodynamics
- Since $T_r = T_{case} + 0.0007044\ V_{tp}$, and response time of thermopile is faster than case temperature response, therefore, NREL equation reduces response time of measuring $W_{downwelling}$ …. needed for fast changes in sky conditions
- At present, with the instruments/data-acquisition limitations, all equations might achieve U_{95}= (1 to 3) 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.