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
Pyrgometer thermodynamics
NREL & PMOD equations
NREL calibration method
Conclusion.
Effect of increased junctions on thermopile

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

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

\[ V_{tp} = n.s.e(T_r - T_{case}) \]

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

therefore,

\[ T_r = T_{case} + 0.0007044 \, V_{tp} \]
Simplified pyrgeometer thermodynamics

- Net Irradiance = $W_{net} = K_1 \cdot V_{tp}$
  
  $$= W_{incoming} - W_{outgoing} = W_{transmitted} + K_3 \cdot (W_{dome} - W_r) - K_2 \cdot W_r$$

  where $W_{transmitted} = \tau \cdot W_{downwelling}$, and $\tau = \text{Dome+Filter transmittance}$ 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 rename constants, therefore,

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


$K_0$ is reserved for troubleshooting regressions & blackbody calibrations only
Comparing NREL and PMOD equations

**NREL Equation:**

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

**Expansion of NREL Equation to compare with PMOD equation:**

1. \( T_r = T_{\text{case}} + 0.0007044 V_{tp} \) …… for PIRs
2. \( W_{\text{downwelling}} = K_1 V_{tp} + K_2 \sigma (T_{\text{case}} + 0.0007044 V_{tp})^4 - K_3 [W_{dome} - \sigma (T_{\text{case}} + 0.0007044 V_{tp})^4] \)
   
   Expand \( (T_{\text{case}} + 0.0007044 V_{tp})^4 \) using \( (a+b)^4 = a^4 + 4a^3b + 6a^2b^2 + 4ab^3 + b^4 \)
3. Arrange terms and re-name coefficients,

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

**PMOD Equation:**

\[ W_{\text{downwelling}} = V_{tp} (1 + k_1 \sigma T_{\text{case}}^3) / c + k_2 W_{\text{case}} - k_3 (W_{dome} - W_{\text{case}}) \]

\[ = K_1 V_{tp} + k'_1 T_{\text{case}}^3 V_{tp} + k_2 W_{\text{case}} - k_3 (W_{dome} - W_{\text{case}}) \]

! 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:

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

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
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.
Conclusions

NREL method achieves uncertainty of < 3 W/m² for all sky conditions

NREL equation accounts for the pyrgeometer thermodynamics

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

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

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/m² is needed

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