Measuring Broadband IR Irradiance in the Direct Solar Beam and Recent Development

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Motivation

- Never measured !! ... any known literature?
- Discrepancy in calibrating shortwave radiometers (pyranometers and Pyrheliometers) using Absolute Cavity Radiometers
- Lack of daytime reference for longwave radiometers (pyrgeometers)
- Raise awareness to modify calibration procedures of shortwave and longwave radiometers
- Might be used to develop method quantifying effect of dome heating without dome thermistors.

Discrepancy in Shortwave Calibration

- Solar and atmospheric science radiometers are calibrated with traceability to the World Radiometric Reference (WRR), maintained by Absolute Cavity Radiometers (ACRs)*
- An ACR is open cavity with no window, developed to measure the extended broadband spectrum of the terrestrial direct solar beam irradiance beyond ultraviolet and infrared bands (i.e., below 0.2 µm and above 50 µm)
- Pyranometers and pyrheliometers are developed to measure the broadband shortwave irradiance (~0.3 µm to ~3 µm), while photovoltaic cells are limited to ~0.3 µm to ~1 µm
- The broadband mismatch of the ACR versus such radiometers causes discrepancy in radiometers’ calibration methods, which has not been discussed or addressed in solar and atmospheric science literature.

Discrepancy in Shortwave Calibration (Cont.)

- Responsivity of radiometer (Pyranometer or pyrheliometer), $RS$,
  \[ RS = \frac{V_{tp}}{I} \]
  where $V_{tp}$ is the thermopile output voltage from the test radiometer, and $I$ is the measured irradiance using an ACR.
- The measured $I$ by the ACR includes the IR component from the sun beam which is not sensed by the test radiometer. Results in an underestimated $RS$!
- When the radiometer is deployed in the field, the irradiance $I_{SW}$,
  \[ I_{SW} = \frac{V_{tp}}{RS} \]
  Since $RS$ is underestimated, then $I_{SW}$ would be overestimated!
- The measured irradiance in the field* might be overestimated by ~16 Wm$^{-2}$ at solar noon, and approaches zero as zenith angle approaches 90°.

*At NREL’s Solar Radiation Research Laboratory (SRRL)
Lack of Daytime IR Reference

• Pyrgeometers are used for solar and atmospheric science applications and calibrated with traceability to the interim World Infrared Standard Group (WISG)

• They are calibrated during the nighttime only, because no consensus reference has yet been established for the daytime longwave irradiance.

Measurement Setup

- Shortwave Dome, 0.3 µm-3 µm
- Shaded Pyrgeometer
- Unshaded Pyrgeometer
- Solar Tracker
Pyrgeometer Measurement Equation

\[ W = K_0 + K_1 \times V_{tp} + K_2 \times W_r + K_3 \times (W_d - W_r) \]  \hspace{1cm} (1)

where,

- \( W \) is the calculated atmospheric longwave irradiance, in Wm\(^{-2}\)
- \( K_0, K_1, K_2, \) and \( K_3 \) are the calibration coefficients
- \( V_{tp} \) is the thermopile output voltage, in µV
- \( W_r \) is the receiver irradiance, in W m\(^{-2}\) = \( \sigma \times (T_c + 0.0007074 \times V_{tp})^4 \), where \( T_c \) is the case temperature, in Kelvin, and \( \sigma \) is Stefan-Boltzmann constant = 5.6704*10\(^{-8}\) W m\(^{-2}\) K\(^{-4}\)
- \( W_d \) is the dome irradiance, in Wm\(^{-2}\) = \( \sigma \times T_d^4 \), where \( T_d \) is the dome temperature, in Kelvin.

Long and Shortwave Irradiance Sources

- **Shaded**
  - Longwave Irradiance from the sun ($W_{LW}$)
  - Diffuse Irradiance ($W_{LW&SW}$)

- **Unshaded**
  - Longwave Irradiance from the sun ($W_{LW}$)
  - Diffuse Irradiance ($W_{LW&SW}$)
  - Shortwave Irradiance from the sun ($W_{SW}$)

- **Clear sky**
  - Direct Beam
  - Diffuse Irradiance ($W_{LW&SW}$)

- **Solar Tracker**
  - Shading using PSP Dome
Measurement Equation of IR Irradiance from the Sun Disk

• $W_u = W_{u,LW,D} + W_{u,LW,\text{Sun}} + W_{u,SW}$ \hspace{1cm} (2)

  where, $W_u$ is the irradiance measured using the unshaded PIR, calculated using
  Equation 1, $W_{u,LW,D}$ is the diffuse IR irradiance, and $W_{u,SW}$ is the direct and diffuse
  shortwave irradiance

• $W_s = W_{s,LW,D} + W_{s,SW}$ \hspace{1cm} (3)

  where, $W_s$ is the irradiance measured using the shaded PIR, calculated using
  Equation 1, $W_{s,LW,D}$ is the diffuse IR irradiance, and $W_{s,SW}$ is the direct and diffuse
  shortwave irradiance

• Data is collected instantaneously from the pyrgeometers; therefore, $W_{u,LW,D} = W_{s,LW,D}$. The longwave
  irradiance from the sun disk ($W_{LW}$) is calculated by subtracting Equation 3 from Equation 2,
  $W_{LW} = W_{u,LW,\text{Sun}} = W_u - W_s - (W_{u,SW} - W_{s,SW})$ \hspace{1cm} (4)

• The unshaded and shaded pyrgeometers are chosen to have minimum spectral difference;
  therefore, the term $(W_{u,SW} - W_{s,SW})$ in Equation 4 will be minimum. This is verified to be less than
  0.73 Wm$^{-2}$ by deploying pyrgeometers unshaded under clear sky. Then $(W_{u,SW} - W_{s,SW})$ is then
  considered zero, and the 0.73 Wm$^{-2}$ is added to the uncertainty. Therefore, the IR irradiance in the
  sun beam equals $W_{LW}$,
  $W_{LW} = W_u - W_s$ \hspace{1cm} (5)

• And the IR direct normal irradiance from the sun disk equals $W_{DNLW}$,
  $W_{DNLW} = \frac{W_{LW}}{\cos z}$ \hspace{1cm} (6)

  where $z$ is the solar zenith angle
Calculated IR Irradiance from the Sun

\[ W_{\text{LW}} = W_u - W_s \]
\[ W_{\text{DNLW}} = \frac{W_{\text{LW}}}{\cos z} \]
Calibrated five SW radiometers using SW-Cavity and BB-Cavity
Preliminary Results of New Development, cont.

Calculated RS of SW-Radiometers Using SW-Cavity versus BB-Cavity

Solar Zenith Angle °

% Difference [RS(SW)/RS(BB)]
Conclusion

- The LW irradiance in the direct solar beam might reach ~16 Wm\(^{-2}\) during SW radiometer calibration; might result in a ~1.6% underestimated shortwave responsivity at solar noon (RS), where RS = Thermopile voltage/Reference irradiance, i.e. at irradiance ~1000 Wm\(^{-2}\).
- When the biased RS is used in the field, the calculated direct beam irradiance might be overestimated by ~16 Wm\(^{-2}\) at solar noon, and approaches zero as zenith angle approaches 90°.

Should we correct for this bias?
Comments/Questions?