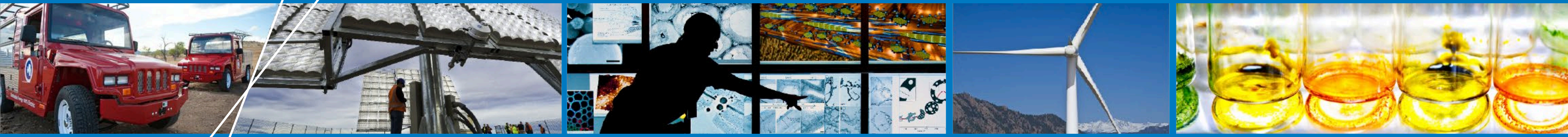
Measuring Broadband IR Irradiance in the Direct Solar Beam and Recent Development



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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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.

I. Reda; J. Konings; Y. Xie, 2015. Method to Measure the Broadband Longwave Irradiance in the Terrestrial Direct Solar Beam. Journal of Atmospheric and Solar-Terrestrial Physics Vol. 129 July 2015 pp. 23-29.

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.

ISO, 1990. ISO 9059: Solar energy-Calibration of field pyrheliometers by comparison to a reference pyrheliometer. International Organization for Standardization, Geneva, Switzerland, 8 pp.

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.**

Gröbner, J., 2010. Tutorial Pyrgeometer, presented at 11th International Pyrheliometer Comparison in Davos, Switzerland, available from ftp://ftp.pmodwrc.ch/pub/julian/.

Measurement Setup

Shortwave Dome, 0.3 µm-3 µm

Shaded Pyrgeometer

Unshaded Pyrgeometer

Solar Tracker

Figure 1. Unshaded and shaded pyrgeometers at NREL/SRRL

Pyrgeometer Measurement Equation

$$\boldsymbol{W = K_0 + K_1 * V_{tp} + K_2 * W_r + K_3 * (W_d - W_r)} \qquad \textbf{(1)}$$

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 $W\ m^{-2} = \sigma * (T_c + 0.0007074 * V_{tp})^4$, where T_c is the case temperature, in Kelvin, and σ is Stefan-Boltzmann constant = $5.6704*10^{-8}\ W\ m^{-2}\ K^{-4}$
- W_d is the dome irradiance, in $Wm^{-2} = \sigma * T_d^4$, where T_d is the dome temperature, in Kelvin.

Reda, I., Hickey, J.R., Stoffel, T., Myers, D., 2002. Pyrgeometer calibration at the National Renewable Energy Laboratory (NREL). J. Atmos. Sol-Terr. Phy. 64 (2002) 1623–1629

Long and Shortwave Irradiance Sources

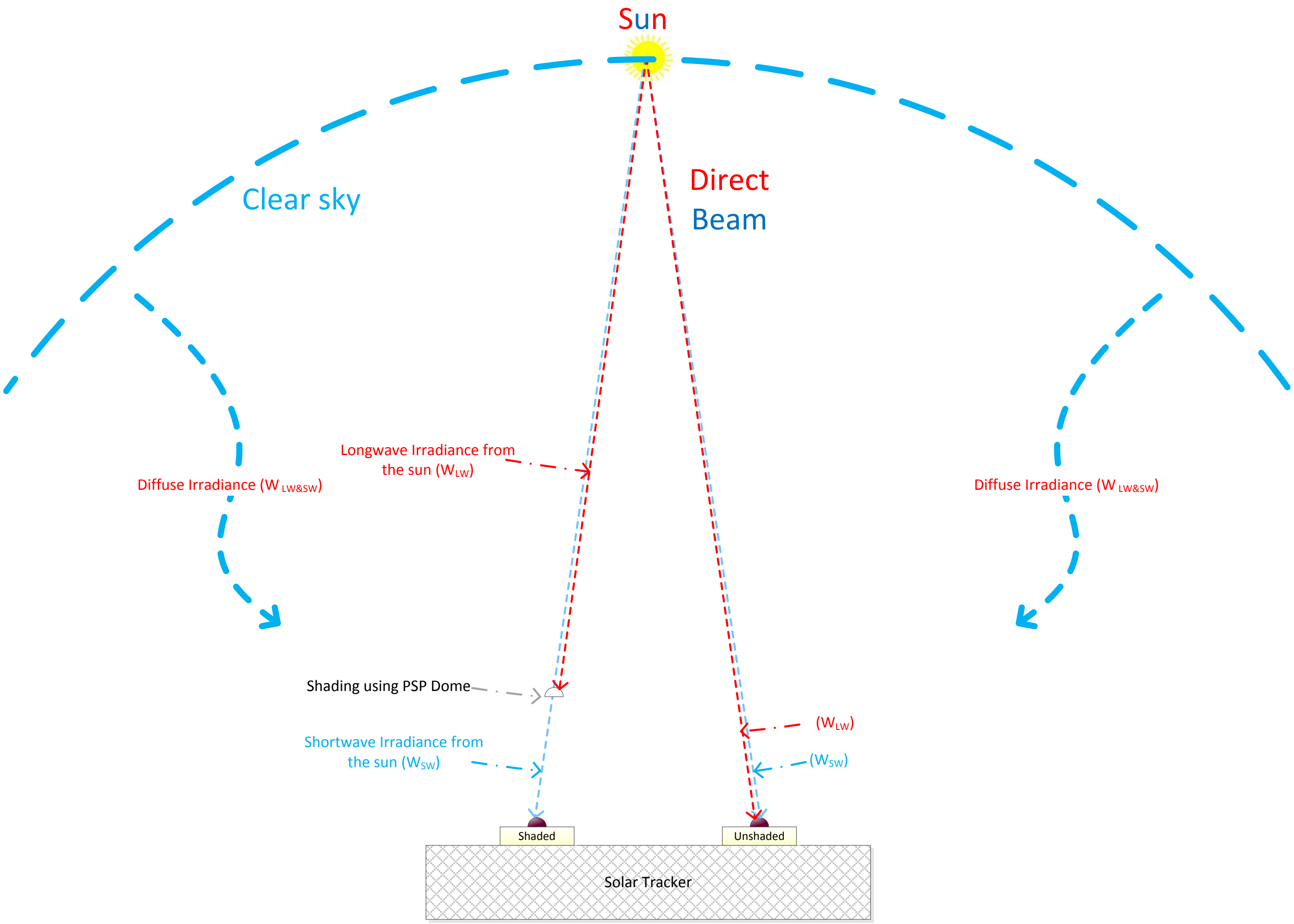


Figure 2. Sensed irradiance by unshaded and shaded pyrgeometers

Measurement Equation of IR Irradiance from the Sun Disk

- $$W_u = W_{u,LW,D} + W_{u,LW,Sun} + W_{u,SW} \qquad (2)$$

  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

- $$W_s = W_{s,LW,D} + W_{s,SW} \qquad (3)$$

  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,

  $$W_{LW} = W_{u,LW,Sun} = W_u - W_s - (W_{u,SW} - W_{s,SW}) \qquad (4)$$

- 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},

  $$W_{LW} = W_u - W_s \qquad (5)$$

- And the IR direct normal irradiance from the sun disk equals W_{DNLW},

  $$W_{DNLW} = \frac{W_{LW}}{\cos Z} \qquad (6)$$

  where z is the solar zenith angle

Calculated IR Irradiance from the Sun

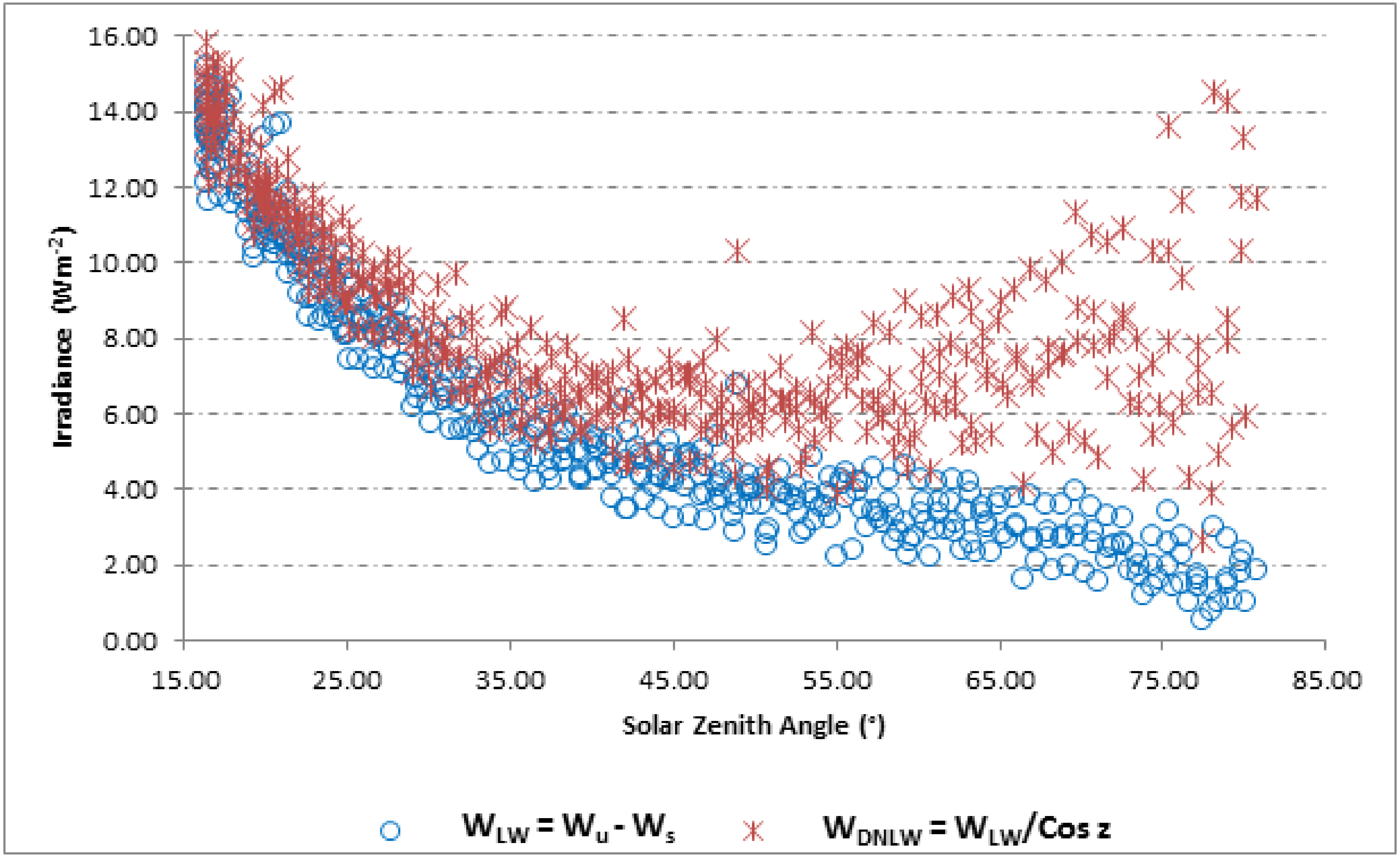
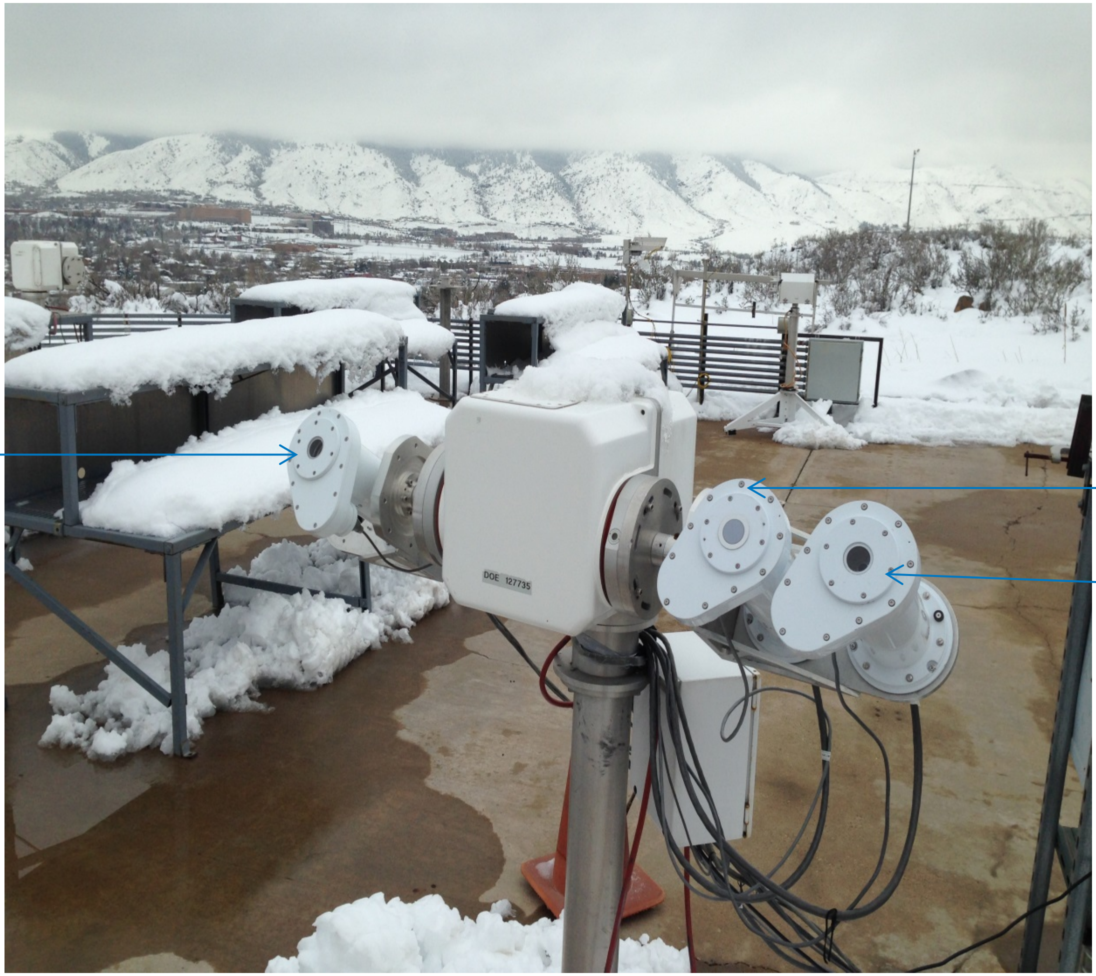


Figure 5. Calculated longwave irradiance from the sun versus zenith angle Time for five clear sky days at NREL/SRRL

Preliminary Results of New Development



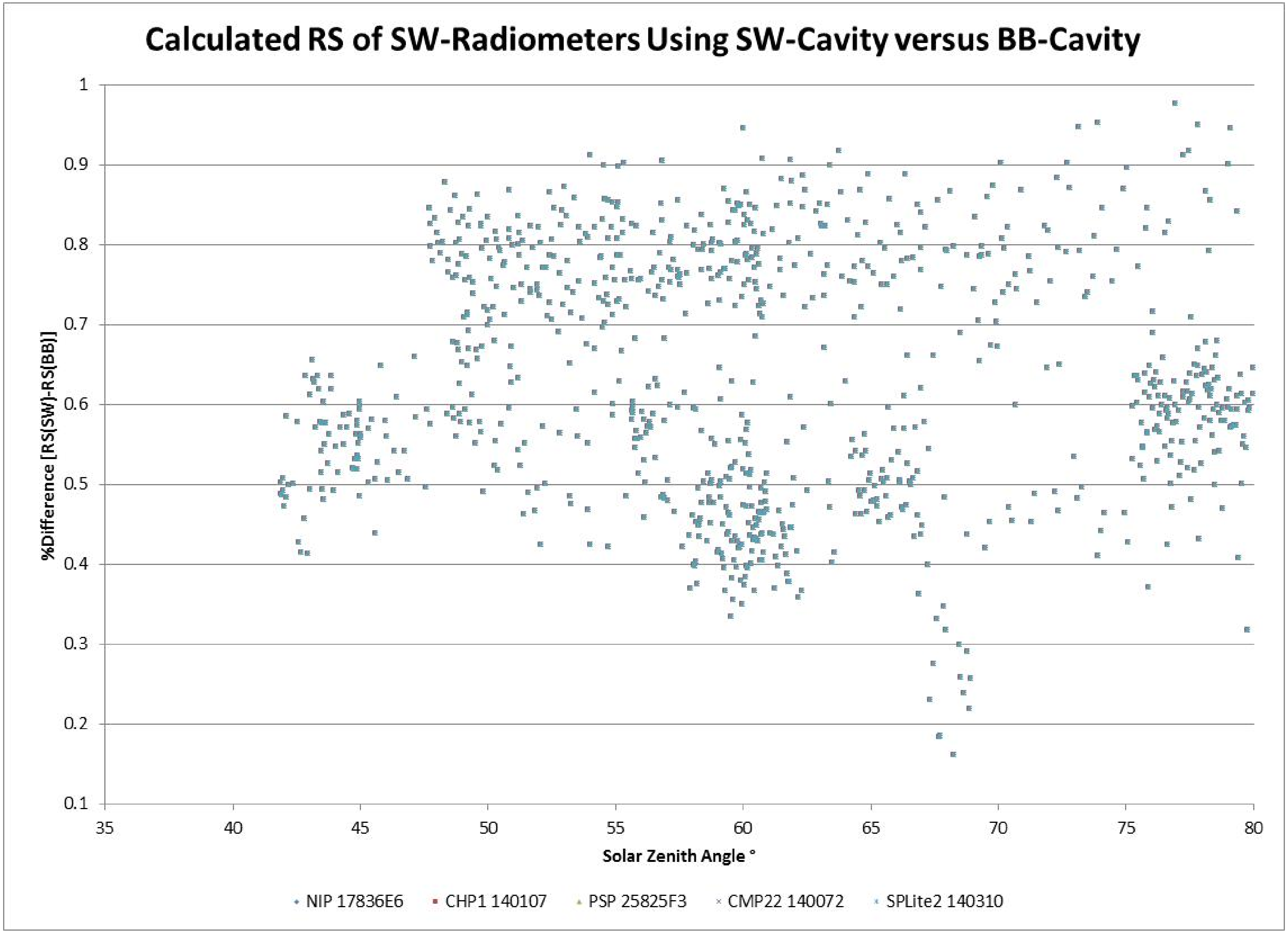
Broadband Cavity
(BB-Cavity)

Broadband LW Cavity
(LW-Cavity)

Broadband SW Cavity
(SW-Cavity)

Calibrated five SW radiometers using SW-Cavity and BB-Cavity

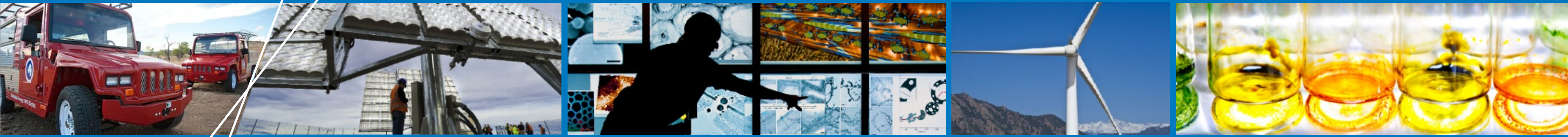
Preliminary Results of New Development, cont.



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?