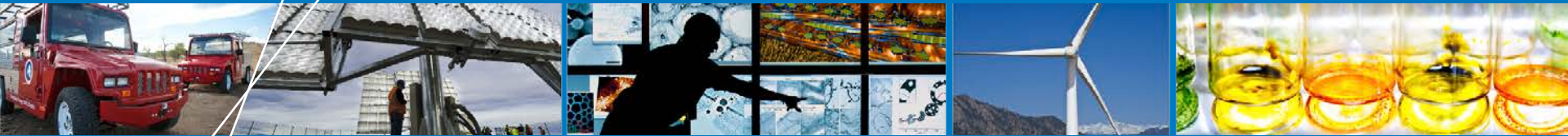


Measuring Broadband IR Irradiance in the Direct Solar Beam



2015 ASR Science Team Meeting

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Motivation

- **Never measured !! ... any known literature?**
- **Discrepancy in calibrating shortwave radiometers (pyranometers and Pyrhemimeters) 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.**

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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 $0.2 \mu\text{m}$ and above $50 \mu\text{m}$)
- Pyranometers and pyrhemometers are developed to measure the broadband shortwave irradiance ($\sim 0.3 \mu\text{m}$ to $\sim 3 \mu\text{m}$), while photovoltaic cells are limited to $\sim 0.3 \mu\text{m}$ to $\sim 1 \mu\text{m}$
- 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 pyrhemometers by comparison to a reference pyrhemometer. International Organization for Standardization, Geneva, Switzerland, 8 pp.

Discrepancy in Shortwave Calibration (Cont.)

- Responsivity of radiometer (Pyranometer or pyrhelimeter), 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 $\sim 16 \text{ Wm}^{-2}$ 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



Figure 1. Unshaded and shaded pyrheliometers at NREL/SRRL

Pyrgeometer Measurement Equation

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

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

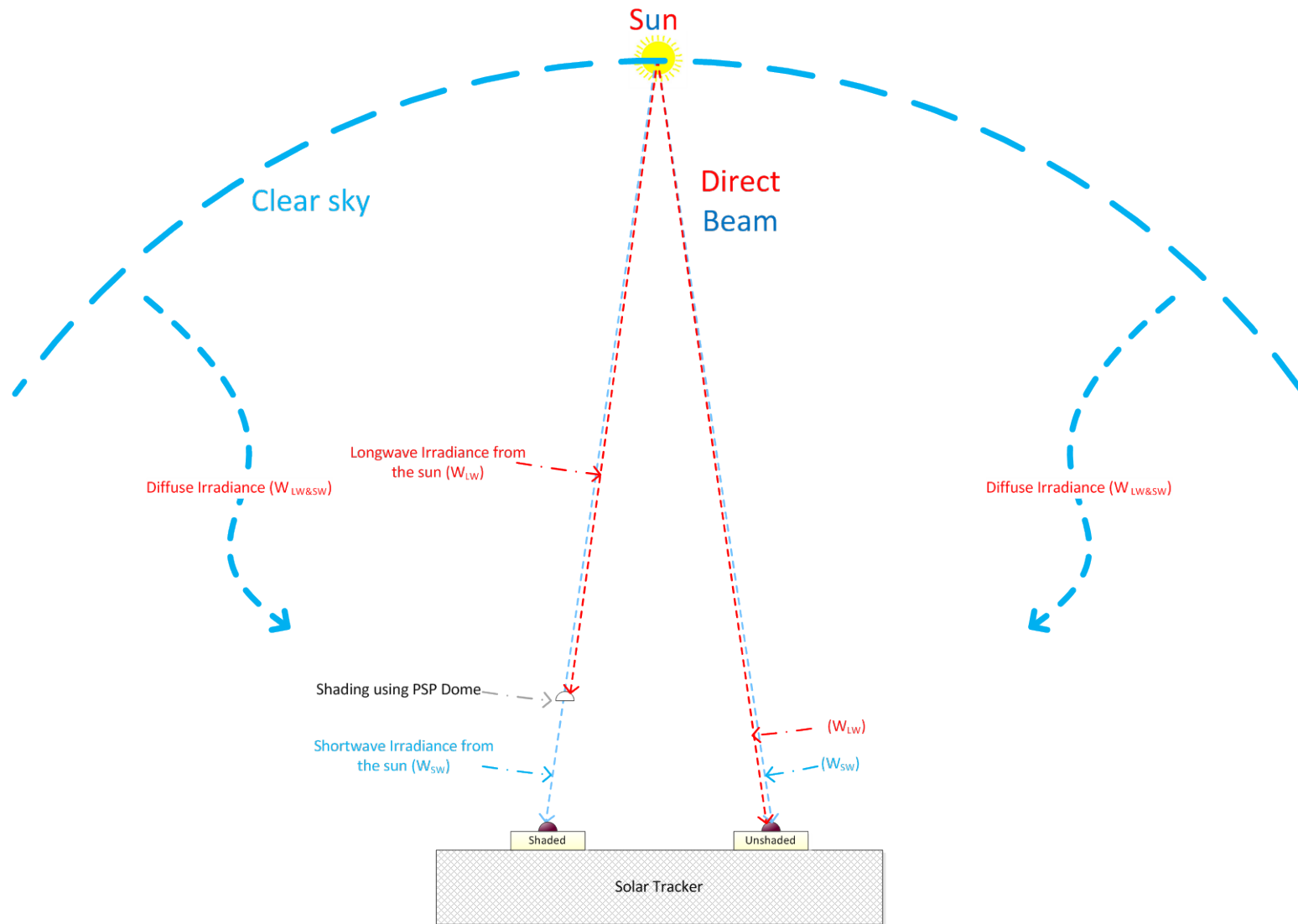


Figure 2. Sensed irradiance by unshaded and shaded pyrometers

Measurement Equation of IR Irradiance from the Sun Disk

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

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

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

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,

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

- 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} ,

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

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

$$W_{DNLW} = \frac{W_{LW}}{\cos z} \quad (6)$$

where z is the solar zenith angle

Verifying Spectral Match of Shaded and Unshaded PIRs

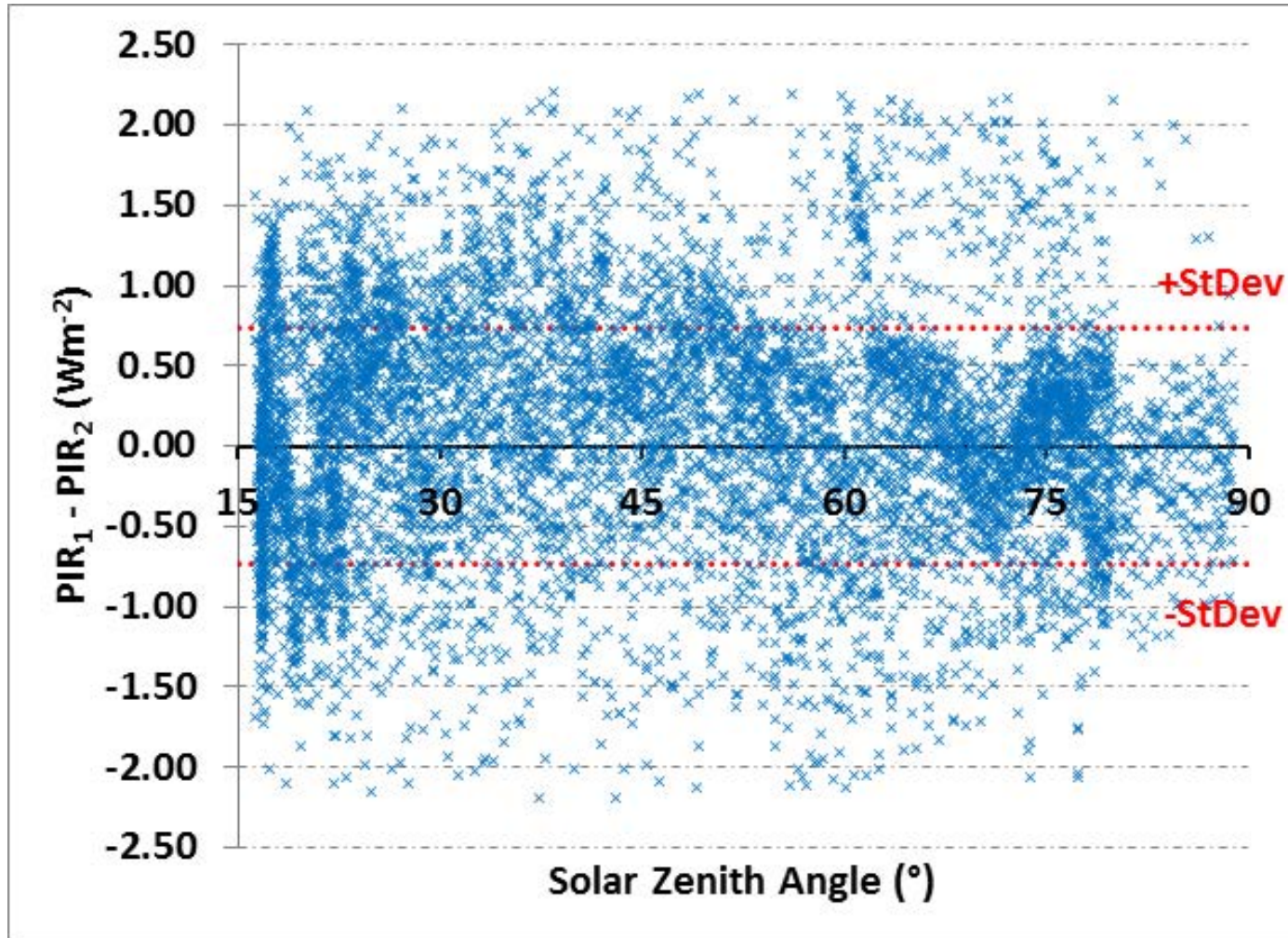


Figure 3. Irradiance difference when both pyrometers are unshaded during the daytime at NREL/SRRL, spectral match validation

Calculated IR Irradiance from the Sun

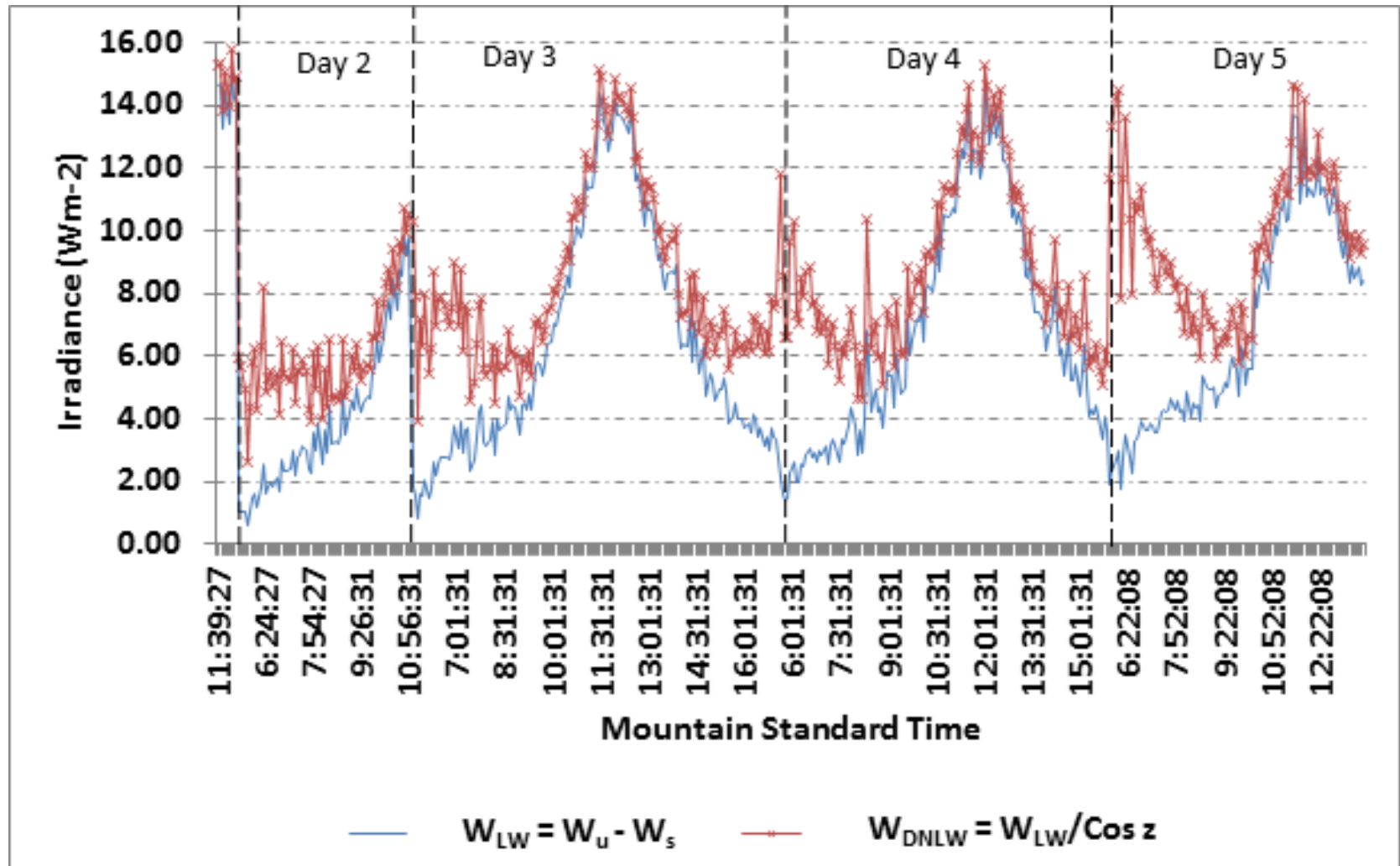


Figure 4. Calculated longwave irradiance from the sun versus Mountain Standard Time for five clear sky days at NREL/SRRL

Calculated IR Irradiance from the Sun

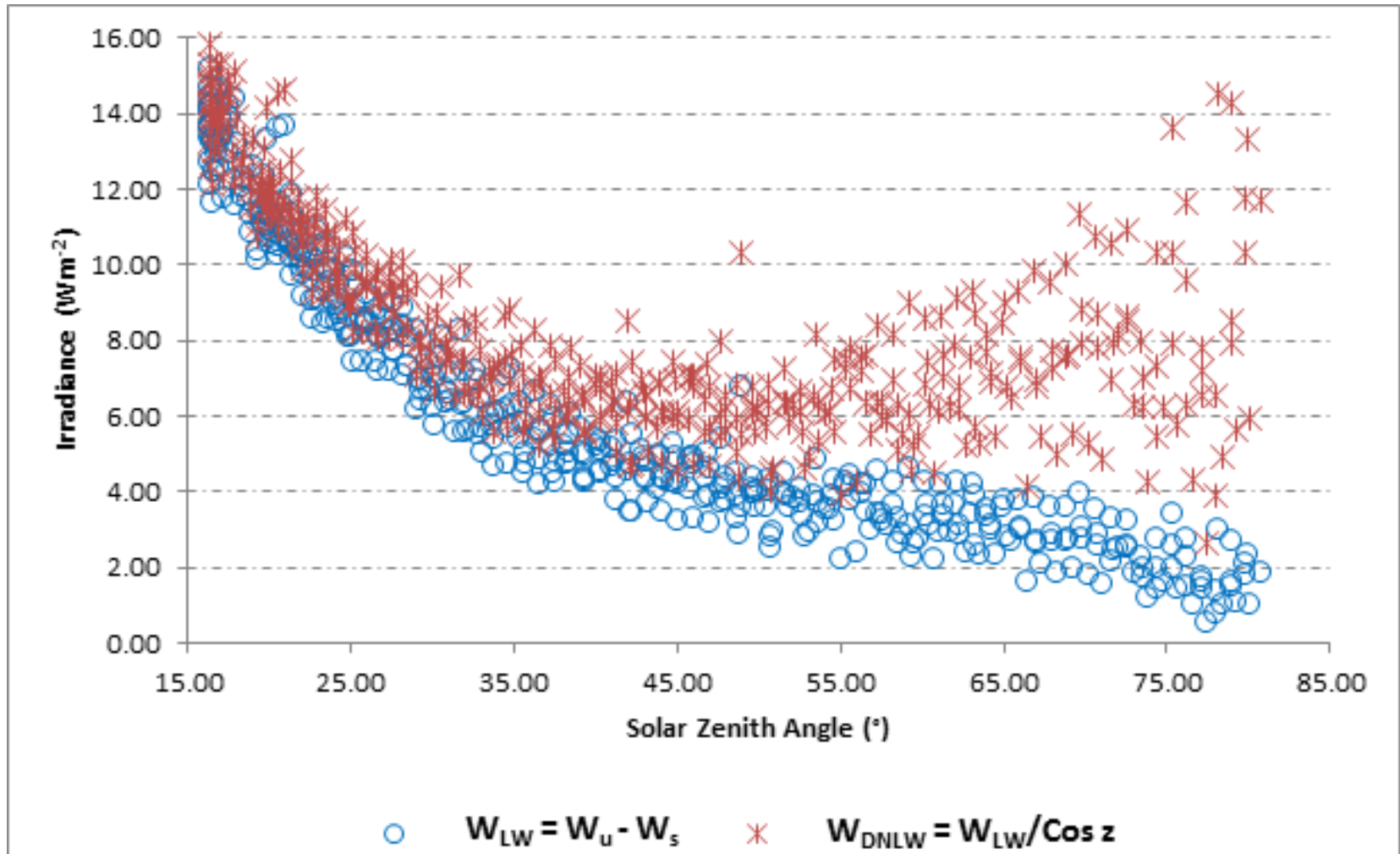
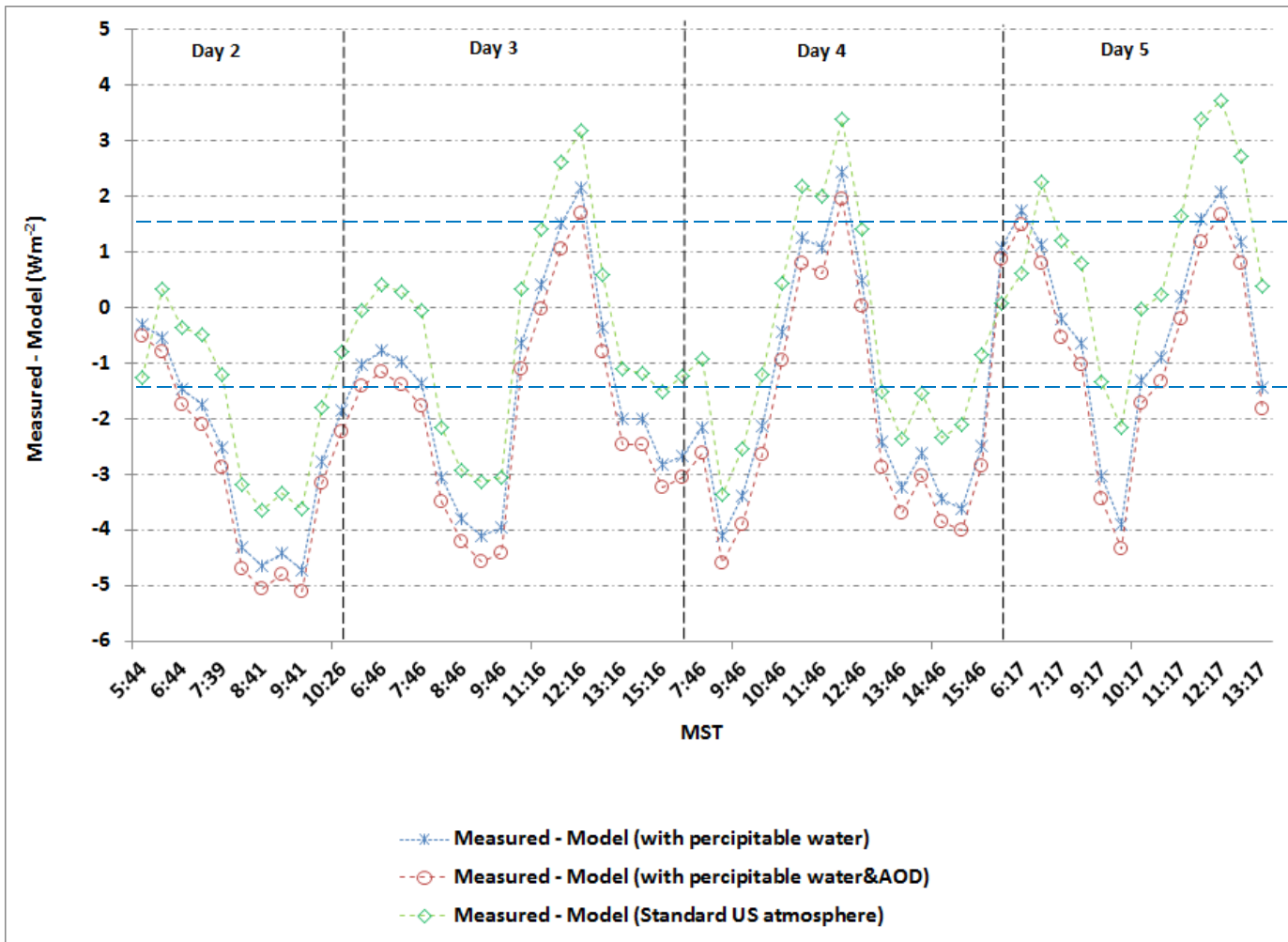


Figure 5. Calculated longwave irradiance from the sun versus zenith angle Time for five clear sky days at NREL/SRRL

Comparison of Measured IR Versus Model Calculation



~50% are within
+/- 1.5 Wm^{-2}

*Can it be the difference
between the actual
atmospheric contents and
the model's input
parameters?*

Stamnes, K., Tsay, S.C., Wiscombe, W., Jayaweera, K., 1988. Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. Appl. Opt., 27, 2502-2509.

Mayer, B., Kylling, A., 2005. The libRadtran software package for radiative transfer calculations - description and examples of use. Atmos. Chem. Phys., 5, 1855-1877.

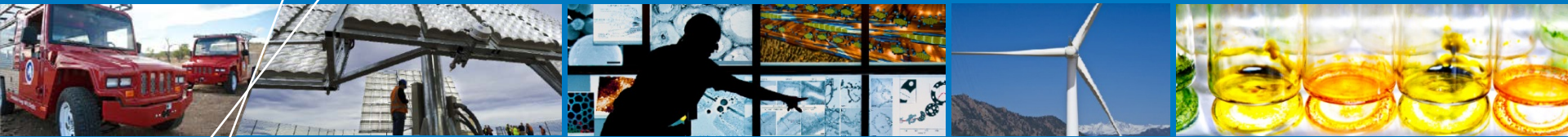
Conclusion

- The longwave irradiance from the sun was measured with expanded uncertainty of 1.5 Wm^{-2} . The measured irradiance was also compared to model calculation with $\sim 50\%$ agreement with the estimated expanded uncertainty of 1.5 W/m^2
- This method is preliminary step that might contribute to establishing consensus world reference for the direct-beam longwave irradiance that might be used to calibrate future radiometers dedicated to such measurement
- A pyrhelimeter fitted with solar blind coated silicon windows has been proposed to measure direct-beam longwave irradiance from the sun. Its initial results were presented at the 14th BSRN Scientific Review and Workshop (Konings, 2014)

Konings, J., 2014. Direct far infra-red radiometers, the measurement of direct longwave radiation. Presented at the 14th BSRN Scientific Review and Workshop in Bologna, Italy, available from: http://www.isac.cnr.it/~radiclim/bsrn2014/userfiles/downloads/POSTER_SESSION/P13_Konings.pdf.

Future Work

- **Once a method is refined and consensus reference is established, it might be used to correct for the spectral mismatch that results from calibrating shortwave radiometers using an unwindowed absolute cavity radiometer, and to develop calibration method to calibrate pyrgeometers during daylight time, instead of present nighttime calibration**
- **Next step, replicate this setup using matched pairs of other commercially available pyrgeometer models. As different models have slightly different spectral transmission characteristics, the spectral distribution of direct-beam longwave irradiance can be studied in more detail. Also, perform this measurement at other geographical locations.**



Comments/Questions?

www.nrel.gov/docs/fy15osti/63830.pdf