State of the Practice for Diffuse Solar Irradiance Measurements

Tom Stoffel
SOLAR RESOURCE SOLUTIONS, LLC

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

This presentation contains no confidential information

To Measure Is to Know

Solar Resource Solutions, LLC

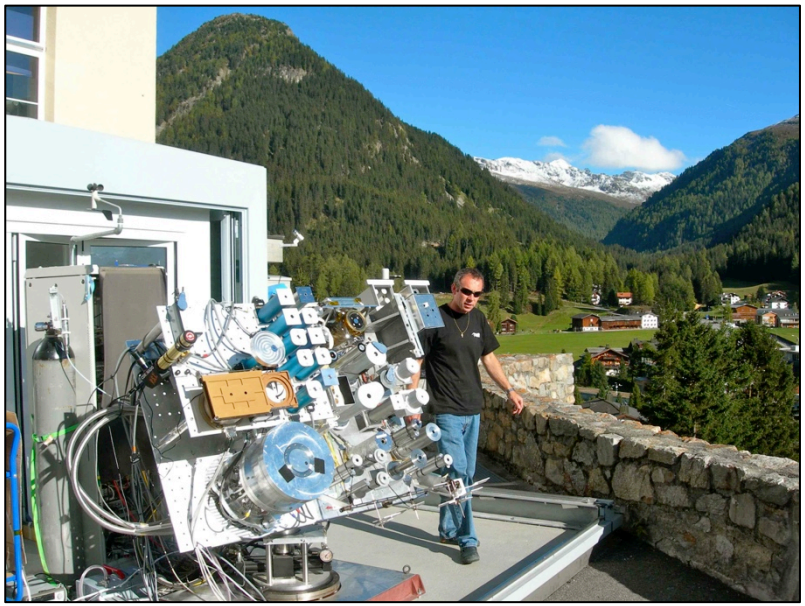
- Lord Kelvin (1824-1907)
- **Know Your Measurement**
  Tom Stoffel

Optical Radiometry

- The most **uncertain** measurement discipline
- **No absolute standard** for diffuse solar irradiance

World Radiometric Reference

- Only Internationally **Recognized** Measurement **Reference** for Solar Radiation
- **WRR** Uncertainty: **±0.3%**
  - **Detector-based** standard using **electrical** power equivalence and **area** measurements
  - Applies only to **Direct Normal Irradiance** > 700 Watts/meter^2

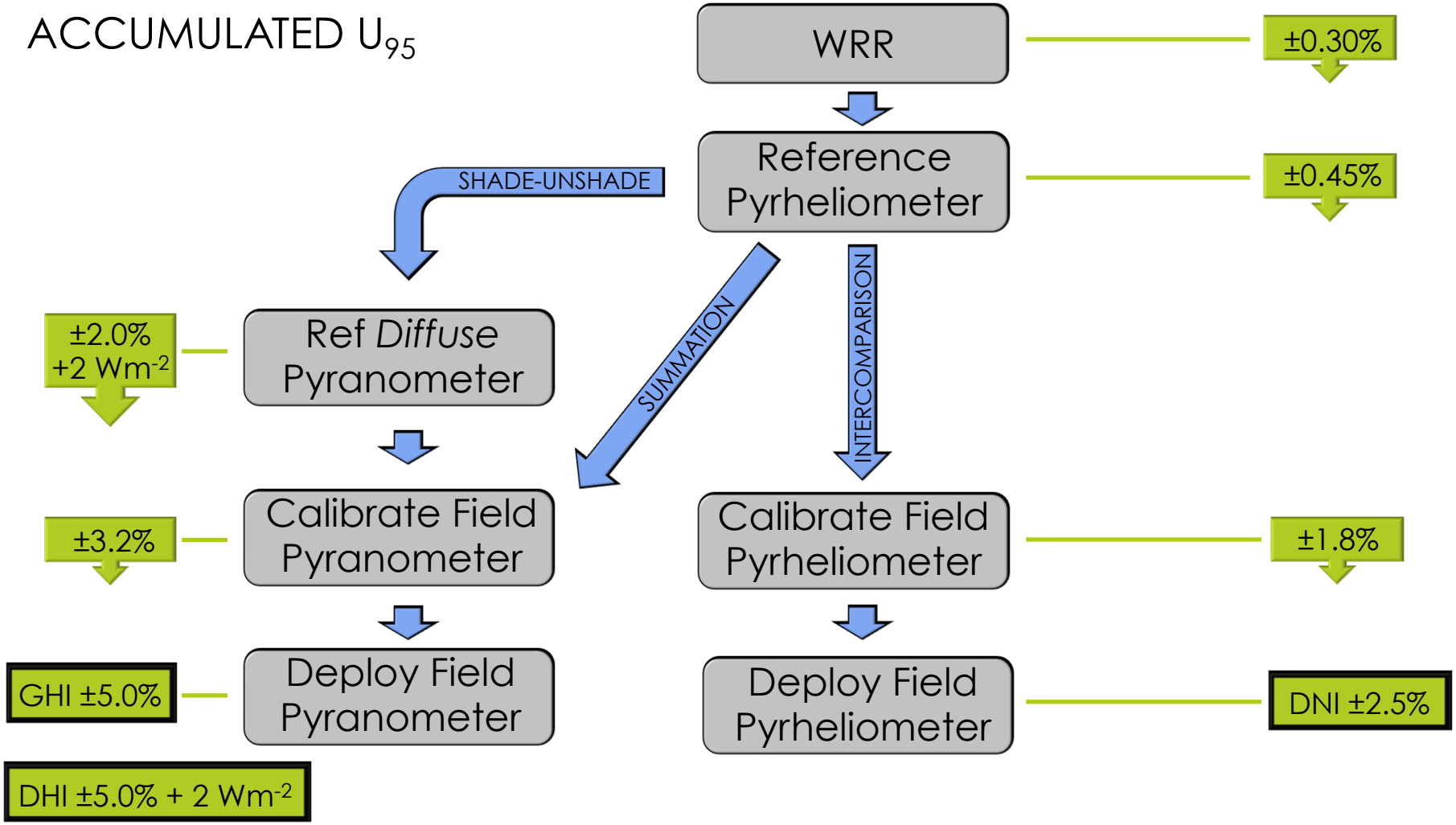


World Standard Group:
6 electrically self-calibrated absolute cavity radiometers

Physikalisch-Meteorologisches Observatorium Davos
World Radiation Center
www.pmodwrc.ch

International Pyrheliometer Comparison

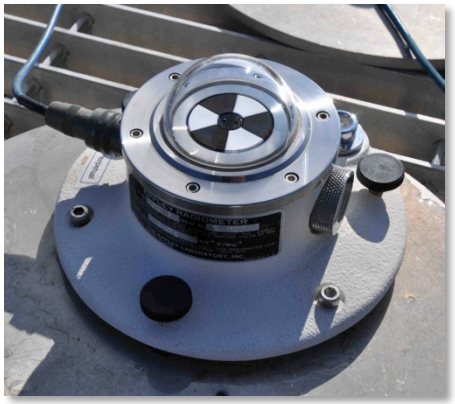
Uncertainty Tree

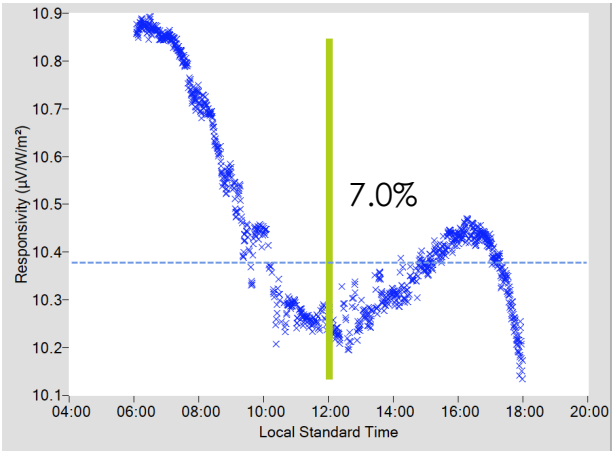


[After Sengupta, et al. 2015]

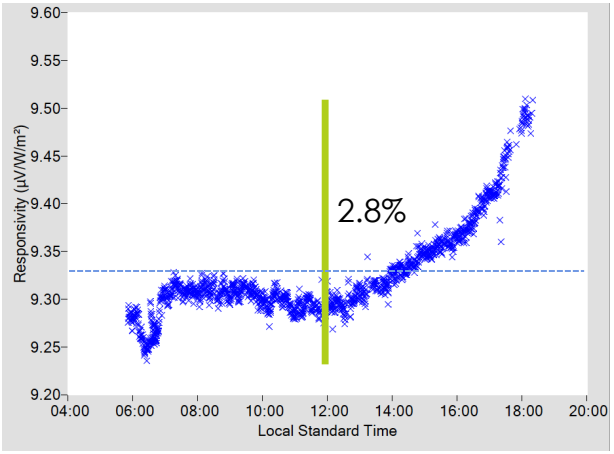
Outdoor Calibrations

Calibration Factors Vary Through the Day…

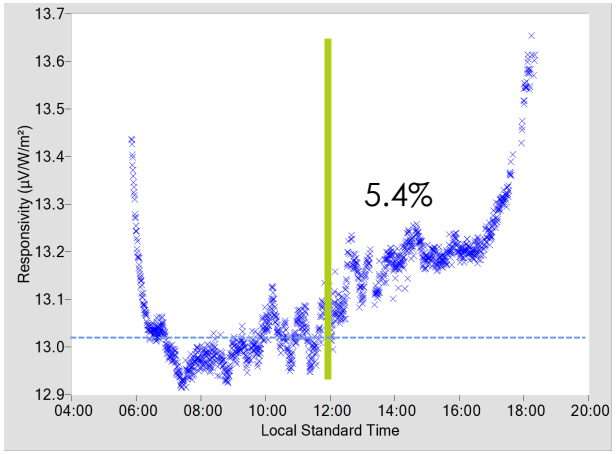




Model 8-48



Model CM22



Model LI-200

---------- Responsivity (µV / Wm^{-2}) @ 45° solar zenith angle

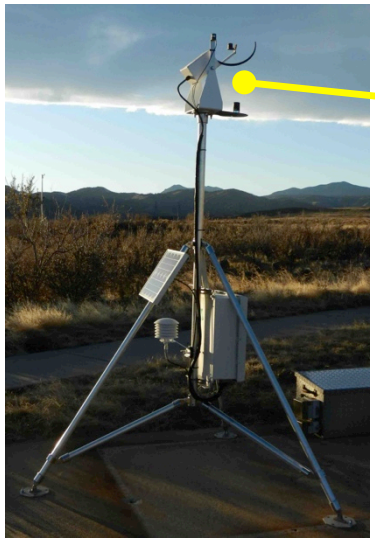
Measuring Diffuse Irradiance

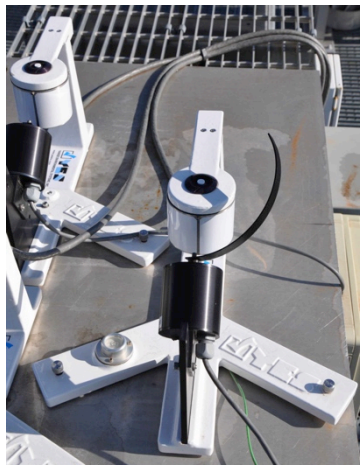
Shadowband

*

Shading Ball or Disk

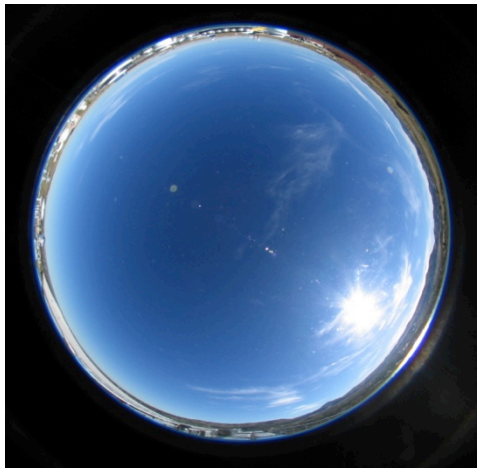
Rotating Shadowband Radiometers*





* Measures GHI & DHI for computing DNI

Getting to POA



Horizontal Plane

Plane of Array (?)

$$GHI = DNI \cos(Z) + DHI$$

$$\begin{aligned} POA^{1} = {} & DNI \cos(\theta)/\cos(Z) + && \text{<Direct-Sky} \\ & 0.5\ DHI\ [1-\cos(\beta)] + && \text{<Diffuse-Sky} \\ & 0.5\ \rho\ DNI\ [1-\cos(\beta)] + && \text{<Direct-Reflected} \\ & 0.5\ \rho\ DHI\ [1-\cos(\beta)] && \text{<Diffuse-Reflected} \end{aligned}$$

[1] **Isotropic Model:**

θ = solar incidence angle
Z = solar zenith angle
β = panel tilt angle from horizontal
ρ = ground albedo

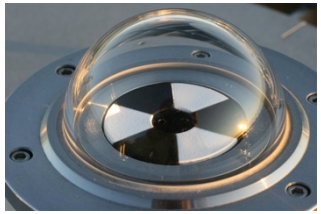
[After Myers, 2013 and Stoffel, et al., 1987]

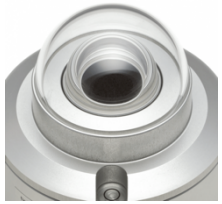
Key Measurement Issues

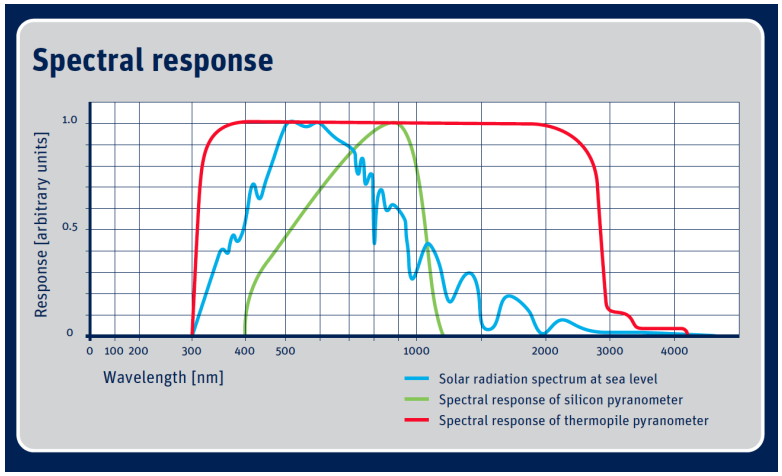
- Pyranometer Detector Types
- Spectral Irradiance Variations
- Temperature/Thermal Offsets
- Sky Radiance Distributions
- Orientation & Alignment

Photodiode

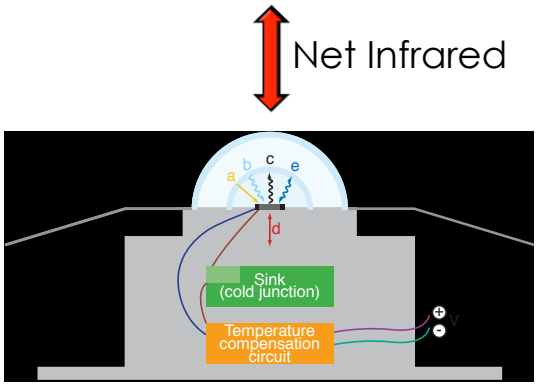
Thermopile







From www.kippzonen.com



Thermal Offset Corrections
Needed for
Single-black thermopile
pyranometers UNDER measure
clear sky diffuse
(i.e., cold atmosphere)
by ~3 to 30 Wm^{-2}

Pyranometer Measurements

Thermopile Pyranometers

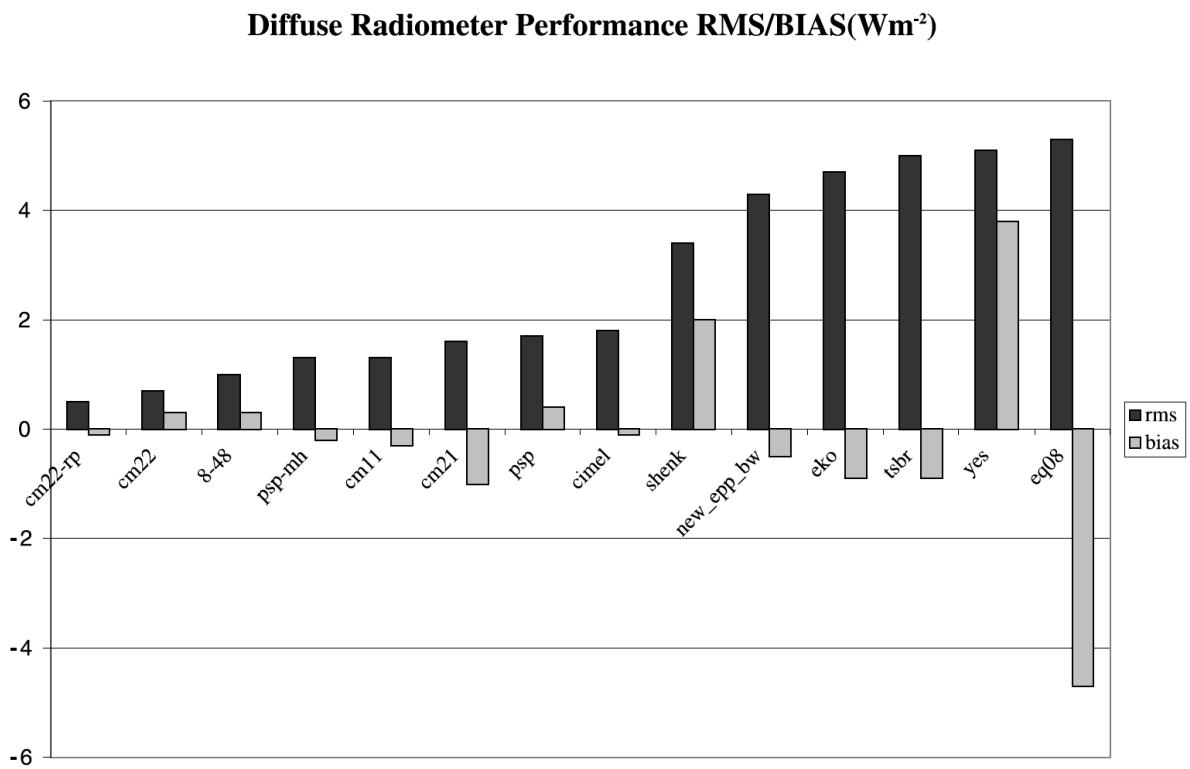
<u>DOE/ARM:</u>

Intensive Observational Period (Fall of 2001)

14 T.P. Pyranometers
- Shade/Unshade Calibrations
- Ventilated & Unventilated
- Tracking Shade Ball

2 Weeks of Data - mostly clear sky

Precision is within **2 Wm^{-2}** or ~2% @ ~100Wm^{-2} Diffuse



RMS & Bias (Wm^{-2}) wrt the *mean* of **5** most stable pyranometers *after correction* for thermal offsets

[Michalsky, et al. 2003]

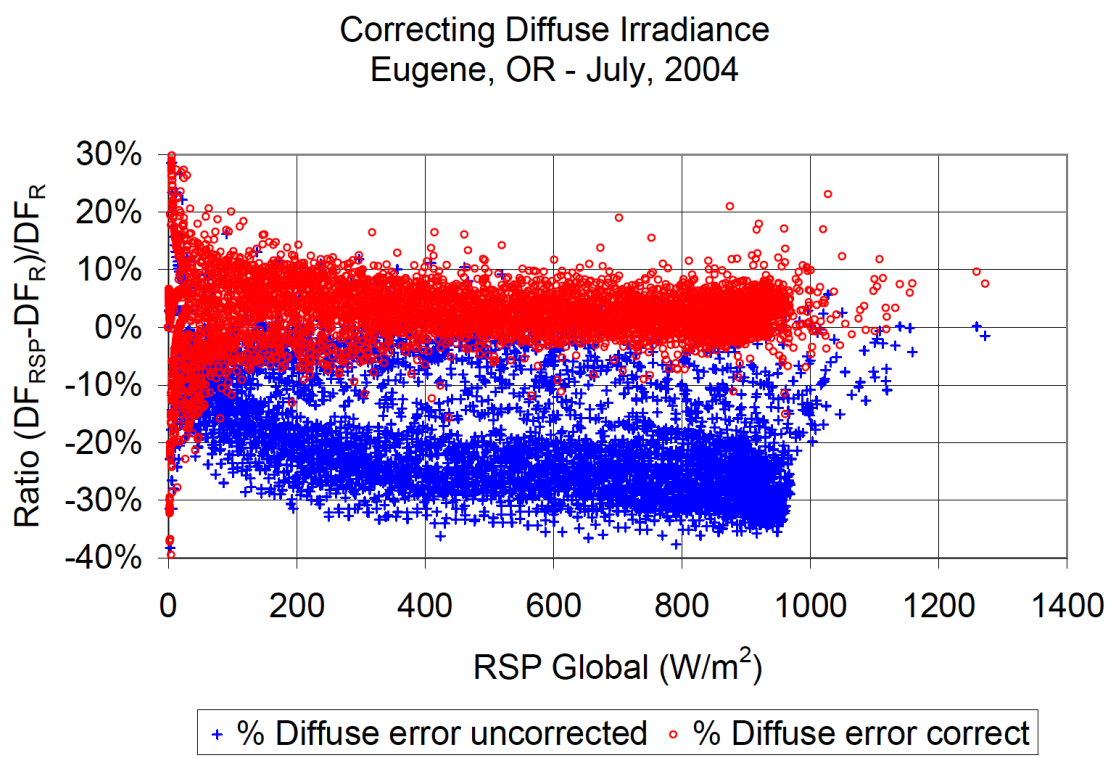
Pyranometer Measurements

Photodiode Pyranometers

- Temperature Response
  - ✓ Silicon PV
- Spectral Response
  - ✓ Under-measures "blue"
  - ✓ Blind to $\lambda > 1{,}100$ nm

Note: Calibrations are performed under clear-sky conditions. The manufacturers' Instructions clearly state, *For this reason, we do not recommend its use under artificial lighting, within plant canopies or to measure reflected radiation.*

Vignola Diffuse Correction
Applied to LI-200 measurements



[Vignola, 2006]

State of the Practice

Uncertainty of Clear Sky Diffuse Irradiance

± 30+% Photodiode – No corrections for temperature or spectral response

± 10% Photodiode – Corrections for temperature and spectral response

± 5%* Thermopile – Single-Black detector with thermal offset corrections & mounted in ventilator (upper range)

± 2%* Thermopile – Black/White detector or Single-Black detector with thermal offset corrections & mounted in ventilator (lower range)

* Percentage of Reading + 2 Wm^{-2}

Conclusions

- How much **uncertainty** can you afford?

  There is a wide range of options for commercial instrumentation.

- **Model** accuracy is limited by the uncertainties of the **measurements** used for development and validation.

- Know your **pyranometer!**

- Observe **Best Practices** for Installation, O&M.

Acknowledgments

Thank You!

And for the mountains of work done by:

- ARM – Atmospheric Radiation Measurement Program (U.S. DOE)
- BSRN – Baseline Surface Radiation Network (WMO)
- DOE/NREL – Staff at the Solar Radiation Research Laboratory
- K.A.CARE – King Abdullah City for Atomic and Renewable Energy; Renewable Resource Monitoring & Mapping (RRMM) Program.
- NOAA/ESRL/GMD – Global Monitoring Division Radiation Group
- University of Oregon – Solar Radiation Monitoring Laboratory

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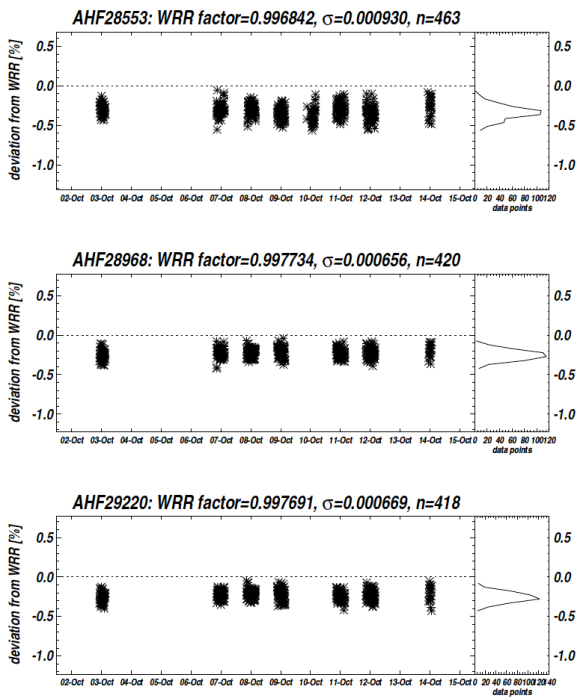
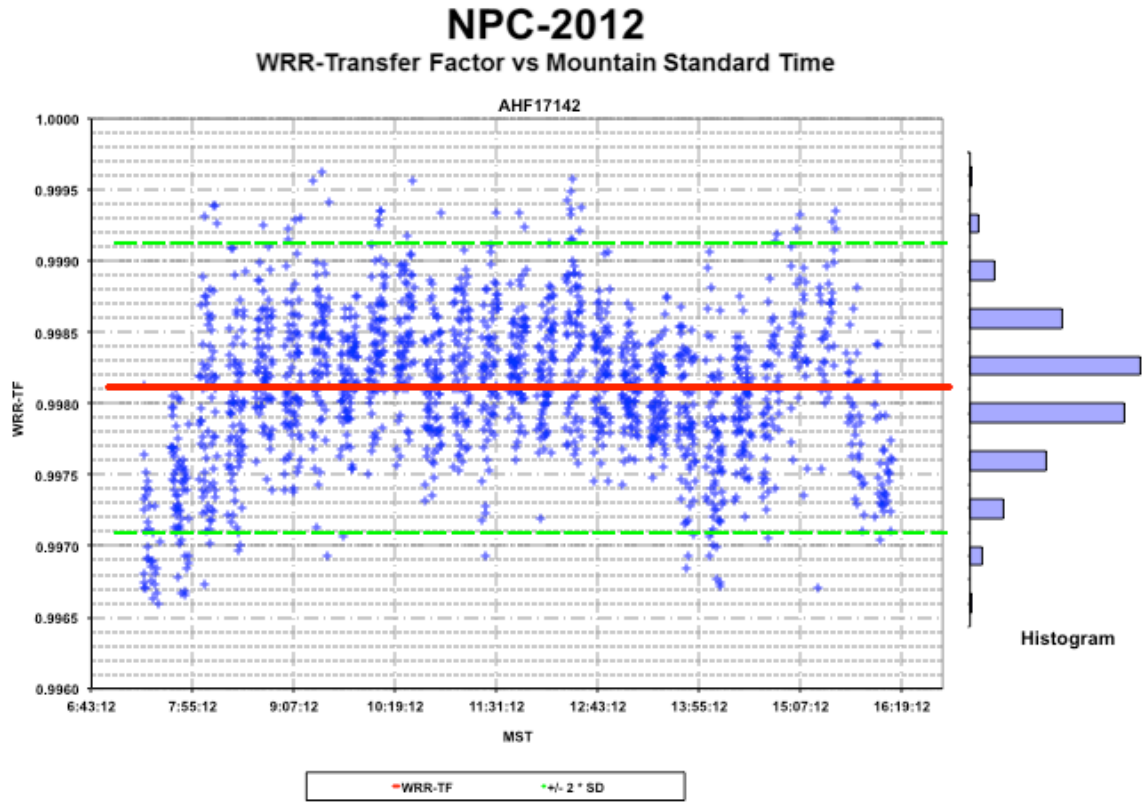
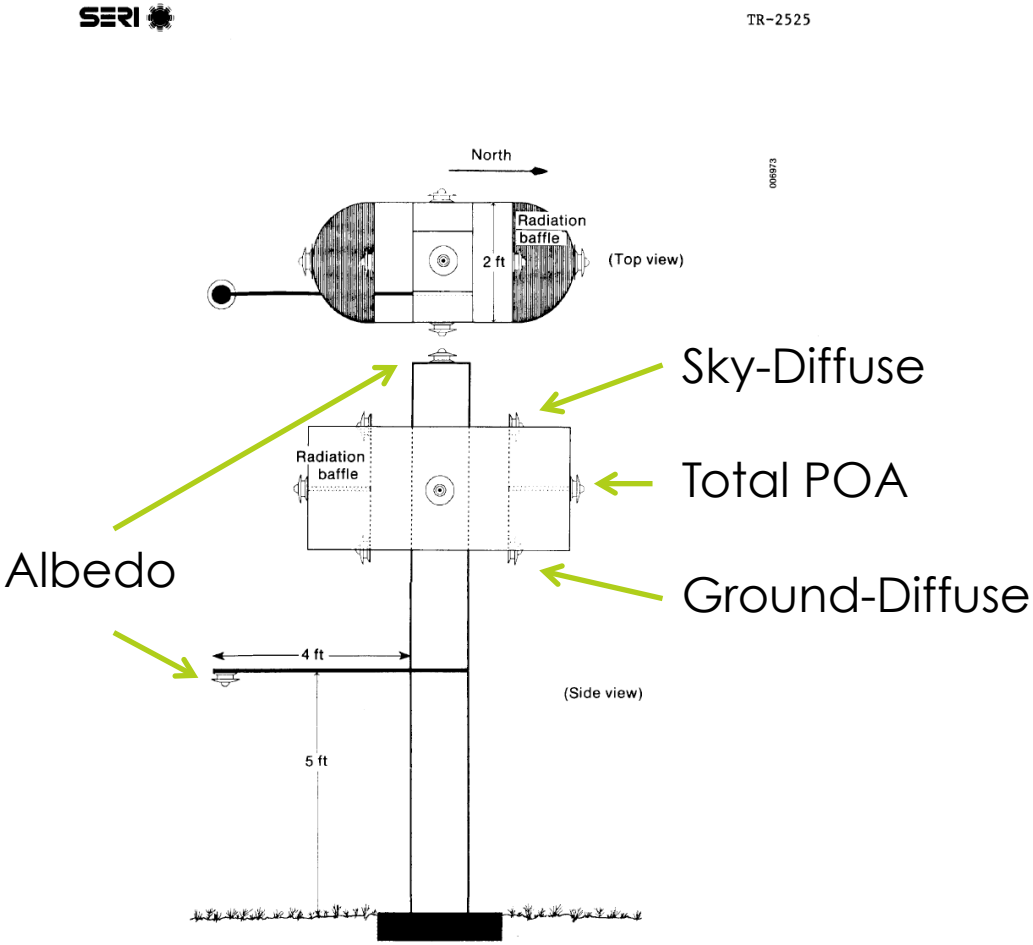
Comparison of Absolute Cavity Radiometers (4 instruments: - 0.1% to - 0.5% wrt WRR)

International Pyrheliometer Comparisons – IPC XI
+
NREL Pyrheliometer Comparisons – NPC 2012





Measuring Diffuse Irradiance on Vertical Surfaces



Circa 1984

Figure 3-2. Locations of Pyranometers on Radiometer Tower for Measuring Solar Irradiance on Vertical Surfaces

Evaluated 5 *Tilt Models*:

- Isotropic
- Temps and Coulson
- Klucher
- Hay
- Perez

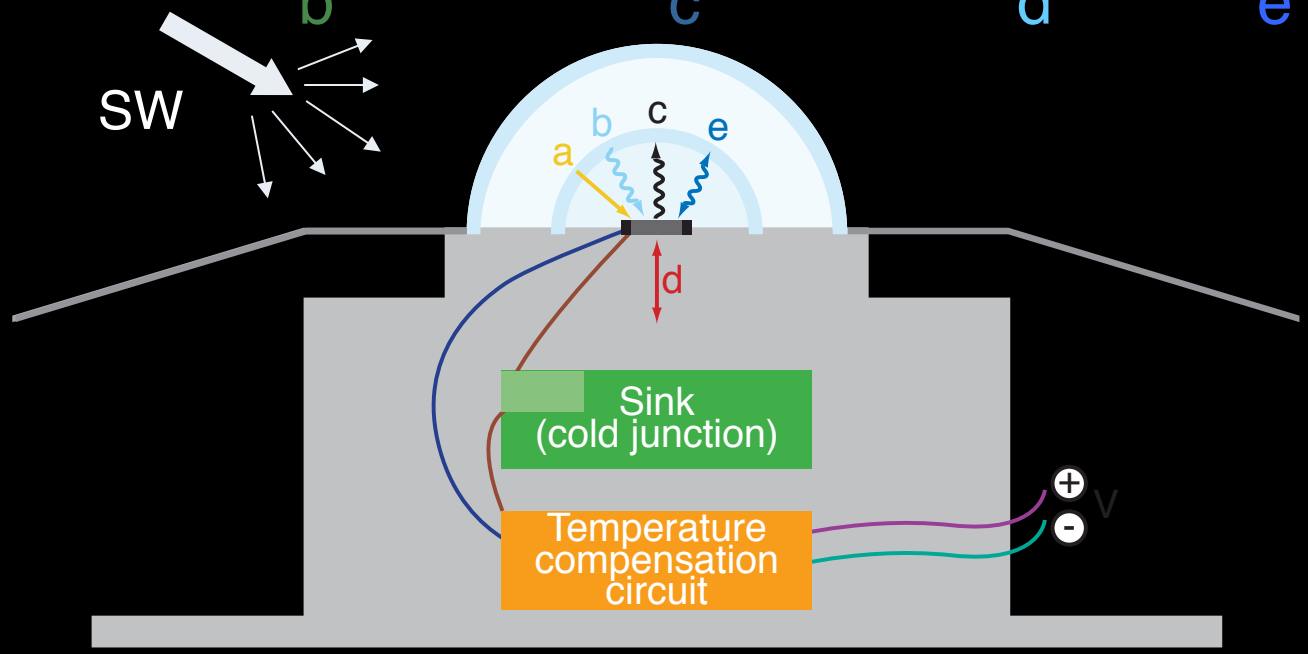
North: 18% to 45% Overestimate

East & West: -3% to 23%

South: ± 5% (except ±10% T&C)

Heat Budget of Generic Pyranometer with Single Black Detector

$$\underbrace{SW\, t_g(1-\rho)}_{a} + \underbrace{F_{gd}A_g\varepsilon_g\sigma\, T_g^{\,4}}_{b} - \underbrace{F_{dg}A_d\varepsilon_d\sigma\, T_d^{\,4}}_{c} - \underbrace{(T_d - T_s)k}_{d} \pm \underbrace{Con}_{e} = 0 \qquad [1]$$



SW = shortwave solar
F = config factor (area=A)
k = heat conduction coeff.
d = detector surface

t = transmission of glass dome(s)
T = temperature (°K)
Con = convection &unwanted conduction
V = pyranometer output voltage (μV)

ρ = SW reflectance
ε = emissivity
g = glass dome
s = thermopile heat sink