Exploring Sources of Uncertainties in Solar Resource Measurements

Presenter: Manajit Sengupta
Authors: Aron Habte, Manajit Sengupta

2016 6th PV Performance and Monitoring Workshop
Freiburg, Germany (October 24-25, 2016)
Sensing, Measurement, and Forecasting

Provide high-quality meteorological and power data for energy yield assessment, resource characterization, and grid integration.

**Measurements**
- The right observations of wind and solar resources

**Modeling**
- Targeted predictions of resources and plant performance

**Standards**
- Raising everyone to the same level and enabling dialog
Why Explore Sources of Uncertainty?

- NREL’s Sensing, Measurement, and Forecasting Group collects and disseminates accurate solar resource measurements.
- Best practices for solar resources measurement, calibration, and characterization are followed.
- Advancing best practices benefits solar conversion projects by improving the bankability of the underlying data.
- The accuracy of solar resource measurements depends on:
  - Instrument specifications
  - Calibration procedures
  - Measurement setup
  - Maintenance (cleaning)
  - Location and environmental conditions.
Sources of Measurement Uncertainty

- Calibration
- Spectral response
- Zenith angle response
- Maintenance---Soiling
- Data logger uncertainty
- Temperature dependence
- Nonlinear response
- Thermal offset
- Instrument aging

Understanding and quantifying each source of uncertainty is essential for the determination of overall uncertainty.
Evaluating Calibration Methods
• Both indoor and outdoor methods are traceable to the World Radiometric Reference.
• Indoor calibration of radiometers provides:
  o Control of test conditions
  o Calibration results independent of outdoor conditions
  o Convenience.
• Outdoor calibrations are useful for cosine response correction, which ultimately assists in reducing measurement uncertainty.
### Calibration Methods

**Calibration Methods**

<table>
<thead>
<tr>
<th>Cases</th>
<th>Calibration Method</th>
<th>Thermal Offset Correction Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Thermopile Pyranometer</td>
</tr>
<tr>
<td>Case 1</td>
<td>BORCAL(^b) responsivity as a function of solar zenith angle (SZA)</td>
<td>Yes</td>
</tr>
<tr>
<td>Case 2</td>
<td>Manufacturer calibration responsivity at manufacturer-specified SZA in degrees</td>
<td>N/A</td>
</tr>
<tr>
<td>Case 3</td>
<td>BORCAL responsivity at 45°</td>
<td>Yes</td>
</tr>
<tr>
<td>Case 4</td>
<td>BORCAL responsivity at 45°</td>
<td>No</td>
</tr>
<tr>
<td>Case 5</td>
<td>Manufacturer calibration responsivity at manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation</td>
<td>N/A</td>
</tr>
</tbody>
</table>

---

**Ten months of 1-minute data for clear-sky conditions (\(KN>0.6\)) from 12 radiometers were compared.**

---


\(^b\) Broadband Outdoor Radiometer Calibrations
CMP22 has relatively small difference among all the methods compared to the MS-410 and SPP radiometers.

For photodiode pyranometers, the manufacturer-supplied responsivities have higher deviation.

(1) BORCAL: Function of SZA, (2) manufacturer-specified SZA in degrees, (3) BORCAL responsivity at 45° with thermal offset correction, (4) BORCAL responsivity at 45° without thermal offset correction, (5) manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation.
The sNIP pyrheliometer data show better agreement to the reference direct normal irradiance (DNI) (CHP1) data than the DR02 and MS-56 pyrheliometers. The NREL responsivity function method provides better results for the DR02 radiometer than the factory responsivity method.

(1) BORCAL: Function of SZA, (2) manufacturer-specified SZA in degrees, (3) BORCAL responsivity at 45° with thermal offset correction, (4) BORCAL responsivity at 45° without thermal offset correction, (5) manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation.
Quantifying Spectral Error
In the International Standards Organization (ISO) and World Meteorological Organization (WMO) “spectral selectivity” term is the only specification that does not translate directly into a measurement error.

This is a problem in uncertainty evaluation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-linearity (100 to 1000 W/m²)</td>
<td>± 0.5 %</td>
</tr>
<tr>
<td>Directional response</td>
<td>± 10 W/m²</td>
</tr>
<tr>
<td>Spectral selectivity (350 to 1500 x 10⁻⁹ m)</td>
<td>± 3 %</td>
</tr>
<tr>
<td>Temperature response (interval of 50 K)*</td>
<td>2 %</td>
</tr>
</tbody>
</table>
Spectral Mismatch Equation

\[
\text{spectral mismatch} \% = \left[ \frac{\int_{350}^{2400} \tau_{\text{dome, new aged}}(\lambda) \cdot \alpha_{\text{coating, new aged}}(\lambda) \cdot E_{\text{AM}_i}(\lambda) \, d\lambda}{\int_{350}^{2400} E_{\text{AM}_i}(\lambda) \, d\lambda} \cdot \frac{\int_{350}^{2400} E_{\text{AM}_{1.41}}(\lambda) \, d\lambda}{\int_{350}^{2400} \tau_{\text{dome, new aged}}(\lambda) \cdot \alpha_{\text{coating, new aged}}(\lambda) \cdot E_{\text{AM}_{1.41}}(\lambda) \, d\lambda} - 1 \right] \times 100
\]

- \( \tau_{\text{dome}} \) = Dome transmittance
- \( \alpha_{\text{(coating)}} \) = Absorptance of coating
- \( E_{\text{AM}_i} \) = Spectral irradiance under various air mass (obtained using SMARTS)
- \( E_{\text{AM}_{1.41}} \) = Reference spectral data at AM 1.41 (SZA 45).
## Radiometers Included in the Study

<table>
<thead>
<tr>
<th>Inst#</th>
<th>Model</th>
<th>Type</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PSP</td>
<td>Double dome and aged coating</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>PSP</td>
<td>Double dome and aged coating</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>PSP</td>
<td>Double dome and aged coating</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>PSP</td>
<td>Double dome and aged coating</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>TSP-1</td>
<td>Double dome and aged coating</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>---</td>
<td>Transmission 2 mm and new coating data</td>
<td>Provided by manufacturer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Hukseflux)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>---</td>
<td>Transmission 4 mm (Kipp &amp; Zonen)</td>
<td>Provided by manufacturer</td>
</tr>
<tr>
<td>8</td>
<td>---</td>
<td>Transmission 4 mm + Fresnel (Kipp &amp; Zonen)</td>
<td>Provided by manufacturer</td>
</tr>
<tr>
<td>9</td>
<td>---</td>
<td>SCHOTT-N-WG295</td>
<td>Data sheet</td>
</tr>
</tbody>
</table>

Radiometers Included in the Study:

1. PSP
2. PSP
3. PSP
4. PSP
5. TSP-1
6. Hukseflux (Data from manufacturer)
7 & 8. Kipp & Zonen (Data from manufacturer)
9. N-WG295
Transmittance and Absorptance Measurement

In-door Domes Transmittance Measurement

Indoor Coating Absorptance Measurement:

ASD—reflectance

Flat black cloth

Labsphere reference plaque
• Results are based on combined transmittance measurement of the inner and outer dome for Inst# 1–5.
• Numbers 1–9 are instrument numbers and 10 locations under different air mass.
• Numbers 6–9 are new radiometers with new glass transmittance and coating absorptance.
—Data obtained from the manufacturers.
Quantifying Soiling Effects
Overview

• Artificial soiling that simulates various environments complements and/or substitutes natural soiling determination.
• Various degrees of soiling reduce the optical transmittance of the glass dome of the pyranometer, which ultimately reduces the detector output (energy loss).
• The study demonstrates how cleaning radiometers is essential in obtaining accurate radiometric data.
• The study is beneficial for overall measurement uncertainty estimation of radiometric data.
• The study will also assist meteorological station operators in estimating the irradiance reduction due to soiling by comparing the images of the artificial soiling to the field conditions.
Artificial Soiling: Various Types and Levels of Soiling

Fourteen artificially soiled pyranometer domes were measured.
Method: Indoor Measurement

- Working toward the development of a standardized artificial soiling method for thermopile radiometers:
  - ASD spectroradiometer was used to measure the transmittance (350–2,400 nm).
  - Stable light source was used to measure the transmittance.
  - Twelve-inch integrating sphere was used.

Result

Dry Condition

<table>
<thead>
<tr>
<th>Test Types</th>
<th>Average Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>~5g Dry Soil</td>
<td>-0.95</td>
</tr>
<tr>
<td>~5ml Dry Spots - Water</td>
<td>-0.30</td>
</tr>
<tr>
<td>0.2 g/ml Dry Spots - Water &amp; Salt</td>
<td>-0.18</td>
</tr>
<tr>
<td>0.36 g/ml Dry Spots - Water, Salt, and Soil</td>
<td>-1.97</td>
</tr>
<tr>
<td>0.2 g/ml Dry Spots - Water &amp; Soil</td>
<td>-0.77</td>
</tr>
<tr>
<td>0.36 g/ml Dry Spots - Water &amp; Extra soil</td>
<td>-1.13</td>
</tr>
<tr>
<td>20g Smudge</td>
<td>-27.74</td>
</tr>
</tbody>
</table>

Wet Condition

<table>
<thead>
<tr>
<th>Test Types</th>
<th>Average Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>~5ml Water droplets</td>
<td>-0.91</td>
</tr>
<tr>
<td>0.2 g/ml Water droplets - water and salt</td>
<td>-0.69</td>
</tr>
<tr>
<td>0.36 g/ml Water droplets - water, salt &amp; soil</td>
<td>-3.73</td>
</tr>
<tr>
<td>0.2 g/ml Water droplets - water &amp; soil</td>
<td>-1.83</td>
</tr>
<tr>
<td>0.36 g/ml Water droplets - water &amp; Extra soil</td>
<td>-3.84</td>
</tr>
<tr>
<td>~10 g Simulated snow</td>
<td>-11.01</td>
</tr>
<tr>
<td>~10 ml Simulated Dew/condensation</td>
<td>-1.10</td>
</tr>
</tbody>
</table>
Solar resource data with known and traceable uncertainty estimates are essential for the site selection of renewable energy technology deployment, system design, system performance, and system operations.

Developing consensus methodologies for determining solar resource measurement uncertainties is essential in obtaining accurate radiometric data.

Calibration differences between manufacturers’ and outdoor NREL BORCAL provided irradiance differences up to 1%–2% for pyranometers and less than 1% for pyrheliometers.

Spectral mismatch contributes to spectral error up to 1.6% for indoor transmittance measurement.

Various degrees of soiling reduce the optical transmittance of the glass dome of the pyranometer, which ultimately reduces the detector output (energy loss). The observed reduction was 0.2%–27%.
Thank you!

Questions?

manajit@nrel.gov
Sensing, Measurement, and Forecasting Group
Power Systems Engineering Center
National Renewable Energy Laboratory

Office: 303-275-3706 | Fax:303-275-3835

Note: Except as otherwise indicated, all images are NREL owned.