Quantifying Spectral Error in Thermopile Radiometers

14th BSRN Scientific Review and Workshop – Canberra, Australia
April 26-29, 2016

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Acknowledgment:

• Emiel Hall and Chuck Long – NOAA: For lending us radiometers for the study.
• Marc Korevaar – Kipp and Zonen: for providing us data for the study.
Motivation:

• The accuracy of solar radiation measured by radiometers depends on the **specifications of the instrument**, calibration procedure, measurement conditions, maintenance, location, and environmental conditions.
  
  o Some of the pyranometer specifications include;
    - **Spectral Mismatch/Error**
    - Thermal Offset
    - Directional Response
    - Etc.
Motivation

• ISO/WMO term “spectral selectivity” is the only specification that does NOT translate directly in a measurement error

<table>
<thead>
<tr>
<th>Specification</th>
<th>Error</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>

• That is a problem in uncertainty evaluation
Spectral Error Equation:

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

- $\tau_{\text{dome}}$ = Dome transmittance
- $\alpha_{\text{coating}}$ = Absorptance of coating
- $E_{\text{AM}_i}$ = Spectral irradiance under various Airmass (obtained using SMARTS Model)
- $E_{\text{AM}_{1.41}}$ = Reference Spectral Data (ASTM G173) 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>
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</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 2mm and new coating data (HukseFlux)</td>
<td>Provided by Manufacturer</td>
</tr>
<tr>
<td>7</td>
<td>---</td>
<td>Transmission 4mm(Kipp and Zonen)</td>
<td>Provided by Manufacturer</td>
</tr>
<tr>
<td>8</td>
<td>---</td>
<td>Transmission 4mm +Fresnel (Kipp and 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>
Indoor and Outdoor Glass Transmittance Measurement:

- Care was taken to minimize Stray Light by putting baffle and diaphragm in between the light source (FEL lamp) and the unit under test.
- ASD spectroradiometer was used to measure the transmittance (350 to 2400 nm).
Coating Absoptance Measurement:

ASD – Reflectance

Labsphere reference plaque

Flat Black Cloth
Coating Absorptance Measurement:

Absorptance Ratio vs. Wavelength (nm)

**MEASURED, AGED**

1 2 3 4 5 6 7 8 9

DATASHEET, NEW
SMARTS Model Input:

- Data for various climatic regions
  - For Solar Zenith Angles: 0, 45, 60, 65, 70, 75, 80, and 85 degrees corresponding to AM1, AM1.41, AM2, AM2.3, AM2.92, AM3.86, AM5.76, and AM11.47
- ASTM G173 spectral data at 45 degree was used as a reference data

<table>
<thead>
<tr>
<th>Site</th>
<th>Lat.</th>
<th>Long.</th>
<th>Elev. (m)</th>
<th>Alpha</th>
<th>Beta</th>
<th>PW (cm)</th>
<th>Ozone (DU)</th>
<th>NO2 (DU)</th>
<th>Pressure (mb)</th>
<th>SSA (assumed)</th>
<th>ASY (assumed)</th>
<th>Surface (assumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mauna Loa (MLO)</td>
<td>19.539</td>
<td>-155.578</td>
<td>3397</td>
<td>1.498</td>
<td>0.003</td>
<td>0.235</td>
<td>266</td>
<td>0.072</td>
<td>680.1</td>
<td>0.98</td>
<td>0.68</td>
<td>Basalt rock</td>
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<td></td>
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<td></td>
<td>0.867</td>
<td>0.010</td>
<td>0.075</td>
<td>270</td>
<td>0.076</td>
<td>680.0</td>
<td>0.98</td>
<td>0.68</td>
<td>Basalt rock</td>
</tr>
<tr>
<td>Tucson (TUC)</td>
<td>32.233</td>
<td>-110.953</td>
<td>779</td>
<td>1.572</td>
<td>0.010</td>
<td>0.707</td>
<td>281</td>
<td>0.154</td>
<td>929.0</td>
<td>0.96</td>
<td>0.65</td>
<td>Light soil</td>
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<tr>
<td></td>
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<td>1.067</td>
<td>0.026</td>
<td>0.364</td>
<td>293</td>
<td>0.158</td>
<td>929.1</td>
<td>0.96</td>
<td>0.65</td>
<td>Light soil</td>
</tr>
<tr>
<td>Nauru (NAU)</td>
<td>-0.521</td>
<td>166.916</td>
<td>7</td>
<td>0.670</td>
<td>0.033</td>
<td>5.280</td>
<td>251</td>
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<td>1007.5</td>
<td>0.95</td>
<td>0.66</td>
<td>Water</td>
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<tr>
<td>Dalanzagad (DAL)</td>
<td>43.577</td>
<td>104.419</td>
<td>1470</td>
<td>0.827</td>
<td>0.043</td>
<td>0.113</td>
<td>356</td>
<td>0.075</td>
<td>857.6</td>
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<td>0.65</td>
<td>Light soil</td>
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<tr>
<td>Alta Floresta (ALT)</td>
<td>-9.871</td>
<td>-56.104</td>
<td>277</td>
<td>1.553</td>
<td>0.508</td>
<td>3.567</td>
<td>272</td>
<td>0.157</td>
<td>980.2</td>
<td>0.96</td>
<td>0.65</td>
<td>Trees</td>
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<td>Beijing (BEI)</td>
<td>39.977</td>
<td>116.381</td>
<td>92</td>
<td>0.902</td>
<td>1.190</td>
<td>1.746</td>
<td>344</td>
<td>0.654</td>
<td>1000.4</td>
<td>0.80</td>
<td>0.65</td>
<td>Asphalt</td>
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<td>Solar Village (SOV)</td>
<td>24.907</td>
<td>46.397</td>
<td>764</td>
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<td>280</td>
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<td>924.3</td>
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<td>0.70</td>
<td>Sand</td>
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<td>Gandhi College (GAN)</td>
<td>25.871</td>
<td>84.128</td>
<td>60</td>
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<td>0.033</td>
<td>1.416</td>
<td>344</td>
<td>0.200</td>
<td>1013.3</td>
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<td>0.70</td>
<td>Light soil</td>
</tr>
</tbody>
</table>
SMARTS Model Input:

- 8 locations were selected representing various climatic conditions
- The plot below shows the distribution of the climatic locations based on PWV and Turbidity
Result Using Indoor Transmittance Measurement (400 to 2400 nm):

- Results are based on combined transmittance measurement of the inner and outer dome for Inst# 1-5
- 1 to 9 are instrument numbers and 10 location conditions
- 6 to 9 are new radiometer with new glass transmittance and coating absorptance – Data Obtained from the manufacturer
Result Using Outdoor Transmittance Measurement (400 to 2400 nm):

- Outdoor: Result is based on combined transmittance measurement of the inner and outer dome
### INDOOR Result

<table>
<thead>
<tr>
<th>Location</th>
<th>Error</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alta Floresta_XHA</td>
<td>Max (%)</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
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</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>3.03</td>
<td>3.03</td>
<td>3.03</td>
<td>3.03</td>
<td>3.03</td>
<td>3.03</td>
<td>3.03</td>
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<tr>
<td>Beijing_XHA</td>
<td>Max (%)</td>
<td>1.39%</td>
<td>1.39%</td>
<td>1.39%</td>
<td>1.39%</td>
<td>1.39%</td>
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<td>1.39%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
<td>4.96</td>
</tr>
<tr>
<td>Dalanzagad_LA-LW</td>
<td>Max (%)</td>
<td>0.34%</td>
<td>0.34%</td>
<td>0.34%</td>
<td>0.34%</td>
<td>0.34%</td>
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<td>3.48</td>
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<td>3.48</td>
<td>3.48</td>
<td>3.48</td>
<td>3.48</td>
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<tr>
<td>Gandhi_College_XHW</td>
<td>Max (%)</td>
<td>1.38%</td>
<td>1.38%</td>
<td>1.38%</td>
<td>1.38%</td>
<td>1.38%</td>
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<tr>
<td></td>
<td>Max (W/m²)</td>
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<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
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<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
</tr>
<tr>
<td>MaunaLoa XLA</td>
<td>Max (%)</td>
<td>0.63%</td>
<td>0.63%</td>
<td>0.63%</td>
<td>0.63%</td>
<td>0.63%</td>
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</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>3.65</td>
<td>3.65</td>
<td>3.65</td>
<td>3.65</td>
<td>3.65</td>
<td>3.65</td>
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<tr>
<td>MaunaLoa XWH</td>
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<td>0.31%</td>
<td>0.31%</td>
<td>0.31%</td>
<td>0.31%</td>
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</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
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<td>0.59</td>
<td>0.59</td>
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<td>0.59</td>
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<td>Nauru.LA-XHW</td>
<td>Max (%)</td>
<td>1.71%</td>
<td>1.71%</td>
<td>1.71%</td>
<td>1.71%</td>
<td>1.71%</td>
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<tr>
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<td>Max (W/m²)</td>
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<td>0.14</td>
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<td>0.14</td>
<td>0.14</td>
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<tr>
<td>Solar_Village_XHA</td>
<td>Max (%)</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
<td>0.71%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
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<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>Tucson_LW</td>
<td>Max (%)</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
<td>0.96%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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</tr>
</tbody>
</table>

### OUTDOOR Result

<table>
<thead>
<tr>
<th>Location</th>
<th>Error</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alta Floresta_XHA</td>
<td>Max %</td>
<td>0.55%</td>
<td>0.39%</td>
<td>0.36%</td>
<td>0.04%</td>
<td>0.20%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>1.90</td>
<td>1.91</td>
<td>1.18</td>
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<td>2.28</td>
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<tr>
<td>Beijing_XHA</td>
<td>Max %</td>
<td>1.03%</td>
<td>0.51%</td>
<td>0.55%</td>
<td>0.16%</td>
<td>0.22%</td>
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<tr>
<td></td>
<td>Max (W/m²)</td>
<td>3.26</td>
<td>1.35</td>
<td>0.95</td>
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<tr>
<td>Dalanzagad_LA-LW</td>
<td>Max %</td>
<td>0.22%</td>
<td>0.19%</td>
<td>0.15%</td>
<td>0.03%</td>
<td>0.11%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>1.77</td>
<td>2.24</td>
<td>1.25</td>
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<td>Gandhi_College_XHW</td>
<td>Max %</td>
<td>0.91%</td>
<td>0.59%</td>
<td>0.56%</td>
<td>0.10%</td>
<td>0.28%</td>
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<td>Max (W/m²)</td>
<td>2.66</td>
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<td>2.09</td>
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<td>0.31</td>
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<td>MaunaLoa XLA</td>
<td>Max %</td>
<td>0.42%</td>
<td>0.31%</td>
<td>0.27%</td>
<td>0.04%</td>
<td>0.16%</td>
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<td>Max (W/m²)</td>
<td>0.66</td>
<td>0.43</td>
<td>0.22</td>
<td>0.31</td>
<td>0.69</td>
</tr>
<tr>
<td>MaunaLoa XWH</td>
<td>Max %</td>
<td>0.20%</td>
<td>0.18%</td>
<td>0.14%</td>
<td>0.02%</td>
<td>0.11%</td>
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<td></td>
<td>Max (W/m²)</td>
<td>0.60</td>
<td>1.62</td>
<td>1.31</td>
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<td>1.17</td>
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<td>Max %</td>
<td>1.14%</td>
<td>0.77%</td>
<td>0.72%</td>
<td>0.15%</td>
<td>0.36%</td>
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<td></td>
<td>Max (W/m²)</td>
<td>0.14</td>
<td>0.15</td>
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<td>Max %</td>
<td>1.00%</td>
<td>0.63%</td>
<td>0.62%</td>
<td>0.10%</td>
<td>0.31%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>0.10</td>
<td>0.07</td>
<td>0.03</td>
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<td>0.10</td>
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<td>Tucson_LW</td>
<td>Max %</td>
<td>0.47%</td>
<td>0.34%</td>
<td>0.30%</td>
<td>0.04%</td>
<td>0.18%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>0.27</td>
<td>0.05</td>
<td>0.27</td>
<td>0.28</td>
<td>0.09</td>
</tr>
<tr>
<td>Tucson_LA</td>
<td>Max %</td>
<td>0.63%</td>
<td>0.43%</td>
<td>0.41%</td>
<td>0.06%</td>
<td>0.23%</td>
</tr>
<tr>
<td></td>
<td>Max (W/m²)</td>
<td>0.04</td>
<td>0.08</td>
<td>0.06</td>
<td>0.09</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Summary

- Spectral Error was calculated under clear sky spectral condition for various climate locations and differing Airmass.
- ASTM G173 spectra - AM1.41 (45 SZA) was used as a reference.
- The result shows non-flat transmittance of the glass dome and non-flat absorptance of the black coating due to aging contribute to spectral error up to 1.6% for indoor transmittance measurement and up to 1.2% for outdoor transmittance measurement.
- Performing a round-robin by multiple labs to measure the transmittance and absorptance of glass dome and coating would assist in confirming the result obtained in this study.
- The intent of the study is to quantify the spectral error of thermopile radiometers and thus promote the update and development of uncertainty and classification standards of radiometers.
Thank You!

Questions?