Measurement uncertainty of radiometers from ASTM International perspective
• Jörgen Konings
• Physicist

• Product Development
  – Pyrheliometers
  – Pyranometers
  – Pyrgeometers
“The (...) Guide to the Expression of Uncertainty Measurement (GUM) provides a standard method for the determination of uncertainty in measurement. (...) the BSRN recommends that all uncertainty calculations follow the procedures of the guide.”

*BSRN operations manual*
• **measurand:** 1 minute average DNI

\[
E \left[ \frac{W}{m^2} \right] = \frac{V \left[ \mu V \right]}{S \left[ \mu V / (W/m^2) \right]}
\]

• **measurement equation**

\[
u(V) = \sqrt{u_A^2(V) + u_B^2(V)}
\]

\[
u(S) = \sqrt{u_A^2(S) + u_B^2(S)}
\]

statistical non-statistical

• **standard uncertainty**

• **combined standard uncertainty**

\[
u_C(E) = \sqrt{\left( \frac{\partial E}{\partial V} \right)^2 u^2(V) + \left( \frac{\partial E}{\partial S} \right)^2 u^2(S)}
\]

• **expanded uncertainty**

\[
U = k \cdot u_C(E)
\]

**level of confidence**

**coverage factor**

JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement
• Subcommittee G03.09 on Radiometry

• **WK36479** New Practice for uncertainty evaluation of calibration and measurements with pyranometers and pyrheliometers

• Technical contact: Aron Habte (NREL)

• Subcommittee E44.09 on Photovoltaic Electric Power Conversion
Click on Cell "B1" then Select Instrument from Drop Down List

<table>
<thead>
<tr>
<th>Index</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>470</td>
<td>72.69</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

Max Irradiance = 1115.90 W/m²

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+U95(E)</td>
<td>+U95(E)</td>
</tr>
<tr>
<td>W/m²</td>
<td>%</td>
</tr>
</tbody>
</table>

**Graph:**
- Data Logger
- Calibration
- Zenith response
- Azimuth response
- Spectral response
- Tilt response
- Nonlinearity
- Temperature response
- Aging per year
- Maintenance
- Directional Error

**Contributions to Uncertainty (%):**

<table>
<thead>
<tr>
<th>Irradiance (W/m²)</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>100</td>
<td>5%</td>
</tr>
<tr>
<td>200</td>
<td>10%</td>
</tr>
<tr>
<td>300</td>
<td>15%</td>
</tr>
<tr>
<td>400</td>
<td>20%</td>
</tr>
<tr>
<td>500</td>
<td>25%</td>
</tr>
<tr>
<td>600</td>
<td>30%</td>
</tr>
<tr>
<td>700</td>
<td>35%</td>
</tr>
<tr>
<td>800</td>
<td>40%</td>
</tr>
<tr>
<td>900</td>
<td>45%</td>
</tr>
<tr>
<td>1000</td>
<td>50%</td>
</tr>
<tr>
<td>1100</td>
<td>55%</td>
</tr>
<tr>
<td>1200</td>
<td>60%</td>
</tr>
</tbody>
</table>
• Input:
  – Data
  – Uncertainty sources
  – for pyranometers: solar position

• Output
  – Dynamical uncertainty (per datapoint)
  – Integration over hours, day taking correlations into account
  – Contributions to final uncertainty broken down per source
# Spreadsheets

<table>
<thead>
<tr>
<th>non-stability</th>
<th>non-linearity</th>
<th>spectral selectivity</th>
<th>temperature response</th>
</tr>
</thead>
<tbody>
<tr>
<td>S relative rectangular symmetric</td>
<td>S relative rectangular symmetric</td>
<td>S relative rectangular symmetric</td>
<td>S relative rectangular symmetric</td>
</tr>
<tr>
<td>correlated yes</td>
<td>correlated yes</td>
<td>correlated no</td>
<td>correlated yes</td>
</tr>
<tr>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
</tr>
<tr>
<td>0.5</td>
<td>0.2</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
<td>[%]</td>
</tr>
<tr>
<td>0.29</td>
<td>0.12</td>
<td>0.00</td>
<td>0.29</td>
</tr>
</tbody>
</table>

**DNI [W/m²] 1-minute averages**

![DNI Graph](image-url)
Typical uncertainty budget

- Calibration uncertainty
- Instrument specifications
  - known systematic errors may be corrected
- Datalogger accuracy
- Maintenance
- ...
- Definitional uncertainty (DNI)
Example: non-linearity

“deviation from S at 500 W/m² due to the change in irradiance within 100 W/m² to 1000 W/m² < ± 0.5%”

- non-statistical (type B)
- limits are -0.5 % and +0.5 %
- no other information

- rectangular distribution with a specification limit of 0.5 % (a standard uncertainty contribution of 0.3 %)
- applies on the sensitivity
Example: spectral selectivity

Translation of instrument data into specification limits

“Spectral MisMatch” between Global Sky Spectra
due to Water Vapor variations not seen by shaded pyranometer

\[
M = \frac{\int E_t(\lambda) S_r(\lambda) \, d\lambda}{\int E_f(\lambda) S_r(\lambda) \, d\lambda} \cdot \frac{\int E_f(\lambda) S_t(\lambda) \, d\lambda}{\int E_t(\lambda) S_t(\lambda) \, d\lambda}
\]

Et = Test Spectrum (Global A, 3.5 cm H₂O)
Eref = Ref Spectrum (Global B, 0.5 cm H₂O)
St = Test WG295 Transmission
Sr = Ref Transmission = 1.0

Spectral MisMatch:
PW = 0.5 atm-cm = 1.002
PW = 3.5 atm-cm = 1.008
\( \Delta = 0.5\% \)

SMRTS Spectral Model Results
US Std Atmosphere 1976
Optical Depth = 0.20
Sea Level
Rural Aerosol
Radiance (W cm⁻² um⁻¹ str⁻¹) x 2π
Water vapor 0.5 and 3.5 atm-cm

Daryl Myers (personal communication)
### Results: $U_{95}$ for DNI

<table>
<thead>
<tr>
<th>pyrheliometer according to this method</th>
<th>minute total at solar noon</th>
<th>hourly total at solar noon</th>
<th>daily total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO first class</td>
<td>2.7 %</td>
<td>2.7 %</td>
<td>2.7 %</td>
</tr>
<tr>
<td>ISO first class + calibration</td>
<td>2.9 %</td>
<td>2.9 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>NREL analysis on first class pyrheliometer</td>
<td></td>
<td></td>
<td>2.3 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pyrheliometer from other sources</th>
<th>minute total at solar noon</th>
<th>hourly total at solar noon</th>
<th>daily total</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMO Guide good quality (excluding calibration uncertainty)</td>
<td>1.8 %</td>
<td>1.5 %</td>
<td>1.0 %</td>
</tr>
<tr>
<td>BSRN uncertainty requirement 2004 target</td>
<td></td>
<td></td>
<td>0.5 %</td>
</tr>
<tr>
<td>VCPC clear skies with on-site calibration to cavities (statistical)</td>
<td></td>
<td></td>
<td>± 0.7 %</td>
</tr>
</tbody>
</table>
### Results: $U_{95}$ for GHI

<table>
<thead>
<tr>
<th>pyranometer statements according to this method</th>
<th>minute total at solar noon</th>
<th>hourly total at solar noon</th>
<th>daily total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO secondary standard</td>
<td>2.0 %</td>
<td>2.0 %</td>
<td>2.0 %</td>
</tr>
<tr>
<td>ISO secondary standard + calibration</td>
<td>2.3 %</td>
<td>2.3 %</td>
<td>2.5 %</td>
</tr>
<tr>
<td>NREL analysis on secondary standard pyranometer</td>
<td>3.6 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pyranometer statements from other sources</th>
<th>minute total at solar noon</th>
<th>hourly total at solar noon</th>
<th>daily total</th>
</tr>
</thead>
<tbody>
<tr>
<td>WMO Guide high quality (excluding calibration uncertainty)</td>
<td></td>
<td>3 %</td>
<td>2 %</td>
</tr>
<tr>
<td>BSRN uncertainty requirement 2004 target</td>
<td></td>
<td>2 %</td>
<td></td>
</tr>
</tbody>
</table>
Results: $U_{95}$ for GHI

- GHI measurement uncertainty varies strongly with location and season, mainly from directional errors

<table>
<thead>
<tr>
<th>Pyranometer class (ISO 9060)</th>
<th>season</th>
<th>latitude</th>
<th>uncertainty minute totals at solar noon</th>
<th>uncertainty hourly totals at solar noon</th>
<th>uncertainty daily totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>secondary standard</td>
<td>summer</td>
<td>mid-latitude</td>
<td>2.7 %</td>
<td>2.0 %</td>
<td>1.9 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equator</td>
<td>2.6 %</td>
<td>1.9 %</td>
<td>1.7 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pole</td>
<td>7.9 %</td>
<td>5.6 %</td>
<td>4.5 %</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>mid-latitude</td>
<td>3.4 %</td>
<td>2.5 %</td>
<td>2.7 %</td>
</tr>
</tbody>
</table>
Open questions

- Correlations over time?
- Shaded, tilted, longwave
- Degrees of freedom
- Expanded measurement equations

- How does this relate to real-world measurements?
  - See Aron Habte’s evaluation of radiometers employed at NREL
2.29
Type B evaluation of measurement uncertainty

Type B evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty.

EXAMPLES  Evaluation based on information
— associated with authoritative published quantity values,
— associated with the quantity value of a certified reference material,
— obtained from a calibration certificate,
— about drift,
— obtained from the accuracy class of a verified measuring instrument,
— obtained from limits deduced through personal experience.

NOTE  See also ISO/IEC Guide 98-3:2008, 2.3.3.

uncertainty may be derived from an "accuracy class"!
Acceptance rules

tolerance limits versus acceptance limits

simple acceptance

Valid acceptance (a)

(b) False acceptance

(c) False rejection

(d) Valid rejection

$T_u = A_u$

guarded acceptance

$w > 0$

Acceptance interval Guard band

$A_u$ $T_u$

guarded rejection

$w < 0$

Acceptance interval Guard band

$T_u$ $A_u$

JCGM 106:2012 Evaluation of measurement data – The role of measurement uncertainty in conformity assessment
• ASTM standard on uncertainty evaluation of calibration of and measurements with radiometers
• Based on the GUM
• Adopting a standardized method allows comparison of quoted uncertainties, based on documented methods of derivation

• Any input is very much welcome
Thank You!