Illustrations from a Study of 42 Radiometers

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Introduction

Output: ± 1% or better

Input: ± 3% or worse
Introduction

Goals
Reduced uncertainty
Quantified uncertainty
Qualified uncertainty

Method
Detailed characterization of irradiance sensors

Input: ± 3% or worse
Looking back

1981 - IEA Conference on Pyranometer Measurements

Goal 2: Determine ways to improve the measurement accuracies of pyranometers currently available by developing a more complete understanding of the instruments' performance characteristics.

1996 - IEA Solar Heating and Cooling Programme Task 9

Improved Measurements of Solar Irradiance by Means of Detailed Pyranometer Characterisation
### Solarstrahlungssensoren: Tageseinstrahlungssummen

<table>
<thead>
<tr>
<th>Hersteller</th>
<th>Typenbezeichnung</th>
<th>Bauart</th>
<th>Abweichung zur Referenzmessung in %</th>
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<tbody>
<tr>
<td>Apogee Instruments Inc.</td>
<td>SP-215</td>
<td>Pyranometer mit Photodiode</td>
<td>15,15</td>
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<tr>
<td>EKO Instruments Co. Ltd.</td>
<td>MS-602</td>
<td>Thermosäulenpyranometer</td>
<td>-4,26</td>
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<td>Hukseflux Thermal Sensors BV</td>
<td>LP02</td>
<td>Thermosäulenpyranometer</td>
<td>2,88</td>
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<td>IKS Photovoltaik GmbH</td>
<td>Iset Sensor (amorph)</td>
<td>Solarzelle (amorphes Silizium)</td>
<td>-1,08</td>
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<td></td>
<td>Iset Sensor (monokristallin) Solarzelle (monokristallin)</td>
<td>-4,99</td>
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<td></td>
<td>Iset Sensor (polykristallin) Solarzelle (polykristallin)</td>
<td>-3,19</td>
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<td>Kipp &amp; Zonen BV</td>
<td>CMP3</td>
<td>Thermosäulenpyranometer</td>
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<td>LI-COR Biosciences</td>
<td>LI-200SA</td>
<td>Pyranometer mit Photodiode</td>
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<td>Mencke &amp; Tegtmeyer GmbH</td>
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<td>NES Mess- und Meldeysteme, Lothar Viel</td>
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<td>SOZ-03 mit Verstärker Solarzelle (monokristallin)</td>
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<td>Skye Instruments Ltd.</td>
<td>SKS 1110</td>
<td>Pyranometer mit Photodiode</td>
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<td>Soluzione Solare</td>
<td>Sunmeter</td>
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<td>Technische Alternative GmbH</td>
<td>GRS01</td>
<td>Photodiode (monokristallin)</td>
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<td>Tritec International AG</td>
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<td>Spektron 310</td>
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</tbody>
</table>

* wird nicht mehr hergestellt, Referenzwert gemessen mit *Secondary Standard* Pyranometer (Kipp & Zonen CM 21)

Messungen von November 2009 bis September 2010
Looking forward: PVSENSOR

• Project methodology
  – subject all sensors to the same* operating conditions and compare their outputs
  – vary single* operating condition while keeping all others constant
  – extract systematic differences from the measurements

• Project phases
  – Indoor tests (ESTI, PV Performance Labs)
  – Outdoor tracker-mounted experiments (Sandia)
  – Extended monitoring (Sandia, PV Performance Labs)
The Sensors

1. Secondary standard thermopile pyranometers
2. Second class thermopile pyranometers
3. Photodiode pyranometers
4. Reference cells
The Facilities

ESTI

- Multiple flash testers
  - temperature controlled enclosure
  - narrow band spectral filters
  - neutral density filters
- Apollo large area continuous solar simulator
- LS1 large temperature chamber with continuous full sun simulation

PV Performance Labs

- Rotating platform and narrow beam light source for angular response evaluation

Sandia
Some Results*

• The analysis of the measurements is work in progress, therefore results and graphs may still evolve.

• Some graphs are new for this presentation, whereas others were recently published in the proceedings of the 2015 European Photovoltaic Solar Energy Conference and the 2015 IEEE Photovoltaic Specialists Conference.

• This document is made available for the benefit of attendees. The illustrations are not intended to be self-explanatory.
42 Instruments - 42 Irradiances measured in a horizontal plane
12 Secondary Standard Pyranometers measured in a horizontal plane
+8 Second Class Pyranometers measured in a horizontal plane
+10 Photodiode Pyranometers measured in a horizontal plane
+12 Outdoor Reference Cells measured in a horizontal plane
Indoor vs. Outdoor Responsivity

vertical indoors, horizontal outdoors
42 Instruments - 42 Responsivities

![Graph showing 42 Instruments - 42 Responsivities on a date of 2015-09-20.]
“Recalibration” at Solar Noon
“Recalibration” at AM1.5
Differences after “Recalibration”
Differences after “Recalibration”

only thermopile pyranometers
Angular Response

subset of instruments
Differences vs. Angle of Incidence

Only thermopile pyranometers

Morning only

Graph showing differences vs. angle of incidence for thermopile pyranometers, with data points indicating variations in solar irradiance as the angle of incidence changes.
Differences vs. Angle of Incidence

only thermopile pyranometers

![Graph showing differences vs. angle of incidence.](image)
Instrument Temperatures
Irradiance while Tracking

![Graph showing irradiance data over time on 2015-08-20]
Temperatures while Tracking
Indoor Temperature Response
Irradiance vs. Temperature

only thermopile pyranometers
Temperature-Corrected Irradiance

only thermopile pyranometers

![Graph showing the relationship between instrument temperature and difference from CMP22 (W/m²)].
Ref Cells before Temp Correction

with thermopile as reference
Ref Cells after Temp Correction

with thermopile as reference
Spectral Response

photovoltaic devices
Ref Cells before Temp Correction

with PV cell as reference
Ref Cells after Temp Correction
with PV cell as reference
Closing Comments

- There is already strong evidence of systematic instrument errors, which reinforces the study’s rationale. Further comparison between indoor and outdoor measurements will clarify these relationships.

- The relative magnitudes and overall significance of various factors will be evaluated. It is not possible to draw conclusions about the suitability of an instrument from a single characteristic.

- The variability between instruments of the same model cannot be fully assessed from only two samples.
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Sandia National Laboratories
and their talented and supportive staff