Measurement, Modeling, and Database of Solar Irradiance

Manajit Sengupta
and
Aron Habte

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Support the U.S. Department of Energy (DOE) Solar Energy Technology Office to reduce the costs of solar deployment and financing by improving accuracy in solar resource measurement and modeling.

Figure from https://www.nrel.gov/docs/fy18osti/68886.pdf
**Solar Resource Assessment**

- Develops state-of-the-art models and creates high-quality long-term solar resource data for the United States and distributes it via the **National Solar Radiation Database (NSRDB)**.
- Conducts research on **accurate, robust, low-cost solar radiation instrumentation and methods**.
- Uses new knowledge and technology to develop **consensus national standards and best practices** for solar energy.
- Provides **solar measurement reference to all instruments in the United States** through the annual National Renewable Energy Laboratory (NREL) Pyrheliometer Comparison conducted by the Solar Radiation Research Laboratory (SRRL).

**Satellite-based irradiance modeling**

[Image of Satellite-based irradiance modeling]

**NSRDB:**

[Link to NSRDB: http://nsrdb.nrel.gov]

**Irradiance measurements in global horizontal and single-axis tracking at the Measurement and Instrumentation Data Center:**

[Link to Measurement and Instrumentation Data Center: https://midcdmz.nrel.gov/]

*Photos by NREL*
Solar Radiation Components

Radiation from the sky dome:
- **Directly** from the sun
- Everywhere **except** the sun
- **Entire** sky
- Available to a photovoltaic (PV) **panel**.

**We call it:**
- Direct normal irradiance (DNI)
- Diffuse horizontal irradiance (DHI)
- Global horizontal irradiance (GHI)
- Plane-of-array irradiance (POA)
### ISO-9060: 2018
Solar energy—Specification and classification of instruments for measuring hemispherical solar and direct solar radiation

### IEC 61724
Photovoltaic system performance monitoring—Guidelines for measurement, data exchange and analysis

#### Table 1 — Pyranometer classification list

<table>
<thead>
<tr>
<th>Specification parameter No. (see 4.1.2)</th>
<th>Parameter</th>
<th>Name of the classes, acceptance intervals and width of the guard bands (in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Roughly corresponding class from ISO 9060:19900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Secondary standard</td>
</tr>
<tr>
<td>a</td>
<td>Response time (see also 4.1.3 on fast response pyranometers); time for 95% response</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 10 s (1 s)</td>
</tr>
<tr>
<td>b</td>
<td>Zero off-set</td>
<td></td>
</tr>
<tr>
<td>a) response to -200 W m^{-2} net thermal radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b) response to 5 K h^{-1} change in ambient temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c) total zero offset including the effects a), b) and other sources</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.7 W m^{-2} (2 W m^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±1.5 W m^{-2} (0.5 W m^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±1 W m^{-2} (2 W m^{-2})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.5 W m^{-2} (0.2 W m^{-2})</td>
</tr>
<tr>
<td>c1</td>
<td>Non-stability: percentage change in responsivity per year</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.8% (0.25%)</td>
</tr>
<tr>
<td>c2</td>
<td>Nonlinearity: percentage deviation from the responsivity at 500 W m^{-2} due to the change in irradiance within 100 W m^{-2} to 1 000 W m^{-2}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.5% (0.2%)</td>
</tr>
<tr>
<td>c3</td>
<td>Directional response (for beam radiation): the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring from any direction (with an incidence angle of up to 90° or even from below the sensor) a beam radiation whose normal incidence irradiance is 1 000 W m^{-2}</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>±10 W m^{-2} (4 W m^{-2})</td>
</tr>
</tbody>
</table>

NOTE: The acceptance intervals should not be used for uncertainty estimations for conditions different from those stated for each criterion. In particular, the spectral error can be different under different conditions. The spectral error for diffuse horizontal irradiance measurements is also different from that for global horizontal irradiance.
Broadband Radiometer Calibration

- Absolutely critical for maintaining minimum measurement uncertainties
- Traceable to the World Radiometric Reference
- Standard procedures:
  - ASTM:
    - ASTM G167-15
    - ASTM E816-15
    - ASTM E824-10
    - ASTM G207-11
  - ISO:
    - ISO 9847:1992
    - ISO 9846:1993
  - Accredited facilities
    - ISO 17025

World Radiation Center, Davos
Standard radiometers
Field instruments

Photos by NREL
Maintaining Data Quality

• Quality assessment requires judgment and analysis. *This happens after the measurements.*

• Quality control is a supervisory process. *This happens before and during the measurements.*
Data Quality and Uncertainty: What Do You Get?

Data quality analysis procedure:

• View all data as frequently as possible (daily is best).
  - The longer the delay, the longer error conditions will persist.
  - The more frequent your data checks, the more in tune you are with your stations.

• View in context of other measurements.
  - Measurements by themselves can be deceiving.

• Automate the data plots as much as possible.
  - Spend your time analyzing data, not assembling data sets.

• Set up a feedback infrastructure.
  - Communicate findings back to the station
  - Good results should be communicated also.
Spectral radiometric calibrations are accredited by the International Organization for Standardization and traceable to the National Institute of Standards and Technology (NIST), enabling accurate baseline data sets for model and standards development, PV cell and module characterization, and reliability studies.
SRRL Baseline Measurement System
Radiometer Tower

- Atmospheric Electric Field Monitor
- Boltek EM200
- Global Normal (3-Axis)
  - Kipp & Zonen CMP11 @ 12 feet
- Licon LI-200 tracker
- Global 45-South
  - Kipp CMP11 @ 11 feet
- Global 45-South
  - Licon LI-200
- Storage Battery for LI-2020
- PV Panel for LI-2020
- Global 90-North
  - Eppley PSP
  - Licon LI-200
- Global 90-North
  - Eppley PSP
  - Licon LI-200
- Global 90-West
  - Eppley PSP
  - Licon LI-200
- J-Box with underground wire to SRRL database patch panel
- Wind Speed & Direction @ 5 feet
  - RM Young 05501
- Snow Depth & Rain Gauge @ 5 feet (not shown, are 25-50 feet to the west)
  - CSI SR50A & Hydrological Services TB4
- Temperature & Relative Humidity @ 2m
  - CSI HMP-50
- Upwelling Instruments @ 5 feet:
  - Kipp CM1
  - Licon LI-200
- CR2000 logger, AM16/32B MUX, and NL120 (inside weatherproof box)
  - Collect data from all except Upwelling PR (C2/C52/C202) via ethernet to SRRL database
- Station Pressure @ 2m (not shown, measured just below 90-South radiometers)
  - Sera 278

NREL v1.1E, 3/23/15
J.N. Amedee, NREL
Different radiometers have different albedo values and different surfaces respond differently along the solar spectrum (e.g., because of the photosynthesis process, vegetation tends to reflect more after the green portion of the spectrum). Therefore, spectral measurements are essential to understanding the spectral distribution of albedo irradiance.
All ultraviolet radiometers are calibrated using spectroradiometers and are traceable to NIST.

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Model</th>
<th>#</th>
<th>Band</th>
<th>Spectral Range (nm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>Kipp &amp; Zonen</td>
<td>CUVA2</td>
<td>1</td>
<td>UVA</td>
<td>315–400</td>
<td></td>
</tr>
<tr>
<td>(5° FOV)</td>
<td>Kipp &amp; Zonen</td>
<td>UVB</td>
<td>1</td>
<td>UVB</td>
<td>280–315</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Epptley</td>
<td>TUVR</td>
<td>1</td>
<td>TUV</td>
<td>295–385</td>
<td>Response time is order (milliseconds)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>Kipp &amp; Zonen</td>
<td>CUVA1</td>
<td>1</td>
<td>UVA</td>
<td>315–400</td>
<td></td>
</tr>
<tr>
<td>(180° FOV)</td>
<td>Yankee</td>
<td>UVA-1</td>
<td>1</td>
<td>UVA</td>
<td>320–400</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Systems, INC.</td>
<td>UVS-A-T</td>
<td>1</td>
<td>UVA</td>
<td>315–400</td>
<td>Response time &lt; 2 seconds</td>
</tr>
<tr>
<td></td>
<td>Kipp &amp; Zonen</td>
<td>UVS-B-T</td>
<td>1</td>
<td>UVB</td>
<td>280–315</td>
<td>Response time &lt; 2 seconds</td>
</tr>
<tr>
<td></td>
<td>Kipp &amp; Zonen</td>
<td>CUVB1</td>
<td>1</td>
<td>UVB</td>
<td>280–315</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yankee</td>
<td>UVB-1</td>
<td>1</td>
<td>UVB</td>
<td>280–320</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental Systems, INC.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EKO</td>
<td>MS-210W</td>
<td>1</td>
<td>UVB</td>
<td>280–320</td>
<td>Response time ~ 1 second</td>
</tr>
<tr>
<td></td>
<td>Solar Light</td>
<td>501A</td>
<td>1</td>
<td>UVB</td>
<td>280–315</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kipp &amp; Zonen</td>
<td>CUV4</td>
<td>1</td>
<td>TUV</td>
<td>280–400</td>
<td>Response time &lt; 1 second</td>
</tr>
<tr>
<td></td>
<td>Epptley</td>
<td>TUVR</td>
<td>1</td>
<td>TUV</td>
<td>295–385</td>
<td>Response time is order (milliseconds)</td>
</tr>
</tbody>
</table>
Ultraviolet Measurement and Modeling

- Developed ultraviolet conversion model using the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) model and global horizontal irradiance (GHI).
  - Based on the model, a new ASTM standard is under development.

Example from https://ieeexplore.ieee.org/abstract/document/8529229
Broadband and Spectral Solar Resource Data from the National Solar Radiation Data Base

Physical Solar Model Version 3
The NSRDB seeks to advance our knowledge of solar radiation and its applications for renewable energy and beyond.

The NSRDB provides a serially complete database of solar irradiance and meteorological information across the United States and in an increasing number of international locations.

The NSRDB provides **21 years** (+ typical meteorological year [TMY]) of half-hourly data at a 4-km by 4-km spatial resolution. Five-minute 2-km data are also available from 2018.

The NSRDB uses a physics-based model, Physical Solar Model (**PSM**).
Evolution of the National Solar Radiation Database

248 weather stations with 26 *solar measurement* stations (ERDA, NOAA, 1979)

239 *modeled* stations with 56 partial measurement stations (DOE, NOAA, 1994)

1,454 *modeled* locations (DOE, SUNY-A, NOAA, 2007)

1,454 *modeled* locations (DOE, CPR, 2012)

Satellite-based, gridded, 4 km x 4 km, half-hourly (DOE, NOAA, UW, SCS 2018)

http://nsrdb.nrel.gov
National Solar Radiation Database
Physical Solar Model Workflow
Cloud transmittances can be parameterized as exponential functions of cloud optical thickness and solar zenith angles.
Models for meteorology can solve solar radiances in all possible directions.

Models for solar energy use regression functions to empirically link with long-term observations of GHI.
The overall difference between Discrete Ordinates Radiative Transfer (DISORT) and FARMS-NIT is less than 5% for both clear-sky and cloudy-sky conditions. FARMS-NIT has a better accuracy than TMYSPEC.
NSRDB Improvement: MODIS-Derived Surface Albedo Data Set

Technical report: NREL developed an improved white-sky (bi-hemispherical reflectance) broadband (0.3–5.0 μm) surface albedo data set for processing the NSRDB from two existing data sets: a gap-filled albedo product and a daily snow cover product. See http://www.nrel.gov/docs/fy17osti/67306.pdf.
What Is Available from the National Solar Radiation Database?

- Global horizontal irradiance (GHI)
- Direct normal irradiance (DNI)
- Diffuse horizontal irradiance (DHI)
- Clear-sky GHI, DNI, and DHI
- Cloud type
- Dew point*
- Air temperature*
- Atmospheric pressure*
- Relative humidity*
- Solar zenith angle
- Precipitable water*
- Wind direction*
- Surface Albedo
- Wind speed.*

* Source: MERRA-2
Validation of the National Solar Radiation Database

1998–2018

Impact: Improvement in the NSRDB accuracy has directly impacted the accuracy of grid integration, energy modeling, resource planning, production cost modeling, and project and product development.
Typical Meteorological Year

- TMY data were first created by Sandia National Laboratories to assess building performance.
- TMY data sets were developed from long-term data such as in the NSRDB.

<table>
<thead>
<tr>
<th>Source</th>
<th>Years</th>
<th>Description</th>
<th>Spatial Information</th>
<th>Temporal Information</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSRDB MTS1</td>
<td>1961–1990</td>
<td>TMY 2: METSTAT (METeorological STATistical) Model—93% and Measured—7%</td>
<td>Point data set</td>
<td>1-hour</td>
<td>239 stations. TMY3 was generated using versions 1 and 2 of the NSRDB.</td>
</tr>
<tr>
<td>NSRDB MTS1 and MTS 2</td>
<td>1961–2005</td>
<td>TMY 3: METSTAT SUNY Empirical model Measured (&lt;1%)</td>
<td>Point data set</td>
<td>1-hour</td>
<td>The update includes fields that allow users the flexibility to choose modeled or, if available, measured data for an application. Includes 1,020 stations.</td>
</tr>
<tr>
<td>NSRDB Version 3–PSM TMY</td>
<td>1998–2018</td>
<td>Gridded TMY</td>
<td>Gridded</td>
<td>1-hour</td>
<td>4 km² spatial resolution for all U.S. and part of South America</td>
</tr>
</tbody>
</table>
Data download options:
- NSRDB Viewer
- API
- AWS.

https://nsrdb.nrel.gov/
Other Sources of Solar Resource Data

https://www.nrel.gov/docs/fy18osti/68886.pdf

Table 5-1 in the handbook contains a list of data sources around the world.