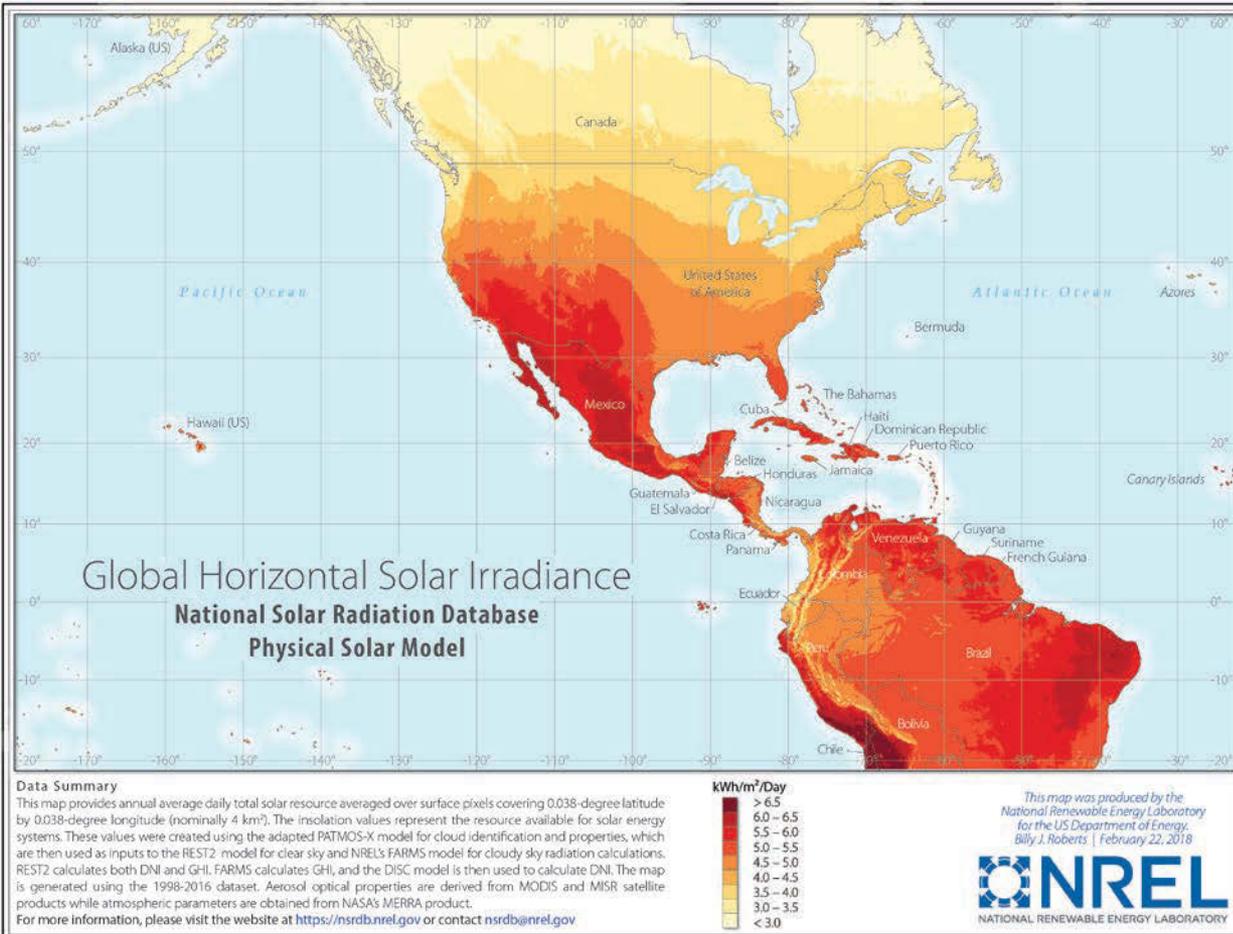


Measurement, Modeling, and Database of Solar Irradiance

Manajit Sengupta
and
Aron Habte



2019 NIST/UL Workshop on Photovoltaic Materials Durability,
December 12 - 13, 2019 Gaithersburg, Maryland

Solar Resource Assessment

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.

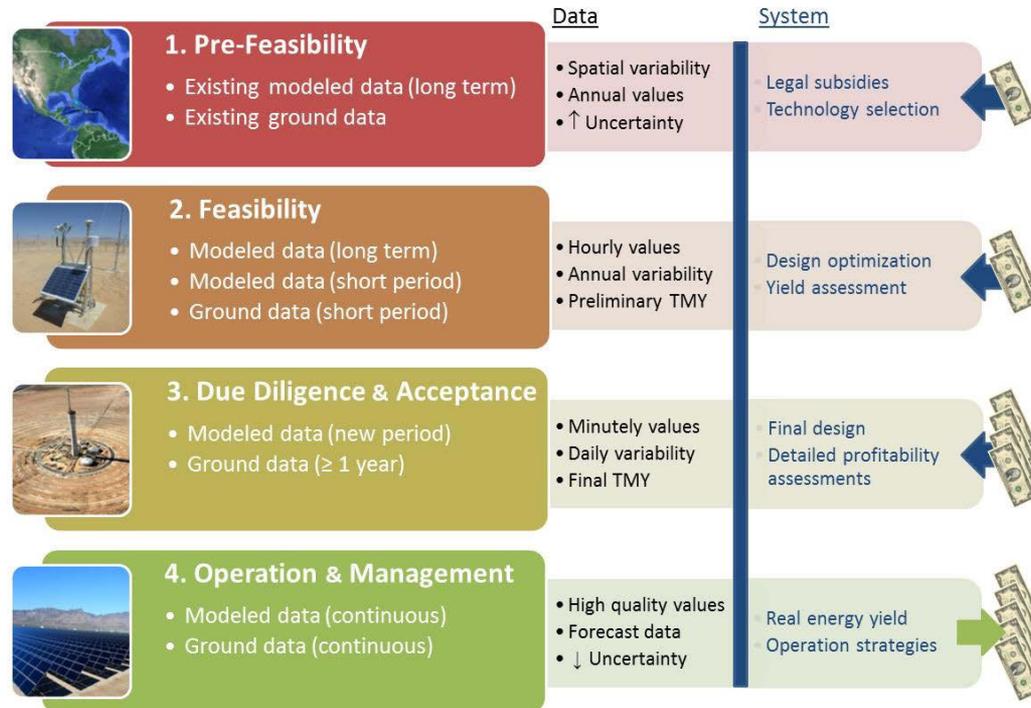


Figure from <https://www.nrel.gov/docs/fy18osti/68886.pdf>

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

nsrdb_2018_dni_8760.png



NSRDB:
<http://nsrdb.nrel.gov>



Photos by NREL

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

Center: <https://midcdmz.nrel.gov/>

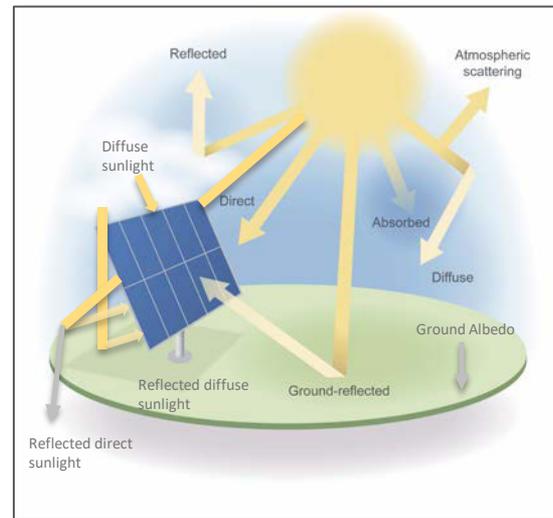
Solar Radiation Components

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)



Broadband Solar Irradiance Specification

Table 1 — Pyranometer classification list

Specification parameter No. (see 4.3.2)	Parameter	Name of the classes, acceptance intervals and width of the guard bands (in brackets)		
	Name of the class	A	B	C
	<i>Roughly corresponding class from ISO 9060:1990¹⁾</i>	<i>Secondary standard</i>	<i>First class</i>	<i>Second class</i>
a	Response time (see also 4.3.3 on fast response pyranometers): time for 95 % response	< 10 s (1 s)	< 20 s (1 s)	< 30 s (1 s)
b	Zero off-set: a) response to $-200 \text{ W}\cdot\text{m}^{-2}$ net thermal radiation b) response to $5 \text{ K}\cdot\text{h}^{-1}$ change in ambient temperature c) total zero off-set including the effects a), b) and other sources	$\pm 7 \text{ W}\cdot\text{m}^{-2}$ ($2 \text{ W}\cdot\text{m}^{-2}$) $\pm 2 \text{ W}\cdot\text{m}^{-2}$ ($0,5 \text{ W}\cdot\text{m}^{-2}$) $\pm 10 \text{ W}\cdot\text{m}^{-2}$ ($2 \text{ W}\cdot\text{m}^{-2}$)	$\pm 15 \text{ W}\cdot\text{m}^{-2}$ ($2 \text{ W}\cdot\text{m}^{-2}$) $\pm 4 \text{ W}\cdot\text{m}^{-2}$ ($0,5 \text{ W}\cdot\text{m}^{-2}$) $\pm 21 \text{ W}\cdot\text{m}^{-2}$ ($2 \text{ W}\cdot\text{m}^{-2}$)	$\pm 30 \text{ W}\cdot\text{m}^{-2}$ ($3 \text{ W}\cdot\text{m}^{-2}$) $\pm 8 \text{ W}\cdot\text{m}^{-2}$ ($1 \text{ W}\cdot\text{m}^{-2}$) $\pm 41 \text{ W}\cdot\text{m}^{-2}$ ($3 \text{ W}\cdot\text{m}^{-2}$)
c1	Non-stability: percentage change in responsivity per year	$\pm 0,8 \%$ ($0,25 \%$)	$\pm 1,5 \%$ ($0,25 \%$)	$\pm 3 \%$ ($0,5 \%$)
c2	Nonlinearity: percentage deviation from the responsivity at $500 \text{ W}\cdot\text{m}^{-2}$ due to the change in irradiance within $100 \text{ W}\cdot\text{m}^{-2}$ to $1\ 000 \text{ W}\cdot\text{m}^{-2}$	$\pm 0,5 \%$ ($0,2 \%$)	$\pm 1 \%$ ($0,2 \%$)	$\pm 3 \%$ ($0,5 \%$)
c3	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 $1\ 000 \text{ W}\cdot\text{m}^{-2}$	$\pm 10 \text{ W}\cdot\text{m}^{-2}$ ($4 \text{ W}\cdot\text{m}^{-2}$)	$\pm 20 \text{ W}\cdot\text{m}^{-2}$ ($5 \text{ W}\cdot\text{m}^{-2}$)	$\pm 30 \text{ W}\cdot\text{m}^{-2}$ ($7 \text{ W}\cdot\text{m}^{-2}$)



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

NOTE The acceptance intervals should not be used for uncertainty estimations for conditions different from the ones 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

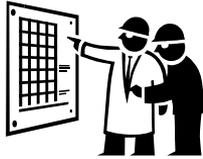


Field instruments

Photos by NREL

Maintaining Data Quality

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



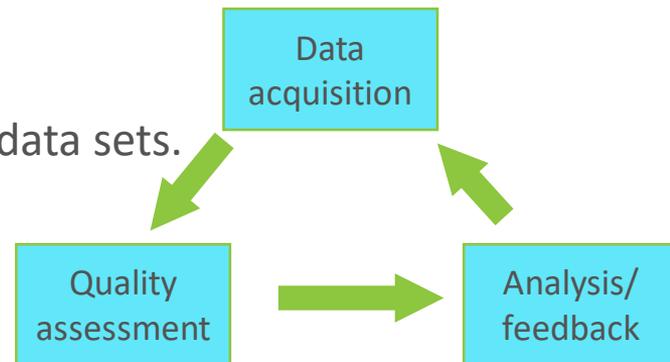
- Quality control is a supervisory process. *This happens before and during the measurements.*



Data Quality and Uncertainty: What Do You Get?

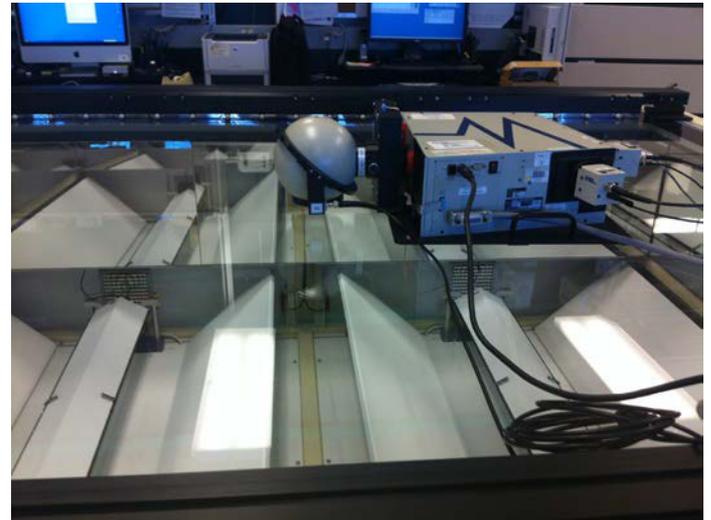
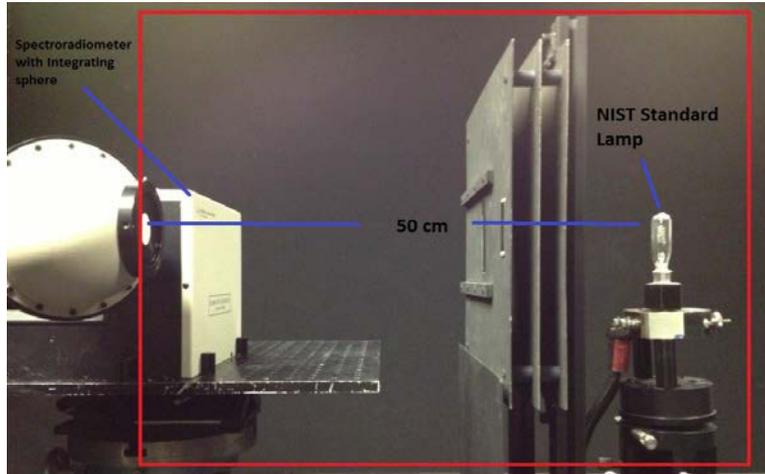
Data quality analysis procedure:

- **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 Radiometer Traceability and ISO 17025 Accreditation

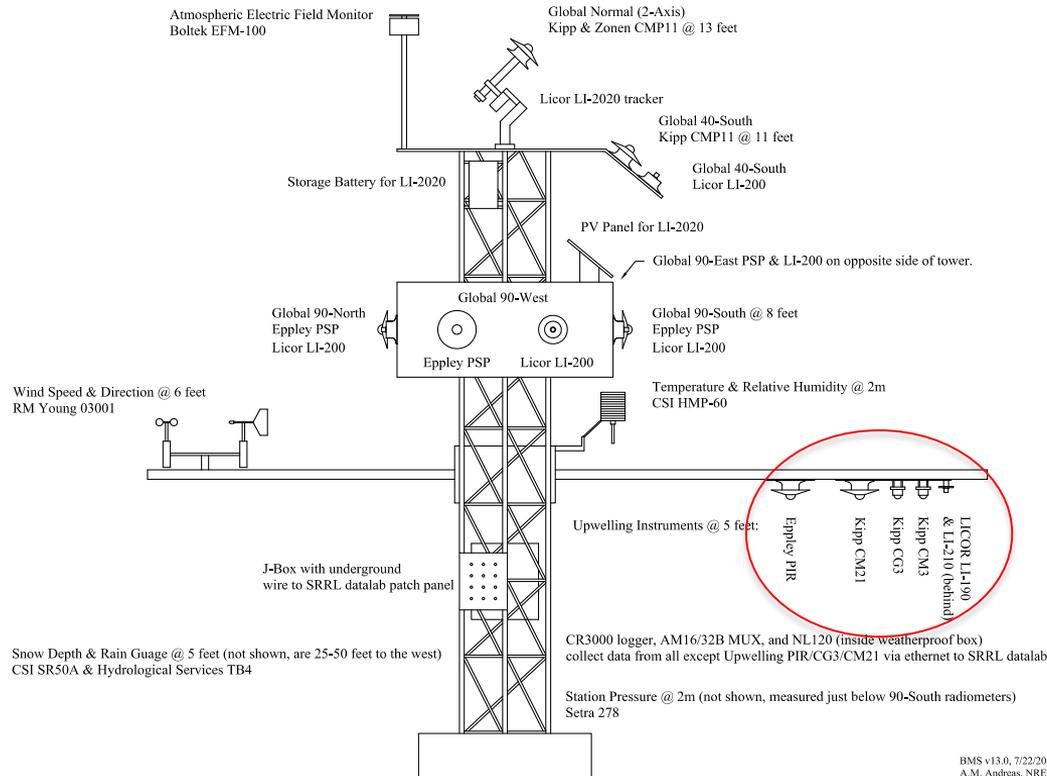
Spectral radiometric calibrations are accredited by the International Organization for Standardization and traceable to the National Institute of Standards and Technology (NIST), enabling accurate baseline data sets for model and standards development, PV cell and module characterization, and reliability studies.



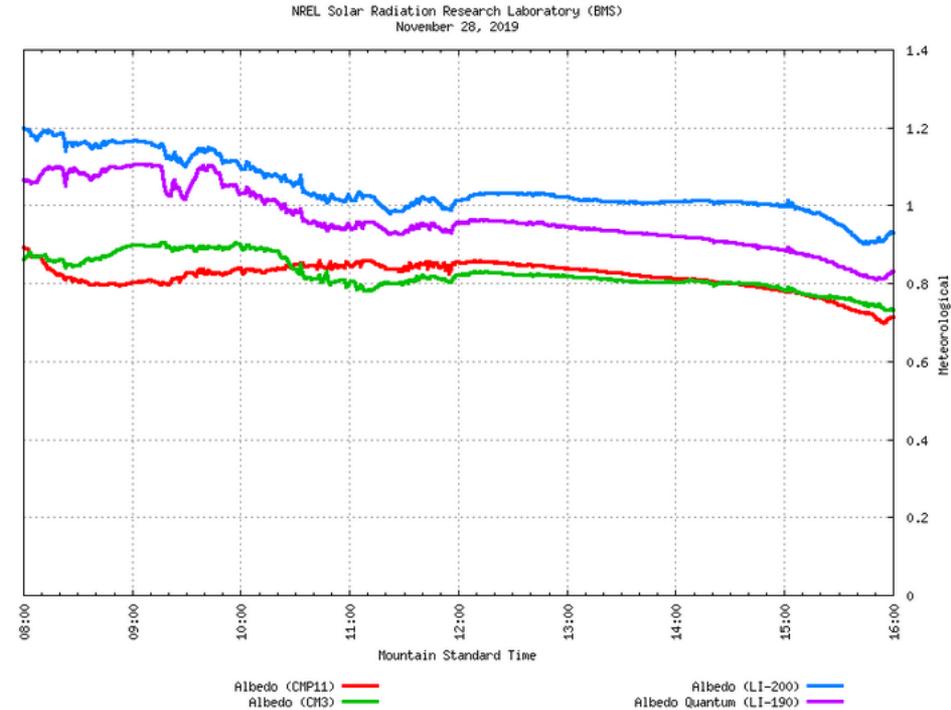
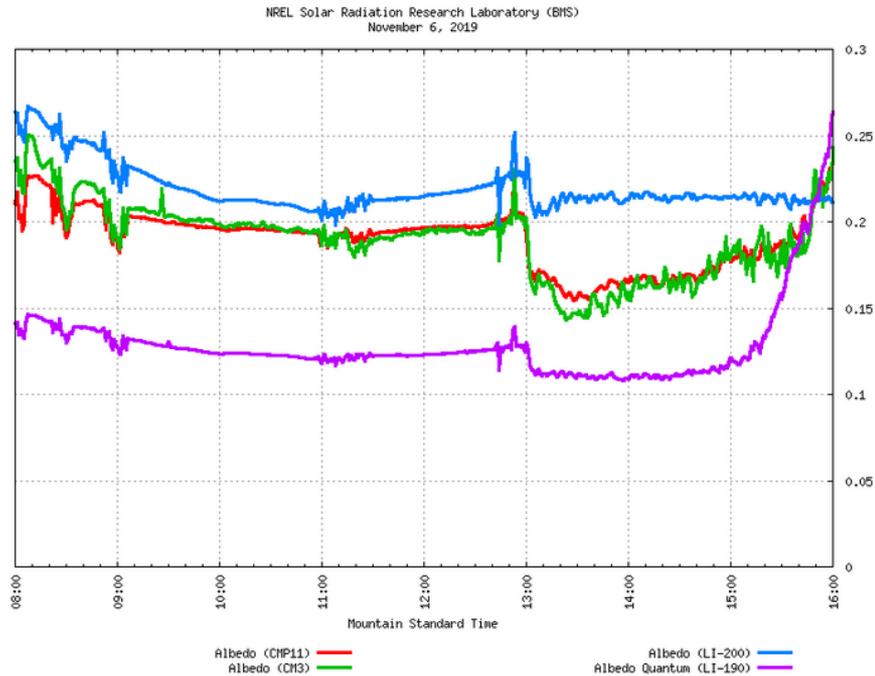
Photos by NREL

National Renewable Energy Laboratory- Solar Radiation Research Laboratory Albedo Data

SRRL Baseline Measurement System Radiometer Tower



National Renewable Energy Laboratory- Solar Radiation Research Laboratory Albedo Data



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.

Ultraviolet Measurement and Modeling

All ultraviolet radiometers are calibrated using spectroradiometers and are traceable to NIST.

Component	Manufacturer	Model	#	Band	Spectral Range (nm)	Notes
Direct (5° FOV)	Kipp & Zonen	CUVA2	1	UVA	315–400	
	Kipp & Zonen	UVB	1	UVB	280–315	
	Eppley	TUVR	1	TUV	295–385	Response time is order (milliseconds)
Global (180° FOV)	Kipp & Zonen	CUVA1	1	UVA	315–400	
	Yankee Environmental Systems, INC.	UVA-1	1	UVA	320–400	
	Kipp & Zonen	UVS-A-T	1	UVA	315–400	Response time < 2 seconds
	Kipp & Zonen	UVS-B-T	1	UVB	280–315	Response time < 2 seconds
	Kipp & Zonen	CUVB1	1	UVB	280–315	
	Yankee Environmental Systems, INC.	UVB-1	1	UVB	280–320	
	EKO	MS-210W	1	UVB	280–320	Response time ~ 1 second
	Solar Light	501A	1	UVB	280–315	
	Kipp & Zonen	CUV4	1	TUV	280–400	Response time < 1 second
	Eppley	TUVR	1	TUV	295–385	Response time is order (milliseconds)

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.

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National Renewable Energy
Laboratory
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Browse ▾ My Settings ▾ Get Help ▾

All ▾ Enter keywords or phrases (Note: Searches metadata only by default. A search for 'smart grid' = 'smart AND grid')

Journals & Magazines > IEEE Journal of Photovoltaics > Volume: 9 Issue: 1

Estimating Ultraviolet Radiation From Global Horizontal Irradiance

6 Author(s) Aron Habte ; Manajit Sengupta ; Christian A. Gueymard ; Ranganath Narasappa ; Olivier Rosselet ; ... View All Authors

13 Full Text Views

PDF Download RSS Email Cite Share Alert

Abstract

Document Sections

- I. Introduction
- II. Method
- III. Results and Discussion
- IV. Conclusion

Authors

Abstract: Terrestrial ultraviolet radiation (UV) radiation is a primary factor contributing to the degradation of photovoltaic (PV) modules' efficiency and reliability over time. Therefore, accurate knowledge of terrestrial UV incident on the surface of the PV materials is essential to understand the degradation of PV modules and provide reliable assessment of their service life. As PV is deployed in various climate zones, it is crucial that terrestrial UV information is available at various locations. However, the availability of terrestrial UV data—measured or modeled—is extremely limited. On the other hand, total solar irradiance (TS) datasets are relatively abundant. In this study, the National Renewable Energy Laboratory, its industry partners, and ASTM's International Subcommittee on Radiometry and Service Life Prediction are developing a simple method to estimate the clear-sky terrestrial UV irradiance (280–400 nm, 295–400 nm, 285–385 nm, or 295–385 nm) from total irradiance data (280–4000 nm). The goal is to provide reliable estimates of the UV received by samples as a function of location, orientation, tilt, and airmass, thus encompassing a variety of conditions. The Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) model is used to estimate the I_V/I_T ratio under various scenarios, and examines the

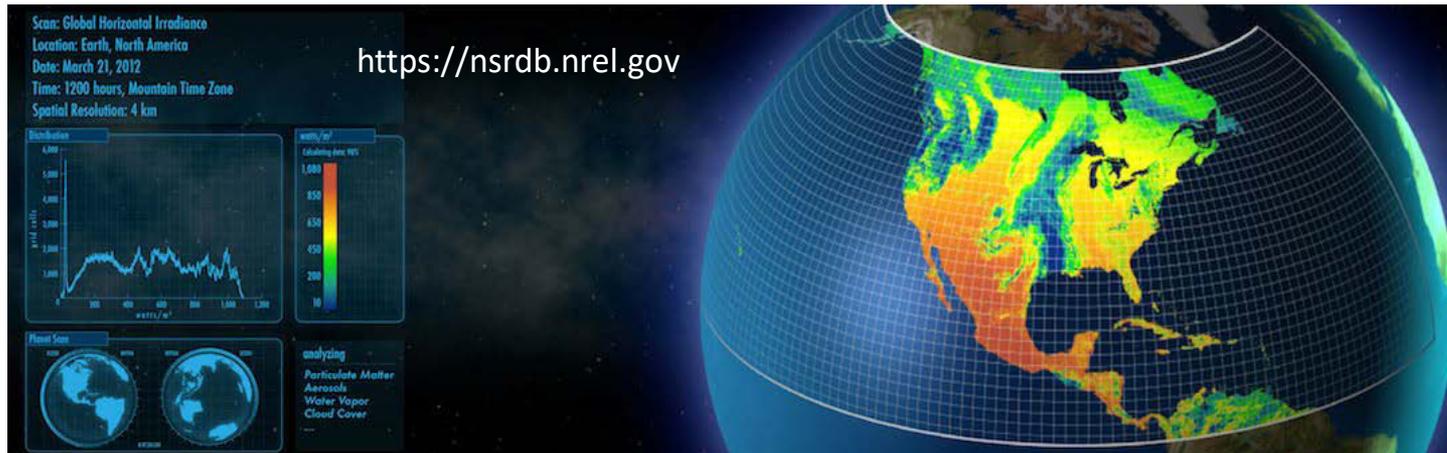
Example from <https://ieeexplore.ieee.org/abstract/document/8529229>

Broadband and Spectral Solar Resource Data from the National Solar Radiation Data Base

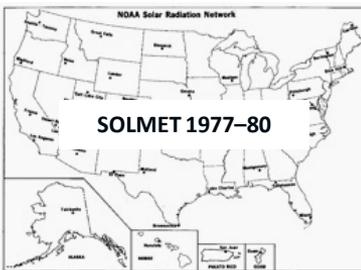
Physical Solar Model Version 3

The National Solar Radiation Database

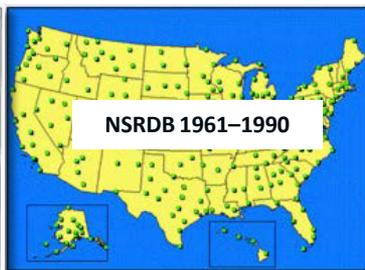
- The NSRDB seeks to advance our knowledge of solar radiation and its applications for renewable energy and beyond.
- The NSRDB provides a serially complete database of solar irradiance and meteorological information across the United States and in an increasing number of international locations.
- The 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**).



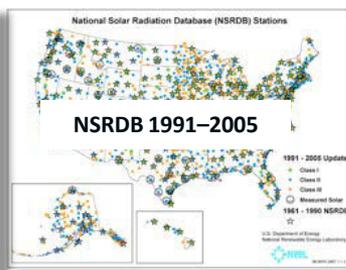
Evolution of the National Solar Radiation Database



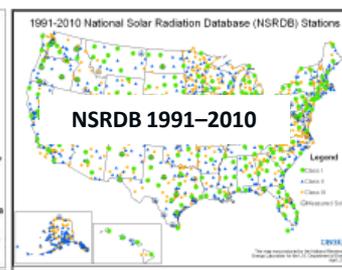
248 weather stations with 26 **solar measurement** stations (ERDA, NOAA, 1979)



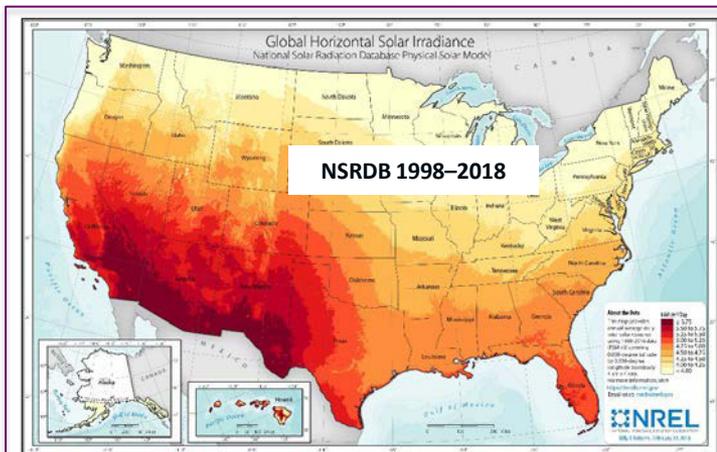
239 **modeled** stations with 56 partial measurement stations (DOE, NOAA, 1994)



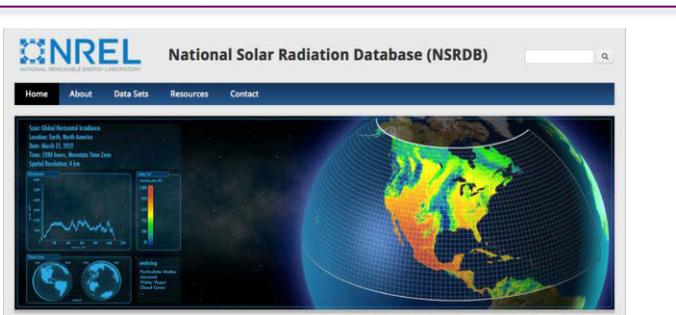
1,454 **modeled** locations (DOE, SUNY-A, NOAA, 2007)



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

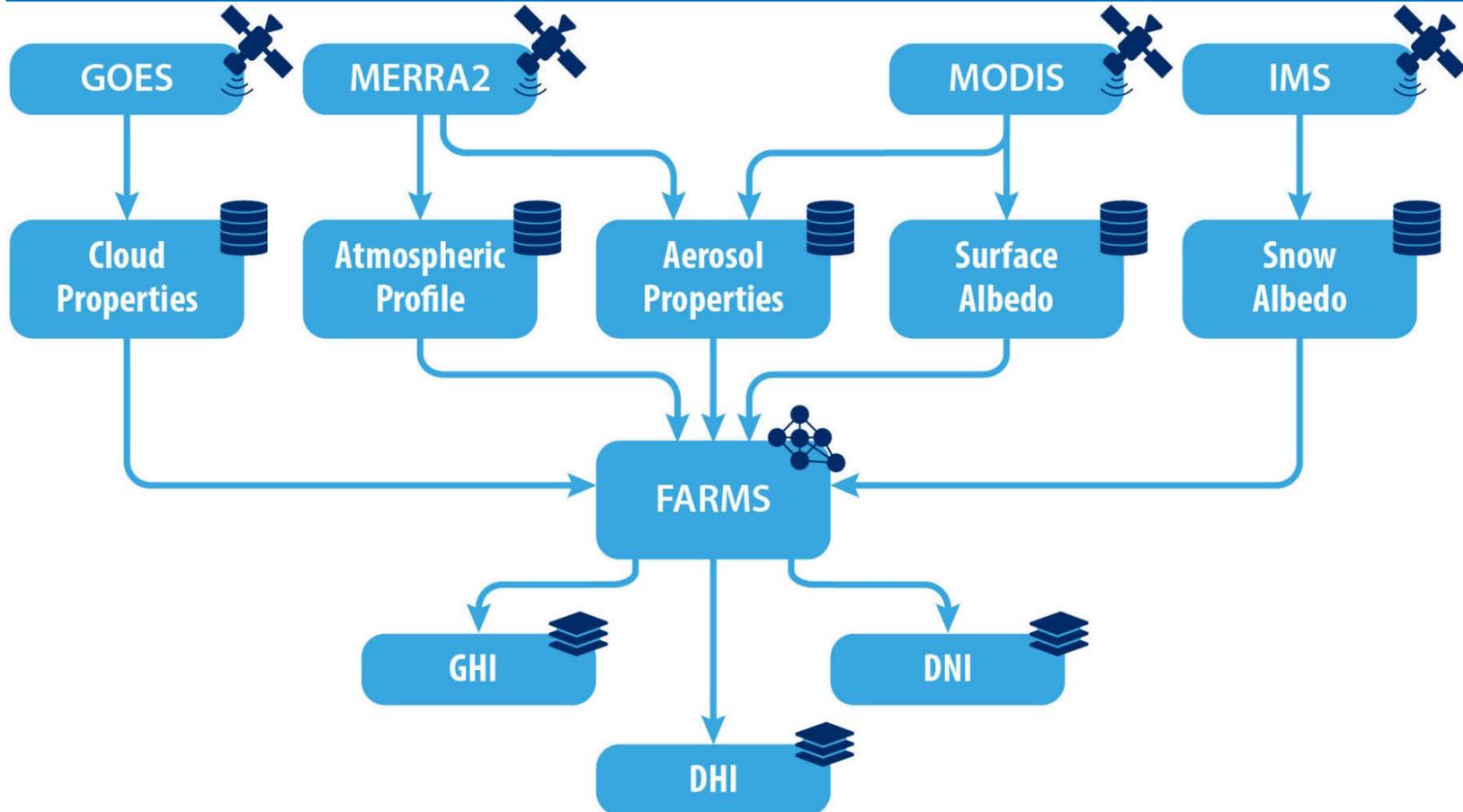


Satellite-based, gridded, 4 km x 4 km, half-hourly (DOE, NOAA, UW, SCS 2018)

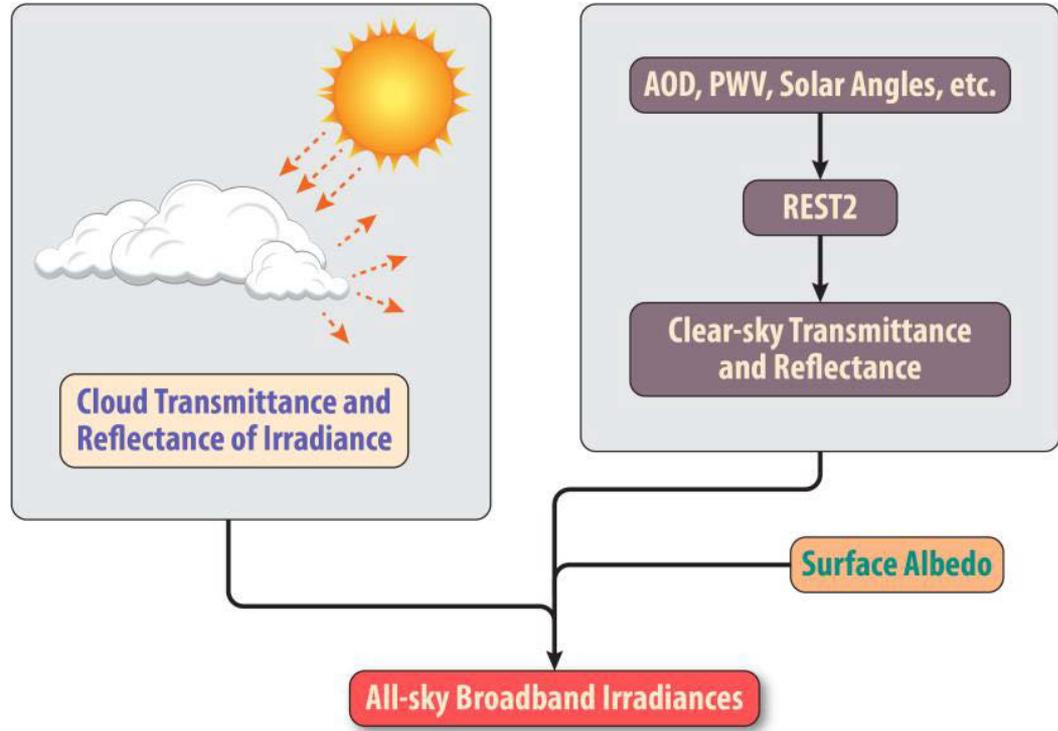
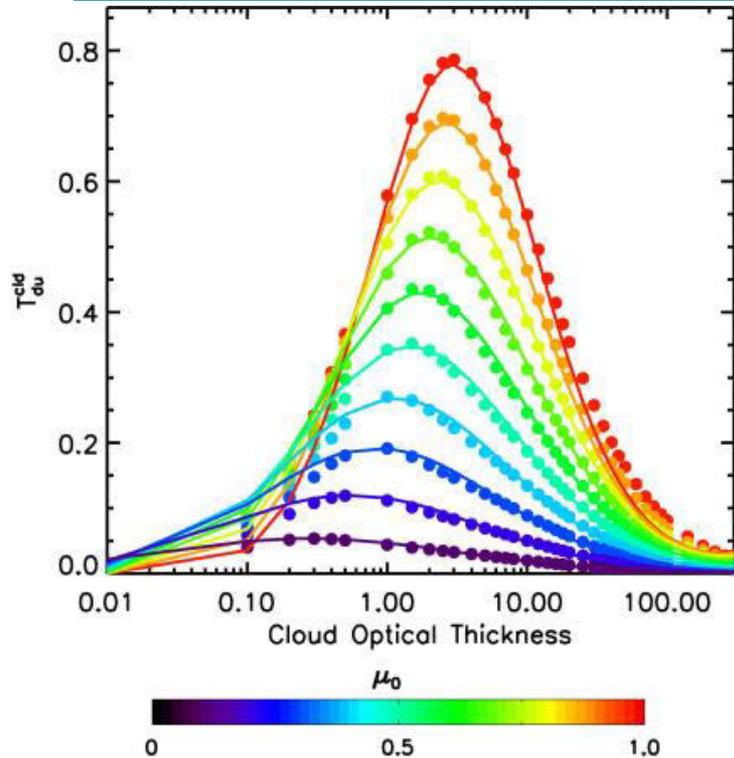


<http://nsrdb.nrel.gov>

National Solar Radiation Database Physical Solar Model Workflow

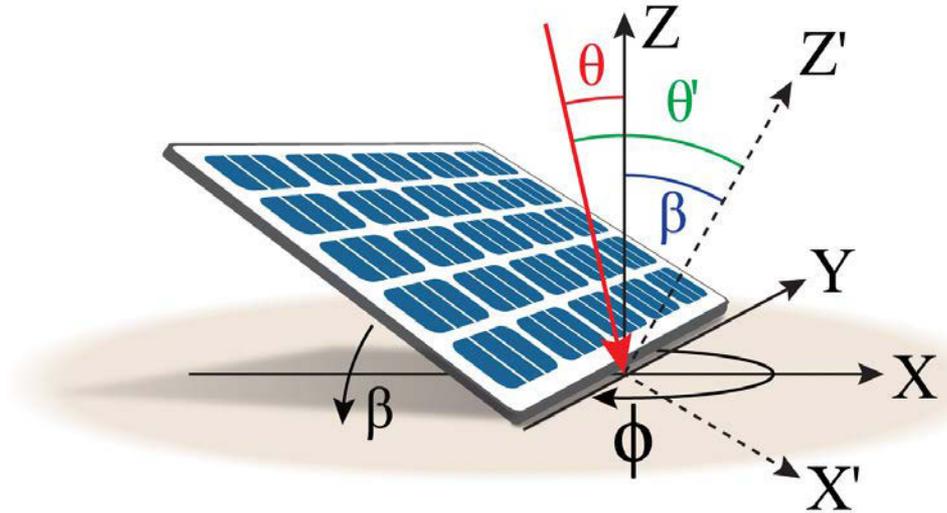
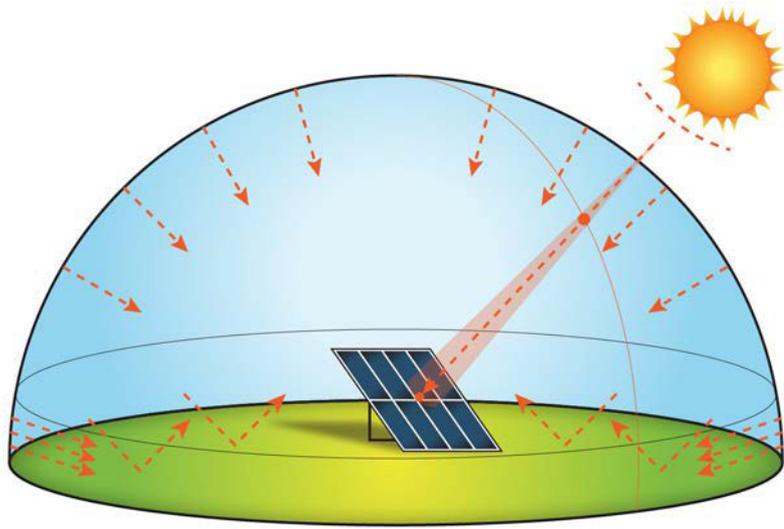


Fast All-Sky Radiation Model for Solar Applications (FARMS)



Cloud transmittances can be parameterized as exponential functions of cloud optical thickness and solar zenith angles.

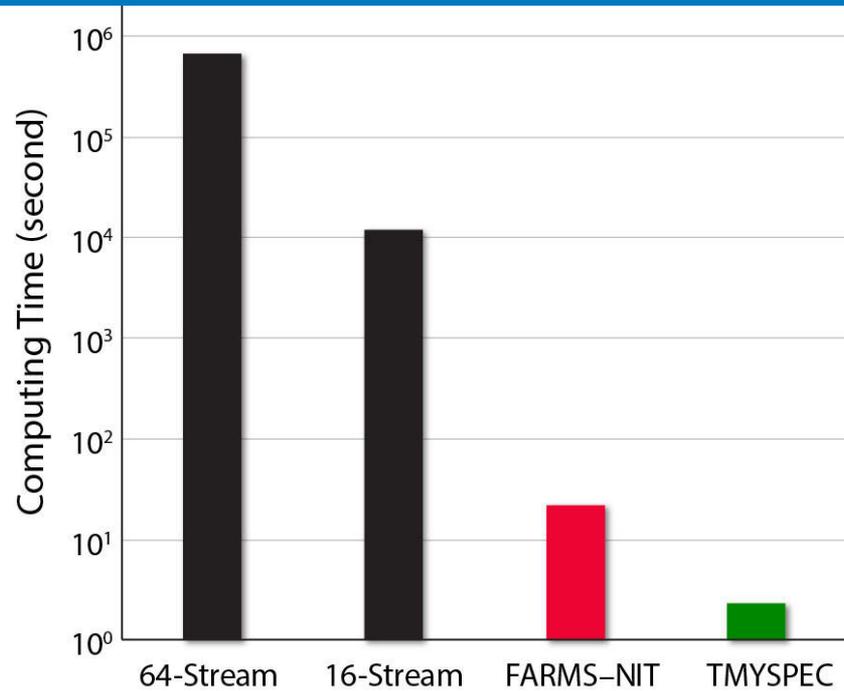
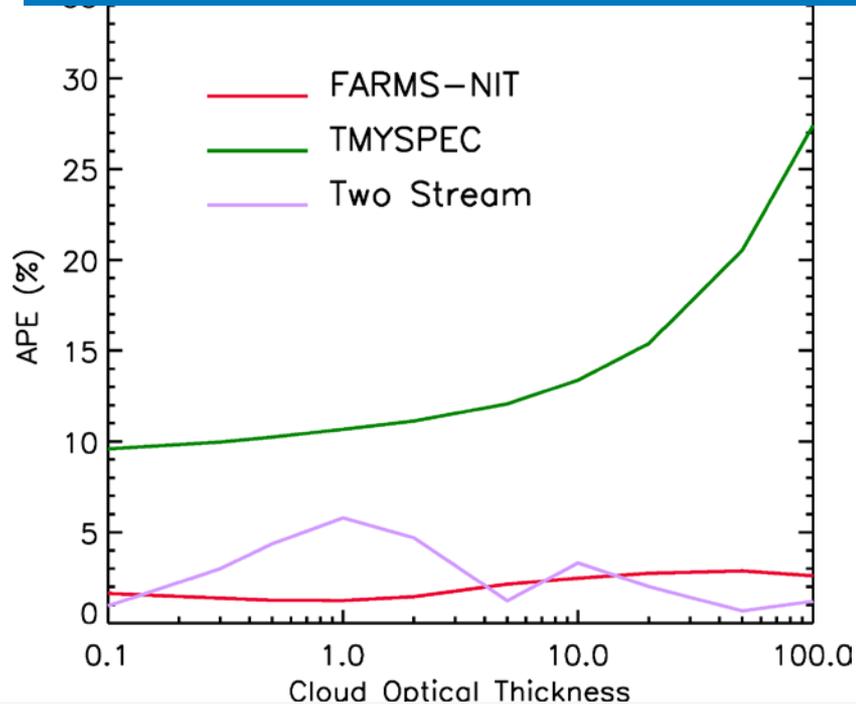
Fast All-Sky Radiation Model for Narrowband Irradiances on Tilted Surfaces



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.

Fast All-Sky Radiation Model for Narrowband Irradiances Is Accurate and Time-Efficient

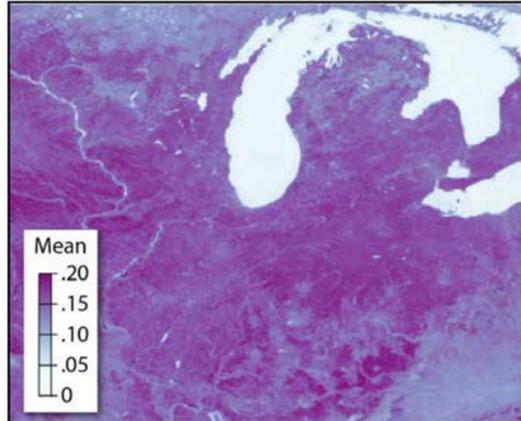
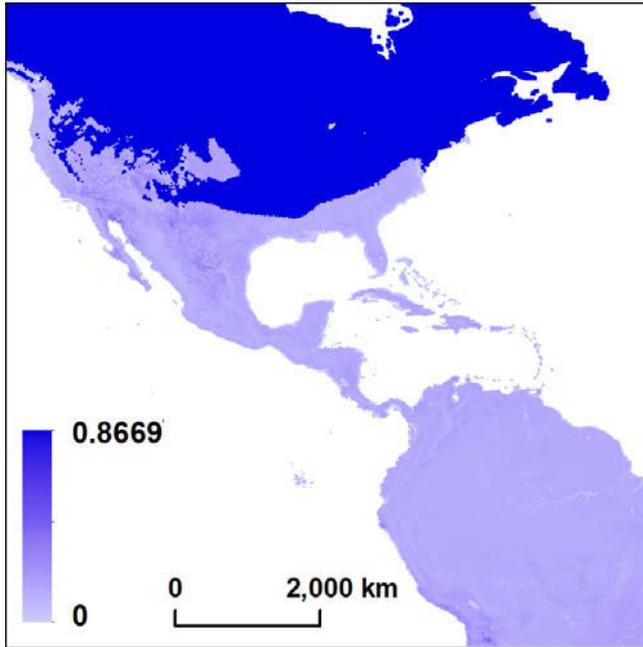


The overall difference between Discrete Ordinates Radiative Transfer (DISORT) and FARMS-NIT is less than 5% for both clear-sky and cloudy-sky conditions.

FARMS-NIT has a better accuracy than TMYSPEC.

National Solar Radiation Database Surface Albedo

NSRDB Improvement: MODIS-Derived Surface Albedo Data Set



Development of a MODIS-Derived Surface Albedo Data Set: An Improved Model Input for Processing the NSRDB

Galen MacLaurin, Manojit Sengupta, Yu Xie, and Nicholas Gilroy
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC
This report is available at no cost from the National Renewable Energy
Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-6A20-67306
December 2016
Contract No. DE-AC36-08G028308

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>.

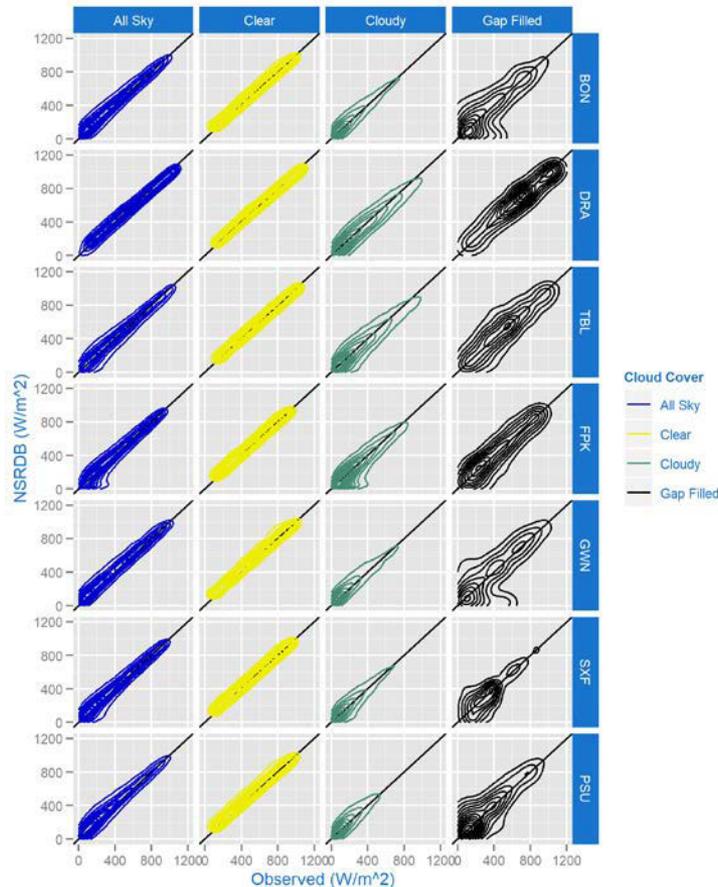
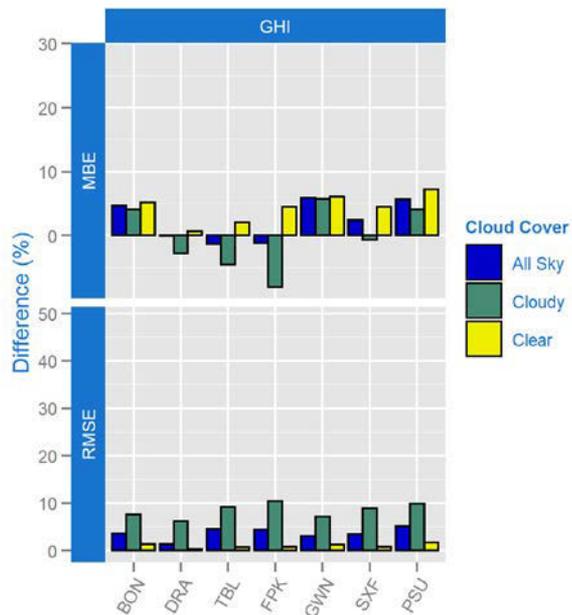
What Is Available from the National Solar Radiation Database?

- 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.

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

National Solar Radiation Database Data Access

Welcome to the
National Solar Radiation Database

HOME ABOUT DATA SETS RESOURCES **NSRDB VIEWER** CONTACT US

Spatial Resolution

DOWNLOAD INSTRUCTIONS
ADMINISTRATIONS
ADVISORIES
NSRDB DATA - HIGGINS DEMO

What Is the NSRDB?

The National Solar Radiation Database (NSRDB) is a serially complete collection of hourly and half-hourly values of meteorological data and the three most common measurements of solar radiation: global horizontal, direct normal and diffuse horizontal irradiance. It covers the United States and a growing subset of international locations. These data have been collected at a sufficient number of locations and temporal and spatial scales to accurately represent regional solar radiation climates. For a given location covered by the dataset, it is possible to see the amount of solar energy that was at a given time, and to predict the potential future availability of solar energy based on past conditions.

Learn More | Latest Publication

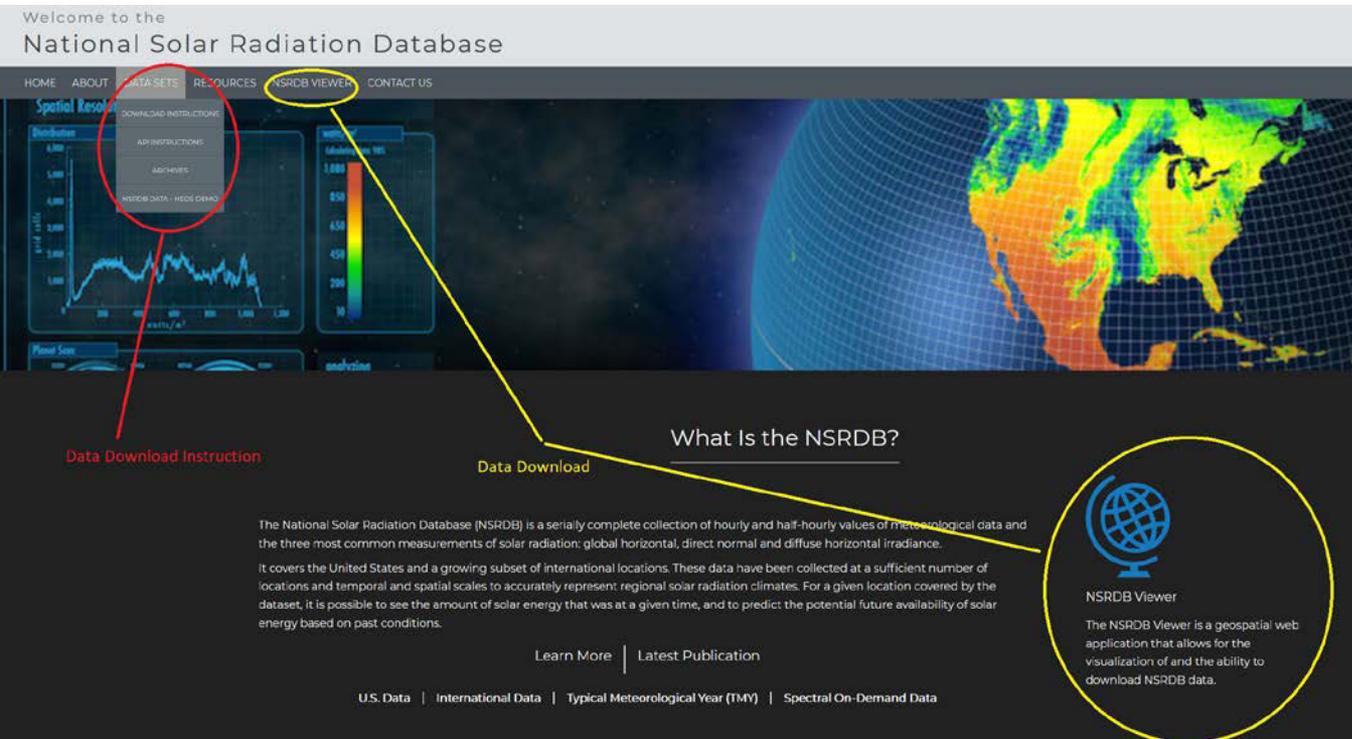
U.S. Data | International Data | Typical Meteorological Year (TMY) | Spectral On-Demand Data

Data Download Instruction

Data Download

NSRDB Viewer

The NSRDB Viewer is a geospatial web application that allows for the visualization of and the ability to download NSRDB data.



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>

Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Second Edition

Edited by Manajit Sengupta,¹ Aron Habte,¹
Christian Gueymard,² Stefan Wilbert,³
Dave Renné,⁴ and Thomas Stoffel⁵

¹ National Renewable Energy Laboratory

² Solar Consulting Services

³ German Aerospace Center (DLR)

⁴ Dave Renné Renewables, LLC

⁵ Solar Resource Solutions, LLC

This update was prepared in collaboration with the International Energy Agency Solar Heating and Cooling Programme: Task 46



NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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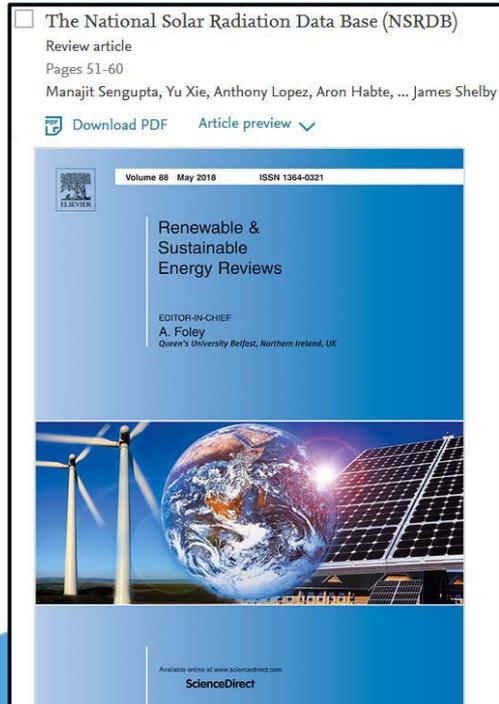
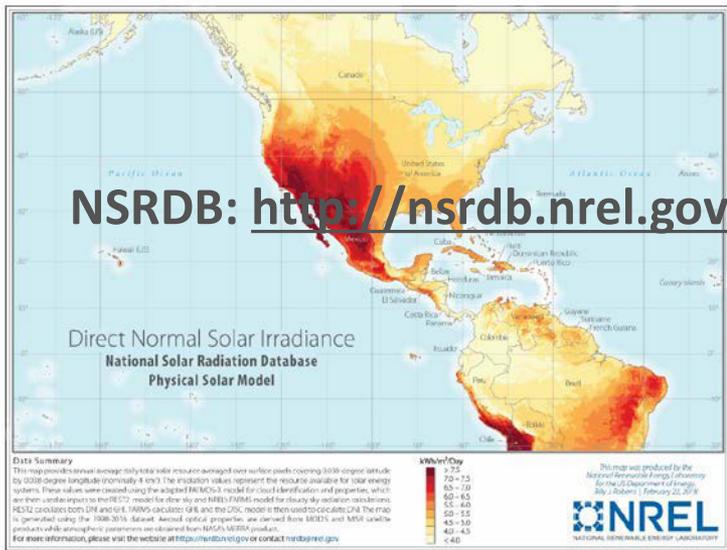
Technical Report
NREL/TP-5D00-68886
December 2017

Contract No. DE-AC36-08GO28308

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

Thank You!

Contact: Manajit.Sengupta@nrel.gov



Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. 2018. "The National Solar Radiation Data Base (NSRDB)." *Renew. Sustain. Energy Rev.*, 89: 51–60. <https://doi.org/10.1016/j.rser.2018.03.003>.

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