Solar Resource Calibration, Measurement, and Dissemination

Final Report FY 2016–FY 2018

Manajit Sengupta,[1] Aron Habte,[1] Yu Xie,[1] Anthony Lopez,[1] Mike Dooraghi,[1] Mark Kutchenreiter,[1] Afshin Andreas,[1] Ibrahim Reda,[1] Galen Maclaurin,[1] Michael J. Foster,[2] and Christian Gueymard[3]

[1] *National Renewable Energy Laboratory*
[2] *Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin*
[3] *Solar Consulting Services*

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Technical Report
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
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Acknowledgments

We are grateful to the U.S. Department of Energy Solar Energy Technologies Office and the systems integration subprograms for supporting this project. Specifically, we acknowledge Dr. Tassos Golnas, Dr. Guohui Yuan, and Dr. Charlie Gay for their support and encouragement.

List of Acronyms

ACP	Absolute cavity pyrgeometer
ACR	Absolute cavity radiometer
AOD	Aerosol optical depth
ASTM	American Society for Testing Materials
AVHRR	Advanced very-high-resolution radiometer
BMS	Baseline Measurement System
BORCAL	Broadband Outdoor Radiometer Calibration
CLAVR-X	Clouds from AVHRR-extended
CRADA	Cooperative research-and-development agreement
CSP	Concentrating solar power
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
DOE	U.S. Department of Energy
FARMS	Fast All-sky Radiation Model for Solar Applications
GHI	Global horizontal irradiance
GOES	Geostationary Operational Environmental Satellite
GUM	Guide to the Expression of Uncertainty in Measurement
HF/AHF	Automatic Hickey-Frieden
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPC	International Pyrheliometer Comparison
IRIS	Infrared integrating sphere
ISO	International Organization for Standardization
MBD	Mean bias difference
MBE	Mean bias error
MERRA	Modern Era Retrospective analysis for Research Applications
MIDC	Measurement and Instrumentation Data Center
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPC	NREL Pyrheliometer Comparisons
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
PASS	Pulse Analysis Spectroradiometer System
PMOD/WRC	Physikalisch-Meteorologisches Observatorium Davos World Radiation Center
PSM	Physical Solar Model
PV	Photovoltaics
PVPS	[IEA] Photovoltaic Power Systems Programme
R&D	Research and development
RMSE	Root mean square error
RReDC	Renewable Resource Data Center
SETO	Solar Energy Technologies Office
SMARTS	Simple Model of the Atmospheric Radiative Transfer of Sunshine

SRRL	Solar Radiation Research Laboratory
SuNLaMP	SunShot National Laboratory Multiyear Partnership
SURFRAD	Surface Radiation Budget Network
UV	Ultraviolet
WISG	World Infrared Standard Group
WRR	World Radiometric Reference

Executive Summary

The Solar Resource Calibration, Measurement, and Dissemination project supports the U.S. Department of Energy's Solar Energy Technologies Office (SETO) initiative to make solar energy cost-competitive with other forms of electricity by improving the tools and methods to measure and model solar radiation and therefore reduce uncertainty in predicting solar output and improve the bankability of solar projects. This project has three tasks that conduct research on advancing solar resource measurements and modeling:

- Task 1: Applied solar Radiation Measurements
- Task 2: National Solar Radiation Data Base (NSRDB)
- Task 3: Knowledge Sharing.

The National Renewable Energy Laboratory's (NREL's) Solar Radiation Research Laboratory (SRRL) activities ensure traceable solar measurements throughout the United States that are essential for project feasibility, due diligence, financing, and plant operations. The SRRL houses NREL's Baseline Measurement System (BMS), which provides a platform for improving the accuracy of solar measurements through research to improve the calibration and characterization of instruments and enable the development of new measurement technology and standards. The platform contains a variety of instruments measuring solar radiation and other meteorological parameters. Following best practices, BMS instruments are calibrated to ensure traceability to the World Radiometric Reference in compliance with ISO/IEC 17025[1] accreditation requirements. The BMS data sets are quality-controlled and made publicly available through the Measurement and Instrumentation Data Center website.

The NSRDB is the most accessed public database of solar irradiance and associated weather parameters for use in energy modeling. It supports SETO's goals of reducing barriers to high penetrations of solar technologies by providing easy access to high-quality, foundational data essential for innovative product development and downstream modeling through the NSRDB website. Data are currently available for the contiguous United States and beyond for 20 years covering 1998–2017. The Physical Solar Model (PSM) that underpins the current NSRDB data sets is a unique physics-based model that has been developed at NREL and has opened the door to the use of next-generation satellite data sets for solar resource assessment and forecasting.

Through the American Society for Testing Materials (ASTM) International and other international standards organizations, NREL continues to provide leadership in the development of standards that are relevant to the measurement and modeling of solar radiation for solar energy applications. Standards developed cover the calibration method of pyrheliometers (direct normal irradiance measurements), pyranometers (global horizontal irradiance measurements), spectroradiometers, ultraviolet radiometers, correct field deployment of these instruments, spectral distribution reference tables for photovoltaic modeling, and transfer of indoor calibrations. Further, NREL leads the International Energy Agency (IEA) Photovoltaic Power Systems Programme Task 16: Subtask 1, which focuses on the evaluation of current and emerging resource assessment methodologies. NREL and the IEA updated the *Best Practices*

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[1] International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 17025:2005: General Requirements for the Competence of Testing and Calibration Laboratories

Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications,[2] which is widely used by the solar industry.

[2] See https://www.nrel.gov/docs/fy15osti/63112.pdf.

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1 Background

Accurate solar resource data are essential for reducing technical and nontechnical barriers to achieving the U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO) SunShot National Laboratory Multiyear Partnership (SuNLaMP) goals. Solar energy is a weather-driven renewable resource that poses unique challenges to researchers, developers, financiers, utilities, and system operators. Uncertainty in solar resource data can lead to significant risks and increased costs for the design, installation, financing, and integration of renewable energy conversion systems. Since 1977, DOE has invested millions of dollars to develop unique capabilities at the National Renewable Energy Laboratory (NREL) for providing world-class solar resource measurements and model estimates. The primary objectives of this project are to provide improved solar resource data of known accuracy, traceable radiometer calibrations for bankable solar irradiance measurements, and advanced methods for resource information dissemination supporting foundational research and development (R&D) needed to address DOE's SuNLaMP goals.

NREL's Solar Radiation Research Laboratory (SRRL) is one of the few sources of high-quality long-term solar radiation data sets in the nation and probably the only source of a complete set of measurements for solar radiation modeling research. This includes the development and testing of industry-standard models, such as the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) and the testing of NREL's Fast All-sky Radiation Model for Solar Applications (FARMS). FARMS is further used to develop the National Solar Radiation Database (NSRDB). The SRRL serves as a living laboratory that allows experience gathered from operating instruments, developing standards, and testing models to be shared quickly and easily across the solar energy industry. This experience is shared through the American Society for Testing Materials (ASTM) International and International Organization for Standardization (ISO) standards, conference presentations, technical reports, and journal articles. The data are available in real time through the Measurement and Instrumentation Data Center (MIDC) portal.[3]

Measurement research is an important part of SRRL R&D. This includes research into sources of uncertainty in solar measurements, their quantification, and mitigation. Examples of recent work include investigation of differences in outdoor and indoor calibrations as well as instrument degradation as a result of long-term field deployment. New and improved instruments are deployed for validation and characterization against the Baseline Measurement System (BMS). The validation process provides an understanding of the quality of a new instrument when compared to peers. The characterization process provides an understanding of the variability between instruments of the same make and model and essentially provides an understanding of the manufacturing quality. These tests are carried out in collaboration with manufacturers, including Kipp & Zonen, Hukseflux, EKO Instruments, Inc., Eppley Laboratory, Inc., Irradiance, Inc., LI-COR, and Apogee. The data that are collected from these tests and published in reports allow the solar energy industry to understand the performance of sensors and make informed decisions regarding the deployment and use of data collected by those sensors. Data collected by the instruments are used as inputs to U.S. and international standards. Examples are ASTM

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[3] See http://www.nrel.gov/midc.

E824: Standard Test Method for Transfer of Calibration from Reference to Field Radiometers and ASTM G183: Standard Practice for Field Use of Pyranometers, Pyrheliometers, and UV[4] Radiometers. The standards are essential for acquiring traceable solar resource data sets for solar energy conversion applications and are described in more detail later in this document. Development of new types of instrumentation, advancement in measurement methods and techniques, and updates in measurement best practices resulting from SRRL R&D forms an essential part of regular updates to NREL's *Best Practices Handbook* for solar measurement and modeling. Recent advances include understanding the use of photodiodes for solar measurement and the development of a standard to estimate uncertainty in field measurements.

Many solar irradiance models have been developed using empirical, semiempirical, or physical models (Pinker, Frouin, and Li 1995; Hammer et al. 2003). Empirical models develop regression functions relating long-term global horizontal irradiance (GHI) measurements at selected local stations to the simultaneous data recorded by satellites' visible channels (Cano et al. 1986; Perez et al. 2002), which are then used to simulate GHI from global satellite observations. The GHI is combined with empirical relationships developed using modeled or observed solar radiation to retrieve direct normal irradiance (DNI) (Ineichen et al. 1992; Maxwell 1987). A well-known solar radiation data set developed by an empirical model is HelioClim, based on the observations of Meteosat geostationary satellites covering Europe, Africa, the Mediterranean Basin, the Atlantic Ocean, and part of the Indian Ocean (Cano et al. 1986; Rigollier, Lefèvre, and Wald 2004; Diabaté et al. 1987). Compared to empirical models, semiempirical models use a hybrid approach to derive solar radiation in which clear-sky background irradiance is solved from simple radiative transfer schemes (Rigollier, Lefèvre, and Wald 2004; Cebecauer, Šúri, and Perez 2010; Šúri, Cebecauer, and Skoczek 2011). A cloud index representing the proportion of radiation reflecting back to the satellite is converted to a clearness index that represents the proportion of incident radiation reaching the surface. The clearness index scales the clear-sky radiation to estimate the GHI, which is then partitioned to estimate DNI, similar to the empirical models. This semiempirical approach has been widely implemented in global solar radiation data sets, including SolarGIS (Cebecauer, Šúri, and Perez 2010; Šúri, Cebecauer, and Skoczek 2011) and SolarAnyWhere (Rigollier, Lefèvre, and Wald 2004).

Physical models are conventionally categorized by single-step and two-step models according to the procedures in determining solar radiation (Cano et al. 1986). Single-step models directly solve for GHI using satellite observations and radiative transfer theory (Diak and Gautier 1983; Gautier 1982). Two-step models intend to understand the complete physics affecting the transmission of solar radiation from the top of the atmosphere to the land surface. They retrieve aerosol, cloud, and other atmospheric properties from various satellite channels or modeling efforts and use the information to precisely simulate GHI by solving the radiative transfer equation (Pinker, Frouin, and Li 1995; Hammer et al. 2003). A typical product of a two-step model is the National Aeronautics and Space Administration's (NASA's) global surface radiation budget, where International Satellite Cloud Climatology Project pixel-level data and Goddard Earth Observing System Version 4 reanalysis products are used to infer atmospheric

[4] Ultraviolet

properties at a 250-km resolution for every 3 hours. The solar radiation is then derived using the atmospheric properties and a model developed by Pinker and Laszlo (Pinker and Laszlo 1992).

Compared to empirical, semiempirical, and single-step physical models, most two-step physical models require significant computational capability because extensive information from satellite observations and other ancillary inputs need to be processed to estimate solar radiation. The multiple processes in the production chain require sufficient quality inputs to make full use of the advanced models for reducing uncertainties of GHI and DNI. During the years, rapid development of satellite technologies and modeling capabilities (e.g., the availability of Moderate Resolution Imaging Spectroradiometer [MODIS] spectral channels and multichannel geostationary satellites) have effectively increased the reliability and accuracy of the two-step physical models (Cano et al. 1986, Xie et al. 2012, Xie et al. 2012, Minnis et al. 2011). More recently, the expansion of spectral channels with improved temporal and spatial resolution on the third-generation Geostationary Operational Environmental Satellite-16 (GOES-16; previously GOES-R) is expected to lead to remarkable improvements in aerosol and cloud products (Schmit et al. 2005), which the two-step physical models are capable of exploiting. The improvements in reanalysis data such as NASA's Modern Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) bring observations and numerical models together in a unified standardized framework, resulting in high-quality ancillary information that significantly enhances the quality of the two-step physical models (Gelaro et al. 2017). In contrast, empirical, semiempirical, and single-step physical models are not expected to reap equivalent benefits from advances in satellite technology and reanalysis data sets because of inherent limitations in the underlying methods.

NREL has an extensive history of developing solar resource data over the United States and beyond using various sources of observations and modeling tools. NREL developed the Physical Solar Model (PSM), a physics-based solar irradiance model, in collaboration with the University of Wisconsin, the National Oceanic and Atmospheric Administration (NOAA), and Solar Consulting Services. PSM uses a two-step process where cloud properties are retrieved using the Clouds from AVHRR-extended (CLAVR-X)[5] model and then used as inputs to the Fast All-sky Radiation Model for Solar applications (FARMS) model for clear-sky and cloudy-sky radiation calculations. The PSM is used for the current NSRDB covering North, Central, and parts of South America. Physical models such as the PSM can assimilate additional information content from future satellites (such as GOES-16) to improve solar radiation estimates. We will therefore use the PSM approach for future updates to the NSRDB.

[5] AVHRR: advanced very-high-resolution radiometer

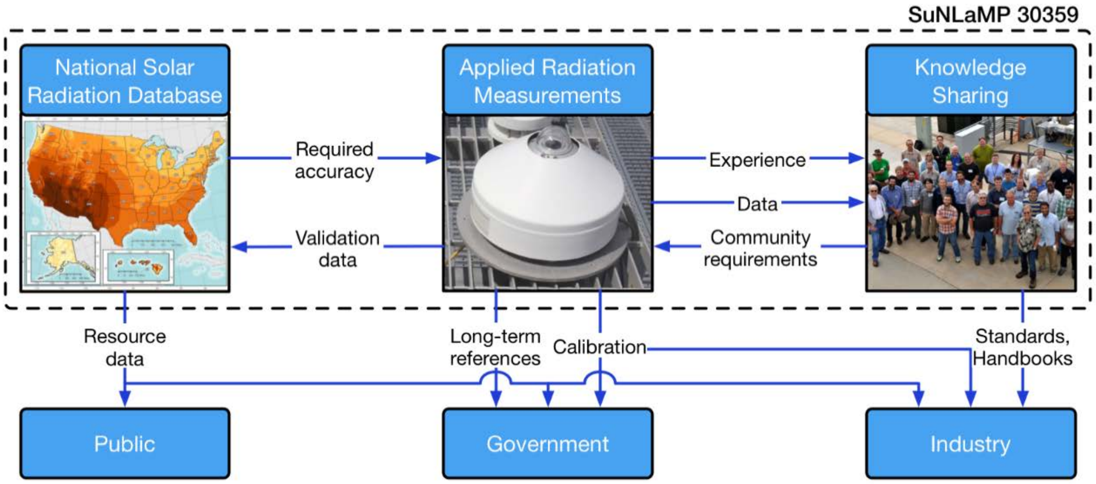

Figure 1. Activities enabling the development of standards, best practices, and national databases. *Images by NREL*

2 Project Objectives

The project supported and enabled DOE's SuNLaMP goals in making solar energy fully cost-competitive with traditional energy sources. The work described in this project supported SuNLaMP goals as follows:

- Shorten the amount of time needed to move promising new solar photovoltaic (PV) and concentrating solar power (CSP) technologies from development to commercialization by providing the calibrated hardware, infrastructure, and software required for the design and testing of new technologies.
- *Increase efficiency, reduce production costs, and open new markets for solar energy* by providing high-resolution resource data for the United States and internationally that enable and give increased confidence for system design and deployment.
- *Foster collaboration for utility-scale solutions and clear the way for high-penetration solar* by increasing the accuracy of resource data to reduce financing costs and providing information about the variability of solar resources during shorter timescales to enable cost-effective grid integration and management.
- *Strengthen the U.S. supply chain for solar manufacturing and commercialization of cutting-edge solar technologies* by providing instrumentation and software to test generating technologies and providing test facilities for new sensor technologies.
- *Invest in education, policy analysis, and technical assistance to remove critical barriers* through stakeholder engagement in measurement and modeling activities by disseminating accurate data and providing expert advice to industry and stakeholders through outreach and standards development.
- Develop a well-trained workforce to foster U.S. job creation in the solar industry by providing training to industry in the area of solar resource assessment.

Table 1. Summary of Milestones and Go/No-Go Decision Points

FY	Milestone	Go/No-Go
2016	An ASTM standard for “integration of digital spectral weather data for weathering applications” will be developed, balloted, and published. Calibration certificates for all instruments deployed in the BMS are available, ensuring that data available via the MIDC is of known and traceable accuracy and uncertainty.	Produce regular updates to the existing NSRDB by adding the most currently completed full year of half-hourly solar and meteorological data (2015) for the spatially uniform 4-km x 4-km grid of the continental United States and make the data publicly available through the NSRDB website.
2017	Update the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications* and publish as a freely available report. Calibration certificates for all instruments deployed in the BMS are available, ensuring that data available via the MIDC is of known and traceable accuracy and uncertainty. Collect and analyze information on the use of SRRL facilities for research and its interdependencies, including information on instruments deployed in the BMS. Collect and analyze information on the NSRDB process and usage as well as data production and dissemination by other government agencies.	Produce regular updates to the existing NSRDB by adding the most currently completed full year of half-hourly solar and meteorological data (2016) for the spatially uniform 4-km x 4-km grid of the continental United States and make the data publicly available through NSRDB website.
2018	Provide traceable, ISO-accredited fundamental measurement and calibration of solar resource measurement by conducting the NREL Pyrheliometer Comparison. Complete development of ASTM standard on classification of radiometers, including balloting and addressing negative comments as part of the consensus process. Calibration certificates for all instruments deployed in the BMS are available, ensuring that data available via the MIDC is of known and traceable accuracy and uncertainty.	Produce regular updates to the existing NSRDB by adding the most currently completed full year of half-hourly solar and meteorological data (2017) for the spatially uniform 4-km x 4-km grid of the continental United States and make the data publicly available through NSRDB website.

3 Project Results and Discussion

3.1 Task 1: Applied Solar Radiation Measurements

3.1.1 National and International Pyrheliometer Comparison

Every 5 years, the Physikalisch-Meteorologisches Observatorium Davos World Radiation Center (PMOD/WRC) in Davos, Switzerland, hosts an International Pyrheliometer Comparison (IPC) for transferring the World Radiometric Reference (WRR) to participating radiometers. Representing DOE, NREL staff participated in the 12th IPC (IPC-XII) from September 28, 2015–October 16, 2015. During the event, 134 participants with 157 instruments from 32 countries attended. NREL's participation maintains the traceability to WRR for U.S. industry, academia, and other national and international organizations. The WRR is the internationally recognized standard for direct normal irradiance measurements of broadband solar radiation, essential for compliance with ISO/IEC 17025[6] accreditation requirements to demonstrate inter-laboratory proficiency testing. NREL has been participating in the IPC events since 1980. Figure 2 demonstrates that the 5 cavity radiometers in use at NREL have stable calibrations with an average change of 0.06% compared to the responsivities from the previous IPC, which was conducted in 2010.

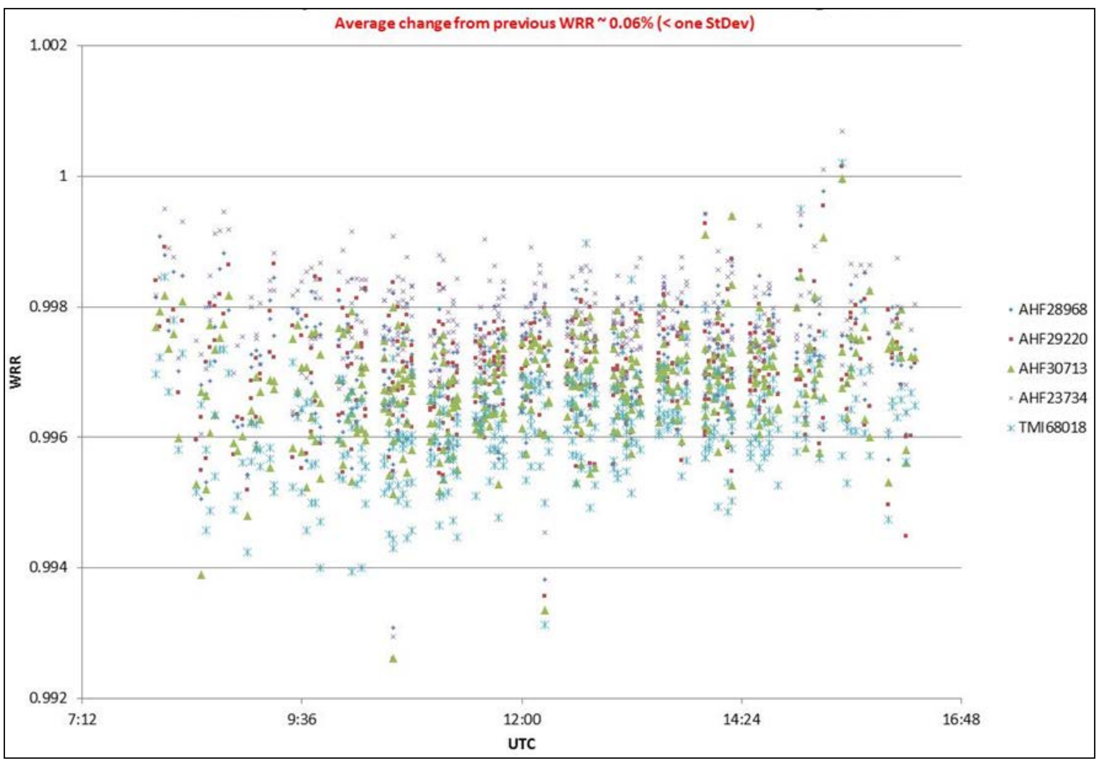

Figure 2. WRR values for NREL reference cavities during IPC-XII

[6] International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 17025:2005: General Requirements for the Competence of Testing and Calibration Laboratories

To disseminate the capability to obtain and maintain high-quality solar radiation data sets, NREL organizes the NREL Pyrheliometer Comparisons (NPC) every year for the non-IPC years (Figure 3). As a result, NREL has developed and maintained a select group of absolute cavity radiometers with direct calibration traceability to the WRR (Reda 2017a). These instruments are used by NREL to transfer WRR calibration to other radiometers used and owned by industries. During the NPC, participants from many national and international agencies participate to retain radiometer calibration traceability to the WRR. Some of these include NREL, Sandia National Laboratories, NOAA, NASA, DOE's Atmospheric Radiation Measurement Program, Brookhaven National Laboratory, Lockheed Martin, Dset Laboratories, Directorate General Joint Research Centre's Institute for Energy and Transportation—Renewable Energy Unit, GroundWorks Renewables, Inc., and PMOD Technologies. After each NPC, NREL publishes the result of this comparison as a technical report.[7]

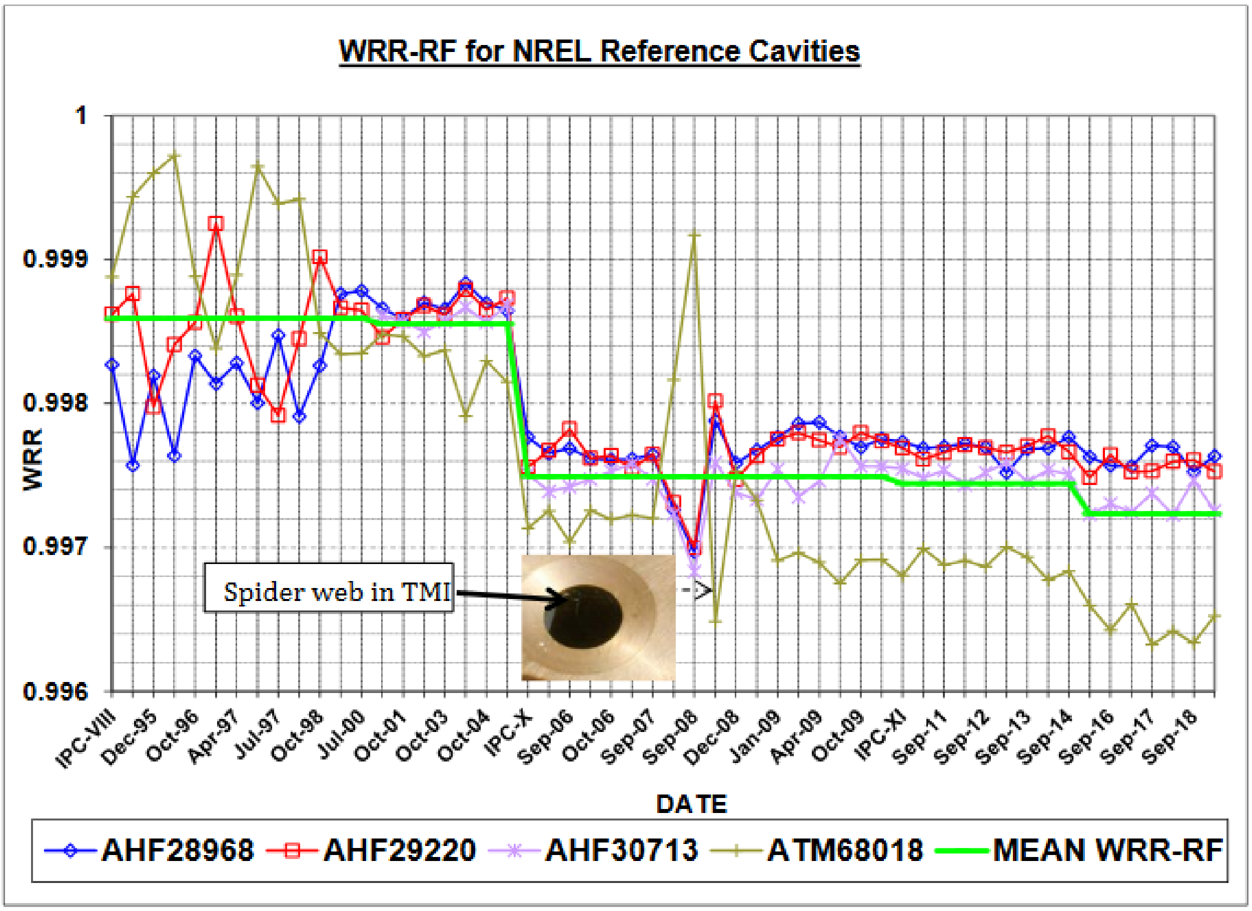

Figure 3. History of WRR reduction factors for NREL reference cavities. ***Figure from Reda et al. (2018)***

[7] See https://www.nrel.gov/docs/fy19osti/72607.pdf.

3.1.2 Development and Status of Absolute Cavity Pyrgeometer

The downwelling longwave irradiance is traceable to the World Infrared Standard Group (WISG) of pyrgeometers, which consists of four pyrgeometers. Since 2004, the WISG had been providing uniformity to atmospheric downwelling longwave radiation measurements; however, additional work was needed to establish traceability to the International System of Units. This is necessary to integrate longwave irradiance with broadband irradiance. NREL and other national and international organizations were working to develop a new downwelling longwave irradiance standard. The devices in the development include the absolute cavity pyrgeometer (ACP) by NREL, infrared integrating sphere (IRIS), and atmospheric emitted radiance interferometer.

NREL continues to upgrade the hardware and software of the ACP. This upgrade assists in having a fully automated system. When it was developed, it was run manually, and the data were post-processed after measurement. The ACP is a patented instrument that was developed by NREL in an effort to establish a world reference for atmospheric longwave irradiance measurement and ultimately substitute the current WISG, which comprises a set of windowed pyrgeometers that have significantly higher uncertainty than instruments such as the ACP.

NREL participated in multiple pyrgeometer comparisons. Table 2 shows a comparison among the ACP, the WISG, and the IRIS. The Table shows that the WISG has significant differences when compared to the ACP and IRIS. Because the WISG consists of a group of windowed pyrgeometers, it is apparent that they are biased when compared to the absolute cavity instruments.

Table 2. Results of the ACP, IRIS, and WISG from the First to Fifth International Pyrgeometer Comparisons (Reda et al. 2018)

W/m^2	First	Second	Third	Fourth	Fifth
Average difference between ACPs&IRISs	0.10	0.31	-1.17	-1.58	-1.77
StDev of Difference	0.08	0.65	0.70	1.15	0.88
Difference within 95%	0.19	1.34	1.82	2.79	2.50
Average of ACPs&IRISs - WISG	3.93	6.14	3.82	3.50	6.50
StDev of Difference	0.97	0.76	0.67	0.81	0.66
Difference within 95%	4.38	6.33	4.05	3.86	6.63

3.1.3 Broadband Outdoor Radiometer Calibration

The Broadband Outdoor Radiometer Calibrations (BORCAL) procedure is used to calibrate pyranometers and pyrheliometers outdoors using the sky and sunbeam irradiance as the reference source. This unique calibration procedure was developed by NREL staff using peer-reviewed reports and journal articles (Reda 1996; Reda et al. 2005; Reda, Stoffel , and Myers 2003; Reda, Myers, and Stoffel 2008; Reda and Andreas 2004; Stoffel and Reda 2009; Reda 1996; Reda et al. 2008; Habte, Sengupta, and Reda 2015; JCGM 2008). NREL conducts active research to improve the BORCAL procedure. The BORCAL procedure is then used to provide calibration services both within NREL and outside the lab.

BORCAL assists in:

- Achieving consistent performance results, regardless of the sensor model or data processing scheme, with accurate and quantifiable uncertainties and risk
- Engaging industry and sensor manufacturers on instrumentation requirements
- Quantifying uncertainties in measured data
- Supporting national solar resource measurement networks through formal arrangements with other federal agencies, universities, and the private sector
- Without BORCAL:
    - Traceability of radiometric data would not be maintained and reduced uncertainty of radiometric data would not be attained, which would then have a direct impact on SETO goals.
    - It would cost DOE/NREL more than the current budget to calibrate/ship the radiometers and maintain the existing NREL-SRRL radiometric setup.

During the project period (2016–2018), BORCAL was carried out in compliance with ISO/IEC 17025 accreditation for 482 radiometers (Figure 4 and Table 3). These radiometers came from NREL, various labs, and industry. Further, during this period, NREL upgraded the radiometer calibration and characterization software to improve the BORCAL configuration, expand radiometer internal temperature sensor support, and add a longwave data export feature.

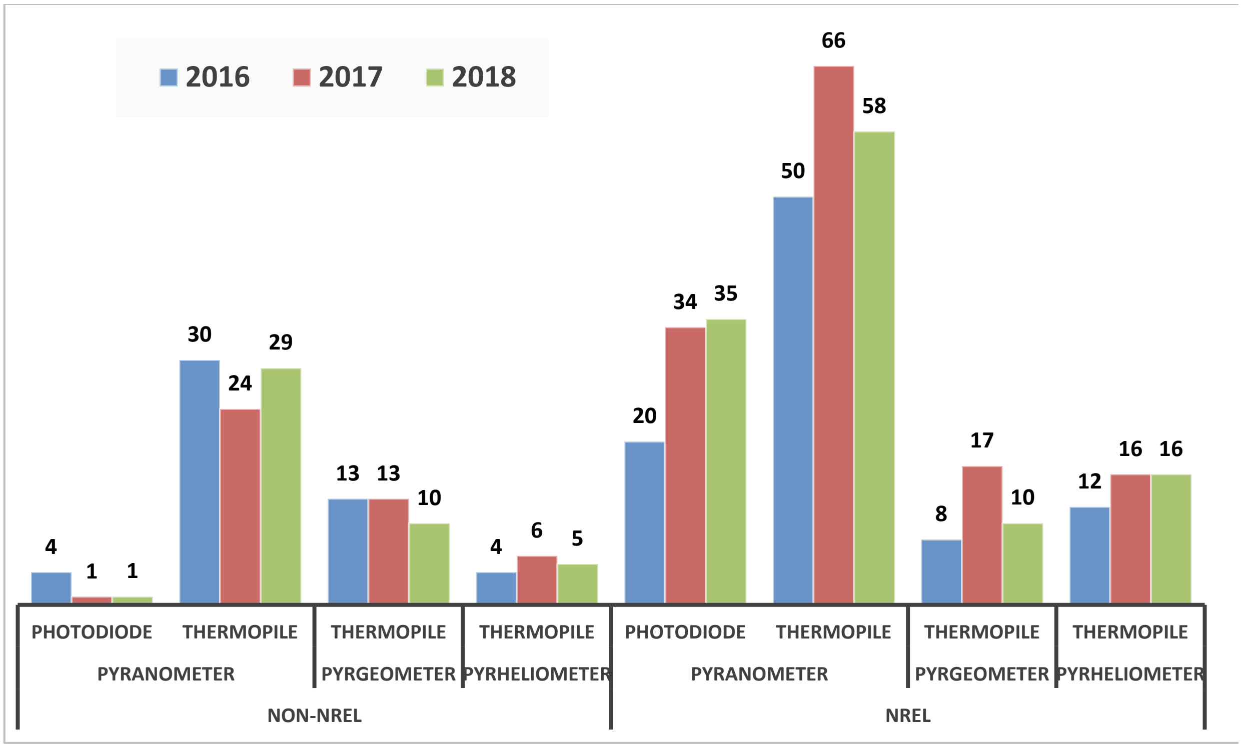

Figure 4. Total number of radiometers calibrated during 2016–2018. The table shows the

Table 3. Summary Result of the Number of Calibrations Performed During 2016–2018

Count of Model	Column Labels			
Row Labels	2016	2017	2018	Grand Total
Non-NREL	**51**	**44**	**45**	**140**
Pyranometer	**34**	**25**	**30**	**89**
Photodiode	4	1	1	6
Thermopile	30	24	29	83
Pyrgeometer	**13**	**13**	**10**	**36**
Thermopile	13	13	10	36
Pyrheliometer	**4**	**6**	**5**	**15**
Thermopile	4	6	5	15
NREL	**90**	**133**	**119**	**342**
Pyranometer	**70**	**100**	**93**	**263**
Photodiode	20	34	35	89
Thermopile	50	66	58	174
Pyrgeometer	**8**	**17**	**10**	**35**
Thermopile	8	17	10	35
Pyrheliometer	**12**	**16**	**16**	**44**
Thermopile	12	16	16	44
Grand Total	**141**	**177**	**164**	**482**

3.1.4 Support NREL and Industry Partners on Providing Calibration Services of Spectral Measuring Devices

The NREL Optical Metrology Laboratory is responsible for spectral calibrations, field measurements, instrumentation troubleshooting/repair, and consultation. The laboratory has the ability to provide field measurements to non-NREL customers at their facility under the Metrology Services Agreement for a fee. In mid-2000, the laboratory developed an in-house, unique, one-of-kind, spectroradiometer system called the Pulse Analysis Spectroradiometer

System (PASS), which can measure the spectrum from pulse solar simulators. Pulse simulators are commonly used today because they have much lower power requirements, do not increase the temperature of the PV test device, and can produce high-intensity flashes (several hundred times the intensity of the sun). Unfortunately, there is not an off-the-shelf spectroradiometer that can measure these light sources with all the needed functionality and accuracy as that provided by the PASS. As a result, industry has often been seeking NREL's assistance for measurements of pulse solar simulators. Through the years, under technical services agreements, NREL has built two additional PASS instruments: one for Spire Solar and one for Newport Corporation.

For this project period, the laboratory has maintained the National Institute of Standards and Technology (NIST) traceable calibration with reduced uncertainty for many spectroradiometers to support optical solar simulator characterizations for NREL and industry, such as Sandia National Laboratories and the University of Oregon. A summary of the number of instruments calibrated is provided in Figure 5.

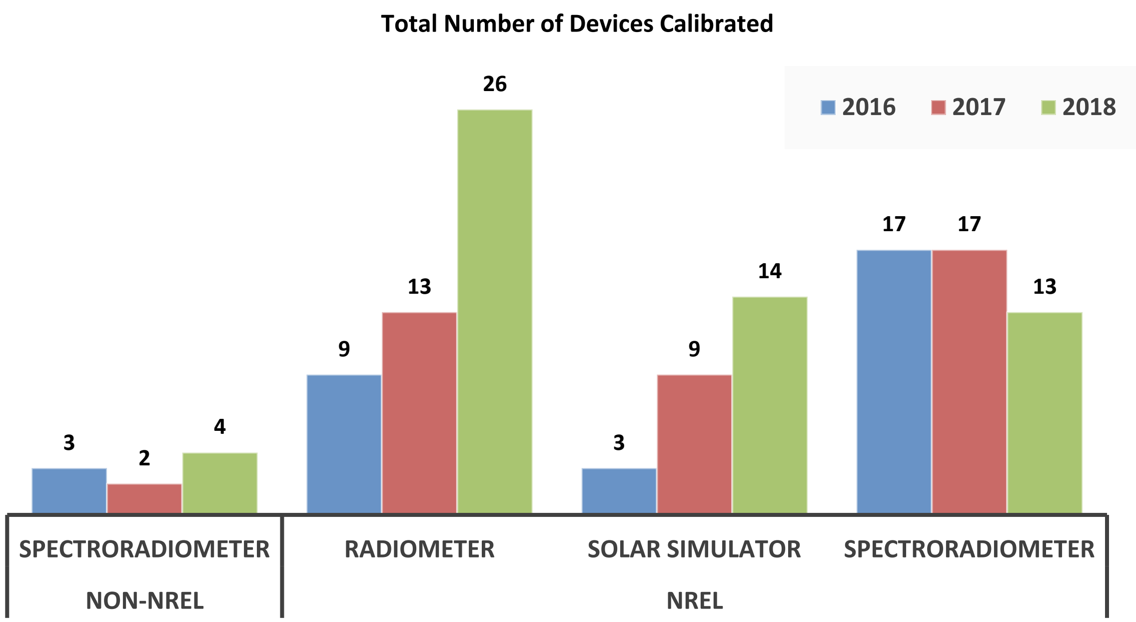

Figure 5. Total number of spectral devices calibrated during Fiscal Year 2016–2018

3.1.5 Cooperative Research and Development Agreement

1. NREL, through a cooperative research-and-development agreement (CRADA), has worked with Arable Labs to install, operate, calibrate, and maintain a low-cost sensor for solar resource assessments at the SRRL for demonstrating the ease of installation, system value to stakeholders, and validation of measurement accuracy by comparison with existing instruments in the BMS.

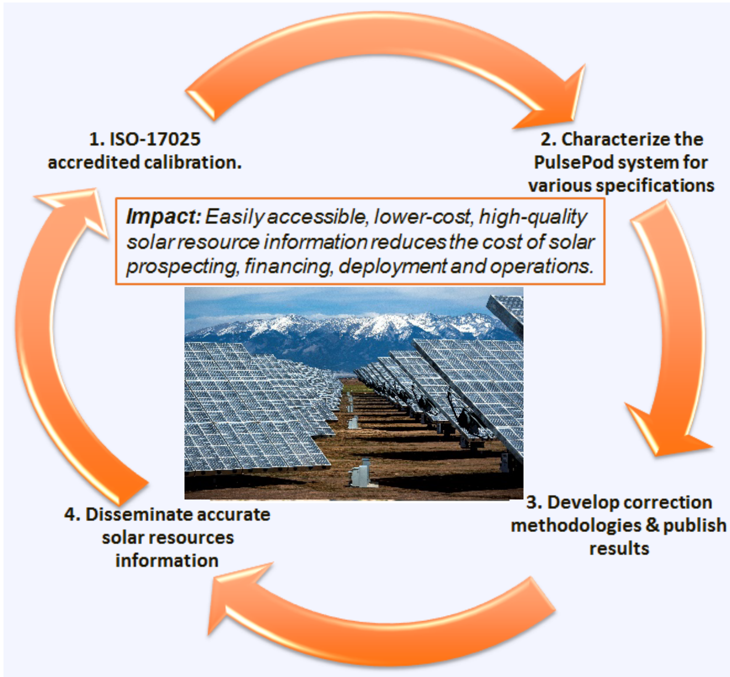

Figure 6. Workflow for calibrating and characterizing Arable Labs' low-cost sensor using the SRRL's BMS for solar resource assessments. ***Photo by Dennis Schroeder, NREL 30542-C***

2. Through a CRADA, NREL continues to work with EKO Instruments to test new instruments and evaluate radiometers deployed at the SRRL. Work conducted under this CRADA includes:

    A. Evaluation of a fast-response pyranometer (MS-80)

    B. A study of various approaches to grounding viewed through the effects observed with subsecond data on the MS-80

    C. Study of rotating shadowband for an MS-711 spectroradiometer

    D. Additionally, evaluation will be conducted with subsecond data collected from the MS-57 instruments.

    Some preliminary results for the MS-80 compared with BMS instruments under various sky conditions (all sky, clear sky, and cloudy sky) show good agreement with high-quality pyranometers. The cost of the MS-80 is about 50% less than the high-quality pyranometers. Figures 7 and 8 shows the comparison of multiple radiometers. The MS-80 shows less than 2% bias compared to the reference data, which are the component sum of direct and diffuse measurements from our highest quality instrument set. The direct measurements are from an EKO Instruments CHP1, and the diffuse measurements are from an Eppley 8-48.

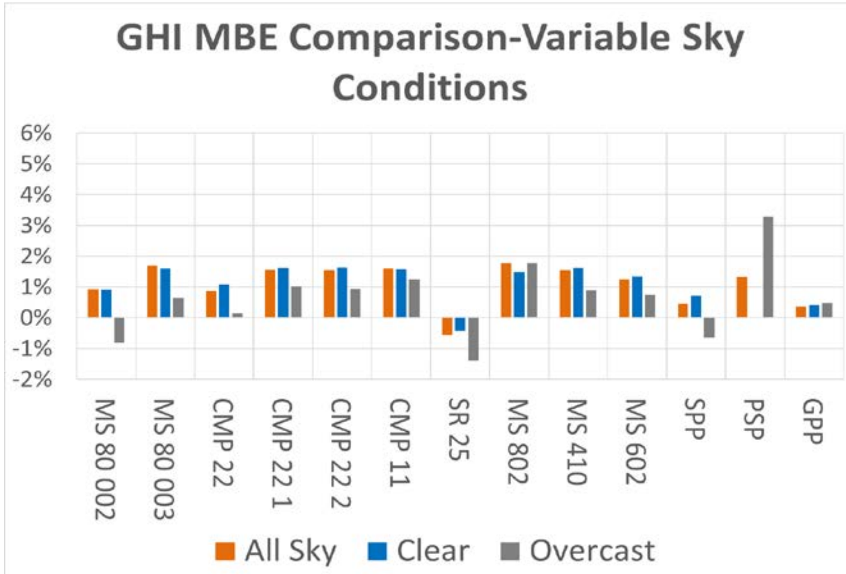

Figure 7. GHI MBE comparison under various sky conditions

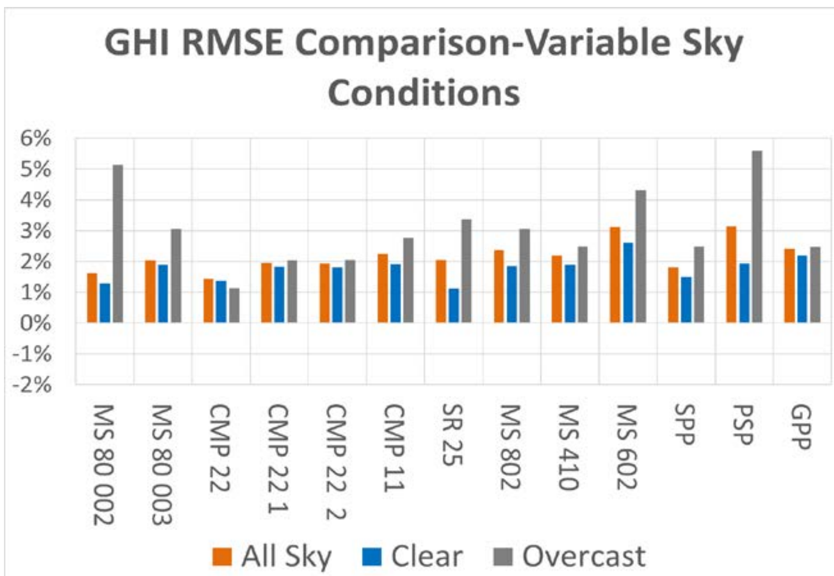

Figure 8. GHI comparison using RMSE under various sky conditions

3. Kipp & Zonen has developed a new all-in-one solar monitoring instrument, the RaZON+. The RaZON+ accurately measures both DNI and diffuse horizontal irradiance (DHI) from the sun and sky, enabling it to provide very reliable values of GHI and sunshine duration. Kipp & Zonen partnered with NREL under the NREL Commercialization Assistance Program to install the RaZON+ at NREL's SRRL so that it is collocated with the reference instruments from the SRRL and can be operated under a controlled maintenance schedule. Under the agreement, the SRRL will monitor the performance of the RaZON+, particularly how its performance compares under difference weather conditions and under different maintenance regimes (e.g., daily cleaning, no cleaning, modified cleaning schedule). NREL is working with Kipp & Zonen to evaluate the data and produce a report describing how it performed from a data quality standpoint and an

instrument performance standpoint. If we discover improvements that can be made, NREL's SRRL staff will work with Kipp & Zonen to implement and test those improvements. Moreover, Kipp & Zonen would like to conduct additional calibrations at NREL and plans to use the south pad of the SRRL and a couple of our trackers to do these calibrations. This requires minimal NREL effort and is funded by Kipp & Zonen.

4. AccuFlux CRADA. Through this CRADA, NREL and AccuFlux developed a framework to conduct research and develop new radiometric devices and supporting equipment to provide more accurate, site-specific, long-term, continuous measurements of the solar resources needed by industry to reduce deployment costs and improve the operations of PV and CSP plants.[8]

   The deployment of the AccuFlux system was a success, having fully assessed the overall system and tracker design. The result showed an objective performance of the system:

   A. 2AT solar tracker long-term reliability and tracking accuracy
   B. Radiometer long-term stability
   C. 2AT solar tracker system AC power year-round with DC power backup operational effectiveness for current battery and panel sizing
   D. Accurate back-calculation of global and diffuse measurements relative to the NREL SRRL BMS best radiometers (CM22 and 8-48 reference shaded/diffuse) data, via subtraction of the 2AT system temp-corrected DR03 pyrheliometer converted 1-minute average. DHI signal data from the SR20 temp- and directional response-corrected 1-minute average and GHI signal data.

3.1.6 Data Quality Reporting

Evaluating the performance of PV cells, modules, and arrays that form large solar deployments relies on accurate measurements of the available solar resource. Therefore, determining the accuracy of these solar radiation measurements provides a better understanding of investment risks. This becomes especially important as deployment size and investment costs increase to hundreds of millions of dollars. The accuracy of measurements is also important for acceptance testing and operations. NREL maintains a suite of the highest quality solar radiation measurement systems that are maintained following the best practices for industry (Sengupta et al. 2017). These instruments provide a continuous stream of research quality data for baseline research through the continuous application of data-quality evaluation using NREL's SERI QC software (Maxwell, Wilcox, and Rymes 1993). SERI QC defines ranges of acceptable data, depending on whether one, two, or all three GHI, DNI, and DHI elements are present. Ranges are defined based on dimensionless parameters normalized with respect to extraterrestrial radiation, where:

- Kt = Clearness index or global horizontal transmittance
  = Global horizontal radiation/extraterrestrial horizontal radiation
- Kd = Diffuse horizontal transmittance
  = Diffuse horizontal radiation/extraterrestrial horizontal radiation

[8] See https://www.nrel.gov/docs/fy18osti/71837.pdf.

- Kn = Direct normal transmittance
  = Direct normal radiation/extraterrestrial direct normal radiation.

Overall, the quality assessment tool demonstrates less than 5% of the data with lower quality (Figure 9).

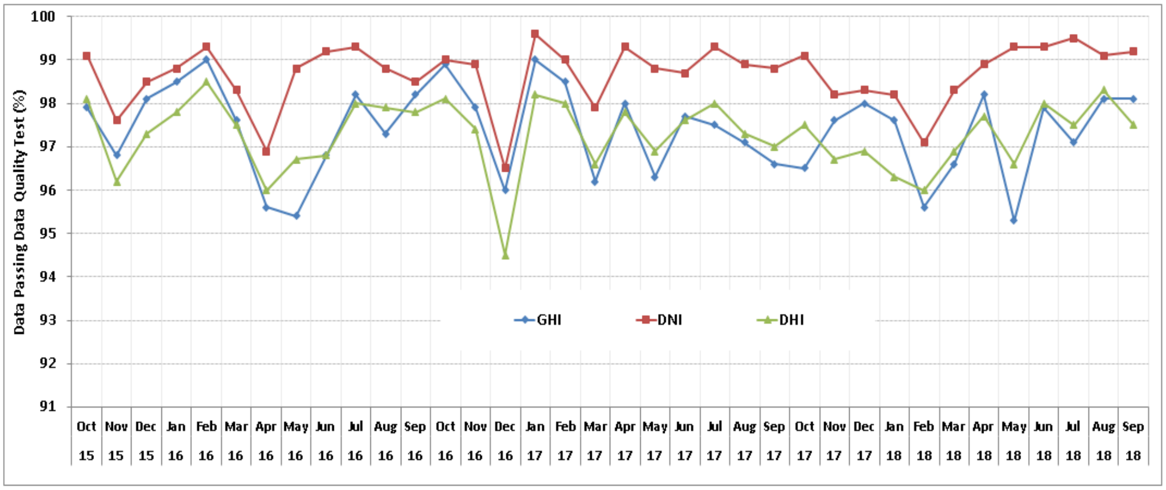

Figure 9. Monthly MIDC data passing data quality test in percentages

3.1.7 Data Dissemination

NREL continued to disseminate solar resource information using the MIDC and Renewable Resource Data Center (RReDC) websites.[9,10] RReDC and the MIDC continue to be among the most visited sites at NREL, with nearly 200,000 users and more 120,000 unique users annually, or more than 1 user per second. The data and models available from these portals enable all stakeholders to easily access information for improving the quality and reducing the cost of projects.

3.1.8 Measurement Research and Publications

1. NREL published an article in the *Solar Energy* journal about the performance of 51 commercially available and prototype radiometers used for measuring GHI or DNI.[11] The performance and accuracy of these radiometers are essential for determining system efficiencies of solar energy conversion installations, developing improved satellite-based models for estimating solar resources, and validating solar radiation forecasts. The study included pyranometers, pyrheliometers, rotating shadowband radiometers, and a pyranometer with an internal shading mask deployed at the SRRL. Figures 10 and 11 show the results of the study under all-sky conditions. The statistical measure used here is mean bias difference (MBD), which is the same as mean bias error (MBE), and the two are interchangeable in the document. The study assists in differentiating the similarities and differences among DNI and GHI measuring radiometers when compared to the

[9] See https://midcdmz.nrel.gov/.
[10] See https://www.nrel.gov/grid/solar-resource/renewable-resource-data.html.
[11] See http://www.sciencedirect.com/science/article/pii/S0038092X16300184.

reference data set with the lowest estimated measurement uncertainties of the corresponding measurement type. The study identified significant improvements in newer radiometers. Increasing numbers and sizes of solar energy conversion systems have created more opportunities and demands for improvements to radiometry within the industry. Under these circumstances, various manufacturers of radiometers are working to improve instrument performance and harmonizing the methodology for acquiring radiometric data. These improvements are based on customer feedback; government research (NREL, NOAA, NIST, et al.); international standards development groups, such as ISO, ASTM International, and International Energy Agency (IEA) Task 46; and the needs/requirements of the solar and utility industries. The focus on improvement in radiometer design has been to identify the significant contributors to uncertainty and change instrument design and manufacturing accordingly.

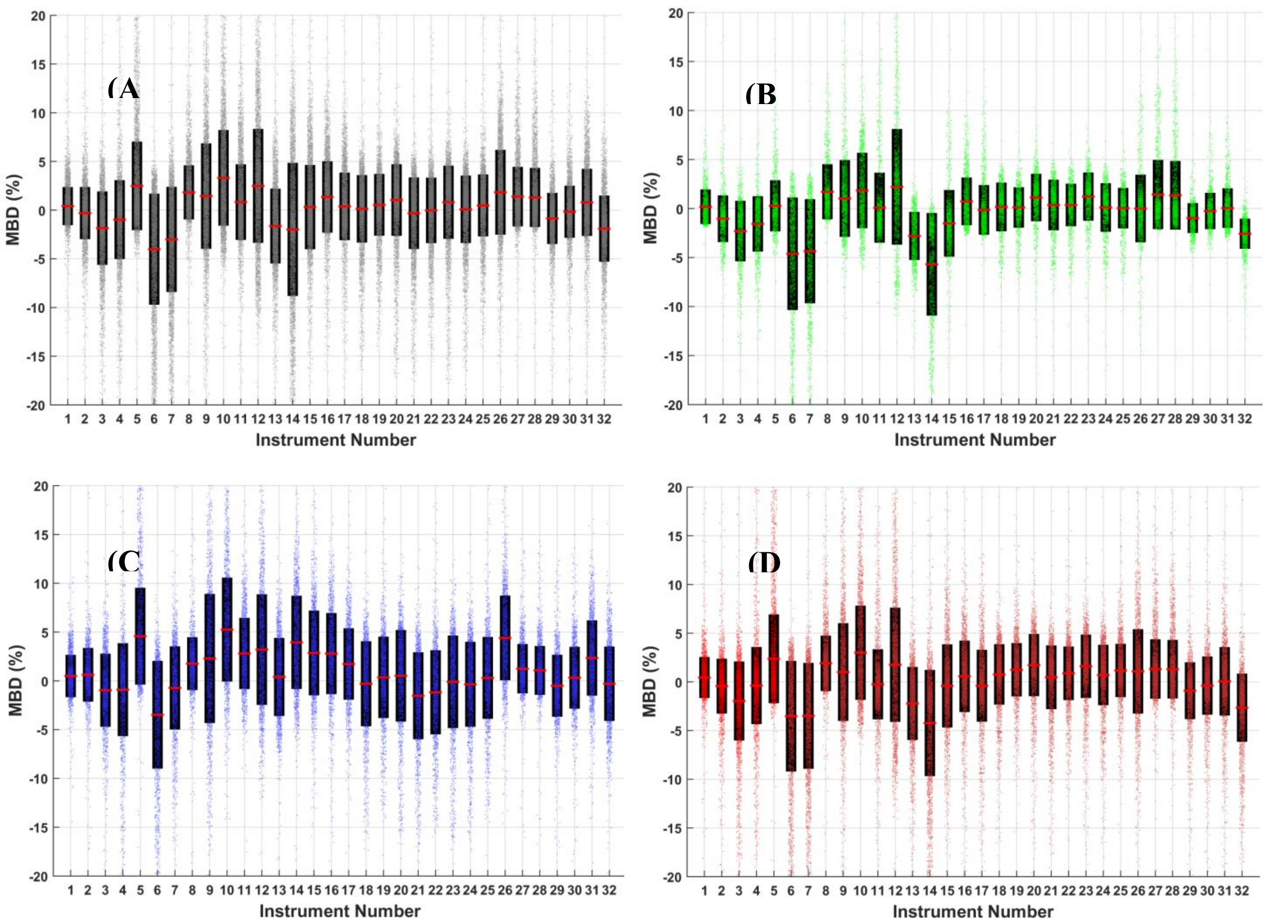

Figure 10. MBD in percentage for the hourly averaged GHI data under study: (A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky. The horizontal red line signifies the mean value of the MBD for the data that fall within the 95% confidence interval (black color box). ***Figure from Habte et al. (2016b)***

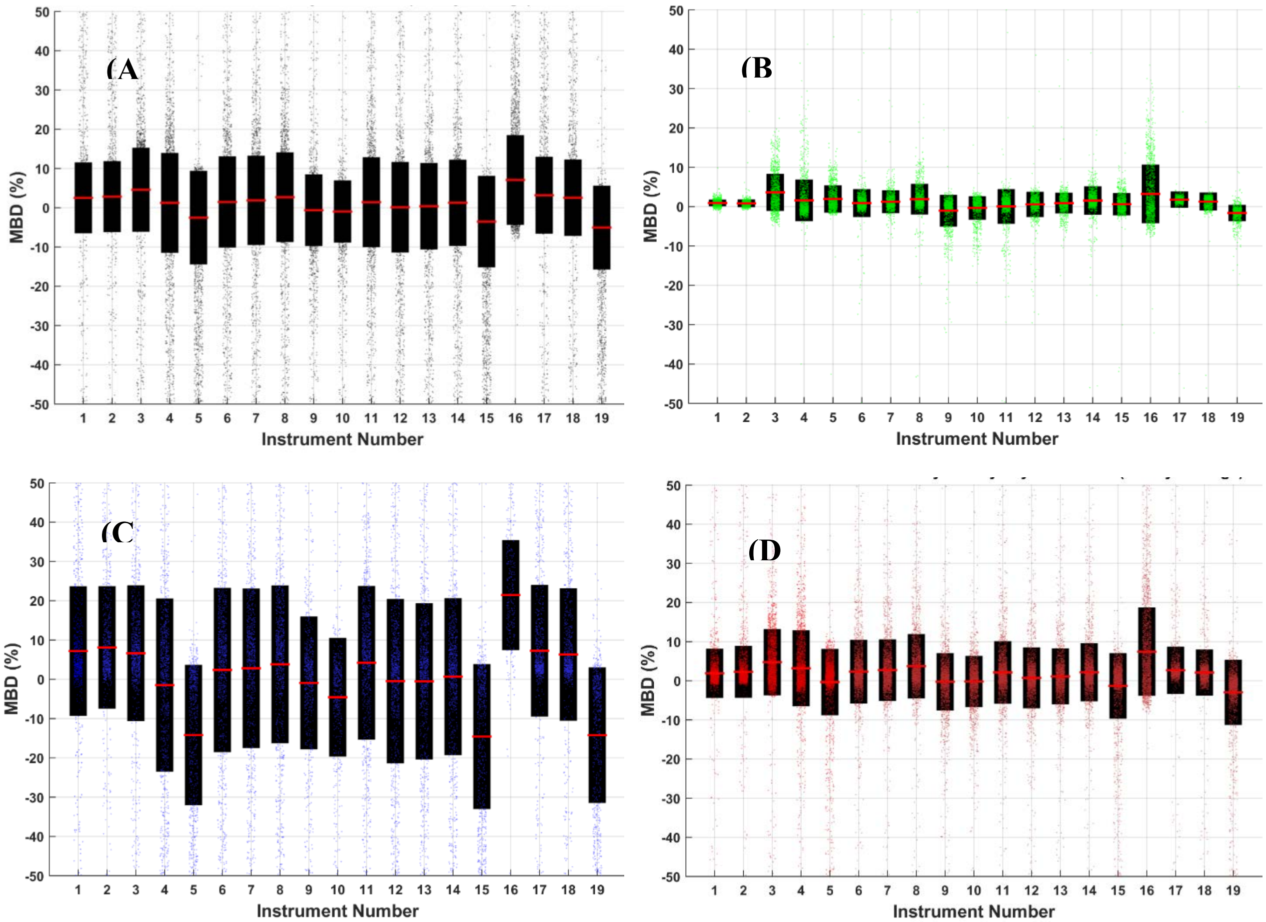

Figure 11. MBD in percentage for the hourly average for all DNI data under study: (A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky. The red line signifies the mean value of the MBD for the 95% confidence level. *Figure from Habte et al. (2016b)*

2. NREL published a journal article in *Progress in Photovoltaics* on "Radiometer Calibration Methods and Resulting Irradiance Differences." This study addresses the effect of calibration methodologies and the resulting calibration responsivities provided by radiometric calibration service providers such as NREL and manufacturers of radiometers. Improved calibration of radiometers based on consensus methodology will help reduce the uncertainty of resource measurements for solar energy power plants, reducing the cost of financing those plants and thus potentially reducing the cost of electricity from such facilities.

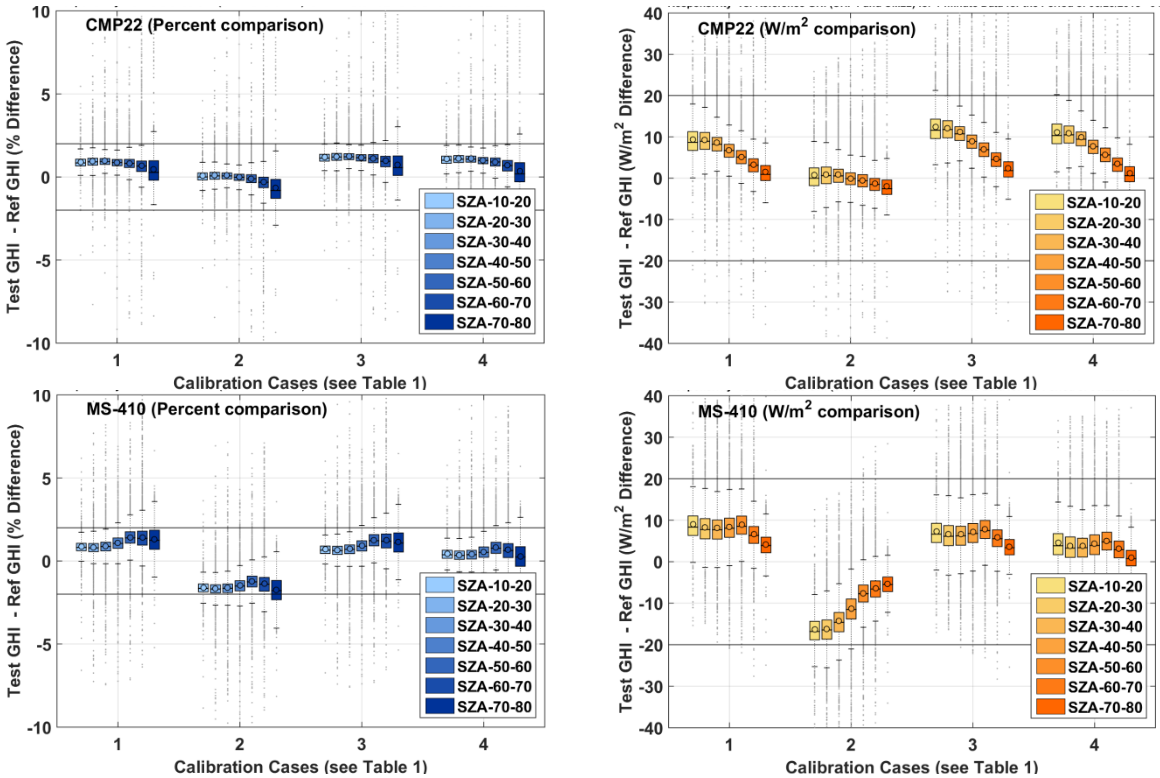

Figure 12. Comparison between manufacturer's supplied calibration responsivity and NREL's calibration responsivity under clear skies, differences in both percentages and W/m^2. *From Habte et al. (2016a)*

"Note: Each blue and orange box represents a 10-degree bin, and it also represents the upper quartile and the lower quartile (also called an "interquartile range") of the data in each bin. The circle in each blue box is a mean, and the black line signifies the median value. Ninety-nine percent of the data set is within the whiskers; beyond the whiskers is plotted with a symbol (dots)" (Habte et al. 2016a)

3. NREL published an article in *Journal of Atmospheric and Oceanic Technology*, "Significant Improvements in Pyranometer Nighttime Offsets Using High-Flow DC Ventilation," in collaboration with the Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Earth System Research Laboratory, Boulder, Colorado.

   Ventilators are used to keep the domes of the pyranometers clean and dry, but they affect the nighttime offset as well. This paper examines different ventilation strategies. For the several commercial single-black-detector pyranometers with ventilators examined here, high-flow-rate (50-cfm and higher), 12-VDC fans reduce the offsets, reduce the scatter, and improve the predictability of the offsets during the night compared with lower-flow-rate 35-cfm, 120-VAC fans operated in the same ventilator housings (example result is shown in Figure 13). Black-and-white pyranometers sometimes show improvement with DC ventilation, but in some cases DC ventilation makes the offsets slightly worse.

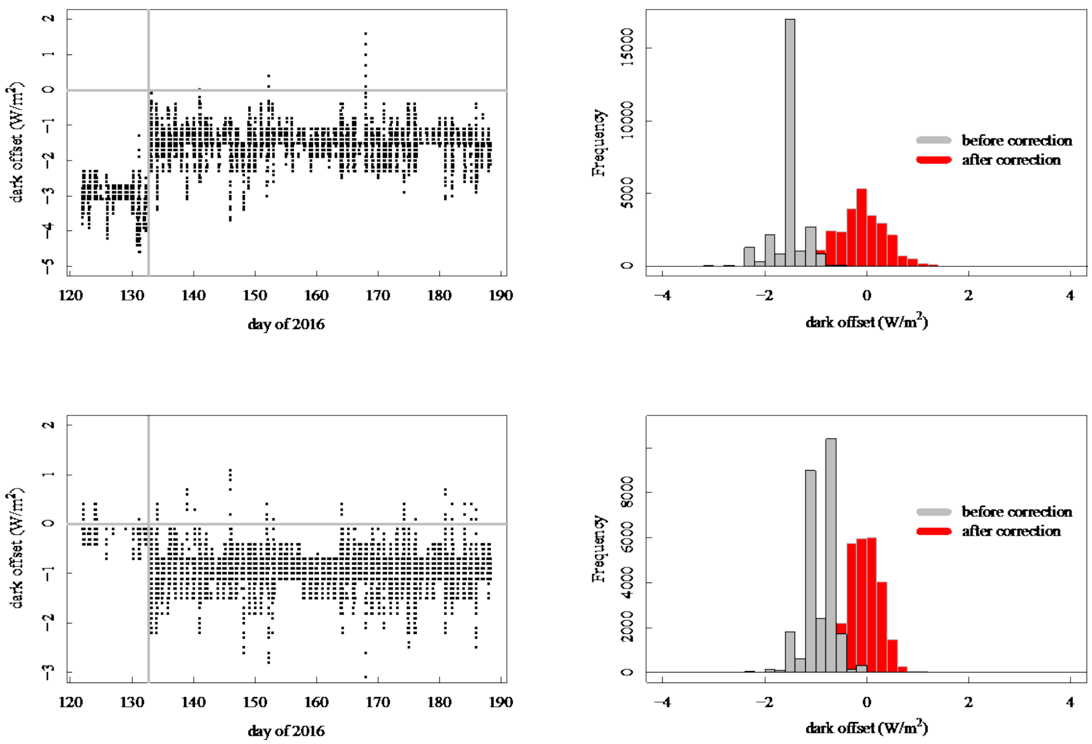

Figure 13. Top left: Plot of SpectraSun pyranometer dark offsets before and after switching to DC ventilation on Day 133. Top right: The gray histogram is for the offsets after Day 133 but before the correction; the red histogram is for the offsets after Day 133 after a correction based on a linear fit of offset versus instrument net infrared forced through zero at zero net infrared irradiance. *From Michalsky, Kutchenreiter, and Long (2017)*

4. NREL's Metrology Laboratory and Sensing and Predictive Analytics group performed a study and published a paper in the *Atmospheric and Climate Sciences* journal on reducing calibration biases caused by longwave irradiance in the reference direct beam.[12] Shortwave radiometers—such as pyranometers, pyrheliometers, and PV cells—calibrated with traceability to a consensus reference, maintained by absolute cavity radiometers (ACRs). The ACR is an open cavity with no window that measures the extended broadband spectrum of the terrestrial direct solar beam irradiance, unlike shortwave radiometers that cover a limited range of the spectrum. The difference between the two spectral ranges might lead to calibration bias that can exceed 1%. This article describes a method to reduce the calibration bias resulting from using broadband ACRs to calibrate shortwave radiometers by using an ACR with Schott glass window to measure the reference broadband shortwave irradiance in the terrestrial direct solar beam from 0.3 µm to 3 µm. The experimental setup is shown in Figure 14.

[12] See https://www.scirp.org/Journal/PaperInformation.aspx?PaperID=73462.

Figure 14. Setup of shaded and unshaded pyrgeometers to measure the longwave irradiance in solar beams. ***From Reda et al. (2017a), photo by Mark Kutchenreiter, NREL***

5. NREL published a paper in collaboration with the University of Oregon in the *Solar Energy* journal that outlines a methodology to determine the uncertainty of a spectroradiometer that is consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) method has been published. This methodology is applicable to all spectroradiometers and is not specific to a particular instrument. Moreover, the methodology aims to characterize the uncertainties of a spectroradiometer in the laboratory under conditions that resemble those in the field. Specifically, tests on the deviation from the true cosine response (Figure 15) and the temperature sensitivity of the instrument are added to the uncertainties typically considered when calibrating a spectroradiometer.[13]

[13] See https://www.sciencedirect.com/science/article/pii/S0038092X17302591.

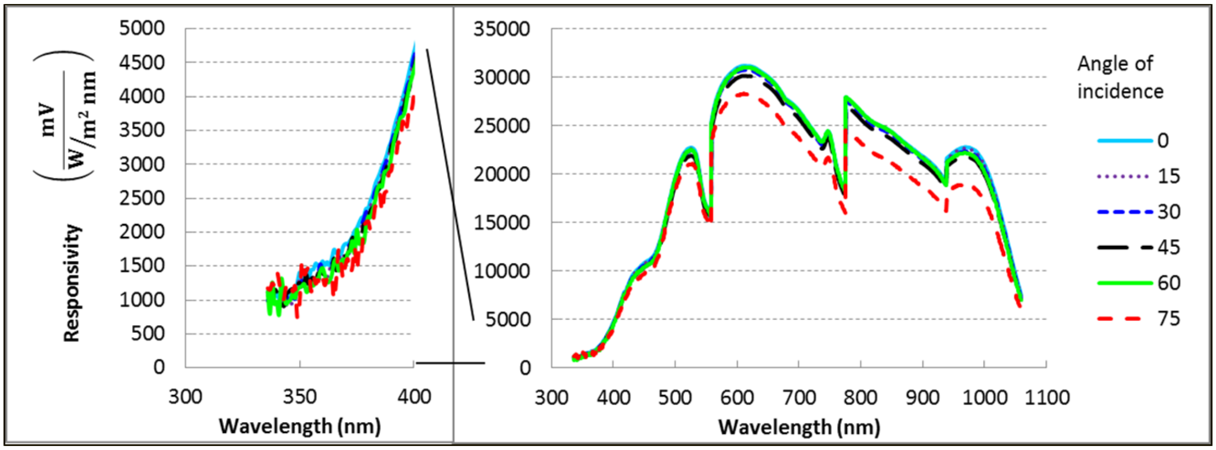

Figure 15. Responsivity compared to wavelength for various angles of incidence. The responsivity is nearly constant as the angle of incidence changes. Only when the angle of incidence is increased to 75°is there a noticeable change in the responsivity compared to the other angles. A detailed view of the wavelengths from 300–400 nm is shown in the left panel. *From Peterson et al. (2017)*

3.2 Task 2: National Solar Radiation Data Base

With the increasing adoption of PV solar panels for energy production by both utility-scale and residential customers, in 2012 DOE chose to develop a gridded solar resource data set covering the entire United States for use by DOE researchers. It was also decided that this data set would be made available to the public for free, which would enable the widespread deployment of PV and CSP. This data set would become the latest version of NREL's NSRDB. A physics-based approach was developed to produce the data set that paved pathways to scientific improvement and adoption of information from newer satellites to reduce uncertainty in the solar resource information.

The PSM is a physics-based solar irradiance model developed by NREL in collaboration with the University of Wisconsin, NOAA, and Solar Consulting Services. PSM uses a two-step process where cloud properties are retrieved using the clouds from the CLAVR-X model and then used as inputs to the FARMS model (Xie, Sengupta, and Dudhia 2016) for clear- and cloudy-sky radiation calculations. The PSM is used for the current NSRDB covering North America and Central America. Physical models such as the PSM can assimilate additional information content from future satellites (GOES-R) to improve solar radiation estimates.

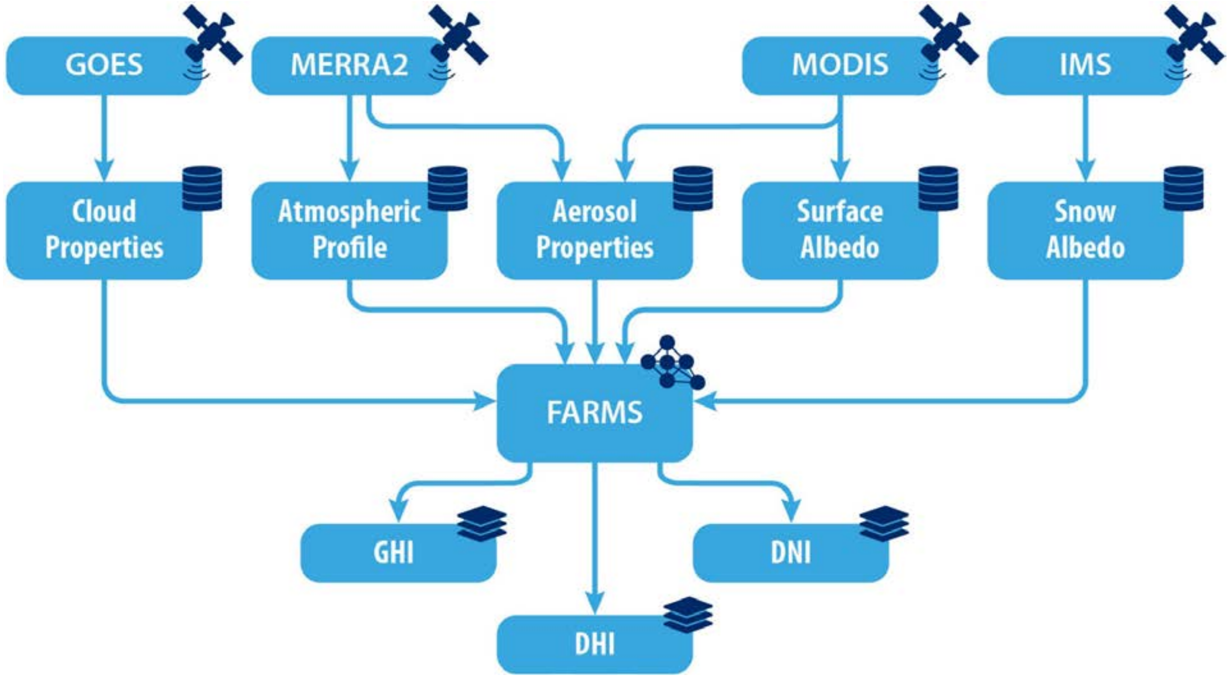

Figure 16. A flowchart of the NSRDB PSM model

NSRDB Version 3 is a spatially resolved time-series database of solar irradiance data for North America, Central America, and parts of South Asia.[14]

Following are the steps taken to process the NSRDB V3 data using the PSM:

1. Acquisition of calibrated and navigated geostationary cloud property data from two satellites

   NREL, in collaboration with NOAA and the University of Wisconsin, acquired the GOES-West and GOES-East 1998–2017 data set. The data set provided by the University of Wisconsin includes cloud properties such as cloud optical depth, cloud type, and cloud mask at a 4-km x 4-km spatial resolution and half-hourly temporal resolution.

2. An aerosol dataset and ancillary data sets were obtained from MERRA-2.

   NREL, in collaboration with Solar Consulting Services, investigated the MERRA-2 aerosol data set for the North and South American continents. The data set was used in the PSM model to estimate solar radiation in clear-sky situations. The data set was adjusted for elevation and interpolated to the NSRDB grid. Hourly aerosol optical depth (AOD) estimates are produced for each pixel.

3. NREL mapped cloud properties, aerosol, and meteorological data to the NSRDB grid at a 4-km half-hourly resolution through various physically consistent interpolation techniques.

[14] See http://nsrdb.nrel.gov.

The AOD data set is being mapped to the static grid. The cloud properties delivered from University of Wisconsin in the native satellite grid had been mapped to the NSRDB grid.

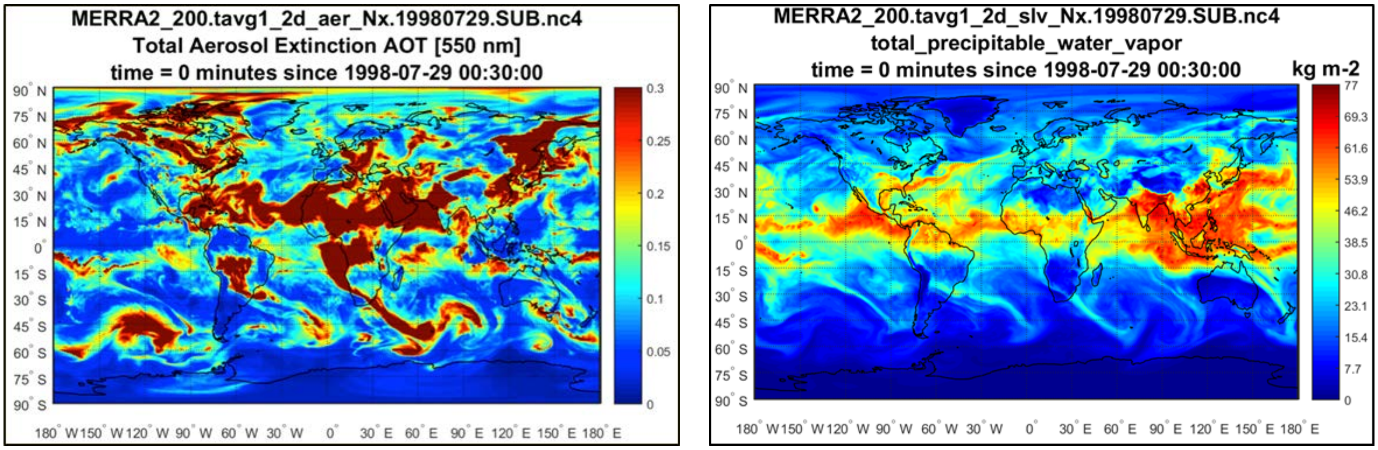

Figure 17. MERRA-2 sample AOD and precipitable water data

4. NREL implemented gridded cloud properties, aerosols, and meteorological information in REST2 (clear-sky radiative transfer model) and FARMS (cloudy-sky radiative transfer model) to calculate solar radiation (GHI and DNI).

5. NREL filled missing values and merged data from two satellites to create seamless 30-minute solar radiation updates.

   The satellite data have gaps as a result of transmission errors, satellite/instrument ageing, malfunction, and the eclipse periods in the spring and fall, so NREL implemented highly parallelized algorithms to fill the existing time gaps in the satellite data. Further, NREL set up a framework to blend the satellite images. The satellite images originate from two satellites GOES-East and GOES-West, with the dividing line between 105º and 110º west longitude.

6. NREL validated a new product using surface measurements.

   And evaluation of the new NSRDB data set was carried out using high-quality ground stations. The spatial and temporal differences between the ground-measured and satellite-derived data sets were analyzed. The ground measurements were averaged to hourly values centered at the satellite time stamp. This serves two purposes: (a) to convert a point measurement to a representation of a finite area covered by a satellite pixel and (b) to provide a half-hourly average estimate that the satellite data are meant to represent.

   Further, NREL developed a consensus uncertainty methodology to assess the differences between the surface measurement and the NSRDB data. Setting up a uniform benchmark is essential to improving the existing satellite-derived data or creating other satellite-based methods to improve the underlying uncertainties.

7. NREL developed summary products such as typical meteorological year using the 20-year NSRDB record.

8. NREL updated the geographic information system-based NSRDB portal to deliver all time-series and statistical summary data including the development of new layers. NREL also updated the website documentation to reflect changes in the model/data.
9. NREL provides a response to users of the NSRDB in user forums and through email and disseminates and publicizes the NSRDB through webinars and conference publications.
10. NREL analyzed user data to understand the NSRDB's user base (organization, frequency of use, volume of data transferred, geographic areas with highest number of downloads, etc.) as a function of time (quarterly or annually).

3.2.1 Changes in National Solar Radiation Database from Version 2 to Version3

During the years, the NSRDB has been updated to meet the increasing demand for solar resource data at a high spatiotemporal resolution for solar conversion systems. Such resource information is needed from the conceptual phase to routine solar power plant operation. Recently, NREL released the gridded NSRDB (1998–2017) based on NSRDB Version 3 of the PSM. The NSRDB data sets contain gridded solar irradiance—DNI, GHI, and DHI—at a 4-km by 4-km spatial resolution and half-hourly temporal resolution covering 20 years. Details on the model and the data set are available at the NSRDB website.[15] Additional details about the development of the NSRDB are also available in (Xie, Sengupta, and Dudhia et al. 2016; Sengupta et al. 2018. Relative to NSRDB Version 2, in the current version of the NSRDB (developed using PSM Version 3), NREL implemented major changes in the meteorological input and processing. Hourly variables, such as AOD or precipitable water vapor, are now extracted from NASA's MERRA-2 (Gelaro et al. 2017). These variables are particularly important to correctly evaluate DNI under clear-sky conditions. Additionally, downscaling methodologies to match the lower resolution MERRA-2 data (0.5 x 0.625°) to the high-resolution 4-km NSRDB grid were redesigned to improve the accuracy in the ancillary variables, such as precipitable water vapor, AOD, temperature, pressure, and relative humidity. In parallel, the information from GOES-East satellite data requires being shifted in time to produce data at the top and middle of the hour. Whereas PSM Version 2 (used in the NSRDB Version 2) shifted the solar radiation directly using a parametric model, PSM Version 3 (used in the NSRDB Version 3) shifts the cloud products derived from GOES-East and uses those properties to compute solar radiation at the correct time. More importantly for DNI calculations, NSRDB Version 2 used monthly averaged AOD, whereas NSRDB Version 3 uses hourly AOD from MERRA-2.

3.2.2 Improved PATMOS-x Algorithm for Retrieving Satellite Cloud Properties

The current PATMOS-x algorithm version will retire because it is not capable of processing GOES-R data. GOES-R, which is the first of the next generation of GOES satellites, was launched in November 2016. Upon successful launch, GOES-R was renamed GOES-16, and after a 12-month deployment and checkout period was moved to the East position and became operational. In an effort to be immediately prepared for processing GOES-16 data, the 2016 data were processed with a newer GOES-R-ready version of PATMOS-x. The University of Wisconsin analyzed a week during May 2016 with both versions to inform algorithm impact changes, particularly in daytime cloud optical and microphysical properties.

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[15] See https://nsrdb.nrel.gov.

Several differences between the two processed versions of PATMOS-x were noted, though most were small. Perhaps the largest difference is the solar zenith and sensor zenith angle criteria now applied to PATMOS-x optical retrievals. In the latest stable version of PATMOS-x, optical retrievals are not performed for solar zenith or sensor zenith angles above 75°. This is shown in Figure 18. The reason for this change is that it was determined that the quality of the retrievals degraded above 75°. A related change is that solar transmission is set to the missing value for clear skies. In the older version of PATMOS-x, solar transmission was set to 1 in these cases. Application of the cloud mask may be used to account for this change.

Cloud fraction in the newer version of PATMOS-x is slightly higher than that of the previous version. The average difference over the continental United States is on the order of 3%–4%. This corresponds to a decrease in the solar transmission through cloud of about 2%–3% and a decrease in cloud optical depth of around 1. This is likely caused by changes in cloud detection of thin cirrus, which produces more cloud, and which decreases transmission, but much of the additional cloud is optically thin cirrus, which decreases average optical depth. That said, the magnitude of these differences depends on the satellite (GOES-13 versus GOES-15) as well as the time of day the clouds are being observed.

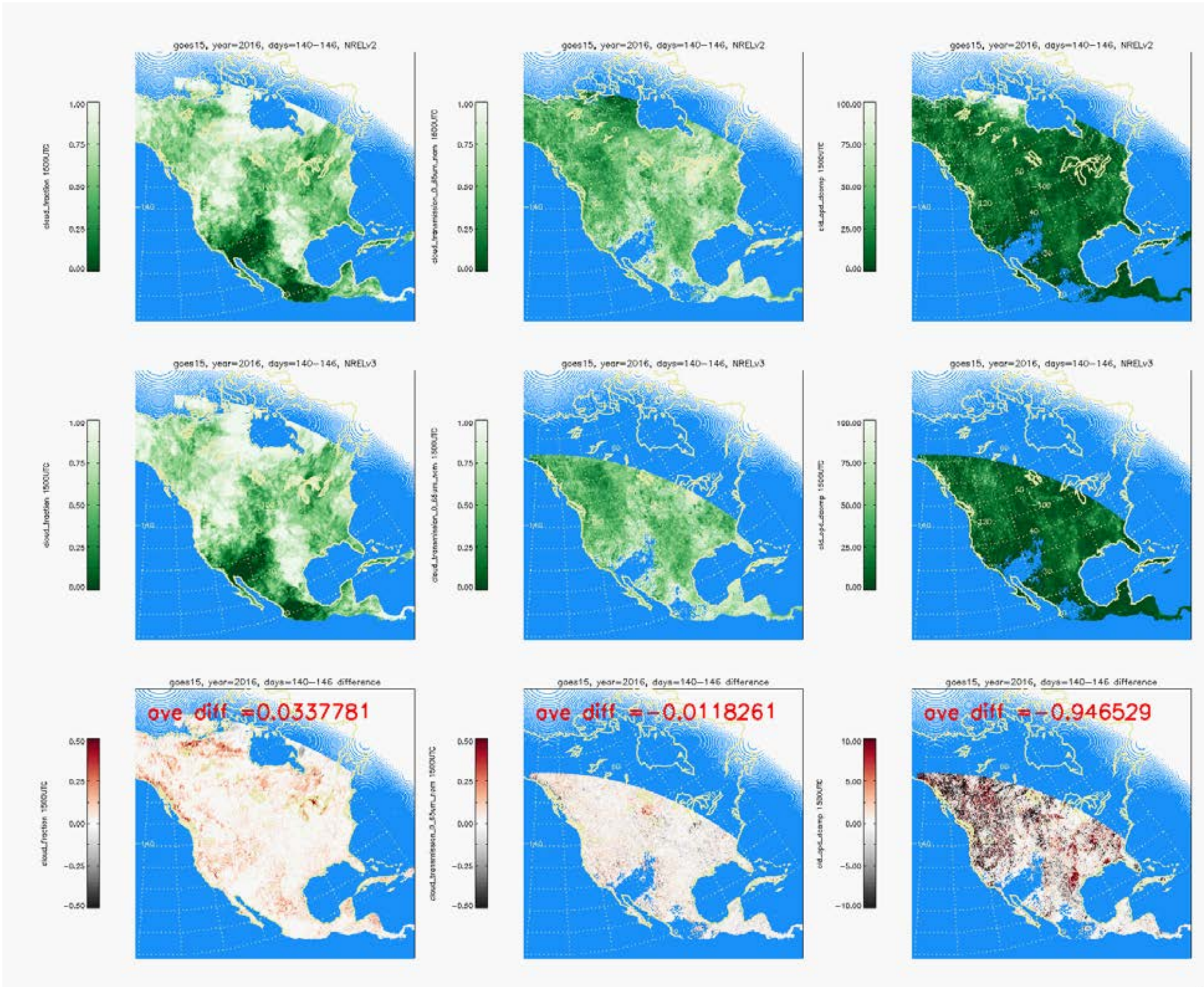

Figure 18. Comparison of NREL historical version of PATMOS-x (labeled NRELv2) and the latest stable release, 'stable_release_2016B' (labeled NRELv3). The first column is cloud fraction, the second is solar cloud transmission, and the third is cloud optical depth. The top row represents NRELv2, the second NRELv3, and the bottom row is the difference between the two. Data are taken from GOES-15 at 1500 UTC from May 19–25.

3.2.3 National Solar Radiation Database Validation

A validation of the performance of NSRDB 1998–2017 Version 3 was conducted to quantify the accuracy and spatial and temporal variability of the solar radiation data. Comparisons of the NSRDB 1998–2017 Version 3 estimates with selected ground-measured data were conducted under both clear- and cloudy-sky conditions and covered the period from 1998–2017 for seven Surface Radiation Budget Network (SURFRAD) stations (Figure 19).

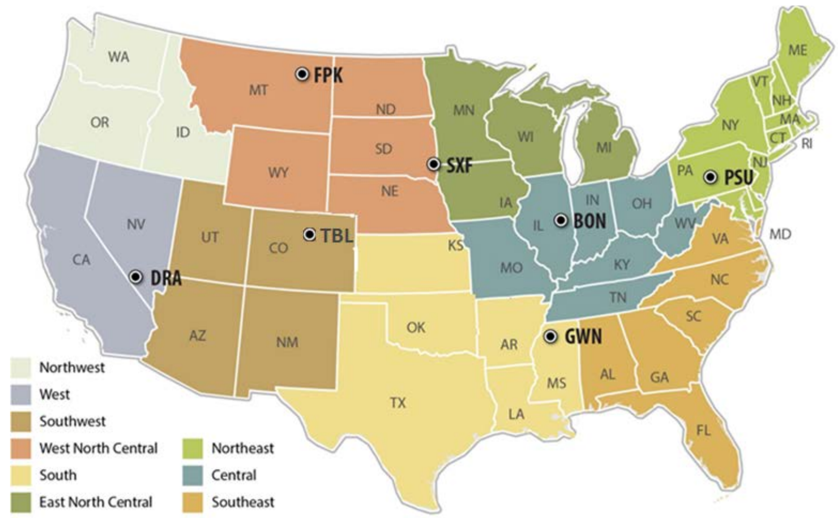

Figure 19. SURFRAD locations overlaid on U.S. climatic regions. ***Image modified from Habte, Sengupta, and Lopez (2017)***[16]

The comparison demonstrates that the difference between the NSRDB and surface measurement is within ± 5% (bias). There is significant reduction in the RMSE. The improvement is assumed to result from a combination of factors, including better downscaling methodologies, particularly in the interpolation and extrapolation used to align the multiple data sets to the same grid, the use of hourly values of aerosol information, and the use of surface albedo instead of interpolated monthly averages.

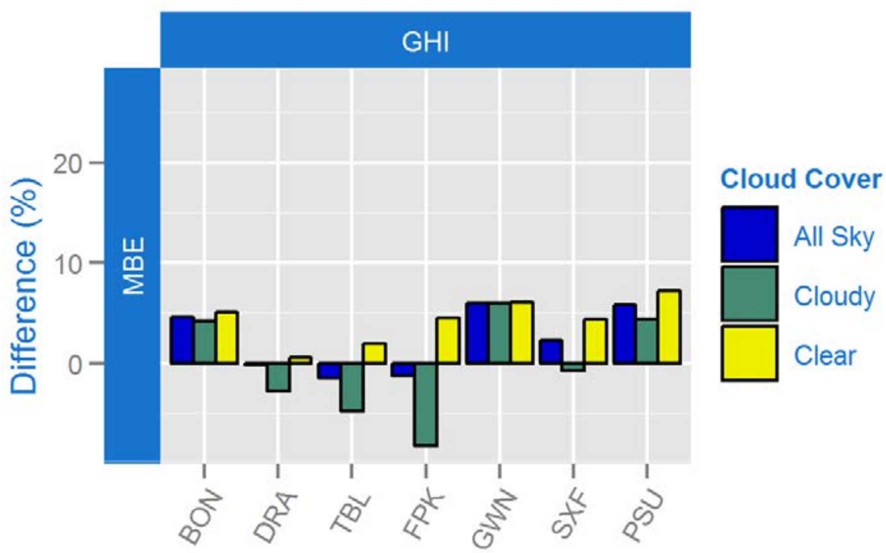

Figure 20. GHI statistical result for seven SURFRAD locations for NSRDB Version 3 (data: 1998–2017)

[16] For more information about the stations, see https://www.esrl.noaa.gov/gmd/grad/surfrad/sitepage.html.

The distribution of irradiance from NSRDB 1998–2017 versus ground measurement under varying sky conditions (Figure 20) shows good agreement. The clear-sky condition demonstrates a close relationship with the measurement.

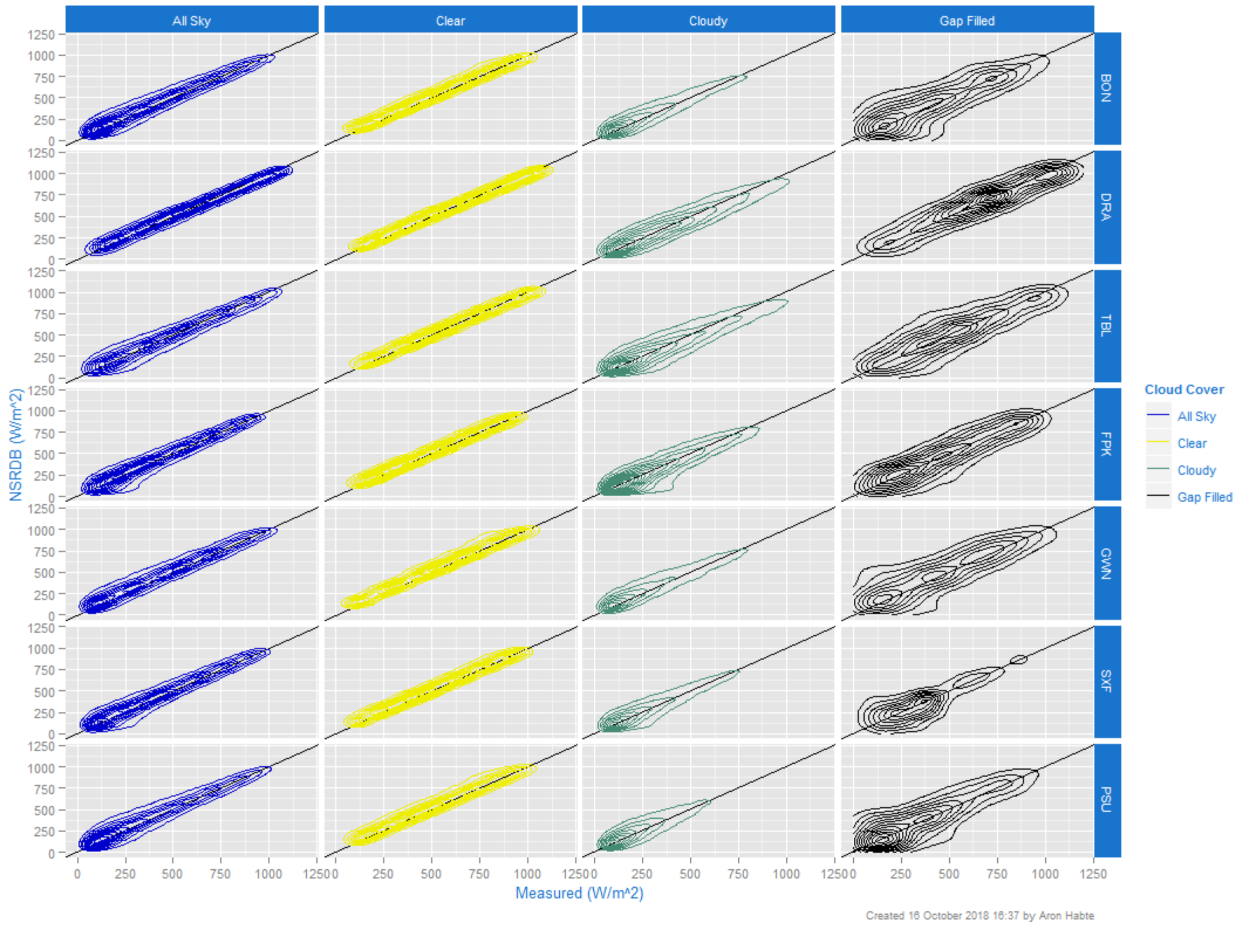

Figure 21. GHI distribution for the seven stations under varying sky conditions

Further, NREL implemented a comprehensive uncertainty determination approach using GUM (JCGM 2008). The approach identifies the source of uncertainties and quantifies standard uncertainties using the measure of statistic for each source. The standard uncertainties are then combined using the root sum squared method (Figure 21). The statistics, such as bias and RMSE, were derived by comparing the NSRDB data to the seven ground measurement stations. The evaluation was conducted for hourly values, daily totals, monthly mean daily totals, and annual mean monthly mean daily totals and demonstrates the quality of the new data sets currently available from the NSRDB (Figure 21).

The hourly data set demonstrated increased uncertainty; however, with increasing average timescales, the uncertainty approaches the measurement uncertainty, e.g., annual. As described in (Habte, Sengupta, and Lopez 2017), one reason for the high uncertainty in the hourly data set is because the NSRDB pixel represents a 4-km by 4-km area, whereas a ground-based solar measurement represents only a small area above the measuring station. The subpixel variability in clouds appears to contribute to increased differences.

The NSRDB Version 3 demonstrates a significant reduction in hourly uncertainty estimations compared to Version 2, as shown in Figure 22. These improvements are clearly noticeable for all locations, especially Desert Rock, Nevada, where the uncertainty was reduced to approximately 12% in NSRDB Version 3 from approximately 18% in NSRDB Version 2.

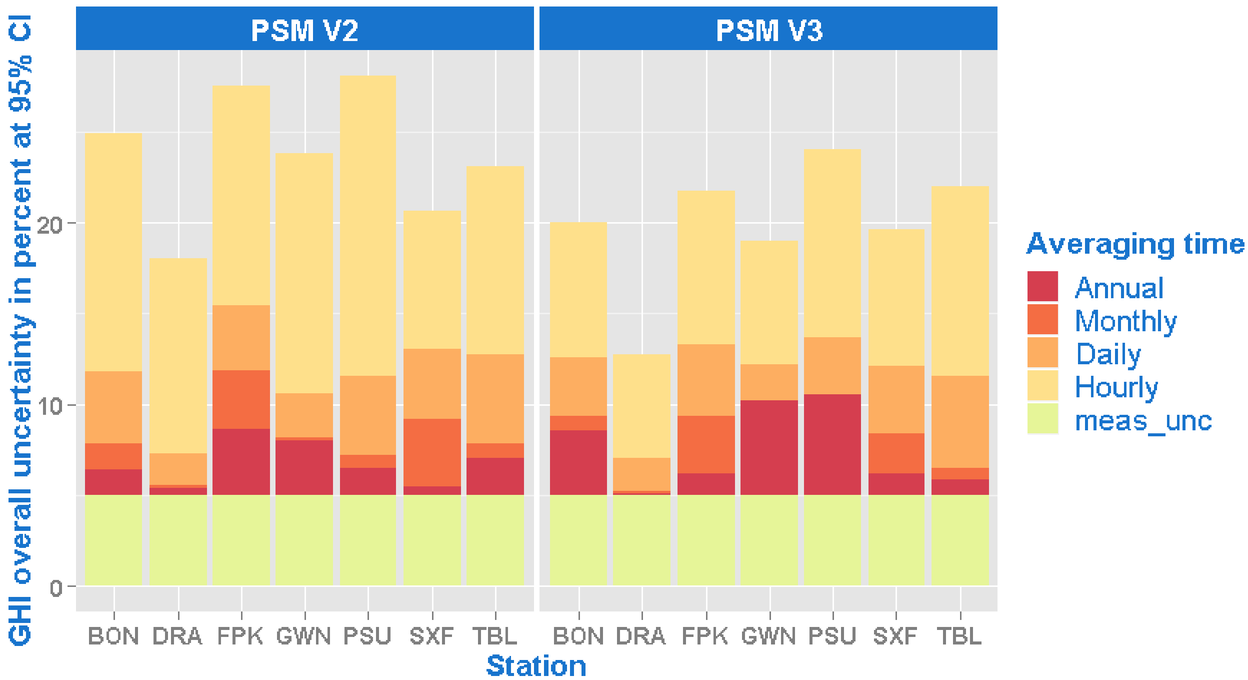

Figure 22. Overall uncertainty estimation of GHI for NSRDB PSM Version 2 (left) and PSM Version 3 (right) using seven ground-based solar measurement locations. Data used in this figure are from 1998–2015 for Version 2 and 1998–2017 for Version 3.

3.2.4 National Solar Radiation Database Users

Industry, labs, and academia outside of NREL also use the NSRDB. Some users include:

- **Industry:** EDP Renewables; First Solar; Southern Company; Suncore Photovoltaics; SolPEG GmbH; Iberdrola; Sono solar; DNV GL; Leidos, Strata Solar; OneEnergy Renewables; kWh Analytics; Lincoln Clean Energy; SunPower; Cypress Creek Renewables; Midwest Renewable Energy Association; GE Energy Consulting; LKS Energy; CFE Mexico; Arizona Public Service; Duke Energy; Sunpath Power & Electric; ISRO; OST Energy; Sunshine Analytics; GRID Alternatives Colorado; Invenergy LLC; Global Weather Corporation; Infinity Renewables; Oregon Department of Transportation; Sol Systems; NRG Energy; Carolina Solar Energy; New Energy Equity; Radian Generation; DOE National Energy Technology Laboratory; American Cancer Society; Black & Veatch; Birdseye Renewable Energy and Academia; White Box Technologies.
- **Academia and research labs:** Lawrence Berkeley National Laboratory; U.S. Bureau of Reclamation; U.S. Air Force; U.S. Army Research Laboratory; National Energy Board Canada, Department of Agricultural Economics; Purdue University; European Commission, Joint Research Centre; VNIT, Nagpur, INDIA; Sandia National

Laboratories; U.S. Energy Information Administration; U.S. Environmental Protection Agency.

3.2.5 Research and Publications

NREL published an article on the NSRDB in *Renewable and Sustainable Energy Reviews*, a high-impact journal with an impact factor of 8.05 and a 5-year impact factor of 9.122. This paper briefly reviews the complete package of surface observations, models, and satellite data used for the latest version of the NSRDB as well as improvements in the measurement and modeling technologies deployed in the NSRDB during the years.[17]

The journal paper discusses the evolution of the NSRDB and states that the data are a widely used public solar resource that have been developed and updated during more than 20 years to reflect advances in solar radiation measurement and modeling. The paper also discusses the current NSRDB model, PSM. Future updates of the NSRDB are expected annually. Advanced information in the planned data set will involve new satellite retrievals for the year 2017 and improved AOD data from MERRA-2. Future advancements in the PSM, however—e.g., identifying low clouds and fog in coastal areas; improving the discrimination of clouds from snow; providing specular reflection on bright surfaces; and reducing uncertainties of parallax, especially under high-resolution conditions—are also desired to further increase the accuracy of the NSRDB.

3.2.6 MODIS-Derived Surface Albedo Data Set for NSRDB

NREL developed an improved white-sky (bihemispherical reflectance) broadband (0.3–5.0 µm) surface albedo data set for use in NSRDB applications using two data sources: (1) the bidirectional reflectance distribution function/albedo product (designated MCD43D) from the MODIS[18] and (2) the Integrated Multisensor Snow and Ice Mapping System (IMS) daily snow cover product.[19,20] The report found that the daily albedo data set provides a significant improvement from climatological products in spatial resolution and representation of the temporal variability of albedo. Although the gap-filled MODIS albedo product provides high-quality estimates of surface albedo, the 8-day temporal resolution does not capture the ephemeral nature of snow cover. Changes in snow cover play a major role in the variability of surface albedo, particularly during months of snow accumulation and ablation (Déry and Brown 2007). Integration of the gap-filled MODIS albedo product and the Integrated Multisensor Snow and Ice Mapping System snow cover data set provide high-quality albedo estimates and fine temporal resolution of snow cover.

[17] See https://www.sciencedirect.com/journal/renewable-and-sustainable-energy-reviews/vol/89/suppl/C.

[18] NASA, Land Processes Distributed Active Archive Center (2015)
[19] National Snow and Ice Data Center (2016)
[20] See www.nrel.gov/docs/fy17osti/67306.pdf.

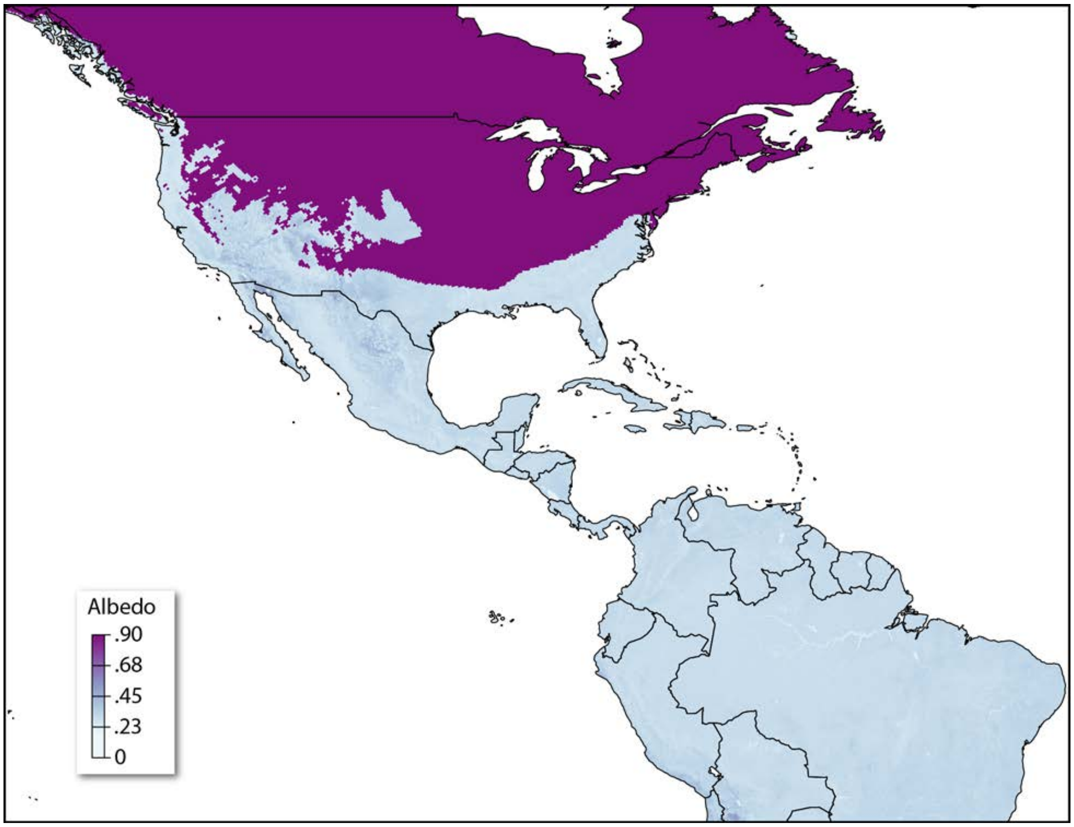

Figure 23. Final data set for January 1, 2001, integrating MODIS-based surface albedo and Integrated Multisensor Snow and Ice Mapping System snow cover. ***From Maclaurin et al. (2016)***

3.2.7 Use Case of NSRDB Data for the August 21, 2017, Total Solar Eclipse

NREL and collaborators have created a clear-sky probability analysis to help guide viewers to the August 21, 2017, total solar eclipse, the first such continent-spanning eclipse in nearly 100 years for the United States (figure 24 and 25). Using cloud and solar data from the NSRDB, the analysis provides cloudless-sky probabilities specific to the date and time of the eclipse. Although not intended to be an eclipse weather forecast, the detailed maps helped guide eclipse enthusiasts to likely optimal viewing locations. Additionally, high-resolution data are presented for the centerline of the path of totality, representing the likelihood for cloudless skies and atmospheric clarity.

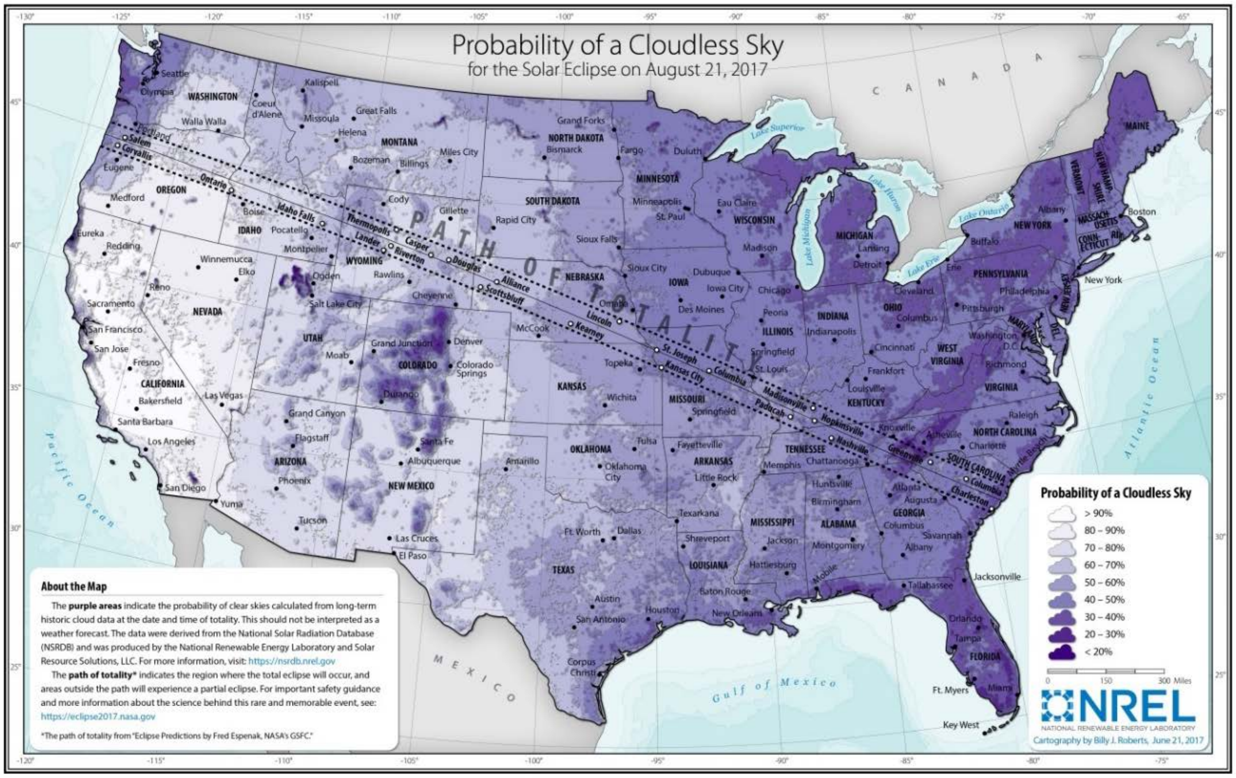

Figure 24. Cloudless-sky probabilities for August 21, 2017, and the path of the total solar eclipse. ***Path of totality from "Eclipse Predictions by Fred Espenak, NASA/GSFC Emeritus." Cartography by Billy J. Roberts, NREL***

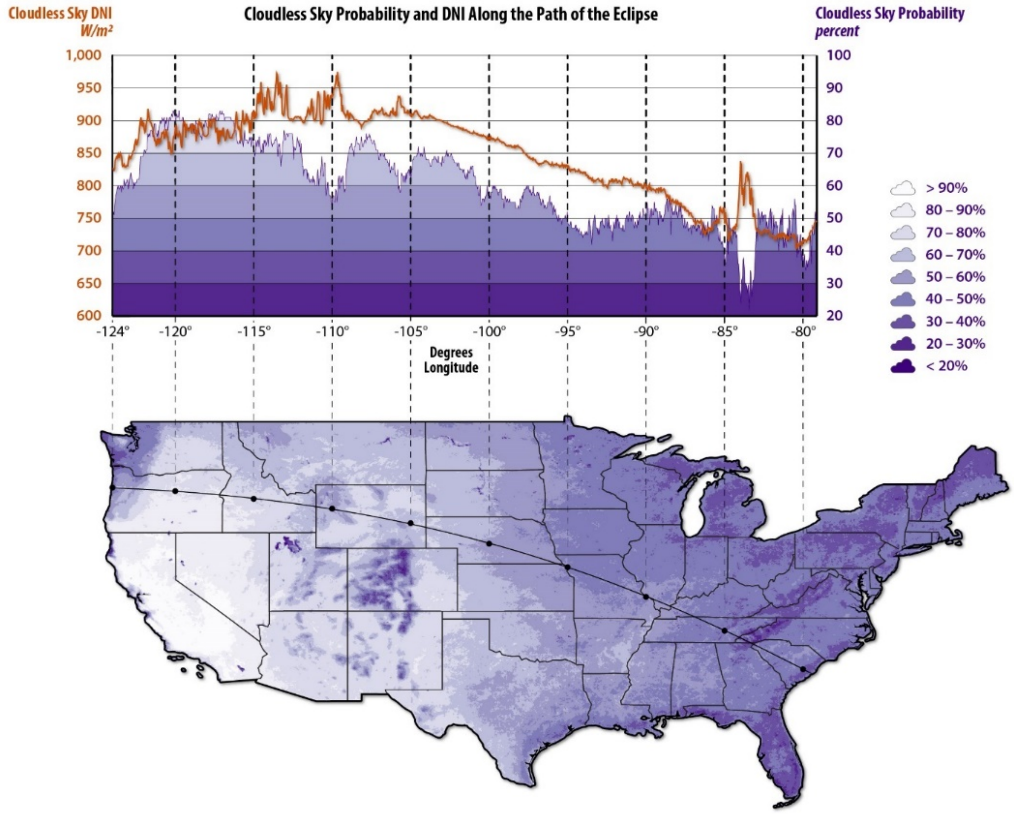

Figure 25. Centerline profile of the path of the total solar eclipse (Wilcox et al. 2017). ***Path of totality from "Eclipse Predictions by Fred Espenak, NASA/GSFC Emeritus." Cartography by Billy J. Roberts, NREL***

3.3 Task 3: Knowledge Sharing

This task developed and updated international consensus standards and best practices in solar measurement and modeling to represent the state-of-the-art knowledge through continuous formal engagement of various stakeholders.

3.3.1 International Energy Agency Photovoltaic Power Systems Programme Task 16

NREL leads the IEA Photovoltaic Power Systems Programme (PVPS) Task 16: Subtask 1, which focuses on the evaluation of current and emerging resource assessment methodologies. The subtask covers three areas: ground-based methods, numerical weather prediction models, and satellite-based methods. For each methodology, a separate activity is defined. The objective of this subtask is to contribute to the improvement of established and new measurement methods for solar resource assessment, analyze the numerical weather prediction models and improvements in cloud detection, and contribute to the evaluation and improvement of satellite-derived data and their uncertainty and formulation of measurement best practices/standards. Figure 26 shows a group photo of the participants in the third IEA PVPS Task 16 meeting, which was held in Rapperswil, Switzerland, and attended by more than 40 participants representing 14 countries. There are 56 institutions participating in the task.

3.3.1.1 *Publication of the* Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications

In collaboration with international partners within the IEA, the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Second Edition* was published.[21] The handbook is assembled by scientists and engineers who have many decades of combined experience in state-of the-art atmospheric science, radiometry, meteorological data processing, and renewable energy technology development. The paper contains contributions from an international group of experts primarily from knowledge gained through participation in the IEA's Solar Heating and Cooling Programme. The handbook discusses solar resource components, instrument types, measurement station design, and current best practices in modeling and forecasting solar radiation, historical radiation data, and methods to apply solar radiation data to solar energy projects. It also contains a summary of solar forecasting and its development throughout the last few years. Solar energy project developers; engineering, procurement, and construction firms; utility companies; electric power system operators; energy suppliers; financial investors; and others involved in solar energy systems planning and development will find this handbook to be a valuable resource for collecting and interpreting data that can be used as a reference during each project stage.

Figure 26. Participants in the third meeting of the IEA PVPS Task 16, held in Rapperswil, Switzerland. *Photo by Jan Remund*

3.3.2 *American Society for Testing and Materials International*

NREL continued to provide leadership in the development and update of standards that are relevant to the measurement and modeling of solar radiation for solar energy applications. Standards developed cover calibration method of pyrheliometer (DNI measurements),

[21] See https://www.nrel.gov/docs/fy18osti/68886.pdf.

pyranometer (GHI measurements), spectroradiometer, ultraviolet (UV) radiometers, correct field deployment of these instruments, spectral distribution reference tables for PV modeling, and transfer of indoor calibrations.

3.3.2.1 Existing American Society for Testing and Materials Standard Under Subcommittee Radiometry

Existing ASTM standards are subjected to revision at any time by the technical committee and must be reviewed every 5 years, and if not revised, either reapproved or withdrawn. The standards under ASTM Subcommittee G03.09 on Radiometry, which is led by NREL, are responsible for the following existing standards:

- E816: Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers
- E824: Standard Test Method for Transfer of Calibration From Reference to Field Radiometers
- G130: Standard Test Method for Calibration of Narrow- and Broad-Band Ultraviolet Radiometers Using a Spectroradiometer
- G138: Standard Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance
- G167: Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer
- G173: Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface
- G177: Standard Tables for Reference Solar Ultraviolet Spectral Distributions: Hemispherical on 37° Tilted Surface
- G183: Standard Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers
- G197: Standard Table for Reference Solar Spectral Distributions: Direct and Diffuse on 20° Tilted and Vertical Surfaces
- G207- Standard Test Method for Indoor Transfer of Calibration from Reference to Field Pyranometers
- G213 - 17: Standard Guide for Evaluating Uncertainty in Calibration and Field Measurements of Broadband Irradiance with Pyranometers and Pyrheliometers
- G214 - 16: Standard Test Method for Integration of Digital Spectral Data for Weathering and Durability Applications

3.3.2.2 New Standards Developed During the Project Period

NREL led and shepherded the publication of new standards through ASTM.

- ASTM G213-17: Guide for Evaluating Uncertainty in Calibration and Field Measurements of Broadband Irradiance with Pyranometers and Pyrheliometers [22]

  As stated in this guide provides guidance and recommended practices for evaluating uncertainties when calibrating and performing outdoor measurements

[22] https://www.astm.org/Standards/G213.htm

with pyranometers and pyrheliometers used to measure total hemispherical and direct solar irradiance. This guide quantifies the uncertainty in measuring the total (all angles of incidence) broadband (all wavelengths of light) irradiance experienced either indoors or outdoors.

The standard also included an interactive Excel spreadsheet as adjunct, ADJG021317. The intent is to provide users real-world examples and to illustrate the implementation of the GUM method.

- ASTM G214-16: Standard Test method for Integration of Digital Spectral Data for Weathering and Durability Application.[23]

  NREL led the development of a new standard that was published in 2016. This standard specifies a single relatively simple-to-implement common integration technique, the Modified Trapezoid Rule, to integrate digital or tabulated spectral data. The intent is to produce greater consistency and comparability of weathering and durability test results between various exposure regimes, calculation of materials properties, and laboratories with respect to numerical results that depend on the integration of spectral distribution data. Weathering and durability testing often require the computation of the effects of radiant exposure of materials to various optical radiation sources, including lamps with varying spectral power distributions and outdoor and simulated sunlight. Changes in the spectrally dependent optical properties of materials, in combination with exposure source spectral data, are often used to evaluate the effect of exposure to radiant sources; develop action spectra; and classify, evaluate, or rate sources with respect to reference or exposure source spectral distributions. Computation of these bulk optical properties requires the integration of measured wavelength-dependent digital data, sometimes in conjunction with tabulated wavelength-dependent reference or comparison data. Here the term *integration* refers to the numerical approximation to the true integral of continuous functions, represented by discrete, digital data. As stated in the standard, there are numerous mathematical techniques for performing numerical integration. Each method provides different levels of complexity, accuracy, ease of implementation and computational efficiency, and, of course, resultant magnitudes. Thus, the need for a standard integration technique is to simplify the comparison of results from different laboratories, measurement instrumentation, or exposure regimes.

3.3.2.3 Standards Under Development

- Standard Performance Classification of Solar Radiometers
  NREL provided input in the update of ISO 9060: Solar energy—Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation Standard. The international standard was accepted.

- The ASTM subcommittee on radiometry has a draft standard on Guide for Performance

[23] https://www.astm.org/Standards/G214.htm

Classification of Solar Radiometers. This guide describes available international specifications for the performance classification for instruments that measure hemispherical solar and direct solar radiation. The guide is limited to instruments optimized for measurement of the solar irradiance in W/m^2. These instruments typically respond over the solar spectrum of wavelengths from 285 nm to 3,000 nm but are calibrated with respect to the internationally recognized WRR maintained by a group of absolute cavity pyrheliometers that respond to radiation out to the far infrared (~50 micrometer) spectral region. The referenced classification schemes are based on a set of instrument specifications published in the referenced documents. The specifications are obtained through characterization experiments, involving indoor as well as outdoor testing. The objective of this guide is to reference the performance classification documents, provide background to the development of the classifications, and provide guidance to the user in using performance classification to select instruments appropriate for the user's application. The user should realize that the measurement uncertainty as obtained during outdoor measurements is a function of (1) instrument class or classification, (2) calibration procedure, (3) measurement conditions and maintenance, and (4) environmental conditions. Therefore, statements about the overall measurement uncertainty can be made only on an individual basis, taking all these factors into account. Uncertainty evaluation is covered by ASTM Work Item WK 36479: Standard Practice for Uncertainty Evaluation of Calibration and Measurements with Pyranometers and Pyrheliometers.

- New Standard estimation of UV irradiance received by samples as a function of location, orientation, and tilt angle

  Many companies and academic researchers use commercial or in-house UV calculators to estimate yearly UV dose received by samples as a function of location, orientation, and tilt angle. These calculations are used to roughly estimate service life based on dose to failure in laboratory or natural weathering experiments. The subcommittee recognizes the opportunity to standardize these practices and proposes to put forward:

  A. A set of equations used to calculate the direct and diffuse total solar radiation and total UV radiation as a function of position, orientation, and tilt angle

  B. A method to separate the total UV components of the GHI from the typical meteorological year data to be used as inputs in these equations

  C. An agreed-upon conversion method to estimate the equivalent accelerated weathering test duration in standard weathering cycles, based on UV dose. Other factors contribute to the acceleration of aging, such as temperature and moisture, which are not accounted for in such calculators. The standard will include the appropriate disclaimers. Future development might include these factors in a more comprehensive climate and acceleration factor calculation.

  To support of this draft standard, NREL published a on "Estimating Ultraviolet Radiation from Global Horizontal Irradiance" in the *Journal of Photovoltaics*. As stated in this paper, a model was developed to estimate the global UV irradiance contained in multiple wavebands (280–400 nm, 295–400 nm, 285–385 nm, and 295–385 nm) using the total broadband solar irradiance, as obtained from usual radiation models or measured with, e.g., a conventional pyranometer. The method is based on simulations of both global UV and total broadband solar irradiance obtained with the SMARTS spectral radiation model. Under clear-sky conditions, the airmass was found to be the primary driver of the global UV/total broadband solar irradiance ratio, at least under "typical" atmospheric conditions. Further, still using SMARTS, the model was extended to estimate the global UV/total broadband solar irradiance ratio for a variety of tilt angles.

The proposed model can be applied to estimate the total UV irradiance from total solar irradiance (GHI or global tilted irradiance) under all-sky conditions. The necessary input data can be obtained from actual measurements, satellite-derived modeled time series, or usual typical meteorological year data files.

The results (e.g. Figure 27) show that the modeled UV results are in good agreement with actual measurements at different timescales, multiple locations, and tilt angles, which provides confidence about the accuracy of the model. The model typically under- or overestimates the measured UV irradiance within only ±2 W/m^2. The RMSE appears slightly better for the horizontal than the tilt results. This situation could be related to the model's limitation under tilted conditions or to data quality of the global tilted irradiance data (which are estimated from GHI with a transposition model, thus adding uncertainty). As usual, the quality of the model's inputs largely conditions the UV predictions' accuracy.

The model proposed here is meant to characterize the UV irradiance or irradiation at any location, and hence to help understand the degradation of various materials used in PV modules, and ultimately to provide a reliable assessment of their service life. In this perspective, the model demonstrated results within 2%–8% of the measured irradiance values on various tilts.

Additionally, the model does not seem to be significantly affected by cloudiness (except possibly at Miami), but it appears sensitive to large excursions in AOD, precipitable water, or surface albedo, which will require further attention.

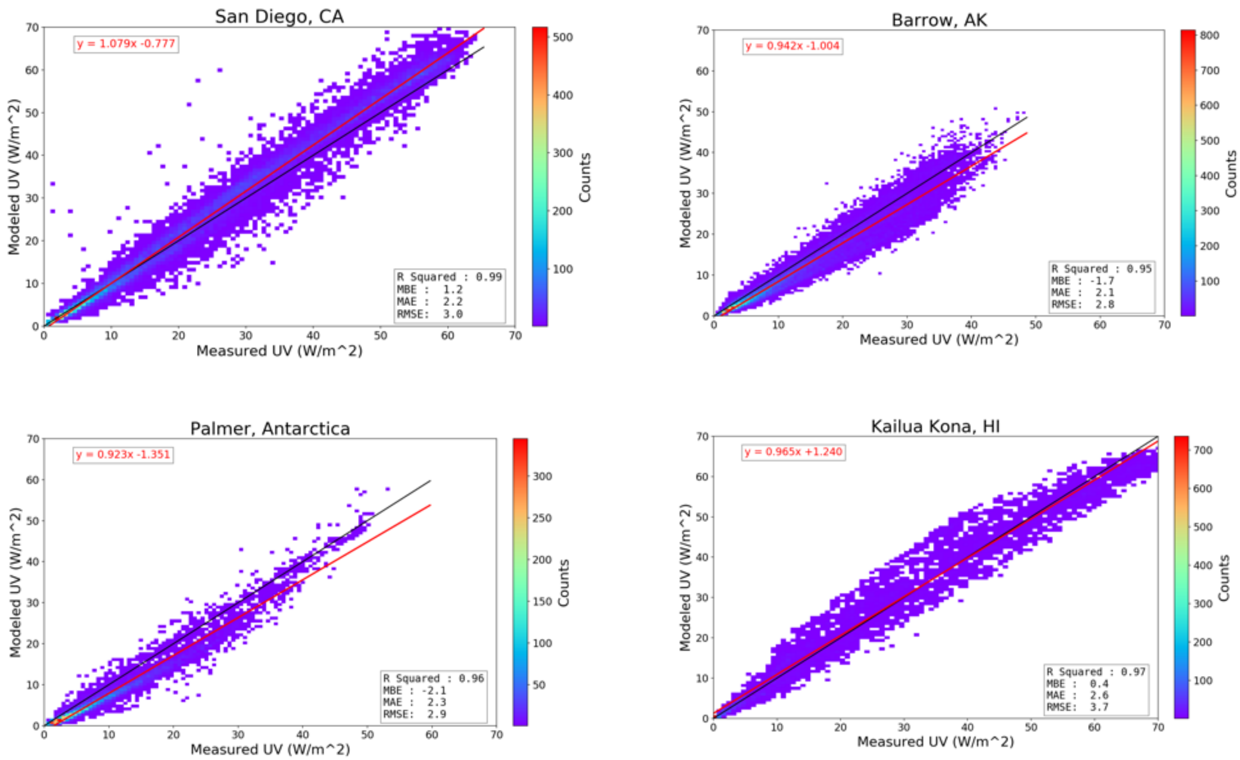

Figure 27. Modeled vs. measured global UV irradiance under all-sky conditions and zero tilt. RMSE and MBE values are in W/m^2. The black line is the 1:1 line, and the red line is the regression line. The dot colors refer to a "density scale" from blue to red, with red showing the highest density of points. ***From Habte et al. (2019)***

- Standard Practice for Measurement and Calibration of the Specimen Irradiance in Accelerated Weathering Devices

- Weathering device manufacturers have their own approach to calibrating irradiance measuring radiometers. Lack of specific guidelines for the reliable determination of specimen irradiance in weathering devices is a significant factor in the variability of artificial weathering test results. This standard will propose a uniform set of best practices for the choice and calibration of radiometers used to measure the irradiance provided by the various types of weathering devices. It is intended for use by manufacturers, test laboratories, and end users of weathering devices. This practice covers the basic principles and procedures for measuring the irradiance incident upon specimens in a weathering device when operating a specified weathering method. This practice is applicable to all types of weathering devices, including fluorescent UV lamp devices, filtered xenon-arc devices, and metal halide devices.

4 Significant Accomplishments and Conclusions

4.1 Summary of Accomplishments

- Continuous, real-time, high-quality 1-minute data from 60 instruments measuring GHI, DNI, DHI, spectrum, AOD, UV, water vapor, and other meteorological parameters that can be used for solar modeling
- Calibration of 342 NREL and 140 non-NREL radiometers using the BORCAL process to enable accurate solar measurements nationwide
- Transferred world radiation standard to more than 120 ACRs from national and international shareholders including calibration service providers
- Twenty years (1998–2017) of high-resolution (30-minute and 4-km temporal and spatial resolution) solar resource information provided free to users through the NSRDB website. The area covered is bordered by longitudes 25° W on the east and 175° W on the west and by latitudes -20° S on the south and 60° N on the north.
- Incorporated advanced NASA MERRA-2 data set in the NSRDB to improve aerosol characterization and other meteorological data sets
- Eighteen peer-reviewed journal publications, 10 technical reports, 15 conference papers, and 21 conference presentations and posters that demonstrate advances the state of the art in satellite-based resource estimation and reducing uncertainty in solar measurements
- Published the second edition of the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy* Applications in collaboration with world-leading experts through IEA's Solar Heating and Cooling Programme Task 46
- Led technical contributions for the United States for two new ASTM standards and one ISO standard on measurement uncertainty and instrument classification
- Disseminated research to 300,000 users per year through the MIDC, RReDC, and NSRDB websites.

4.2 Challenges

4.2.1 Maintaining Traceability: Developing the Next-Generation Absolute Cavity Radiometer to Maintain Solar Measurement Accuracy

The automatic Hickey-Frieden (HF/AHF) has been manufactured by Eppley Laboratory, Inc. since 1977 but was discontinued in 2015. The AHF is a critical part of the traceability chain for calibrating all radiometers in the United States and potentially worldwide. As the demand for solar energy grows, there will be an increased need for calibration of radiometers that are deployed at these solar generation sites (PV and CSP plants). In the absence of a replacement and with the nonavailability of the AHF, a critical break in the traceability chain might happen in the future. This could result in degradation of U.S. capabilities to provide accurate solar radiation measurements for resource assessments and plant operations, which would result in an increase in uncertainty and a corresponding increase in the both the development and cost of operations of PV and CSP plants. NREL, in collaboration with NIST and Eppley Laboratory, Inc., are attempting to redesign and manufacture AHF to ensure the traceability of all calibrated instruments that are deployed at PV and CSP plants around the United States.

4.2.2 Changes in DNI Prediction Caused by the Aerosol Data Timescale

DNI data demonstarted differences between Version 2 and Version 3 of the NSRDB, as evident in Figure 28. A posible reason for the difference in the AOD between the two versions is that Version 3 shows potential locations for solar development, whereas they were previously excluded by the U.S. Bureau of Land Management Solar Energy Programmatic Environmental Impact Statement. Previously, the U.S. Bureau of Land Management developed a rule excluding lands from solar development with a solar insolation less than 6.5 kWh/m^2/d.

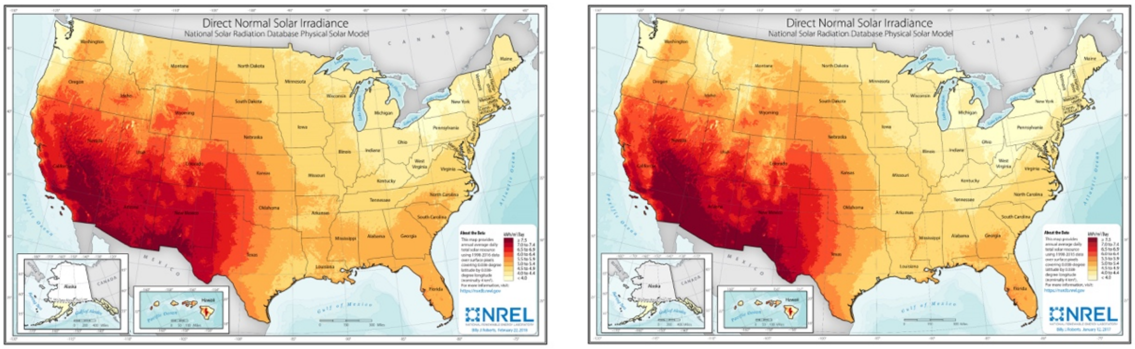

Figure 28. DNI differences between NSRDB (left) Version 3 and (right) Version 2

4.2.3 Differences Between GOES-East and GOES-West NSRDB Data

The satellite information that is used to produce NSRDB data originates from two satellites: GOES-East and GOES-West, with the dividing line between 105º and 110º W longitude. GOES-East data have time-shift applied to cloud properties instead of solar radiation. The solar radiation data from both satellites are available at the top and middle of every hour. The data from both satellites were joined to provide a complete uninterrupted satellite image every half hour at a 4-km resolution for the United States, as shown in Figure 29.

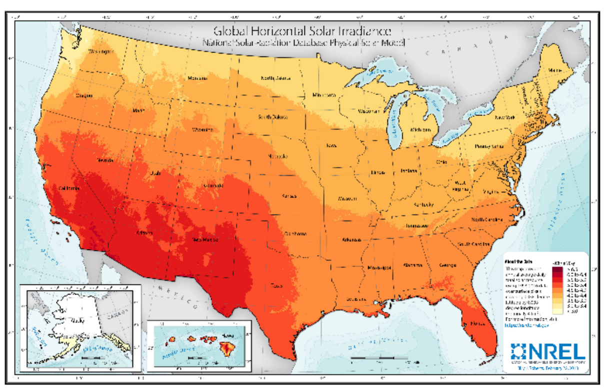

Figure 29. NSRDB Version 3 blended GHI data set

Table 4. GOES-East and GOES-West Comparison with Surface Measurements (%MBE)

Station	Latitude	Longitude	GOES-East			GOES-West		
			All Sky	Clear Sky	Cloudy Sky	All Sky	Clear Sky	Cloudy Sky
Ashland	42.19	-122.7	4	5	2	1	6	-5
Burns	43.52	-119.02	0	2	-1	-1	2	-7
Eugene	44.05	-123.07	0	0	1	-1	2	-6
Silverlake	43.12	-121.06	0	0	-1	-2	1	-7

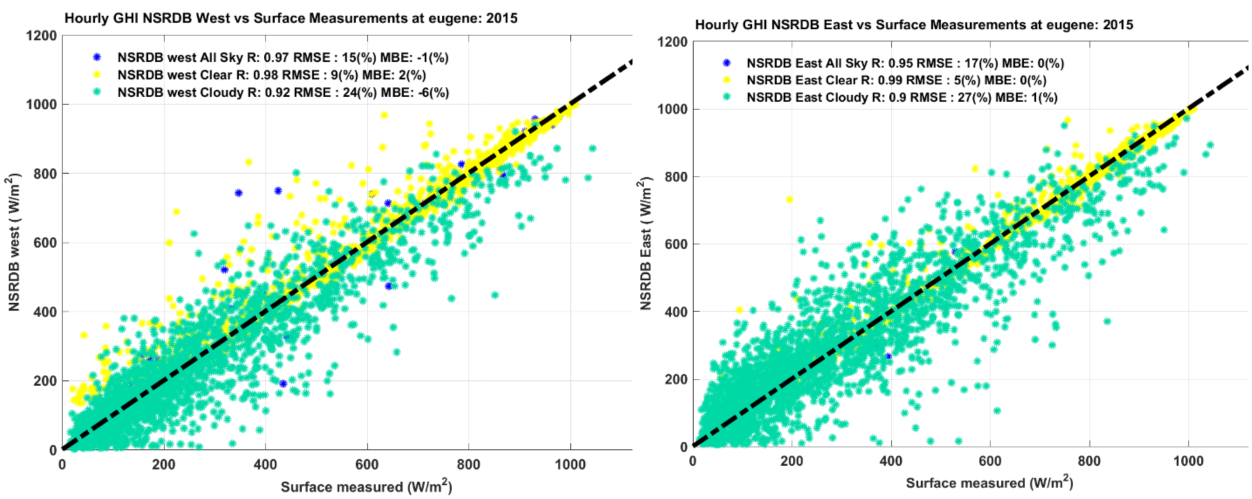

Figure 30. Comparison for Eugene, Oregon, using (left) GOES-West satellite and (right) GOES-East satellite

We noticed differences between the two versions, however, along the dividing line (105° longitude). To better understand these differences, we compared GHI estimates from the GOES-East and GOES-West satellites to four University of Oregon Solar Radiation Measurement Laboratory ground measurement stations. Both satellites cover the State of Oregon where these stations are located. The result using 2014 data shows that the GOES-East satellite performs better than the GOES-West satellite for this region (Table 4 and Figure 30). Note that the GOES-West satellite has a better viewing angle for the State of Oregon than the GOES-East satellite.

Overall, the GOES-East comparison shows zero bias for all-sky conditions and less than ±2% for clear and cloudy conditions for three out of four stations. The GOES-West satellite shows higher biases in all conditions, clear and cloudy skies, except for Ashland, where the all-sky condition shows less bias compared to GOES-East; however, there is a cancellation of error because clear and cloudy have opposite signs of equal magnitude. But the results obtained here need further study to better understand the cause of the outcome.

5 Path Forward

NREL is internationally recognized for its continued expertise in solar resource measurements, calibration, and modeling. Developments in these areas and continued support from DOE and NREL will directly impact the outcomes of other R&D projects supported by SETO, including PV performance and characterization, numerous economic and performance models, policy analysis, geographic information system products, and grid integration systems.

Regular dissemination of NSRDB data containing GHI, DNI, DHI, and spectrally resolved irradiance will continue. Data will be delivered as time series or typical meteorological year data sets; however, currently NSRDB data do not include the effect of subgrid effects such as terrain or building shading on the irradiance and must be combined with other tools to estimate energy production. In the future, NREL will attempt to estimate the effects and incorporate the result in the data set. Moreover, NREL will seek to improve the quality and resolution of the NSRDB to represent the state of the art in the science of satellite remote sensing of clouds and radiation. With the deployment of the next-generation satellite GOES-16 (former GOES-R), there is an opportunity to provide grid awareness every 5 minutes at a 2-km resolution. Also, the addition of additional sensing channels on the satellite provides information that improves the detection of clouds and retrieval of their properties. This proposal seeks to enhance the methods used to develop the NSRDB to incorporate both the additional information from the new satellites as well as new science that uses this additional information to improve the quality of the products.

NREL will continue to make available the world-class continuous measurements of solar radiation and meteorological parameters from the BMS to enable R&D activities in support of SETO as follows. NREL through SRRL will continue to serve as a living laboratory that allows experience gathered from operating instruments, developing standards, and testing models to be shared quickly and easily across the solar energy industry. This experience will continue to be shared through ASTM and ISO standards, conference presentations, technical reports, and journal articles. Measurement research will continue such as identifying sources of uncertainty in solar measurements, their quantification, and mitigation. New and improved instruments are continuously deployed for validation and characterization against the BMS. The validation process provides an understanding of the quality of a new instrument when compared to peers. The characterization process provides an understanding of the variability between instruments of the same make and model and essentially provides an understanding of the manufacturing quality. These tests will continue to be carried out in collaboration with manufacturers, including Kipp & Zonen, Hukseflux, EKO Instruments, and Eppley Labs. The result obtained will be available to allow the solar energy industry to understand the performance of sensors and make informed decisions regarding their deployment of the use of data collected by those sensors. Development of new types of instrumentation, advancements in measurement methods and techniques, and updates in measurement best practices resulting from SRRL R&D forms an essential part of regular updates to NREL's *Best Practices Handbook* for solar measurement and modeling.

NREL will continue long-standing leadership roles and involvements in international standards and best practices with ASTM and IEA to advance radiometry, solar modeling, and support stakeholder needs for relevant standards addressing solar resource characterization.

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