Standard Operating Procedure for Optimal Deployment of Meteorological Instrumentation Within the Solar Radiation Research Laboratory (BMS and RMS SOP)

Aron Habte, Manajit Sengupta, and Afshin Andreas

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-85645
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Suggested Citation
Habte, Aron, Manajit Sengupta, and Afshin Andreas. 2023. *Standard Operating Procedure for Optimal Deployment of Meteorological Instrumentation Within the Solar Radiation Research Laboratory (BMS and RMS SOP)*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-85645. https://www.nrel.gov/docs/fy23osti/85645.pdf.

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Golden, CO 80401
303-275-3000 • www.nrel.gov

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Acknowledgments

We are grateful to the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office and to the Photovoltaic subprogram for supporting this project. Specifically, we acknowledge Dr. Tassos Golnas, Dr. Inna Kozinsky, and Dr. Lenny Tinker for their support and encouragement.

List of Acronyms

ARM	Atmospheric Radiation Measurement
BIPM	International Bureau of Weights and Measures
BMS	Baseline Measurement System
BORCAL	Broadband Outdoor Radiometer Calibration
BSRN	Baseline Surface Radiation Network
CRADA	Cooperative Research and Development Agreement
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
FARMS	Fast All-Sky Radiation Model for Solar Applications
GHI	global horizontal irradiance
ISO	International Organization for Standardization
LASP	Laboratory for Atmospheric and Space Physics
MIDC	Measurement and Instrumentation Data Center
NCAR	National Center for Atmospheric Research
NEON	National Ecological Observatory Network
NIST	National Institute of Standards and Technology
NMI	National Metrology Institute
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
POA	plane of array
PV	photovoltaic
R&D	research and development
RMS	Research Measurement System
SETO	Solar Energy Technologies Office
SMARTS	Simple Model of the Atmospheric Radiative Transfer of Sunshine
SolarTAC	Solar Technology Acceleration Center
SOP	Standard Operating Procedure
SRRL	Solar Radiation Research Laboratory
VIM	International Vocabulary of Metrology
WISG	World Infrared Standard Group
WRR	World Radiation Reference

Executive Summary

The National Renewable Energy Laboratory (NREL)-Solar Radiation Research Laboratory (SRRL) has been in continuous operation since 1981, with an objective to collect and use high-quality solar radiation data sets for research leading to the widespread adoption of solar technologies. Using International Organization for Standardization-accredited methodologies, the NREL-SRRL maintains a varied and extensive array of solar monitoring equipment to test, evaluate, and characterize the solar sensors used by federal and international agencies as well as the solar industry to determine the solar resource. To appropriately populate and track the diverse array of instruments at the SRRL, NREL has established a Standard Operating Procedure (SOP) for optimal deployment within the SRRL for both the Baseline Measurement System (BMS) and the Research Measurement System (RMS). Based on the SOP, instruments are annually evaluated for continued deployment. Instruments that do not meet the SOP criteria are decommissioned, and new instruments that meet the criteria are deployed.

Therefore, streamlining and optimizing the use of this facility ensures that the lab continues to be a world-leading solar calibration and measurement facility. The SOP provides the industry with guidance for solar resource assessment and is used for procedures in the long-term continuous monitoring of legacy instruments alongside state-of-the-art instruments.

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1 Introduction

The Solar Radiation Research Laboratory (SRRL) is located on the top of South Table Mountain on the north side of the National Renewable Energy Laboratory's (NREL's) campus in Golden, Colorado (Figure 1), where it has excellent solar access because of its unrestricted view of the horizon from sunrise until sunset throughout the year. The NREL-SRRL is home to the world's largest collection of radiometers in continuous operation and has measurements dating back to 1981. The NREL-SRRL houses both solar resource assessment activities and campus-wide metrology services.

The NREL-SRRL has served as the U.S. Department of Energy's (DOE's) lead laboratory for radiometer calibrations traceable to the World Radiometric Reference (WRR), which is essential for obtaining accurate measurements and to support DOE's goals of reducing the costs of solar energy deployment and integration and improving the accuracy of climate models. Working with the World Radiation Center, in Davos, Switzerland, the NREL-SRRL team participates in the quinquennial International Pyrheliometer Comparisons to maintain the WRR. In turn, annual NREL Pyrheliometer Comparisons provide stakeholders with access to the WRR. Using WRR working standard absolute cavity radiometers, the NREL-SRRL team developed a unique Broadband Outdoor Radiometer Calibration (BORCAL) method for calibrating pyrheliometers and pyranometers for field measurements. The NREL-SRRL annually calibrates, on average, more than 150 radiometers for NREL, academia, industry, and federal agencies. The BORCAL process is an International Organization for Standardization (ISO) 17025-accredited method, which is essential for the other ISO-accredited measurement programs at NREL that address photovoltaic (PV) performance. Moreover, the availability of world-class continuous measurements of solar radiation and meteorological parameters from the NREL-SRRL through the Baseline Measurement System (BMS) and the Research Measurement System (RMS) enables research-and-development (R&D) activities in support of the DOE Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO), the DOE Office of Science, and other researchers and industry. Both the BMS and the RMS are equipped with solar irradiance and a variety of meteorological sensors required for solar research.

Researchers at the NREL-SRRL conduct R&D in applied solar radiation measurements and operate a suite of instruments for solar irradiance, meteorological measurements, and solar-specific instrument calibrations. Solar resource assessment research activities related to solar instrumentation and measurement at the NREL-SRRL are funded by the DOE EERE SETO PV program, the DOE Office of Science Atmospheric Radiation Measurement (ARM) program, various agreements such as technical service agreements, and NREL indirect funds through the metrology task.

Figure 1. Aerial view of the NREL-SRRL mesa-top facility

The NREL-SRRL hosts a BMS and an RMS that provide real-time, high-quality baseline data using instruments from various manufacturers for research and standards development. The BMS data sets provide a unique capability for measurement and modeling research and for instrument development because of their completeness and quality.

All radiometers in the BMS are calibrated using either BORCAL or NREL's spectral calibration service. All meteorological instruments are calibrated in the NREL Metrology Laboratory (except wind sensors, which are replaced with new calibrated sensors from the manufacturer). The BMS and the RMS include more than 175 instruments that measure independent components of solar radiation and meteorological conditions.

The collected data are widely used by researchers and industry, with approximately 5,000 unique users per month, and they provide the basis for the development of various international standards. The bibliography of this document shows publications released in the last 15 years that used NREL-SRRL data for their research and applications. Collaborative research with universities and industry conducted using the BMS helps reduce the cost and improve the accuracy of radiometric measurements. NREL also conducts active research on identifying sources of uncertainty in measurements and developing processes to reduce those uncertainties.

Therefore, it is essential to develop a Standard Operating Procedure (SOP) for optimal deployment within the NREL-SRRL for both the BMS and the RMS. Based on the SOP, instruments are annually evaluated for continued deployment. Instruments that do not meet the SOP criteria are decommissioned, and new instruments that meet the criteria are deployed.

1.1 Purpose

This document describes the regular and recurring operation procedures relevant to the deployment of instrumentation within the NREL-SRRL platform and serves as the guiding document for commissioning and decommissioning instruments for the optimal and efficient use of resources.

1.2 Scope

This SOP for the optimal use of the NREL-SRRL platform covers the commissioning and decommissioning process of all BMS instrumentation. The document provides a set of guidelines on how deploy instruments at the NREL-SRRL and assists NREL-SRRL personnel in the equipment commissioning and decommissioning process for the optimal use of the NREL-SRRL lab.

1.3 Current Instrumentation

Appendix tables A.1–A.11 describe the current instrumentation of the NRLE-SRRL as of March 2023.

2 Measurement and Instrumentation Data Center

The Measurement and Instrumentation Data Center (MIDC) is a platform that allows NREL to collect, store, and provide solar resource measurements and other meteorological/ancillary information to many stakeholders with a diverse set of needs. Through the MIDC's web portal,[1] NREL disseminates—in near real time—quality-controlled, traceable measurements collected from the SRRL and other partner sites around the United States that take high-quality solar radiation measurements. All legacy and near-real-time measurement data are available through the MIDC, which continues to be accessed by more than 100,000 users annually. The data and models available from the website support stakeholders by providing easy access to information for improving the quality and reducing the cost of solar projects.

[1] See https://www.nrel.gov/midc/.

3 Baseline Measurement System

The BMS at the NREL-SRRL is an active R&D site for measurement, calibration, instrumentation, evaluation, model development, validation, and standards development. The BMS has been in continuous operation at the NREL-SRRL since 1981, with an objective to collect and use high-quality solar radiation data sets for research leading to the widespread adoption of solar technologies and for climate research.

The BMS provides long-term reference data for use in DOE projects, for use in support of other activities at the NREL-SRRL, and for use by the broader industry and R&D community. (See Section 3.1 for details.) Publications related to some of these uses are listed in the bibliography of this document.

Appendix tables A.1–A.11 enumerate the many types of radiometers, spectroradiometers, and meteorological instruments installed and deployed at the NREL-SRRL in the BMS and RMS.

3.1 Baseline Measurement System Use Case Examples

The availability of world-class continuous measurements of solar radiation and meteorological parameters from the BMS enables R&D in support of DOE activities. Some of these are summarized as follows:

- **Model development and validation:** The NREL-SRRL BMS is one of the few sources of high-quality, long-term solar radiation data sets in the United States 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 the NREL Fast All-Sky Radiation Model for Solar Applications (FARMS). FARMS is further used to develop the National Solar Radiation Database (NSRDB) as part of the NSRDB project funded by SETO.
- **Standards development:** The NREL-SRRL serves as a living laboratory that allows the experience gathered from operating instruments, developing standards, and testing models to be quickly and easily shared across the solar energy industry. This experience is shared through ASTM and ISO standards, conference presentations, technical reports, and journal articles. For example, data collected by the instruments are used as inputs to U.S. and international standards, such as ASTM 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 Radiometers). The standards are essential for acquiring and maintaining traceable solar resource data sets for solar energy conversion applications.
- **Uncertainty quantification:** The BMS system serves as a platform for best practices measurement, as a source of data for research, and is an important part of NREL-SRRL R&D. This includes research into sources of uncertainty in solar measurements, their quantification, and mitigation. Investigations of differences in outdoor and indoor calibrations as well as instrument degradation from long-term field deployment are also conducted..
- **Instrument characterization:** New and improved instruments are deployed for validation and characterization against the BMS. The validation process provides an

understanding of the quality of a new instrument compared to peers. The characterization process provides an understanding of the variability among 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., and Eppley Laboratory, Inc. 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 their deployment and the use of the data collected from those sensors. Collaborations with other entities, such as DLR (German Aerospace Agency) and Arable, and deployments, such as at the Solar Technology Acceleration Center (SolarTAC) and NREL's Flatirons Campus, further support the testing of solar technologies and grid integration.

- **Metrology research:** The development of new types of instrumentation, advances in measurement methods and techniques, and updates in measurement best practices resulting from the NREL-SRRL R&D form an essential part of regular updates to NREL's *Best Practices Handbook*[2] for solar measurement and modeling. Example chapters for these applications include Chapter 3 "Measuring Solar Radiation," 4 "Modeling Solar Radiation," 5 "Relevant Meteorological Parameters," and 7 "Solar Irradiance Uncertainty and Data Quality Assessment" (Sengupta et al. 2021).
- **Grid integration:** Collected data are important to understand ramp rates of solar energy plants with large changes in the solar resource. These ramp rate events, which are typically associated with varying sky conditions, cause significant uncertainty in the dispatchability of power sources available for balancing generation and load.
- **PV research:** The spectral data collected by the BMS through spectroradiometers are critical measurements for many solar energy projects, such as NREL's PV cell and module performance project, which tests PV modules and cells under a known set of standard reporting conditions. Frequent spectral measurements are required for outdoor measurements to understand the varying spectral content of the solar resource. Spectral measurements are also required for indoor solar simulators because their spectrums can change over time as optics and lamps age.

[2] See https://www.nrel.gov/docs/fy21osti/77635.pdf.

4 Research Measurement System

The RMS is a separate data acquisition system that allows research devices to be deployed at the NREL-SRRL separate from the semipermanent instruments in the BMS. The RMS is used to support work for DOE programs over a short time period and to support cooperative R&D agreements, work for others (commercial work), and strategic partnership projects. The RMS employs the same data acquisition technology and maintenance protocols afforded the BMS instruments. This assures a standard of care that reduces unwanted variables when comparing RMS instruments with BMS instruments.

Similar to the BMS data, RMS data are acquired and delivered to customers and the public through the MIDC. Although nearly all data are made publicly available, occasionally some data might be password-protected because of their proprietary nature.

5 Standard Operating Procedure for the Deployment of NREL-SRRL Instrumentation

5.1 Regular Instrument Inventory Procedure

The NREL-SRRL team maintains regular inventory of the SRRL BMS instrumentation, which is essential for consistency, replacement, commissioning, and decommissioning. Moreover, some instruments in the inventory list in appendix tables A.1–A.11 are essential for:

- Expanding ISO 17025 and maintaining the existing ISO 17025 accreditation for BORCAL and spectral calibrations. Regular instrument inventory maintenance is essential to fulfil the mandatory ISO 17025 accreditation requirement of providing a list of laboratory equipment as the equipment applies to the accreditation. Similarly, having the instruments and maintaining the list is also important for the expansion of ISO 17025 accreditation, for example, seeking longwave ISO 17025 accreditation.
- Introducing and evaluating new instrumentation, such as digital irradiance sensors.
- Decommissioning instrumentation that might be obsolete or is no longer used frequently by R&D organizations and industry.

5.2 Selection of Instruments

The selection of instruments to be deployed at the NREL-SRRL depends on a set of criteria and procedures. The details of the selection for each instrument type are described in sections 5.2.1–5.2.6. In some cases, however, the NREL-SRRL team selects prototype instruments based on the potential applicability of the instrument to renewable energy applications and/or climate studies. This is accomplished through the NREL team and/or in collaboration with industry and government agency partners. Further, the selection process follows the use cases of instruments by the solar energy stakeholders and the DOE ARM climate research program. To accomplish the evaluation of each instrument, NREL team members will provide expertise in:

- Metrology
- Modeling
- International standards
- Instrument design and operational theory
- Field solar measurement campaigns
- Network operations
- Data acquisition technologies

5.2.1 Broadband Shortwave Radiometers

The selection process follows a set of standards and protocols. The radiometers are traceable to the WRR (ISO 2018). An ISO 9060 classification is also a key standard in selecting radiometers for irradiance measurements based on a set of criteria. The NREL-SRRL team will not select instruments solely based on the best fit of the criteria below, but rather will attempt to include widely used and available radiometers that fall under each class within the ISO 9060 classification (WMO 2018). Table 1 and Table 2 describe the classification criteria for pyranometers and pyrheliometers, respectively.

Table 1. ISO 9060:2018(E) Specification Summary for Pyranometers

Pyranometer Classification List			
Specification	**Class of Pyranometer**		
	A	**B**	**C**
Approximate Corresponding Class From ISO 9060:1990	***Secondary Standard***	***First Class***	***Second Class***
Response time for 95% response	<10 s	<20 s	<30 s
Zero offset:			
a) Response to -200-W/m^2 net thermal radiation	±7 W/m^2	±15 W/m^2	±30 W/m^2
b) Response to 5-K h^{-1} change in ambient temperature	±2 W/m^2	±4 W/m^2	±8 W/m^2
c) Total zero offset, including the effects a), b), and other sources	±10 W/m^2	±21 W/m^2	±41 W/m^2
Stability: Change in responsivity per year	±0.8%	±1.5%	±3%
Linearity: Percentage deviation from the responsivity[3] at 500 W/m^2 because of change in irradiance from 100–1000 W/m^2	±0.5%	±1%	±3%
Directional response for beam radiation (range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring, from any direction, a beam radiation that has a normal incidence irradiance of 1,000 W/m^2)	±10 W/m^2	±20 W/m^2	±30 W/m^2
Clear-sky global horizontal irradiance spectral error[4]	±0.5%	±1%	±5%
Temperature response: Deviation because of change in ambient temperature within the interval from -10°C–40°C relative to 20°C	±1%	±2%	±4%
Tilt response: Percentage deviation from the responsivity at 0° tilt because of tilt change from 0–180° at 1,000-W/m^2 irradiance	±0.5%	±2%	±5%
Additional signal-processing errors	±2 W/m^2	±5 W/m^2	±10 W/m^2

Table 2. ISO 9060:2018 Specification Summary for Pyrheliometers Used to Measure Direct Normal Irradiance

Pyrheliometer Classification List				
Parameter	**Name of Class, Acceptance Interval**			
Name of Class	**AA**	**A**	**B**	**C**
Approximate Corresponding Class From ISO 9060:1990	***Not Defined***	***Secondary Standard***	***First Class***	***Second Class***
Response time for 95% response	No requirement	<10 s	<15 s	<20 s
Zero offset: a) Response to 5-K/h change in ambient temperature	±0.1 W/m²	±1 W/m²	±3 W/m²	±6 W/m²
b) Complete zero offset, including the effect a) and other sources	±0.2 W/m²	±2 W/m²	±4 W/m²	±7 W/m²
Stability: Percentage change in responsivity per year	±0.01%	±0.5%	±1%	±2%
Linearity: Deviation from the responsivity at 500 W/m² because of change in irradiance from 100–1,000 W/m²	±0.01%	±0.2%	±0.5%	±2%
Clear-sky DNI spectral error	±0.01%	±0.2%	±1%	±2%
Temperature response: Percentage deviation because of change in ambient temperature within interval from -10°C–40°C relative to 20°C	±0.01%	±0.5%	±1%	±5%
Tilt response: Percentage deviation from the responsivity from 0°–90° at 1,000-W/m² irradiance	±0.01%	±0.2%	±0.5%	±2%
Additional signal-processing errors	±0.1 W/m²	±1 W/m²	±5 W/m²	±10 W/m²

- The selection of these instruments is based on their applications:
  - Performance assessment of solar energy systems, such as PV and solar thermal systems, and mapping of solar energy resources

[3] Responsivity is usually expressed in microvolt per watt per square meter $\mu V/(Wm^{-2})$.
[4] Details of spectral error can be found in ISO 9060:2018 Annex A.

  - Other types of technologies and systems, such as agriculture, building efficiency, material degradation and reliability, climate, weather, and health.
- The selection of these instruments is also based on:
  - Metrological traceability: According to the International Bureau of Weights and Measures (BIPM) International Vocabulary of Metrology (VIM), this is defined as the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" (BIPM 2021).
  - Measurement uncertainty: According to the BIMP VIM, this is defined as the "parameter characterizing the dispersion of the values being attributed to a measurand, based on the information used" (BIPM 2021).
  - Instrument stability: According to the BIMP VIM, this is defined as the "property of a measuring instrument, whereby its metrological properties remain constant in time" (BIPM 2021).
  - Availability in the market: whether the instrument is readily available or not, prototype or obsolete.

Note: These selection and application criteria also apply to sections 5.2.2–5.2.6 of this report.

5.2.2 Longwave Radiometers

Selected pyrgeometers are traceable to the World Infrared Standard Group (WISG). The broadband longwave irradiance ranges from 4,000 nm to 50,000 nm, which is important to understand the total energy of the earth surface longwave irradiance, which is also important for correcting the thermal offset of broadband shortwave irradiance data (Dutton et al. 2001; Habte et al. 2016; Habte et al. 2017; Michalsky, Kutchenreiter, and Long 2017; Sengupta et al. 2021; Younkin and Long 2003).

The selection and application of these radiometers are based on the lists provided in Section 5.2.1.

5.2.3 Filtered Radiometers

In this document, filtered radiometers include ultraviolet (UV), photosynthetic active radiation, and photometric spectral wavelengths. These radiometers are used in climate studies and to understand the service life and durability of materials such as those used in PV panels. For example, UV is one of the major factors that causes degradation of materials. The radiometers are traceable to National Metrology Institutes (NMIs), such as the U.S. National Institute of Standards and Technology (NIST).

The selection and application of these radiometers are based on the lists provided in Section 5.2.1.

5.2.4 Photovoltaic Reference Cells

Similar to shortwave radiometers, PV reference cells can measure solar irradiance, and they are closely matched to solar panels. Typically, they are used to understand PV performance and efficiency. Reference cells are traceable to NMIs and/or the WRR.

The selection criteria of these PV reference cells are based on the lists provided in Section 5.2.1.

5.2.5 Spectroradiometers

Spectroradiometers are used for solar energy applications that need to expressly account for the impact of the radiation spectrum, such as understanding the spectral behavior of the PV modules. These spectroradiometers are most frequently used for measuring the spectrum of solar simulators or outdoor natural sunlight. Spectroradiometers are also used for climate research to evaluate the atmospheric constituents and spectral irradiance characteristics.

Spectroradiometers are traceable to NMIs, such as NIST. The NREL metrology laboratory is ISO 17025 accredited for spectroradiometer calibration with NIST traceability.

The selection criteria of these radiometers are based on the lists provided in Section 5.2.1.

5.2.6 Meteorological/Ancillary Instruments

In addition to solar irradiance, meteorological parameters are fundamental for solar resource assessments. These additional parameters are required for solar modeling, for PV generation performance and characterization, and for numerous economic and performance models. Meteorological parameters are used to advance solar radiometry, with such information being used during the calibration of broadband irradiance (e.g., during BORCAL); longwave calibration using, for example, the absolute cavity pyrgeometer; and the calibration of metrological equipment. For spectral calibration and measurement, meteorological data sets are essential to monitor the calibration condition and to fully interpret the variations in spectral distribution.

As stated, meteorological sensors are important for many solar measurement sensors. There are standards for such measurements, such as wind speed at 10 m and ambient temperature at 2 m. All sensors (wind, temperature, pressure) should be calibrated on a schedule with traceability to NMIs, such as NIST. Moreover, instruments used to measure precipitable water vapor and aerosol optical depth are calibrated by internationally recognized networks.

Temperature, humidity, and pressure sensors are calibrated in the NREL metrology laboratory. Wind sensors are purchased with calibration from the vendor.

The NREL-SRRL is also equipped with ancillary meteorological measurements that are important to ensure the operation of outdoor solar trackers and the indoor standard calibration laboratory condition. As part of the ISO 17025 accreditation of the metrology labs, monitoring the indoor environmental conditions is required because these spaces are temperature and humidity controlled.

The selection criteria of the meteorological/ancillary instruments are based on the measurement requirements provided in Section 5.2.1.

5.3 Commissioning Process

Once an instrument is selected, the installation and inspection of the instrument follows. The instrument is then connected to the MIDC platform, and incoming data are verified according to procedures for that instrument type. At this point, the instrument is referred to as commissioned. The instrument could be deployed into three setups:

1. RMS: As mentioned in Section 4, these instruments are under separate data acquisition systems that allow research devices to be deployed at the NREL-SRRL separate from the semipermanent instruments in the BMS. The selected instrument is deployed in this setup when the following conditions are fulfilled:
    A. The instrument is deployed to support research for DOE programs over a short time period. These instruments could be either DOE/NREL owned or under various agreements between NREL and the instrument owner.
    B. The instrument is new and has never been evaluated at the NREL-SRRL, but DOE and NREL see value for solar energy stakeholders and climate research.
2. BMS: The selected instrument is deployed in this setup when one of the following conditions are fulfilled:
    A. The instrument has been previously deployed and tested in the RMS or by various measurement service providers, such as an NMI or other meteorological monitoring networks.
    B. DOE and NREL see value for solar energy stakeholders and climate research in the long term.
    C. The instrument has been adopted by industry and is regularly deployed at meteorological monitoring networks, solar energy generating facilities, or climate measurement facilities.
    D. New advances in instruments: Based on previous testing for quality and reliability and/or planned improvements that enhance measurement accuracy.
3. Meteorological/ancillary instrument: The selected instrument is deployed in this setup when one of the following conditions are fulfilled:
    A. The instrument is complementary to radiometric and/or other instrumentation deployed within the NREL-SRRL.
    B. The instrument is relevant for renewable energy stakeholders, solar energy modeling and climate research.

Note: The BMS, RMS, and ancillary data are acquired, quality controlled, and delivered to internal and external customers and the public through the MIDC (see Section 2).

5.4 Decommissioning Process

The specific criteria that will guide the NREL-SRRL staff during the decommissioning process:

1. The instrument does not conform to the specifications of one or more of the lists provided in Section 5.2.1 regarding selection and application.
2. Loss of functionality: The reliability of the instrument cannot serve its purpose well. A newer instrument of higher quality is commercially available.

3. Cost of maintenance: The cost to maintain or repair an instrument is expensive relative to the usage/outcome.
4. A new/improved/revised version of the instrument is available from manufacturer. This is applicable when an instrument is discontinued by the manufacturer.
5. Stakeholder adoption: The instrument is no longer commonly used by industry/research institution. Exception: Continuity is required for long-term records.

In all cases, a candidate instrument's period of record in the MIDC database will be considered. For an instrument with a long history of data that adequately characterizes its performance in a variety of operating scenarios, a greater emphasis will be given to its decommissioning.

If one or more of these criteria apply to an instrument deployed at the NREL-SRRL, the team use expert judgement on proceeding with the decommissioning process. For example, an Eppley model 8-48 used for diffuse measurement is continually deployed because it meets Criterion 1 but not Criterion 5.

5.5 Evaluation Schedule

A set of procedures is followed when an instrument is in the decommissioning category. Some or all of these procedures will be carried out based on relevance:

- Identify and engage the stakeholders, including the manufacturer (i.e., if it is in business), on the decision.
- Notify users ahead of time (at least 1 month prior) about the decommissioning plan.
- Assign responsibility within the NREL-SRRL team to assume the decommissioning process.
- Develop documentation of the reasons for decommissioning, and place it on record at the MIDC.
- Establish an estimated timetable for the decommissioning.
- Archive the data before decommissioning. (Note: The MIDC automatically does this.)

5.6 Standard Operating Procedure Update

This document will be evaluated and, if necessary, updated annually.

References

Dutton, E. G., J. J. Michalsky, T. Stoffel, B. W. Forgan, J. Hickey, D. W. Nelson, T. L. Alberta, and I. Reda. 2001. "Measurement of Broadband Diffuse Solar Irradiance Using Current Commercial Instrumentation With a Correction for Thermal Offset Errors." *Journal of Atmospheric and Oceanic Technology* 18: 297–314. https://doi.org/10.1175/1520-0426(2001)018%3C0297:MOBDSI%3E2.0.CO;2.

Habte, A., M. Sengupta, A. Andreas, I. Reda, and J. Robinson. 2017. "Radiometer Calibration Methods and Resulting Irradiance Differences." *Progress in Photovoltaics: Research and Applications* 25: 614–622. https://doi.org/10.1002/pip.2812.

Habte, A., M. Sengupta, A. Andreas, S. Wilcox, and T. Stoffel." 2016. "Intercomparison of 51 Radiometers for Determining Global Horizontal Irradiance and Direct Normal Irradiance Measurements." *Solar Energy* 133: 372–393.

International Bureau of Weights and Measures (BIPM). 2021. *International Vocabulary of Metrology: Fourth Edition—Committee Draft (VIM4 CD)*. January 11, 2021. Saint Cloud, France: Joint Committee for Guides in Metrology. JCGM-WG2-CD-01. https://www.bipm.org/documents/20126/54295284/VIM4_CD_210111c.pdf/a57419b7-790f-2cca-f7c9-25d54d049bf6.

International Organization for Standardization (ISO). 2018. ISO 9060:2018 Solar Energy—Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation. Geneva, Switzerland.

Michalsky, J. J., M. Kutchenreiter, and C. N. Long. 2017. "Significant Improvements in Pyranometer Nighttime Offsets Using High-Flow DC Ventilation." *Journal of Atmospheric and Oceanic Technology* 34 (6): 1323–1332. https://journals.ametsoc.org/view/journals/atot/34/6/jtech-d-16-0224.1.xml

Sengupta, M., A. Habte, S. Wilbert, C. Gueymard, and J. Remund. 2021. *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Third Edition*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-77635. https://www.nrel.gov/docs/fy21osti/77635.pdf.

World Meteorological Organization (WMO). 2018. *Guide to Instruments and Methods of Observation: Volume 1—Measurement of Meteorological Variables (WMO-No. 8), 2018 edition*. https://library.wmo.int/index.php?lvl=categ_see&id=10586.

Younkin, K., and C. N. Long. 2003. *Improved Correction of IR Loss in Diffuse Shortwave Measurements: An ARM Valued-Added Product*. Washington, D.C.: U.S. Department of Energy. DOE/SC-ARM/TR-009. https://www.arm.gov/publications/tech_reports/arm-tr-009.pdf?id=37.

Bibliography

Xie, Y., M. Sengupta, A. Habte, and A. Andreas. 2022. "The 'Fresnel Equations' for Diffuse Radiation on Inclined Photovoltaic Surfaces (FEDIS)." *Renewable and Sustainable Energy Reviews* 161. https://doi.org/10.1016/j.rser.2022.112362.

Zhu, T., Y. Li, Z. Li, Y. Guo, and C. Ni. 2022. "Inter-Hour Forecast of Solar Radiation Based on Long Short-Term Memory With Attention Mechanism and Genetic Algorithm." *Energies* 15 (3). https://doi.org/10.3390/en15031062.

Xie, Y., M. Sengupta, and A. Habte. 2021. "Evaluation of Models and Measurements to Estimate Solar Radiation for 1-Axis Tracking Modules at NREL's SRRL." *Proceedings of the 2021 IEEE 48th Photovoltaic Specialists Conference*: 83–87. https://doi.org/10.1109/PVSC43889.2021.9518481.

Feng, C., D. Yang, B.-M. Hodge, and J. Zhang. 2019. "OpenSolar: Promoting the Openness and Accessibility of Diverse Public Solar Datasets." *Solar Energy* 188: 1369–1379. https://doi.org/10.1016/j.solener.2019.07.016.

Kumler, A., Y. Xie, and Y. Zhang. 2019. "A Physics-Based Smart Persistence Model for Intra-Hour Forecasting of Solar Radiation (PSPI) Using GHI Measurements and a Cloud Retrieval Technique." *Solar Energy* 177: 494–500. DOI: https://doi.org/10.1016/j.solener.2018.11.046.

Tatsiankou, V., K. Hinzer, H. Schriemer, P. McVey-White, and R. Beal. 2018. "Efficient, Real-Time Global Spectral and Broadband Irradiance Acquisition." *Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC 2018)—A Joint Conference of the 45th IEEE PVSC, 28th PVSEC, and 34th EU PVSEC*: 2362–2365. https://doi.org/10.1109/PVSC.2018.8547671.

Habte, A., M. Sengupta, A. Andreas, R. Narasappa, T. Thomas, A. Wolf, and C. A. Gueymard. 2018. "Characterization of a Low-Cost Multi-Parameter Sensor for Solar Resource Applications." *Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC 2018)—A Joint Conference of the 45th IEEE PVSC, 28th PVSEC, and 34th EU PVSEC*: 2309–2312. https://doi.org/10.1109/PVSC.2018.8547790.

Xie, Y., M. Sengupta, and M. Dooraghi. 2018. "Assessment of Uncertainty in the Numerical Simulation of Solar Irradiance Over Inclined PV Panels: New Algorithms Using Measurements and Modeling Tools." *Solar Energy* 165: 55–64. https://doi.org/10.1016/j.solener.2018.02.073.

Habte, A., M. Sengupta, A. Andreas, I. Reda, and J. Robinson. 2017. "Radiometer Calibration Methods and Resulting Irradiance Differences." *Progress in Photovoltaics: Research and Applications* 25 (7): 614–622. https://doi.org/10.1002/pip.2812.

Zhu, T., H. Wei, X. Zhao, K. Zhang, and S. Fang. 2016. "A Method of Cloud Classification Based on DNI." *Proceedings of the 2016 35th Chinese Control Conference (CCC)*: 4155–4160. DOI: https://doi.org/10.1109/ChiCC.2016.7554001.

Habte, A., M. Sengupta, A. Andreas, S. Wilcox, and T. Stoffel. 2016. "Intercomparison of 51 Radiometers for Determining Global Horizontal Irradiance and Direct Normal Irradiance Measurements." *Solar Energy* 133: 372–393. https://doi.org/10.1016/j.solener.2016.03.065.

Dooraghi, M., A. Habte, I. Reda, M. Sengupta, P. Gotseff, and A. Andreas. 2014. Quantifying the Impact of Incidence-Angle Dependence on Solar Radiometric Calibration. *Proceedings of the 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC 2014)*: 2662–2667. https://doi.org/10.1109/PVSC.2014.6925477.

Habte, A., A. Andreas, L. Ottoson, C. A. Gueymard, G. Fedor, S. Fowler, J. Peterson, E. Naranen, T. Kobashi, A. Akiyama, and S. Takagi. 2014. "Spectroradiometer Intercomparison and Impact on Characterizing Photovoltaic Device Performance." *Proceedings of the 43rd ASES National Solar Conference 2014, SOLAR 2014, Including the 39th National Passive Solar Conference and the 2nd Meeting of Young and Emerging Professionals in Renewable Energy* 2: 794–801. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84944728190&partnerID=40&md5=aff374e0d013252c36a60e568b0dc070.

Zhang, Y., S. He, J. Chen, Y. Sun, and X. S. Shen. 2013. "Distributed Sampling Rate Control for Rechargeable Sensor Nodes With Limited Battery Capacity." *IEEE Transactions on Wireless Communications* 12 (6): 3096–3106. https://doi.org/10.1109/TCOMM.2013.050613.121698.

Dhakal, B., F. Mancilla-David, and E. Muljadi. 2012. "Centralized and Modular Architectures for Photovoltaic Panels With Improved Efficiency." Proceedings of the 2012 North American Power Symposium (NAPS 2012): https://doi.org/10.1109/NAPS.2012.6336314.

Zhang, Y., S. He, J. Chen, Y. Sun, and X. Shen. 2012. "Distributed Adaptive Sampling by Rechargeable Sensor Nodes With Limited Battery Capacity." *Proceedings of the 2012 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*: 1460–1465. https://doi.org/10.1109/PIMRC.2012.6362578.

Myers, D. R. 2012. "Direct Beam and Hemispherical Terrestrial Solar Spectral Distributions Derived From Broadband Hourly Solar Radiation Data." *Solar Energy* 86 (9): 2771–2782. https://doi.org/10.1016/j.solener.2012.06.014.

Dooraghi, M., M. Sengupta, B. Mather, P. Gotseff, A. Andreas, C. Wright, R. McMorrow, J. Paulino, and A. Kankiewicz. 2012. "High Resolution Solar Measurements at the DeSoto Next Generation Solar Energy Center: The Deployment Experience." *Proceedings of the World Renewable Energy Forum (WREF 2012), Including World Renewable Energy Congress XII and Colorado Renewable Energy Society (CRES) Annual Conference* 3: 2299–2306. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84871533667&partnerID=40&md5=7bd15e6f24ad71a18647cd14b5ef52bf.

Chong, W., Y. Sha, H. Xing, and W. Lü. 2012. "A New Correction Algorithm for Diffuse Irradiance Measured With Rotating Shadow-Band Pyranometer Based on Support Vector Regression." *Guangxue Xuebao/Acta Optica Sinica* 32 (1): 0112001-1-0112001-9. https://doir.org/10.3788/AOS201232.0112001.

Wang, Z., F. Wang, Z. Mi, and L. Liu. 2011. "Regression-Based Modeling Methods for Solar Radiant Exposure. *Proceedings of the 2011 International Conference on Mechatronic Science, Electric Engineering and Computer (MEC 2011)*: 2567–2570. https://doi.org/10.1109/MEC.2011.6026017.

Brooks, M. J. 2010. "Performance Characteristics of a Perforated Shadow Band Under Clear Sky Conditions." *Solar Energy* 84 (12): 2179–2194. https://doi.org/10.1016/j.solener.2010.08.010.

Stoffel, T. L., D. R. Myers. 2010. "Accuracy of Silicon Versus Thermopile Radiometers for Daily and Monthly Integrated Total Hemispheric Solar Radiation." *Proceedings of SPIE—The International Society for Optical Engineering* 7773. https://doi.org/10.1117/12.859743.

Ruffing, S. M., and G. H. K. Venayagamoorthy. 2009. "Short to Medium Range Time Series Prediction of Solar Irradiance Using an Echo State Network." *Proceedings of the 2009 15th International Conference on Intelligent System Applications to Power Systems (ISAP 2009)*. https://doi.org/10.1109/ISAP.2009.5352922.

Vignola, F., C. N. Long, and I. Reda. 2009. "Testing a Model of IR Radiative Losses." *Proceedings of SPIE—The International Society for Optical Engineering* 7410. https://doi.org/10.1117/12.826325.

Myers, D. R. 2009. "Terrestrial Solar Spectral Distributions Derived From Broadband Hourly Solar Radiation Data." *Proceedings of SPIE—The International Society for Optical Engineering* 7410. https://doi.org/10.1117/12.825307.

Brooks, M. J., and L. W. Roberts. 2009. "Establishment of a Broadband Radiometric Ground Station on the South African East Coast." *Proceedings of SPIE—The International Society for Optical Engineering* 7410. https://doi.org/10.1117/12.826089.

Hosseini, M., S. Katragadda, J. Wojtkiewicz, R. Gottumukkala, A. Maida, and T. L. Chambers. 2020. "Direct Normal Irradiance Forecasting Using Multivariate Gated Recurrent Units." *Energies* 13 (15). https://doi.org/10.3390/en13153914.

Kang, D.-K., E.-J. Yang, and C.-H. Youn. 2019. "Deep Learning-Based Sustainable Data Center Energy Cost Minimization with Temporal MACRO/MICRO Scale Management." *IEEE Access* 7: 5477–5491. https://doi.org/10.1109/ACCESS.2018.2888839.

Habte, Aron, Stephen Wilcox and Thomas Stoffel. 2015. *Evaluation of Radiometers Deployed at the National Renewable Energy Laboratory's Solar Radiation Research Laboratory*. Golden, CO: National Renewable Energy Laboratory. https://www.osti.gov/biblio/1126287.

Wilcox, S. M., and D. R. Myers. 2008. *Evaluation of Radiometers in Full-Time Use at the National Renewable Energy Laboratory Solar Radiation Research Laboratory*. Golden, CO: National Renewable Energy Laboratory. http://www.osti.gov/servlets/purl/946331-7wa2rg/.

Habte, Aron, and Manajit Sengupta. 2017. "Best Practices of Uncertainty Estimation for the National Solar Radiation Database (NSRDB 1998-2015): Preprint." Presented at the European PV Solar Energy Conference and Exhibition Amsterdam, The Netherlands, September 25–29, 2017. https://www.osti.gov/biblio/1414821.

Habte, Aron, Afshin Andreas, Manajit Sengupta, Ranganath Narasappa, Anderson F. Hoke, Peter Gotseff, Ramanathan Thiagarajan, Adam Wolf, Loreli Carranza, and Danielle Watts. 2019. *Low-Cost Multiparameter Device for Solar Resource Applications*. Golden, CO: National Renewable Energy Laboratory. https://www.osti.gov/biblio/1505549.

Sengupta, Manajit, Aron Habte, Yu Xie, Peter Gotseff, Mark Kutchenreiter, Afshin Andreas, Ibrahim Reda, Frank Vignola, Anton Driesse, Christian Gueymard, Soutir Bandyopadhyay, and Alexis Denhard. 2022. S*olar Radiation Research Laboratory (SRRL) Final Report: Fiscal Years 2019–2021*. Golden, CO: National Renewable Energy Laboratory. https://www.osti.gov/biblio/1846616.

Vignola, Frank, Josh Peterson, Rich Kessler, Sean Snider, Afshin Andreas, Aron Habte, Peter Gotseff, Manajit Sengupta, and Fotis Mavromatakis. 2022. Evaluation of Solar Reference Cells on a Two-Axis Tracker Using Spectral Measurements, United States: N. p., 2022. Web. doi:10.1063/5.0085841. Lester, A., and D. R. Myers. 2006. "A Method for Improving Global Pyranometer Measurements by Modeling Responsivity Functions. *Solar Energy* 80 (3): 322–331. https://doi.org/10.1016/j.solener.2005.02.010.

Lave, Matthew, and Jan Kleissl. 2011. "Optimum Fixed Orientations and Benefits of Tracking for Capturing Solar Radiation in the Continental United States." *Renewable Energy* 36 (3): 1145–1152. https://doi.org/10.1016/j.renene.2010.07.032.

Habte, Aron, Manajit Sengupta, Christian A. Gueymard, Ranganath Narasappa, Olivier Rosseler, and David M. Burns. 2019. "Estimating Ultraviolet Radiation From Global Horizontal Irradiance." *IEEE Journal of Photovoltaics* 9 (1): 139–146. https://doi.org/10.1109/JPHOTOV.2018.2871780.

Gueymard, Christian A. 2009. "Direct and Indirect Uncertainties in the Prediction of Tilted Irradiance for Solar Engineering Applications." *Solar Energy* 83 (3): 432–444. http://doi.org/10.1016/j.solener.2008.11.004.

Gueymard, Christian A., and Daryl R. Myers. 2009. "Evaluation of Conventional and High-Performance Routine Solar Radiation Measurements for Improved Solar Resource, Climatological Trends, and Radiative Modeling." *Solar Energy* 83 (2): 171–185. https://doi.org/10.1016/j.solener.2008.07.015.

Reda, Ibrahim, Jörgen Konings, and Yu Xie. 2015. "A Method to Measure the Broadband Longwave Irradiance in the Terrestrial Direct Solar Beam." *Journal of Atmospheric and Solar-Terrestrial Physics* 129: 23–29. https://doi.org/10.1016/j.jastp.2015.04.003.

Zhu, Tingting, Yiren Guo, Cong Wang, and Chao Ni. 2020. "Inter-Hour Forecast of Solar Radiation Based on the Structural Equation Model and Ensemble Model." *Energies* 13 (17): 4534. https://doi.org/10.3390/en13174534.

Kutscher, Charles F., and Judy C. Netter. 2014. "A Method for Measuring the Optical Efficiency of Evacuated Receivers." *Journal of Solar Energy Engineering* 136 (1): https://doi.org/10.1115/1.4026335.

Duan, Qiuhua, Yanxiao Feng, and Julian Wang. 2021. "Clustering of Visible and Infrared Solar Irradiance for Solar Architecture Design and Analysis." *Renewable Energy* 165: 668–677. https://doi.org/10.1016/j.renene.2020.11.080.

Liu, Hongda, Lun Li, Yang Han, and Fang Lu. 2019. "Method of Identifying the Lengths of Equivalent Clear-Sky Periods in the Time Series of DNI Measurements Based on Generalized Atmospheric Turbidity." *Renewable Energy* 136: 179–192. https://doi.org/10.1016/j.renene.2018.12.119.

Westbrook, Owen W. 2015. "A Sky Radiance-Based Approach to Diffuse Irradiance Transposition." *Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. https://doi.org/10.1109/PVSC.2015.7356210.

Feng, Cong, and Jie Zhang. 2020. "SolarNet: A Sky Image-Based Deep Convolutional Neural Network for Intra-Hour Solar Forecasting." *Solar Energy* 204: 71–78. https://doi.org/10.1016/j.solener.2020.03.083.

Xie, Yu, and Manajit Sengupta. 2018. "A Fast All-sky Radiation Model for Solar Applications with Narrowband Irradiances on Tilted Surfaces (FARMS-NIT): Part I. The Clear-Sky Model." *Solar Energy* 174: 691–702. https://doi.org/10.1016/j.solener.2018.09.056.

Gueymard, Chris, and Donnell Myers. 2007. "Performance Assessment of Routine Solar Radiation Measurements for Improved Solar Resource and Radiative Modeling." https://www.researchgate.net/profile/Chris-Gueymard/publication/236314658_Performance_assessment_of_routine_solar_radiation_measurements_for_improved_solar_resource_and_radiative_modeling/links/0c960524c81361f692000000/Performance-assessment-of-routine-solar-radiation-measurements-for-improved-solar-resource-and-radiative-modeling.pdf.

Chan, N., T. Young, H. Brindley, B. Chaudhuri, and N. J. Ekins-Daukes. 2010. "Variation in Spectral Irradiance and the Consequences for Multi-Junction Concentrator Photovoltaic Systems." *Proceedings of the 2010 35th IEEE Photovoltaic Specialists Conference*: 003008–003012. https://doi.org/10.1109/PVSC.2010.5614136.

Lin, Yanbin, Dongliang Duan, Xueming Hong, Xiang Cheng, Liuqing Yang, and Shuguang Cui. 2020. "Very-Short-Term Solar Forecasting with Long Short-Term Memory (LSTM) Network." *Proceedings of the 2020 Asia Energy and Electrical Engineering Symposium (AEEES)*: 963–967. https://doi.org/10.1109/AEEES48850.2020.9121512.

Sharma, Amandeep, and Ajay Kakkar. 2018. "Forecasting Daily Global Solar Irradiance Generation Using Machine Learning." *Renewable and Sustainable Energy Reviews* 82: 2254–2269. https://doi.org/10.1016/j.rser.2017.08.066.

Zhu, Tingting, Liang Wei, and Yiren Guo. 2021. "Cloud Classification of Ground-Based Cloud Images Based on Convolutional Neural Network." *Journal of Physics: Conference Series* 2035 (1): 12020. https://doi.org/10.1088/1742-6596/2035/1/012020.

Saber, Ahmed Yousuf, and Ganesh Kumar Venayagamoorthy. 2011. "Plug-in Vehicles and Renewable Energy Sources for Cost and Emission Reductions." *IEEE Transactions on Industrial Electronics* 58 (4): 1229–1238. https://doi.org/10.1109/TIE.2010.2047828.

Shaffery, Peter, Aron Habte, Marcos Netto, Afshin Andreas, and Venkat Krishnan. 2020. "Automated Construction of Clear-Sky Dictionary From All-Sky Imager Data." *Solar Energy* 212: 73–83. https://doi.org/10.1016/j.solener.2020.10.052.

Tatsiankou, V., K. Hinzer, H. Schriemer, S. Kazadzis, N. Kouremeti, J. Gröbner, and R. Beal. 2018. "Extensive Validation of Solar Spectral Irradiance Meters at the World Radiation Center." *Solar Energy* 166: 80–89. https://doi.org/10.1016/j.solener.2018.03.044.

Al Hamidi, Yasser, Shameel Abdulla, Mahmoud El Zamli, Ihab Rizk, and Nesrin Ozalp. 2012. "Design, Manufacturing and Testing of an Aperture Mechanism for a Solar Reactor." *American Society of Mechanical Engineers: Proceedings Series—Energy Sustainability*: 1661–1672. https://doi.org/10.1115/ES2011-54567.

Reda, Ibrahim, Afshin Andreas, and Peter Gotseff. 2021. "Using an Absolute Cavity Pyrgeometer to Validate the Calibration of a Transfer Standard Pyrgeometer Outdoors, Independent from the Reference Value of the Atmospheric Longwave Irradiance." Presented at the International Pyrheliometer Comparisons XIII, October 2021. https://www.osti.gov/biblio/1820319.

Feng, Cong, Jie Zhang, Wenqi Zhang, and Bri-Mathias Hodge. 2022. "Convolutional Neural Networks for Intra-Hour Solar Forecasting Based on Sky Image Sequences." *Applied Energy* 310: 118438. https://doi.org/10.1016/j.apenergy.2021.118438.

Kim, Myungchin, and Sungwoo Bae. 2017. "Decentralized Control of a Scalable Photovoltaic (PV)-Battery Hybrid Power System." *Applied Energy* 188: 444–455. https://doi.org/10.1016/j.apenergy.2016.12.037.

Appendix

Table A.1. Pyranometers Used for Broadband Downwelling Irradiance Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
Apogee	SP-510	1	---	---	385 to 2105	Thermopile	---	12/1/17	Available	---
EKO	MS-80	1	---	2	285 to 3,000	Thermopile	---	12/1/17	Available	---
EKO	MS-802	1	---	---	285 to 3,000	Thermopile	---	3/10/15	Available	Baseline Surface Radiation Network (BSRN)
EKO	MS-410	1	---	---	285 to 3,000	Thermopile	---	3/10/15	Discontinued	---
EKO	MS-602	1	---	---	285 to 3,000	Thermopile	---	3/10/15	Discontinued	---
Eppley	SPP (ventilated)	1	---	---	295 to 2,800	Thermopile	Ventilator	2/24/15	Discontinued	Atmospheric Radiation Measurement (ARM)
Eppley	GPP	1	---	---	295 to 2,800	Thermopile	---	2/25/15	Discontinued	---
Eppley	PSP (ventilated)	1	---	34	295 to 2,800	Thermopile	Ventilator	11/1/00	Discontinued	ARM, National Oceanic and Atmospheric Administration (NOAA), University of Oregon
Hukseflux	SR25	1	---	1	285 to 3,000	Thermopile	---	8/1/16	Available	---
Hukseflux	SR30-D1	0		1	285 to 3000	Thermopile	Internal fan, heater	2021	Available	Hukseflux
Kipp & Zonen	CMP11	1	---	----	285 to 2800	Thermopile	---	3/10/15	Available	---
Kipp & Zonen	CMP22	2	---	---	200 to 3600	Thermopile	---	6/22/15	Available	National Ecological Observatory Network (NEON), NOAA, University of Miami, University of Oregon, BSRN
Kipp & Zonen	CMP22 (ventilated)	1	---	---	200 to 3600	Thermopile	Ventilator	6/22/15	Available	NEON, NOAA, University of Miami, University of Oregon, BSRN
Kipp & Zonen	CM6B	1	---	---	285 to 2,800	Thermopile	---	8/4/01	Current model: CMP6	---
Kipp & Zonen	CM3	1	---	---	300 to 2,800	Thermopile	---	1/1/15	Current model: CMP3	---
YSI	TSP-700 (ventilated)	1	---	---	300 to 3000	Thermopile	Ventilator	1/1/04	Discontinued	---
Apogee	SP-110	1	---	---	360 to 1120	Photodiode	---	10/20/08	Available	---
EKO	ML-01	1	---	---	400 to 1100	Photodiode	---	3/13/15	Available	---
Kipp & Zonen	SP Lite2	1	---	---	400 to 1100	Photodiode	---	1/8/15	Available	---
LI-Cor	LI-200R	1	---	---	400 to 1100	Photodiode	---	4/10/15	Available	---
LI-Cor	LI-200	1	---	Several	400 to 1100	Photodiode	---	7/15/81	Current model: LI-200R	University of Oregon

Table A.2. Pyranometers Used for Downwelling DHI Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
Eppley	SPP (ventilated)	1	1	---	295 to 2,800	Thermopile	Ventilator	1/23/20	Discontinued	ARM, BSRN
Eppley	8 48 (ventilated)	1	1	8	295 to 2,800	Thermopile	Ventilator	1/13/99	Discontinued	ARM, NOAA, BSRN
Eppley	8 48 (shadowband)	1	1	---	295 to 2,800	Thermopile	Eppley shadowband	8/10/09	Discontinued	---
Hukseflux	SR25	1	1	---	285 to 3,000	Thermopile	---	12/1/17	Available	---
Kipp & Zonen	CM22 (ventilated)	2	1	---	200 to 3600	Thermopile	Ventilator	8/4/2001, 6/22/2015	Current model: CMP22	---

Table A.3. Pyranometers Used for Broadband Upwelling Irradiance Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
Kipp & Zonen	CM3	1	1	1	300 to 2,800	Thermopile	---	1/1/15	Current model: CMP3	---
Kipp & Zonen	CMP11	1	1	---	285 to 2800	Thermopile	---	11/27/17	Available	---
LI-Cor	LI-200	1	1	---	400 to 1100	Photodiode	---	1/7/04	Current model: LI-200R	---

Table A.4. Pyrheliometers Used for DNI Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
EKO	MS-57	1	---		200 to 4000	Thermopile	---	1/6/2014(MS56), 4/29/2019 (MS57)	Available	
Eppley	NIP	1	---	19	250 to 3000	Thermopile	---	7/15/81	Obsolete	ARM, NOAA, University of Oregon, BSRN
Eppley	sNIP	1	---	---	250 to 3000	Thermopile	---	2/25/15	Discontinued	ARM
Hukseflux	DR02	1	---	---	200 to 4000	Thermopile	---	5/22/15	Discontinued	BSRN
Kipp & Zonen	CHP1	2	---	---	200 to 4000	Thermopile	---	1/1/2015 (CHP1-1), 6/23/2015 (CHP1-2)	Available	BSRN, University of Oregon
LI-Cor	LI-201	1	---	1	400 to 1100	Photodiode	---	8/4/01	Discontinued	---
EKO	MS-56	---	---	1	---	Thermopile	---	---	---	BSRN

Table A.5. Pyranometers Used for POA Irradiance Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
Vertical:										
Eppley	PSP	4	4		295 to 2,800	Thermopile		10/25/84	Not in production	University of Oregon
LI-Cor	LI-200	4	4		400 to 1100	Photodiode		6/14/04	Current model: LI-200R	---
Fixed 40S (Rad. Twr):										
Kipp & Zonen	CMP22	1	1		200 to 3600	Thermopile		10/3/19	Available	---
Kipp & Zonen	SP Lite2	1	1		400 to 1100	Photodiode		4/10/20	Available	---
LI-Cor	LI-200R	1	1		400 to 1100	Photodiode		10/3/19	Available	---
1 Axis:										
Kipp & Zonen	CMP22	1			200 to 3600	Thermopile		3/27/20	Available	---
Kipp & Zonen	SP Lite2	1			400 to 1100	Photodiode		3/27/20	Available	---
LI-Cor	LI-200R	1			400 to 1100	Photodiode		3/27/20	Available	---
2 Axis:										
Kipp & Zonen	CMP22	1			200 to 3600	Thermopile		3/27/20	Available	---
Kipp & Zonen	SP Lite2	1			400 to 1100	Photodiode		3/27/20	Available	---
LI-Cor	LI-200R	1			400 to 1100	Photodiode		3/27/20	Available	---

Table A.6. Filtered Radiometers Used for POA and Downwelling Irradiance Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
UV radiometers, Deck, GHI:										
EKO	MS210W210W	1			280 to 315	UV filter optics		11/1/00	New model available	---
Eppley	TUVR	1		Sever al	295 to 385	Selenium barrier-layer		3/14/88	Discontinued	University of Oregon
Kipp & Zonen	CUV4	1		---	305 to 385	UV filter, photodiode		8/8/08	New model: CUV5	---
Kipp & Zonen	UV-S-A-T	1			315 to 400 (AA cal)	UV filter, photodiode		8/4/01	Discontinued	BSRN
Kipp & Zonen	UV-S-B-T	1			280 to 315 (AA cal)	UV filter, photodiode		8/4/01	Discontinued	BSRN
Solar Light	501A, UVA	1			315 to 400	UV filter optics		12/1/17	Available	BSRN
Solar Light	501A, UVB	1		2	280 to 315	UV filter optics		11/1/00	Available	BSRN
YES	UVB-1	1		1	280 to 315	UV filter optics		11/1/00	Not available	NOAA, BSRN
UV Radiometers, Deck, DNI:										
Eppley	TUVR	1			295 to 385	Selenium barrier-layer	Collimation tube	7/3/90		---
Kipp & Zonen	CUVA2	1			315 to 400	UV filter, photodiode		11/1/00	Discontinued	---
Kipp & Zonen	CUVB2	1			280 to 315	UV filter, photodiode		11/1/00	Discontinued	---
Eppley	RG780 NIP	1			Cut-on 780	Thermopile		3/14/88	Discontinued	---
UV radiometers, 40S:										
Kipp & Zonen	CUV4	1			305 to 385	UV filter, photodiode ?		8/14/18	New model: CUV5	---
Filtered radiometers:										
Eppley (GHI)	PSP RG780	1			Cut on - 780	Thermopile		3/14/88	Not available	---
Kipp & Zonen (GHI)	PQS-1	1			400 to 700	Photodiode		3/10/15	Available	NEON
LiCor (GHI)	Li-190 Quantum	1		Sever al	400 to 700	Photodiode		8/4/01	Li-190R available	NOAA

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
LiCor (GHI)	Li-210 Photometric	1		Sever al	Curve center - 555	Photodiode		12/21/05	Li-210R available	University of Oregon
LiCor (Upwelling)	LI-190 Quantum	1			400 to 700	Photodiode		1/7/04	Li-190R available	---
LiCor (DNI)	LI-190 Quantum	1			400 to 700	Photodiode		8/27/12	Li-190R available	---
Kipp & Zonen (GHI)	CUVA1	0		1					Discontinued	---
Kipp & Zonen (GHI)	CUVB1	0		1					Discontinued	---
EKO	MS-210W	0		4						---
Eppley Photometer				1						---
TWC	Photometer	1			500	Photodiode		3/14/88	Discontinued	---
Prede	POM-01C	1			Channels, 315 to 1020	Si-photodiode	Solar tracker	10/16/08	Available	National Center for Atmospheric Research (NCAR)

Table A.7. Pyrgeometers Used for Near-Surface Downwelling Infrared Irradiance Measurements in the BMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
Apogee	SL-510	1	1		5 to 30 um	Thermopile		12/1/17	Available	---
Eppley	PIR (shaded)	1	1		3.5 to 50 um	Thermopile	Ventilator	1/13/99	Not in production	ARM, NOAA, BSRN
Kipp & Zonen	CGR4 (shaded)	1	1		4.5 to 42 um	Thermopile	Ventilator	8/4/01	Available	BSRN
UPWELLING:										---
Eppley	PIR	1	1		3.5 to 50 um	Thermopile		1/13/99	Discontinued	University of Oregon
Kipp & Zonen	CG3	1	1		4.5 to 42 um	Thermopile		1/1/15	New model: CGR3	---

Table A.8. Reference Cells Used for Measurements of the Irradiance Available to PV Cells in the Research Channel

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
<u>Deck:</u>										
Autonometrics	810226-02	1		1		Si			Available	---
Autonometrics	810157	1							Available	---
EETS	RCO	1		3		Si			Available	---
IMT	IMT 17-18	1		6		Si			Available	---
<u>40 Tilt:</u>										
Autonometrics	810226-02	1						4/29/20	Available	---
Autonometrics	810226-03 (CdTe)	1						4/29/20	Available	---
EETS	RCO1	1						4/29/20	Available	---
Fraunhofer	RS-05-D	1				Si		4/29/20	Available	---
IKS	ISET Amorph	1				Si		4/29/20	Available	---
IKS	ISET Mono	1						4/29/20	Available	---
IKS	ISET Poly	1						4/29/20	Available	---
IMT	IMT 17-18	1						4/29/20	Available	---
NES	Mono	1				Si		4/29/20	Available	---
NES	Poly	1						4/29/20	Available	---
<u>1-Axis:</u>										
Autonometrics	810226-03 (CdTe)	1						3/27/20	Available	---
EETS	RCO1	1						3/27/20	Available	---
IKS	ISET Mono	1						3/27/20	Available	---
IMT	IMT 17-18	1						3/27/20	Available	---
NES	SOZ-03 Mono	1						3/27/20	Available	---
<u>2-Axis:</u>										
Autonometrics	810226-03 (CdTe)	1						3/27/20	Available	---
EETS	RCO1	1						3/27/20	Available	---
Fraunhofer	RS-05-D	1						3/27/20	Available	---
IKS	ISET Mono	1						3/27/20	Available	---

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
IMT	IMT 17-18	1						3/27/20	Available	---
NES	SOZ-03 Mono	1						3/27/20	Available	---

Table A.9. Spectroradiometers Used for Spectral Irradiance Measurements

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
Deck:										
EKO	Wiser MS 711	1			300 to 1100	Grating spectroradiometer	Collimation tube	3/13/2014	Available	---
EKO	Wiser MS 712	1			900 to 1700	Grating spectroradiometer	Collimation tube	3/13/2014	Available	---
Spectrafy	Solar SIM-G	1			280 to 4000 derived	Filters + photodiodes		4/30/21	Available	---
Spectrafy	Solar SIM-D2+	1			280 to 4000 derived	Filters + photodiodes		9/1/2016	Available	---
Prede	PGS-100	1			350 to 1050	Si-CCD	Solar tracker	8/6/08	Available	Laboratory for Atmospheric and Space Physics (LASP)
1-Axis:										
EKO	Wiser MS 710	1			350 to 950	Grating spectroradiometer		10/3/2017	Discontinued	---
EKO	Wiser MS 712	1			900 to 1700	Grating spectroradiometer		10/3/2017	Available	---
2-Axis:										
EKO	Wiser MS 711	1			300 to 1100	Grating spectroradiometer		1/27/2000	Available	---
EKO	Wiser MS 712	1			900 to 1700	Grating spectroradiometer		1/27/2000	Available	---
Not at SRRL:										
EKO	MS 711	1				Grating spectroradiometer		8/24/2018		---
EKO	MS 700	1				Grating spectroradiometer		8/20/2008		NREL Outdoor Testing Facility, University of Oregon
EKO	MS 701			1	300 to 400	Grating spectroradiometer			Discontinued	---
LICOR	LI-1800			6	300 to 1100	Monochromator	Temp Ctrl, DNI tube		Discontinued	---
NREL	AOCS			1	300 to 4000 derived	Filtered photodiodes			Discontinued	---

Table A.10. Radiometers in the RMS

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any other Meteorological Networ1k
Deck SE Corner 40S:										
Kipp & Zonen	SP Lite	1			400 to 1100	Photodiode		8/4/2001	Current model: SP Lite2	---
Sun Edison:										
LI-Cor	LI-200	1	1		400 to 1100	Photodiode		11/15/11	Current model: LI-200R	---
SRRL:										
Kipp & Zonen	SP Lite	1	---	---	400 to 1100	Photodiode	---	8/4/01	Current model: SP Lite2	---
Delta-T	SPN-1	1	---	1	400 to 2700	Thermopile	Internal shade	1/1/08	Available	NEON
Irradiance	RSR2/LiCor Li200/WXT-520	1	---	---	400 to 1100	Photodiode	Motorized Rotating Shadowband Radiometer (RSR), Wind Speed (WS),Wind Direction (WD), Temperature (Temp), Relative Humidity (RH), Barometric Pressure (BP)	6/19/07	New product: RSR3	---
LBL	Circumsolar Telescope	0		1		Multi wavelength		2006	Inoperative-in storage and not deployed	---

Table A.11. Meteorological Measurements Within SRRL (BMS, RMS, and Other)

Manufacturer	Model	QTY #	Calibration Spare QTY#	Spare QTY#	Spectral Range (nm)	Sensor	Accessories	Commission Date	Availability From Manufacturer	Availability in Any Other Meteorological Network
EKO (Deck)	ASI-16 All sky camera	1			N/A	All sky camera	Ventilator	9/26/17	ASI-16 is now sold	---
YES (Deck)	TSI-880 All sky camera	1			N/A	All sky camera	Heated reflector	8/1/04	Not available	ARM
Novalynx (Deck)	260-2590	1			N/A	Moisture detector		12/1/17	Not available	---
Trimble (Deck)	PWV	1			N/A	Precipitable water vapor	GPS Antenna	6/13/1012		---
Vaisala (E. Rail)	HMP60	1	1		N/A	Temp, RH	Nat. Asp. Radiation shield	11/1/00	Available	---
Vaisala (Rad. Tower)	HMP60	1	(swaped w/above)		N/A	Temp, RH	Nat. Asp. Radiation shield	9/1/08	Available	---
Vaisala (Sun Ed. PV)	HMP60	1	(swaped w/above)		N/A	Temp, RH	Nat. Asp. Radiation shield	11/1/00	Available	---
Vaisala (Data lab)	HMP60	1	(swaped w/above)		N/A	Temp, RH				---
Vaisala (Optics Lab)	HMP45	2			N/A	Temp, RH				---
Vaisala (Staging Area)	HMP45	1			N/A	Temp, RH				---
Fluke (Metrology Lab)	Dewk	2	2		N/A	Temp, RH				---
RM Young (Deck)	3001	1	1		N/A	WS, WD		9/24/08	Available	---
RM Young (Rad. Tower)	3001	1	1		N/A	WS, WD		9/8/08	Available	---
NRG (Sun Ed. PV)	40C	2	2		N/A	WS 2 levels		9/9/00	Available	---
NRG (Sun Ed. PV)	200P	2	2		N/A	WD 2 levels		11/1/2000?	Available	---
Boltec (Rad. Tower)	EFM-100	1			N/A	Atmospheric Electric field	Motorized shutter	9/27/10	Available	---
Campbell Scientific (Snow pad)	TB4	1			N/A	Tipping bucket - precipitation		9/8/17	Available	---
Campbell Scientific (Snow pad)	SR50A	1			N/A	Ultrasonic, snow depth		9/6/2007 (orig. sensor 12/21/2005)	Available	---
Setra (Rad. Tower)	278	1	1		N/A	BP	RM Young pressure port	7/28/99	Available	---

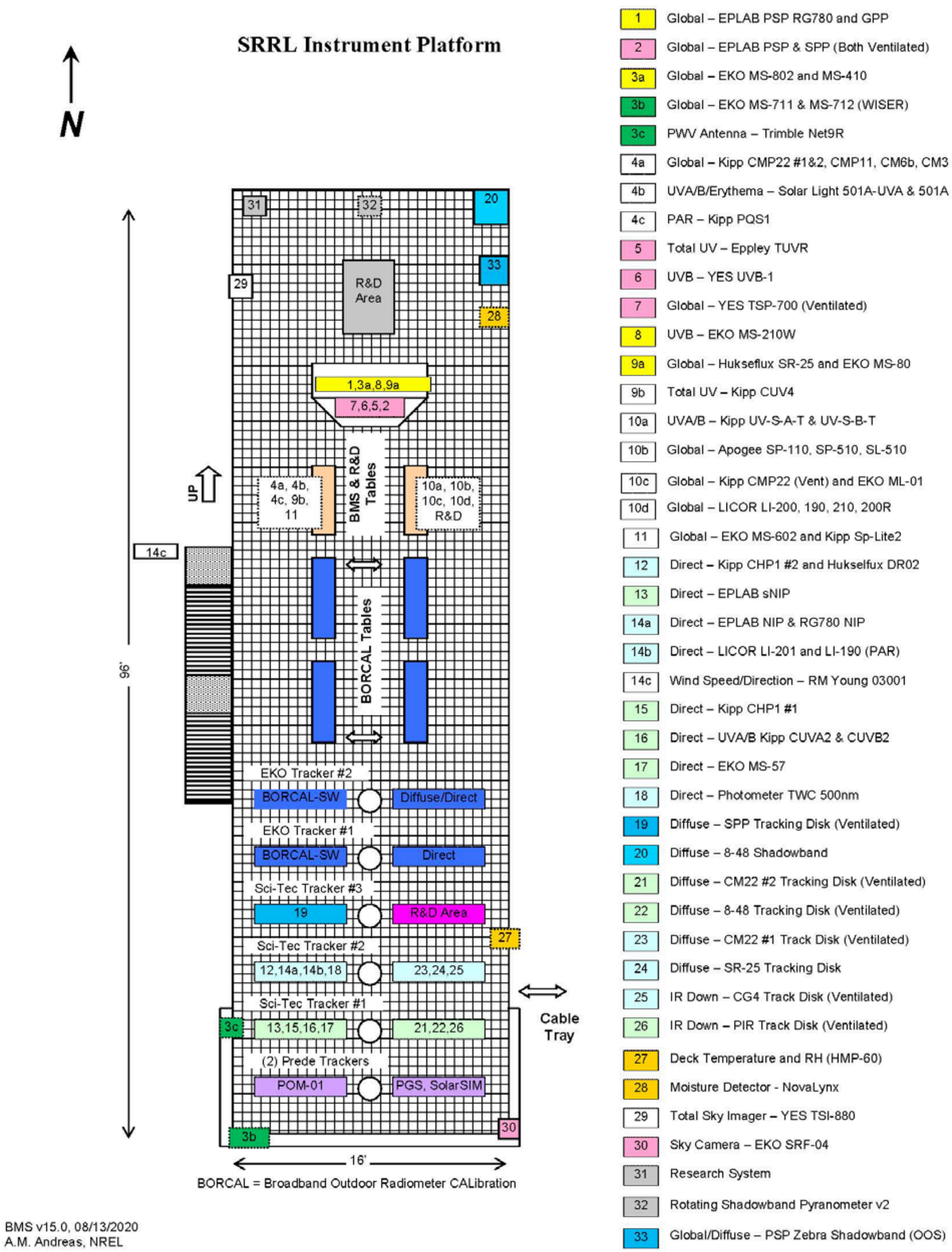

Figure A.1. BMS measurement devices on the NREL-SRRL deck

Current as of February 1, 2022

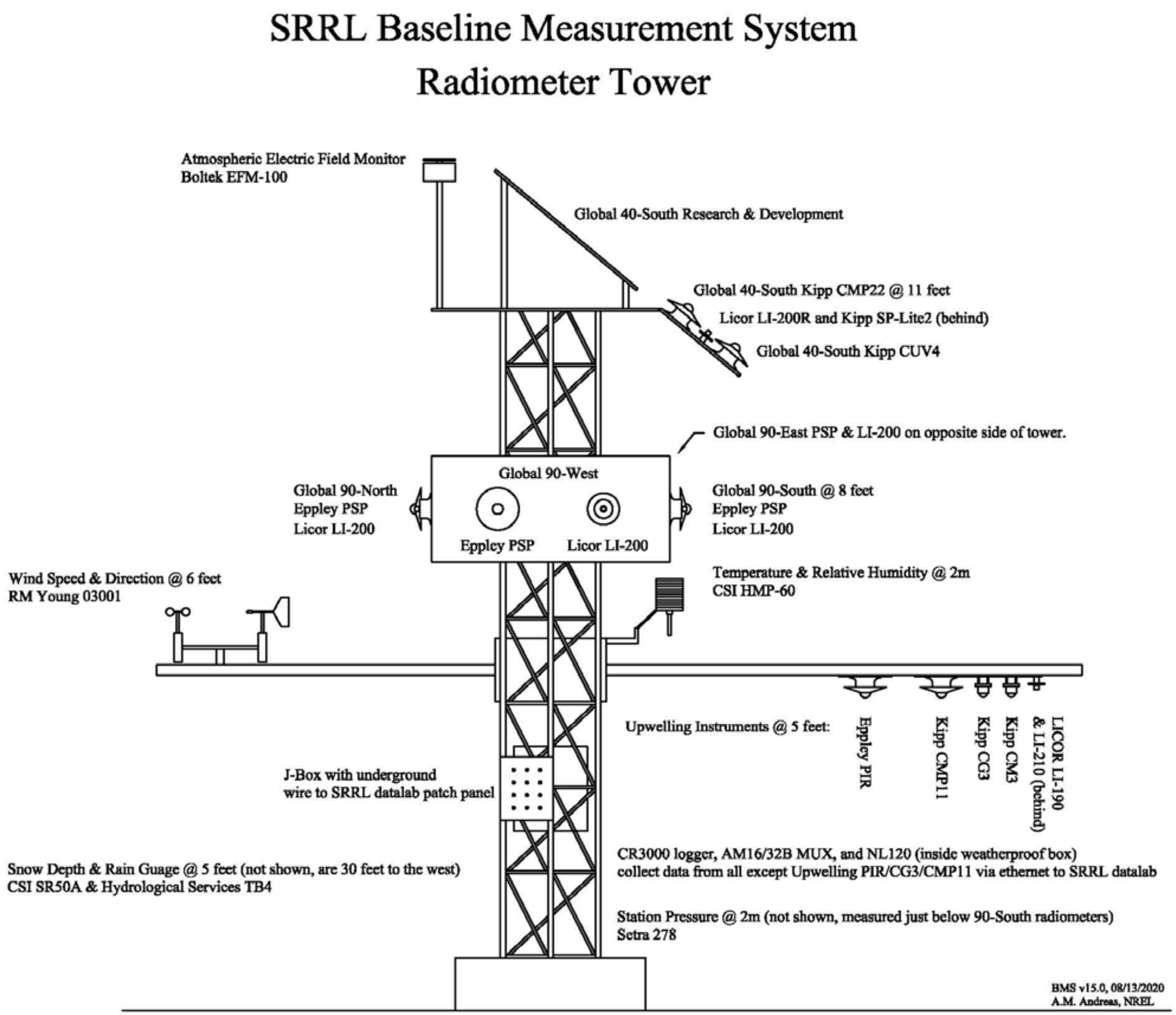

Figure A.2. Instrumentation of the NREL-SRRL radiometer tower

Current as of February 1, 2022

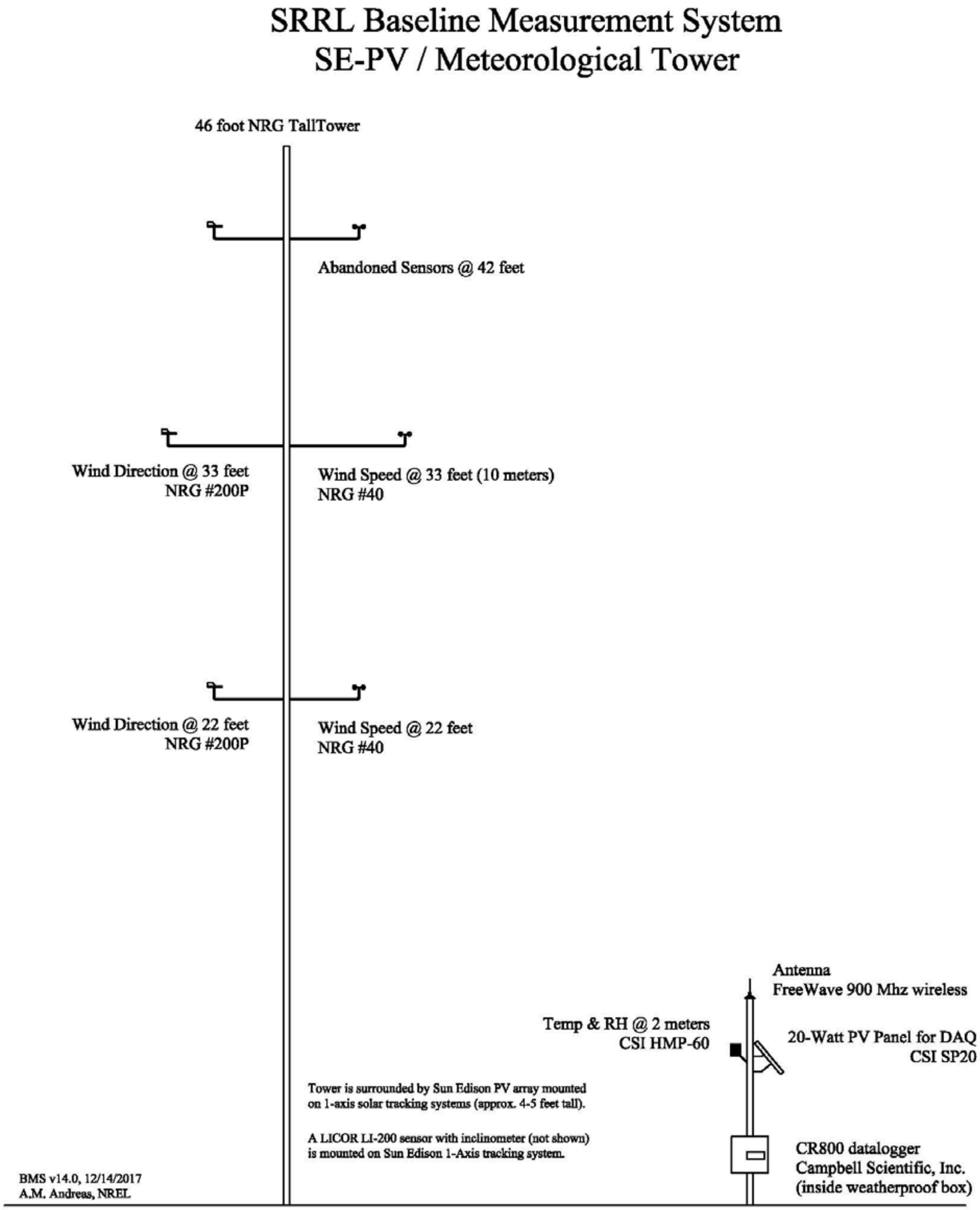

Figure A.3. Instrumentation of the NREL-SRRL meteorological tower

Current as of February 1, 2022

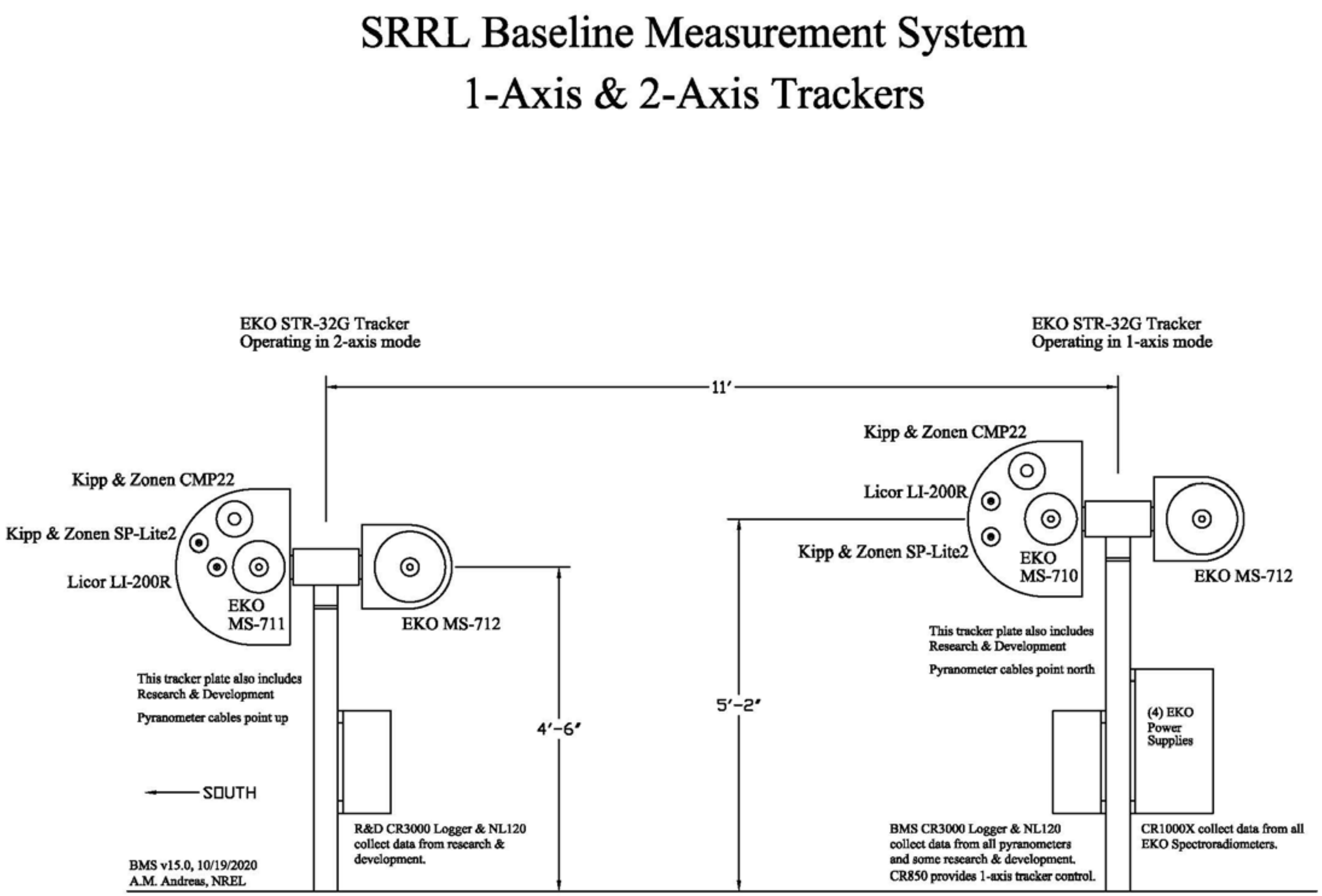

Figure A.4. Instrumentation of the NREL-SRRL PV resource setup

Current as of February 1, 2022