P1.15 CURRENT SOLAR RADIATION MEASUREMENT AND MODELING IN THE UNITED STATES

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1. INTRODUCTION

High-quality solar resource data is essential for the development and successful application of solar energy technologies. Because the spatial distribution of solar resources across the United States is far more complex than can be represented by a few dozen monitoring stations, significant progress is being made in using satellite imaging technology to provide high-resolution, large-area assessments (Renné et al. 1999). Nevertheless, a network of high-quality, long-term solar monitoring stations is still needed to validate the satellite-derived results and to provide the time-series data needed by solar technology designers and planners. However, despite the importance of the data to the solar industry, the existence of an enduring, long-term national solar network remains elusive. Therefore, efforts are currently underway to coordinate major regional and national network activities to support these national renewable energy assessments.

2. BACKGROUND

Historically, the primary national resource for high-quality, ground-based solar data has been the solar monitoring network maintained by the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS). Over the years, this network suffered periodic funding reductions, and in the late 1970s, it would have disappeared altogether if not for support by the U.S. Department of Energy (DOE) because of the increased interest in renewable energy technologies. However, in the early 1990s the NWS decided to terminate its solar measurement activities as part of a modernization and streamlining program. Since that time, there have been several efforts, including interagency efforts by the National Renewable Energy Laboratory (NREL) and others, to resurrect a national network. Although not formally coordinated, there are a number of measurement programs in the United States with a "common thread" of multi-component measurements, common calibration practices traceable to world standards, common sampling and data quality assessment procedures, and web-based data dissemination. The agencies and organizations are conducting these measurement programs for somewhat independent purposes, but have often agreed to cost share resources and collaborate on data quality assessment, calibration, and data dissemination procedures in a way that provides some commonality and uniformity across all participating stations.

3. SPECIFIC PROGRAMS

In this section, we describe several major high-quality measurement programs that are coordinated in a number of ways. These activities provide long-term, high-quality insolation data with calibrations traceable to the World Radiometric Reference (WRR) established in Davos, Switzerland, common data quality assessment tools, and web-based data dissemination.

3.1 *NREL's CONFRRM/HBCU Network*

In the mid-1990s, NREL initiated a cooperative measurement program based on cost sharing with local and regional agencies. The program is known as the Cooperative Network for Renewable Resource Measurements (CONFRRM).

The original concept for CONFRRM was to cost share efforts between NREL and other agencies with experience in operating solar and wind energy monitoring networks. The objective is to expand the geographic coverage of measurement locations and provide high-quality data for determining site-specific solar and wind energy resources, as well as data for validation and testing models to predict available resources based on meteorological or satellite data. The CONFRRM solar sites consist of an Eppley™ Precision Spectral Pyranometer (PSP) and a Licor™ for global horizontal measurements, an Eppley™ Normal Incidence Pyrheliometer (NIP), and an Eppley PSP on a SCI-TEC™ tracker with a shading ball for diffuse sky measurements. The five original CONFRRM solar sites are all located in Texas and are operated by the Solar Energy Laboratory at the University of Texas/Austin. These CONFRRM sites have also been incorporated into the other 10 stations that comprise the Texas Solar Monitoring Program. The CONFRRM solar data web site, which contains further information about the program as well as specific information and data sources for each site, can be found at http://rredc.nrel.gov/solar/new_data/confrrm.

Prior to CONFRRM, NREL also supported the six-station Historically Black Colleges and Universities (HBCU) network in the southeastern United States.

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This network operated from November 1985 through December 1996, and provided 5-minute averages of global and diffuse horizontal solar radiation. Three stations also monitored the direct normal solar resource. In January 1997, five of the six stations (South Carolina State University stopped operations at that time) became part of the CONFRRM network and are still in operation. Historical HBCU data can be found at http://rredc.nrel.gov/solar/old_data/hbcu. Financial support for operating these remaining HBCU stations is provided by the National Center for Photovoltaics at NREL.

Since CONFRRM was originally established, three additional sites have been added to the configuration. Two of these sites, the Southwest Technology Development Institute in Las Cruces, NM, and the Florida Solar Energy Center in Cocoa, FL, operate regional solar energy research laboratories for the U.S. DOE. Both sites have been conducting solar measurements for a long time. The third site, in Eugene, OR, is operated by the University of Oregon Solar Monitoring Laboratory and is part of the Pacific Northwest Solar Monitoring Network (information can be found at http://solardat.uoregon.edu).

The CONFRRM network is a highly cost-shared activity, and without the efforts of the participating stations, the network's existence would not be possible. NREL provides instrument calibration support with the calibrations traceable to the WRR established in Davos, Switzerland. NREL also assists with some site maintenance support, data quality assessment support, and maintenance of the CONFRRM web site. The station operators provide all routine site operations and preliminary data processing.

Information on the CONFRRM sites is provided in Table 1, and their location is shown in Figure 1.

3.2 *The NOAA ISIS/SURFRAD Network*

In the mid-1990s, as the NWS modernized its observation systems and terminated its solar measurement activities, NOAA's Air Resources Laboratory (ARL) agreed to maintain a subset of the original network, renaming it the Integrated Surface Insolation Study (ISIS). In addition, through support from NOAA's Office of Global Programs, several new high-quality stations, known as Surface Radiation (SURFRAD) stations, were installed as part of a climate change research program. This revamped ISIS/SURFRAD network is described by Hicks, DeLuisi, and Matt (1996). ISIS is known as a Level 1 network, which essentially continues the earlier NOAA surface-based solar monitoring programs, with measurements conducted in the visible and ultraviolet wavebands. The Level 2 network, SURFRAD, focuses on the surface radiation balance. There are currently nine ISIS stations and six SURFRAD stations in operation. Desert Rock, NV, formerly an ISIS station, was upgraded to SURFRAD status in March 1998 (see Table 1). The network is shown in Figure 2. Further information on the ISIS network can be found at http://www.atdd.noaa.gov/isis/isis.htm. Information on SURFRAD is found at http://www.srrb.noaa.gov/surfrad/sitepage.htm.

3.3 *Other Solar Monitoring Programs*

Besides the CONFRRM and ISIS/SURFRAD networks, a variety of other measurement programs are underway with which NREL has either direct involvement or some coordination responsibility with the operators. We include these programs here, which serve to add to a national network of high-quality solar measurement stations. Stations described in this section are also shown in Figure 3 for the 48 contiguous United States.

3.3.1 *NREL's Solar Radiation Research Laboratory*

NREL has maintained continuous measurements as part of the Baseline Measurement System (BMS) program at the Solar Radiation Research Laboratory (SRRL), located at the top of South Table Mountain near Golden, CO. The SRRL is also the premier site in the United States for conducting broadband outdoor radiometer calibrations, which assure that the calibration of the radiometers is traceable to the WRR. All instruments used in CONFRRM, as well as NOAA's ISIS network, are calibrated at the SRRL. In addition, each year a number of agencies participate in an absolute cavity intercomparison at SRRL. These intercom-parisons allow each participant to conduct its own radiometer calibrations traceable to the WRR. Consequently, most of the thermopile-type instruments that are included in the existing "virtual" national network have calibrations traceable to the WRR. Information on the SRRL Baseline Surface Measurements is included in Table 1, and SRRL data can be found at http://srrl.nrel.gov.

3.3.2 *The Atmospheric Radiation Measurement Program*

The Atmospheric Radiation Measurement (ARM) Program began in 1990 to provide a high-quality, continuous source of data from key regimes around the world. These data would be used to improve our understanding of the role of clouds in the climate system and the treatment of cloud processes in general circulation models. Three regions around the world have been chosen to conduct long-term, continuous measurements: the Southern Great Plains (SGP) site in central Oklahoma; the North Slope of Alaska (NSA) site near Barrow, AK; and the Tropical Western Pacific (TWP) site in the western equatorial Pacific region.

In 1991, measurements began at the Central Facility (CF) of the SGP site, and there are currently 23 radiometric measurement stations over a 200-km x 200-km region in the SGP. More information on ARM can be found at http://www.arm.gov. NREL plays an essential role in the ARM program through radiometer mentorship, calibration, and data quality assessment. As part of the virtual national network, the radiometric station located at the ARM CF and the Baseline

Surface Radiation Network (BSRN) station adjacent to the CF are included here and are shown in Table 1.

3.3.3. *NOAA's Climate Monitoring and Diagnostics Laboratory*

The Climate Monitoring and Diagnostics Laboratory (CMDL) of NOAA includes activities in empirical and theoretical research of the Earth's surface radiation budget. These activities include meteorological measurements made at diverse sites around the world. In the United States, these sites include Point Barrow, AK; Mauna Loa Observatory, HI; and the Boulder Atmospheric Observatory near Erie, CO. Information on the CMDL measurement sites can be found at http://wwwsrv.cmdl.noaa.gov/ star/field. The U.S.-based sites are also included in Table 1.

3.3.4 *The Baseline Surface Radiation Network*

The BSRN is an activity of the World Climate Research Program aimed at detecting important changes in the Earth's radiation budget that may cause climate change (Ohmura et al., 1998). At approximately 40 stations around the world, solar and atmospheric radiation is measured with instruments of the highest available accuracy and at a very high frequency (minutes). The radiation data, along with associated meteorological data, are stored in an integrated database at the World Radiation Monitoring Center at the Eidgenössiche Technischen Hochschule, Zurich, Switzerland. Information on the BSRN can be found at http://bsrn.ethz.ch/wrmc/ bsrn_menu.html.

At present, there are seven BSRN stations operating in the United States: the SURFRAD stations at Fort Peck, MT, Boulder, CO, Bondville, IL, and Goodwin Creek, MS; the ARM/SGP Clouds and Radiation Testbed site near Lamont, OK (co-located with the ARM/SGP Central Facility); the Erie Meteorological Tower near Boulder, CO (operated by CMDL, as described in Section 3.3.3); and Barrow, AK (co-located with the ARM/NSA site and also operated by CMDL as described in Section 3.3.3). These stations are included in Table 1.

3.3.5 *The International Daylight Measurement Programme*

The International Daylight Measurement Programme (IDMP) was established in 1991 by the Commission Internationale de l"Eclairage (International Lighting Commission) based in Vienna, Austria. Information on the IDMP can be found at http://idmp.entpe.fr. Currently, two IDMP stations are operating in the United States: the Atmospheric Sciences Research Center (ASRC) of the State University of New York at Albany (SUNY/Albany), and the University of Michigan at Ann Arbor. Although not a formal participant in CONFRRM, the IDMP station in Albany is included in Table 1 because of the long-term funding support by the U.S. DOE of the solar radiation conducted by the ASRC, which is responsible for maintaining the IDMP station.

4. THE U.S. NETWORK

Figure 4 shows a combined view of all the stations and networks in the 48 contiguous United States, as described in Section 3. The figure also includes the extended networks associated with the University of Texas and the Pacific Northwest and the full complement of stations at the ARM site in Kansas and Oklahoma (these extended stations are not listed separately in Table 1).

TABLE 1: Partial List of Stations Involved in a National Coordinated Solar Monitoring Activity.

NETWORK IDENTIFIER	OPERATOR	STATION NAME	N LATITUDE (DEG.)	W LONGITUDE (DEG.)	START of MEASUREMENTS
CONFRRM	UNIVERSITY OF TEXAS SOLAR LA	AUSTIN, TX	30.29	97.74	APRIL, 1997
CONFRRM	UNIVERSITY OF TEXAS SOLAR LA	CANYON, TX	34.99	101.9	JUNE, 1997
CONFRRM	UNIVERSITY OF TEXAS SOLAR LA	CLEAR LAKE, TX	29.57	95.09	AUGUST, 1997
CONFRRM	UNIVERSITY OF TEXAS SOLAR LA	EDINBURG, TX	26.3	98.17	APRIL, 1997
CONFRRM	UNIVERSITY OF TEXAS SOLAR LA	EL PASO, TX	31.77	106.5	JULY, 1997
CONFRRM/HBCU	BETHUNE-COOKMAN COLLEGE	DAYTONA BEACH, FL	29.18	81.02	AUGUST, 1985
CONFRRM/HBCU	BLUEFIELD STATE UNIVERSITY	BLUEFIELD, WV	37.27	81.24	NOVEMBER, 1985
CONFRRM/HBCU	ELIZABETH CITY STATE UNIV.	ELIZABETH CITY, NC	36.3	76.25	SEPTEMBER, 1985
CONFRRM/HBCU	MISSISSIPPI VALLEY STATE UNIV.	ITTA BENA, MS	33.5	90.33	JULY, 1985
CONFRRM/HBCU	SAVANNAH STATE UNIVERSITY	SAVANNAH, GA	32.03	81.07	AUGUST, 1985
CONFRRM/OTHER	SW TECHNOLOGY DEV. INSTITUTE	LAS CRUCES, NM	32.27	106.74	MARCH, 1998
CONFRRM/OTHER	FLORIDA SOLAR ENERGY CENTEF	COCOA, FL (1)	28.4	80.8	JANUARY, 2000
CONFRRM/OTHER	U OF OR SOLAR ENERGY LAB.	EUGENE, OR	44.05	123.07	MAY, 1975
ISIS	NOAA/ARL	HANFORD, CA	36.31	119.63	MAY, 1995 (2)
ISIS	NOAA/ARL	TALLAHASSEE, FL	30.38	84.37	JANUARY, 1995 (2)
ISIS	NOAA/ARL	ALBUQUERQUE, NM	35.04	106.62	JANUARY, 1995 (2)
ISIS	NOAA/ARL	BISMARK, ND	46.77	100.77	JANUARY, 1995 (2)
ISIS	NOAA/ARL	OAK RIDGE, TN	35.96	84.29	JANUARY, 1995 (2)
ISIS	NOAA/ARL	SALT LAKE CITY, UT	40.77	111.97	APRIL, 1995 (2)
ISIS	NOAA/ARL	STERLING, VA	38.98	77.47	AUGUST, 1995 (2)
ISIS	NOAA/ARL	SEATTLE, WA	47.68	122.25	MARCH, 1995 (2)
ISIS	NOAA/ARL	MADISON, WI	43.13	89.33	JUNE, 1996 (2)
SURFRAD	NOAA/ARL	TABLE MT., CO	40.13	105.24	JULY, 1995 (3,4)
SURFRAD	NOAA/ARL	BONDVILLE, IL	40.05	88.37	APRIL, 1994 (3)
SURFRAD	NOAA/ARL	GOODWIN CREEK, MS	34.25	89.87	DECEMBER, 1994 (3)
SURFRAD	NOAA/ARL	FORT PECK, MT	48.31	105.10	NOVEMBER, 1994 (3)
SURFRAD	NOAA/ARL	DESERT ROCK, NV	36.62	116.02	JULY, 1995 (2)
SURFRAD	NOAA/ARL	PENN STATE U, PA	40.72	77.93	JUNE, 1998
SRRL	NREL	GOLDEN, CO	39.74	105.18	APRIL, 1985
ARM/SGP CF	USDOE	LAMONT, OK	36.61	97.49	NOVEMBER, 1992 (3)
ARM/NSA	USDOE	BARROW, AK	71.30	156.68	JULY, 1997
ARM/SGP BSRN	NOAA/ARL	LAMONT, OK	36.61	97.49	JANUARY, 1995
BSRN	NOAA/CMDL	ERIE, CO (3)	40.05	105.01	JANUARY, 1992
BSRN	NOAA/CMDL	BARROW, AK	71.32	156.61	JANUARY, 1992 (3,5)
IDMP	ASRC, SUNY/ALBANY	ALBANY, NY	42.42	73.51	OCTOBER, 1991
CMDL	NOAA/CMDL	BOULDER, CO (6)	39.99	105.26	1975
CMDL	NOAA/CMDL	MAUNA LOA, HI	19.54	155.58	1976

NOTES:

(1) Eighteen years of data from previous site in Cape Canaveral, FL; 15 km east of present site

(2) Earlier data at or near this site available through the National Climatic Data Center, Asheville, NC

(3) Also designated as a BSRN station

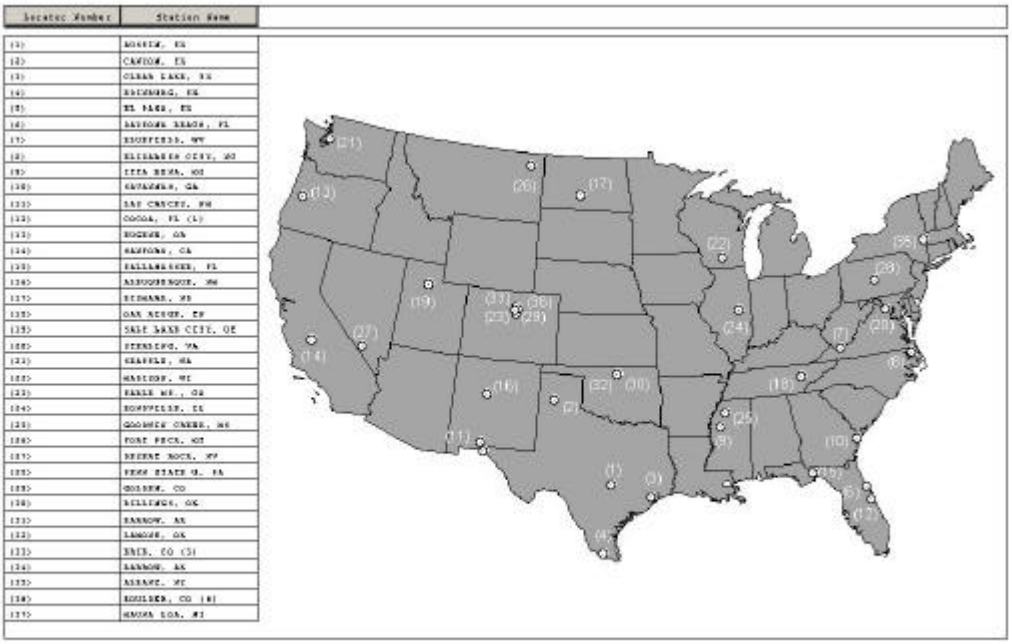
(4) Boulder Atmospheric Observatory, Located near Erie, CO

(5) Earlier data available through the CMDL web site

Figure 1: NREL's CONFRRM 13-station solar monitoring network

Figure 2: The 15-station NOAA/ARL ISIS/SURFRAD network.

Figure 3: Five additional solar monitoring stations, described in Section 3.3 (contiguous 48 United States).



Locator Number	Station Name
(1)	BOSTON, TX
(2)	CANTON, TX
(3)	CLEAR LAKE, TX
(4)	EDINBURG, TX
(5)	EL PASO, TX
(6)	DAYTONA BEACH, FL
(7)	MORGANTOWN, WV
(8)	ELIZABETH CITY, NC
(9)	FORT PECK, MT
(10)	CHATHAM, GA
(11)	SAN CARLOS, AZ
(12)	COCOA, FL (L)
(13)	ROCKER, GA
(14)	SEDONA, CA
(15)	TALLAHASSEE, FL
(16)	ALBUQUERQUE, NM
(17)	BISMARK, ND
(18)	OAK RIDGE, TN
(19)	SALT LAKE CITY, UT
(20)	STERLING, VA
(21)	SEATTLE, WA
(22)	MADISON, WI
(23)	EAGLE NE., CO
(24)	BONNEVILLE, IL
(25)	GOODWIN CREEK, MS
(26)	FORT PECK, MT
(27)	DESERT ROCK, NV
(28)	PENN STATE U, PA
(29)	GOLDEN, CO
(30)	BILLINGS, OK
(31)	BARROW, AK
(32)	LANDER, CO
(33)	ERIE, CO (3)
(34)	BARROW, AK
(35)	ARRANT, NY
(36)	BOULDER, CO (H)
(37)	HAUNA LOA, HI

Figure 4: The current national network for the 48 contiguous United States

Data access to these sites is available through NREL's Renewable Resource Data Center (RReDC) web site http://rredc.nrel.gov. This site provides direct access to the CONFRRM and SRRL data and links to the other data sources described in this paper. Information on other sources is being added continuously.

5. EXTENDING THE SPATIAL COVERAGE

The spatial coverage offered by this national monitoring program is still inadequate for the solar energy industry. Thus, over the years a number of steps have been taken to supplement measured data with modeled estimates derived from independent measurements. For example, NREL developed a National Solar Radiation Data Base, which provides modeled estimates of solar insolation for 239 NWS stations, making use of the extensive cloud cover reports available from these stations (Maxwell 1998). More recently, several activities to provide high spatial resolution, satellite-derived estimates of insolation, using models that use imagery from Geostationary Operational Environmental Satellites and Polar Orbiting Environmental Satellites, as well as ground-based observations, have also been undertaken.

6. SUMMARY AND CONCLUSIONS

Although there has been a discouraging trend toward decreased federal support for solar measurement programs in the United States over the past decade, it is heartening to find that interest in this activity remains high. Along with this comes a willingness by agencies and organizations to share resources and expertise to keep individual measurement programs and networks operational. The result of this ad hoc collaboration is that a virtual network of several dozen stations exists in the United States. This paper shows an example of what this network looks like. The authors by no means view this as a complete set, and we encourage other station operators to contact us with information on their stations so that we can add to the network shown here.

This network of current measured data sources will be a major component of the National Atlas. Although a significant amount of information is available from modeled and satellite-derived techniques, data from these measurement stations are still needed to validate the algorithms used to provide solar estimates, to provide long-term time series data, and, where direct normal data are being obtained, to calculate aerosol optical depth.

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