NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Improved Instrumentation for Solar Resource Measurements and Forecasting

Cooperative Research and Development Final Report

CRADA Number: CRD-09-349

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CRADA Report
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NOTICE

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Cooperative Research and Development Final Report

Report Date: 2/12/18

In accordance with Requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of Subject Inventions, to be forwarded to the DOE Office of Science and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: AccuFlux, Inc.

CRADA number: CRD-09-349

CRADA Title: Improved Instrumentation for Solar Resource Measurements and Forecasting

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$120,000.00
Year 2	$60,000.00
Year 3	$60,000.00
Year 4	
TOTALS	$240,000.00

Abstract of CRADA Work:

Under this Agreement, NREL will work with Participant to improve the instrumentation and measurement systems available for measuring and monitoring solar radiation elements needed by the electric utilities and solar power system integrators to adequately characterize the spatial and temporal variations of the renewable energy resources. This work includes, but is not limited to, research and development for making cost effective radiometers, solar trackers, and related instrumentation for solar resource measurements and forecasting. Cooperative R&D is proposed in three areas: Improved radiometric systems for cost effective irradiance measurements (direct normal, global, diffuse and plane-of-array); evaluation of innovative disruptive technology approaches for deriving the constituent solar energy components utilizing new fast-response thermopile measurement technologies, coupled with innovative shading geometry and tracker motion control; and low-cost solutions for sky imaging needed for resource forecasting. This work will be conducted at NREL and Participant facilities.

Introduction:

Accurate solar resource data are essential for reducing solar energy conversion deployment barriers. Solar energy is a weather-driven resource that poses unique challenges to researchers, developers, financiers, utilities, and system operators. Lack of accurate solar resource can lead to significant risks and increased costs for the design, installation, financing, and integration of renewable energy conversion systems. Through this CRADA, NREL and AccuFlux developed a framework to 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 cost and improve the operations of photovoltaic and concentrating solar power plants. This CRADA addressed the needs for a proven solar irradiance measurements to validate resource

assessment models and data used for site selection, energy system design, deployment, maintenance and operation. The deployment of the AccuFlux system was a genuine success, having fully vetted the overall system and tracker design. The result showed an objective performance of the system:

- 2AT Solar tracker long-term reliability and tracking accuracy.
- Radiometers long-term stability.
- 2AT solar tracker system remote AC power year-round with DC power backup operational effectiveness for current battery and panel sizing.
- Accurate back-calculation of global and diffuse measurement relative to the NREL Solar Radiation Research Laboratory's (SRRL) baseline Measurement System (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. Diffuse Horizontal Irradiance (DHI) signal data from the SR20 temp and directional response corrected 1 minute average and Global Horizontal Irradiance (GHI) signal data.

Solar irradiance data for BMS can be found on the Measurement and Instrumentation Data Center (MIDC) web site (http://www.nrel.gov/midc/srrl_bms/).

Result:

The 2AT solar tracking and monitoring system as tested under the CRADA, was intended to validate the feasibility of alternative methods for deriving global diffuse irradiance, in addition to vetting diffuse obtained under an unconventional shading method (i.e. pyranometer shaded by an azimuth tracking vertically fixed 90˚ shadow-band). The 2AT system demonstrated global diffuse can be back-calculated with high confidence from the horizontal normalized direct (pyrheliometer) and total global (non-shaded pyranometer) measurements, provided the global pyranometer is a performance validated secondary standard pyranometer with very low thermal offset-A bias effect. Correlation was excellent between the 2AT system back-calculated global diffuse by comparison to SRRL's CMP22_vent-corr diffuse MIDC reported hourly and daily average diffuse totals. The long-term reliability, tracking accuracy of the 2AT tracker, as well as the validity of the azimuth tracking vertically fixed shadow-band approach were all successful vetted over the duration of the CRADA campaign.

Figure 1 shows a one day comparison of the radiometers performance relative to the NREL Solar Radiation Research Laboratory's (SRRL) baseline measurement system (BMS) reference data. The 2AT Tracker system shaded SR03 diffuse data versus the SR20 back-calculated diffuse data (i.e. SR20 tcorr GHI – DR03 tcorr DHI) relative to the BMS shaded CM22 (vent/corr) diffuse data. The SR20 back-calculate diffuse is outperforming the shaded/measured SR03 tcorr diffuse pyranometer. This is because the SR03 is a single dome instrument, so dome thermal offset-A is higher than the double domed instrument like the SR20 and Kipp CM22 model. The SR20 back-calculated diffuse does correlated extremely well with the BMS CM22 (vent/corr) diffuse data for both clear and overcast sky conditions.

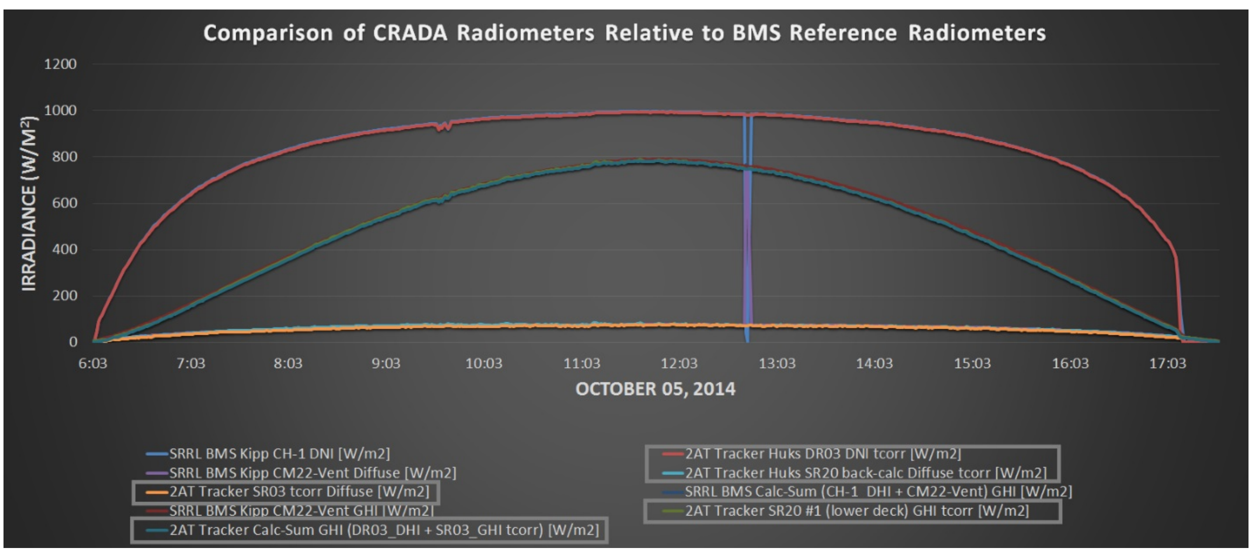

Figure 1. CRADA instruments (legend: grey box) versus BMS reference data. One day comparison

The system as a whole performed very well with the configuration of the encoder and software upgrades. The total daily averages for the 2AT Tracker system DNI, Diffuse and GHI relative to SRRL's BMS reference DNI, Diffuse were calculated(Table 1). From Table 1, the SR20 GHI total daily average vs. the BMS Calc-Sum GHI total daily average agreed within < 0.25%, The sensitivity scales of the SR20 is well aligned with the BMS reference instrument, as is the DR03 pyrheliometer installed on the tracker based on the preliminary NPC results.

Table 1: Daily irradiance comparison

Radiometers	Total Daily average (W/m^2)
SRRL BMS: Kipp CH1 DNI [W/m^2]	805.61
2AT Tracker / DR03 DNI TCorr [W/m^2]	806.26
SRRL BMS: Kipp CM22 (vent/cor) Diffuse [W/m^2]	61.48
2AT Tracker / Back-Calc DIFF TCorr [W/m^2]	59.21
2AT Tracker / SR03 DIFF_TCorr [W/m^2]	55.29
SRRL BMS: Calc-Sum GHI (Kipp CH-1_DHI + CM22-Vent_Diff) [W/m^2]	473.35
SRRL BMS: Kipp CM22 (vent/cor) GHI [W/m^2]	479.15
2AT Tracker / SR20 GHI TCorr [W/m^2]	472.27
2AT Tracker / GHI (DR03_DHI + SR03_GHI TCorr) [W/m^2]	468.34

Furthermore, figure 2 shows evaluation of one year dataset (January 2017 to November 2017) for one-minute interval. The global horizontal irradiance (GHI) evaluation was carried out by comparing each test instrument/data relative to the reference instrument using direct normal irradiance (DNI) (Kipp and Zonen model CHP1 pyrheliometer) and diffuse horizontal irradiance (DHI) (Eppley Laboratory, Inc., model 8-48) instruments. The difference or deviations from the reference irradiance measurements were calculated as a percent of the reference value for solar zenith angles less than 85 degrees (the range of available solar zenith angles throughout the year at SRRL, excluding data near sunrise and sunset). The DNI and DHI datasets were also evaluated using the DNI and DHI reference instruments.Bias greater than ±20% were considered outliers. Below are a list of possible reasons for the presence of outliers;

- The CRADA instruments were located about 200 feet away from the NREL's baseline measurement system (BMS) which includes reference data.
- The BMS instruments are on top of 19 feet height deck
- The CRADA instruments were located at 3-4 feet height with seasonal building obstruction.
- Radiometer maintenance/cleaning time differences between the CRADA and BMS radiometers.

Table 2. Instrument list and description				
	Inst.#	Radiometer	Model	Comment
GHI	1	CRADA	SR20	---
	2	CRADA	SR20	SR20 with Temperature correction
	3	CRADA	---	Calculated GHI - from models SR03 and DR03
	4	CRADA	---	Calculated GHI with temperature correction- from models SR03 and DR03
	5	BMS	CMP22	---
	6	BMS	MS-410	---
	7	BMS	SPP	---
DNI	1	CRADA	DR03	---
	2	CRADA	DR03	DR03 with Temperature correction
	3	BMS	MS-56	---
DHI	1	CRADA	SR03	---
	2	CRADA	SR03	SR03 with Temperature correction
	3	CRADA	SR03	Calculated DHI - from models DR03 and SR20
	4	CRADA	SR03	Calculated GHI with temperature correction- from models DR03 and SR20
	5	BMS	CMP22	---

As shown in Figure 2, the red line is the mean difference relative to reference data and most CRADA and BMS radiometers under test tended to have small mean perecentage difference compared to the BMS reference radiometers for GHI, DNI and DHI. The black color -boxes demonstrate the 95% confidence interval and provides information about the scatter of the differences between the reference instrument and the radiometers under test. Smaller/larger ranges of the 95% confidence intervals depict small/larger differences in the data.

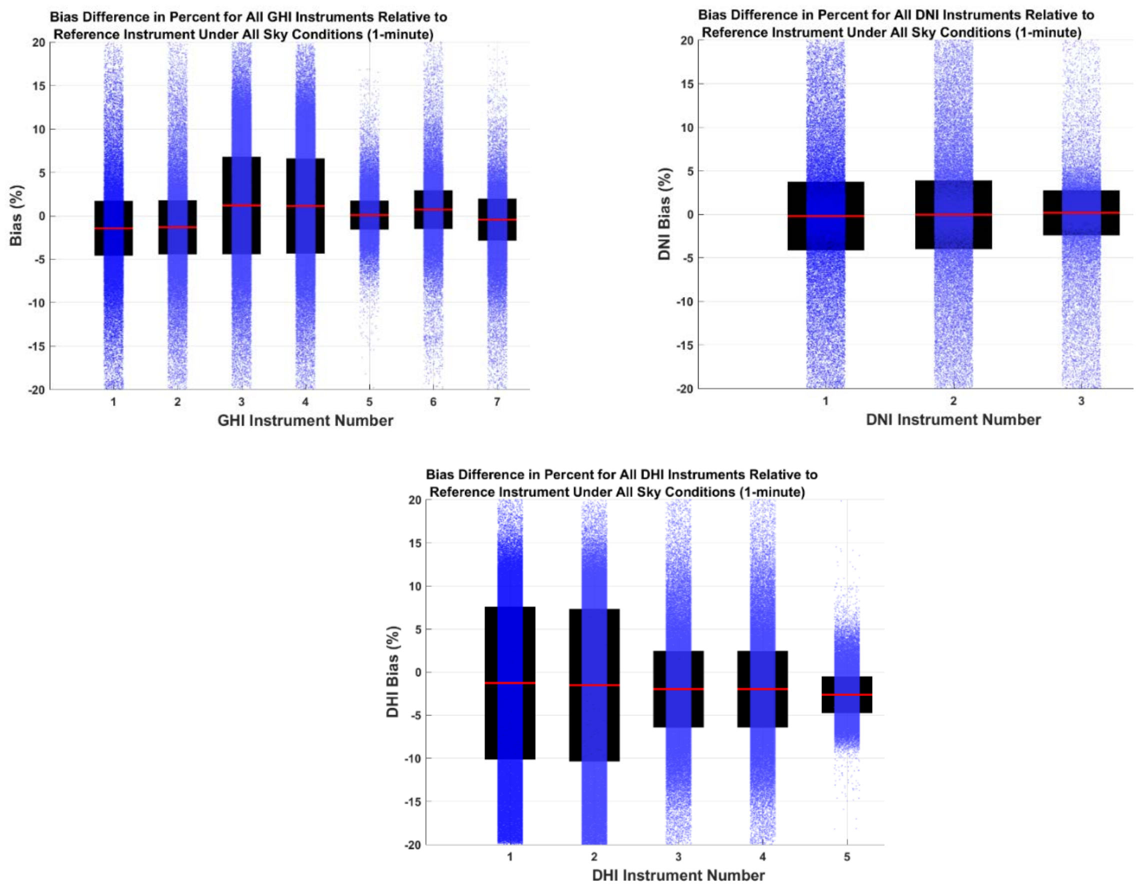

Figure 2. one-minute comparison between CRADA and BMS radiometers versus BMS reference data.

There are few installation issues that contributed to the 2AT GHI outliers in the CRADA radiometers (Figure 2). The SR20 secondary standard global pyranometer was mounted on the east side of the tracker cross-arm below the diffuse pyranometer deck. It became evident over the course of the CRADA in year by mid-March as the seasonal solar azimuthal range increased with each passing day approaching the summer solstice, the placement of the SR20 GHI pyranometer was not optimal as the position of the vertical shadow-band cast a shadow on the GHI pyranometer in the late afternoon, once the daily solar azimuth range was =/> 270°. The ultimate remedy to resolve the obstruction of the GHI pyranometer was to relocate the SR20 due south out over the 50 Watt solar panel, or relocate the GHI pyranometer to the north side of the tracker and elevated slightly above the height of the vertical shadow-band, to avoid any later afternoon shading effect. We never actually relocated the position of the SR20 GHI pyranometer during the CRADA campaign, however the cause of the late afternoon 2AT system GHI deviation from mid-March to mid-September was identified. The bias was only present in the late afternoon for ~ 25 minutes during the affected months.

The 2AT diffuse vertically shaded SR03 second class single-dome pyranometer exhibited a daily average global diffuse that was ~ 6 W/m² less than the BMS CMP22 (vent/corr) reference global diffuse daily average under clear sky conditions. A thermal offset-A ranging from -5 to -6 W/m² under clear sky conditions is typical for the SR03 under clear sky. Putting aside the expected difference between the 2AT / SR03 pyranometer measured diffuse relative to the BMS CMP22 (vent/corr) reference diffuse, the concept of a vertically fixed azimuth tracking 92.5° accurate shading band was successfully examined during the CRADA campaign. This was one of the key objectives of the CRADA campaign. Thus overall the CRADA campaign was a success as it vetted this new and novel diffuse measurement approach.

Finally, barring the late afternoon shading obstruction issue noted above, the CRADA campaign also demonstrated that global diffuse can be accurately back-calculated from a well calibrated First Class pyrheliometer and a performance "validated" secondary standard pyranometer like the SR20 model which according to the manufacturer it inherently has an extremely low thermal offset-A bias due to the sensors improved dome design, as well as exceptionally good directional response function.

Task Descriptions and Estimated Completion Dates

Task 1: Improved Radiometric Measurement Systems

Project Name: More Cost-Effective Pyranometers and Pyrheliometers

PI: ***Robert Dolce and Aron Habte***

Under this task, NREL will work with Participant to assemble, install, operate, and maintain new designs of pyranometers and pyrheliometers at the Solar Radiation Research Laboratory (SRRL) for comparison with existing instruments in the Baseline Measurement System.

As part of this task, the following items will be addressed:

- Participant shall provide up to three each pyranometers and pyrheliometers for installation at SRRL
- NREL shall provide instrumentation infrastructure for the radiometers (e.g. network communications links, equipment mechanical support structure, site security, etc.).
- NREL shall provide qualified staff for installation and routine maintenance (Monday through Friday) of the radiometers.
- Participant shall assist NREL with instrument calibrations as required to maintain traceability to calibration standards (e.g., instrument swaps, shipping, site visits)
- NREL shall provide on-going data quality assessment, data distribution, and archiving.
- NREL shall have explicit access to all data for research, including restricted data.

Deliverables include: Project plan (within 30 days after project start), measurement system operation (within 90 days after project start), and measurement system maintenance (continuous).

Task 2: Investigation of Fast-Response Thermopile Technology

Project Name: Determining Constituent Solar Irradiance Components

PI: ***Robert Dolce and Aron Habte***

Under this task, NREL will work with Participant to develop a method for determining the direct normal, global horizontal, diffuse horizontal, and plane-of-array irradiances with traceability to the World Radiometric Reference (WRR).

As part of this task, the following items will be addressed:

- Participant shall provide prototype system hardware and software sufficient for routine operations
- NREL shall provide reference radiometers with calibrations traceable to the WRR

Deliverables include: Project plan (within 30 days after project start) and a technical report describing calibration method research and development activities (within 24 months after project start).

Subject Inventions Listing:

None

ROI #:

None

Report Date:

12 February 2018

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DOE Program Office:

Solar Energy Technologies Office

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