Solar Radiometer Instrumentation Evaluation

Cooperative Research and Development Final Report

CRADA Number: CRD-16-00619

NREL Technical Contact: Aron Habte

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-81853
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Cooperative Research and Development Final Report

Report Date: January 4, 2022

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

Parties to the Agreement: EKO Instruments USA Inc.

CRADA Number: CRD-16-00619

CRADA Title: Solar Radiometer Instrumentation Evaluation

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Solar Energy Technologies Office (SETO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$9,000.00
TOTALS	$9,000.00

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Executive Summary of CRADA Work:

The purpose and intent of this agreement is to evaluate newly manufactured thermopile pyranometers and spectroradiometers. The purpose also extends to provide a framework for Participant to conduct research to improve and develop new radiometric devices and application in the future. The overall objective is to provide more accurate, site-specific, long-term, continuous measurements of the solar resources needed by industry to increase the deployment and improve the operations of photovoltaic and concentrating solar power plants. This CRADA addresses the needs for proven solar irradiance measurement to validate resource assessment models and generate high quality data used for site selection, energy system design, deployment, maintenance, and operation. This work will be conducted at NREL and Participant facilities.

This project will place instrumentation at the NREL Solar Radiation Research Laboratory (SRRL) in cooperation with EKO Instruments, USA. Participant instruments will be deployed for the purpose of evaluation under controlled conditions. The scope of the project will be a 3 years-long segmented comparison of the instruments vs. other NREL baseline instruments with a well-characterized history. These evaluations will include planned improvements to instruments as well as extensions of future instrument applications. The final evaluation will be a written report similar to the work done by Wilcox and Myers (see http://www.nrel.gov/docs/fy09osti/44627.pdf).

Comparison Provisions:

1. Participant will provide instrumentation and necessary support equipment to be installed at SRRL at a mutually agreeable position and will verify correct operation (thus removing the possibility of installation error by NREL staff).
    - Participant provided all the necessary support to acquire and deploy the instrumentation in the CRADA. The details in this report confirm this provision as supported by Tables and Figures
2. Participant will remove instruments and arrange crating and shipping at the end of the evaluation period.
    - Participant provided all the necessary arrangement to decommission and ship back of the instrumentation.
3. The instrument will be deployed at NREL for reasonable amount of time that is mutually agreed upon between NREL SRRL personal and Participant.
    - The deployment time was based on mutually agreed time between NREL SRRL members and Participant.
4. Participant will train NREL staff on maintenance and operation and will include written procedures and documentation (e.g., Instrument Manuals)
    - Participant provided all the necessary procedures including instrument user manuals.
5. NREL will maintain the instruments and communicate with Participant regarding potential operation problems during the experiment.
    - Throughout the CRADA period NREL and Participant were in constant communication to troubleshoot and solve operational and deployment problems.

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6. Data will be taken directly from the instrument and will include all internal or other necessary post processing that is part of normal instrument operation. Data with post processing external to NREL may be part of the evaluation data set.
   - Data from the CRADA instruments were available to NREL during the deployment period.
7. Other instruments may be included in this evaluation without permission of Participant. Participant will be notified of all instruments in the evaluation.
   - Participant is aware of the presence of other instrumentation during the evaluation.
8. All data will be made available in near real-time and will be accessible by Participant and NREL.
   - The data was available for both Participant and NREL through the NREL's Measurement and Instrumentation Data Center (MIDC)
9. NREL will issue a report similar to the report cited. Other interested parties may use the data for other joint or independent evaluations.
   - This CRADA report with detailed evaluation results will be publicly available for citation.
10. All instruments will be included in the report, excluding any instrument with an identified malfunction that would affect the validity of the evaluation.
    - This is addressed during the evaluation and details contained in this report.
11. As with the existing report, this report will not endorse or approve (or disapprove) instruments, but rather quantify the comparison with other high-quality instruments to allow users to choose based on the needs of their application. Manufacturers would be free to cite the report.
    - This report does not endorse or approve (or disapprove) instruments, but rather quantifies the comparison with other high-quality instruments to allow users to choose based on the needs of their application. The report is freely available.

These evaluations will provide the instrument manufacturer performance information related to the engineering design of the instruments provided. Instrument performance information critical to instrumentation choices for solar resource data will be developed by NREL and supplied to interested parties. This information will help provide the best resource data and uncertainties necessary for the analyses that support the deployment of major solar conversion projects in the United States. These improvements to what is already high fidelity data will produce greater amounts of "bankable" data. This will yield more efficient and greater cost savings resulting in greater efficacy of the US taxpayer's investment. In addition, NREL experts will have the opportunity to provide input to instrument manufacturers that could contribute to advancements in their instrumentation for solar radiation research and solar resource measurements and solar conversion system evaluation in particular. Evaluation of the spectroradiometers using specific algorithms will also provide cost competitive options to commercially available imported sun photometers. This new proliferation of data and instruments will be beneficial to the photovoltaic industry in reducing the uncertainties of models and improving overall profitability of large and small-scale projects.

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Summary of Research Results:

SRRL was utilized to deploy the radiometers under this CRADA. Various types of radiometers were deployed and characterized at NREL-SRRL. These radiometers were used to measure:

- Global Horizontal Irradiance (GHI)
- Direct Normal Irradiance (DNI)
- Diffuse Horizontal Irradiance (DHI)
- Downwelling Infrared Irradiance
- Spectral data using spectroradiometers

Shortwave Irradiance:

Radiometers are used for many solar energy applications such as to understand the performance of the PV modules under a known set of standard reporting conditions, for example. Multiple shortwave radiometers were utilized under this CRADA. The radiometers measure GHI, DNI and DHI irradiance where the data collection and data quality assessment were done using the NREL-SRRL measurement instrumentation data center (MIDC) infrastructure.[1]

Global Horizontal Irradiance (GHI): (Comparison Provisions 1-11)

NREL and EKO collaborated to analyze the performance of pyranometers, and EKO provided all the necessary procedures including instrument user manuals (Comparison Provision 4). The methods and results employed are as follows.

One-minute data from 8 Spectrally flat Class A pyranometers measuring GHI for the period of one year (June 01, 2020, to July 02, 2021, Comparison Provision 3) was collected from MIDC (Comparison Provision 8). Table1 shows the list of pyranometers which includes from various manufacturers including EKO models. Two of the EKO models include new thermopile technology with a faster temporal response (<0.5 sec) than traditional thermopile ISO 9060:2018 Class A pyranometers (<5 sec).

[1] https://midcdmz.nrel.gov

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Table 1. Pyranometers list (Comparison Provision 1-2)

Model	QTY	Correction	Ancillary Equipme	Calibrated by	Manufacturer	ISO 9060:2018 Classification
CMP22	1	Thermal Offset	External ventilator	BORCAL (NREL)	Kipp & Zonen	Spectrally flat Class A
CMP22	1	Thermal Offset	---	BORCAL (NREL)	Kipp & Zonen	Spectrally flat Class A
CMP11	1	Thermal Offset	---	BORCAL (NREL)	Kipp & Zonen	Spectrally flat Class A
SR25	1	---a	---	BORCAL (NREL)	Hukseflux	Spectrally flat Class A
MS-80	1	---	---	BORCAL (NREL)	EKO Instruments, Inc.	Fast response Spectrally flat Class A
MS-80S	1	---	---	Normal incidence	EKO Instruments, Inc.	Fast response Spectrally flat Class A
MS-802	1	Thermal Offset	---	BORCAL (NREL)	EKO Instruments, Inc.	Spectrally flat Class A
SPP	1	Thermal Offset	External ventilator	BORCAL (NREL)	Eppley Laboratory, Inc.	Spectrally flat Class A
Manufacture specified "temperature" correction was applied						

As shown in Table 1, some pyranometers contain thermal offset correction supplied by NREL's BORCAL process. Many studies such as, Sengupta et al., 2021; Michalsky et al., 2017; Habte et studies al., 2017; Younkin and Long, 2003; Dutton et al., 2001, affirm that thermal offset correction provides better quality radiometric data in some radiometers.

<u>Methods: (Comparison Provisions 1-11)</u>

Reference data: (Comparison Provisions 5-7)

A reference data with lowest possible uncertainty was obtained using a component sum method using a Kipp and Zonen models CHP1 pyrheliometer and CM22 DHI shaded pyranometer (Habte et al., 2017; Wilcox and Myers, 2008).

Data Normalization: (Comparison Provisions 5-11)

MS-80S was calibrated at EKO; however, the 9 pyranometers were calibrated at NREL using the Broadband Outdoor Radiometer Calibration (BORCAL) process. Therefore, data normalization was necessary to remove calibration biases. The normalization was carried out using Eq.1 and Eq.2 by isolating the irradiance data under all sky conditions between 44° and 46° solar zenith angles and summing and then ratio all the data in this solar zenith angle range for reference data and unit under test pyranometer for the study period (June 1, 2020, to July 02, 2021). The solar zenith angle range conform to the NREL convention of reporting all broadband radiometer calibrations at a 45-deg solar zenith angle (Habte et al., 2017). The ratio for each test radiometer

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was then used to acquire the new normalized irradiance value by multiplying each test irradiance value for the time interval by the normalization ratio (Eq.1):

$$Normalization\ Factor = \frac{\sum I_{Ref_{44^\circ\ to\ 46^\circ}}}{\sum I_{UUT_{44^\circ\ to\ 46^\circ}}} \quad (1)$$

where IUUT 44o to 46o is the irradiance data under all sky condition for the UUT within the two-degree solar zenith angle bin and IRef 44o to 46o is the irradiance data of the reference instrument within the same solar zenith angle range.

The new normalized irradiance data from the UUT were then computed as (Eq.2):

$$I_{UUT(New)} = I_{UUT} * Normalization\ Factor \quad (2)$$

Data filtering: (Comparison Provisions 5-11)

Missing data which accounted for about 25% of the 1-year data was removed from the analysis. This data gap was for EKO model MS-80S; however, this data gap was due to data acquisition problem. The period of the missing dataset was removed from all the 7 remaining pyranometer dataset before the analysis to ensure a rigorous comparison of the pyranometer data. Moreover, the analysis only included data for solar zenith angle less than 80°, this excludes night early morning and late afternoon data.

Data quality assessment: (Comparison Provisions 5-11)

After implementing data normalization and filtering, NREL's SERI-QC software package which is a data quality assessment tool was employed for the dataset from all 8 pyranometers. As stated in the SERI-QC software user's manual (Maxwell, Wilcox, and Rymes (1993)), the software uses three component data analysis for GHI, DNI and DHI and implements the clearness index (K) derived by standardizing the GHI, DNI, and DHI irradiance data to extraterrestrial solar radiation at the top of the atmosphere. These standardized quantities are represented by Kt, Kn and Kd, respectively. The K-values of any one of the three components can be computed from the other two. Further the K-values are shown in Figure 1 in conjunction of flags. The flags range from 0 to 99 where the latter refers to missing data which was taken care of during data filtering process. For this analysis, flags from 10-97 which signifies failed two- or three-component tests (flags 10-93) and data fall into a physically impossible region where Kn > Kt by K-space distances of 0.05–0.10 (flag 94), 0.10–0.15 (flag 95), 0.15–0.20 (flag 96), or ±0.20 (flag 97). The 10-97 flags were excluded from the analysis if flags occur in four or more of the 8 pyranometers. This exclusion accounted to about 1.5% of the dataset and this is on top of the 25% missing data that was mentioned above.

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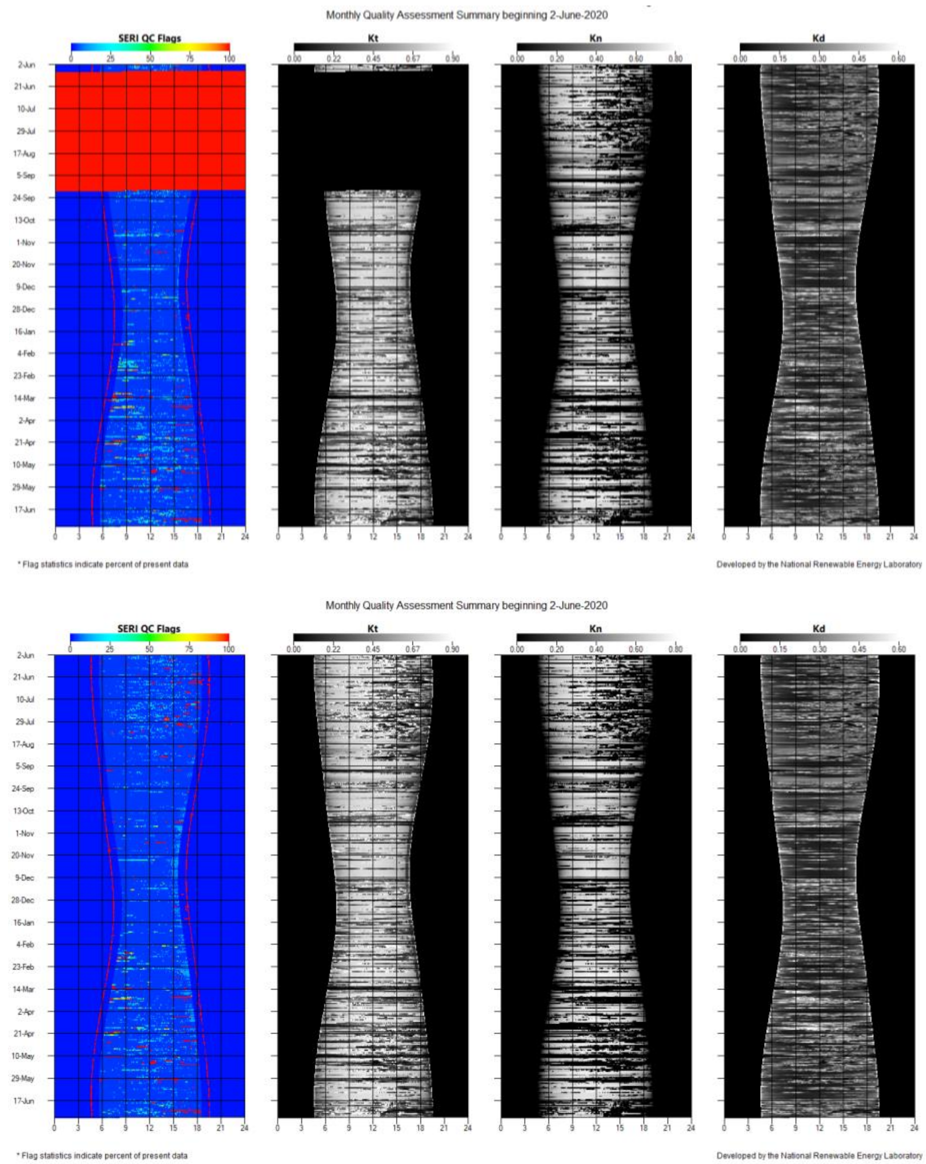

Figure 1. Example of SERI-QC software data quality assessment for EKO model MS-80S (top) and Kipp and Zonen model CMP22_vencor (bottom). Clearness index Kt is describing these two pyranometers. Kn and Kd are from reference DNI and DHI, respectively. Note: in 2020, the MS-80S had three-month worth of missing data due to data acquisition problem.

Figure 1, the left most chart shows the most severe flags from among the three components (Kt, Kn and Kd) at each time interval. Lowest error levels are represented as dark blue and the highest as red.

The remaining three charts present the relative solar irradiance for Kt, Kn, and Kd clearness ranges where dark represents overcast or missing data and white represents clear sky.

Clear and Cloudy sky partitioning: (Comparison Provisions 5-11)

To analyze the comparison among the different pyranometer models, a partitioning of the sky condition at each time stamp was implemented. A PVLIB clear sky algorithm by Reno and Hansen, 2016) was used to distinguish clear and cloudy skies.

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Results: (Comparison Provisions 11)

The analysis was done for each unit under test instrument relative to the reference instrument under various sky conditions. The results of the analysis are shown in Figure 2 and for ease of understanding, the results of the comparison were partitioned into 10° solar zenith angle bins. Each blue box represents a 10º bin and it also represents the upper and lower quartiles (it is also called an interquartile range) of the data in each bin. The circle in each blue-box is a mean and the black line signifies the median value. Ninety-nine percent of the dataset is within the whiskers and beyond the whiskers are outliers which are plotted by dot symbols.

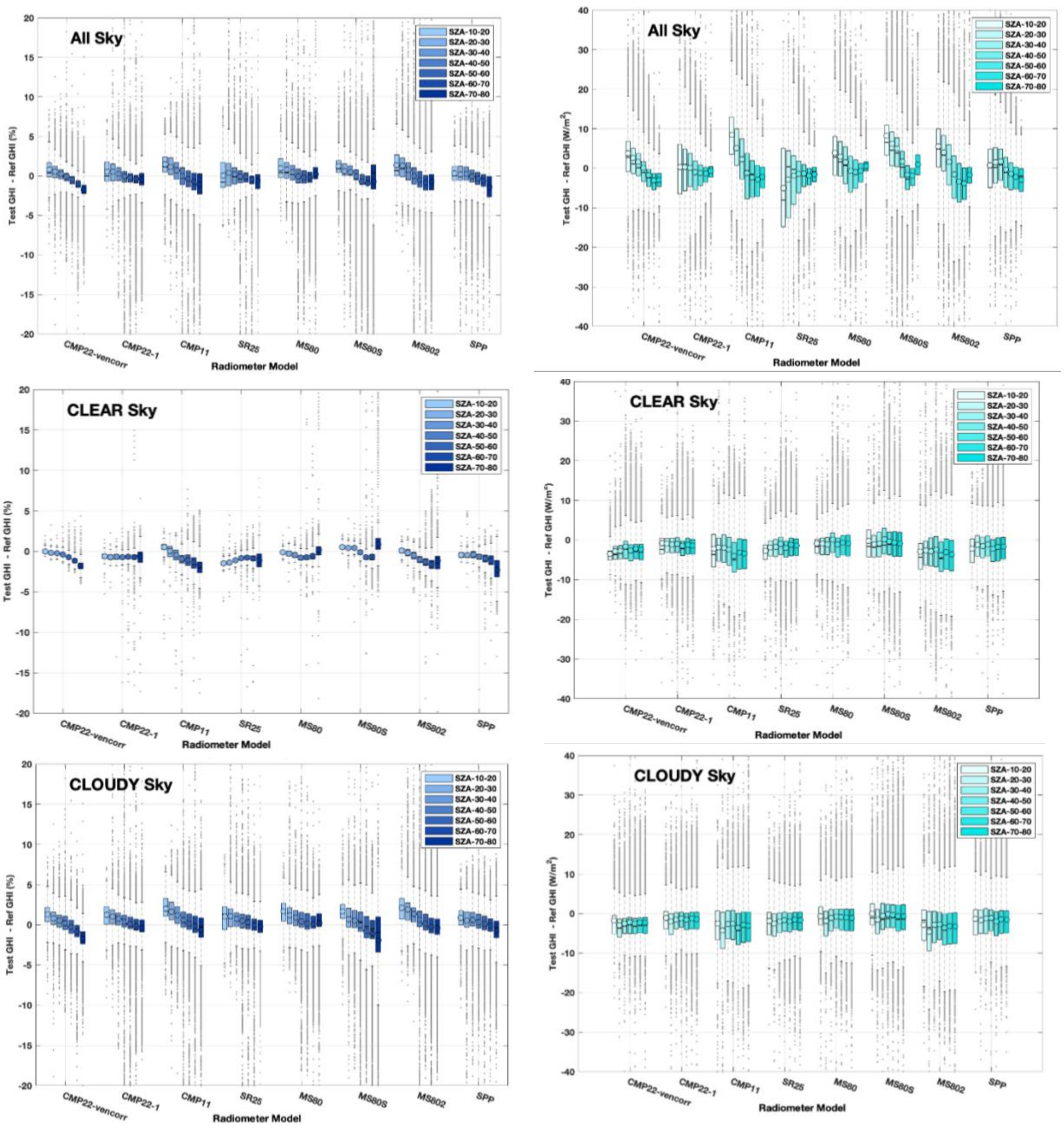

Figure 2. Comparison of the 8 pyranometers relative to the reference data under various sky conditions. Left column is bias in percent and right is in W/m^2.

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The comparison demonstrated Class A pyranometers have small bias on average relative to the reference data. Under clear sky condition, the interquartile range is within about ± 1% and ± 2 W/m^2. On the other hand, the former EKO class A pyranometer, model MS-802 showed relatively higher deviation compared to the Class A pyranometers. Under cloudy and all sky (cloudy + clear) conditions, the deviation is slightly higher than the clear skies biases and as expected the outliers are less under clear skies.

Furthermore, the external ventilation system for Model CMP22-vencorr and Model SPP appears to assist in improving the accuracy and reliability of the pyranometers data that are deployed outdoors and exposed to various environmental and meteorological conditions. Under clear skies, the reduction of the outliers due to external ventilation system was evident which are mainly caused due to snow, frost, soiling, bugs, etc. Therefore, as previously reported, the advantage of external ventilators is twofold; Not only do the external ventilation system assist in reducing errors due to snow, frost, etc., but also it assists in stabilizing the pyranometer body temperature which in turn reduce thermal offset errors (Sengupta et al., 2021; Michalsky et al., 2017; Habte et al., 2017; Younkin and Long, 2003; Dutton et al., 2001). The remaining pyranometers including the EKO MS-80 and MS-80S are not equipped with external ventilation system; therefore, the data is prone to outliers. However, these two pyranometers are fast time response radiometers that can capture relatively fast changing atmospheric condition compared to the rest of pyranometers including the reference radiometers; consequently, some of the outliers observed from these two radiometers could be accurate data which occurred due to the relatively slow time response of the reference data that didn’t capture the fast-changing atmosphere.

DNI Comparison: (Comparison Provisions 1-11)

MS-57 Evaluation:

DNI dataset is traditionally collected using pyrheliometer mounted on a tracker. The NREL-SRRL baseline measurement system is equipped with multiple pyrheliometers mounted in trackers including the EKO model MS-57 pyrheliometer (Table 2). The evaluation of the pyrheliometers was done by comparing each unit under test to the reference DNI measurements which was taken by a Kipp & Zonen Model CHP1 pyrheliometer. As described above and reported previously, this reference pyrheliometer has less calibration and measurement uncertainty. However, more studies are needed to collaborate these previous studies because in recent years there many technological advancements made in the radiometry industry to lower uncertainty. It is safe to assume these Class A pyrheliometers can be a reference pyrheliometer based on the results obtained in this study. Additional point to mention is that the EKO model MS-57 pyrheliometer, fast response spectrally flat Class A pyrheliometer has an advantage to capture and quantify fast changing atmospheric condition as compared to similar Class of pyrheliometers with relatively slower time responses.

The data filtering, normalization and data quality assessment was carried out, the same way as the GHI analysis. Figure 3 shows data quality assessment using SERI-QC.

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Table 2. Pyrheliometer list

Model	QTY	Calibrated by	Manufacturer	ISO 9060:2018 Classification
CHP-1[a]	1	BORCAL (NREL)	Kipp & Zonen	Spectrally flat Class A
CHP-1	1	BORCAL (NREL)	Kipp & Zonen	Spectrally flat Class A
sNIP	1	BORCAL (NREL)	Eppley Laboratory,	Spectrally flat Class A
MS-57	1	BORCAL (NREL)	EKO Instruments,	Fast response Spectrally flat
Reference Pyrheliometer				

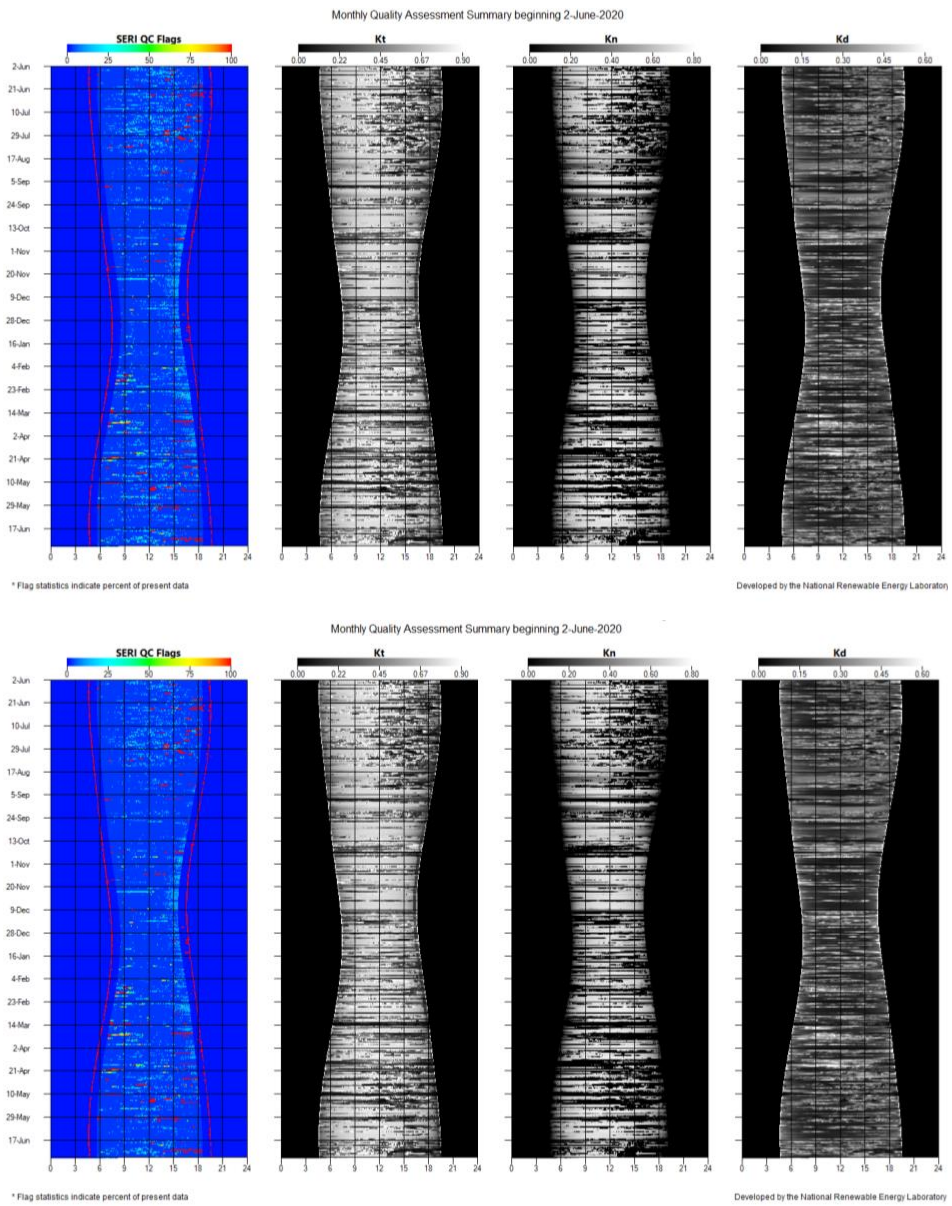

Figure 3. Example of SERI-QC software data quality assessment for EKO model MS-57 (top) and Eppley Laboratory, Inc. model sNIP (bottom). Clearness index Kn is describing these two pyranometers.

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Dataset from 3-pyrheliometer were included in this evaluation. Figure 4 demonstrates comparison result in the sky condition categories. The clear-sky conditions demonstrated smaller differences among the instruments than the cloudy sky conditions. Further, as the GHI analysis, the differences were divided in various solar zenith angle ranges, however, solar zenith angle dependence is not likely for pyrheliometers.

Under cloudy conditions, EKO model MS-57 demonstrated relatively higher differences and the possible reason for this is, this particular pyrheliometer has fast time response (< 0.2 sec); therefore, fast moving clouds are captured in the measurement but not by the reference instrument which has < 5 sec response time.

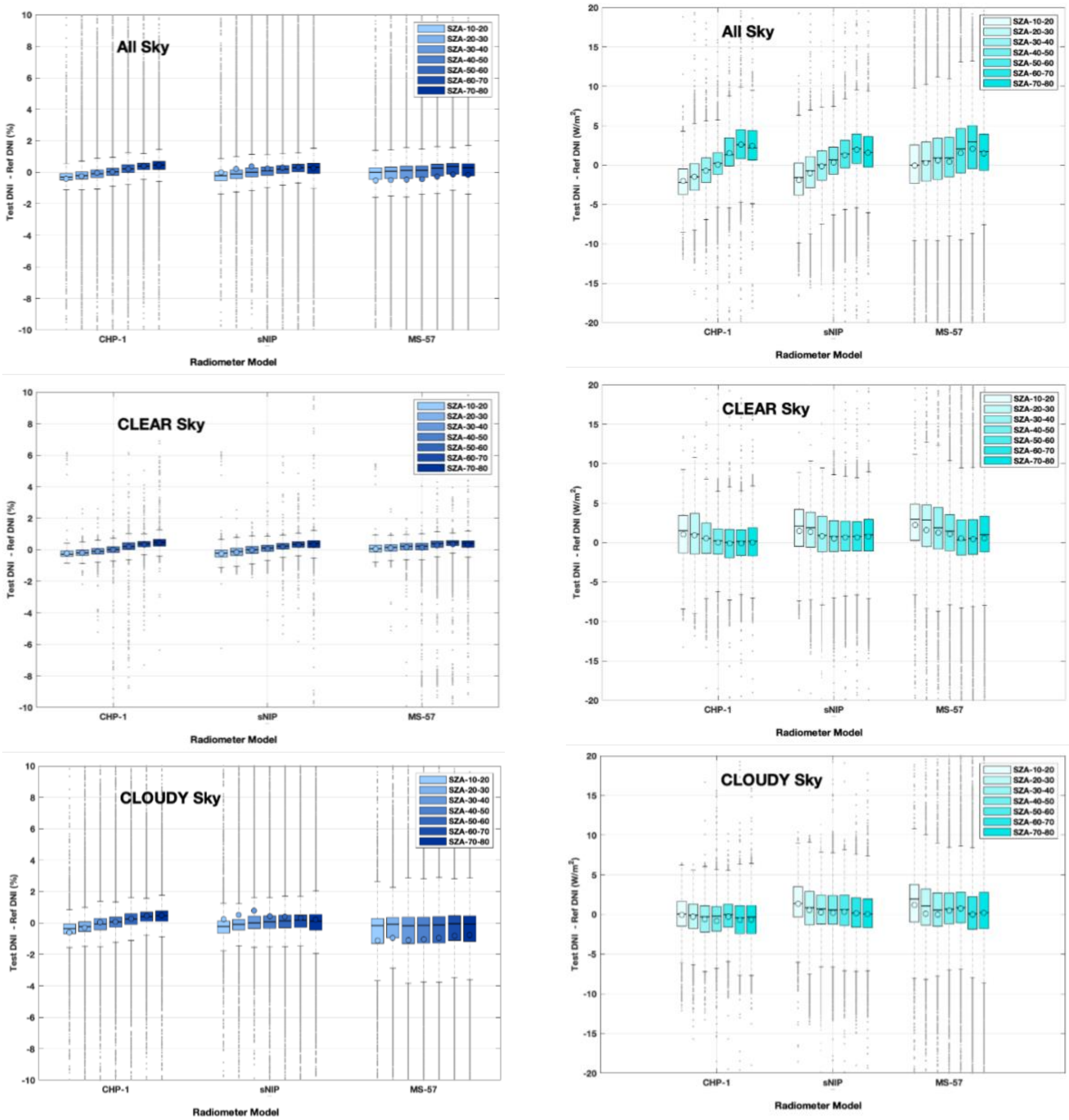

Figure 4. Comparison of the 3 pyrheliometer relative to the reference data under various sky conditions. Left column is bias in percent and right is in W/m^2.

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MS-90 Evaluation: (Comparison Provisions 1-11)

NREL and EKO instruments deployed a new pyrheliometer that measures the direct normal irradiance (DNI) without a sun-tracker. The concept is based on an earlier sunshine recorder sensor (MS-093). It uses a rotating mirror within a fixed glass tube tilted to latitude (–58° to +58°). With a rotation period of 15 sec, the mirror reflects the direct beam onto a broadband pyroelectric detector that measures DNI four times per minute. This new approach will significantly reduce the cost of deployment and measuring DNI for solar energy application. As shown in Figure 5, the pyrheliometer model EKO MS-90 was deployed on a fixed tilt and adjusted according to the location latitude. The operational details of the pyrheliometer are described in (Pó et al., 2018) MS-90 concept has no external moving parts, remaining protected from outer harsh environments, requiring lesser on-site maintenance. The system has a large optical window which makes it typically less accurate to measure DNI than a traditional pyrheliometer on a sun-tracker. Still it is less affected by soiling, which, when maintenance is lacking, can have a dramatic effect on a pyrheliometer measurements.

Figure 5. EKO MS-90 deployed at NREL SRRL Baseline Measurement System.

Furthermore, by combining the MS-90 DNI data with a GHI pyranometer, the DHI can be determined. Referred to MS-90+ system.

Preliminary results demonstrated the low cost and easy to set up EKO MS-90 can accurately measure DNI without a sun tracker. Under clear sky condition, the evaluation demonstrated small difference compared to the reference pyrheliometer. Under all sky conditions, the bias reached to ± 5% for irradiances greater than 700 W/m^2. See (Pó et al., 2019) for detailed evaluation result.

Further evaluation of this new concept was carried out for a longer period by comparing the data from MS-90 to the same reference instruments mentioned earlier in this document (CHP1 pyrheliometer and CM22 DHI shaded pyranometer) deployed in a tracker at NREL-SRRL. The data set for this analysis was from 2019/06/01 till 2020/10/01, and only datapoints from the reference instruments flagged with SERI-QC are used. To filter the clear sky conditions the Reno, M.J. and C.W. Hansen (2016) methodology is also employed.

The analysis was done relative to the reference instrument under various sky conditions. The results of the analysis are shown in Figure 6 for both DNI and DHI. The results of the comparison were partitioned into 1° solar zenith angle bins. Each box represents a 1° bin and, similarly to the previous analysis, it also represents the upper and lower quartiles of the data in each bin. The middle line in each box is a mean. Ninety-nine percent of the dataset is within the whiskers. A

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generally flat yet slightly tilted directional response is observed for the DNI, going from positive to negative bias from lower to higher zenith angles. This small tilt error could also be related to installation error of the MS-90 at SRRL. A more pronounced angular dependency is observed for the DHI derived from the system, with a signal opposite of the DNI measured by the MS-90 and similar curvature to the MS-80 GHI pyranometer directional response observed earlier. Furthermore, the larger differences observed under all weather conditions are owed to the measurement principle of the MS-90 which only allows 4 samples per minute.

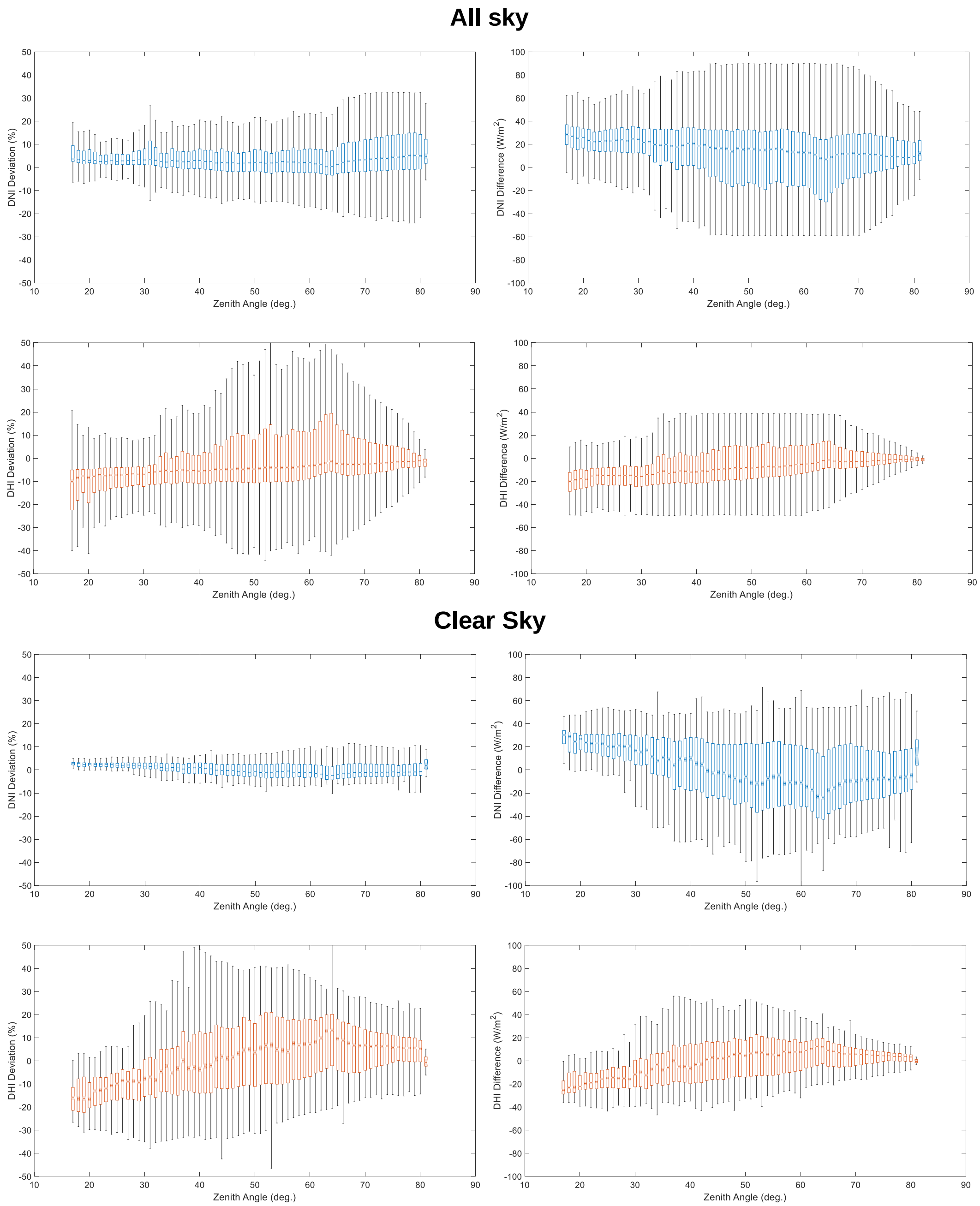

Figure 6. Comparison of the MS-90 DNI and MS-90+ DHI relative to the reference data under all sky (top) and clear sky conditions (bottom). Left column is bias in percent and right is in W/m².

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DNI and DHI derived from MS-80 + MS-90 (MS-90+ system) seasonal effects: (Comparison Provisions 1-11)

Seasonal effects are also visible (Figure 7) which are related to the angle of incidence. Measurement errors are minimal during the equinoxes, while DNI positive and negative bias during winter and summer, respectively. Consequently, the DHI follows a complementary trend. These effects could still be minimized by either mechanically adjusting the MS90 inclination to compensate for seasonal solar elevation, or by applying a directional response correction.

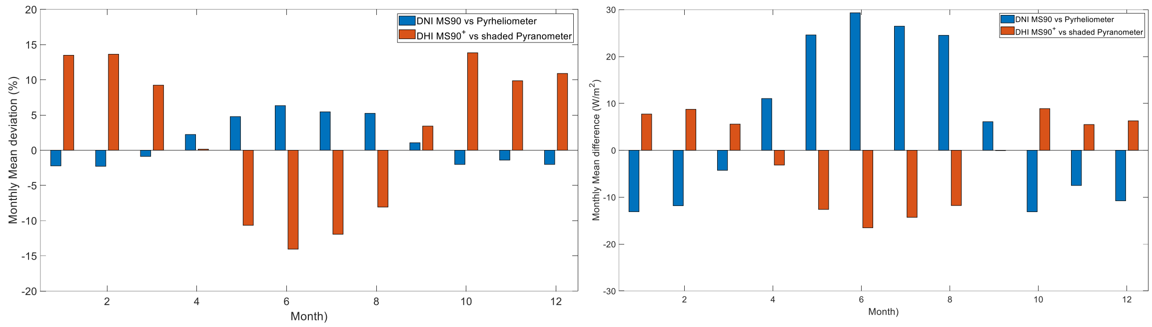

Figure 7. Seasonal comparison of the MS-90 DNI and MS-90+ DHI relative to the reference data under all sky conditions. Mean bias in percent and right is in W/m^2.

IR: MS-20 Evaluation: (Comparison Provisions 1-11)

For meteorological and climate applications the downwelling broadband long-wave irradiance at the Earth's surface is commonly measured with pyrgeometers. Pyrgeometers, provide the near surface infrared radiation between 4.5 nm till 42 µm (or 50 µm). Typical construction consists of a thermopile under a meniscus-shaped or hemispherical silicon dome with a coating that rejects solar radiation, where the thermopile voltage signal is proportional to the difference between the downward long wave radiation emitted from the atmosphere and the upward emitted radiation from the pyrgeometer.

A new pyrgeometer, EKO MS-20 measurement performance is compared against one of the reference pyrgeometers, Kipp & Zonen CG4 at SRRL-BMS. The MS-20 was calibrated at NREL-SRRL during BORCAL removing potential bias between test and reference instrument that could originate from differences in the calibration procedure. Two small campaigns were performed with the instrument under shaded and unshaded configurations. The instrument was unshaded from September 20 till October 28, 2020, and shaded from November 6, 2020, till February 12 2021. This allowed to estimate the dome heating effects from sun light. Dome heating remains one of the main sources of measurement error from pyrgeometers, typically it occurs when the pyrgeometer is exposed to the sun and solar radiation is absorbed by the window producing a heat transfer to the thermopile from the window originating an offset to the measurement proportional to the sun light. Shading the pyrgeometer with a sun-tracking shading ball, is a countermeasure commonly applied to minimize window heating in monitoring networks, such as the BSRN.

Results of the comparison are summarized in Figure 8, and Table 3. Under unshaded conditions the difference between night and daytime data suggests that the window heating is present and well within the 6 W/m^2 specification. Under shaded conditions the sensor measurement

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performance is very similar for both night and daytime data, under this configuration the observed differences between MS-20 and CG4 were typically within -1 to 2 W/m^2, remaining within the calibration uncertainty of ±3.0 W/m^2.

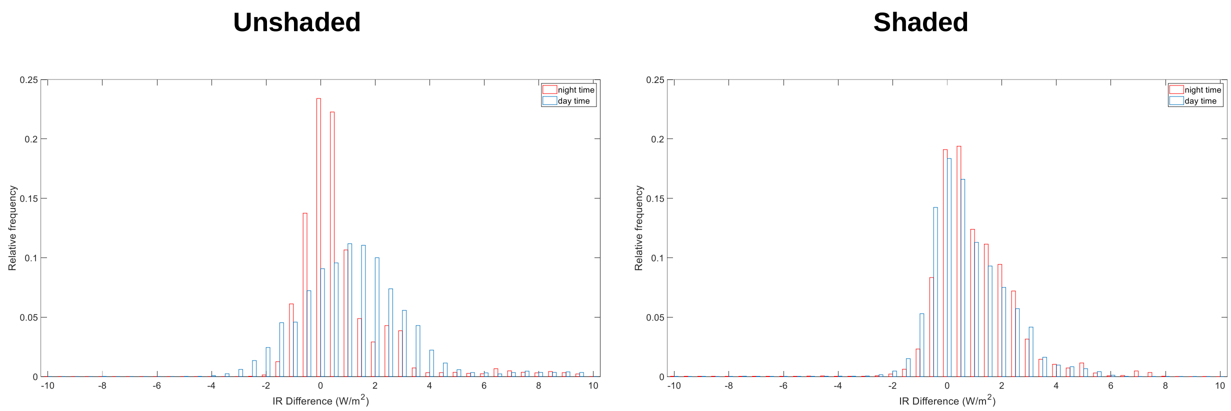

Figure 8. MS-20 and CGR difference distributions for shaded and unshaded measurement configurations

Table 3. Mean Bias Error and Mean Absolute Error observed Under Various Sky Conditions and time of the day for MS-20 as compared to Reference Pyrgeometer

Mean bias error (W/m2)			
	All sky	Night time	Day time
Shaded	1.71	1.94	1.26
Unshaded	1.44	1.13	1.94
Mean absolute error (W/m2)			
	All sky	Night time	Day time
Shaded	1.85	2.05	1.48
Unshaded	1.73	1.32	2.36

Spectroradiometer Characterization: Spectral DNI - RSB MS-711: (Comparison Provisions 1-11)

Spectroradiometers are used for many solar energy applications such as to understand the spectral properties of the PV modules. These spectroradiometers are most frequently used for measuring the spectrum of solar simulators or outdoor natural sunlight. These are critical measurement for many solar energy stakeholders including NREL, because it is important to know the performance of PV modules and cells under a known set of standard spectral reporting conditions, for example.

Spectral properties are typically measured with a spectroradiometer; the spectroradiometer must be calibrated with traceability to national or international standards, such as the National Institute of Standards and Technology (NIST). NREL Optical Metrology Laboratory maintains NIST Traceable Lamp Standards of Spectral Irradiance. These lamps are used to calibrate spectroradiometers that indicate the irradiance (W/m^2/nm) as a function of wavelength (nm). The

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laboratory is responsible for spectral field measurements, instrumentation troubleshooting/repair and consultation.

The EKO spectroradiometer model MS-711 which is widely used for outdoor applications was calibrated in the EKO calibration facility in Tokyo, Japan, following the standard spectroradiometer calibration procedure using a National Institute of Standards and Technology (NIST) traceable method (Yoon and Gibson, 2010). The instrument was then deployed and characterized at NREL-SRRL mounted on a rotating shadow band EKO RSB-01. By using a rotating band, the system is capable of measuring the GHI and DHI and derive the DNI (Pó et al., 2018).

A short measurement campaign was performed from 9th of April 2018 till 11th of June 2018 with the RSB-01 system, during the campaign it was compared against the NREL EKO MS-711 mounted on a sun-tracker with collimation to measure DNI. A few days of clear sky were experienced (25/5, 31/5, 02/06, 11/06), in which the measurement error of the system was evaluated. For the evaluation a subset of wavelength bands is defined from 300 nm to 1100 nm, with 100 nm step intervals, data for each band is also grouped in sets of 10° bins from 10° to 80° solar zenith angle, the mean deviation is plotted in Figure 9). Overall, the system tends to underestimate DNI due to the band coverage effect, additionally the cosine dependency is observed where at narrow incidence angles the system tends to overestimate the DNI.

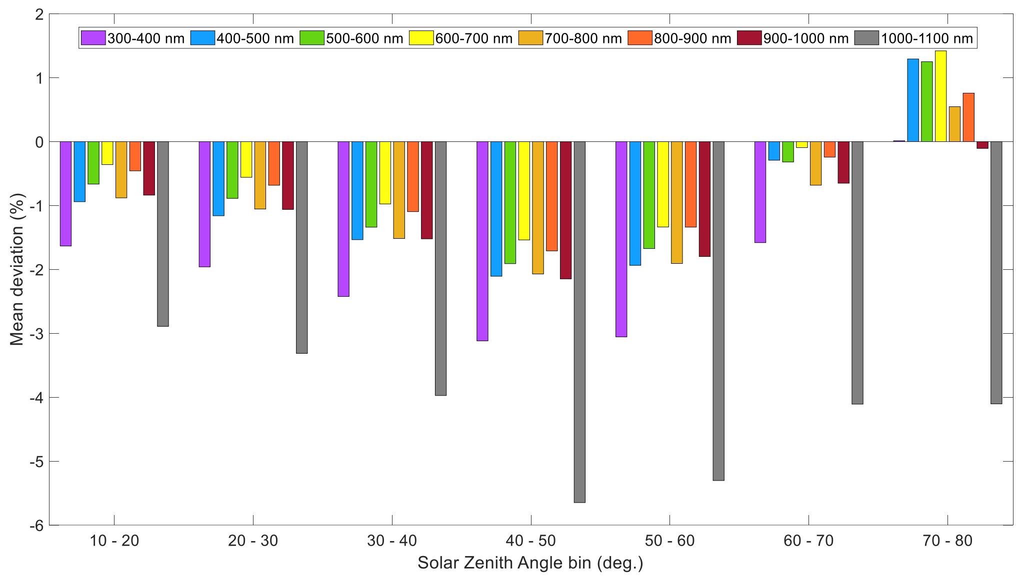

Figure 9. Mean deviation of wavelength and solar zenith angles subsets.

<u>Subject Inventions Listing</u>:

None

<u>ROI #</u>:

None

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