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Frank Vignola, Chun-Yun Chiu, and Josh Peterson
University of Oregon

Mike Dooraghi and Manajit Sengupta
National Renewable Energy Laboratory

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Comparison and Analysis of Instruments Measuring Plane of Array Irradiance for One Axis Tracking PV Systems

Frank Vignola[1], Chun-Yu Chiu[1], Josh Peterson[1], Michael Dooraghi[2], Manajit Sengupta[2]

[1]University of Oregon, Eugene, Oregon, Material Science Institute, 1274-University of Oregon, Eugene, Oregon, 97403-1274, [2]National Renewable Energy Laboratory, Golden, Colorado, 80301

Abstract – A variety of sensors are studied on a one-axis tracking surface and a horizontal surface in Golden, Colorado and Eugene, Oregon. This is the first year of a long-term study that will not only look at the comparison between the instruments but will also look at the longer-term degradation in calibration and/or performance. Initially results from each location will be analyzed and then results are compared between the two locations. A quick comparison at Eugene indicates that reference solar cells seem to compare better against a secondary standard pyranometer on a one-axis tracker than photodiode-based pyranometers. More study is needed to characterize and specify this finding.

Index Terms – irradiance, POA, one-axis tracking, reference cell, pyranometer.

I. INTRODUCTION

Evaluation of photovoltaic system performance is important for many reasons, including analysis of system degradation rates, estimation of long-term system production, and forecasting system performance. Analysis of absolute system performance depends on accurate measurement of the incident irradiance along with temperature and other meteorological parameters. Some of these questions can be best addressed using knowledge of the relative performance of the system over time. A variety of instruments are used to understand system performance including thermopile-based pyranometers, photodiode-based pyranometers and reference cells. When analyzing photovoltaic (PV) system performance and developing models for PV system performance, the myriad of devices used to gauge the incident irradiance often yield results that can vary by 10% or greater. With such a large discrepancy modeling and analysis of PV system performance becomes difficult.

This is especially true with one axis tracking systems where there is a minimum of data gathered that compare the results of various instruments used to monitor the incident irradiance. In 2016 NREL initiated a program to study irradiance measurements for one-axis tracking and horizontal systems to better understand the measurements coming from the different instruments. Since instruments are known to perform differently at different locations similar experiments were set up in Golden, Colorado and at the University of Oregon in Eugene.

This is a report on preliminary findings after nearly a year's worth of data has been collected. First the instruments used in the experiment are described along with procedures used to calibrate the instruments. Next the experimental configuration is illustrated. The findings comparing the measurements are shown along with a brief discussion of the results.

II. INSTRUMENTS USED IN THE EXPERIMENT

At the Eugene location five instruments are compared both on a tracking and a horizontal surface. The instruments mounted on the one-axis tracker are a Kipp & Zonen CMP22 pyranometer, a LI-COR LI-200 SA pyranometer, a Kipp & Zonen SP Lite2 pyranometer, an RCO reference solar cell, and an IMT reference solar cell. The CMP22 is a secondary reference pyranometer and during calibrations is reputed to have an absolute accuracy of 1.5% or better at the 95% level of confidence [1].

At the Golden location, a similar set of instruments are used except a CMP 21 pyranometer is used instead of the CMP 22. In addition, other photodiode-based pyranometers are included. To make a more comprehensive study, instruments at a fixed tilt are also co-located.

The LI-200 and SP Lite2 pyranometers are photodiode-based pyranometers that are widely used for monitoring PV system performance. The responsivity of the photodiode-based pyranometer has been shown to vary with the spectral distribution of the incident irradiance [2, 3, 4]. Their irradiance values are expected to vary over the day in comparison with the CMP22 output as the CMP22 is a thermopile pyranometer and has a special dome designed to uniformly transmit irradiance over a wide range of wavelengths. These specially designed double glass domes also produce a more accurate cosine response in the instrument and reduce thermal losses.

The LI-200 SA pyranometer is a photodiode-based pyranometer that essentially monitors the short circuit current of a solar cell under a diffusing lens. The pyranometer body and diffusing lens are designed to minimize deviations from a true cosine response. In addition, there is some internal circuitry that helps minimize the effect of temperature on the pyranometer's performance. The LI-200 SA pyranometer utilizes blue

Fig. 1. One-axis tracker with sensor instruments mounted on plate at the University of Oregon station.

enhanced solar cells with a higher response in the blue portion of the spectrum to more accurately simulate the performance of high quality thermopile-based pyranometers [5].

The SP Lite2 pyranometer is also a photodiode-based pyranometer with a different body and diffusing lens. While the performance of the LI-200 SA and the SP Lite2 have similar characteristics, their outputs differ measurably.

The reference cells utilize single crystalline silicon cells and are used to calibrate PV modules on factory production lines. They have also been used in the field to evaluate the performance of PV systems that utilize the same technology as the reference solar cells. The reference solar cells are expected to have a similar spectral response as the photodiode-based pyranometers since photodiodes and reference cells are both solar cells for which the output is monitored in a short circuit configuration. There are two main differences between reference cells and photodiode-based pyranometers. The photodiode-based pyranometers have a diffusing lens to help provide a true cosine response and the reference cells have a glazing like PV modules (see Fig. 1). The other difference is that the reference cells monitor cell temperature that is used to adjust the temperature dependence of the measured irradiance from the reference cells. While photodiode-based pyranometers usually do not have an internal temperature measurement that can be used to correct for temperature effects, some photodiode-based pyranometers do have internal circuitry that helps compensate for some temperature effects. In addition, the temperate effects can be modeled on ambient temperature [2].

III. CONFIGURATION AND DATA

The one-axis tracker is a modified LI-200SA automatic tracker (LI-2020) that has been configured to rotate the pyranometers from east to west over the day. The tracker is oriented with the axis aligned along the north-south direction and pointed due east at sunrise and due west at sunset. A plate mounted along the north-south axis holds the pyranometers being evaluated. A similar plate is mounted in a horizontal fixed position. At solar noon, all the instruments will be horizontal and this can act as a check on the instrument output.

A photo of the experimental setup in Eugene is shown in Fig. 1. The instruments at both sites are cleaned five days a week and a maintenance log is maintained on the instruments. The instruments are calibrated once a year using an Absolute Cavity Radiometer for the direct normal component and a pyranometer shaded by a sphere for the diffuse component. The reference global irradiance is then calculated from these measurements and the responsivity of the test instruments are obtained by comparison to the reference global measurements.

One-minute average measurements are then gathered using Campbell Scientific CR 1000 data loggers and the data are downloaded daily. Co-located at the Eugene and Golden sites are a variety of irradiance and meteorological instruments that can be used to supplement the test measurements. Spectral measurements are also available that can be used for future analysis.

IV. CALIBRATIONS

Initially the instruments were calibrated at NREL and shipped to Eugene. Subsequently the Eugene instruments were calibrated in Eugene using an AHF absolute cavity radiometer. Because the atmospheric conditions in Eugene differ from those at NREL and the AHF cavity has been calibrated against the NREL absolute cavity radiometer, the calibration values determined in Eugene are used for the Eugene data in this study.

The 2016 calibration results at Eugene are shown in Fig. 2. The photodiode-based pyranometers are within ±5% over the range of 30° to 80° while the CMP22 is within ±2.5%. The reference solar cells are within ±5% out to 60° but start to deviate significantly from a true cosine response at larger solar zenith angles. These calibrations were performed under clear

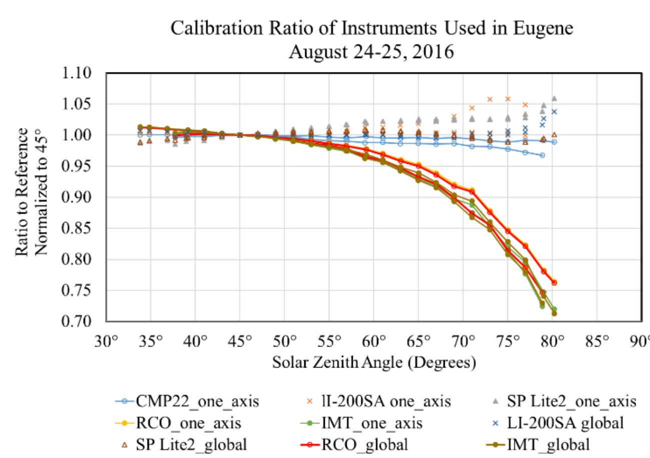

Fig. 2. Calibration comparison of instruments used in this study. The responsivities at 45° are used to normalize the calibrations.

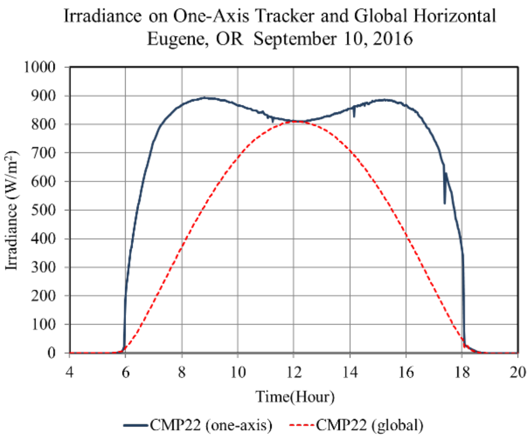

Fig. 3. Comparison of clear sky GHI and POA irradiance for a one-axis tracking system. This system tracks from east to west. At solar noon, the tracker is horizontal and the two values should agree when the solar zenith angle is 45°.

sky conditions. Night time offsets were subtracted from the values before the responsivities were determined. No other adjustments were applied to the data.

V. EVALUATING THE DATA

The first comparisons are made under clear sky conditions. Under clear sky conditions, the Diffuse Horizontal Irradiance (DfHI) is small compared to the Global (or total) Tilted Irradiance (GTI) and the results are dominated by the characteristics of the direct normal irradiance (DNI). GTI is also called Plane of Array (POA) irradiance and this term is particularly apt for instruments mounted on a one-axis tracker. Fig. 3 shows a typical comparison of Global Horizontal Irradiance (GHI) and the POA irradiance for a one-axis tracking system.

The irradiance as measured by the CMP22 pyranometer has the lowest uncertainty and, thus, the CMP22 will be used as the reference instrument. The CMP22 does deviate from a true cosine response and has some thermal offsets, but these are small (Fig. 2). However, these systematic effects should be kept in mind if one is using data from this instrument to evaluate other instruments or adjust the readings of other instruments as these effects can skew the evaluation.

Using the CMP22 as the reference and keeping in mind the uncertainties that are contained in the CMP22 measurements, one can examine the performance of the other sensors over the day by taking the ratio of their measurements to those obtained from the CMP22. This comparison is shown in Fig. 4 for clear skies on September 10, 2016. The ratio is plotted against the incident angle between the normal to the one-axis tracker and the sun. Since it is September when the sun rises and sets near the equinox and the one axis tracker is pointed due east in the morning and due west in the afternoon, the incident angle between the normal to the one-axis tracker is smallest in the

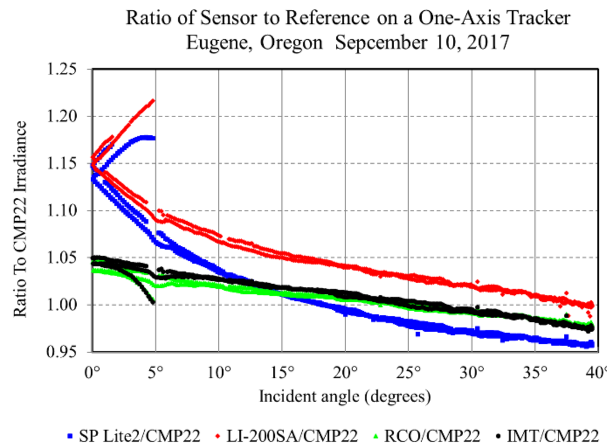

Fig. 4. Ratio of readings of instruments on a one-axis tracker to the reference CMP22 values. The incident angle is the angle between the sun and the normal to the plate on the one-axis tracker. The smallest incident angle in September occur near sunrise and sunset and results are likely to be affected by obstructions near the surface.

morning and afternoon hours. The spectral distribution also changes the most during the morning and evening hours near sunrise and sunset when the air mass between the sun and the sensors is greatest, consequently the effects of changes in spectral distribution on instrument performances are most pronounced during the morning and evening hours.

One September 10, the incident angle is smallest a little after sunrise when the sun is due east and a little before sunset when the sun is due west. Much of the change in ratio between the photodiode-based pyranometers and the reference pyranometer is related to the change in spectral distribution. One can see this effect when the ratio continues to increase even after the incident angle reaches near zero. In contrast, the ratio between the reference cells and the reference pyranometer is linear over the whole data. One might assume that the difference between the two types of instruments is related to temperature effects. However, the values in the morning and evening are nearly identical indicating that the temperature effects are much smaller than the observed changes in ratios over the day. While there are temperature effects that can be measured, they are small compared to the changes in the responsivities seen in Fig. 4.

To better understand the difference seen in Fig. 4, the ratio of the LI-200SA pyranometer and the reference cell irradiance to that measured by the CMP22 pyranometer is shown in Fig. 5. The comparison is made for total horizontal irradiance (Global Horizontal Irradiance – GHI).

The results in Fig. 5 are for one day of clear periods per month over a year. As expected, the results are consistent with calibration results shown in Fig. 2.

For the instruments on the one-axis tracker, the results are expected to be more complicated, and they are. The irradiance

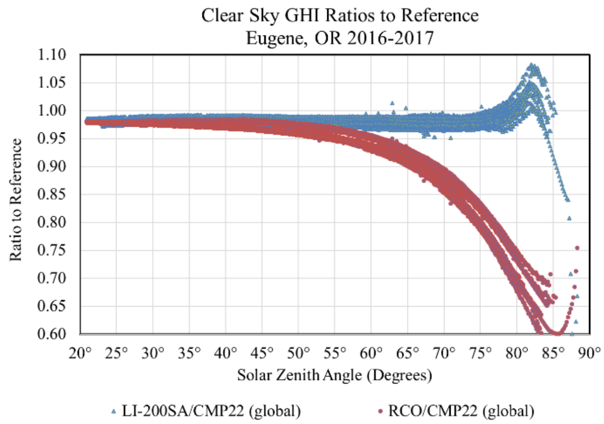

Fig. 5. Ratios of GHI measurements to reference measurement on selected clear periods over the year in Eugene.

incident angle is always smaller for instruments mounted on a one-axis tracker than the incident angle to the horizontal instruments except at solar noon where all instruments are horizontal. The instruments on the tracker also measure some ground reflected irradiance. Ground reflected irradiance has its own spectral distribution and as the instruments are tilted more vertically, the ground reflected irradiance contribution increases. Fig. 6 shows the comparison of a LI-200SA pyranometer and a RCO reference cell divided by the equivalent irradiance from a co-located CMP 22 reference pyranometer mounted on the one-axis tracker.

The low values of the ratio of the RCO reference cell divided by the CMP 22 output on the lower right of Fig. 6 are December, 2016 data. The ratio moves up and to the left as the sun gets higher in the sky (during spring and fall). The ratio of the LI-200SA pyranometer increases significantly for larger solar zenith angles. These results are different than what is seen with the GHI measurements.

Another way to plot the data is against the incident angle instead of the solar zenith angle. This is done in Fig. 7. For the

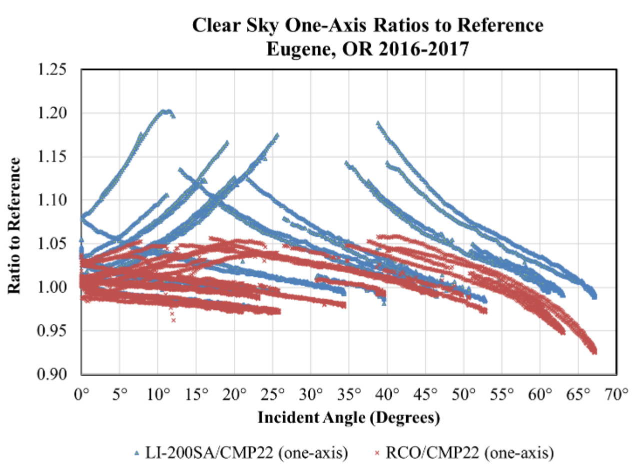

Fig. 7. Comparison of the LI-200SA pyranometer and the RCO reference cell with the output of a CMP 22 pyranometer plotted against incident angle.

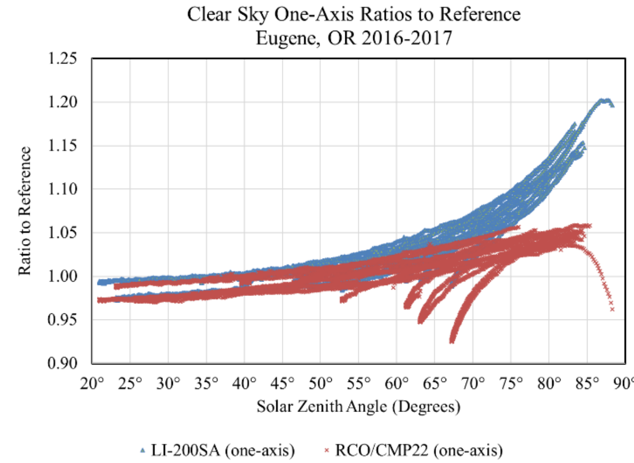

Fig. 6. Comparison of the LI-200SA pyranometer and the RCO reference cell with the output of a CMP 22 pyranometer.

LI-200SA pyranometer there is not a clear relationship between the angle of incident and the ratio to the reference CMP 22. However, there is a clear relationship with solar zenith angle as shown in Fig. 6, giving credence to the spectral influence. The RCO reference cell ratio may indicate a slight dependence on incident angle, especially at larger incident angles. This is consistent with an angular dependence seen in the calibrations shown in Fig. 2. The RCO ratio to reference does not show as much dependence.

A. *Clear and Cloudy Data*

Clearly more than clear sky data are needed for a comprehensive comparison of measurements. In Fig. 8, ratio data from the LI-200SA and IMT reference cells are plotted for May 2017. There is a fair scatter during the morning and evening hours resulting from reflections from objects near the horizon and changes in the spectral distribution of incident

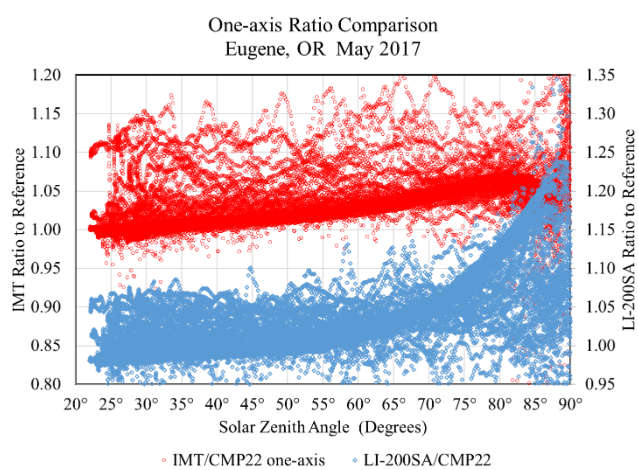

Fig. 8. The ratio between the LI-200SA pyranometer and the reference pyranometer measurements is show as blue diamonds. Axis on the right. The ratio between the IMT reference cell and reference pyranometer measurements is shown as red 'O'. Axis on the left.

irradiance. The IMT reference cell ratio values typically range between 1.0 to 1.1 during the whole month while the ratios of the LI-200SA pyranometer ratio values range between 1.0 and 1.2. The reasons for the different responses need to be further studied. For clarity and to keep the different data sets from being on top of each other, the scale for the LI-200SA, shown on the right, was shifted to show both data sets.

VI. DISCUSSION

The comparisons of the data from the various instruments demonstrate why it is difficult to evaluate and compare various photovoltaic systems using different sensors. Even similar irradiance sensors have large uncertainties that make it difficult to develop and validate PV performance models. This is especially true for instruments measuring POA irradiance on a one-axis tracking system. Algorithms to remove systematic effects can be developed, but it is unclear how well these adjustments would work at different locations with different aerosol and ground reflective characteristics.

The deviation of reference cells from a true cosine response is fairly well understood and the effects of transmission through the glazing can be modeled. While the reference cells adjust for cell temperature using measured cell temperature, some temperature dependence may remain and any additional temperature effects need to be evaluated. With knowledge of the spectral responsivity of the reference cells, the spectral effects on the measurements can be modeled [4]. However, the advantage most reported for reference cells is that they behave much like PV modules made of similar material. Therefore, if one wants to evaluate the performance over time using a reference cell, it may not be worth the effort to adjust the reference cell measurements to better simulate the total irradiance incident on the PV module.

On the other hand, if one has a very accurate measurement of the incident irradiance, a model must be used to simulate the performance of the PV module. This is the methodology most used to estimate PV system performance. A problem arises because these models are validated against various type of irradiance sensors and the data gathered so far in Golden and Eugene demonstrate the performance differences between various irradiance sensors.

Because irradiance sensors have a wide variety of characteristics and exhibit systematic effects [1], it might be necessary to specify that the performance model is tested and validated using a given sensor, and data gathered by difference sensors should be modified to match the characteristics of the sensor used to develop and validate the model.

Spectral and other meteorological data are also being gathered at the Golden and Eugene stations and this information is important to better identify the causes that result in the diverse measurement results. Untangling the causes and magnitudes of the various effects is the goal of future efforts. In the meantime, it is difficult to recommend the best method to track the performance of a photovoltaic system with a high degree of accuracy.

VII. SUMMARY

This study reports the initial results of an analysis of pyranometer measurements on a horizontal and one-axis tracking system. Because there are many PV systems that utilize one-axis tracking technology and it is important to monitor the performance of these systems over time, there is concern about the measurements of irradiance on one-axis tracking systems. This is not only important for evaluating the performance of the systems, especially when systems have some benchmark performance standards, it is also important when evaluating potential solar facility locations. As subsidies for solar facilities are reduced and financing becomes more dependent upon revenue from production, accurate evaluation of the incident irradiation becomes increasingly important as production of electricity is directly tied to the incident irradiance.

This study shows that there is considerable variation between high quality irradiance measurements and other lower cost options. One can either choose between more accurate instruments or developing models to adjust measurements from less accurate instruments. Two things should be considered, the accuracy of measurements under different conditions and if adjustment algorithms can be reliably developed.

Realizing that with tacking systems a majority of incident angles are less than 45 degrees during the summer months, one might consider using instrument calibrations at angle other than 45 degrees, a standard for most pyranometer calibrations for instruments that measure GHI irradiance.

This effort provides a trove of high quality data that can determine the uncertainty of irradiance measurements on one-axis tracking systems, an important piece of information for those planning, financing, and operating one-axis tracking systems.

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