Conference Proceedings

ASES National Solar Conference 2017

Denver, Colorado 9-12 October 2017

Comparison of Pyranometers and Reference Cells on Fixed and One-axis Tracking Surfaces

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Abstract

Photovoltaic (PV) system perfomance is monitored by a wide variety of sensors. These instruments range from secondary standard pyranometers to photodiode-based pyranometers to reference cells. Although instruments are mounted in the plane of array of the modules a wide range of results have been obtained. Some of these difference have been assumed to come from systematic uncertainties associated with the irradiance sensors. This study is an attempt to quantify these differences by comparing the output of selected thermopile-based pyranometers to photodiode-based pyranometers and reference cells on a horizontal surface, a fixed-tilt surface, and a one-axis tracking surface. This analysis focuses on clear-sky results from two sites with different climatic conditions. Several important features were observed. Photodiode-based pyranometers and reference cells produce widely different results under clear skies, especially at larger angles-of-incidence even though both instruments are based on measuring the short circuit current of solar cells. The difference is caused by the scattering of light as it passes through the glazing of the reference cell or the diffuser lens of the photodioded-base pyranometer. Both instruments are shown to have similar response to the spectral distribution of the irradiance when compared to the thermopile-based pyranometer that has a response nearly independent of the wavelength of light used by PV modules.

Keywords: *pyranometer, reference cell, one-axis tracking, solar, measurements*

1. Introduction

Now that photovoltaic (PV) generating systems are springing up around the world and that the cost of PV generated electricity is approaching or less than that of other generating technologies, it is important to predict the performance of PV facilities both for planning and financing. In addition, there is considerable interest in the long-term performance of PV systems and the degree to which the system performance degrades over time. Unfortunately, studies in the literature tend to produce different results and this uncertainty adds risk and cost to those deploying and financing PV generating facilities. Developers and operators want to know how well their systems are performing. Users are working to forecast the incident irradiance and want to know the amount of electricity that will be produced. Financers want to have confidence that the facility will be able to

doi:10.18086/solar.2017.07.01 Available at http://proceedings.ises.org

generate and sell enough electricity to cover their loans. Regulators want to be able to set rates that cover the cost of PV generating facilities but they do not want to generate windfalls if systems perform better than expected.

For these reasons and more, it is important to understand the accuracy and uncertainty of measurements of PV systems. Measured incident solar radiation is a large source of uncertainty. A series of measurements comparing the output of various irradiance sensors was initiated by the National Renewable Energy Laboratory (NREL) in Golden, Colorado and at the University of Oregon in Eugene, Oregon. These measurements were on horizontal, fixed-tilt, one-axis tracking, and a two axis tracking surfaces in Golden, and on horizontal and one-axis tracking surfaces in Eugene. This is a report of the findings from the first year of deployment, and the focus of this study, will be during clear skies. This paper provides a more detailed evaluation of an earlier report (Vignola, 2017).

The paper is organized as follows:

1. Description of the experimental setup
2. Calibration discussion
3. Comparison under clear skies
4. Brief discussion under all weather conditions
5. Discussion of results
6. Future directions

2. Description of the Experimental setup

The thermopile-based pyranometers at Golden were Kipp and Zonen CMP21 for the one-axis tracker, a CMP 11 for the fixed array, and a CMP 21 for the horizontal and two-axis tracker. Mounted on the surfaces were LI-COR 200A pyranometers, Kipp and Zonen SP Lite2 pyranometers, RCO reference cells, and IMT reference cells. The CMP 21s were replaced with CMP 22s on June 23, 2017. In Eugene, the thermopile-based pyranometers were Kipp and Zonen CMP22 pyranometers. LI-COR 200A pyranometers, Kipp and Zonen SP Lite2 pyranometers, RCO reference cells, and IMT reference cells were mounted on both a one-axis tracker and the horizontal surface.

The reference cells monitor the cell temperature and adjust the measurements to values that would be obtained at 25°C. Measurements from the reference cells before correction for temperature are also recorded.

The instruments on the one-axis tracker in Eugene are shown in Fig. 1. The sensors are connected to a Campbell Scientific data logger and one second readings were averaged throughtout one minute. The sensors are cleaned five days a week and calibrated once per year.

Fig. 1: Pyranometers and reference cells on a one-axis tracker in Eugene, Oregon.

3. Calibrations

Initially the instruments were calibrated at NREL before being deployed. 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 instruments in this study.

The 2016 calibration results at Eugene are shown in Fig. 2 for a range of solar zenith angles (SZA) from 30° to 80°. The results are normalized to 45° to illustrate the change in responsivity as a function of SZA. These instruments were calibrated in a horizontal position and the angle-of-incidence is the same as the SZA. The photodiode-based pyranometers are within ±5% throughout the range from 30° to 80°, and the CMP22 is within ±2.5%. The reference solar cells are within ±5% out to 60° but they start to deviate significantly from a true cosine response at larger SZAs. These calibrations were performed under clear-sky conditions. Night time offsets were subtracted from the values before the responsivities were determined. No other adjustments were applied to the data.

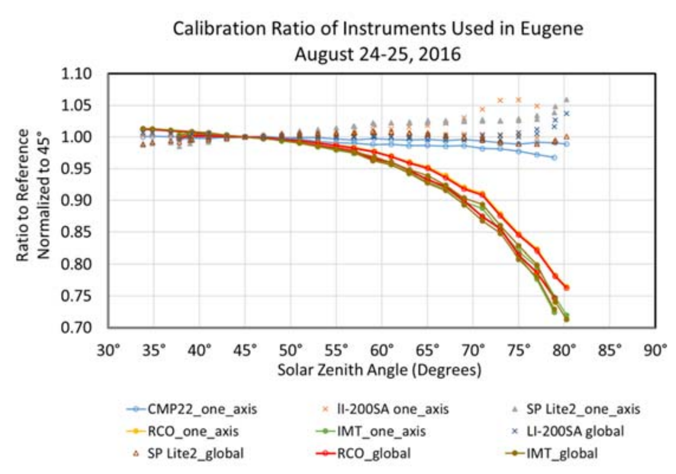

Fig. 2. Calibration comparison of instruments used in this study. The responsivities at 45° are used to normalize the calibrations.

The calibration results at 45° had uncertainties that ranged from 0.54 to 1.5% at the 95% level. These uncertainties varied somewhat from one year to another, but the general shape of the curves as a function of SZA remained the same.

4. Comparisons under clear skies

Once the instruments were calibrated, one set of pyranometers as placed on a horizontal surface with a CMP 22 pyranometer serving as the reference instrument in Eugene, Oregon. Data for one year have been collected both in Eugene, Oregon, and Golden, Colorado, with measurements continued into a second year. Initial findings on under clear skies are examained to help identify characteristics of the instruments and identify any consistent behaviors. Becayse photodiode-based pyranometers respond in a similar manner and to simplify the figures in this article, the LI-COR SA-200A was chosen as representative of photodiode-based pyranoemeters. The RCO reference cell was chosen to be representative of the reference

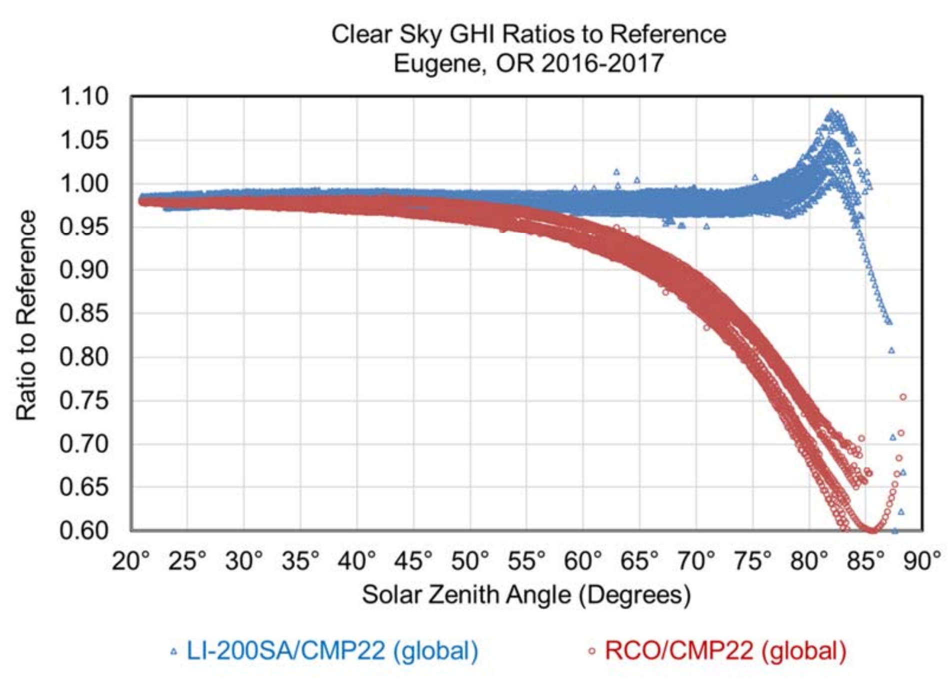

Fig. 3: Ratio of a LI-200SA pyranometer (blue triangles) and RCO reference cells (red circles) values divided by the values from the reference CMP 22 pyranometeer on a horizontal surface during clear skies for selected days throughout the year at Eugene, Oregon.

cells. To illustrate how the instruments behave throughtout the year, clear-sky values were chosen for each month. The measured values from the instruments were divided by the values from the reference pyranometer. The results from one year of data for the horizontally mounted instruments are shown in Fig. 3.

4.1 Global measurements

Comparisons of data in Fig. 2 with those in Fig. 3 demonstrate that the instruments closely match the dependence on SZA that was found during instrument calibration. The reference pyranometer, the CMP 22 has only a small dependence on SZA and hence most of the dependence shown in Fig. 3 is the result of the cosine dependence of the instrument itself. There is a slight increase in spread in the data during the year and most of this varience probably reflects the different clear-sky atmospheric conditions that vary during the year.

4.2 Fixed-tilt measurements

With the relationship between incident angle and responsivities demonstrated under clear skies on a horizontal surface, next the behavior for fixed-tilt is examined and then the one-axis tracking surfaces. At Golden, CO, an array of pyranometers tilted at latitude ~40° facing south was monitored. Several photodiode-based pyranometers and reference cells were placed on the surface along with a thermopile-based CMP 21 pyranometer that served as a reference. Clear sky data in June were selected for the examination because during the early morning and evening hours the sun is behind the instruments and the direct normal irradiance (DNI) is not seen by the instruments. This means that the instruments are measuring the diffuse irradiance. Diffuse irradiance comes from across the sky, and this mitigates some of the angle-of-incidence effects. In addition, the diffuse irradiance has a different spectral composition than the DNI irradiance that dominates under clear skies and this illustrates the different behavior of the instruments based on photodiode and solar cells, which have a large dependence on the spectral distribution of the incident radiation whereas thermopile pyranometers have minimal spectral dependence. The ratio data are shown in Fig. 4 and Fig. 5.

The data shown in Figs. 4 and 5 exhibit similar behavior to the calibration data in Fig. 2, however, one might expect the behavior to be different because the surface is tilted and oriented more directly toward the sun. The photodiode pyranometer performs as expected and an SZA of 70° gives results that are almost equal to the reference pyranometer. For the RCO reference cell, the ratio deviated almost 20% from the reference measurements at an SZA of 65°. This is nearly twice as much as it varied from the reference measurements on

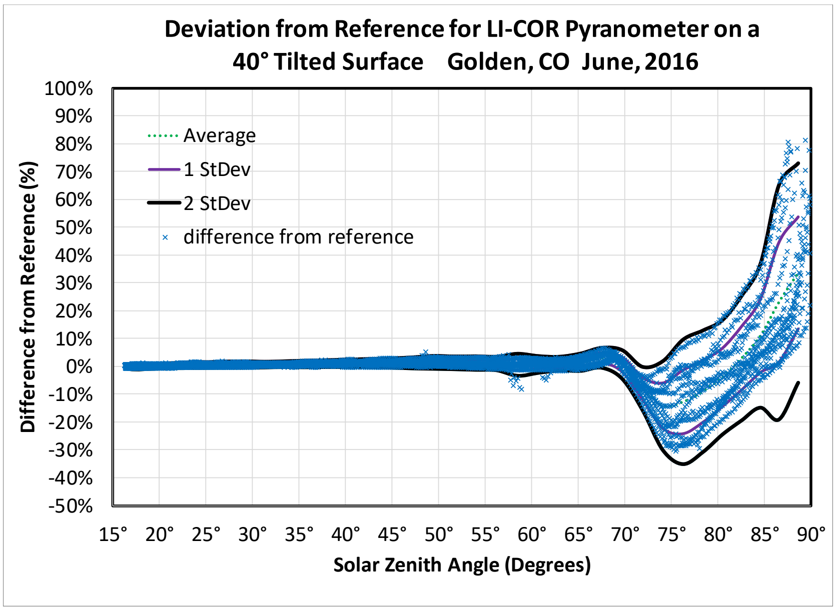

Fig.4: Plot of the ratio of a LI-200A pyranometer divided by the reference pyranometer measurements under clear-sky conditions in June, 2016 at Golden, CO.

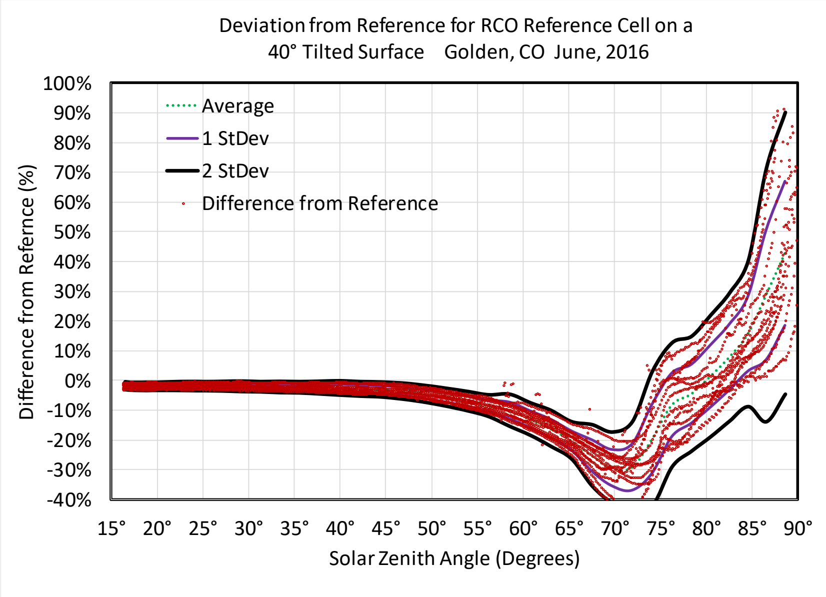

Fig. 5: Plot of the ratio of a RCO reference cell divided by the reference pyranometer measurements under clear-sky conditions in June, 2016 at Golden, CO.

a horizontal surface at an SZA of 65°. The reason for the increased deviance is that the angle-of-incidence is greater than in the horizontal case. In fact, at an SZA of approximately 75°, the sun is setting behind the tilted surface. The spectral distribution of the ground reflected irradiance also plays a role. The magnitude of the spectral distribution effects will be the subject of a future paper.

Once the sun is behind the sensors, the diffuse irradiance is the dominate contributor to the incident irradiance. In fact, the behavior of the photodiode-based pyranometer and the reference cell become very similar when measuring only the clear-sky diffuse irradiance.

Under clear skies in June at Golden, the difference between the reference measurements and the photodiode-based pyranometer are small, from -1% to +4% at an SZA of 50° to a 95% level of confidence. For reference cells at a SZA of 50°, it is on the order from -2% to -8% at a 95% level of confidence. These estimates do not include the uncertainty in the reference measurements that would increase the uncertainty estimates by approximately 1% on either side of the quoted uncertainties.

4.3 One-axis tracking surface

Instruments mounted on a one-axis tracker are pointed more directly at the sun than on a tilted surface during much of the day, especially during the early morning and later afternoon hours. During the noon time hour, the instruments are essentially horizontal and receive less irradiance than instruments on a fixed-tilt surface. For the most part, the angle-of-incidence plays less of a role on a one-axis tracking surface whereas spectral distribution changes that occur mostly in the morning and afternoon hours play a much bigger role.

Fig. 6 shows this behavior as it plots the deviation from the reference instrument throughout the day for instruments mounted on a one-axis tracker. One clear-sky period was chosen for each month of the year. The LI-200A does not show the steep angle of incident effects that occur when incident angles reach 80°, as is shown in Fig. 3. This is because the incident angle is never larger than 70° on the one-axis tracker in Eugene, however, because the tracker is pointed close to the sun in the morning and evening hours when the solar spectrum distribution is shifted to the longer wavelength, the spectral effects become very pronounced and can result in photodiode-based pyranometers yielding results that are 15% to 20% larger than the reference pyranometer measurements.

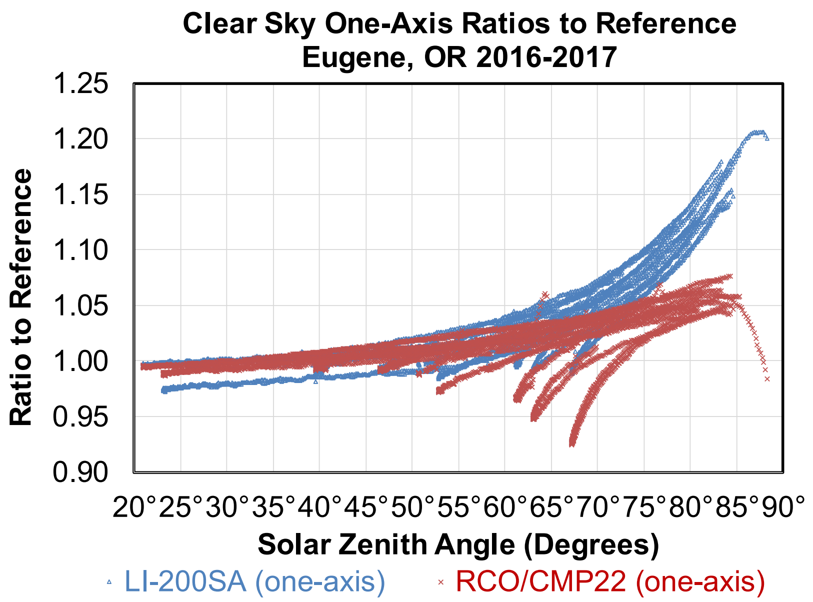

Fig. 6: Clear-sky ratio data between a LI-200S pyranometer and a RCO reference cell against the reference CMP 22 pyranometer. Clear-sky periods were shown for each month of the year.

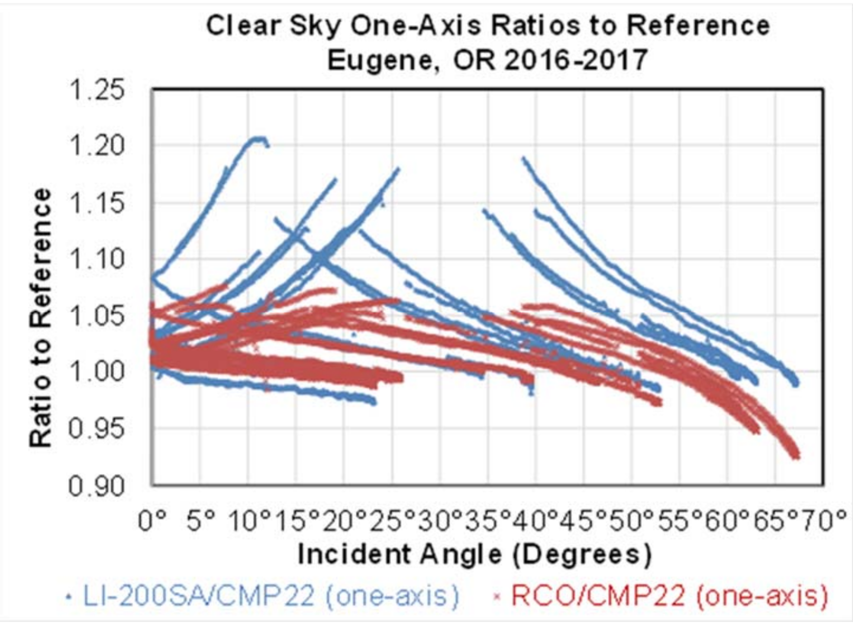

Fig. 7: Clear-sky ratio data between a LI-200A pyranometer and an RCO reference cell compared to the reference CMP 22 pyranometer plotted against the incident angle instead of SZA. Clear-sky periods are shown for each month of the year.

Although the spectral response of the photodiode-based pyranometers and reference cells are similar, they are not identical. The diffuser on the photodiode-based pyranometers has a different spectral response than the glazing on the reference cells.

Reference cells do not exhibit such extreme divergence from the reference pyranometer. Extreme clear-sky values vary only ±7% from the reference pyranometer measurements on a one-axis tracking surface (see Fig.

6). Reference cells measure the short circuit current much like photodiode-based pyranometer, so one would expect a similar spectral response. In fact, that is the case. However, reference cells have a glazing that affects the transmission of light, just like PV modules. The transmission transmittance of light decreases as the angle-of-incidence increases. This is opposite of the spectral enhancement seen with the photodiodes caused by the spectral distribution shifts to longer wavelengths as the path length through the atmosphere increases in the morning and evening hours.

One way to illustrate the angle-of- incidence affects is to plot the ratio to the reference instrument against the angle-of-incidence instead of the SZA. This is shown in Fig. 7. The deviation from the reference pyranometer decreases, as expected from the calibration results shown in Fig. 2, however, the increase in responsivity caused by the changing spectral distribution at these large angles-of-incidence somewhat offsets the decrease in responsivity caused by the reduction of transmission of light through the glazing at larger angles. The clear-sky ratios in Fig. 7 for the RCO data are a better fit to the reference pyranometer than the photodiode-based pyranometer. The photodiode-based pyranometer does not show any consistent dependence on the angle-of-incidence as it does when plotted against the SZA. Again, this is expected because the data from the photodiode-based pyranometer closely matches the data from reference pyranometer out to angles of 75° to 80° (see Fig. 2).

5. Comparisons under all weather conditions

Clear-sky conditions are easier to model and evaluate than all weather conditions when clouds are distributed randomly across the sky. Reflections off clouds, the different spectral distributions of cloudy skies and clear skies, and the variety of clouds increase the variance in the measurements. Even the response time of the reference pyranometer in relationship to the photodiode-based pyranometer or the reference cell adds to the scatter. However, in general, the relationships tend to follow those observed under clear-sky conditions with considerable more variation from the average.

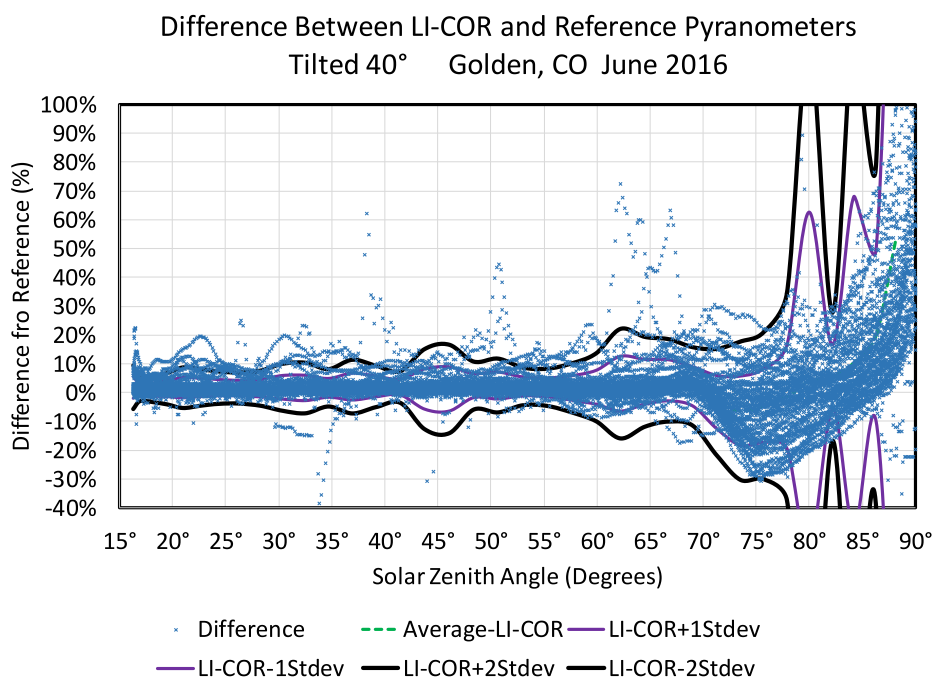

Fig. 8: Ratio of LI-200A measurements to those of the reference pyranometer in Golden, CO under all weather conditions in June, 2016. The dotted green line shows the average value and the thin purple lines show one standard deviation from the average. The thick black lines show the two standard devations from the average. 95% of the data points should be within two standard deviations for a Guassian distribution of the differences.

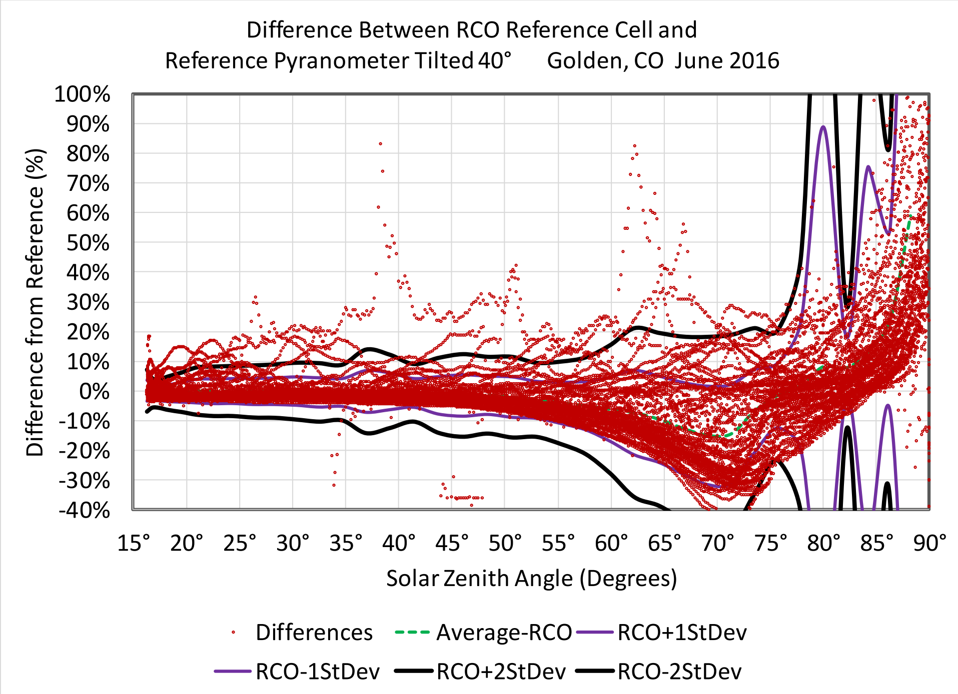

Fig. 9: Ratio of RCO reference cell measurements to those of the reference pyranometer in Golden, CO under all weather conditions in June, 2016. The dotted green line shows the average value and the thin purple lines show one standard deviation from the average. The thick black lines show the two standard devations from the average. Ninety five percent of the data points should be within two standard deviations for a Guassian distribution of the differences.

All-weather plots for the ratios in June are shown for the LI-200A pyranometer in Fig. 8 and for the RCO reference cell in Fig. 9. For the LI-200A pyranometer. the deviation from the reference pyranometer ranges from -7% to 11% at an SZA of 50° with the 95% level of confidence. This compares to -1% to +4% under clear-sky conditions in June, which is an approximate increase of three-times in the scatter of the data. Some of this scatter is caused by outliers. There are a lot of clear skies in June. At SZAs greater that 75°, there is no DNI, and only the DfHI and ground-reflected light contribute to the irradiance. Spectral and angle-of-incidence effects also come into play, resulting in a large scatter in the ratios.

For the reference cells, the variance at an SZA of 50° is between +12% and -14%. However, the distribution is non-Gaussian, and very few data point less than -8%. Even at this +12% to -8% range, the scatter is still at least three times larger than the clear-sky results. The clear-sky ratios for the reference cells have a range from -8% to -2%. Most of the scatter in the results is more than the -2% results. The clear-sky data shown in Fig. 9 produces the lower grouping of data in the plot showing the ratio with the reference pyranometer. This indicates that during clear periods, the angle-of-incidence effects are maximum. Under cloudy conditions, the diffuse contribution increases and because the diffuse irradiance is the sum of DfHI from all portions of the sky the angle-of-incidence is averaged over many value, thus reducing the angle-of-incidence effects. Under totally cloudy conditions, the angle-of-incidence effect is negligible and the spectral effects dominate.

6. Discussion

An understanding of how a photodiode-based pyranometer and a reference cell behave has been established. The following conclusions can be drawn from the data gathered to date. The photodiode-based pyranometers and reference cells measure the global and tilted to approximately ±10% at a 95% level of confidence under all weather conditions for SZA up to 50° compared to the reference thermopile-based pyranometer that exhibits minimal thermal offset. Much of this deviance from the reference pyranometer comes during cloudy or partially cloudy periods.

For larger SZAs, the reference cell measurements systematically differ from the reference pyranometers with transmission losses through the glazing most likely causing most of the decreased response. The reflection of light off the glazing and decrease in transmission through a glazing are well understood through the work of Fresnel and Snell's Law (Lvovsky, 2013). This difference between the reference cell and a reference pyranometer can reach 40%. During the early morning and late evening hours (larger SZA) the spectral distributions are shifted to the larger wavelengths. This increases the responsivity of the photodiode-based pyranometers and reference cells as compared to periods in the middle of the day because the solar cells used in these instruments respond better to the longer wavelengths. In reference cells, this increase in responsivity during the morning and evening hours is countered by the decrease in responsivity caused by the reduction in light transmitted through the glazing.

Photodiode-based pyranometers have diffuser domes or lenses that significantly reduce the angle-of-incidence effects out to angles-of-incidence near 75° to 80°. On a fixed-tilt or one-axis tracking surface, the angles-of-incidence are typically reduced, and photodiode-based pyranometers exhibit little angle-of-incidence effects (see Fig. 6), however, the increased responsivity to the spectral shift in the morning and evening hours is enhanced with a one-axis tracker. It turns out that reference cell measurements on one-axis trackers more closely match reference measurements than photodiode-based pyranometers because the angle-of-incidence effects are opposite of the spectral shift effects.

Using photodiode-based pyranometers to measure the incident irradiance on horizontal, tilted, or one-axis tracking surfaces yield differences from thermopile-based pyranometer because of spectral effects. To provide accurate measurements of incident irradiance during the morning and evening hours, the effects of the spectral distribution shift need to be considered. Work on modeling the effect of spectral shift was discussed early on [King, 1997, 1997, 1998, Vignola, 1999] and has been the foundation of adjustment algorithms that remove systematic effects for rotating shadowband radiometers the utilize photodiode-based pyranometers (Augustyn, 2004, Lee, 2016, Vignola, 2014, Vignola, 2016, Wilbert, 2016).

To use reference cell measurements to estimate incident irradiance requires two steps. One is to account for the angle-of-incidnece effects, and the other is to account for the spectral effects. Because two steps are necessary to adjust reference cell measurements to estimate the incident irradiance, the uncertainty is increased as compared to photodiode-based pyranometers that only need to make the spectral shift adjustment. Because of the larger uncertainties, reference cells are not recommended to obtain irradiance measurements.

When evaluating the performance of a PV array, reference cells provide an excellent measurement. If the reference cells use the same glazing and technology as the PV module being monitored, the data more closely emulate the PV module performance. The usefulness of reference cells in evaluating PV performance is negated if the glazing and/or solar cell technology of the reference cell differs from that used in the modules being tested. Each type of glazing and solar cell technology has a unique set of characteristics. The characteristics of the materials used in the reference cell would need to be adjusted to match the characteristics of the material used in the PV module because removing one set of characteristics and substituting another set of characteristics leads to increased uncertainties. If reference cells use materials that are the same as the PV modules under study, the only adjustment that needs to be made with the reference cell data to translates into short-circuit values being measured to the max power point values under which the PV array operates.

With photodiode-based pyranometers, spectral-caused effects must be considered. Then a model needs be used to estimate the PV module performance. This model has spectral adjustment algorithms and angle-of-incidence adjustments. Typically, these adjustments can result in larger uncertainties of the irradiance than occur if reference cells were used to estimate module performance

7. Future tasks

It has been postulated that the effects of changes in the spectral distribution during the day and the angle-of-incidence effects are incorporated into the data with reference cells and photodiode-based pyranometers. Because some spectral data are already being gathered and plans for including spectral data on one-axis trackers are being made, the effects of the spectral shift can be tested. One can also model the angle-of-incidence effects. This paper has not discussed or considered ground reflected irradiance and how this can affect the measurements. With estimates of the spectral and angle-of-incidence effects, differences between the reference cell and photodiode-based pyranometer and reference pyranometers can be better analyzed.

8. Acknowledgement

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office.

NREL's contribution to this work was supported by subcontract number XGJ-7-70143-01. We would also like to thank the other sponsors of the UO Solar Radiation Monitoring Laboratory, the Bonneville Power Administration, the Energy Trust of Oregon, and Portland General Electric.

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