SOLAR CELL BASED PYRANOMETERS: EVALUATION OF THE DIFFUSE RESPONSE

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ABSTRACT

The responsivity to diffuse radiation of a solar cell based pyranometer is studied. Diffuse measurements are made using a shade disk for a LiCor Pyranometer and an Eppley PSP pyranometer mounted side by side on an automatic tracker. The difference in the diffuse responsivity varies by 30 to 40% between cloudy conditions and clear skies. This difference is attributed to the spectral dependence of the LiCor pyranometer. A slight sensitivity in the diffuse responsivity was found for both ground based relative humidity measurements and ambient temperature. A simple method to estimate the spectral dependence of the diffuse responsivity of the LiCor pyranometer is presented. Implication of the spectral dependence of the solar cell based pyranometers is discussed for LiCor calibrations and for measurements made by rotating shadowband instruments using solar cell based pyranometers.

1. INTRODUCTION

Solar cell based pyranometers are widely used as inexpensive instruments to measure solar irradiance. These pyranometers are used in most agricultural based solar monitoring networks and are also extensively used to evaluate the performance of photovoltaic (PV) systems. Rotating Shadowband Pyranometers (RSP) that are used to evaluate the performance of hundreds of PV system use LiCor solar cell pyranometers. Other sophisticated instruments such as the Y.E.S. Rotating Shadowband Radiometer (RSR) also incorporate solar cell based pyranometers.

It is well known that solar cell based pyranometers are spectrally sensitive to the incident radiation. Pioneering work by J. J. Michalsky [1] developed algorithms to correct for the spectral response of solar cell based pyranometers. More recent work by David King [2] developed new algorithms to correct for spectral limitations of solar cell based pyranometers.

While evaluating the beam, global, and diffuse values from a Rotating Shadowband Pyranometer, it became apparent that most of the diffuse measurements made on clear days were significantly lower than diffuse values obtain by subtracting the beam irradiance measured by an Eppley NIP from the global values measured by an Eppley PSP. Since the discrepancy might have been related to the cosine response of the PSP, it was necessary to directly compare diffuse measurements made with a shade disk for both the PSP and the LiCor pyranometer. These side by side measurements were done with a SciTech automatic tracker.

This study reports on one year of high quality diffuse measurements and confirms that there is a 30-40% drop in the responsivity to diffuse irradiance of a LiCor pyranometer from cloudy to clear skies. The information is presented in four sections. The first section shows the change of the diffuse responsivity as a function diffuse and global irradiance. The second section evaluates the dependence of this change as a function of temperature and relative humidity. The third section presents the best correlation fit and discusses the impact of the spectral dependency of the diffuse responsivity on the calibration of the LiCor pyranometer. The fourth section looks how this spectral dependence affects measurement from rotating shadowband

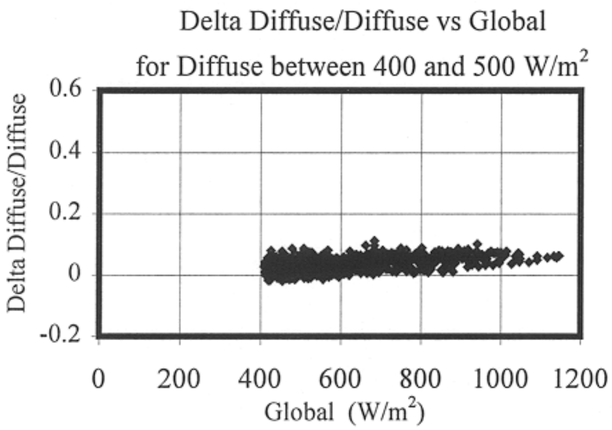

Fig. 1: For diffuse irradiance above 400 W/m^2 the difference between the diffuse values from the PSP and the LiCor pyranometer average about 4% and are less than 10%. Data in this range are representative of cloudy conditions.

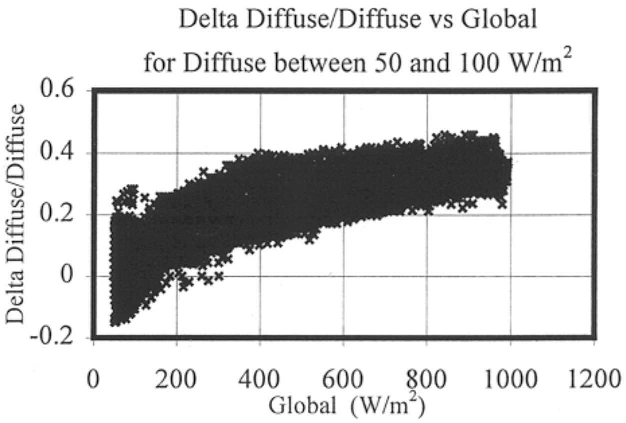

Fig. 2: For diffuse irradiance between 50 and 100 W/m^2 the difference between the diffuse values from the PSP and the LiCor pyranometer vary from just a few percent to over 40%. Clear skies occur when the diffuse values are low and the global values are high.

instrument. The fifth section presents a conclusion and summary of the results.

2. SPECTRAL DEPENDENCE OF DIFFUSE MEASUREMENTS MADE BY LICOR PYRANOMETERS

The spectral dependence of beam responsivity of the LiCor pyranometer has been studied with high quality data [1,2]. The same can not be said for this diffuse responsivity. The most accurate diffuse measurements are obtained by using a shade disk to block the direct sunlight from striking the pyranometer. Use of the shading disk eliminates the need to correct the measurement for shading of the rest of the sky by the shadowband. While beam measurement can be accurately obtain from NIP measurements, the calculation of the diffuse component obtained by subtracting the beam irradiance from the global is subject to errors in the relative calibration of the instruments and the deviation from the true cosine response of the pyranometer.

The data used in this study are 5 minute integrated values obtained using a Campbell Scientific CR-10 data logger. One year's worth of data from March 1, 1998 to February 28, 1999 are represented in the data plots. All values with the global radiation equal to zero have been eliminated from the study. There are over 54,000 data points in the study. All data were taken at Eugene, Oregon with latitude 44.05º North and longitude 123.07º West. At the end of April 1998, a large dust cloud from China settled over the Pacific Northwest. Data from this time period are included in the study.

The percentage difference between the diffuse values measured by the LiCor pyranometer as opposed to a PSP pyranometer depend both on the global intensity and the diffuse irradiance (See Figs. 1 & 2). During cloudy periods, the difference between the LiCor and PSP diffuse readings is only a few percent. However, during clear periods under blue skies, the LiCor readings are low by about 30-40%.

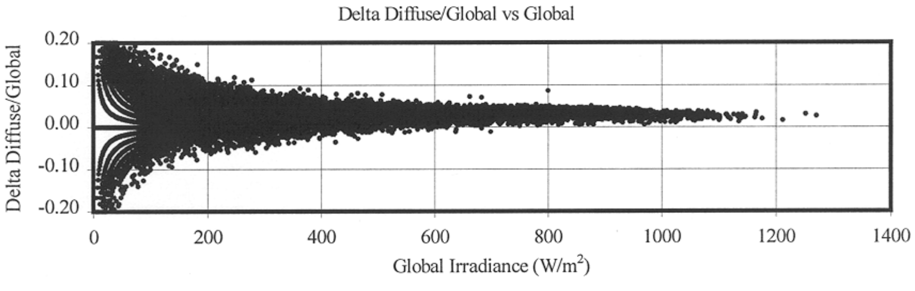

Fig. 3: Plot of the difference between the PSP and LiCor diffuse measurements divided by global irradiance verse global irradiance. Data points represent one year of 5 minute integrated data values. Over much of the range, this ratio is nearly linear.

TABLE 1: COMPARISON OF CORRELATION RESULTS

Global (W/m^2)	Measured Δ Df	Δ Df (W/m^2)	Global Corr.	Corr. Δ Df (W/m^2)
0-10	0.0546	0.4	0.0358	0.3
10-25	0.0501	0.9	0.0358	0.6
25-50	0.0441	1.7	0.0356	1.3
50-100	0.0402	3.0	0.0354	2.6
100-200	0.0363	5.3	0.0350	5.1
200-400	0.0329	9.5	0.0342	9.9
400-600	0.0327	16.3	0.0331	16.4
600-800	0.0327	22.9	0.0320	22.4
800-1000	0.0314	27.8	0.0309	27.3
>1000	0.0268	28.3	0.0298	31.4

Because low values of diffuse irradiance are obtained when it is clear and when it is very cloudy, global diffuse correlations are studied by dividing the diffuse irradiance by the global irradiance. There is then a one to one relationship between the diffuse fraction (diffuse divided by global) and global irradiance. To take advantage of this one to one relationship, the diffuse values are divided by the measured global irradiance. The result of utilizing the diffuse fraction is shown in Fig. 3.

Over the much of the range, the ratio of the difference as a function of global irradiance is nearly constant. This means that the difference between the PSP and LiCor diffuse values is approximately equal to 3.5% of the global irradiance.

As opposed to the diffuse data from a previous study [1], the LiCor diffuse values were almost always smaller than the PSP diffuse values for diffuse irradiance greater than 400 W/m^2. On partially sunny days with high diffuse values, it is difficult to obtain accurate diffuse values without use of a shade disk for diffuse measurement.

To visualize the magnitude of the difference between the two measurements, the average of the delta diffuse fraction are listed in Table 1 in bins based on global irradiance. Also listed in the table are estimates of the difference as calculated from simple correlations.

Eqn. 1 is a simple linear fit to the data for all diffuse values with global irradiance greater than 100 W/m^2 .

$$\Delta Df/G = 0.0359 - 0.00000554 * G \qquad \text{Eqn. 1}$$

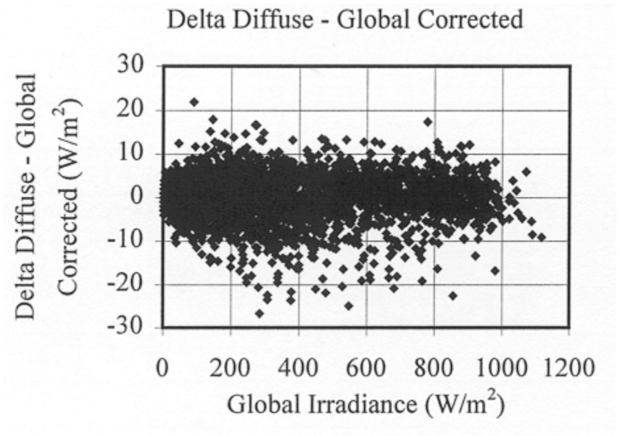

Fig. 4: The difference in the LiCor and PSP diffuse values after the correction for global irradiance given in Eqn. 1.

G is the global irradiance in W/m^2 and Δ Df/G is the difference between the diffuse irradiance and the LiCor diffuse measurement divided by the global irradiance. The standard deviation is ±0.0213. Give that the precision of the data is one $Watt/m^2$, the differences in the mean bias errors as shown in Table 1 are insignificant except for instances when the global irradiance is greater that 1000 W/m^2. In Eugene, the global irradiance values exceed 1000 W/m^2 when the sun is shining through the clouds and the diffuse values are typically several hundred W/m^2.

Fig. 4 shows the corrected diffuse difference plotted against global irradiance. The systematic change of the difference with global irradiance has now disappeared and the data points are now fairly evenly distributed around zero. The standard deviation of the difference between the diffuse measurements from the LiCor and PSP is reduced from nearly 10 W/m^2 to less than 5 W/m^2. This is close to the limit to which the incident solar energy can be measured.

3. INFLUENCE OF TEMPERATURE AND RELATIVE HUMIDITY

The responsivity of both the LiCor Pyranometer and the PSP vary with temperature. Fig. 5 shows that there is a small temperature influence on the diffuse measurements. Over a 50º C change in temperature the change in delta diffuse factor is 0.018.

The linear correlation between the change in diffuse ratios and temperatures is:

$$\Delta Df/G = 0.0397 - 0.000358 * T \qquad \text{Eqn. 2}$$

The standard deviation is ± 0.0212. From earlier studies [1,2] the change in the LiCor responsivity over a 50° C temperature change is expected to be about 4%. The change in the responsivity of the PSP over that temperature range about 1% or less. However, both these estimates come from tests of the instruments under a full sun, not the instrument measuring the diffuse component.

The results for this correlation are very similar to the results shown in Fig. 4 for the correlation with global irradiance.

Relative humidity measurements were also made during this period. When the difference in diffuse fraction is plotted against relative humidity (Fig. 6), it increases slightly as relative humidity increases. The difference in diffuse fraction correlates best with the square of the relative humidity.

$$\Delta \text{ Df/G} = 0.0247 - 0.00000238 * RH^2 \qquad \text{Eqn. 3}$$

The standard deviation is ± 0.0207. The correlation with relative humidity is stronger than with temperature. The square of the relative humidity was used because it is a better match of the correlation. Again, the correlation results are similar to the global correlation results shown in Fig. 4. While the use of the relative humidity can statistically improve the correlation results, in practical the improvement is small.

The reason that the difference in diffuse fraction increases as relative humidity increases is because the LiCor pyranometer is insensitive to the infrared portion of the solar spectrum while the PSP pyranometer does respond to solar irradiance in this spectral region. Ground based relative humidity measurements are often used to estimate the total water vapor content of the atmosphere when measurements are lacking and in general when relative humidity increase, water vapor content of the atmosphere increases. Under clear sky conditions, an increase in water vapor causes an increase in diffuse irradiation in the infrared bands. The PSP measures this increase while the LiCor does not. Hence, the difference in the measured diffuse between the two instruments increases.

4. CORRELATION RESULTS & LICOR CALIBRATION

The difference in diffuse fraction correlates to some degree of significance with global irradiance, temperature, and relative humidity, and the combination of all three.

The correlation with all three parameters is given in Eqn. 4.

$$\Delta \text{ Df/G} = 0.0163 + 0.00000568 * G + 0.000175 * T + 0.00000321 * RH^2 \quad \text{Eqn. 4}$$

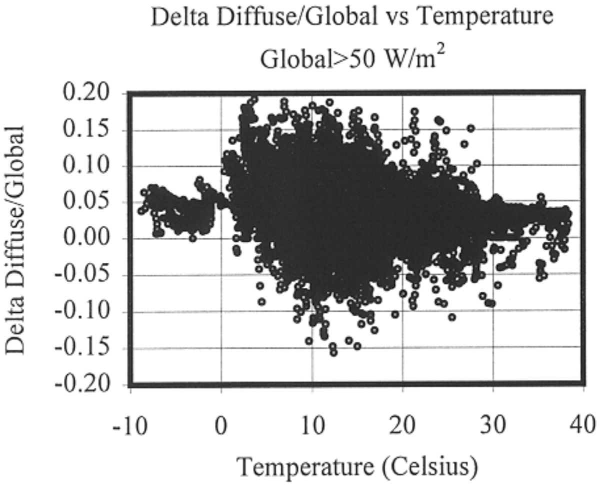

Fig. 5: Plot of the difference between the diffuse values divided by global irradiance verse temperature. There is a slight decrease as the temperature decreases.

The standard deviation is ±0.0206. While there is a very slight decrease in the standard deviation from 4.61 W/m^2 for the correlation in Eqn. 1 to 4.58 W/m^2, the improvement is minimal.

Calibration of LiCor Pyranometer

If the responsivity of the LiCor diffuse component is varies by 30 W/m^2 depending on the sky conditions, how should the calibration of the LiCor pyranometer be determined? The most accurate way would be a shade-unshade method with the beam and diffuse responsivity being determined separately. Of course the change in the responsivity of the beam component as a function of sky condition must also be determined. The work of King et. al. [2] probably makes a good determination of this because the diffuse contribution

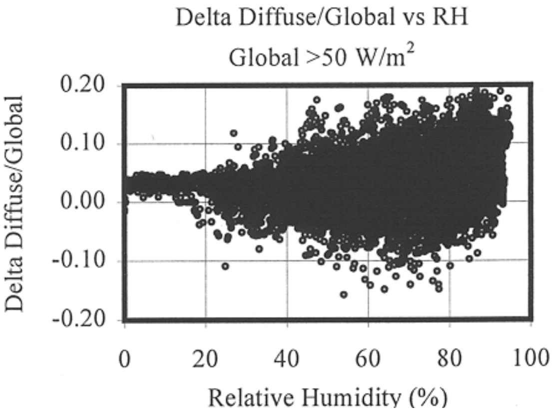

Fig. 6: Plot of the difference between the diffuse values divided by global irradiance verses relative humidity. There is a small increase in the difference with the increase in relative humidity.

is small under clear sky conditions. However, it is difficult to untangle the spectral dependence of the beam and diffuse responsivity from the total calibration number.

Fortunately the cloudy sky diffuse responsivity is close to the clear sky beam responsivity for the LiCor pyranometer. That enables the LiCor pyranometer to give fairly decent measurements of global irradiance under clear and cloudy conditions.

5. IMPORTANCE FOR ROTATING SHADOWBAND INSTRUMENTS

While LiCor measurements of total irradiance are minimally affected by the spectral dependence of the diffuse responsivity, measurements of the diffuse irradiance by rotating shadowband instruments systematically underestimate the diffuse component during clear periods. If the 30 W/m^2 decrease in the diffuse responsivity under clear conditions in the Pacific Northwest is typical of the decrease elsewhere, systematic errors in the calculation of the beam irradiance will result.

Of course, the uncertainties in calibration of the solar cell based pyranometer complicate these generalizations. RSPs measure the global and diffuse irradiance and the subtract the diffuse from the global and project the horizontal direct component onto the normal to obtain the beam irradiance. This involves dividing by the cosine of the zenith angle. On clear days, a diffuse value that is 30 W/m^2 less than the actual value and divided by the zenith angle can result in a systematic increase of 5 to 10 % in the calculated beam irradiance. Of course any deviations of the global measurements from the actual global irradiance will also affect this calculated value.

In a Rotating Shadowband Radiometer (RSR), the instrument is calibrated on a bench with an artificial lamp. This procedure will likely result in the calculated beam irradiance being more accurate while the global irradiance measurements will be slightly low. This results from the fact that diffuse responsivity is assumed to be the same as the beam responsivity. With the RSP, the pyranometer is calibrated outdoors and the decrease in the diffuse responsivity in factored into the calibration constant.

In Eugene, measurements are made with a Multi Filter Rotating Shadowband Radiometer (MFR) that will produce similar results to an RSR. The broadband diffuse measurements from the RSR closely match those of the diffuse LiCor measurements while the broadband beam irradiance measurements are slightly high, the broadband global irradiance values noticeably lower than global values from other instruments.

The examples of the RSP and the RSR show that while correction of the diffuse measurement can be accomplished, care is needed when applying the correction to the other components. With an RSP, the corrections will reduce the beam irradiance values, but some consideration needs to be given to the calibration value assigned the LiCor pyranometer. With a RSR, the global value will be increased by the correction factor and there will be no correction to the beam value. Of course other spectral corrections may be needed for the beam component for both instruments.

6. CONCLUSIONS

The diffuse responsivity of the LiCor pyranometer has been compared with that of an Eppley PSP. It was found that under clear sky conditions that the LiCor pyranometer significantly underestimated the diffuse irradiance by 30 to 40%. By correlating the difference in the diffuse values divided by the global irradiance against global irradiance, a simple correlation was developed to correct for this systematic shift.

The use of an automatic tracker to accurately measure the diffuse irradiance by both the Eppley PSP and the LiCor solar cell pyranometer may be one reason why such a clear sign of diffuse spectral dependence was found. Another possibility remains that the spectral dependence is site specific. These results were studied only in the Pacific Northwest. Other investigations using different techniques in the southwest and at the National Renewable Energy Laboratory did not report such a large spectral effect.

If these results are found elsewhere, then systematic errors will likely result in other solar cell based instruments, especially rotating shadowband instruments that use solar cell based pyranometers. Comparisons also need to be made against the model developed earlier [1]. Preliminary studies indicate that high quality diffuse data could be used to refine earlier models.

The 30-40% change in the diffuse responsivity depending on sky condition, can significantly alter the calibration values of solar cell based pyranometers. At a minimum, these effects will introduce systematic errors into the standard calibration methodology.

7. ACKNOWLEDGMENTS

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8. REFERENCES:

(1) J.J. Michalsky, R. Perez, L. Harrison, and B.A. LeBaron, Spectral and Temperature Correlation of Silicon Photovoltaic Solar Radiation Detectors, *Solar Energy* **47**, 299 (1991).

(2) J.D. King and D.R. Myers, Silicon-Photodiode Pyranometers: Operational Characteristics, Historical Experiences, and New Calibration Procedures, 26th IEEE PV Specialist Conference, 1997, pp. 1285-1288