Removing Systematic Errors from Rotating Shadowband Pyranometer Data

Frank Vignola
Solar Radiation Monitoring Laboratory
Department of Physics
University of Oregon
Eugene, OR 97403-1274
fev@uoregon.edu

ABSTRACT

Rotating Shadowband Pyranometers (RSPs) have been deployed to measure global, beam, and diffuse irradiance because they do not require manual adjustment of trackers. However, a RSP requires the use of solar cell based pyranometers which underestimate diffuse irradiance by 20-30% under clear sky conditions. Algorithms were derived to address many of the systematic errors in solar cell based measurements, and these algorithms were incorporated into a new series of RSP instruments. This is an analysis of how similar algorithms can be used to remove some of the systematic errors associated with the data from the original RSPs and an evaluation of the uncertainties and remaining errors in the corrected RSP data.

1. INTRODUCTION

This article will evaluate a method for removing systematic errors from global, diffuse, and beam measurements made using Rotating Shadowband Pyranometers (RSPs). The data that are evaluated come from RSPs manufactured by Ascension Technology (AT). The AT RSP uses a Li-Cor pyranometer for global measurements; however, the methodology should be applicable to other RSPs using solar cell based pyranometers. Generally, a RSP measures diffuse irradiance by having a narrow band rotate in front of the pyranometer to briefly shade the pyranometer once a minute. Direct horizontal irradiance is calculated by subtracting the diffuse value from the global value, and the direct normal beam irradiance is calculated by dividing the horizontal beam value by the cosine of the incident angle. In this manner, global, diffuse, and beam irradiance can be obtained in an automated manner.

There are several hundred solar monitoring sites around the world that use RSPs to measure global, diffuse, and calculates beam irradiance. In earlier work[1], solar cell based pyranometers were found to underestimate the diffuse irradiance by 20-30% during clear periods. In RSPs, the underestimation of diffuse irradiance causes the beam irradiance to be systematically overestimated. Using the work on diffuse responsivity and earlier work on solar cell pyranometers [2, 3], algorithms were developed for a new model of RSP that eliminated many of the systematic errors in original RSP measurements [4, 5].

The lessons learned in developing algorithms for new RSPs suggest that it is possible to modify data collected by the original RSPs and eliminate many of the systematic errors in the data. This study will evaluate how well this corrective methodology works.

There are several important reasons to go back and correct the RSP data. Basically, removing the systematic errors will greatly enhance the value and utility of the RSP data. This is especially important because there are a limited number of datasets available with measured direct normal irradiance. In addition, RSP data were used in programs evaluating the performance of photovoltaic systems, and systematic errors in the data could affect models that were, or will be, validated using this data.

This article is organized as follows. The sources of systematic errors in the original RSPs are discussed. Next, a description of the algorithms used to adjust the RSP data is presented, along with the methodology used to adjust the data. Results from the application of the corrections are then evaluated. The utility of performing corrections is then given along with a summary of the results.

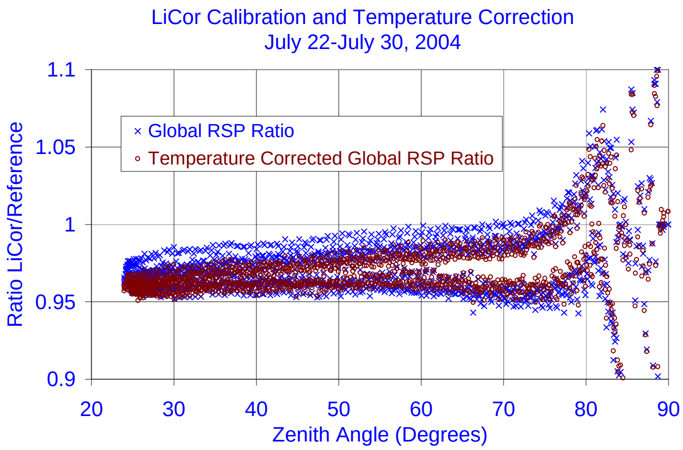

Fig. 1: Calibration of a LiCor pyranometer. The reference global value is the sum of diffuse obtained by a Schenk Star pyranometer and an Eppley NIP pyrheliometer projected onto the horizontal surface. x's show the ratio of the LiCor to the reference global values. Circles show the same comparison with a solar cell temperature correction applied.

2. SYSTEMATIC RSP ERRORS

In general the sources of systematic errors in RSP data are:

- The change of responsivity of solar cell based pyranometers as a function of air mass (a spectral dependence), zenith angle, and temperature
- The change of responsivity of diffuse irradiance for a clear blue sky to a cloudy white sky (the diffuse spectral dependence) is about 30%.
- The approximation employed by the RSP to compute the zenith angle used to calculate beam values.

It is always important to know the absolute responsivity of the pyranometer and to calibrate the instrument under standard conditions since the responsivity of the pyranometer is a function of temperature, zenith angle, and sky conditions. When calibrations are done under standard conditions the corrections to systematic errors can always be referred back to those standard conditions if a re-analysis needs to happen.

The ATI RSP uses a Li-Cor pyranometer for its sensor. A typical plot of calibration numbers for a Li-Cor pyranometer is shown in Fig. 1. The responsivity increases as the zenith angle increases. In this example there appears to be a split in the calibration numbers, especially at high zenith angles. This is caused by the inability to properly level the pyranometer and by the temperature dependence of the pyranometer. The circles show the same calibration with a temperature correction applied. This reduces the difference over the day. It is probable that most of the 2% difference between the morning and afternoon values at a zenith angle of 60° results from a pyranometer that is tilted about 1/4° facing west. Note that temperature corrections were not used for the reference instruments used in calibration.

Data in Fig. 1 demonstrates the need to define how the calibration number was determined. For this project, the calibration number was determined from the average responsivity between 45° and 55° without the temperature correction. The solar cell temperature correction and the other corrections will be included in the algorithm to correct global data.

3. CORRECTING RSP DATA

Once a good calibration factor has been obtained for the pyranometer, it is time to apply the other corrections. The procedure for correcting RSP data and removing systematic errors is as follows:

1. Correct the responsivity errors of the pyranometer to obtain better global irradiance values
2. Modify the diffuse values to compensate for the spectral dependency of the diffuse responsivity
3. Subtract the corrected diffuse values from the corrected global values and divide by an accurate value of the zenith angle to obtain direct normal beam irradiance.

3.1 Correcting Global Data

The combination of the deviation from true cosine response and the spectral response of the solar cell based pyranometer give rise to the increase of responsivity with zenith angle shown in Fig. 1. Reference [2] gives formulas to compensate for these effects.

An alternative formula to correct for the spectral irradiance is:

$$F_A=0.061*\ln(AM)+0.9771 \qquad \text{Eqn. 1}$$

where AM is pressure corrected air mass and ln is the natural log. This formula closely matches the formula given by King[2] but fits better at very high air masses where the polynomial nature of the King fit leads to unrealistic values.

The formula to correct for the cosine response is:

$$F_B=1+0.0006074*Z + 0.00001357*Z^2 -0.0000004504*Z^3 \qquad \text{Eqn. 2}$$

where Z is the pressure corrected zenith angle. The formula to correct for the temperature response of the Li-Cor is:

$$F_T = (1-0.00082*(T - 25)) \qquad \text{Eqn. 3}$$

where T is the temperature of the solar cell in Celsius. Since the solar cell temperature is not measured, the ambient temperature is used.

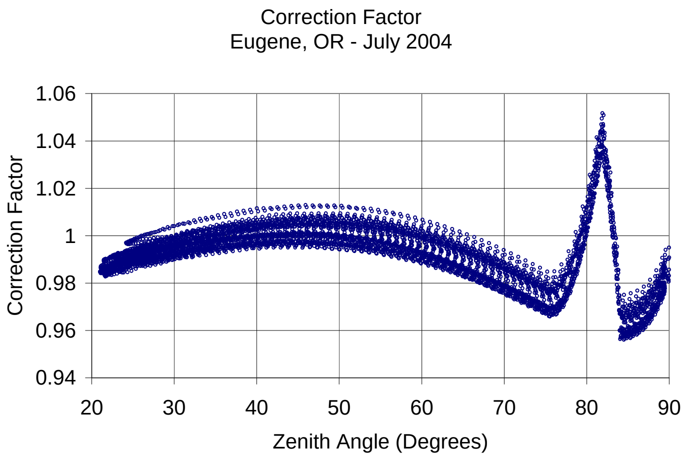

Fig. 2: Correction factor for global irradiance. The spread in the correction factor is related to the temperature. Note the similarity with the shapes in Fig. 1. It may be possible to improve on the correction factor, but a study of a large number of pyranometers at a variety of locations would be required to get the optimum shape.

The diffuser on top of the Li-Cor is shaped to maintain a reasonable cosine response. However, this shape results in the peak of responsivity decreasing sharply when the zenith angle reaches about 82° [see Fig. 1]. This is known as the "Cat Ears" affect [4].

The Cat Ear correction factor is a function of zenith angle. For a zenith angle between 75º and 81º the correction factor is:

$$F_C=10.164664-0.24242*Z+1.001603*Z^2 \quad \text{Eqn. 4a}$$

where Z is the zenith angle. For the zenith angle between

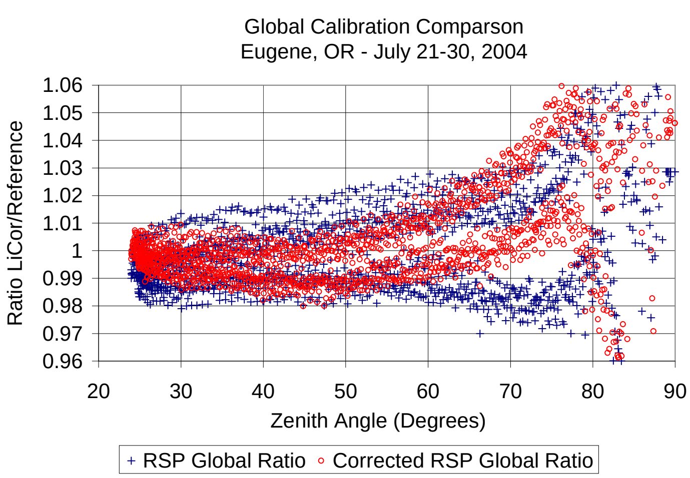

Fig. 3: Calibration comparison of corrected RSP global irradiance against uncorrected RSP global on clear days. The difference between morning and afternoon ratios is reduced, but the calibration value is shifted down by about 0.5%. The high ratios at large zenith angles indicate this is an area that might benefit from more research.

81º and 83.2º, the correction factor is:

$$F_C=-58.03442+1.4557577*Z-0.00899*Z^2 \quad \text{Eqn. 4b}$$

For all other values the Cat Ear correction factor is 1.

The correction for the Li-Cor global data is:

$$G_C = G_{RSP}*F_T*1.01/(F_A*F_B*F_C) \qquad \text{Eqn. 5}$$

Where G_C is the corrected global irradiance and G_{RSP} is the global data from the RSP. The factor of 1.01 is needed to set the correction factor equal to 1 over the 45º to 55º zenith angle range that was used to calibration the RSP. A more thorough discussion of each correction factor is given in references [2-5]. The global correction factor for July 2004 for Eugene, Oregon is plotted in Fig. 2.

A comparison of the corrected global values compared to reference global values is shown in Fig. 3 for clear days. The corrections significantly reduce the standard deviation from the reference values in these plots, but there is still room for improvement. The fit to this data is excellent considering that the algorithms were developed at different locations and the reference data has an absolute uncertainty of about ±3%.

The reference global values are calculated from direct normal beam irradiance data projected onto a horizontal surface plus high quality diffuse measurements made on an automatic tracker using a star type pyranometer. Star type pyranometers exhibit minimal re-radiation errors common with other thermopile pyranometers such as the Eppley PSP. These instruments have calibrations traceable to World Meteorological Organization standards through calibrations at the National Renewable Energy Laboratory.

3.2 Diffuse Corrections

The diffuse corrections come from references [1, 4 and 5]. For global values below 865.2 kW/m^2 the diffuse correction factor is:

$$DF_C = DF_{RSP} + G_C*(0.110657578794 -0.00023132934*G_C+0.00000023978*G_C^2 -0.000000000091*G_C^3) \qquad \text{Eqn. 6a}$$

where DF_C is the corrected diffuse data, DF_{RSP} is the RSP diffuse data, and G_C is the corrected RSP global data. If G_C is greater than 865.2 kW/m^2 then the diffuse correction factor is:

$$DF_C = DF_{RSP} +G_C*(0.0359-0.00000554*G_C) \quad \text{Eqn.6b}$$

It is important to note that if the corrected diffuse values are greater than the global values then the diffuse values are set

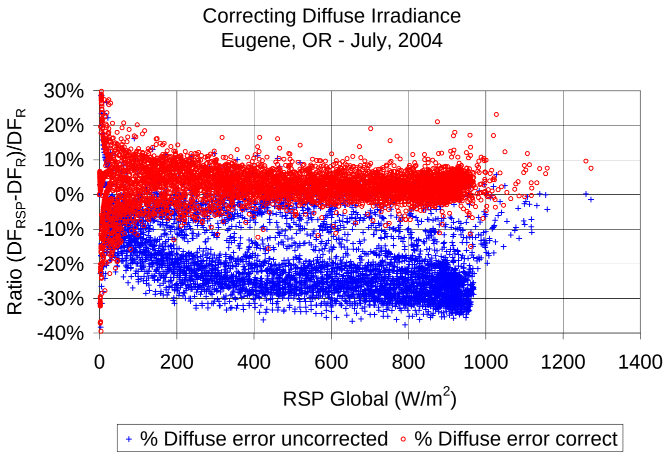

Fig. 4: Comparison of RSP diffuse values and corrected RSP diffuse values plotted against G_{RSP}. On clear days the RSP diffuse values are typically 20 to 30% low. This is mainly the result of the spectral characteristics of diffuse irradiance and the spectral responsivity of the solar cell based pyranometer.

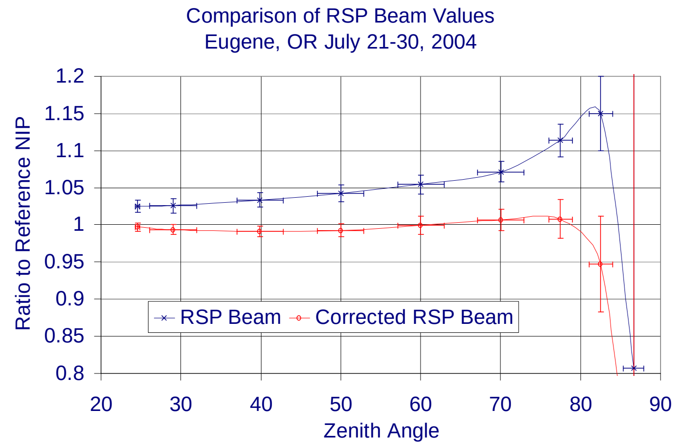

Fig. 5: Comparison of RSP Beam values to reference NIP values on clear days from July 21 to July 30. The corrected beam values are shown by the red circles (o) and the normal beam values are shown by the blue x's (x).

equal to the global values. This diffuse correction factor was developed for use with accurate high quality global measurements. It still works with the corrected RFP global values, but it has not been optimized using these data.

3.3 Correct Beam Values

Using corrected global and diffuse values, new beam values can be derived. Instantaneously an exact formula for the beam values would be:

$$B_C = (G_C - DF_C)/\text{Cos}(Z) \qquad \text{Eqn. 7}$$

However, when the RSP measurements are averaged over recorded data interval, Eqn. 7 becomes an approximation as the zenith angle varies over time. The product of the average beam irradiance times the average cosine of the zenith angle is not equal to the integrated production of the beam times cosine of the zenith angle, especially when the zenith angle changes rapidly. The weighting of beam times the cosines of the zenith angle is in the RSP data and can be extracted by dividing the ratio of RSP values by the average of the cosine of zenith angle over the period as shown in Eqn. 8.

$$C_{WF} = (G_{RSP}\text{-}DF_{RSP})/B_{RSP}/\text{Cos}(Z)_{AVG\text{-}RSP} \qquad \text{Eqn. 8}$$

where C_{WF} is the cosine weighting factor; G_{RSP}, DF_{RSP}, and B_{RSP} are uncorrected global, diffuse, and beam values from the RSP, respectively, and $\text{Cos}(Z)_{AVG\text{-}RSP}$ is the cosine of the zenith angle in the middle of the interval using the RSP zenith angle algorithm. Note that datalogger memory constraints limited the accuracy of the zenith angle algorithm.

With the use of the C_{WF}, a more accurate calculation of the corrected beam component would be:

$$B_C = (G_C - DF_C)/(\text{Cos}(Z)*C_{WF}) \qquad \text{Eqn. 9}$$

Since this study is using 5-minute data, this factor is small (less than 20 W/m^2) and will not be used in the analysis. The zenith angle (Z) is easily calculated in the middle of the time interval, but other averaging methods work.

A comparison of beam values on clear days is shown in Fig. 5. The top curve represents uncorrected RSP beam values. The RSP beam values range from about 2.5% to 15% higher than Normal Incident Pyrheliometer (NIP) beam values, depending on zenith angle. In the 45° to 55° range they are about 4.2% higher. The corrected beam values are 1% lower than the NIP values and this results from errors in the global and diffuse correction. However, the corrected beam values are within 1% of the NIP values for zenith angles between 20° and 75°. In addition, the standard deviation from the reference NIP values is about 30% less than the standard deviation of the uncorrected RSP beam values. Having a good calibration of the RSP's pyranometer is key to getting the best results.

A comparison between RSP beam values, corrected beam values, and beam measured with an Eppley NIP for all weather conditions for the whole of July are shown in Fig. 6. Again, this figure shows that the improved match to high quality beam data extends across the range of zenith angles. The extreme scattering in the data is expected and is more indicative of the methods used to obtain the beam values than the average results. Beam values obtained by an RSP through one-minute samples can differ significantly from

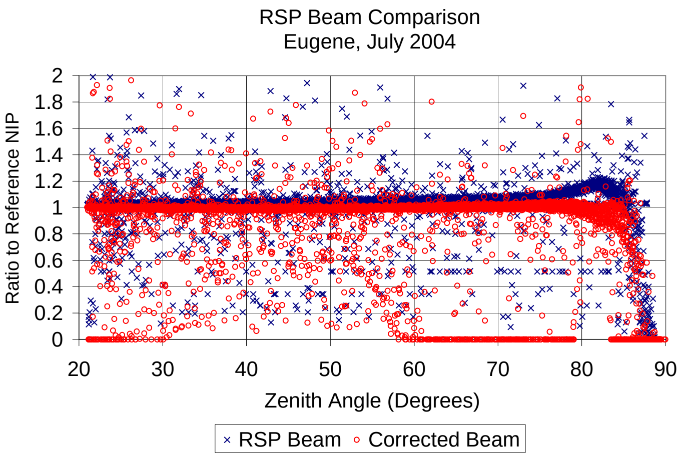

Fig. 6: Comparison reference NIP data to uncorrected and corrected RSP beam values using all five-minute data intervals in July, 2004. RSPs take one sample of diffuse irradiance every minute and derive the beam irradiance. These values are averaged into 5-minute averages. The reference NIP data are integrated measurements over the 5-minute interval. The different data gathering methods cause most of the scatter.

beam values integrated over a five-minute period because beam irradiance can vary dramatically during a partially cloudy period. The sun can be completely obscured by a cloud one minute and unblocked in the next. Hence, during partially cloudy periods, the RSP often records the interval as more sunny or cloudy than readings taken continuously over the time interval. As the length of the interval increases this difference averages out. The reference NIP data are integrated values. For 5-minute data, the effects of the different sampling methods is very apparent as seen in Fig. 6.

So far, the data presented are from July 2004 in Eugene, Oregon. Comparisons to other times of year and locations are important to show that this methodology can be applied throughout the year and at other locations. Figs. 7 and 8 show a comparison between RSP beam, corrected RSP beam, and NIP measurements for Eugene in July and October. In both cases, the corrected beam irradiance is much closer to the NIP data than the uncorrected beam values. This is especially true at higher beam values.

The University of Oregon Solar Radiation Monitoring Network also has a RSP and a NIP located in Hermiston, Oregon. This data allows an independent check on the methodology from a site not used to derive and validate the algorithms. A comparison of RSP beam, the corrected RSP beam, and the NIP beam data are shown in Fig. 9.

In all three cases, the corrections move the RSP beam irradiance much closer to the reference beam values. The reference Eppley NIP has an absolute accuracy of around

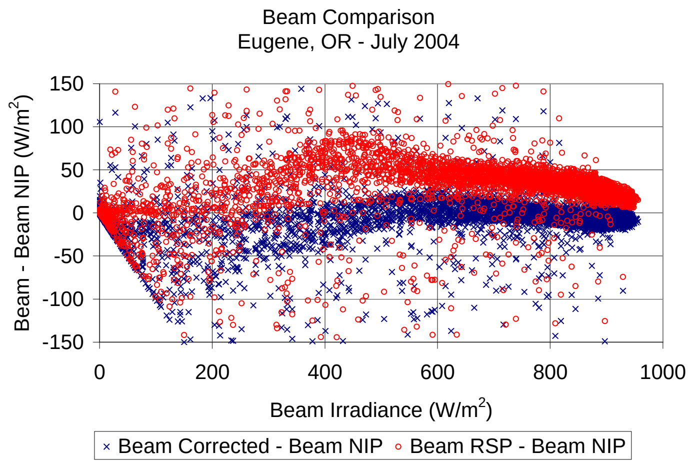

Fig. 7: Comparison of RSP beam data with beam data from the reference NIP. The red circles (o) show the RSP beam data minus the NIP data. The blue x's show the corrected RSP beam data minus the NIP data.

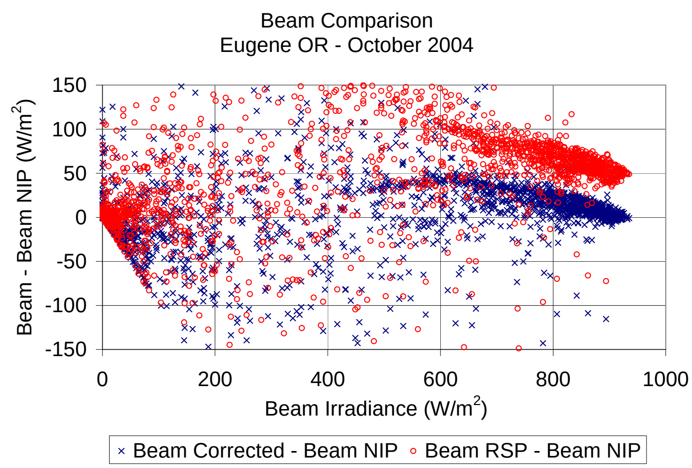

Fig. 8: Beam comparison for October, 2004. Symbols are the same as in Fig. 7.

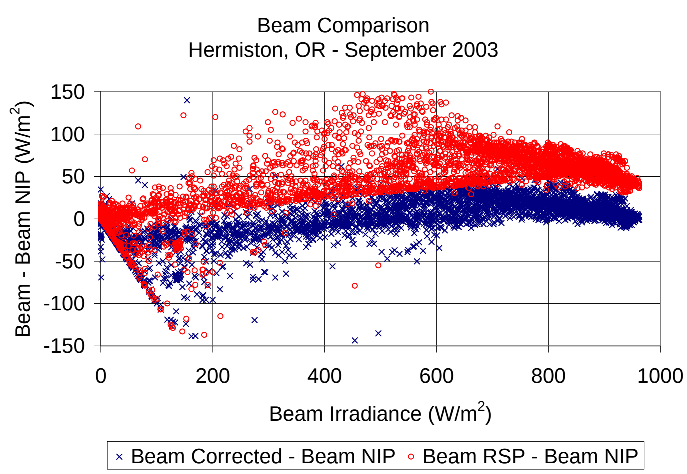

Fig. 9: Beam Comparison for September, 2003 at Hermiston, OR. Symbols are the same as in Fig. 7.

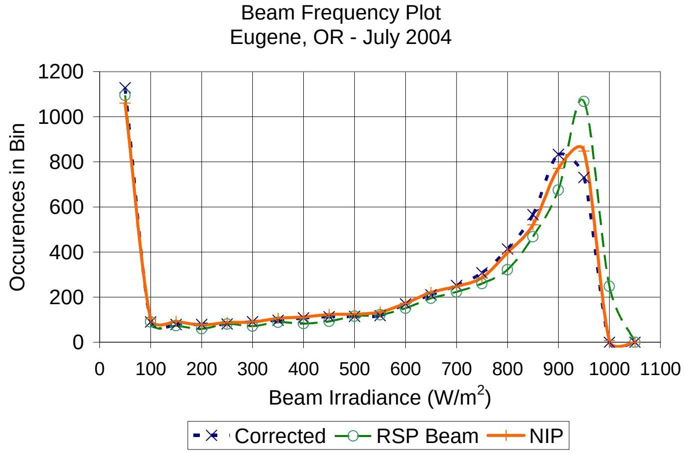

Fig. 10: Frequency distribution of beam irradiance comparing RSP, NIP, and corrected RSP beam values. The biggest differences occur at high values of beam irradiance.

±2-3%. Figs. 7-9 also show that the algorithm does not work as well for beam values below 400 W/m^2. This might be explained by the fact that the algorithms from references 2 and 3 were derived for clear sky conditions. When there are cloudy conditions, the spectral characteristics of the solar radiation change.

The best way to check if the data have the same statistics as reference data is evaluate a frequency distribution plot as in Fig. 10. The only significant difference between the frequency distribution of the three sets of beam data occurs when the beam irradiance is between 700 and 1100 Watt/m^2. The RSP beam data overestimates the number of occurrences when the beam irradiance is between 900 and 1100 W/m^2; this is balanced out by fewer occurrences of beam irradiance between 700 and 900 W/m^2. The corrected RSP beam data show a closer match, although it is not a perfect match. The deviations from reference beam data plotted in Fig.7 illustrate the cause for the shift in the frequency plot.

It is interesting to note that below 700 W/m^2, the corrected RSP beam values are a very good match to the reference beam frequency distribution. This would be very hard to see in Fig. 7.

4. SUMMARY

Use of algorithms designed to account for the spectral, temperature, and cosine response of solar cell based pyranometers are also useful in correcting some of the systematic errors occurring in irradiance measurements using the original RSP pyranometers. Therefore, it is possible to adjust the global, beam, and diffuse irradiance to within a few percent, on average, of values obtained by high quality first-class instruments.

The largest percentage difference is in the diffuse values where the RSP values underestimate the diffuse irradiance by 20 to 30% during cloudless periods. In addition the beam irradiance better matches the reference beam values obtained with an Eppley NIP.

During partially cloudy periods, the adjustment of the RSP data could be improved. It seems that the algorithms are overcorrecting the RSP data. This may result from using both a spectral correction to the global data and spectral adjustment to the diffuse irradiance.

While it may be possible to modify the algorithms for a better overall fit to the data, there is a danger of overanalyzing and correcting for just one instrument, especially when the uncertainty gets down to a few percent. Many other factors, such as dirt on the lens of the pyranometer or inaccuracies in leveling the pyranometer, can systematically distort the data.

5. ACKNOWLEDGEMENTS

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