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# HIGH ACCURACY DIFFUSE HORIZONTAL IRRADIANCE MEASUREMENTS WITHOUT A SHADOWBAND


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## ABSTRACT

The standard method for measuring diffuse horizontal irradiance uses a fixed shadowband to block direct solar radiation. This method requires a correction for the excess skylight blocked by the band, and this correction varies with sky conditions. Alternately, diffuse horizontal irradiance may be calculated from the total horizontal and direct normal irradiance. This method is in error because of the angular (often referred to as cosine) response of the total horizontal pyranometer to direct beam irradiance. This paper describes an improved calculation of diffuse horizontal irradiance from total horizontal and direct normal irradiance using a predetermination of the angular response of the total horizontal pyranometer. We compare these diffuse horizontal irradiance calculations with measurements made with a shading-disk pyranometer that shields direct irradiance using a tracking disk. The results indicate significant improvement in most cases. The remaining disagreement most likely arises from undetected tracking errors and instrument leveling.


## 1. INTRODUCTION

The Atmospheric Radiation Measurement (ARM) program focuses on improving general circulation models for the prediction of climate change. The particular emphasis in the ARM program is an improved treatment of clouds and radiation (Stokes and Schwartz 1994). Changes of a few $W/m^2$ are significant in this climatological context. Therefore, one of the requirements of this program are improved shortwave (solar) and longwave (infrared) measurements over the current accuracies. Some of these goals can not be met without progress in detector technology, but better use of current instruments can constrain some of the models today and for the near future.

A major source of error in pyranometry is angular response (Myers 1988). Because of this problem the best measurement of total solar irradiance is the sum of the horizontal component of direct irradiance and the diffuse horizontal irradiance measured with a shading-disk pyranometer. Shading-disk instruments are few and measurements are difficult because of tracking. In this paper we look at an alternate approach for making an accurate diffuse horizontal irradiance measurement using equipment now available at many stations.

Most diffuse horizontal irradiance measurements are made using a fixed band to block the direct normal irradiance incident on a pyranometer. The literature on correcting these fixed shadowband measurements is reviewed in LeBaron et al. (1990). They developed a correction scheme based on sky conditions and solar position, as well as shading band geometry. Batlles et al. (1995) have produced a scheme that further improves this correction using a similar methodology.

Frequently, diffuse horizontal irradiance is calculated using the direct normal irradiance measured with a pyrheliometer and the total horizontal irradiance measured with a pyranometer. If the direct normal irradiance is multiplied by the cosine of the solar-zenith angle, this direct horizontal component (hereafter, direct horizontal irradiance) may be subtracted from the total horizontal irradiance to yield an estimate of diffuse horizontal irradiance, i.e.,

*diffuse horizontal =*
*total horizontal - direct normal * cos (solar-zenith angle).*

A bias error is introduced in this procedure because the total horizontal is measured with a pyranometer and all pyranometers have an imperfect angular response. The thermopile pyranometers used typically have a response that decreases more rapidly than the cosine of the solar-zenith angle (Nast 1983; Michalsky et al. 1995). As a result, the diffuse horizontal irradiance calculated using the equation above is lower than the true diffuse.

The best diffuse horizontal irradiance measurement uses a tracking disk that blocks the dome and receiver of the thermopile pyranometer at all times of the day. In this paper we compare diffuse horizontal irradiance measurements made with a tracking disk against diffuse horizontal irradiance calculated from direct normal and total horizontal irradiance measurements. In the latter case the angular response of the total horizontal irradiance sensor is used to improve the calculation. The next section describes the measurements. The third section gives some results followed by the final two sections that discuss these results and draws conclusions regarding this study.

## 2. MEASUREMENTS

Data are acquired on the roof of the Atmospheric Sciences Research Center in Albany, New York, every day of the year. The data are screened for obvious problems such as misalignment of tracking sensors and soiling. Total horizontal and diffuse horizontal irradiances were measured with Eppley PSP pyranometers for this experiment, the latter with a Eppley tracking disk. An Eppley NIP pyrheliometer was used for direct normal irradiance measurements. The NIP was calibrated against an Eppley HF absolute cavity radiometer (see Eppley (1994) for a discussion of these sensors). The PSPs were subsequently calibrated by shading and unshading each PSP and then comparing the difference to the direct horizontal irradiance as measured by the NIP. Only solar measurements near the zenith were used for the PSP's calibration because the angular response of the pyranometers deviates little from true cosine response when the sun is high in the sky.

The shading-disk pyranometer directly measures diffuse horizontal irradiance. The disk blocks the direct horizontal irradiance that would normally fall on the sensor. In principle, the direct horizontal irradiance that is excluded would be identical to the direct horizontal irradiance that is calculated from the NIP measurement if the NIP measurement were modified by the angular response of the total horizontal pyranometer.

We have measured the angular (i.e., cosine and azimuth) responses of the PSP used for total horizontal irradiance using our angular response test bench (Michalsky et al. 1995). To calculate diffuse horizontal irradiance, we subtract from the total horizontal irradiance, as measured by the PSP, the direct horizontal irradiance, as measured by the NIP after modifying it by the angular response of the total horizontal irradiance PSP for the particular azimuth and elevation of the sun at that instance.

## 3. RESULTS

Selected data from 1994 near the summer and winter solstices on clear, overcast, and partly cloudy days were selected to compare diffuse measurements and diffuse calculations with and without angular corrections.

Fig. 1a is a plot of diffuse horizontal irradiance versus time of day for a completely overcast day. For overcast skies with no direct irradiance there is no correction to the calculated diffuse horizontal irradiance. The calculated and shading-disk diffuse horizontal irradiances should nearly agree for these conditions. Depending upon the brightness of the skies and elevation of the sun, the shading-disk pyranometer may yield a measurement that is somewhat lower than the calculated value since the disk does block some skylight. Fig. 1b is a smoothed plot of the difference between the shading-disk and calculated diffuse horizontal irradiance as a function of time of day. On average the shading-disk measurements are lower than the calculations by about 0.5 $W/m^2$. The closeness of the agreement indicates that the calibrations of the two instruments are well matched.

Fig. 2a is a plot of the diffuse horizontal irradiance for a clear, low-haze day in December. The three plots of diffuse horizontal irradiance are clearly separated in this

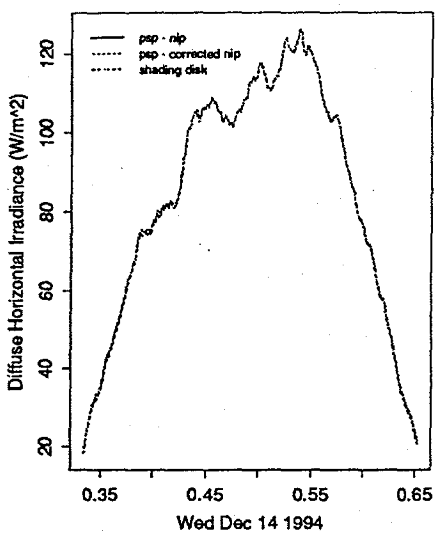


Fig. 1a. Diffuse horizontal irradiance for a completely overcast day.

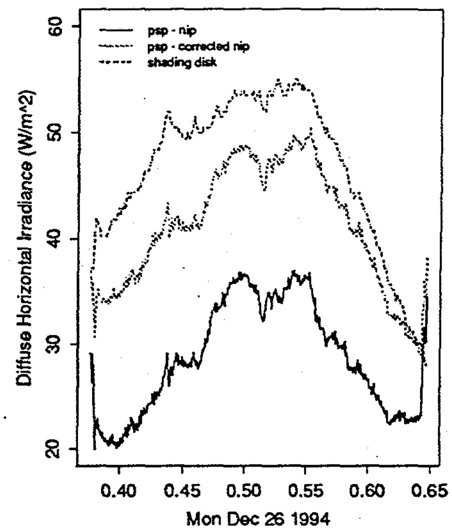


Fig. 2a. Diffuse horizontal irradiance for a clear winter day.

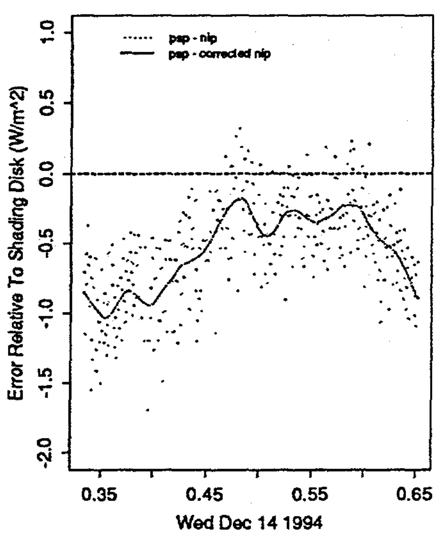


Fig. 1b. Difference in calculated and measured diffuse horizontal irradiances.

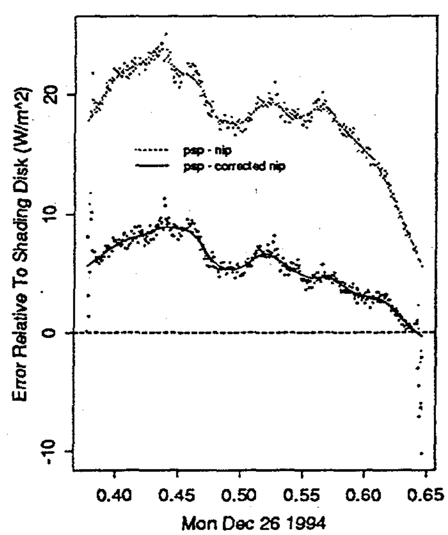


Fig. 2b. Differences in calculated and measured diffuse horizontal irradiances.

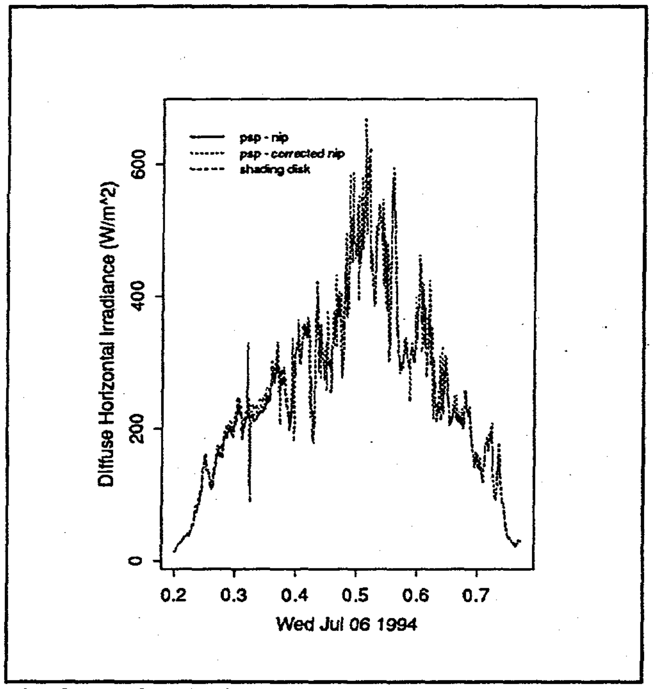


Fig. 3a. Diffuse horizontal irradiance on a partially overcast summer day.

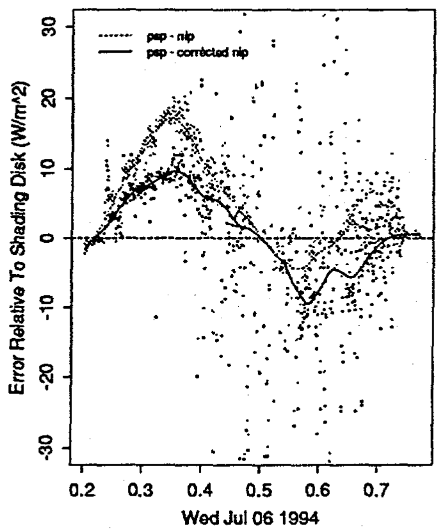


Fig. 3b. Differences in calculated and measured diffuse horizontal irradiances.

plot with the *shading-disk diffuse measurement* higher than the calculated values at all times of the day. The calculated diffuse without a direct normal adjustment is the lowest for all times of the day. As can be estimated in Fig. 2b, on average for this day it is about 18 $W/m^2$ lower than the shading-disk measurement. The diffuse with the adjusted direct normal more closely agrees with the shading disk measurement, but still shows a bias error in Fig. 2b that is, on average, about 6 $W/m^2$ too low.

Fig. 3a is a plot of the diffuse horizontal irradiance for a partly cloudy day. The diffuse horizontal irradiance is quite high for this day with a lot of scattered light by thin clouds. The calculated, but uncorrected, diffuse horizontal irradiance agrees slightly less well than the calculated, corrected diffuse horizontal irradiance agrees with the *shading-disk measurements* as can be seen in Fig. 3b. On average the uncorrected and corrected calculated diffuse horizontal irradiances differ from the shading-disk measurements by about 12 and 11 $W/m^2$, respectively.

## 4. DISCUSSION

Figs. 2 and 3 are typical plots of the diffuse horizontal irradiance (1) as measured by the shading-disk pyranometer, (2) as calculated without adjusting the pyrheliometer values, and (3) as calculated after adjusting the pyrheliometer values according to the angular response of the total horizontal pyranometer. There is an improvement in each instance with the calculated diffuse, based on the adjusted direct, more closely matching the *shading-disk measurements.*

How can we explain the remaining discrepancies? The tracking disk is 6 cm in diameter at 60 cm from the pyrheliometer. The NIP pyrheliometer has a 2.54 cm diameter opening at 25.4 cm from the detector. The responses are meant to complement each other in the sense that the NIP receives what the shading-disk pyranometer does not sense. Major (1994) shows that for a perfectly-tracking instrument set similar to the Eppley instruments used here that differences are less than 1 $W/m^2$, which is negligible in this context.

If the tracking pyrheliometer were slightly misaligned, the calculated diffuse would be higher than if it were perfectly aligned. If the shading-disk instrument were misaligned, the measured diffuse horizontal irradiance would be higher than if it were perfectly aligned. Based on Figs. 2 and 3, which are representative of many calculations, both situations occur. More often, however, the calculated, corrected diffuse is lower than the measured diffuse suggesting that the disk is more often misaligned. This is reasonable since the NIP is on an automated tracker with two-axis tracking. The shading-disk is on a clock-driven motor that requires manual adjustment for the declination of the sun, which is not done every day. Another possible problem is horizontal leveling of the sensors. The asymmetry of the responses in Figs. 1, 2 and 3, and other data not shown, suggests that this as an additional source of error.

## 5. CONCLUSIONS

This study has shown that diffuse horizontal irradiance calculations based on total horizontal and direct normal irradiance measurements can be significantly improved by taking into account the cosine response of the total horizontal pyranometer.

The remaining disagreement in calculated and measured diffuse horizontal irradiance is most likely associated with solar tracking of the pyrheliometer to some degree, but, especially, the shading-disk pyranometer. There is, in addition, some evidence of slight horizontal misalignment that we have been unable to detect by visual and manual inspection. Without paying constant attention to the shading-disk tracking or resorting to two-axis tracking for the shading disk, better comparisons are unlikely.

The diffuse radiation that impinges on the receiver for a perfectly-tracking, shading-disk, thermopile pyranometer of the type used in this study still underestimates the irradiance that would be measured by a pyranometer with a perfect angular response, but it is impossible to know this effect exactly because the skylight angular distribution is unknown for any given situation.

The ultimate solution is to build pyranometers with better angular responses, or with angular responses that closely straddle the perfect angular response so that the net response is close to that of a perfect receiver.

## 6. ACKNOWLEDGMENTS

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