Accuracy of Broadband Shortwave Irradiance Measurements Using the Open Silicon Channel of the MFRSR

J. J. Michalsky
State University of New York
Albany, New York

Introduction

The best routine Atmospheric Radiation Measurement (ARM) Program measurement of downwelling irradiance in the total shortwave band is a sum of diffuse horizontal irradiance and the direct normal irradiance component that is incident horizontally (diffuse horizontal). The latter is obtained by multiplying the direct normal irradiance by the cosine of the solar zenith angle. Ideally, these measurements are made with a near-zero-offset, shaded, thermopile pyranometer and a thermopile pyrheliometer, respectively. At each central and extended facility within the ARM Program, the shaded pyranometers have small offsets or are corrected for their offsets. Each site operates a pyrheliometer. Quality assurance for the operation of these two instruments is provided by a thermopile pyranometer that operates without a shade. The sum should be equal to the pyranometer output to within an established tolerance that depends primarily on the angular response error of the unshaded pyranometer.

This paper concerns the use of the unfiltered silicon channel (open channel) of the Multifilter Rotating Shadowband Radiometer (MFRSR) for measurement of the broadband shortwave irradiance. The open channel's wavelength response is determined primarily by that of the silicon detector and the transmission of the Spectralon® diffuser that serves as the entrance optic of the MFRSR. It is neither flat nor inclusive of all wavelengths in the solar band. However, we will demonstrate that this measurement can be used for quality assurance of the thermopile measurements or as a substitute for those measurements when they are unavailable or when they are suspect, for example, because of poor tracking. Further, there is some evidence that the MFRSR may be less sensitive to light soiling than the glass dome-covered pyranometer and the glass windowed pyrheliometer; this is particularly important at the extended sites that are only visited biweekly.

A previous attempt to correct the MFRSR open channel to mimic thermopile measurements was published in a paper by Chou et al. (1995). The principal improvement since that effort has been a better understanding of how to make thermopile measurements (Michalsky et al. 1999; Dutton et al. 2001). It is worth looking at the problem again in light of what has been learned since that effort. In this paper, we will take a more empirical approach to the correction of the silicon response measurements than used in Chou et al. (1995). The justification for the empiricism will be explained later. The MFRSR measures total horizontal, direct normal, and diffuse horizontal irradiance and each will be compared to its thermopile counterpart.

Total Horizontal Irradiance

The open-channel, total horizontal irradiance is calibrated using the Broadband Outdoor Radiometer Calibration (BORCAL) protocol (Myers et al. 2000). As implemented here, the output of the open channel is ratioed to the sum of the diffuse and direct horizontal thermopile component measurements when the sun is between 40° and 50° above the horizon with the direct normal irradiance exceeding 700 W/m^2. Over 1300 1-minute ratios are averaged to find the calibration of the open silicon channel in our figures and table. Figure 1 is a scatterplot of thermopile 1-minute averages of 60, one-second samples versus MFRSR open channel 1-minute averages of 3, 20-second samples. Included are over 11,000 data points from 17 days from the months of September, October, and November 2000 recorded at the Southern Great Plains (SGP) Central Facility. The bias and root-mean-squared (rms) errors for these 1-minute data are shown in Table 1 (top). The perfect correlation line is drawn in Figure 1. Table 1 indicates a bias of 2.7 W/m^2 with open silicon slightly higher than the thermopile and an rms difference of 8.1 W/m^2. We attempted no further correction of the total horizontal irradiance.

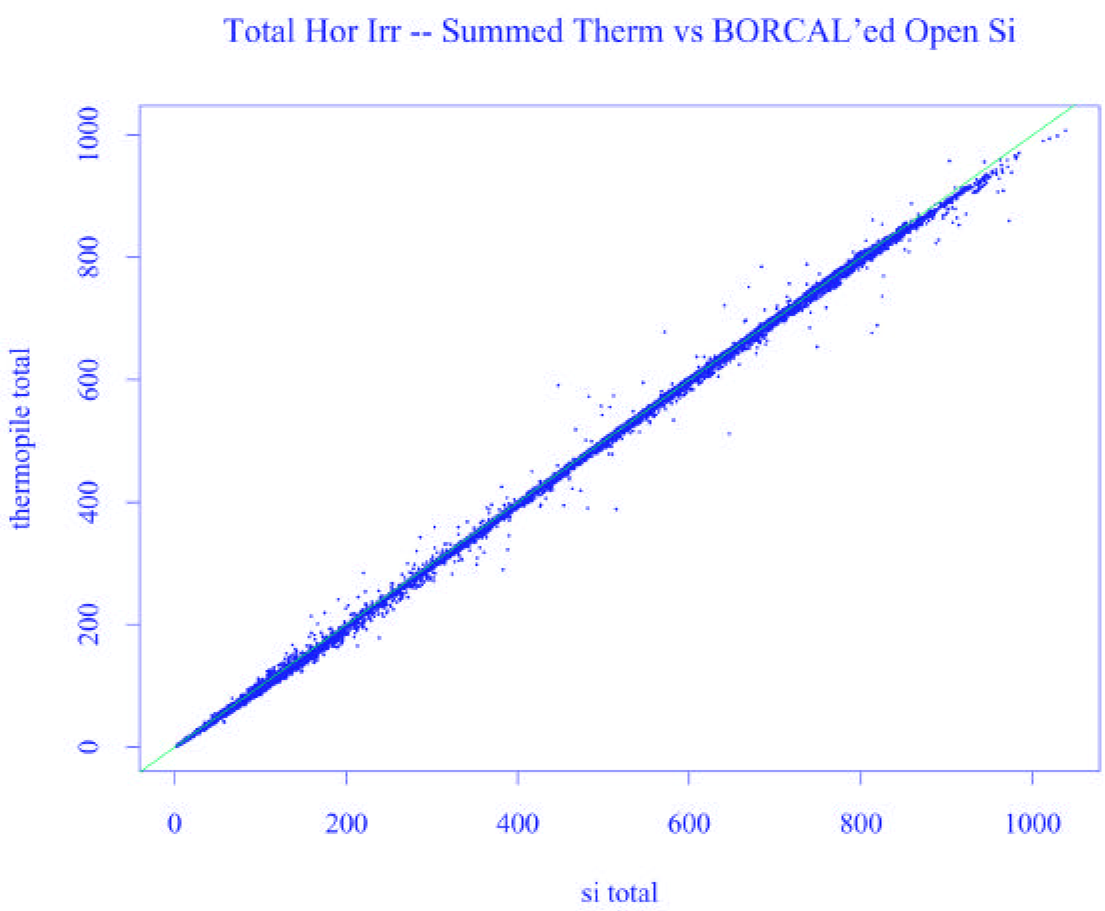

Figure 1. Scatterplot of over 11,000 1-minute values of total horizontal irradiance from the thermopile sum and the open silicon channel calibrated using the BORCAL approach.

Table 1. Mean, mean bias, and rms differences before and after the correction scheme is applied to open silicon channel.

	Mean	Mean Bias	RMS	Post-Correction Bias	Post-Correction RMS
E13 MFRSR Correction					
Total Hor	388 W/m^2	-2.7 W/m^2	8.1 W/m^2	-	-
Direct Normal	501 W/m^2	-32 W/m^2	42 W/m^2	0 W/m^2	14.6 W/m^2
Diffuse Hor Good	98 W/m^2	14 W/m^2	20 W/m^2	-3.4 W/m^2	7.7 W/m^2
Diffuse Hor Better	98 W/m^2	14 W/m^2	20 W/m^2	0 W/m^2	4.9 W/m^2
C1 MFRSR Correction					
Total Hor	345 W/m^2	-1.9 W/m^2	5.3 W/m^2	-	-
Direct Normal	553 W/m^2	-35 W/m^2	48 W/m^2	0 W/m^2	17.9 W/m^2
Diffuse Hor Good	68 W/m^2	13 W/m^2	18 W/m^2	-2.2 W/m^2	4.5 W/m^2
Diffuse Hor Better	68 W/m^2	13 W/m^2	18 W/m^2	0 W/m^2	3.6 W/m^2

As stated in the Introduction, there is an unshaded thermopile pyranometer used to provide quality assurance that the sum of thermopile components is reasonable. The pyranometer, which was used for quality control, is biased in the same direction as the open silicon channel by 2.4 W/m^2 compared to the open silicon bias of 2.7 W/m^2. The rms difference of 12.7 W/m^2 is 50% larger than the open silicon value of 8.1 W/m^2. The open channel total is corrected for angular response. The direct, is separated by the shadowbanding process from the diffuse, corrected by the angular response, and added back to the diffuse to form the total horizontal irradiance. Figure 2 shows that the Precision Spectral Pyranometer (PSP) underestimates the sum at low solar angles and overestimates at the highest solar angles on this mostly clear day as expected for the typical PSP angular response. Since the unshaded thermopile pyranometer is not cosine-corrected, the rms difference is larger than the open channel rms difference.

Another factor that increases the rms difference between the open channel and the sum is the sampling frequency. The thermopile means are based on 60 1-second samples compared to the open silicon means that are based on 3 samples within the minute. The shadowbanding process takes at least 15 seconds to complete in the MFRSR; therefore, improving the agreement caused by infrequent sampling of the MFRSR can only be achieved by using longer averaging times.

Direct Normal Irradiance

The open channel direct normal irradiance is calculated by subtracting diffuse horizontal irradiance from the total horizontal irradiance and dividing by the cosine of the solar zenith angle. This is further corrected by using pre-deployment angular response measurements. Figure 3 is a scatterplot of the thermopile direct and the open channel direct for over 11,000 data points. Clearly, the open channel direct normal overestimates the thermopile direct normal irradiance, but the overestimate appears to be a well-behaved function that we will approximate using a simple quadratic fit. The simple correction is demonstrated in Figure 4, and Table 1 lists the changes in bias and rms difference. The bias after

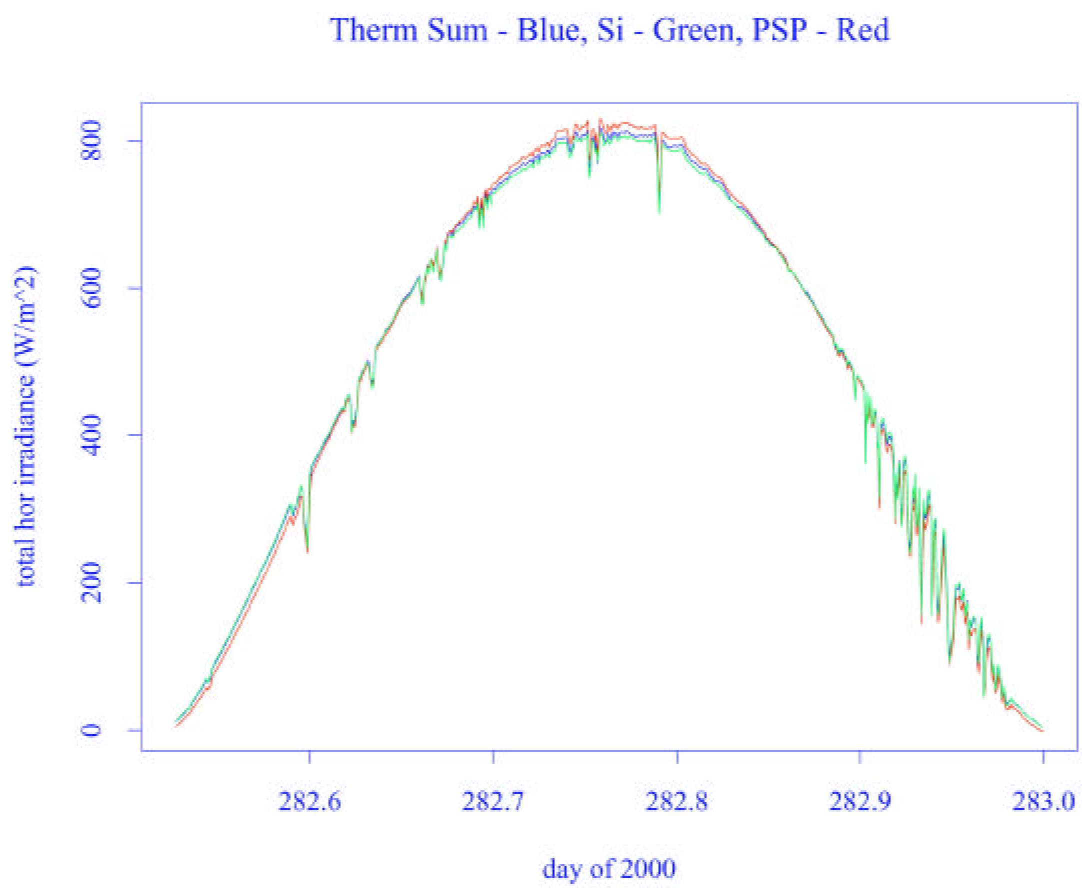

Figure 2. Comparison of three measurements of total horizontal irradiance for a mostly clear day. Blue is the best estimate from the sum of thermopile measurements, green is the open silicon measurement, and red is the unshaded pyranometer measurement. Note that the angular response is the cause of most of the latter's discrepancy.

correction is near zero with an rms difference of 14.6 W/m^2. This compares to a mean overestimate of 32 W/m^2 and an rms difference of 42 W/m^2 before correction. The dramatic improvement can be seen in Figure 5, where a mostly clear day's direct irradiance is plotted.

The spectral response of silicon is about three times less sensitive at blue wavelengths than it is in the near infrared. When the open channel is calibrated using total irradiance the spectral response is not an issue unless the total horizontal irradiance spectral distribution changes dramatically from the calibration spectral irradiance. If we examine Figure 1, this must be a small effect for total horizontal irradiance. For example, low sun angles produce a significant reduction in blue irradiance relative to the near infrared, but there is no suggestion of a significant spread or curvature at the smaller irradiance levels. When we use the open silicon channel, calibrated as above, to measure blue sky diffuse, then the response is expected to be low because of the predominance of blue spectral energy in clear skylight. The calculated direct using this underestimated diffuse term is going to be high as demonstrated in Figure 3. Moreover, as argued previously, the difference in sampling gives rise to a larger rms difference than we would have if sampling frequency were equivalent.

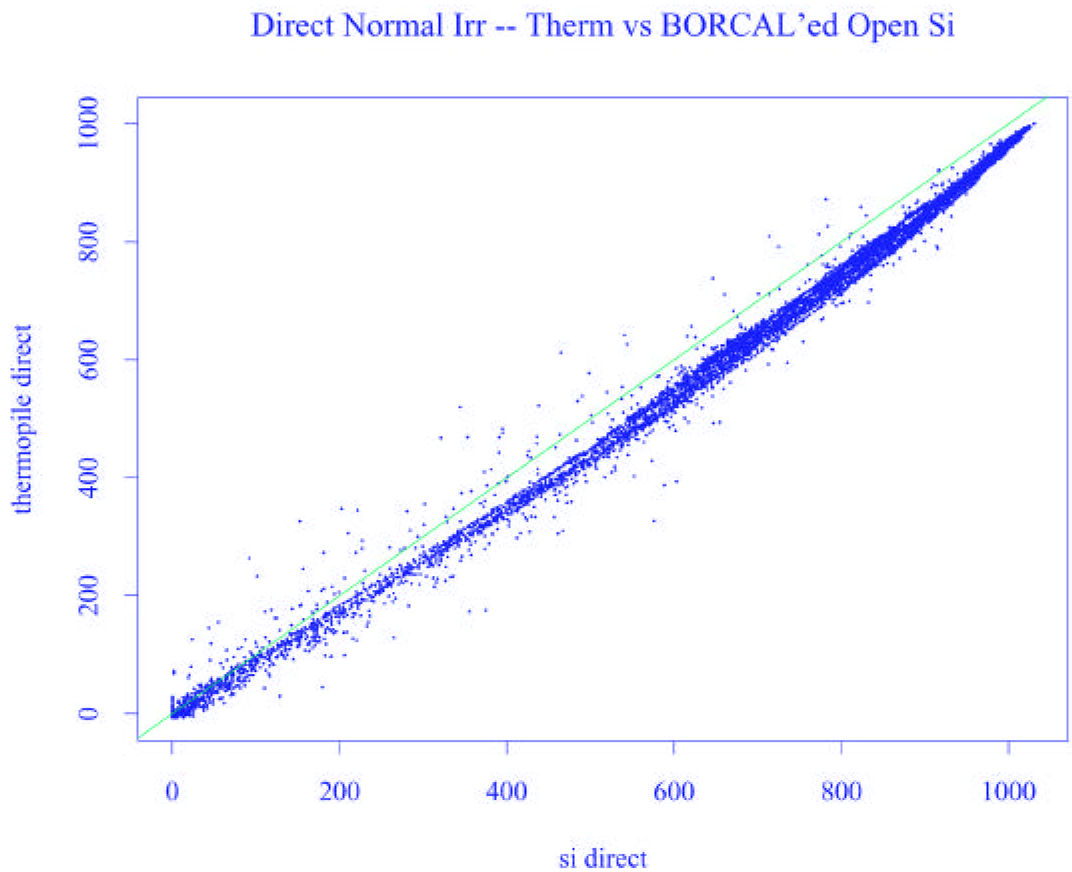

Figure 3. This is a scatterplot of thermopile versus the silicon direct normal irradiance. The one-to-one line suggests that open silicon measurements are generally overestimates of the thermopile pyrheliometer direct irradiance. Moreover, a quadratic would appear to provide a reasonable fit.

Diffuse Horizontal Irradiance

Having corrected the open channel direct irradiance, calculation of diffuse for the open channel was just a matter of subtracting the corrected diffuse horizontal from the total horizontal irradiance. A plot of the 13,000 values of thermopile diffuse versus this open silicon diffuse appear in Figure 6. There is obviously a departure from the one-to-one line for higher diffuse irradiance values, but again a simple quadratic function appears as though it would provide a reasonable correction. Figure 7 shows the results of these corrections, and Figure 8 indicates the level of agreement with the thermopile values for a reasonably clear day. The uncorrected silicon is clearly inadequate, but there is considerable improvement by using either of the corrected diffuse values discussed in this paragraph. Since the inadequacy of the simple correction is primarily for higher values of diffuse (compare Figures 6 and 7), the improvement with the quadratic fit is not obvious in this day's data.

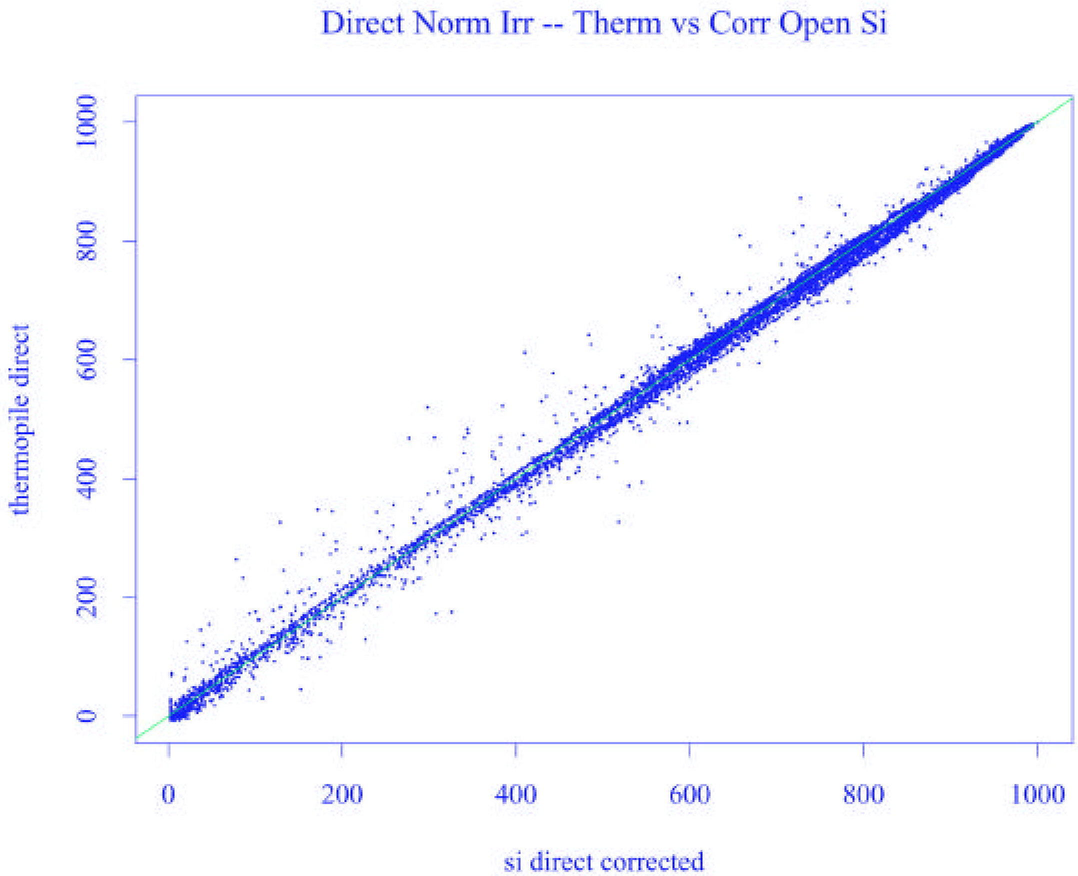

Figure 4. Scatter plot of data in Figure 3 after applying quadratic fit to those data.

Summary

The simple quadratic fits used to improve the open channel agreement with the thermopile measurements of direct normal and diffuse horizontal irradiance explain most of the variance. Attempts to further improve the results using solar zenith angle and the clearness of the atmosphere, as parameterized using the ratio of direct to diffuse irradiance, as independent variables led to small, but statistically insignificant, improvements on the order of 1 W/m^2. Therefore, no additional fits to the data that may have represented a less empirical approach were deemed necessary or useful.

An independent MFRSR's data were analyzed to assess the improvement in the measurements of the open MFRSR channel using the identical procedure. Quadratic forms were found to provide acceptable fits albeit with different coefficients. Consequently, there does appear to be enough spectral difference between open channels due either to subtle sensor responses or diffuser transmission differences that a single set of quadratic coefficients are not adequate for correcting all sensors. According to the comparable results summarized in Table 1 (bottom), the procedure appears fairly robust.

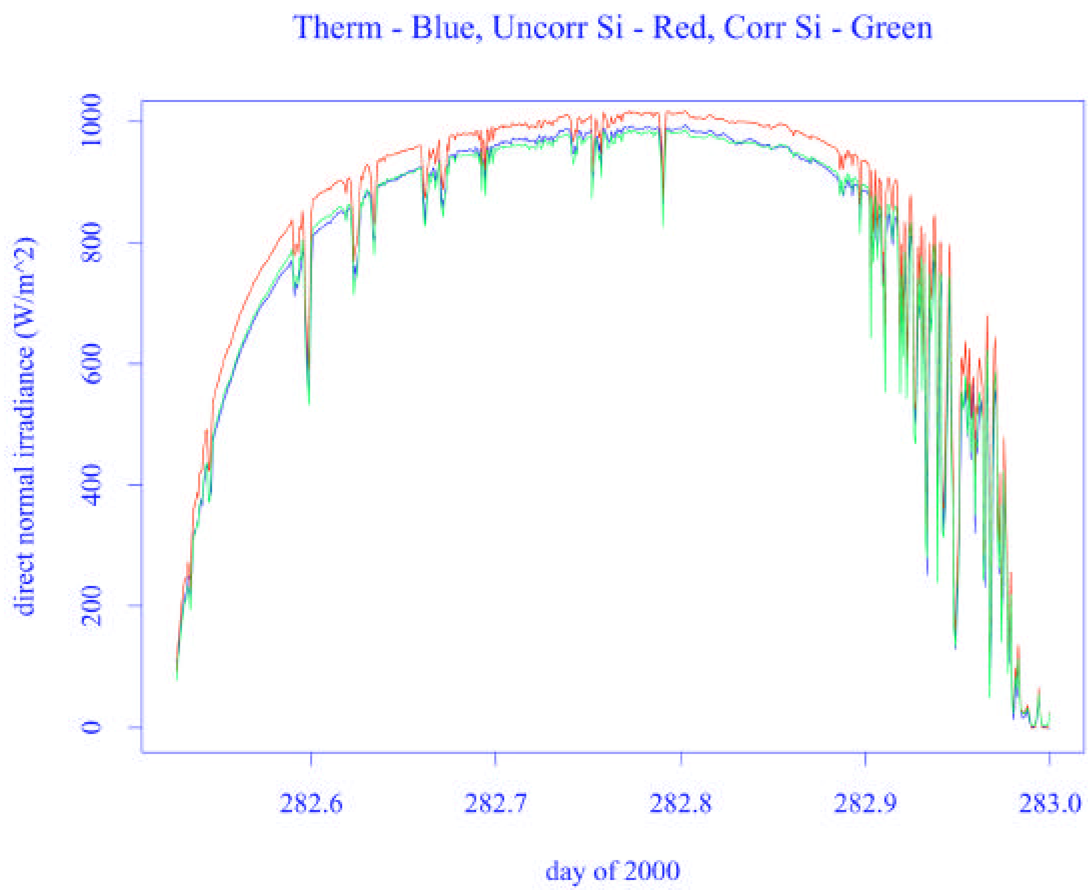

Figure 5. Comparison of three measurements of direct normal irradiance for a mostly clear day. Blue is best thermopile data. Red is open silicon data before correction. Green is open silicon data after correction using quadratic fit to scatterplot data.

References

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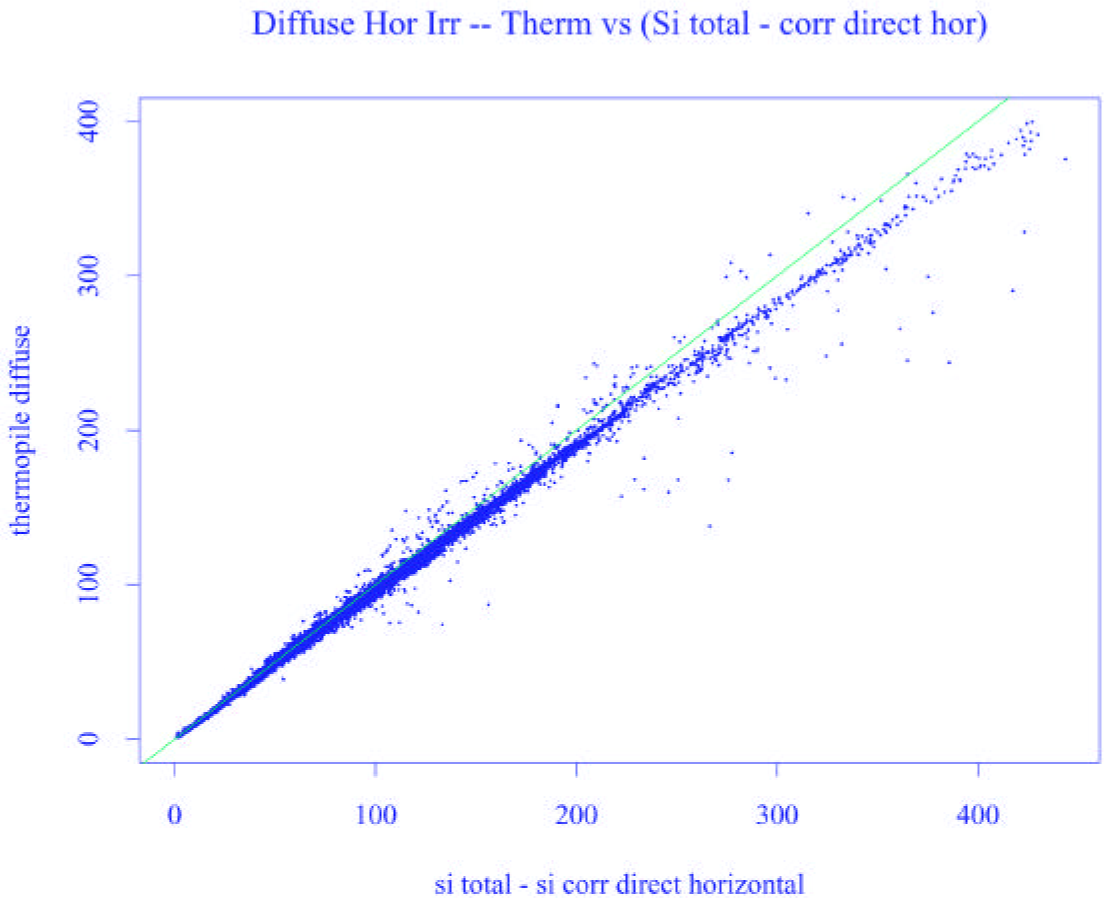

Figure 6. Scatterplot of diffuse horizontal measurement using shaded, zero-offset thermopile pyranometer versus open silicon diffuse obtained by subtracting direct horizontal from total horizontal irradiance. As in Figure 3, there is some departure from the perfect correlation line that could be compensated with a quadratic function.

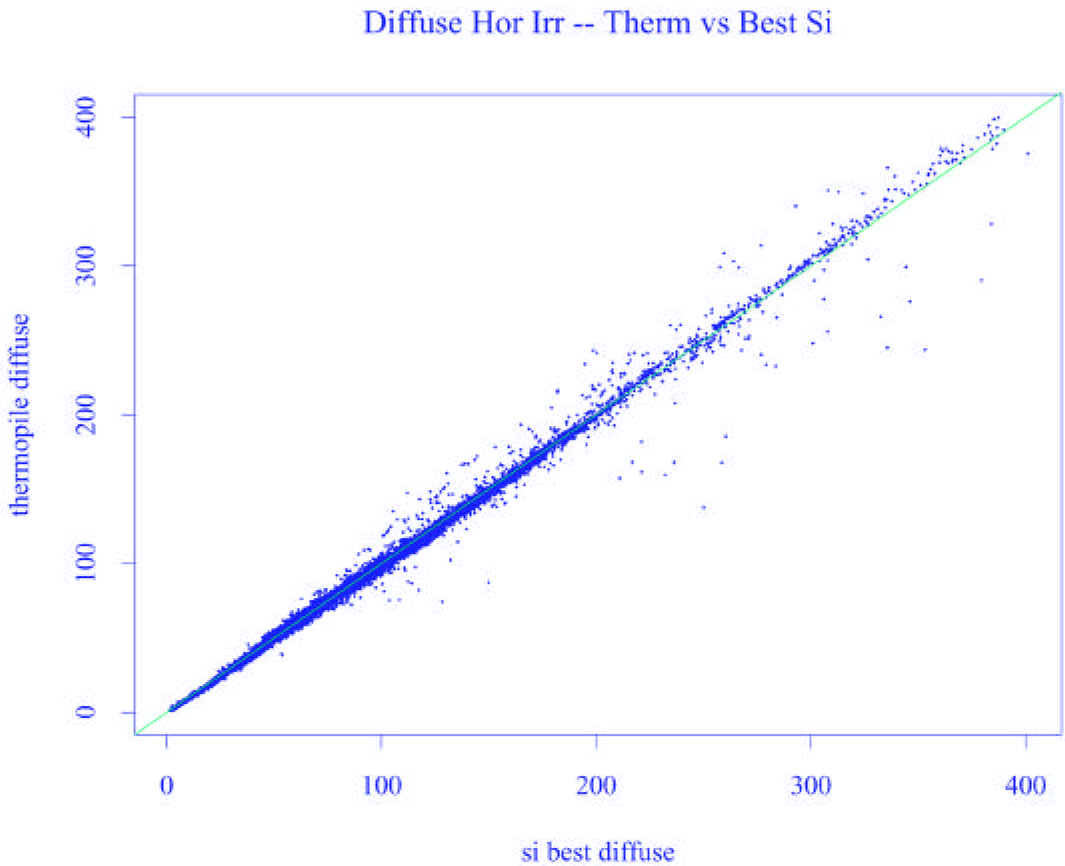

Figure 7. Scatterplot of data of Figure 6 after compensation using the quadratic fit.

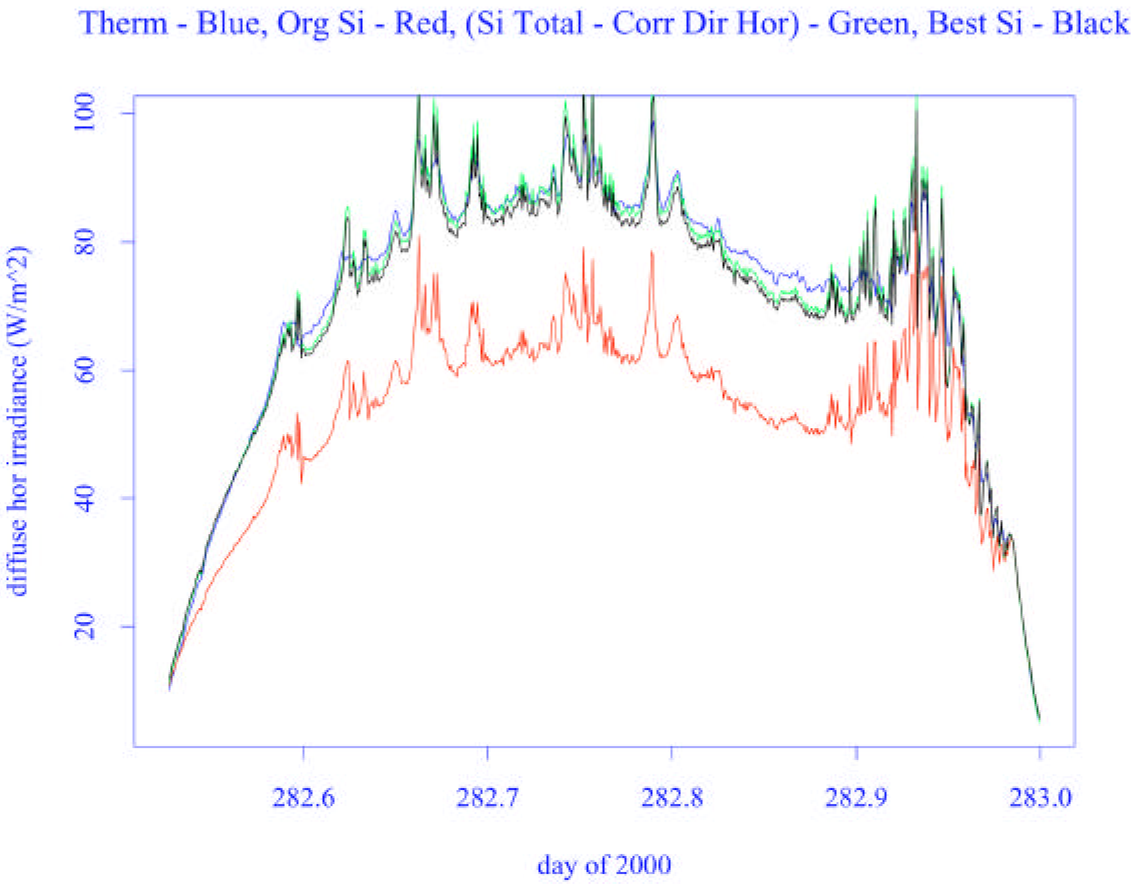

Figure 8. Comparison of four measurements of diffuse horizontal irradiance for a mostly clear day. The blue is the thermopile measurement. The red is the uncorrected silicon data that has not been processed except to apply the BORCAL calibration. The green is the open channel diffuse obtained by subtracting corrected direct horizontal from the total horizontal. Black is the same after compensation for the curvature shown in Figure 6. Since this correction mostly affects the diffuse irradiance above 100 W/m^2, there is little difference in the latter two plots (See Figure 6).