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Twelve Month Performance Evaluation for the Rotating Shadowband Radiometer

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ABSTRACT

The Southwest Technology Development Institute staff compared twelve months of 10-minute average data from a rotating shadowband radiometer (RSR) with data from three thermopile-based reference radiometers. Particular attention was focused on determining the accuracy of the direct normal irradiance data reported by the RSR. Accurate measurement of direct normal irradiance is the most critical requirement of the RSR when used for performance assessment of concentrating solar thermal collectors. Evaluation of three different methods of post-collection data processing was also performed.

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SUMMARY

The rotating shadowband radiometer (RSR) is a single instrument that uses a silicon detector to make direct measurements of solar global horizontal irradiance (G_h) and diffuse horizontal irradiance (D_h) and provides calculated values for direct normal irradiance (I_d). This report evaluates the RSR as a measurement instrument for use in performance assessment of concentrating solar thermal collectors.

For twelve months, 10-minute average data were collected from a RSR and, for comparison, from three thermopile-based radiometers located at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. The data were analyzed as follows: 1) to quantify and explain the measurement uncertainties and inaccuracies associated with the data reported by the RSR, particularly the I_d data; and 2) to assess the long-term reliability of the RSR in field use.

The reliability and availability of the RSR were excellent. No operator intervention, repair, or realignment was required for normal use. However, the internal clock, which the RSR uses for calculation of the solar ephemeris, can drift as much as one minute per month. To prevent this, the clock was reset via modem each week throughout the test period to agree with time provided by the Naval Observatory in Washington, D.C.

Accurate short-term measurements are required for determination of real-time efficiency of concentrating solar thermal collectors. Table S-1 presents an overview of the accuracy of the RSR in measuring irradiance during 10-minute periods. The root-mean square (RMS) difference is the magnitude of the difference between each 10-minute RSR and reference radiometer reading (regardless of sign) averaged over a month. The bias value indicates the magnitude and sign of consistent, systematic differences between the RSR and reference radiometer readings determined for each month. All differences are expressed as percentages in Table S-1.

The RSR measured G_h with an average monthly RMS difference of 4.3% (compared to the reference radiometer). The bias difference in these data was -0.4% indicating that the RSR roughly equally overestimated and underestimated the global irradiance each month.

**Table S-1. Rotating Shadowband Radiometer/Reference Radiometer
10-Minute Data Comparison Summary**

	Mean Monthly RMS Difference (%)	Median Monthly RMS Difference (%)	Mean Monthly Bias Difference (%)
Global Horizontal	4.3	3.8	-0.4
Diffuse Horizontal	12.5	11.5	-7.0
Direct Normal	5.6	5.9	3.4

The RSR D_h data were consistently lower than the reference readings, displaying an average monthly bias error of -7.0%. The predominant reason for this is attributed to the selective spectral response of the RSR's silicon detector pyranometer and differences between the spectral distribution of diffuse irradiance and the global irradiance under which this pyranometer is calibrated (see text).

Accurate measurement of direct normal irradiance is the most critical requirement of the RSR in concentrating solar collector characterization. In determination of I_d , the RSR and reference radiometer data displayed average monthly RMS and bias differences of 5.6% and 3.4%, respectively. Since the RSR calculates I_d by taking the difference between the global and diffuse readings (corrected for solar zenith angle), consistent underestimation of the diffuse irradiance gave rise to overestimation of the calculated direct normal irradiance. It is possible to improve the accuracy of these readings with post collection processing. ATI makes use of algorithms that correct raw readings based on temperature and solar zenith angle after the work of Michalsky, et. al. (15). For comparison, two additional correction procedures are proposed in the text: 1) a simple subtraction of the bias; and 2) a correction algorithm based on solar zenith angle only. All three procedures effectively reduce bias in the data and average RMS errors.

The RSR was also evaluated in its performance of general purpose solar resource assessment. Data were compiled into monthly and yearly totals and the accuracy of these figures was determined. Table S-2 presents the yearly insolation totals recorded by the RSR and reference radiometers for the three irradiance components. The percentage differences between these yearly figures are shown.

**Table S-2. Rotating Shadowband Radiometer/Reference Radiometer
1993 Insolation Comparison Summary**

Global Horizontal			Diffuse Horizontal			Direct Normal		
RSR (kWh)	Ref. (kWh)	Diff. (%)	RSR (kWh)	Ref. (kWh)	Diff. (%)	RSR (kWh)	Ref. (kWh)	Diff. (%)
1906.4	1920.2	-0.7	508.6	548.9	-7.2	2351.0	2277.5	3.3

1.0 INTRODUCTION

A rotating shadowband radiometer (RSR) has been in operation at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories (SNL) in Albuquerque, New Mexico, since the latter part of 1992. Since its installation, the Southwest Technology Development Institute (TDI) has been collecting and archiving the data generated by the RSR. This report summarizes the solar measurement data obtained with this instrument during the 12-month period from January through December 1993 and compares these data with similar data obtained from three first-class thermopile-based radiometers at the same location.

The RSR under test is a commercially available instrument manufactured by Ascension Technology, Inc. (ATI, Waltham, MA). The sensing element is a silicon detector pyranometer (LI-COR model LI-200SZ).

For this study, measurements were taken every minute and averaged over 10-minute periods for both the RSR and the thermopile instruments. This report examines the collected data and assesses both the short-term and long-term accuracy of the global horizontal, diffuse horizontal, and direct normal irradiance data generated by the RSR.

Short-term accuracy is an essential requirement for tasks such as determining the efficiency of a concentrating solar thermal or photovoltaic (PV) collector. In this report, short-term accuracy refers to the accuracy of the 10-minute average data points.

Errors that are randomly caused or periodic in nature can be large in the short-term but self-canceling in the long-term. A task such as solar resource assessment requires accuracy only in the long-term data; instantaneous inaccuracies are of little consequence. To this end, the data were compiled into monthly and yearly totals. The accuracy of these figures was also assessed.

Performance studies of the ATI RSR by NREL/EPRI and ATI have been published elsewhere (3, 7). These studies have addressed the use of the RSR for general resource assessment. This report addresses the use of the RSR for performance characterization of concentrating solar thermal collectors.

2.0 INSTRUMENTATION

2.1 Rotating Shadowband Radiometer

Ascension Technologies, Inc. (ATI, Waltham, MA) developed its model of a rotating shadowband radiometer (RSR) in 1990 under contract with the New York Power Authority (3). In August of 1992, an ATI RSR was installed at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. Since that time, the Southwest Technology Development Institute (TDI) has been collecting data from the RSR via modem and archiving the data.

The RSR is a single instrument that provides direct measurements of global and diffuse irradiance and calculated values for direct normal irradiance. Figure 2-1 shows the ATI RSR.

Figure 2-1. The Ascension Technologies, Inc., Rotating Shadowband Radiometer

The major mechanical components of the RSR are:

1. LI-COR model LI-200SZ silicon detector pyranometer, mounted in a horizontal plane, used for the measurement of global and diffuse radiation
2. motor-driven, curved, aluminum shadowband
3. photovoltaic power supply (18 W PV module, battery charge controller, 31 A-h lead-acid battery)
4. Campbell Scientific, Inc., CR-10 datalogger for control of the shadowband and data acquisition
5. Nema-4 fiberglass enclosure

The datalogger is software driven and pre-programmed with the latitude and longitude of the RSR's location. The datalogger has an on-board clock/calendar circuit so that real-time solar position can be calculated based on site coordinates, time, and date.

In operation, the RSR works as follows. The global horizontal irradiance is measured once per second using the pyranometer in a conventional way. Fifty-four seconds into each minute, the datalogger switches on the motor to rotate the shadowband once completely around the pyranometer. During this rotation, the datalogger acquires data at a high sample rate in order to ensure that the null associated with maximum shading is recorded. This null provides measurement of the diffuse irradiance. The datalogger then calculates the current solar zenith angle based upon time of day, date, and site coordinates using equations that model the motion of the sun. Having derived the solar zenith angle, the direct normal irradiance is calculated using the radiation component equation:

$$G_h = D_h + I_d \cos(z) \quad (2.0)$$

where G_h is global horizontal irradiance, D_h is the diffuse horizontal irradiance, I_d is the direct normal irradiance, and z is the solar zenith angle. At the end of each 10-minute period, the ten 1-minute data points for each irradiance component are averaged and recorded.

In comparison with the reference, thermopile-based instruments, the RSR has some desirable features:

- Some studies indicate that silicon detector pyranometers have greater tolerance to the effects of soiling than do thermopile radiometers (4).

- The increased stability of the silicon detector results in a recommended period of recalibration that is twice as long as required by the thermopile instruments (two years versus one year).

In addition, there is a cost savings associated with the purchase of the RSR. Table 2-1 shows the current (1994) prices for the RSR and reference radiometers used in this study.

Table 2-1. Cost Comparison of RSR and Reference Radiometers

ROTATING SHADOWBAND RADIOMETER

<u>Measurement</u>	<u>Instrument</u>	<u>Cost</u>
Global, Diffuse, and Direct Normal	ATI RSR	\$5,700

REFERENCE RADIOMETERS

<u>Measurement</u>	<u>Instrument</u>	<u>Cost</u>
Global Horizontal	Eppley Precision Spectral Pyranometer (PSP)	\$1,975
Diffuse Horizontal	Eppley PSP with Eppley Shadow Band Stand	\$3,550
Direct Normal	Eppley (Normal Incidence Pyrheliometer) NIP with Eppley ST-3 Solar Tracker	\$10,200

The RSR is not without some undesirable features. Among these are:

- The silicon detector is spectrally and temperature sensitive. In the RSR under test, no corrections are made for this which leads to measurement uncertainties.
- Accurate time must be kept to ensure proper calculation of the solar zenith angle and direct normal irradiance. Unattended, the datalogger clock can drift up to one minute per month. The need to regularly (weekly) reset the datalogger clock prohibits its use in sites without two-way (e.g. telephone) communications.

2.2 Thermopile-based Reference Radiometers

Three thermopile-based radiometers were used to provide reference readings for RSR comparisons. All three of the reference instruments meet the criteria listed for first class designation according to the specifications set by the World Meteorological Organization (1965). Figure 2-2 shows the reference radiometers in use at the NSTTF. The instruments are described in Table 2-2.

Figure 2-2. National Solar Thermal Test Facility
Thermopile-based Reference Radiometers

Table 2-2. Thermopile-based Reference Radiometers

Global Horizontal	Eppley Precision Spectral Pyranometer (PSP)
Diffuse Horizontal	Eppley PSP with Eppley Shadow Band Stand
Direct Normal	Eppley Normal Incidence Pyrheliometer (NIP) with Eppley ST-3 automatic Solar Tracker

The Eppley precision spectral pyranometer (PSP) uses a circular multi-junction thermopile to measure the temperature rise in a black, non-wavelength selective, 1 cm^2 receiver. The PSP is temperature and cosine response corrected. The manufacturer specifies that accuracy is within $\pm 1\%$ for operation over the temperature range -20 to $+40^\circ\text{C}$ and $\pm 1\%$ for incidence angles between 0 and 70° . In the field, however, these instruments often demonstrate deviations with temperature and solar incidence angle in excess of these specifications (5, 8).

For purposes of comparison with the RSR, therefore, the reference global horizontal irradiance used throughout this report was derived (according to equation 2.0) from the measured direct normal and diffuse horizontal (corrected per equation 2.1, below) irradiances. The section that follows (2.3) describes some of the major sources of

measurement uncertainty associated with the use of the various radiometers. As shown in that section, the uncertainty for calculated global horizontal irradiance (based on NIP and PSP/SBS data) is approximately half of that for the PSP measurement alone.

The reference diffuse horizontal irradiance was measured using an Eppley PSP and Eppley Shadow Band Stand (SBS). The SBS requires and received daily adjustment to provide proper shading of the pyranometer. Eppley provides a table of monthly shadowband correction factors (SBCF) for use with the SBS. For this study, a more accurate SBCF was determined (see references Z, 2) and applied to each 10-minute diffuse reading prior to any use of the data. The shadowband correction factor was calculated as follows:

$$\text{SBCF} = 1.04 * (1 + (w/r) * \cos^3 d * (\sin j \sin d + \cos j \cos d \cos h)) \quad (2.1)$$

where w is the shadow band's width and r is its radius, d is the declination, j is the site latitude, and h is the hour angle.

The direct normal irradiance was measured with an Eppley normal incidence pyrheliometer (NIP). The NIP is mounted on an Eppley ST-3 solar tracker. Properly installed, this fully-automatic solar tracker requires no realignment to accurately follow the sun.

All three thermopile radiometers receive yearly recalibration. During the test period, these instruments and the RSR LI-COR were recalibrated during the last week of March, 1993.

2.3 Instrument Measurement Uncertainty Comparisons

Some uncertainty and inaccuracy is a part of every radiometer measurement. Estimates of the magnitude of these values are presented in Table 2-3. Table 2-3 is taken from Stoffel, et. al. (Z), and lists reasonable estimates of the measurement uncertainties inherent in the use of the various radiometers included in this report. Before examining the data, it is important to understand the measurement uncertainties associated with the use of each radiometer. These uncertainties give an indication of the magnitude of the measurement inaccuracies possible even when the radiometer involved is correctly calibrated and properly operated.

Table 2-3. Measurement Uncertainty Estimates (From Stoffel, 1991).

Instrument	Instru. Calib. Uncert.	Level/ Track. Uncert.	Uncert. due to Timing	S-Band Corr. Uncert.	Spectral Uncert.	Direct./ Temp. Uncert.	Total Uncertainty
RSR: Horizontal	±4.9%	±1.3%			±1.0%	±3.7%	±6.4%
RSR: Diffuse	±4.9%	±1.3%		±1.0%	±1.0%	±3.7%	±6.6%
RSR: Direct Norm.			±1.0%				±6.5%
PSP: Horizontal	±4.0%	±1.3%			±0.2%	±1.7%	±4.0%
Calc. Horizontal			±1.0%				±2.4%
PSP/SBS: Diffuse	±3.6%	±1.3%		±2.0%	±0.2%	±1.7%	±4.8%
NIP: Direct Norm.	±1.8%	±0.02%			±0.1%	±1.0%	±2.1%

The data analysis performed during this study largely support the figures in Table 2-3 with one exception. The spectral effects on RSR diffuse measurement uncertainties were found to be several times larger than the ±1% given in the table. This is presented in detail in the Analysis section, below.

Though measurement uncertainties for the reference instruments are smaller in magnitude than those for the RSR, they are not zero. Depending on the sign and magnitude of these uncertainties, inaccuracies in the reference readings can act to minimize some of the differences observed between the reference instruments and the RSR or make them larger.

3.0 DATA COMPARISONS

3.1 Approach

Two different approaches to data analysis were taken in this study. The first approach was to sum the 10-minute data into long-term data sets and to analyze these. In this report, monthly and yearly sums of global horizontal, direct, and diffuse horizontal insolation were calculated for comparison of the RSR and reference radiometer measurements. This approach mitigates the effects of random or periodic errors, which are largely self-canceling in the long-term. A task such as general purpose resource assessment usually requires accuracy only in the long-term data. Table 3-1 presents the monthly and yearly sums of the irradiance components recorded by the RSR and reference radiometers.

**Table 3-1. Rotating Shadowband Radiometer/Reference Radiometer
Monthly Insolation Comparison Summary**

	Global Horizontal			Diffuse Horizontal			Direct Normal		
	RSR (kWh)	Ref. (kWh)	Diff. (%)	RSR (kWh)	Ref. (kWh)	Diff. (%)	RSR (kWh)	Ref. (kWh)	Diff. (%)
Jan	81.1	80.4	0.8	38.0	38.2	-0.6	103.1	100.7	2.4
Feb	97.8	97.7	0.2	47.2	48.6	-2.9	104.2	100.3	3.9
Mar	161.3	161.8	-0.3	48.3	50.4	-4.0	196.1	190.3	3.1
Apr	206.6	209.6	-1.4	58.1	62.7	-7.3	223.2	216.7	3.0
May	220.4	223.3	-1.3	63.0	68.6	-8.2	221.7	216.6	2.4
Jun	235.6	239.0	-1.4	48.6	55.7	-12.8	268.0	261.1	2.6
Jul	178.9	181.3	-1.3	28.9	34.3	-15.8	212.0	206.4	2.7
Aug	190.0	192.5	-1.3	60.8	66.6	-8.8	183.2	177.0	3.5
Sep	188.2	190.9	-1.5	29.0	33.9	-14.5	266.2	257.4	3.5
Oct	145.1	145.9	-0.5	34.8	37.3	-6.7	211.0	202.6	4.2
Nov	109.1	108.1	1.0	25.9	26.6	-2.7	192.0	184.3	4.2
Dec	92.3	89.8	2.9	26.1	26.1	0.2	172.4	164.1	5.1
Year	1906.4	1920.2	-0.7	508.6	548.9	-7.2	2351.0	2277.5	3.3

The second approach to analysis of the data measured the short-term accuracy of the RSR in its agreement with the data recorded by the reference instruments. Statistics based on *each* 10-minute data point recorded by the RSR and the reference radiometers were used for this task. Monthly and yearly sums do not provide the resolution necessary for performance characterization of concentrating solar collectors. Short-term accuracy is required where the 10-minute readings are individually used for efficiency or performance assessment of concentrating solar thermal or PV systems. In this report, the root-mean-square (RMS) difference and the bias difference were used to assess agreement between the 10-minute averages recorded by any two instruments. The RMS difference indicates the magnitude of the average difference between the two data sets (regardless of sign). The bias difference reveals whether or not one instrument reads consistently higher or lower than the other and by what magnitude. Table 3-2 provides a statistical comparison of the RSR and reference radiometer short-term data.

**Table 3-2. Rotating Shadowband Radiometer/Reference Radiometer
10-Minute Data Comparison Summary**

	Mean Monthly RMS Difference (%)	Median Monthly RMS Difference (%)	Mean Monthly Bias Difference (%)
Global Horizontal	4.3	3.8	-0.4
Diffuse Horizontal	12.5	11.5	-7.0
Direct Normal	5.6	5.9	3.4

The three following sections compare the global horizontal, diffuse horizontal, and direct normal irradiance data recorded by the RSR and reference radiometers.

3.2 Global Horizontal Insolation

Figure 3-1 presents monthly sums of the global horizontal insolation recorded by the RSR (i.e. the LI-COR pyranometer) and the reference, calculated global horizontal insolation (derived from measurements of the NIP and PSP/SBS). Also shown in the figure are the percentage differences between the monthly figures.

Figure 3-1. Monthly Global Horizontal Insolation Sums and Differences

Figure 3-2 shows the RMS and bias differences observed between the 10-minute RSR and reference global horizontal data sets. These differences were calculated for each 10-minute data pair and then averaged over monthly periods.

Figure 3-2. Global Horizontal Insolation RMS and Bias Differences

For the 12-month period, yearly global horizontal insolation values of 1906.4 and 1920.2 kWh/m² were recorded by the RSR LI-COR and the calculated reference, respectively, an overall difference of -0.7% for the year.

Monthly average RMS differences in excess of 6% were observed for the 10-minute LI-COR horizontal irradiance readings. At the same time, the average monthly bias for these readings was generally less than half of this value. This indicates that the LI-COR measurements both overestimated and underestimated the global irradiance throughout the month. The result was relatively large inaccuracies in the instantaneous and short-term readings (6%) but much smaller inaccuracies in the monthly sums (2%). The conditions that cause the LI-COR to over and underestimate the global irradiance are described in the Analysis section of this report (Section 4.1).

3.3 Diffuse Horizontal Insolation

Figure 3-3 presents monthly sums of the diffuse horizontal insolation recorded by the RSR and the reference PSP/SBS (corrected). Figure 3-3 also shows the percentage differences between the monthly sums. For the 12-month period, yearly diffuse horizontal insolation values of 508.6 and 548.9 kWh/m² were recorded by the RSR and the reference radiometer, respectively. This represents an overall yearly difference of -7.2%.

Unlike the global irradiance, the diffuse irradiance generally had a large, negative monthly average bias (up to -15%), and this bias was the major constituent of the total, RMS difference. As a result, the RSR consistently underestimated the diffuse radiation. Some of the factors that cause this effect are explained below (Section 4.1).

Figure 3-3. Monthly Diffuse Horizontal Insolation Sums and Differences

Figure 3-4 shows the RMS and bias differences observed between the RSR and reference data. These differences are calculated for each 10-minute data pair and averaged over each month.

Figure 3-4. Diffuse Horizontal Insolation RMS and Bias Differences

3.4 Direct Normal Insolation

Figure 3-5 presents monthly sums of the direct normal insolation recorded by the RSR and the NIP. Also shown in Figure 3-5 are the percentage differences between these monthly sums. For the 12-month period, yearly direct normal insolation values of 2353.1 and 2277.5 kWh/m² were recorded by the RSR and the reference radiometer, respectively. This represents an overall difference of 3.3% in the yearly total.

As would be expected, the bias difference for the RSR direct normal irradiance is consistently positive. This is the result of the RSR's general underestimation of the diffuse component. Monthly average RMS differences in excess of 7% were recorded, though bias differences accounted for greater than half of these values. A data set with a known bias can be corrected to subtract the bias and yield more accurate results. This approach and two more complex methods of data remediation for the RSR direct normal irradiance are presented below in section 4.3.

Figure 3-5. Monthly Direct Normal Insolation Sums and Differences

Figure 3-6 shows the RMS and bias differences between the RSR and reference data. These differences are calculated for each 10-minute data pair and averaged over each month.

Figure 3-6. Direct Normal Insolation RMS and Bias Differences

4.0 ANALYSIS

4.1 Spectral Effects

Thermopile radiometers transfer the radiant energy falling on a detector into heat energy and are generally considered spectrally nonselective. The silicon detector used by the RSR, conversely, converts radiant energy directly to electrical current and is highly spectrally selective. Figure 4-1 shows the response curve for the LI-COR silicon pyranometer (1) superimposed on typical clear sky direct, global, and diffuse spectra. The spectra were created using the SPCTRAL2 model developed by Bird and Riordan (2), with the following major parameters: Julian day = 90; zenith angle = 48.3°; pressure = 1013 mb; turbidity at 500 nm = 0.1 ; water vapor = 1.4 cm; ground albedo = 0.2; and ozone = 0.344 atm-cm.

Figure 4-1. LI-COR Response Curve

As shown in Figure 4-1, the silicon detector provides no response to radiation in the near-UV (NUV, 300 - 380 nm), has a linearly increasing response in the visible (VIS, 380 - 780 nm), a sharp roll-off in response at 950 nm and then no response to the rest of the near-infrared (NIR, 780 - 4000 nm) beyond 1100 nm. The wavelength selective response curve of a pyranometer would not matter if the spectral content of sunlight remained constant. The spectral distribution of visible solar radiation reaching the ground is not

constant but varies with air mass, cloud cover, turbidity, atmospheric water vapor content, and the reflective characteristics of the ground's surface (2). Considering global radiation, some general effects of these parameters are listed below in Table 4-1.

Table 4-1. Parameters Influencing Global Spectral Distribution

Parameter	Effect
Air Mass	Proportionately less transmittance of NUV and blue wavelengths as air mass increases (11)
Clouds	Cloudy skies transmit proportionately more NUV and blue wavelengths than do clear skies (10)
Turbidity	Complex scattering and absorption relationships; spectral effects are difficult to model accurately (13)
Water Vapor	Sharp absorption peaks in selected wavelength bands (724, 824, 938, and 1120 nm)
Albedo	Multiple reflection between the ground and clouds can be important for highly reflective surfaces; ground albedo is highly site and season dependent (10)

Solar spectral radiation that has been proportionately shifted toward the red and NIR, such as under conditions of high air mass, will be overestimated by the LI-COR pyranometer. Solar spectral radiation shifted toward the NUV and blue end of the spectrum, such as under partly-cloudy skies, is underestimated by the LI-COR.

The silicon pyranometer used in the RSR is calibrated against a PSP under natural sunlight over the course of several days (1). The calibration constant arrived at in this way provides a reasonable compromise of response to a variety of conditions under which the detector overestimates or underestimates the incident radiation. The efficacy of this calibration can be judged by comparing the monthly and yearly global horizontal insolation totals for the silicon pyranometer with those of the calculated global horizontal insolation: though individual (10-minute) RMS differences of 7-8% were common, differences between monthly sums did not exceed $\pm 2\%$ and a difference of less than 1% was observed between the yearly totals.

This cancellation of errors is not possible for measurements that demonstrate strong bias differences. This is the case for the diffuse measurements made by the RSR. Under mostly-clear skies, the diffuse component has a spectral distribution that is similar to, but slightly blue-shifted from, the global spectral irradiance (14). That is, the diffuse

component contains proportionately more radiation in the wavelengths of weaker response for the silicon detector. As a result, the calibration constant appropriate for the calculation of global irradiance (in W/m^2) from silicon detector output (an electrical current), is inaccurate when used with a shaded pyranometer under clear sky conditions. Under cloudy conditions, the diffuse and global spectra agree more closely and the RSR inaccuracies are less. In summary, the RSR experiences the most inaccuracies in its determination of the diffuse component under clear sky conditions.

An illustration of the clear sky performance of the RSR is presented in Figure 4-2. This figure presents data collected on a typical clear day, 20 September 1993.

Figure 4-2. Clear Day Global and Diffuse Horizontal Irradiance:
20 September 1993

In this example, mid-day differences for the global horizontal irradiance readings were on the order of 1-2%. At the same time, the mid-day differences for the diffuse horizontal measurements were approximately 20%. As a result, at mid-day, the RSR overestimated the direct normal component under these clear sky conditions by several percent.

4.2 Temperature Effects

The thermopile-based reference radiometers used in this study all incorporate compensation circuitry to overcome changes in instrument output with temperature. Eppley specifies a temperature dependence of $\pm 1\%$ over normal operating conditions. The LI-COR silicon pyranometer contains no temperature compensation mechanism. The specification for the LI-200SZ pyranometer is given as $\pm 0.15\%$ per $^{\circ}\text{C}$.

In practice, it is difficult to isolate the effects of temperature on pyranometer response from the coincident effects of changing air mass, cloud cover, etc. For the RSR under test, the temperature of the LI-COR is not recorded. However, a silicon-based UV pyranometer of similar design is monitored among the reference instruments. The temperature of this pyranometer is recorded and this temperature can be used as an approximation of the LI-COR detector's temperature. This has been done in Figure 4-3. Figure 4-3 presents data recorded during July 1993. Data acquired at solar zenith angles greater than 60° have been excluded. The figure plots the ratio of the LI-COR global horizontal irradiance to the reference (calculated) global horizontal irradiance on the ordinate axis. The UV pyranometer temperature is plotted along the abscissa.

Figure 4-3. Effects of Temperature on LI-COR Response

For this data set (with the necessary instrument temperature approximations), the LI-COR temperature dependence was about 0.19% per °C. The manufacturer does not specify an operating temperature range for this pyranometer. If we assume that in normal operation, the pyranometer will experience an operating temperature range of $\pm 20^{\circ}\text{C}$ of the temperature at which it was calibrated, this can give rise to worst-case temperature induced inaccuracies of approximately $\pm 4\%$.

4.3 RSR Direct Normal Irradiance Data Remediation

Obtaining accurate direct normal irradiance readings is the most important requirement for a radiometer used in performance assessment of concentrating solar thermal arrays. For this reason, three methods were examined to improve the accuracy of the RSR direct normal irradiance data.

The first method was a simple subtraction of the positive bias. This entailed multiplying each direct normal reading by 0.966. As expected, this effectively reduced the average monthly bias difference, from 3.4% to near zero. This simple correction also reduced the average monthly RMS difference from 5.6% to 4.5%, an improvement of 20%.

It is not known if the average bias difference of 3.4% observed at the NSTTF can be used to correct direct normal irradiance data recorded by other RSR instruments in other locations. It may be found that site specific conditions (e.g. the average daily cloud cover) make the average bias difference a site specific variable. In any case, it is likely that a review of the data from other sites operating a NIP and RSR side-by-side (at least two sites are known to the authors) can yield an 'average' RSR correction factor for general use.

The other two techniques used to improve data accuracy were more complex in nature. The first followed the method developed by Michalsky, et. al. (15). Using this procedure, one first corrects for effects of operating temperature on sensor (silicon) output. Actual readings are normalizing against sensor response measured at a standard temperature of 30°C . Additional correction is then performed to compensate for spectral effects. Raw data are sorted into categories based on the solar zenith angle and two calculated parameters named sky clearness (ϵ) and skylight brightness (Δ). A

program that implements this correction procedure was supplied by ATI. However, since the RSR does not monitor the temperature of the silicon detector, the ATI program performs correction based on ambient rather than device temperature. This is a deviation from the technique described in the literature.

For the second correction technique, a limited attempt at derivation of a temperature independent correction algorithm was undertaken. Inspection of the data revealed that errors in the RSR direct normal irradiance readings increased non-linearly with zenith angle. The errors were generally small at small angles and showed a rapid increase at the extremes. When error magnitude was plotted, its shape closely followed the curve traced by the fourth power of the zenith angle. With a constant (1/40) applied to scale the magnitude of the zenith angle correction, the following algorithm was derived and applied to RSR data :

$$I_d (\text{corrected}) = I_d * (1 - z^4/40) \quad (4.1)$$

where I_d is the direct normal irradiance, and z is the solar zenith angle in radians.

Table 4-2 summarizes the results of correcting the raw RSR direct normal irradiance data using the three techniques: a) a simple 3.4% bias subtraction; b) the ATI program (Michalsky (1991) less device temperature correction); and c) the temperature independent algorithm of equation 4.1.

Table 4-2. Direct Normal Irradiance Correction Algorithm Comparison

	Mean Monthly RMS Difference (%)	Median Monthly RMS Difference (%)	Mean Monthly Bias Difference (%)
RSR Uncorrected	5.6	5.9	3.4
3.4% Bias Subtraction	4.5	4.4	-0.1
ATI/Michalsky Method	4.3	3.8	-1.7
Temp. Independent (eq 4.1)	3.8	3.4	0.5

The temperature independent correction (eq 4.1) yielded the best agreement to the reference radiometer readings. The mean RMS difference of 3.8% represents about 22 W/m². The negative bias in the ATI/Michalsky corrected data was expected given the use of ambient (cooler) rather than device (warmer) temperature to correct the raw

readings. It is likely that the ATI/Michalsky technique can be changed to use a calculated approximation for device temperature that will increase the accuracy of the correction and yield results more in agreement with those of the original authors.

5.0 CONCLUSIONS

A study of over one year's data from a rotating shadowband radiometer (RSR) has revealed some of the performance characteristics of this instrument. Based on this study, the following general conclusions are drawn:

- Reliability and availability of the ATI rotating shadowband radiometer were excellent. No operator intervention, repair, or realignment was required for normal use. Regular resetting of the instrument's internal clock (accomplished via modem) was required.
- The accuracy demonstrated by the RSR is adequate for many uses, such as general purpose solar resource assessment, when integration over long periods of time (weeks, months) is performed.
- Inaccuracies inherent in the use of an uncompensated silicon detector pyranometer render the instantaneous and short-duration readings of the RSR less accurate than is normally required for precise monitoring tasks such as are needed for performance assessment of concentrating solar collectors. However, post-collection correction algorithms improve the accuracy of the data and increase the instrument's suitability for these tasks.

REFERENCES

1. LI-COR, inc. *LI-COR Radiation Sensors Instruction Manual*, 14 (1986).
2. Kinsell L. Coulson. *Solar and Terrestrial Radiation*, 94 (1975).
3. Edward C. Kern, Jr. and Miles C. Russell. Rotating Shadow Band Pyranometer Irradiance Monitoring for Photovoltaic Generation Estimation. *The Conference Record of the Twenty Second IEEE Photovoltaic Specialists Conference -- 1991*, 541 (1991).
4. J. J. Michalsky, R. Perez, R. Stewart, B. A. LeBaron and L. Harrison. Design and Development of a Rotating Shadowband Radiometer Solar Radiation/Daylight Network. *Solar Energy* **41**, 577 (1988).
5. D. R. Myers, K. A. Emery and T. L. Stoffel. Uncertainty Estimates for Global Solar Irradiance Measurements Used To Evaluate PV Device Performance. *Solar Cells* **27**, 455 (1989).
6. J. A. Duffie and W. A. Beckman. *Solar Engineering of Thermal Processes*, 55 (1980).
7. Thomas Stoffel, Carol Riordan and John Bigger. Joint EPRI/SERI Project to Evaluate Solar Radiation Measurement Systems for Electric Utility Solar Radiation Resource Assessment. *The Conference Record of the Twenty Second IEEE Photovoltaic Specialists Conference -- 1991*, 533 (1991).
8. Richard Bird. Spectral Terrestrial Solar Radiation. *Solar Resources (Hulstrom ed.)*, 309 (1989).
9. Richard E. Bird and Carol Riordan. Simple Solar Spectral Model for Direct and Diffuse Irradiance on Horizontal and Tilted Planes at the Earth's Surface for Cloudless Atmospheres. *Journal of Climate and Applied Meteorology* **25**, 87 (1986).
10. Stefan Nann and Carol Riordan. Solar Spectral Irradiance under Clear and Cloudy Skies: Measurements and a Semiempirical Model. *Journal of Climate and Applied Meteorology* **30**, 447 (1991).
11. Richard E. Bird. A Simple, Solar Spectral Model for Direct-Normal and Diffuse Horizontal Irradiance. *Solar Energy* **32**, 461 (1984).

12. Bo Leckner. The Spectral Distribution of Solar Radiation at the Earth's Surface--Elements of a Model. *Solar Energy* **20**, 143 (1978).
13. E. C. Flowers, R. A. McCormick and K. R. Kurfis. Atmospheric Turbidity over the United States, 1961-1966. *Journal of Applied Meteorology* **8**, 955 (1969).
14. K. W. Boer. The Solar Spectrum at Typical Clear Weather Days. *Solar Energy* **19**, 525 (1977).
15. J. J. Michalsky, R. Perez, R. Stewart, L. Harrison and B. A. LeBaron. Spectral and Temperature Correction of Silicon Photovoltaic Solar Radiation Detectors. *Solar Energy* **47**, 299 (1991).

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