Calibration Methods for Silicon Photodiode Pyranometers used in Rotating Shadowband Radiometers

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Abstract

Silicon photodiode pyranometers have been studied extensively for application in solar energy resource assessment instruments. An example is the LI-COR, Inc. 200SZ detector that is used in rotating shadowband radiometers. While excellent results have been achieved LI-COR, Inc. calibration methods are not fully disclosed and LI-COR's stated +/- 5% accuracy is less than desirable. This research aims to better define and improve the methodology for calibration and application of LI-COR sensors used in Irradiance, Inc. RSR2™ rotating shadowband pyranometer systems.

Keywords: Rotating shadowband radiometers, LI-COR, RSR2, beam irradiance measurements, pyrheliometers

1. Introduction

A novel, continuously sampling rotating shadowband radiometer was first developed by Ascension Technology, Inc. in the early 1990s and deployed at approximately 150 locations, mostly within the USA during the 1990s. In the late 1990s a second-generation instrument was developed and incorporated adjusting corrections to the measurements based on research that characterized the effects of air mass, angle of incidence and temperature on readings from the LI-COR™ sensor used in the instrument. Few of these instruments were manufactured, however, until Irradiance, Inc. resumed manufacturing of its RSR2™ instrument in 2007. Since that time over 300 of these field grade instruments have been deployed worldwide, principally for solar resource assessment at prospective sites for concentrating solar thermal and solar photovoltaic power plants.

2. Calibration Background

The sensors used in the RSR2 instrument are manufactured and factory calibrated by LI-COR, in Lincoln, Nebraska USA. Over 65,000 of these sensors have been deployed and they have developed a reputation as a low cost pyranometer, that require less frequent maintenance than first class pyranometers, owning mostly to less soiling on the LI-COR sensors' plastic diffuser than on the first class instruments' glass domes. They are used in rotating shadowband radiometers for this reason, but more importantly because thermopile instruments respond too slowly to implement a shade/unshade approach for direct beam solar radiation measurement. The manufacturer's calibration methods lead to measurement uncertainties (+/-5%) that are greater than desirable for solar resource assessment purposes, hence the motivation to devise better methods for calibrating and deploying these sensors.

Work conducted at Sandia National Laboratories by King et al (1998)[1] laid the ground work for the present efforts to better quantify and reduce the uncertainties. In their work the Sandia Laboratory authors conclude that with their corrections accuracy can be improved to +/- 3% for both total and beam irradiance. Irradiance, Inc. has been working to build upon these early studies for application to its RSR2™ instrument.

3. Test Setup, Data screening and Sensor calibration models

A test stand developed by Irradiance, Inc. that holds 27 LI-COR sensors has been located near the U.S. Department of Energy's Solar Radiation Research Laboratory (SRRL) at National Renewable Energy Laboratory (NREL) in Golden, Colorado USA. Each sensor is fitted with a precision 100 Ohm resistor, attached to a Campbell Scientific data logger, and sampled at 3-second intervals that are integrated to one-minute averages. Data from this test is collected by SRRL and made available online. Irradiance uses this data and that from nearby first class instruments at SRRL (also integrated one-minute averages) for its calibration study activities.

These continuous data sets are screened to select only those that meet criteria for clear skies (high direct beam irradiance), sky stability (slow changing global) and absolute air mass (~1.5). Only this limited data is used in calculating calibration coefficient values. Table 1 compares the methods prescribed by the ASTMG167 standard. The entire collection data sets (more than 14 months of data) was then used in testing the calibration methods. Several sets of 25 LI-CORs have been rotated in and out of the test platform, and two instruments have been included in all sets to provide an indication of consistency from one set to the next. Three calibration models were investigated (see below): (1) a simple linear model similar to the LI-COR factory calibration process that relates irradiance to the millivolt signal from the photodiode sensor/resistor pair, (2) the model proposed by King et al (1998) that adds corrections for temperature, absolute airmass and angle of incidence to the simple linear model, and (3) a model proposed and developed by King and Myers[2] that introduces two calibration multipliers, one relating to beam and one to diffuse irradiance.

Table 1 Comparison of calibration methods

	ASTM G167 Methodology	Irradiance / SRRL Methodology
Instrumentation	6.6 *Reference Radiometers*—Both the reference pyrheliometer or pyranometer shall not be used as a field instrument and its exposure to sunlight shall be limited to calibration or to intercomparisons.	NREL Baseline Measurement System instruments used as references.
Data Collection	Minimum 2 days	12-49 days
	10-12 series of 10-20 readings, discard less than half	7-33 series
	series lasting 10-20 minutes	continuous collection over period of test
	readings recorded every 20-30s or integration period <=2 minutes	1 minute average data
Sky Stability	No cloud formation shall be within 30° of the sun during the period that data are taken for record.	10 < Total Horizontal Irradiance < 1500 Wm^{-2}
	Direct irradiance × Cosine(Zenith) > 80% of total global irradiance	0 < Direct Beam Irradiance < 1200 Wm^{-2}
		0.8 < Direct Beam / Bird Model < 1.05

	No cloud formation shall be within 30° of the sun during the period that data are taken for record.	Total Horizontal Irradiance minute-to-minute change < 10 Wm^{-2}
	11.2.2 Limit each series to reasonably stable atmospheric conditions.	56.8° < Zenith Angle < 58.8° ($AM_a \approx 1.5$ at SRRL's 1830 meter elevation)
Multiplier Calculation Criteria	11.3.1 Eliminate from the calculation all sets which deviate from the corresponding series mean by more than 5 %. Discard any series if more than 50 % of the sets have been eliminated.	Visually review plot of multiplier vs. time. Exclude series which deviate by more than 5%

After each set of sensors is removed, the data collected are downloaded from the SRRL MIDC web site, and imported into the Data Quality Management System (DQMS)[3]. Concurrent data from both the output of the sensors, and the SRRL reference irradiance and meteorological instrumentation are included. Once imported into DQMS, the data are tested for validity. In addition to the automatic testing of data, the NREL Maintenance Database and Data Quality Statements log are checked for any events that occurred that would cause data to be excluded.

Table 2 shows the calibration events that have been performed, along with the number of days of data collection, the count of readings, and the number of series of contiguous readings.

Table 2 Calibration events in the data set

Start Date	End Date	Days	Count	Series
04/02/2009	05/07/2009	36	151	15
05/08/2009	05/19/2009	12	77	8
05/20/2009	06/28/2009	40	70	7
06/29/2009	07/14/2009	16	73	7
07/15/2009	07/26/2009	12	87	9
07/27/2009	09/01/2009	37	249	27
09/02/2009	10/04/2009	33	278	23
10/05/2009	11/22/2009	49	905	33
11/23/2009	01/07/2010	46		
01/08/2010	01/24/2010	17		
01/25/2010	02/08/2010	15	309	7
02/09/2010	03/11/2010	31	317	19
03/12/2010	04/13/2010	33	177	15
04/14/2010	05/16/2010	33	81	8
05/17/2010	06/17/2010	32	168	18
06/18/2010	07/08/2010	21	199	20

After filtering the data, the resulting dataset can be seen as the series of readings described in the ASTM Standard. These are typically periods in the morning and afternoon where the zenith angle is in the range described above.

Figure 1 shows the simple calibration multipliers (described below) versus time. This plot, with guidelines at 1%, 2% and 5% above and below the mean, is used to further identify any outlier readings which are then excluded from further calculations in accordance with the ASTM standard; values more than 5% different than the mean are excluded. Figure 2 shows the same dataset after anomalous readings have been removed. These figures emphasize the high level of screening that result from the narrow range of zenith angles accepted for calibration purposes.

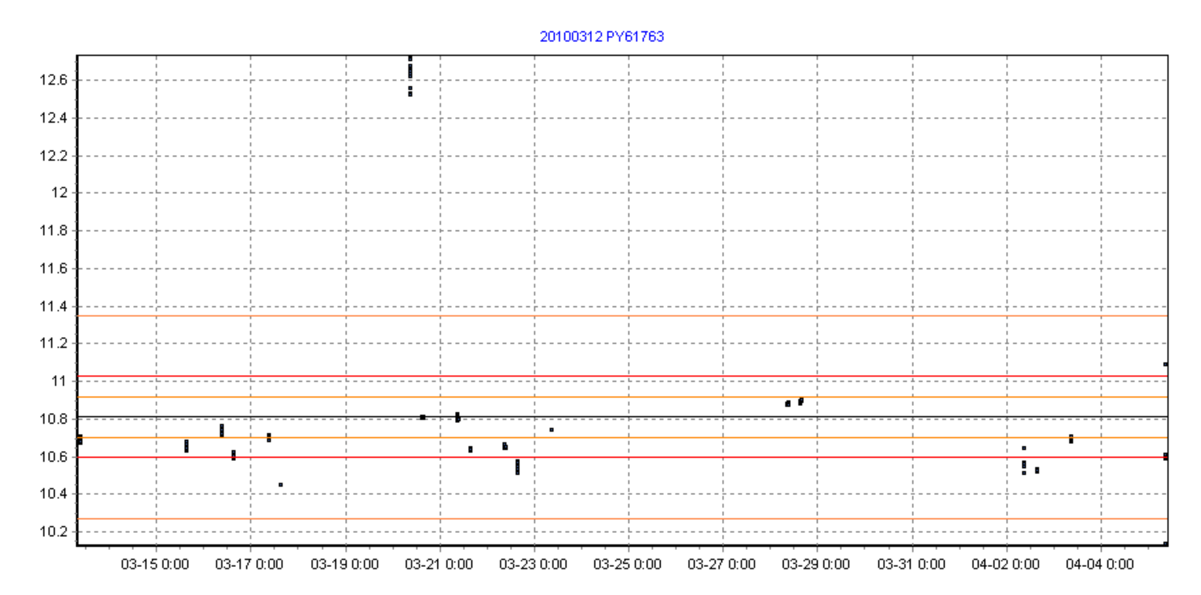

Figure 1 Data showing outliers in +/- 5% band; calibration run starting 2010-03-12.

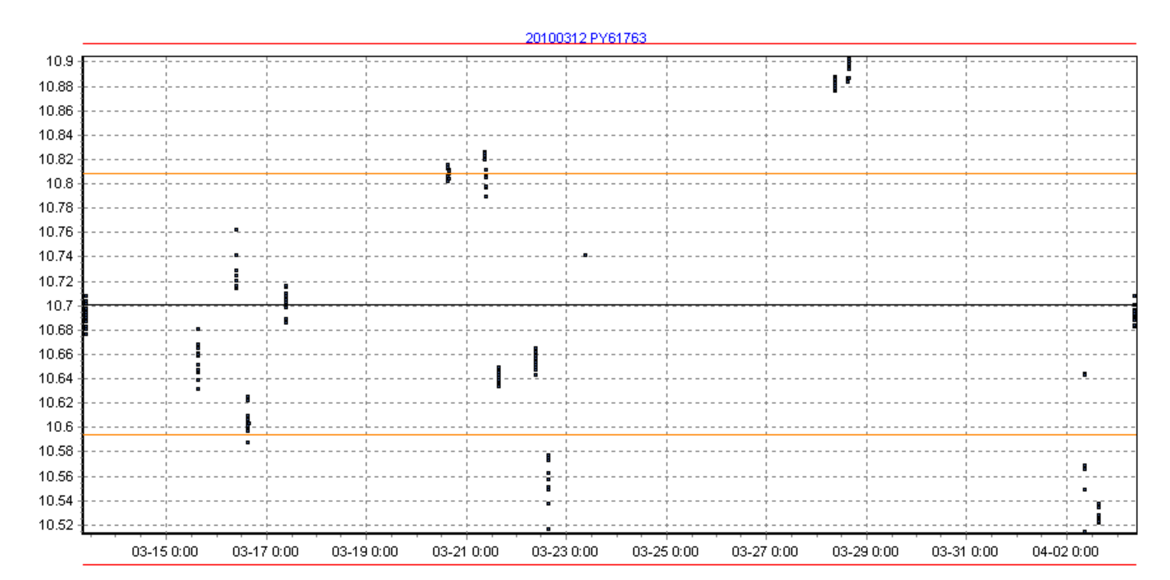

Figure 2 Data screening showing +/- 1% and +/- 2% bands, note the morning and afternoon data clusters as the airmass is passing through the nominal AM_a ~1.5 value

4. Simple linear model

A simple linear model used by LI-COR for calibrations is:

$$E_T = C_s \times R$$

Where R, the response of the sensor current through a shunt resistor, is expressed in mV, E_T is the total (global horizontal) irradiance, and C_s is a calibration coefficient determined by regression analysis of the test data. (Care needs to be taken considering these units, as the response of silicon photodiode sensors is also expressed in micro amps without assuming a shunt resistance. Irradiance, Inc. uses precision 100 Ohm resistors with its instruments, which allows an easy conversion to a voltage response.)

5. King et al (1998) model with air mass and angle of incidence corrections

$$E_T = \frac{R \times E_0 \times [1 - 0.0082 \times (T - T_0)]}{C_k \times f_1(AM_a) \times f_2(AOI)}$$

where

$$f_1(AM_a) = 0.932 + 0.05401 \times AM_a - 0.006319 \times AM_a^2 + 0.0002631 \times AM_a^3$$

$$f_2(AOI) = 1.0 + 0.0006074 \times AOI - 0.00001357 \times AOI^2 + 0.0000004504 \times AOI^3$$

and T is the ambient air temperature (C), T_0 is 25 C, AM_a is the absolute air mass, AOI is the angle of incidence (in degrees) and E_0 is a $1000\ Wm^{-2}$ reference irradiance level.

6. King and Myers (1997) two coefficient response model

$$E_T = \left\{\frac{R \times E_0 \times [1 - 0.0082 \times (T - T_0)]}{C_1 \times f_1(AM_a) \times f_2(AOI)}\right\} \times \left\{1 + k \times \left[\frac{C_2}{C_1 \times f_2(AOI)}\right]\right\}^{-1}$$

where $f_1(AM_a)$ and $f_2(AOI)$ are defined as above, k is the ratio of diffuse to total irradiance, and $C_1$and C_2 are multipliers determined by regression analysis in the calibration process.

Once calibration multipliers are calculated for each calibration event, a calibration report can be prepared. Calibration results for a sensor carried over throughout the entire period are presented in Table 3. Note that there is reasonably tight clustering of these calibration values with the standard deviations being typically under 1% of the calibration results. The King Myers C2 value relates to the contribution of diffuse sunlight to the total response of the LI-COR sensor using the King Myers method. Since the diffuse is a much smaller contributor to the total irradiance, the larger (2.8%) value of the C2 deviations is not expected to introduce absolute variations in final measurements that are larger than the under 1% variations in the other calibration constants.

Table 3 Calibration results for the same sensor over a 14 of 16 calibration events

Start Date	End Date	Simple	King	King Myers C1	King Myers C2
04/02/2009	05/07/2009	10.600	10.449	1012.9	1006.3
05/08/2009	05/19/2009	10.596	10.489	998.0	1058.4
05/20/2009	06/28/2009	10.682	10.570	1001.4	1040.7
06/29/2009	07/14/2009	10.722	10.668	993.5	1062.4
07/15/2009	07/26/2009	10.682	10.656	1001.5	998.5
07/27/2009	09/01/2009	10.676	10.620	1003.1	1004.5
09/02/2009	10/04/2009	10.681	10.590	1013.6	969.4
10/05/2009	11/22/2009	10.768	10.639	1011.7	1008.8
11/23/2009	01/07/2010				
01/08/2010	01/24/2010				
01/25/2010	02/08/2010	10.697	10.481	1019.0	1024.2
02/09/2010	03/11/2010	10.727	10.507	1012.1	1062.0
03/12/2010	04/13/2010	10.701	10.533	1009.8	1039.3
04/14/2010	05/16/2010	10.593	10.462	1002.8	1059.0
05/17/2010	06/17/2010	10.687	10.582	1007.8	1008.1
06/18/2010	07/08/2010	10.779	10.729	1001.4	1011.9
	Mean	10.685	10.570	1006.327	1025.250
	StDev	0.058	0.086	7.132	28.796

To evaluate the three calibration methods, calibration multipliers calculated for the carryover instrument, (SN PY61763) for each of the calibration events were compared. The calibration multipliers derived from each calibration event were applied to all the data collected in all the calibration events and compared with the two component total global irradiance calculated from SRRL's Kipp and Zonen CH1 pyrheliometer and shaded Eppley 8-48 pyranometer. This dataset, after removing intervals of bad data, snow and ice, and those during which sensors were being changed, contains approximately 150,000 one-minute readings (2,500 hours).

The results of this comparison are shown in the following tables. First the mean values of all the irradiance values from SRRL are compared to the mean values calculated from the test LI-COR using the three methods and calibration constants for each of the calibration events. The difference between these mean values is normalized by dividing by the mean value from the SRRL reference instruments.

Table 4 Trial results applying various calibration methods to the entire data set

(Test Mean – Ref Mean) / Ref Mean	Type		
Event	Simple	King	King Myers
20090402	0.73%	1.05%	0.98%
20090508	0.76%	0.63%	1.03%
20090520	-0.08%	-0.15%	0.03%
20090629	-0.47%	-1.12%	-0.46%
20090715	-0.08%	-1.00%	-0.94%
20090727	-0.01%	-0.69%	-0.65%
20090902	-0.05%	-0.37%	-0.71%
20091005	-1.15%	-1.01%	-0.93%
20100125	-0.22%	0.71%	0.88%
20100209	-0.54%	0.47%	0.90%
20100312	-0.33%	0.16%	0.42%
20100414	0.79%	0.92%	1.44%
20100517	-0.12%	-0.28%	-0.26%

20100618	-1.07%	-1.78%	-1.63%
Average	-0.13%	-0.18%	0.01%

Table 4 shows excellent agreement for all three calibration methods. In all cases the methods would produce results for the total insolation using LI-COR sensors over extended periods of time that are within 1% of the measurements using first class instruments. Note that the King-Myers approach on average appears to be the best of the three methods and that the King method, surprisingly, seems to be less accurate than the simple method. One advantage of the King and King Myers methodologies that is not evident in these tests and might enhance the "simple" method in this data set is that all these measurements we made at the same location. Accordingly the absolute airmass corrections in the King and King-Myer methods will not make significant differences as they might moving to higher or lower altitudes. Nonetheless, the differences are very small, indeed smaller than the uncertainties associated with first class thermopile instruments. They are significantly less than the +/- 5% shown in LI-COR's commercial specifications using LI-COR factory calibration.

Table 5 Standard Deviations of test and reference values for the entire data set

Std Dev of (Test -Ref) / Ref	Type		
Event	Simple	King	King Myers
20090402	4.8%	5.0%	4.9%
20090508	5.1%	5.3%	5.1%
20090520	4.8%	4.9%	4.9%
20090629	5.1%	5.2%	5.3%
20090715	5.1%	5.2%	5.3%
20090727	5.2%	5.3%	5.4%
20090902	5.1%	5.2%	5.5%
20091005	4.4%	4.5%	4.6%
20100125	5.0%	5.2%	5.1%
20100209	4.9%	5.0%	4.9%
20100312	4.8%	5.0%	4.9%
20100414	5.0%	5.2%	5.0%
20100517	5.2%	5.3%	5.4%
20100618	5.3%	5.4%	5.5%
Average	5.00%	5.12%	5.12%

Table 5 presents the standard deviations for the differences between the LI-COR sensor with the three calibration methods and the SRRL two-component global measurements. Here the differences are greater, suggesting that individual one-minute measurements will not track as closely as the long term mean values. Fortunately long term (insolation) values are more important for solar power system energy yield calculations than short term (irradiance) fluctuations, so these higher uncertainties in the one-minute values should not be of concern to solar power systems developers and investors.

This mostly like explanation for these deviations is the longer time constants for the SRRL thermopiles relative to the Irradiance LI-COR photodiode sensors.

7. Summary, Implementation and Ongoing Research

This work has confirmed (or exceeded) the accuracy of the LI-COR sensor as stated by its manufacturer and its utility for use in a rotating shadowband radiometer system. It has also demonstrated three calibration and utilization methods that can be applied to achieve results consistently more accurate than those supported by the LI-COR factory's calibration procedures and specifications. While the simple method produces excellent results when applied at the SRRL location, the other methods have the advantage of addressing air mass / spectral response issues encountered when using these sensors at other locations. The King-Myers methodology offers additional potential advantages for interpreting the results of shade/unshade measurements taken with rotating shadowband radiometers.

It is encouraging to note that the differences result in bias errors that are mostly under +/- 1% for the three models and that this is of the same order of magnitude as the reference instruments used in this study: two component total global derived from a direct beam measurements from a Kipp and Zonen CH1 pyrheliometer and diffuse from a shaded Eppley 8-48 pyranometer.

Irradiance, Inc. is continuing to use the (1998) King model for its deployed RSR2™ instruments as the best documented method for application. Ongoing work is focused on understanding the impact of thermopile instrument time constants on calibration procedures and refinement of a King-Myers 2-Component model for implementation in a future release of the RSR2™ program code.

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[3] Developed and supported by Augustyn & Company, (http:www.solarcat.com)