Improved Methodology to Measure Normal Incident Solar Radiation with a Multi-Pyranometer Array

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Abstract

An improved methodology to estimate the normal incident solar radiation based on an anisotropic clear sky model using a Multi-Pyranometer Array (MPA) is analyzed in this paper. The MPA is a static platform, which is used to measure solar energy irradiation at different tilt and azimuth angles, and that can be used to estimate the normal incident component without the tracking devices that require more detailed installation and maintenance. The array’s sensors are of the photovoltaic type, which require both the spectral and incidence angle corrections. These corrections were made by empirical functions; the one for the incidence angle is generic and the spectral effect is satisfied by calibrating each of the sensors with a Precision Spectral Pyranometer (PSP) with a four parameter change-point linear function. For this study, the calibrated data was verified by calculating their corresponding theoretical value based on the beam component from solar tracking Normal Incidence Pyrheliometer (NIP) and the diffuse component from a Black and White Pyranometer (B&W), which were located on the same test bench.

The improved procedure is based on grouping the measurements of two sensors and analytically look for a satisfactory solution; one for the horizontal and south sensors and one for the east and west sensors. The solution for the east and west sensors is expanded to two new solutions by mirroring their readings according to the solar noon; each real measurement and its mirrored values generate a solution. The solutions are grouped to have a more steady and robust expression. A final switching scheme provides the value that was compared with the reference NIP measurement. The analysis of the results showed that the root square mean error (RMSE) of the sample decreased by a 30% in comparison with previous results reported in the literature. The data sample used in this study correspond to clear sky conditions on the fall and winter seasons, so further comparison on other seasons and with regular solar conditions is required.

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1. Introduction

Solar energy is a renewable and plentiful resource that has been widely used, every day more, in numerous applications; some of those using the total extend of the resource and others that require just its main components—as the direct one. The measurement of the solar resource provides and validates the potential of any solar application. Global solar radiation can be measured by using a pyranometer based on thermopile or photoelectric detectors. However, the measurements of the direct and diffuse components required of extra equipment, such as a solar tracker to follow the sun path and the solar shading. In general a precision Normal Incidence Pyrheliometer (NIP) is fixed on a tracker to obtain the direct normal component of the irradiation. The diffuse component is measured by shading a pyranometer using shade disk, either installed on the tracker or with a shadow band. This procedure is accurate if the tracker can precisely track the sun. But there exist some drawbacks to this approach: high cost of the sensors and the adjacent devices, and regular maintenance of the mechanical tracking system.

Nomenclature

- \( I_{b,n} \) Normal incident beam irradiation (W/m²)
- \( I_d \) Diffuse component solar irradiation (W/m²)
- \( I_T \) Total solar irradiation (W/m²)
- \( R_b \) Beam component geometric factor
- \( R_d \) Diffuse component geometric factor
- \( R_r \) Reflective component geometric factor
- \( \theta \) Incidence angle of beam radiation
- \( \beta \) Collector tilt angle
- \( \gamma \) Azimuth angle
- \( \delta \) Declination
- \( \phi \) Latitude
- \( \lambda \) Generic indicator for any tilted surface in the MPA
- \( \rho \) Ground reflectance
- \( \omega \) Hour angle

Subscripts
- \( h \) Horizontal surface
- \( s \) South facing tilted surface
- \( se \) East of south facing tilted surface
Total radiation measured on the west of south facing tilted surface (W/m²)

Therefore, under the opportunity of having a less expensive, equally robust and almost free maintenance devices, some ideas are burst forth to indirectly measure beam and diffuse components of solar irradiance. A Multi-Pyranometer Array (MPA) is one of them, which was originally developed approximately 30 years back, Hämäläinen et al. [1] developed an instrument, which included 25 solar radiation sensors mounted on a metal hemisphere. Since then, many other have further studied how to simplify the instruments and to improve the accuracy of the calculation methodology. Faiman et al. [2] refined the number of the sensors to be four and discussed the practical application issues about using a MPA system and described a calculation method [3, 4]. Curtiss, [5] investigated different diffuse sky models as well as ground reflectance models in the methodology analysis. Munger [6] added an artificial horizon to eliminate the effect from the ground reflection and develop a spectral correction for photovoltaic-type solar sensor, and using similar approach, a number of solutions for switching schemes was presented by Miloslaw [7]. However, those methods still cannot provide high accuracy for the whole estimation period and the methods still present significant mathematical disturbance.

2. Measurement Test Rig Setup

The solar irradiance measurement sensors and the other supplementary devices are installed on the roof of Langford Architecture building at Texas A&M University, College station campus. The location is within the defined climatic zone two with hot and humid summers. The test rig consists of several pyranometers, a couple of Normal Incidence Pyrheliometers (NIP) mounted on a solar tracker, a Multi-Pyranometer Array (MPA) and some other meteorological sensors. Fig. 1 shows the overall view of the test rig and the MPA set used for this study.

The MPA consists of four pyranometers with photovoltaic sensor: one sensor mounted in a horizontal plane, and three others tilted 40 degrees and distributed in azimuth angles of -60, 0, and 60 degrees – toward southeast, south and southwest, respectively. A metallic band around the MPA is used as an artificial horizon to block the ground reflected irradiation.

Fig. 1. (a) Solar test rig overall view and (b) MPA set used for this study
3. Calibration of Sensors

The MPA’s sensors are the photovoltaic-type that in general are not as accurate as the thermopile-type pyranometers as the Precision Spectral Pyranometers (PSP), due to the narrow band of light spectrum that they detect, but they are priced at a fraction of its cost. To calibrate the MPA’s sensors they are positioned on a flat horizontal plate close to the PSP reference during approximate a month. In that period, the recorded measurements of the existing five clear-sky days in the period were analyzed and compared. Fig. 2 shows the relationship between the spectral pyranometer (PSP) measured data and the photovoltaic-type sensors 1 through 4, respectively. Four parameter change-point models ($f_1$) can well represent the correlation of the each sensor. Besides the spectral adjustment, the angle of incidence correction is determined by the cosine correlation ($f_2$) through the following equation (Miloslaw [7]):
\[
f_2 = -0.0000004504 \cdot \theta^3 - 0.00001357 \cdot \theta^2 + 0.0006074 \cdot \theta + 1 \quad (1)
\]

And the calibrated tilted solar irradiance \(I_{\text{corr}}\) is expressed as a function of the tilted one as follows:

\[
I_{\text{corr}} = f_1(I_t) \cdot f_2^{-1} \quad (2)
\]

the function \(f_1\) is the change-point model fitted for each of the MPA sensor.

4. Improved Methodology for the Estimation of the Normal Incident Solar Radiation.

In any surface the total incident solar radiation has three components: direct beam, sky diffuse and reflection from the ground. Considering that the reflection portion can be ignored by the integration of an artificial horizon in the MPA, the incident global solar radiation on each of its surfaces can be expressed by the following equations (3) to (6), for horizontal, toward southeast, south and toward the southwest surfaces, respectively.

\[
I_{T,h} = I_{b,n} \cdot R_{b,h} + I_{d,h} \quad (3)
\]

\[
I_{T,se} = I_{b,n} \cdot R_{b,se} + I_{d,h} \cdot R_{d,se} \quad (4)
\]

\[
I_{T,s} = I_{b,n} \cdot R_{b,s} + I_{d,h} \cdot R_{d,s} \quad (5)
\]

\[
I_{T,sw} = I_{b,n} \cdot R_{b,sw} + I_{d,h} \cdot R_{d,sw} \quad (6)
\]

where all the beam and diffuse coefficients \((R_b \text{ and } R_d)\) can be found by the expression in the Appendix A

Many solutions can be derived from the four equations above to estimate the normal incident and diffuse solar radiation, for example Miloslaw [7] determined three solutions and a switching scheme for choosing an optimal solution, but his results were not consistent and presented significant deviations. The inconsistencies are amplified by a small errors introduced from the measurements. In this study it was found that the measurement error can be overcome by a calibration method, which was described in section 3, and the amplification effect is reduced by a selection and a combination of alternative solutions. The improved proposed methodology is summarized next:

The normal incident solar radiation is estimated by grouping the equations for the MPA sensors, horizontal and south, through equations (3) and (5).

\[
I_{bn,hs} = \frac{I_{T,h} \cdot R_{d,s} - I_{T,s} \cdot R_{b,h}}{R_{b,h} \cdot R_{d,s} - R_{b,s}} \quad (7)
\]
Similar equations for the normal incident solar radiation, using equations (4) and (6), can be derived using the measurement for the sensor toward southeast and its mirrored values, equation (8). In the mirrored equation, the coefficients \((R_{b,se}'\) and \(R_{d,se}'\)) and the measurements are with the angles for the opposite position according to the solar noon

\[
I_{bn,ew} = \frac{I_{T,se} \cdot R_{d,sw} - I_{T,sw} \cdot R_{d,se}}{R_{b,se} \cdot R_{d,sw} - R_{b,sw} \cdot R_{d,se}} 
\]

(8)

In a same way, other expression using the measurements of the sensor toward the southwest and its mirrored can be determined.

\[
I_{bn,we} = \frac{I_{T,sw} \cdot R_{d,se} - I_{T,se} \cdot R_{d,sw}}{R_{b,sw} \cdot R_{d,se} - R_{b,se} \cdot R_{d,sw}} 
\]

(9)

From these expressions, and to minimize the impact of the amplification effect, another alternative solution is realized through a relationship of the sum of the numerators and denominators of both the equations (8) and (9)

\[
I_{bn} = \frac{I_{T,se} \cdot R_{d,sw} - I_{T,sw} \cdot R_{d,se} + I_{T,sw} \cdot R_{d,se} - I_{T,se} \cdot R_{d,sw}}{R_{b,sw} \cdot R_{d,sw} - R_{b,sw} \cdot R_{d,se} + R_{b,sw} \cdot R_{d,se} - R_{b,se} \cdot R_{d,sw}} 
\]

(10)

The selection of the more suitable solution for a clear–day sky would be the one that correspond to the maximum denominator of either equation (7) or (10).

5. Results Analysis.

Fig. 3 shows the measured MPA data and the reference NIP measurements for three selected complete clear-sky days. In Fig. 4 a comparison between the estimated normal incident solar radiation and the corresponding measured value.
It is observed in the Fig. 4 that the differences between the measured and estimated values of the normal incident solar radiation is still significant in certain conditions and time of the day, but the results are not diverging and in general follow the pattern expected for a clear-sky day. More clear days have been analysed and the results are very similar. A deeper analysis is underway to eliminate the small instabilities yet present in this methodology.

6. Conclusion

This paper presented an improved methodology to estimate the normal incident solar radiation though a multi-pyranometer array (MPA), which represent a cost fraction of a traditional tracking measurement device. The photovoltaic sensors in the MPA are bound to the narrow spectrum band and cosine of the incidence angle factors, which made necessary both spectral and incidence angle corrections. The incidence angle correction was referred to an empirical correction equation, and the spectral correction is improved using a four parameter change-point model to fit the relationship between each individual sensor and a PSP.

The model for disaggregating beam and diffuse components is based on an anisotropic sky considerations and an improved methodology was illustrated base on the possible solutions that could be generated from the representative equations for a main pair of photovoltaic sensors in the MPA. The estimation of the normal incidence solar radiation for clear days conditions have shown high reliability. The total difference between the normal incident solar radiation between the MPA estimated and the measured for the testing period is 4%, and the CV-RMSE is around 14% (RMSE equal to 43 W/m²). These variations are little better than the ones reported on Maxwell et al. [9], but the size of our sample is much smaller than theirs because in this study only clear sky conditions have been considered, so more tests for different sky conditions need to be addressed and longer testing periods to confirm the stability of the methodology.

References

Appendix A. Solar energy Expressions for the Sensor of the Multi-Pyranometer Array

The total solar radiation incident upon the horizontal MPA sensor can be estimated directly from the following expression

\[ I_{T,h} = I_{b,n} \cdot R_{b,h} + I_{d,h} \]  \hspace{1cm} (A1)

Similar expression for the total solar radiation incident upon the surfaces of the MPA toward south, southeast and southwest are respectively presented next

\[ I_{T,se} = I_{b,n} \cdot R_{b,se} + I_{d,h} \cdot R_{d,se} + I_{T,h} \cdot \rho \cdot R_{r,se} \]  \hspace{1cm} (A2)

\[ I_{T,s} = I_{b,n} \cdot R_{b,s} + I_{d,h} \cdot R_{d,s} + I_{T,h} \cdot \rho \cdot R_{r,s} \]  \hspace{1cm} (A3)

\[ I_{T,sw} = I_{b,n} \cdot R_{b,sw} + I_{d,h} \cdot R_{d,sw} + I_{T,h} \cdot \rho \cdot R_{r,sw} \]  \hspace{1cm} (A4)

The corresponding beam coefficient for each of the surfaces included in the MPA is

\[ R_{b,\lambda} = \cos(\theta_{i,\lambda}) \]  \hspace{1cm} (A5)

where, \( \lambda \), indicates any surface in the MPA. The diffuse coefficients are calculated based on the Temps-Coulson [8] model and are expressed for each tilted surfaces as

\[ R_{d,se} = \frac{1 + \cos(\beta_{se})}{2} \cdot [1 + \sin^3(\frac{\beta_{se}}{2})][1 + \cos^2(\theta_{i,se}) \cdot \sin^3(\theta_{i,h})] \]  \hspace{1cm} (A6)

\[ R_{d,s} = \frac{1 + \cos(\beta_{s})}{2} \cdot [1 + \sin^3(\frac{\beta_{s}}{2})][1 + \cos^2(\theta_{i,s}) \cdot \sin^3(\theta_{i,h})] \]  \hspace{1cm} (A7)
\[ R_{d,sw} = \frac{1 + \cos(\beta_{sw})}{2} \cdot [1 + \sin(\beta_{sw})\sin^3(\theta_{i,h})] \]

(A8)

The incidence angles in the horizontal surface for the any time interval is are terminated by

\[ \cos(\theta_{i,h}) = \cos(\phi)\cos(\delta)\cos(\omega) + \sin(\phi)\sin(\delta) \]

(A12)

and for the any other MPA surfaces by the following expression

\[ \cos(\theta_{i,\lambda}) = \sin(\delta)\sin(\phi)\cos(\beta_{\lambda}) - \sin(\delta)\cos(\phi)\sin(\beta_{\lambda})\cos(\gamma_{\lambda}) \]
\[ + \cos(\delta)\cos(\phi)\cos(\beta_{\lambda})\cos(\omega) \]
\[ + \cos(\delta)\sin(\phi)\sin(\beta_{\lambda})\cos(\gamma_{\lambda})\cos(\omega) \]
\[ + \cos(\delta)\sin(\beta_{\lambda})\sin(\gamma_{\lambda})\sin(\omega) \]

(A13)