Spectral Error Analyses of Pyranometers Composed of Multiple Photodiodes

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In order to develop a cheap, stable, and high performance pyranometer, we propose the dual sensor pyranometer which measures the irradiance based on the outputs from two kinds of photodiodes. The first photodiode detects the short wavelength range of the irradiance, and the other detects the long wavelength range of the irradiance. To evaluate only the spectral error in pyranometer composed of photodiodes, the method to calculate outputs from each photodiode was developed. As the result, the spectral error in "Si+InGaAs" of the dual sensor pyranometer was smaller than that in the single Si pyranometer.

Keywords: Irradiance, Pyranometer, Spectral Response, Sensitivity Factor, Spectral Error

INTRODUCTION

In order to evaluate the Photovoltaic (PV) system and estimate the amount of power generation, the irradiance data is the most important factor. Thus, it is necessary to measure it precisely. So far, thermopile-based pyranometer is widely used in the PV field. However, since a thermopile-based pyranometer is very expensive as well known and its sensitivity degrades somewhat with time, it is inappropriate for a long time measurement and applying for large number of sites or modules. In order to solve these problems, the pyranometer which is installed a silicon photodiode (single Si pyranometer) has been used. Its spectral response, however, strongly depends on wavelength and does not cover whole solar spectrum. Therefore, the single Si pyranometer cannot measure the irradiance precisely like the thermopile-based pyranometer because a spectral miss match error arises strongly. In consequence, the development of a cheap, stable, and high performance pyranometer base on the new idea is required greatly now, particularly in PV Field.

The purpose of this study aims to the development of the dual sensor pyranometer which is composed of two kinds of photodiodes, which are for both short- and long- wavelength range measurements.

At the present day, the required data has been collected in the open air. However, output voltages from each photodiode measured in the open air muddle directional, temperature, spectral error and the others at same time. Therefore, only the spectral error of the dual sensor pyranometer cannot be evaluated precisely. In this study, the irradiances are estimated by the using output voltages from each photodiode. They are calculated by multiplying the spectral irradiances, absolute spectral response, receiving area of each photodiode and a shunt resistance. Then, the method to evaluate only the spectral error and the result calculated the spectral error independently are described in this paper.

THE DUAL SENSOR PYRANOMETER

Construction

The purposed dual sensor pyranometer produces the irradiance on the outputs from both Si Photodiode that responses from 300 nm to 1100 nm of wavelength and InGaAs Photodiode that responses from 900 nm to 1700 nm of wavelength. In our new dual sensor pyranometer, it is necessary to achieve measurement error within ± 0.01 kW/m^2 compared with the thermopile-based pyranometer. Moreover, GaAsP Photodiode, which responses in the short wavelength range, is introduced instead of the Si photodiode because the maximum of spectral sensitivity for the GaAsP photodiode is closer to that of solar spectrum. That is two combinations, which are "Si+InGaAs" and "GaAsP+InGaAs" for comparison.

Fig. 1 shows relative spectral responses of the Si, InGaAs and GaAsP photodiode compared to Reference Solar Radiation.

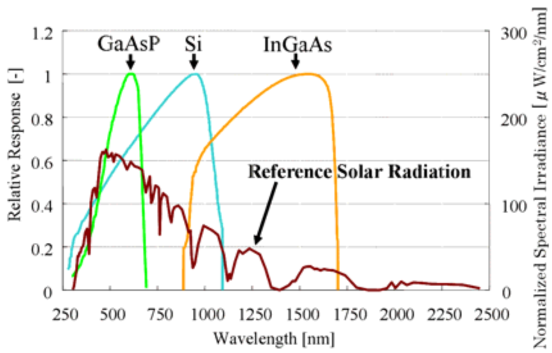

Fig. 1. Relative spectral responses of the Si, InGaAs and GaAsP photodiode and Reference Solar Radiation.

Irradiance and Sensitivity factor

The irradiance obtained from the dual sensor pyranometer is calculated by

$$G_{Dual} = \mathrm{K}_{\mathrm{Si}} \times E_{Si} + \mathrm{K1}_{\mathrm{InGaAs}} \times E_{InGaAs} \qquad (1)$$

or

$$G_{Dual} = \mathrm{K}_{\mathrm{GaAsP}} \times E_{GaAsP} + \mathrm{K2}_{\mathrm{InGaAs}} \times E_{InGaAs}, \qquad (2)$$

where G_{Dual} [kW/m^2] represents the global irradiance, K_{Si}, K_{GaAsP}, $K1_{InGaAs}$ and $K2_{InGaAs}$ [kW/m^2/mV] represent the sensitivity factors to transfer from the output voltage to the irradiance. Moreover, E_{Si}, E_{GaAsP} and E_{InGaAs} [mV] represent the output voltages from each photodiode. They are usually measured in open air and used as data.

In the next place, the calibration method to determine the sensitivity factors is the following explanation. It is to determine them based on spectral irradiance measured by spectroradiometer [1]. In fact, the sensitivity factors are calculated by equation (3), (4), (5) and (6) from the data measured on one clear day.

• Si+InGaAs

$$K_{Si} = \frac{\left\{\sum_{300}^{1000}(I_\lambda \times \Delta\lambda)\right\}}{E_{Si}} \qquad (3)$$

$$K1_{InGaAs} = \frac{\left\{\sum_{1000}^{2500}(I_\lambda \times \Delta\lambda)\right\}}{E_{InGaAs}} \qquad (4)$$

• GaAsP+InGaAs

$$K_{GaAsP} = \frac{\left\{\sum_{300}^{680}(I_\lambda \times \Delta\lambda)\right\}}{E_{GaAsP}} \qquad (5)$$

$$K2_{InGaAs} = \frac{\left\{\sum_{680}^{2500}(I_\lambda \times \Delta\lambda)\right\}}{E_{InGaAs}} \qquad (6)$$

Where: I_λ [μW/cm^2/nm] represents the spectral irradiance measured by the spectroradiometer; Δλ [nm] represents one nanometer interval. Therefore, the numerators for each equation represent the wavelength ranges of the spectral irradiance coverd by each photodiode.

METHOD

Problems for measurement in the open air and its improvement

An advantage of the dual sensor pyranometer is decreasing the spectral error caused by the non-flat spectral response compared with single Si pyranometer. This idea results in that more precise measurement is possible.

However, the spectral error analysis for each pyranometer is very difficult because irradiances are calculated by using the output voltages which include directional, temperature, spectral error and the others at same time in the open air as shown Fig. 2 [2].

Therefore, we proposed a method that irradiances are estimated by using the output voltages from each photodiode which are calculated by multiplying the spectral irradiances, absolute spectral response, receiving area of each photodiode and a shunt resistance as equation (7). The main error in the calculated irradiances is only spectral error caused by the spectral miss match. Then, the spectral error analysis for each pyranometer is possible independently compared with the reference value of the thermopile-based pyranometer [3].

$$E_{estimate} = \left\{\sum_{\lambda 1}^{\lambda 2}(I_\lambda \times \Delta\lambda)\right\} \times S \times R \qquad (7)$$

Where: $E_{estimate}$ [mV] represents the calculated output voltage from each photodiode based on spectral irradiance measured by spectroradiometer; λ1 [nm] represents the starting wavelength of spectral response for each photodiode; λ2 [nm] represents the ending wavelength of spectral response for each photodiode; S [mm^2] represents receiving area of each photodiode; R [Ω] represents a shunt resistance.

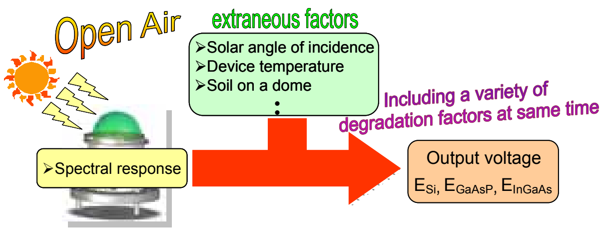

Fig. 2. Including a variety degradation factors in open air.

Spectral Error Analysis

In order to evaluate the spectral error in the pyranometer, the estimated output voltages from each photodiode ($E_{estimate}$) were calculated by equation (7) on the data of both typical cloudless five days and three cloudy days as shown in Table 1. The irradiances which are from single Si pyranometer and two prepared dual sensor pyranometers were calculated by applying the obtained output voltages to the equation (1), (2) and (3). In this regard, however the Sensitivity factors of each pyranometer shown in Table 2 are determined from the data measured on clear day, April 6, 2005. Mean Bias Error (MBE) in a unit of W/m^2, Root Mean Square Error (RMSE) in a unit of W/m^2 and the improvement rate (IR) from single Si pyranometer in a unit of % are calculated by equation (8), (9) and (10) as the index.

Table 1. Used data for evaluating the spectral error in the pyranometer.

	Year/month/day
Fine day	2003/4/22, 2004/10/1, 2004/12/16, 2005/3/31, 2005/4/6
Cloudy day	2003/7/22, 2003/8/28, 2005/5/20

Table 2. Sensitivity factors for each pyranometer.

			K [kW/m^2/mV]
Dual Sensor Pyranometer	Si+InGaAs	Si	0.572
		InGaAs	0.071
	GaAsP+InGaAs	GaAsP	0.889
		InGsAs	0.156
Single Si Pyranometer			0.762

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(G - G_{ref}\right) \quad (8)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(G - G_{ref}\right)^2} \quad (9)$$

Where: G represents the global irradiance of the single Si pyranometer or the dual sensor pyranometer; G_{ref} represents the global irradiance of thermopile-based pyranometer; N represents the number of data.

$$IR = \frac{RMSE_{Si} - RMSE_{Dual}}{RMSE_{Si}} \times 100 \quad (10)$$

Where: $RMSE_{Si}$ and $RMSE_{Dual}$ represent the values for the calculated RMSE of the single Si pyranometer and the dual sensor pyranometer, respectively.

EVALUATION RESULTS

Fig. 3 shows the spectral error distribution from the thermopile-based pyranometer in each pyranometer on five clear days. As time is running out during the day, the error distribution doesn't change, excluding a solar angle dependent error in irradiance measurements. Therefore, only the spectral error in the pyranometer is extracted by the proposed method.

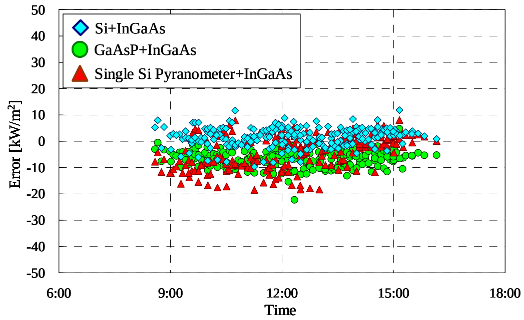

Fig. 3. Spectral error distribution of each pyranometer on five clear and three cloudy days.

Table 3. Value of evaluation index for each pyranometer on five clear and three cloudy days.

		MBE [W/m^2]	3σ [W/m^2]	RMSE [W/m^2]
Si+InGaAs	Fine	2.0	11.0	4.0
	Cloudy	-3.0	20.0	7.0
GaAsP+InGaAs	Fine	-7.0	10.0	7.0
	Cloudy	-14.0	15.0	15.0
Si Pyranometer	Fine	-4.0	20.0	8.0
	Cloudy	17.0	27.0	19.0

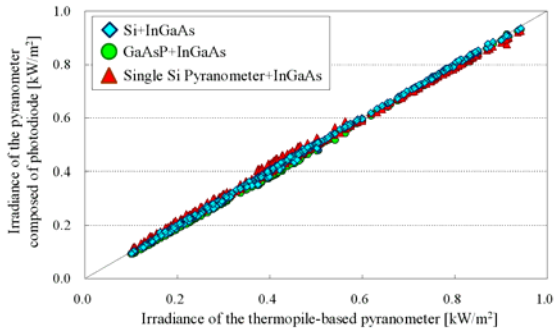

Fig. 4. Correlation of irradiances between the thermopile-based pyranometer and each pyranometer on five clear and three cloudy days.

Table 3 shows MBE, 3σ and RMSE for each pyranometer, then Fig. 4 shows the correlation of irradiances measured by the thermopile-based pyranometer and each pyranometer on five clear and three cloudy days.

As a result, the spectral error of cloudless days was improved 49 % for "Si+InGaAs" compared with the single Si pyranometer. Moreover, that of the cloudy days was improved 62 % for "Si+InGaAs" compared with the single Si pyranometer. The spectral errors calculated as absolute value are 7.0 W/m^2 per 1000 W/m^2 of the irradiance in the cloudless days and 13.0 W/m^2 per 500 W/m^2 in cloudy days and suggest the spectral errors in "Si+InGaAs" are small relatively.

In the next place, same analysis was conducted for more data than those used in the Table 1. Table 4 shows MBE, 3σ and RMSE for each pyranometer. Then, Fig. 5 shows the correlation of irradiances measured by the thermopile-based pyranometer and each pyranometer on more clear and cloudy days.

Table 4. Value of evaluation index for each pyranometer on more clear and cloudy days.

		MBE [W/m^2]	3σ [W/m^2]	RMSE [W/m^2]
Si+InGaAs	Fine	1.0	24.0	8.0
	Cloudy	2.0	21.0	7.0
GaAsP+InGaAs	Fine	-9.0	19.0	11.0
	Cloudy	-14.0	16.0	15.0
Si Pyranometer	Fine	-4.0	22.0	8.0
	Cloudy	19.0	27.0	21.0

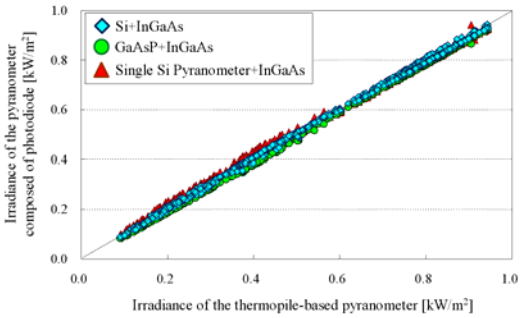

Fig. 5. Correlation of irradiances between the thermopile-based pyranometer and each pyranometer on more clear and cloudy days.

Consequently, the spectral error of cloudless days wasn't improved for "Si+InGaAs" compared with the single Si pyranometer as well as results in Table 1. However, that of the cloudy days was also improved 65% for "Si+InGaAs" compared with the single Si pyranometer as well as results in Table 1. Alternatively, the spectral error in the single Si pyranometer is big for either clear or cloudy day if its sensitivity factor is fixed.

On the other hand, the spectral error in "GaAsP+InGaAs" was a small improvement or not a improvement compared with the single Si pyranometer in both the cloudless and the cloudy days. This reason is considered that both photodiodes in this dual pyranometer has no sensitive wavelength range in between 680 nm and 900 nm.

CONCLUSION

In order to evaluate only the spectral errors in pyranometer composed of photodiode, we proposed a method that irradiances are estimated by using the output voltages from each photodiode which are calculated by multiplying the spectral irradiances, absolute spectral response, receiving area of each photodiode and a shunt resistance.

When the developed method is applied to five clear and three cloudy days, the spectral error in "Si+InGaAs" was improved 49 % for five cloudless days and 62 % for three cloudy days respectively compared with the single Si pyranometer. On the other hand, the spectral error in "GaAsP+InGaAs" was a small improvement on five clear and three cloudy days. This reason is considered that both photodiodes in this dual pyranometer has no sensitive wavelength range in between 680 nm and 900 nm.

Fig. 6. Picture of experimental equipments for the development of the dual sensor pyranometer

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