The Measurements and Estimation of In-plane Irradiation

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ABSTRACT: It is necessary to identify diffuse and direct components from horizontal global irradiation in order to estimate in-plane irradiation where in-plane irradiation itself has not been measured. Some models for estimating the diffuse irradiation from the global irradiation by using relationship between diffuse and circumsolar irradiance have been already proposed by many authors and are often used. However, most of such models sometimes show significant errors that are caused by variable sky condition in their estimation particularly at partial cloud and fluctuation. The purpose of this study is to develop a simplified model for estimating the diffuse fraction. The author's utilizes the time series analysis of minute global irradiation data instead of a simple regression analysis.
Keywords: In-plane Irradiation – 1: Solar Radiation – 2:Pyranometer – 3

1. INTRODUCTION

In-plane irradiance is defined as the sunlight that illuminates tilt plane surface. The measurement of in-plane irradiance is important for the evaluation of solar energy utilization, but very limited sites can measure In-plane Irradiance. While only the horizontal irradiation is available, it is necessary to identify scattered component and direct one in order to know in-plane irradiation on an arbitrary tilt angle. In adition, it is impossible to measure irradiance incidents from various directions with several pyranometers from the cost point of view. Then, In-plane Irradiation can be calculated through this intermediate procedure. All the time, both components are changing due to ever-changing clouds. Even if the measured levels of horizontal irradiation are the same, especially in the range of medium irradiance, it does not assure that both the components are the same. It often gives different in-plane irradiance levels. Therefore, it is difficult to calculate the In-plane Irradiation correctly by using existing method. Some models for estimating Scattered Irradiation from the Horizontal Irradiation by using relationship between scattered and direct irradiation have been already proposed by many authors and are often used [1][2]. However, most of such models show errors that is caused by variable sky condition in their estimation at partially cloudy and fluctuation. It is difficult to understand variable scattering sky conditions as far as ordinary hourly data used. In late years, solar irradiance is measured by personal computer automatically and can be easily transformed by model calculation. On the basis of that background, the authors proposes a new approach, in which minutely measured irradiance is used for identifying the condition of cloud distribution through time series analysis. This paper is intended to prove the validity of thus new model that can estimate scattered Irradiance and to compare it with existing model.

2. THEORY AND METHOD

2. 1 Measurements and Instruments

One-minute sampled data have been obtained with the measurement facilities installed on the top of a building at Koganei Campus. Horizontal Irradiance and Scattered Irradiance have been monitored with EKO MS-801 pyranometer and EKO pyranometer with shadow-ball in our University (35° 696'N, 139° 52'E). In addition, In-plane Irradiance at an incline of 35 degrees has been monitored with EKO pyranometer.

2. 2 Relationship between Scattered Component Ratio and Clearness Index

Figure 1 illustrates a relationship between *Scattered Component Ratio* (Scattered Irradiance / Horizontal Irradiance) and *Clearness Index* (Horizontal Irradiance / Extraterrestrial Irradiance). The graph shows scattered data look very different. Therefore, it is difficult to make a simple model for estimating a *Scattered Component Ratio* from a *Clearness Index*.

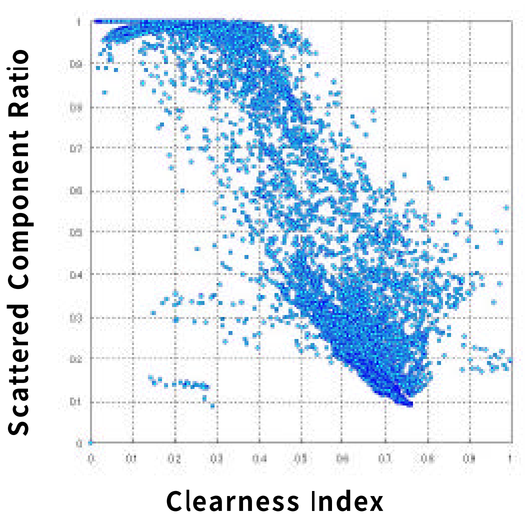


Figure 1: Relationship between *Scattered Component Ratios* and *Clearness Indices*

2. 3 Separation of sky condition from Clearness Index

There are high scatterations each other. It is difficult to make a simple model for estimating a *Scattered Component Ratio*. But setting a classification for sky condition, it is available to make a model that can estimate *Scattered Component Ratio* correctly. In addition, "*Moving Function*

(*MF*)", which is determined by "*Moving Average* (*MA*)" and "*Moving Difference* (*MD*)", has been settled that is a parameter of the model. To obtain an information of weather condition to separation, the "*Moving Function* (*MF*)" was defined. At first, we settled the "*Moving Average* (*MA*)". *MA* is described for *Clearness Index Z (t)* as Eqn. 1. In addition, Figure 2 shows how to calculate *Moving Function* from *Clearness Index*.

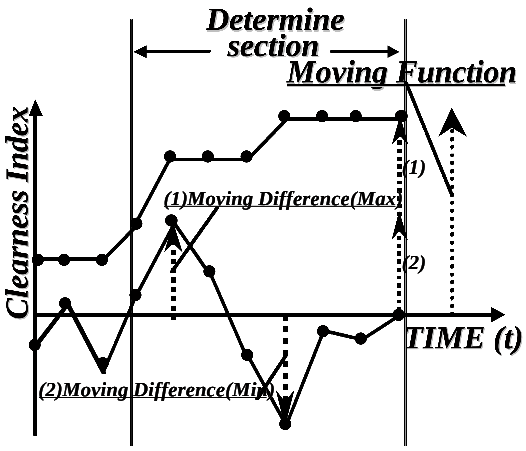


Figure 2: How to calculate *Moving Function* from *Clearness Index*.

$$MA(t) = \frac{1}{DS+1}\sum_{s=0}^{DS} Z(t-s) \qquad (1)$$

Z (t): *Clearness Index* *DS*: *Determine Section*

"*Moving Difference* (*MD*)" is the difference from *MA* at that time. Then, total number of Maximum *MD* and Minimum *MD* is *Moving Function* (*MF*) in the Determine Section (several minutes).

The conditions of not less 8.0 of *Clearness Index* and not over 4.0 are so stable that we can use only *Clearness Indices* to separate the classes.

Models for stable sky condition are as follows:

$S = 0.35$ if $Z > 0.8$

$S = -0.5414 \times Z^2 + 0.154 \times Z + 0.9835$ if $Z < 0.4$

where Z is *Clearness Index*, S is *Scattered Component Ratio*.

The other parties, sky conditions are not so stable. Therefore, it is important to use the "*Moving Function* (*MF*)" additionally. Models for not stable sky condition are as follows:

$0.4 < Z < 0.6$

$S = -0.8537 \times Z + 0.7427$ if $MF < 0.045$

$S = -1.1342 \times Z + 1.0581$ if $0.045 < MF < 0.06$

$S = -1.8807 \times Z + 1.4513$ if $0.06 < MF < 0.1$

$S = -0.8537 \times Z + 0.7427$ if $0.1 < MF < 0.19$

$S = -1.8807 \times Z + 1.4513$ if $0.19 < MF$

$0.6 < Z < 0.8$

$S = -0.8604 \times Z + 0.7505$ if $MF < 0.035$

$S = -0.8687 \times Z + 0.8341$ if $0.035 < MF < 0.06$

$S = -0.8154 \times Z + 0.8185$ if $0.06 < MF < 0.1$

$S = -0.8604 \times Z + 0.7505$ if $0.1 < MF < 0.15$

$S = -0.8154 \times Z + 0.8185$ if $0.15 < MF$

where *MF* is *Moving Function*.

Our model is based on the fact that time series *MF* provides the information of weather condition. Measuring the Horizontal Irradiance data that is monitored at one-minute intervals, we can estimate Scattered Irradiance at the same time by using that model (named "*Time-series-model*").

2. 4 Estimating method from Horizontal Irradiance to In-plane Irradiation

Figure 3 shows order to calculate In-plane Irradiation from *MF*.

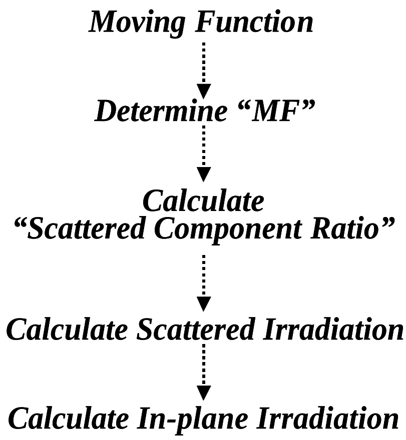


Figure 3: Order to calculate In-plane Irradiation from *MF*

In-plane Irradiation is calculated by using three factors that are In-plane Direct Component, In-plane Scattered Component and In-plane Reflected Component. In-plane Irradiance is total number of three factors (Eqn. 2).

$$I_{\beta\gamma} = I_{d\beta\gamma} + I_{s\beta\gamma} + I_{r\beta\gamma} \qquad (2)$$

where $I_{\beta\gamma}$ is In-plane Irradiance, $I_{d\beta\gamma}$ is direct component of in-plane irradiance (In-plane Direct Component), $I_{s\beta\gamma}$ is scattered component (In-plane Scattered Component) and $I_{r\beta\gamma}$ is reflected component (In-plane Reflected Component).

• *Calculate method of the In-plane Direct Component*

Direct component that incidents horizontal and tilt plane is calculated by following relations as:

$$I_b = I_n \cos\theta_z \qquad (3)$$

$$I_{b\beta\gamma} = I_n \cos\theta \qquad (4)$$

where I_d is direct component of irradiance incidents to horizontal plane (Horizontal Direct Component), $I_{d\beta\gamma}$ is direct component of irradiance incidents to tilt plane (In-plane Direct Component), I_n is Horizontal Irradiance, θ_z is zenith angle of sun and θ is tilt angle of plane. Therefore, ratio of each other is as follows:

$$rb = I_{d\beta\gamma / d} = \cos\theta / \cos\theta_z \qquad (5)$$

Then, it is easy to calculate the In-plane Direct Component using Horizontal Direct Component, altitude of sun and tilt angle of plane at all times. Horizontal Direct Component is difference between Horizontal Irradiance and Scattered Irradiance as follows:

$$I_{d\beta\gamma} = (I - I_s)\cos\theta / \cos\theta_z \qquad (6)$$

$cos\ \theta$ and $cos\ \theta_z$ is calculated by following relations as:

$$\begin{aligned}\cos\theta &= (\sin\phi\ \cos\beta - \cos\phi\ \sin\beta\cos\gamma)\sin\delta \\ &+ (\cos\phi\ \cos\beta + \sin\phi\ \sin\beta\cos\gamma)\cos\delta\cos\omega \\ &+ \cos\delta\sin\beta\sin\gamma\sin\omega \qquad (7)\end{aligned}$$

$$\cos\theta_z = \sin\phi\ \sin\delta + \cos\phi\ \cos\delta\cos\omega \qquad (8)$$

where δ is celestial declination, ω is hour angle, γ is azimuthally angle of tilt plane, ψ is azimuthally angle of sun and β is tilted angle of plane.

• *Calculate method of the In-plane Reflected Component*

Based on the fact that irradiance reached to surface reflected equally omni direction, In-plane Reflected Component is calculated by following relation as:

$$I_{r\beta\gamma} = I\rho\ (1 - \cos\beta)/2 \qquad (9)$$

where ρ is Albedo.

• *Calculate method of the In-plane Scattered Component*

Hay model [3] is selected for no uniformity of sky irradiance. That model is available to calculate the scattered irradiance considering circum solar and other component.

Hay model is as follows:

$$I_{s\beta\gamma} = I_d \left[\begin{aligned} &\{(I - I_d)/I_0\}\cos\theta/\cos\theta_z \\ &+ \{1 - (I - I_d)/I_0\}(1 + \cos\beta)/2 \end{aligned} \right] \quad (10)$$

where I is Horizontal Irradiance, I_0 is Extraterrestrial Irradiance.

In-plane Irradiance is calculated by using above equations.

3. RESULTS AND DISCUSSION

Using data obtained on 2000 at Koganei, the Time-series-model was made. To assess the model, all days are selected from the month for confirmation. These days includes clear-condition that is stable and cloudy-condition that is also stable. In addition, other days of partial-cloud-condition that is not stable and fluctuate-condition that is most fluctuate of 4 are included. The model is used at all of days to calculate In-plane Irradiance at one-minute steps. Therefore, one-minute In-plane Irradiances are calculated to daily value over days. In addition, the results was assessed by Residual Number, one is *Root Mean Square Error* (*RMSE* (11)) for error from Measured and the other is *Mean Bias Error* (*MBE* (12)) for bias error from measured to assess the model.

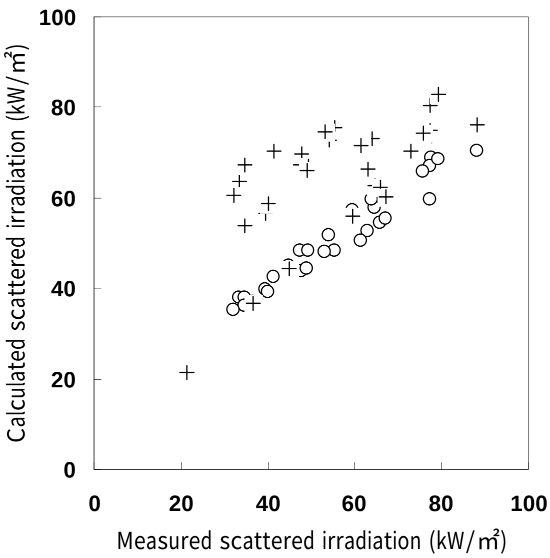
$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(I_C - I_M)^2}{n}} \qquad (11)$$

$$MBE = \frac{\sum_{i=1}^{n}(I_C - I_M)}{n} \qquad (12)$$

I_C: *calculated value*, I_M: *measured value*

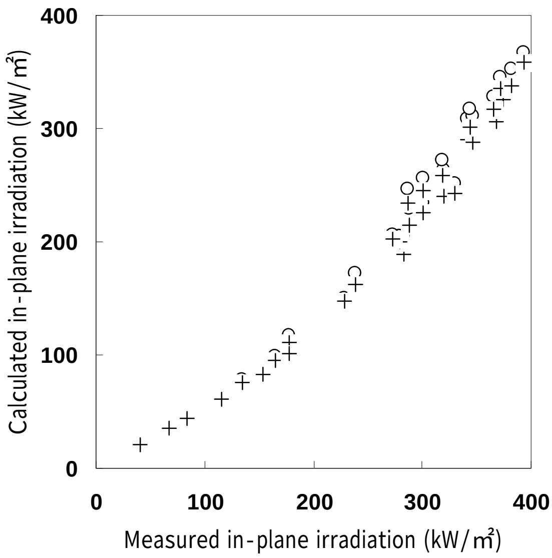
Irradiation calculated was compared *Time-series-model* to *Erbs-model* [2] about daily and monthly scattered and in-plane Irradiation.

Hay-model was used to calculate In-plane irradiation about Daily In-plane Irradiation at January 2000.



※○: Time-series-model, +: Erbs-model

Figure 4: Comparison of measured and calculated value of daily scattered Irradiation



※○: Time-series-model, +: Erbs-model

Figure 5: Comparison of measured and calculated value of Daily In-plane Irradiation.

Figures 4 shows that there are differences between using *Time-series-model* and *Erbs-model* value. It is prominent that *Erbss-model* value is more distributed than *Time-series-model* value, mostly.

And it is showed that calculated value using *Erbs-model* is lower than using *Time-series-model* (Figure 5).

Table1: Error of calculated value by Residual Number (about scattered irradiation)

	MBE	RMSE
Time-series-model	-4.79	5.93
Erbs-model	9.73	12.52

Table2: Error of calculated value by Residual Number (about in-plane irradiation)

	MBE	RMSE
Time-series-model	-50.19	18.01
Erbs-model	-59.5	18.51

Table3: Error of calculated monthly value (Error: %)

	Scattered	In-plane
Time-series-model	-8.68	-18.84
Erbs-model	17.65	-22.34

Table 1 shows error of calculated value using Residual Number about Daily In-plane Irradiation. Calculated value using *Time-series-model* is more proximate to measured value than *Erbs-model*. While calculating the Daily In-plane Irradiation (Table2), the same result each other between *Time-series-model* and *Erbs-model* is showed.

Calculating monthly value(Table3), *Time-series-model* is better than *Erbs-model* about calculating the scattered irradiation.

4. CONCLUSION

In the present work the author proposed the new method of calculating In-plane irradiation by using *Time-series-model* from one-minute Horizontal Irradiance. These results have indicated that the method gives more accurate results compared with existing regression models about scattered irradiation, but further modification seems to be capable to improve the quality of estimation about in-plane irradiation.

5. References

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