Spectral influence analysis on sunshine duration measurement

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Abstract: Sunshine duration is an important variable in surface meteorological measurement. In this article, two methods for measuring sunshine duration are described, one is photovoltaic-based instrument, which ranges from 400 to 1100 nm, and the other is thermopile-based pyrheliometer, which ranges from 300 to 3000 nm. Due to the spectrum is more representative and accuracy for solar radiation, the pyrheliometer is recommended as the reference sensor for the detection of the threshold irradiance for defining the sunshine duration. The comparison between the photovoltaic- and thermopile-based instruments is carried out to uncover the spectral influence on sunshine duration measurement, analysis by the SMARTS tool is presented to calculate irradiance with different spectral ranges under different altitudes.

1 Introduction

Sunshine duration in meteorology is defined as the sum of the time for which the direct solar irradiance exceeds 120 W/m² during a given period [1], it is a crucial meteorological variable associated with the brightness of the solar radiation contractive to the background sky, which reflects the solar radiation intensity for an area; hence, accuracy sunshine duration measurements are widely used in climate change research, medium- and long-term weather forecast, tourist attractions, solar energy resource, and agricultural development.

For a long time in China, sunshine duration is measured with Jordan sunshine recorder in practice, which detects sunshine by burning a specially soaked paper through the concentrated solar beam pass the small hole; therefore, the instrument has to give the sunshine duration by the judgement of human [2, 3]. In order to promote the automatic observation, two methods are introduced for surface meteorological observation: one is pyrheliometric method that the duration values are determined by direct solar irradiance 120 W/m² threshold measured with pyrheliometer, this is recommended as the reference sensor for sunshine duration measurement for its obvious advantage, that is the spectral response of pyrheliometer is flat in 300 to 3000 nm, and this can respond closely to the reality of the solar spectrum; the other method utilises the photovoltaic-based instrument, such instrument consists of three photodiodes, one is exposed to the sunshine to measure global solar irradiance, the other two are shielded from sunshine by a particular mask to measure diffuse solar irradiance, then the direct solar irradiance can be produced from the global and diffuse solar irradiance, and when the direct solar irradiance exceeds 120 W/m² threshold, sunshine duration will be recorded. As of its fast response, robustness, good persistence, small size, and low price, the photovoltaic-based instrument offers a recommendable choice for the meteorological application. However, the spectral response of photodiode mostly ranges from 400 to 1100 nm [4, 5], which is much narrower than the solar spectrum, so evaluating the discrepancy posed by the different spectral response ranges has become a burning question.

In this article, we take use of SMARTS 2.9.5 to compute the spectral irradiance under different air mass (AM) values, the spectral irradiance values within 300 to 3000 nm and 400 to 1100 nm are integrated, respectively, the difference between the irradiance calculated from such two spectrum ranges are analysed. With the help of the comparison test between the photovoltaic- and thermopile-based instruments, spectral influences in practice are investigated. Through theory and practice analysis, spectral influence on sunshine duration measurement can be revealed to some extent.

2 Estimation of spectral errors

It is complicated to estimate the spectral response errors, because the solar spectrum is varying with the time and environment, moreover, the spectral responses of most photodiodes are selective in specific spectrum range [4], an analysis of spectral impacts on photovoltaic-based radiometers shows that the difference in global solar radiation, resulting from the spectrum change of the solar position and the sky conditions, can reach 2% [6]. In order to simplify the calculation, we assume that the spectral response of photodiode are limited from 400 to 1100 nm, and the responsivity is always uniform in this range, as a result, the effect of taking solar energy within 400 to 1100 nm to approximate the energy within 300 to 3000 nm can be assessed using the SMARTS 2.9.5 [7].

The solar spectrum received by sunshine duration recorder is changing with the time and the atmospheric composition [8–10], it is obvious that when in the morning and evening time, the sunshine appears in the shades of red, while at noon time, the sunshine looks abundant in blue light, this can be indicated with AM, which is defined as the relative path length through the atmosphere with respect to the vertical component of the direct solar irradiance, correspondingly, different AM values corresponding to different spectrum distributions to some degree, then the solar altitude angle can be derived for formula (1) [11]:

$$\theta = \arcsin \left(\frac{1}{AM}\right)$$

For the purpose of simulating the solar travelling path in the daytime, AM values are set in Table 1, and the corresponding solar altitude angles are computed using formula (1) and given out together.

From Table 1, the sun going from the zenith to the sunset along with the time can be simulated. To calculate the difference caused by spectral, we take use of SMARTS 2.9.5, set AM values listed in Table 1 for the USSA reference spectrum [12, 13], the curve of spectrum with different AM values are illustrated in Fig. 1.

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E spectral irradiance density, the spectrum interval used by the program in each spectral region is 0.5 nm (280–400) nm, 1 nm (400–1100) nm, but the main solar energy we can see is distributed in about 300 to 3000 nm. With the AM value increases, the shortwave solar energy decreases distinctly, while the longwave solar energy increases. From Table 1, we can see that the spectral irradiance error is getting bigger with the rising of the AM values, when AM is 11, it is about at the sunrise or sunset time, the error is up to 5.5%, but this is the key time for sunshine duration measurement, because after sunrise or before sunset, the irradiance will be close to the threshold 120 W/m², and this is crucial for the sunshine duration recorder to judge if add the time to duration or not.

3 Comparison test

The comparison test is designed to evaluate the spectral discrepancy between photovoltaic-based sunshine duration recorder and thermopile-based pyrheliometer. The test is carried out at the Solar Resource Assessment Site (119°46′19″E, 41°07′08″N, 341 m) in Liaoning province, the test starts from August 1st and ends in August 31st, there are a pyrheliometer and three sunshine duration recorders used in the comparison test, the instrument information is shown in Table 3, and the pyrheliometer serves as the reference [14].

In order to ensure the data quality, all data used to evaluate must go through strict quality control process to remove any abnormal data [15]. Calculating the sum duration of a month, the difference between the pyrheliometer and the sunshine duration recorders are given in Table 4, the daily absolute errors of CSD3 sunshine duration recorders are depicted in Fig. 2.

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Comparison statistic results

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From Table 4, the statistic results show that the error between CSD3 and reference pyrheliometer is within 2%, although the daily absolute errors of this three CSD3 in Fig. 2 are still big on some days, because we sum the sunshine duration together for a month time, the positive errors will combine with the negative ones, then the statistic results will show a desirable results, so the photovoltaic CSD3 can give out a comparable sunshine duration measurements with the reference which validates the photovoltaic-based instrument can be used in some field.

| AM | Altitude angle (°) | AM 1 | AM 2 | AM 3 | AM 4 | AM 5 | AM 6 | AM 7 | AM 8 | AM 9 | AM 10 | AM 11 |
|----|------------------|-----|-----|------|------|------|------|------|------|------|-------|-------|
| 1  | 90.0             | 194.7 | 196.1 | 194.8 | 198.2 |
| 1.2| 56.4             | 194.7 | 196.1 | 194.8 | 198.2 |
| 1.5| 41.8             | 194.7 | 196.1 | 194.8 | 198.2 |
| 3  | 19.5             | 194.7 | 196.1 | 194.8 | 198.2 |
| 5  | 11.5             | 194.7 | 196.1 | 194.8 | 198.2 |
| 7  | 8.2              | 194.7 | 196.1 | 194.8 | 198.2 |
| 9  | 6.4              | 194.7 | 196.1 | 194.8 | 198.2 |
| 11 | 5.2              | 194.7 | 196.1 | 194.8 | 198.2 |

| AM | Spectral irradiance error | AM 300–1100 | AM 400–3000 | AM 300–3000C | AM 900–1100C |
|----|---------------------------|-------------|-------------|---------------|---------------|
| 1  | 0                         | 0.5%        | 0.4%        | 0.2%          |
| 1.2| -0.3%                     | -0.3%       | -0.2%       | -0.1%         |
| 1.5| -0.6%                     | -0.6%       | -0.4%       | -0.3%         |
| 3  | -1.5%                     | -1.5%       | -1.2%       | -1.0%         |
| 5  | -2.2%                     | -2.2%       | -1.9%       | -1.7%         |
| 7  | -2.9%                     | -2.9%       | -2.6%       | -2.4%         |
| 9  | -3.5%                     | -3.5%       | -3.2%       | -3.0%         |
| 11 | -4.0%                     | -4.0%       | -3.7%       | -3.5%         |

| Name | Type | Serial number | Manufacturer |
|------|------|---------------|--------------|
| pyrheliometer | NIP | 36,262 | EPPELEY |
| sunshine duration recorder | CSD3 | 132,140 | Kipp & Zonen |
| | | 132,138 | |

Fig. 1 Spectral irradiance computed using SMARTS 2.9.5 based on USSA reference spectrum with different AM values

Table 4 Comparison statistic results

Parameter | Pyrheliometer | CSD3 | CSD3 | CSD3 |
|----------|--------------|------|------|------|
| sunshine duration | 194.7 | 196.1 | 194.8 | 198.2 |
| absolute error | — | 1.4 | 0.1 | 3.5 |
| relative error | — | 0.7% | 0.1% | 1.8% |

\[ E_{AM}^{300–3000} = \frac{E_{AM}^{400–1100}}{E_{AM}^{400–1100}} \times \frac{E_{AM}^{300–3000C}}{E_{AM}^{300–3000C}} \]

where \( E_{AM}^{300–3000} \) is the solar spectral irradiance within 300 to 3000 nm is replaced by the one within 400 to 1100 nm by formula (4):
**Conclusion**

In this article, we describe two methods for sunshine duration measurement, one is photovoltaic-based instrument, which ranges from 400 to 1100 nm, and the other is thermopile-based pyrheliometer, which ranges from 300 to 3000 nm, the spectral influence and the performance of this two method are analysed by simulation and comparison test. With the help of SMARTS 2.9.5, a series of spectral irradiance with different AM values are calculated, and the biggest error of 5.5% appears at the simulated sunrise or sunset assumed that AM is 11. According to the comparison test between the above-mentioned method, the error of CSD3 relative to the reference pyrheliometer in this test is within 2%, although the daily error is a little bigger, but take the statistic result into consideration, the spectral influence on photovoltaic-based instrument can be neglected to some extent, and the photovoltaic-based instrument can offer a recommendable choice for the meteorological application.

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**Fig. 2** Daily absolute errors of CSD3 type sunshine duration recorders

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