Error Analysis and Correction of Sunshine Duration Sensor

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Abstract: Beginning with the analysis on the principle of photoelectric sunshine duration sensor and combining with the problems occurred in use, various factors affecting the accuracy of observation are discussed. The digital sunshine duration sensor solutions are put forward by analysis on the data detection and observation, the corrections on the error factors are discussed, such as directional response characteristic, stray light and temperature characteristic. As a consequence, the precision of the sunshine duration with automatic observation is improved.

Key words: Sunshine Duration Sensor; Photo-electricity; Digital Correction

1 Introduction

Sunshineduration is a significant meteorological factor and it has a wide range of applications in the fields of meteorology, agriculture and environment. The sunshine duration is observed by various sunshine meters in meteorological observation. The traditional sunshine recorder estimates the sunshine duration based on the scorched or photographic trace of the paper or photographic recording medium after focusing through the sun, which are low precision and high requirements for medium quality, it also requires changing the medium manually and judges the data, which is difficult to adapt to the requirements of automatic observation.

The World Meteorological Organization defines the solar direct radiation greater than 120W/m^2 as the sunshine hour threshold value, that is, the sunshine hours are the cumulative values of direct radiation greater than 120W/m^2.[1] Obviously, the most accurate and direct method of measurement is to use pyrheliometer and accumulate the time greater than the threshold value. [1]However, the pyrheliometer is very expensive and requires the sun tracker. It's not affordable for majority of the sunshine duration observation circumstances.

With the popularity of photoelectric sensing devices, some photoelectric sunshine duration sensors that applicable for automatic observation of sunshine duration have appeared and put into use. Usually they use various shading schemes and measure the global radiation and diffuse radiation simultaneously.[2,4] As its output result is calculated on the global radiation and diffuse radiation received respectively by the sensing device, the performance differences between sensing devices, the rationality of sunshine detection mathematical model and the processing, installation, testing, material features of the key components of instrument will affect the output of sensor.

Aiming at the main problems occurred in the photoelectricsunshine duration sensor, the approach and feasibility in correcting digital sunshine duration sensor to improve the measurement precision are introduced, so as to provide suggestions for the development of automatic observation sunshine duration sensor.

2 Measuring Principle

A variety of shading schemes to identify measurement of global radiation and diffuse radiation simultaneously are used by photoelectric sunshine duration sensor[3,4,7,8,9,10,11,12,13,14], the direct radiation value is obtained indirectly based on the calculation of measured values, so as to achieve the aim of sunshine hours observation.

As shown in Figure 1[4], the photoelectric sensing devices D1, D2 and D3 with diffusers mounted on the axis of baffle by means of co-axial columns corresponding to the fully opened window, ab window group and cd window group of the baffle. ab window group and cd window group are arrayed in staggered form to observe the interlaced segmentation under different vault of heaven. At any time, the direct radiation could reach D1, but only one of D2 or D3. Using D1 output signal to represent the global radiation, the smaller output signal in D2 and D3 represents diffuse radiation. Therefore the direct radiation can be calculated using the formula between global radiation and diffuse radiation. Comparing the direct radiation with threshold value 120W/m^2, sunshine status could be obtained.

If the constantdiffuse radiation is distributed uniformly, the constant direct radiation revolves around the axis of the sensor. So the output of D1 is a horizontal line and the outputs of D2 and D3 are trapezoidal waves with phase difference of half cycle.

Inactual observation, the direct radiation and diffuse radiation values change from time to time, however, the relatively smaller output value of D2 and D3 could represent the diffuse radiation. According to the sunshine detection mathematical model, the output value of D1 representing the global radiation and the diffuse radiation are used to calculate, so the direct radiation value can be gained indirectly, then the sunshine status is obtained and the sunshine hours are calculated.

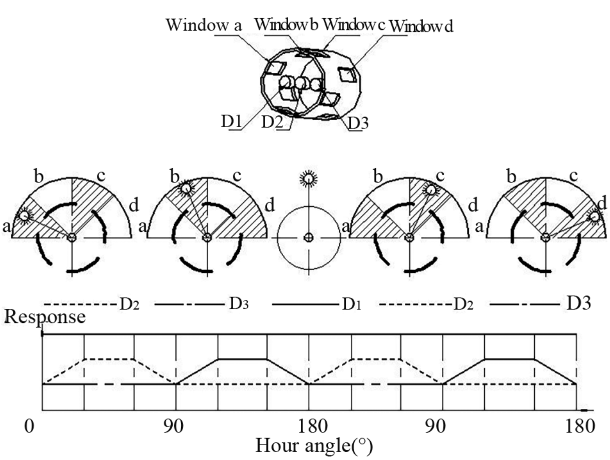

Fig. 1 Working principle diagram of photoelectric sunshine duration sensor

$$E_{dir} = a \times (E_{sum} - b \times E_{dif}) \quad (1)$$

E_{dir} is the direct radiation observation value;

E_{sum} is the D1 sensor output value representing the global radiation;

E_{dif} is the relatively smaller output value of D2 and D3 representing the diffuse radiation;

a is the radiation observation sensitivity;

bis the shading coefficient.

3 Feature Extraction

The basic principle of various shading type sunshine duration sensor mostly implies an assumption that the distribution of diffuse radiation under the vault of heaven is uniform, the observation to the part of the vault of heaven could be presumed as the radiation status of the whole vault of heaven.

However, thesolar radiation distribution is not the case. First, there's strong circumsolar radiation and the intensity and distribution change with the atmospheric condition. Second, the cloud distribution and their changes in characteristics of diffused reflection and diffused transmission of the solar radiation also lead to inhomogeneous distribution of diffuse radiation. In addition, the weather phenomenon, such as dust, haze, rainbow, rosy cloud, clouds could also cause changes in spectral distribution of vault of heaven, which has spectral selective interaction with photoelectric sensing device to produce difference of diffuse radiation observation signals in different range of vault of heaven. Due to the movement of the sun, the angle response of diffuser will affect accuracy of the observed signal. The reflection of direct radiation against the inner wall of the shading device could result in diffuse radiation measurement error brought by the stray light. The temperature and the non-linear characteristics of the sensing device are also the error sources that affect the observation accuracy.

According to the test results of thesunshine duration sensor and the practically observed data of sunshine duration sensor in Kazuo National Standard Radiation Station FS-RZ1 total 10 months from June

2015, the possible error sources are analyzed and discussed respectively.

3.1 Effect of Directional Response

The half opening angle of the pyrheliometer is 2.5° and the observed radiation includes solar disk radiation and part of the circumsolar radiation [1]. The circumsolar radiation caused by the atmosphere will not stop abruptly from 2.5° field of view, but it expands to the whole vault of heaven in different distribution forms with different atmospheric conditions.

According to the graphic presentation on the sky brightness distribution (Figure 2) in "Spatial Distribution of Natural Light - Brightness Distribution in Various Reference Skies" of CIE No. 110 publication, we could find that the sky brightness distributions vary in different weather conditions.

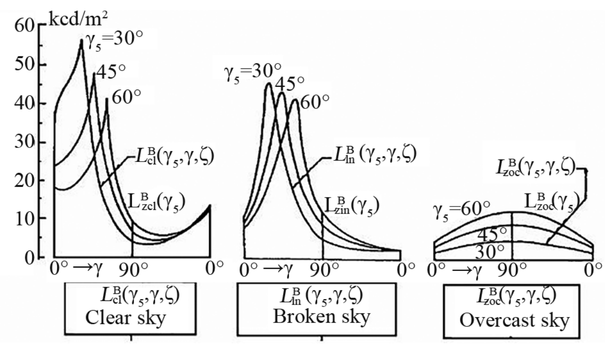

Fig. 2 Spatial Distribution of Natural Light

Through the analysis on theactual observed result of CSD3 sunshine duration sensor, we could obviously find the influence of this factor as shown in Figure 3.

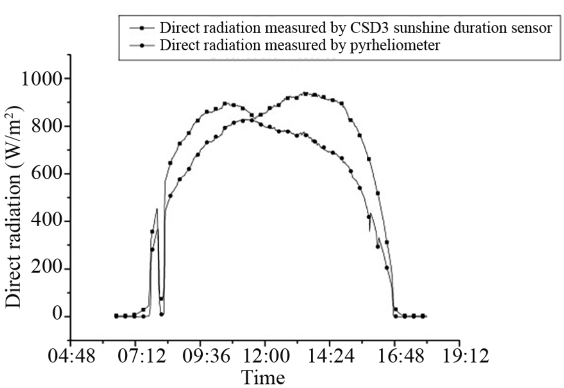

Fig. 3 Data of CSD3 in sunny day

The shadingscheme divides the vault of heaven into two parts, which produce a significant periodic variation of observation error of direct radiation in sunny days. In cloudy weather this form of error is shown in figure 4, obviously it has direct influence on the interpretation of sunshine duration.

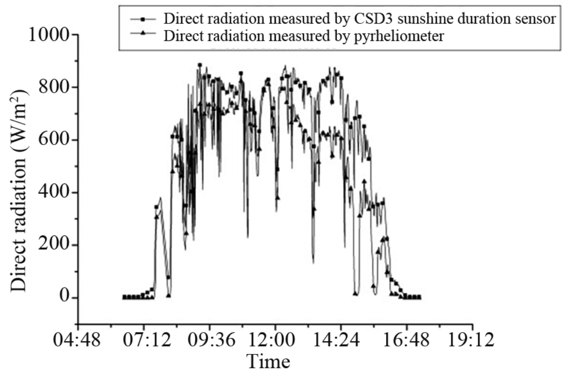

Fig. 4 Data of CSD3 in cloudy day

Thelaw of variation of this error related to the hour angle is fixed and is symmetrical at 12 o'clock in the noon. Each segmentation region of the vault of heaven appears once.

The photoelectric tube has significant directional selectivity, so the sunshine duration sensor needs be installed with a diffuser in front of the sensor. However, problems existed in diffuser design and its optical material make the sunshine duration sensor always having certain directional response error. For the co-axial columns sensing device, the main performance is the hour angle response error and the declination angle response error.

Thehour angle response is caused by the discontinuity and processing error of the diffuser materials and the window materials. The declination angle response is related to the incident characteristics and the corrected design of the diffuser materials. Once the instrument is designed, the systematic errors like hour angle response and declination angle response are confirmed.

The declination angle response will produce an observational error that varies periodically with the season, the measurement accuracy of direct radiation changes with the variations of the declination angle. The hour angle response varies with the hour angle every day and shows the regular error fluctuation within a day.

In figure 5, Kazuo data on August 15, 2015 are taken as an example to show the regular periodical changes. In the sunny days, the direct radiation measured by sunshine duration sensor with six-segmentation vault structure is fluctuating around the pyrheliometer observation values.

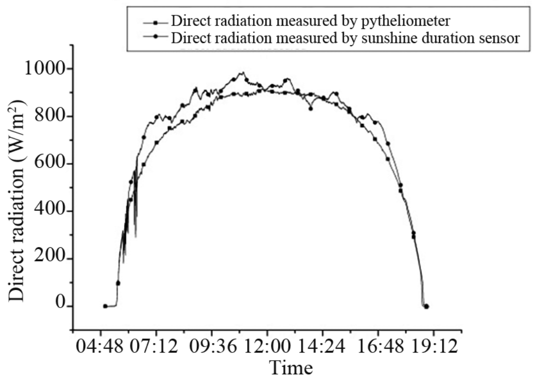

Fig. 5 Actual measured data of Kazuo in sunny days

The dataof total 10 months from June 2015 in Kazuo are used to do statistical analysis of the ratio between direct radiation values output by sunshine duration sensor and the direct pyrheliometer observation values, the absolute value of declination angle is also given at that time. By analyzing the relationship between the two, the results are shown in Figure 6.

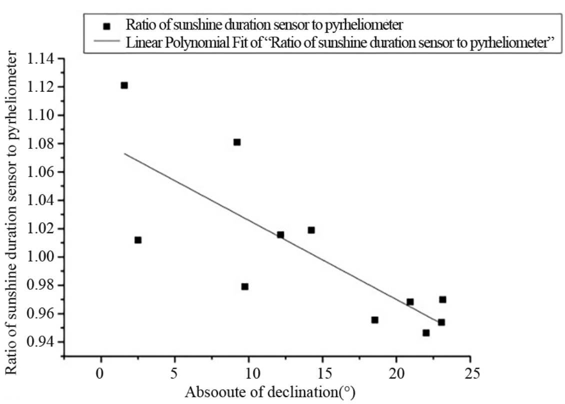

Fig. 6 Declination angle VS direct radiation observational error ratio

The results show that there is a linear correlation between the two, $R^2=0.63$.

The error changing with the time periodically is one of the main error sources of photoelectric sunshine duration sensor. Because of its regularity is very obvious, it has the condition for error correction. However, under actual observation condition, the proportion of the direct radiation component in the global radiation varies with atmospheric condition. Therefore, the error response to declination angle can only be partially corrected.

3.2 Influence of Temperature Characteristics

The photoelectricsunshine duration sensor, with silicon photodiode as sensing device, has the operating temperature ranged from -40 ℃ to +60℃. The environmental temperature changes in one day may reach more than 10 ℃. The output of silicon photodiode will be affected by its temperature characteristics, it may also become one of the error sources in sunshine observation.

The temperature characteristicsof silicon photodiode are shown in figure 7. The sensitivity of temperature deviation varies with wavelength, which is more obvious in the ultraviolet and infrared side. Its shunt resistance also varies with the change of temperature significantly.

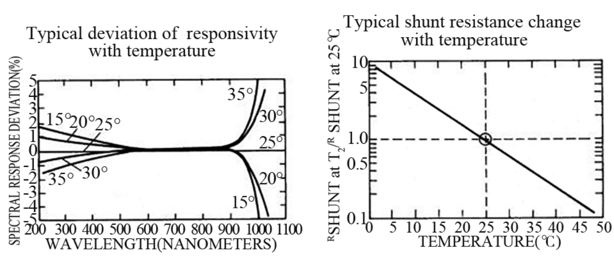

Fig. 7 Temperature characteristics of silicon photodiode

The measured results of temperature characteristics of the two siliconphotodiodes are shown in figure 8. In the range of 0℃ to 40℃, the relative responses varied by 3% and 6% respectively. Moreover, the changing direction of photodiode temperature characteristics of different types is inconsistent.

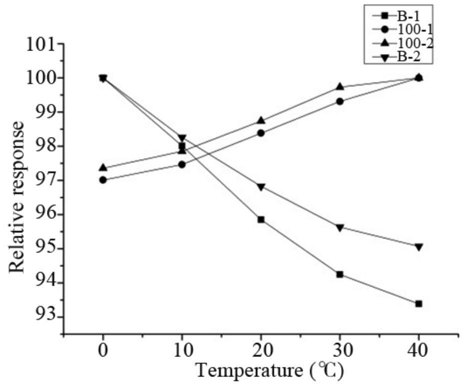

Fig. 8 Measured result of the temperature characteristics of silicon photodiodes

The dataof total 10 months from June 2015 in Kazuo are used to analyze the relationship between the direct radiation error of the sunshine duration sensor and the temperature, the results are shown in figure 9.

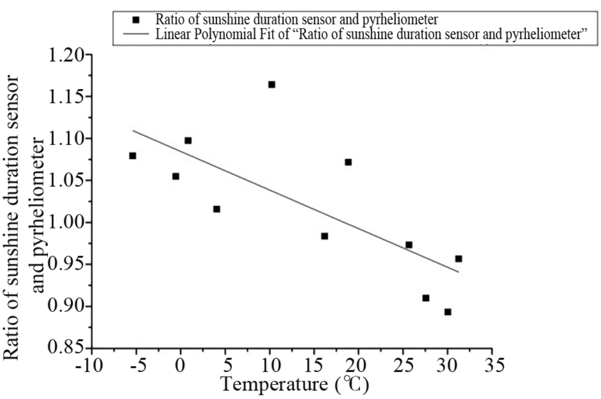

Fig. 9 Temperature VS error of the direct radiation observation value

There is a negative correlation between the environmental temperature and the ratio, which is the ratio of the sunshine duration sensor to the output value of pyrheliometer, R = 0.537. It is basically consistent with the temperature response test data of the photoelectric sensor. Since the temperature characteristics of the photodiode are related to wavelength, the influence of temperature characteristics on the observation error can be partially eliminated by the correction.

3.3 Nonlinear Effects

The response of siliconphotodiode to incident radiation is nonlinear, resulting in errors in detection of global radiation and diffuse radiation. The detection data for the nonlinear error of silicon photodiode are shown in figure 10.

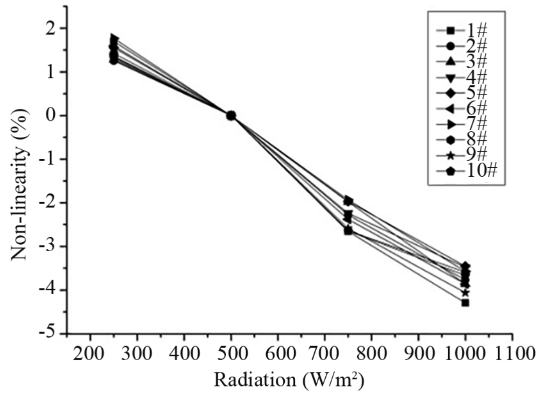

Fig. 10 Nonlinear detection date of photodiode

However, the nonlinear error of the photodiode is related to the intensity of incident radiation, while the sunshine duration is measured at the determined threshold and the nonlinear error has no significant effect on the measurement accuracy of the sunshine duration. In the actual observation, there is no sign that the nonlinearity has a significant effect on the measurement error of sunshine duration.

3.4 Effects of Stray Light

Thediffuse radiation is observed by shading in sunshine duration sensor. The direct radiation is sheltered and cannot be irradiated onto the diffuse radiation sensor, but it can irradiate into the interior of the shading structure, the stray light formed by reflection has influenced on the diffuse radiation observation. Because of the material changes, shape and incident angle of the shading structures, the stray light which affects the diffuse radiation show the regular fluctuation with the direction of the incident radiation.

The variationlaw of stray light is related to the revolution of the sun, so the correction of stray light can be considered together with the correction of circumsolar radiation. In order to ensure the accuracy of sunshine observation, the direct radiation observation accuracy is calibrated and controlled over a full period of time.

3.5 Effects of Spectral Properties

Typical spectral response curves of the silicon photodiode are shown in figure 11[5]. Its spectral response increases gradually from ultraviolet to near infrared, it shows obvious spectral selection characteristics.

Blue sky, white clouds, dark clouds, rosy clouds and other colorful scene distribute randomly in the sky, not only make the vault of heaven appear the random variation of brightness distribution, but also lead to inhomogeneous spectral energy distribution. Due to the spectral selectivity of the photodiode, these inhomogeneous spectral distributions intensify the principle error caused by the inhomogeneous brightness distribution of the actual sky.

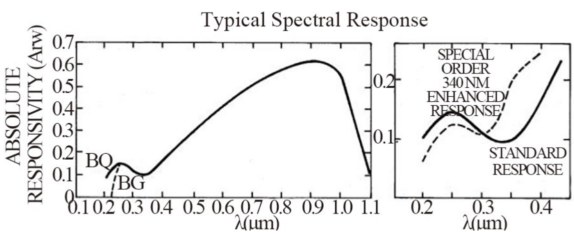

Fig. 11 Spectral response of silicon photodiode

In addition, different observational results can be obtained due to the spectral characteristics of the sensing device for the diffusing vault of heaven formed by the clean cloud and the dim diffusing vault of heaven caused by faint yellow dust haze[6, 15]. In such weather conditions, the measured values of direct solar radiation always vary repeatedly at the level near the threshold and the probability of producing sunshine observation errors is much greater.

For this error source with random variation, the effective solutionhas not been found yet, which could not be corrected effectively. At the same time, these random errors also cause great disturbance to the analysis and judgment of other error factors.

Analyzing from the above sources of error, the influence of non-linearity is largely negligible. The temperature characteristics, directional response and stray light can be corrected to a great extent as systematic errors. Though the influence of circumsolar radiation is greatly affected by atmospheric condition, the overall influence trend is confirmed , so it can be partially corrected. The errors caused by spectral characteristics and the inhomogeneous vault of heaven due to other weather phenomena are influenced by various accidental factors and difficult to be corrected directly. A large number of observational data should be analyzed and studied so as to find related factors for correction.

Through the design and trialmanufacture of digital sunshine duration sensor, the real-time correction of the relevant errors in the observation process has been carried out, the observation accuracy of the instrument has been improved effectively.

On the basis of the photoelectricsunshine duration sensor, the digital circuits and calibration software are added to the digital sunshine duration sensor. The circuit is composed of power supply, interface circuit, sensor signal adjusting circuit, ADC sampling circuit, MCU minimum system circuit, level converting circuit, DAC circuit, heating control circuit module, system status monitoring circuit and so on.

The systemadopts the 32-bit MCU based on ARM Cortex-M4 as the core to construct the digital sunshine duration sensor hardware, the system is under 12V DC power supply.

4 Feature Extraction

4.1 Directional Response and Stray Light Correction

Throughcorrecting the circumsolar radiation affected by periodical changes of hour angles, the direct radiation observation data in sunny days have been improved obviously. Taking the Kazuo data on August 15^{th} 2015 as example, the results are shown in figure 12.

After correction, the fluctuant amplitude of direct radiation measured values of sunshine duration sensor around the direct radiation of pyrheliometer has been reduced, which has restrained the influence of the circumsolar radiation effectively.

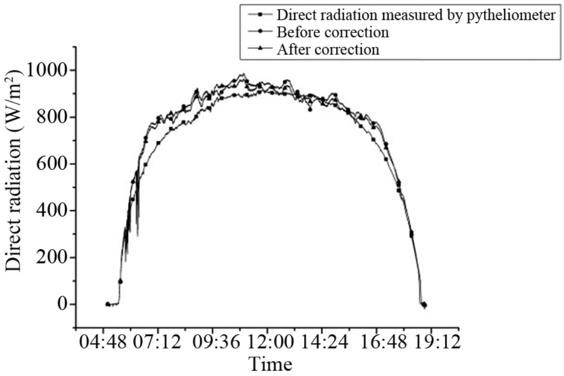

Fig. 12 Circumsolar radiation correctionresults

After restraining the influence of the circumsolar radiation, the effect of stray light is revealed. In figure 13, the regular peak is the product of the periodic variation of the stray light in the shading structure.

The solardeclination angle is determined by the calculation, the observed data can be corrected by the declination angle response data of the actual measured sensor.

Based on theaforementioned methods of directional response error correction, as shown in figure 13, the variation range of the direct radiation observation error is generally reduced after the correction of the directional response error.

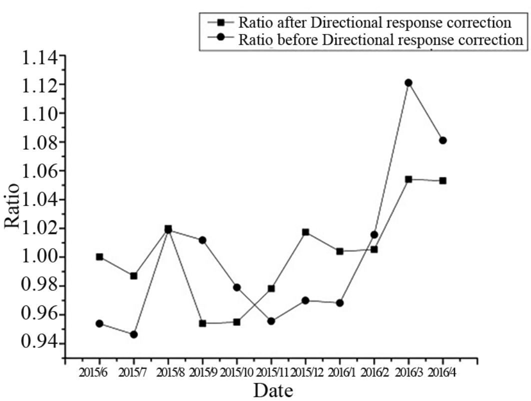

Fig. 13 Directional response correction results

4.2 Temperature Characteristics Correction

The temperature characteristic correction function f(t) can be obtained by measuring the temperature characteristic of the photoelectric sensors, the output value of each photoelectric sensor is corrected by the temperature characteristic compensation in the formula (2).

$$E_{dir} = a \times (E_{sum} - b \times E_{dif}) \times f(t) \qquad (2)$$

Before and after correction, the comparison between monthly observation values from the direct radiation and pyrheliometer of the sunshine duration sensor is shown in figure 14. The ratio no longer has obvious sustained upward trend after correction.

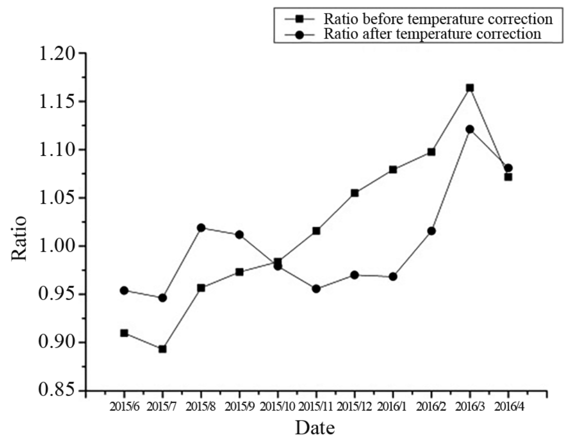

Fig. 14 Correctionresults of the temperature characteristics

6.4 The message overhead

Taking theaforementioned various correction methods, the contrast data of the monthly gross error of sunshine duration before and after correction are shown in figure 15. It can be seen that the observation accuracy of the monthly gross of sunshine duration is improved, the error fluctuation of the monthly gross tends to be symmetrical, but the monthly gross error in July 2015 was deteriorated.

Analyzing the data in July, the direct radiation values were lower which showed cloudy days were more often in that month. Take the data of July 11 and 12, 2015 as examples, as shown in figure 16 and figure 17, the solar direct radiation values fluctuated at a low level, which indicated the atmospheric transparency was poor at that time.

In those two days, the percentage errors of sunshine duration observation were -21% and -11%, the error hours were -62min and -43min and the air pollution indexes were 98 and 116 respectively.

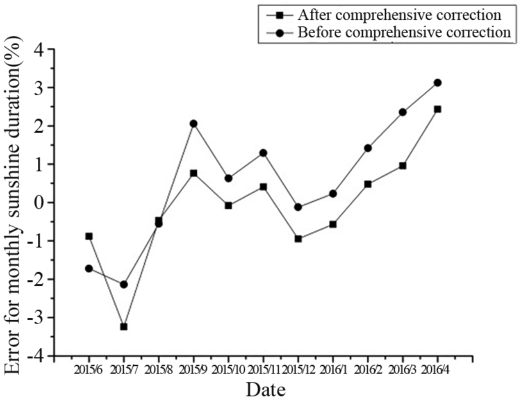

Fig. 15 Comprehensive correctionresults

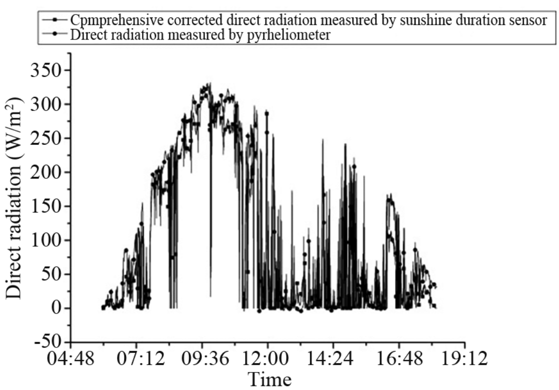

Fig. 16 Data observed on July 11

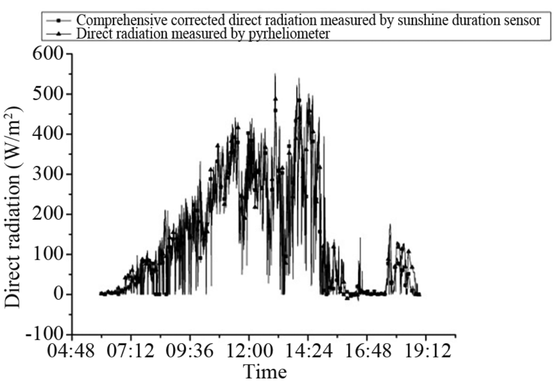

Fig. 17 Data observed on July 12

The main reasons are as follows: the poor air quality leads to variations in the power distribution of scatter spectral (the spectral power density of near infrared increases), so that the observed values of diffuse radiation are on the high side. Also with the frequent handover with or without sunshine, the cumulative error caused by above two factors increase. Besides the 11^{th} and 12^{th}, the 15^{th}, 19^{th} and 20^{th} in that month are similar to this status. Therefore, the monthly gross error is obviously lower.

The observation errors of the sunshine duration caused by these two factors are still waiting for the effective correction methods.

5 Conclusion

The digitalsunshine duration sensor can effectively improve the accuracy level of the sunshine observation and provide monitoring and alarm information for the normal operation and maintenance of the instrument. In some sources of error, many errors can be corrected to varying degrees, such as parts of the principle error caused by the diffuse radiation uniformity assumption, systematic error is relevant to the performance of the components in the temperature characteristics and the solar declination angle response. However, neither the error caused by the spectral selectivity of the sensor nor the randomness in homogeneous distribution of the diffuse radiation brightness of the vault of heaven can be solved properly at present.

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