# Sunlight multiband photon flux density detection based on PFD calculation model

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**Abstract:** The sunlight provides essential light and temperature for photosynthesis in protected cultivation. Sunlight is one of the important plant living environment factors in facility agriculture. Most of the existing light detecting equipment are used to detect the whole band of Photosynthetic Available Radiatio (PAR), which is unable to meet the demand of modern photosynthesis research. In order to solve the problem, a function model between single-band spectral Photon Flux Density (PFD) and solar altitude was established through experiments. Based on the model, a sunlight multiband PFD detecting device was designed, which was using a PAR sensor as the detecting node and microcontroller as the core part. This device can detect the PFD of different bands in PAR by using a single sensor. Meanwhile, detecting band can be set by using keyboard according to the characteristic of spectrum absorption of different plants. The secure digital memory card (SD card) was used in the device to store data. Results of the field test showed that determination coefficients of the device testing red and blue PFD with standard value were 0.986 and 0.993 respectively. The device with little relative error and high reliability could be applied in facility light detecting.

**Keywords:** photosynthetic available radiatio (PAR), photon flux density (PFD), solar altitude, detection, model

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## 1 Introduction

In recent years, the facility agriculture develops rapidly, which can improve crop yield and quality by building microclimate environment to provide plants a good growth environment[1,2]. Photosynthesis is a green plant transformation process from solar energy to chemical energy. The sunlight provides essential light and temperature for photosynthesis after transmission facilities cover material of glass, plastics and so on. The illumination directly affects crop growth. Because of the influence of greenhouses structure and cover, the solar radiation transmittance changes from 14% to 80% according to season and time[3]. Cloudy and rainy weathers make facilities continuously lack of sunshine, which leads to slow growth of vegetables, melons and fruits in the greenhouse, and directly affects the yield and quality. This has become an important factor hindering the development of facility plants. Facilities supplemental lighting has become an important way to solve above problems[4-6].

Modern biology shows that each band of the spectrum of Photosynthetic Available Radiation (PAR) plays an irreplaceable role in the growth of plants[7]. And different band spectrums have different effects on plant physiology. For example, the red light is very important for the normal development of photosynthetic organ, and the blue light controls physiological processes of

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chlorophyll formation, chloroplast development, stomata opening and so on[8,9]. Recently, with development of Light Emitting Diode (LED) technology, it is possible to quantitatively fill light in facilities[10]. But the premises of quantitative supplemental lighting are specific band measurement and controlling of the current intensity. Since the sunlight is full spectrum light, the light intensity monitoring should use a separation band system. Modern research of photosynthesis light intensity has entered the photonic stage and most of them use Photon Flux Density (PFD) as the measurement system[11]. Most existing light detecting equipment are based on optical radiation flux as measurement unit and mainly used to detect photosynthetically active radiation of the whole band. And a few testing equipment of optical radiation flux density can detect different bands, while the disadvantages of them are high price, hard maintenance, low expansibility, etc[12]. Although some testing equipment use PFD as measurement unit in the conversion process from radiation flux density to PFD, the influence of different bands is not considered, which leds to large errors.

In order to solve these problems, a multiband PFD detecting device basing on solar altitude was designed. Regardless of weather conditions, the percentages of different bands light intensity in total sunlight intensity only affected by solar altitude was adopted in this paper. The radiation flux densities of single and whole bands PAR under different solar altitudes were measured by experiments. And the relationship functions about percentages of spectral radiant flux density of single bands in PAR and solar altitude were fitted. Thus, according to the relationship between photon number and radiant energy, the model between single bands PFD and solar altitude was established. Finally combining with calculation of the solar altitude, the calculation model of single-band spectral PFD was established, using the date, longitude, latitude, China Standard Time, average wavelength of the determination band and real-time total radiation as variables. According to above models, the device which could detect different band PFD was designed and developed. This device could realize the PFD of different bands detecting by using a single sensor.

## 2 Materials and methods

### 2.1 Principle and model

2.1.1 Test and data processing

The spectral composition of sunlight radiating on the ground could be changed by the refraction and reflection of the atmosphere[13,14]. Without considering the influence of weather, the proportion of each band in sunlight was only influenced by the solar altitude[15,16]. Based on above researches, this paper established function models between spectral radiant flux density of different bands in sunlight and solar altitude by experiments. In this experiment, the red and blue lights, which have greatest impacts on crop growth, were chosen as research objects. The experiment was carried out in Yangling, Shanxi, China during June and July. 2012. Choosing 30 days continuously in the open outdoors without obstacles, using hand-held spectra radiometer FSPHH (ASD company, America), the spectral radiant flux density of red light 620-700 nm, blue light 440-495 nm and PAR 380-710 nm under the same solar altitude were measured respectively. Then the respective percentages of spectral radiant flux density of red and blue accounted for PAR under different solar altitude were calculated.

Parameters of the model are estimated by the least square method[17-19], the functional relationships of solar altitude and spectral radiant flux density proportions of red and blue single band accounting for PAR were fitted by using the MATLAB 7.8.0 fitting toolbox (curve fitting tool). The red and blue light fitting formulas are shown in Equation (1), (2) respectively.

$$redper = 61.09H^{0.559} + 22 \quad (1)$$

$$blueper = 3.1699\ln(H) - 0.3653 \quad (2)$$

where, *redper* and *blueper* are radiant flux density proportions of red and blue lights accounting for PAR respectively; *H* is the solar altitude. Through this method, the functions of radiant flux density proportions of single bands accounting for PAR with solar altitude which may be expressed by *bandper* can be established. The corresponding function is shown in Equation (3). The basic materials for the establishment of multiband PFD models are provided.

$$bandper = bandper(H) \tag{3}$$

2.1.2 Real-time solar altitude calculation model

Solar altitude directly affects the percentages of different band spectrums in the solar spectrum. Because solar altitude is related with date, hour angle, declination and latitude, we used the calculation model to get the solar altitude[20,21]. The solar altitude can be calculated with Equation (4).

$$H = \arcsin(\sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos\omega) \tag{4}$$

where, $H$ is solar altitude, (°); $\delta$ is declination; $\varphi$ is latitude, (°); $\omega$ is hour angle, (°).

The declination and hour angle can be calculated respectively using following Equations [22]:

$$\delta = 23.45\cos(\frac{2\pi(j-172)}{365}) \tag{5}$$

$$\omega = (T-12)\times 15° \tag{6}$$

where, $j$ is the number of days , e.g. $j$=74 for March 15$^{th}$; $T$ is the real solar time (0-24 h).

In order to facilitate the application, this system makes the conversion of real solar time with China Standard Time.

$$T = h + \frac{m-(120-\phi)\times 4}{60} \tag{7}$$

If this system is used in other time zones, the conversion between China Standard Time and Greenwich Mean Time (GMT) can be made as following: $h$=GMT+8. Where, $h$ is the hour in China Standard Time; $m$ is minute in China Standard Time; $\phi$ is longitude (°).

If $T$ is negative, $T$=$T$+24. Finally, the calculation formula of solar altitude is obtained.

$$H = H(j,\phi,\varphi,h,m) \tag{8}$$

2.1.3 Establishment of PFD calculation model

Combining the solar altitude calculation Equation (8), according to date, time, latitude and longitude, the real-time solar altitude can be calculated. According to Equation (3), binding the real-time solar altitude calculation formula, the function is shown in Equation (9), where the *bandper* is the proportion of radiant flux density that specified single-band accounts for PAR with date, time, latitude and longitude.

$$bandper = bandper(j,\phi,\varphi,h,m) \tag{9}$$

Since the proportion of specified single-band radiant flux density accounting for PAR can be calculated by Equation (9), the real-time specified single-band radiant flux density can be obtained under the premise that the real-time whole band of PAR radiant flux density has been known. The function is shown in Equation (10), where BANDRF ($\mu$mol/m$^2$·s) is single-band radiation flux density and $P$ is real-time total radiation ($\mu$mol/m$^2$·s).

$$BANDRF = P \cdot bandper(j,\phi,\varphi,h,m) \tag{10}$$

According to the relationship between photon number and spectral radiant energy[23,24], the formula of transform from single-band spectral radiant flux density to photon flux density is established, which is shown in Equation (11).

$$bandPFD = \frac{\lambda \cdot BANDRF}{nhc} \tag{11}$$

where, *bandPFD* is the single-band photon flux density, W/m$^2$; $h$ and $c$ are Planck Constant (J·s) and vacuum velocity (m/s); $\lambda$ and $n$ are the average wavelength (m) of the determination band and Avogadro's constant (6.02×10$^{23}$).

Combining with above formulas, finally the calculation model of the single-band spectral PFD was established using the date, longitude, latitude, China Standard Time, average wavelength of the determination band and real-time total radiation as variables.

$$bandPFD = \frac{\lambda \cdot P \cdot bandper(j,\phi,\varphi,h,m)}{nhc} \tag{12}$$

**2.2 System design**

According to above model, the device which could detect sunlight multiband photon flux density was designed. The device collects real-time whole band PAR radiant flux density. By using the key-press to set detecting band by users, the corresponding real-time photon flux density values of detecting band was obtained. This device with high precision can be used in facilities light intensity detection.

2.2.1 System hardware design

This light detection device was designed using a 51 microcontroller (MCU) as the core[25,26]. The system adopts modularity design, which includes a power module, a data collection module, a processor module, a wireless transmission module, an SD memory modules and a human interface module. The system structure diagram is shown in Figure 1 and the specific scheme is shown as follows.

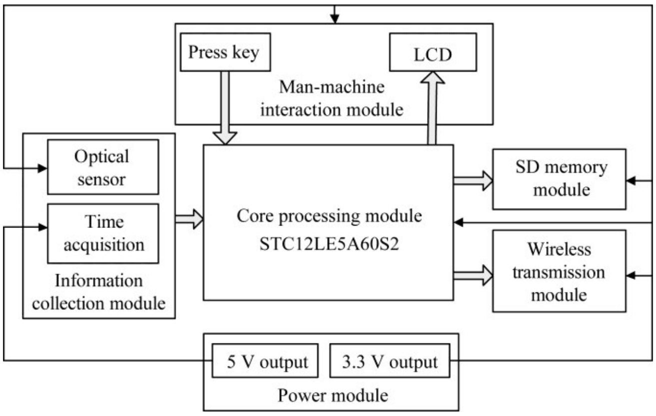


Figure 1 System architecture

The input terminal of control circuit connects with solar energy battery. Using MIC29302 chip, 12 V battery output voltage is converted to 5 V regulated power supply. The system uses standard 5 V DC to supply power. The 3.3 V power supply can be gotten from the conversion of LM1117 chip. Because power supply varies in different modules, the system uses the above two kinds of voltages to supply power for each modules.

The data acquisition module includes light and clock information acquisition, where the light detection part uses Davis's photosynthetic available radiation sensors to collect real-time environmental PAR radiant flux density value, and the clock data acquisition uses DS1302 as core to collect clock information. The working voltages of the sensor and clock collection part DS1302 are 3.3 V and 5 V. The system uses analog PAR sensors to collect real-time PAR radiant flux density. The processor module uses STC12LE5A60S2 MCU as the core processor. It mainly completes the analysis of monitoring date collected by data collection module and the calculation, analysis and processing of single band PFD.

The SD card module is used for storing the detecting single band PFD under data storage mode and light data information, which is easy for deuteric date analysis and processing. Because the STCl2LE5A60S2 MCU has serial peripheral interface (SPI) controller, the data storage can use SPI bus to simplify the operation program of the SD card.

The wireless transmitting module uses SIM900 (SIMCOM UK) as the core chip to realize wireless remote transmission of monitoring data. Data are automatically packed to TCP/IP data package by SIM900 which establishes connection with upper server by GPRS. The acquired data are transmitted to server by wireless way with sensors.

The human interface module mainly includes liquid crystal display (LCD) screen and keyboard. The LCD screen module which can realize real-time display by parallel transmission uses OCM12864-3. It has many advantages such as high data transfer rate. The keyboard adopting 4×4 matrix keyboards which can realize setting and changing parameters of system time, detection of band, etc.

2.2.2 System software design

This system adopts modularity design, using IAR as software development platform and C programming language as development language[27-30]. The system software includes information acquisition model, detection model of single band PFD, local storage model, wireless communications and uploading data model, etc. The software flow chart is shown in Figure 2. When the process started, the system determines whether the program is initialized. If it is not initialized, the system skips to the setting interface automatically for setting the system time, detection of band, longitude and latitude. Otherwise the system continuously detects real time and determines whether it has the detection instruction of single band PFD. If there is no related instruction received, the system continues to detect the time and waits for the detecting instructions; else the system detects and analyses environmental light information. By calling the counting subroutine of different bands' PFD, the detection light intensity is transformed to PFD. After that the system selects the storage mode according to the setting work model to store data. Assuming the mode is data uploading, calling the wireless transmission subroutine for real-time data uploading; otherwise the data will be stored in system's SD card to realize local storage. After completing the storage of PFD, the system waits and detects for the next instructions to perform this process. Considering the SD card's storage space may be shortage and the network transmission may be blocked during the system running, the system joined the automatically switches working mode and the function of data retransmission during the process of saving data. It can avoid losing data effectively.

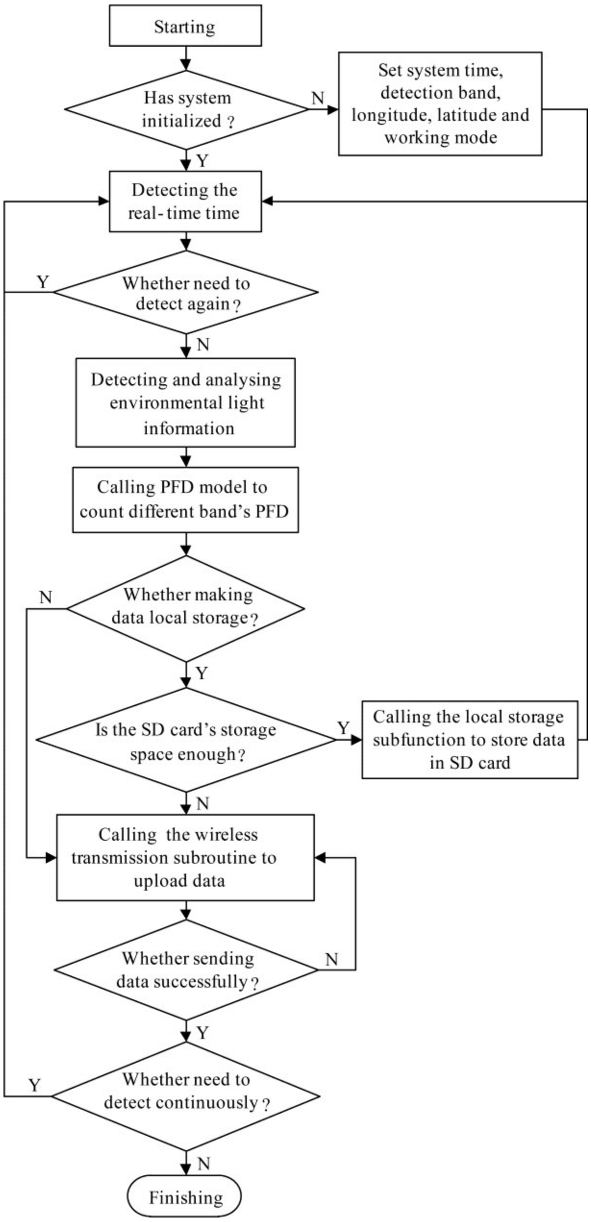


Figure 2 Flow chart of system software

The single-band model of photosynthetic PFD based on solar altitude is used as the core of PFD calculation subroutine. Firstly, according to the time, latitude and longitude information, the real-time solar altitude is calculated. Secondly, depending on the function radiant flux density proportions of single band accounting for PAR with solar altitude, the specific single band radiant flux density proportions are obtained. Finally, according to the real-time detection PAR radiant flux density and the transform relationship from the single-band spectral radiant flux density to PFD, the single band PFD can be obtained.

### 2.3 Application of the detecting device

In order to verify the rationality and reliability of the system, the device has been applied. From the beginning of deploying test, in Yangling, Shaanxi Province, China, this system was deployed in the space unobstructed continuous 30 days at 9:00-17:00 from Oct. 11 to Nov. 11, 2014. Data was recorded every half an hour. In order to verify the influence of weather on the device accuracy, weather conditions were divided into clear days and rainy days. Choosing red and blue as examples, the detection band was set blue band 440-495 nm and red band 620-770 nm. At the same time, in the same condition, the contrast test was made by using hand-held spectra radiometer FSPHH.

## 3 Results and discussion

### 3.1 Experimental data analysis

Using the principle of least square method to fit the experimental data, the functional relationships between solar altitude and spectral radiant flux density proportions of red and blue single band accounting for PAR were got. Making further analysis, the fitting curve is shown in Figure 3.

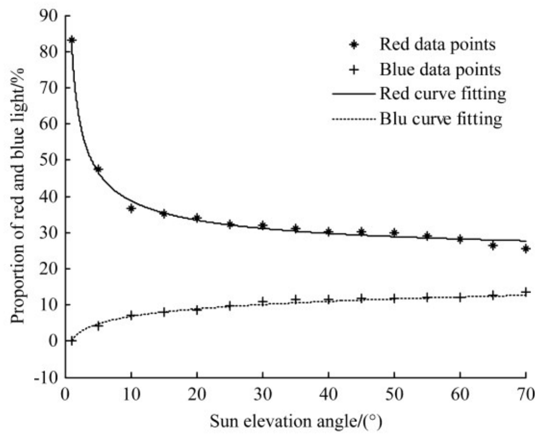


Figure 3 The fitting results of the red and blue single band

Through the error analysis, the red and blue lights fitting degrees were 0.994 and 0.963 respectively. The results showed that each of the fitting functions had good correlation. This method can be applied to other bands of PAR and has good reliability and expansibility. Therefore, the functions of radiant flux density proportions of single bands accounting for PAR with solar altitude can be established by this method.

In order to verify the rationality and reliability of the system, the model and equipment accuracy verifications were conducted respectively.

### 3.2 Model verification and analysis

The system measuring accuracy depends on the model of the percentage of specific single band spectrum radiant flux density accounting for PAR with solar altitude. The model was established under the condition of clear day and the influence of different weather was not considered. When verifying the model's accuracy, spectral radiant flux density percentages of red and blue in PAR were calculated by model under different solar altitude and contrasted with the hand-held spectra radiometer FSPHH testing results. The biggest relative error was less than 5% and the test result on November 11 is shown in Figure 4.

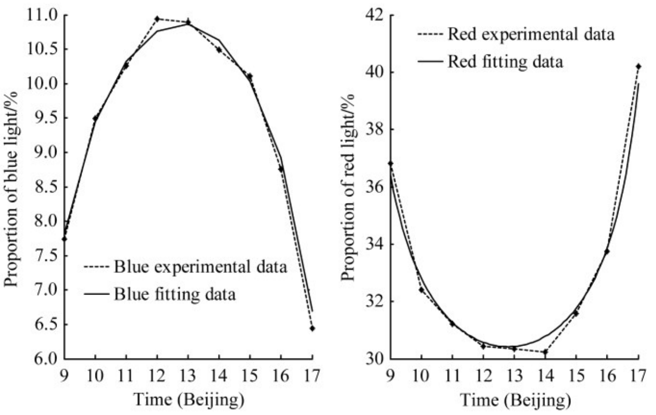


Figure 4 Model validation results

### 3.3 System verification and analysis

In order to verify the equipment's accuracy, the verification test of comparing red and blue's PFD detecting by hand-held spectra radiometer FSPHH and the equipment on clear days and rainy days were conducted respectively. By data analysis, the relation graph between system and hand-held spectra radiometer testing PFD values were established, as are shown in Figures 5 and 6.

It can be found from figures that, either clear days or rainy days, all of the determination coefficients of fitting straight lines $R^2$ are close to 1. That means red and blue testing PFD values between the system and FSPHH have a good correlation. Making further analysis, for the red light, the slope of fitting straight line was 1.0061 and the intercept was 1.8775 on clear days. And on rainy days the slope was 1.001 and the intercept was 8.7282 which is higher than that on clear days. As the error is increasing with the intercept, so the measurement precision is higher on clear days for red light. By error calculation, maximal absolute errors are 1.143% on clear days and 4.345% on rainy days. For blue light, the slope of fitting straight lines were both close to 1, and the intercept was 5.266 on rainy days which was higher than that on clear days 0.0055. And maximal absolute errors were 1.023% on clear days and 4.625% on rainy days. So we can conclude that the equipment has a higher precision when it is used on clear days. On rainy days, the equipment measurement error is relatively high, while is still less than 5%.

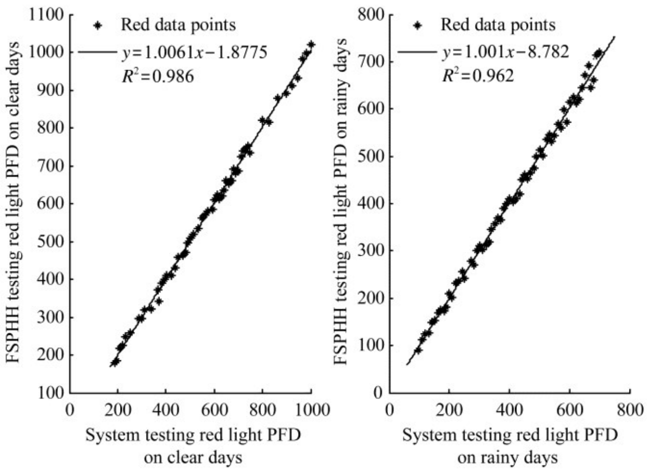


Figure 5 Correlation analysis of system and FSPHH testing red PFD

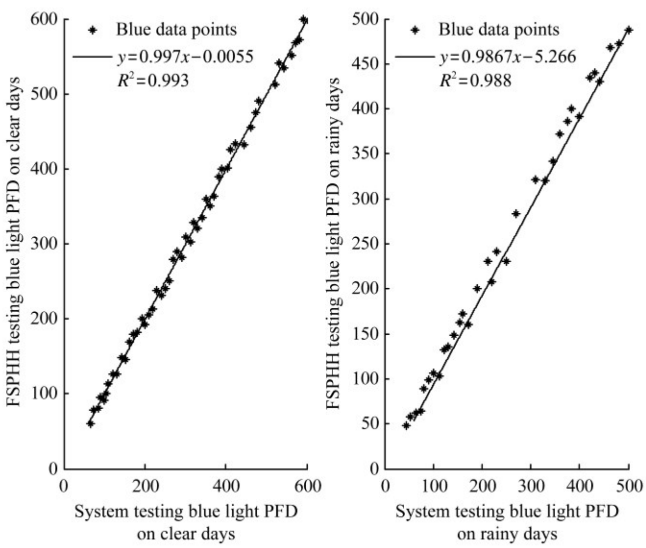


Figure 6 Correlation analysis of system and FSPHH testing blue PFD

Related experiments show that, on rainy days, the long wave parts of the solar spectrum are strengthened[31,32]. It is demonstrated that the weather situation affects equipment's precision and limits its application. But by experimental verification, the error caused by the weather is less than 5%. Therefore, it is still suitable to engineering applications which do not require high accuracy on rainy days.

## 4 Conclusions

A single-band PFD detecting model was established in this study. Through testing and verifying, the relative error of the model was less than 5%. Based on the model, a sunlight multiband PFD detecting device was designed. It can collect the specific band of PFD values combining with the date, the time, latitude, longitude and real-time total environment radiation amount. When the device was applied in a practical greenhouse, the red and blue PFD values testing results showed a good correlation with that by using hand-held spectra radiometer FSPHH and obtained a good accuracy. The system achieved the conversion of PAR radiation energy flux and PFD band by software mode. The function of detecting the specific single band values of PFD according to different crop spectral absorption characteristics can improve the system expansibility. Meanwhile, the system can obtain accurate longitude and latitude by GPS and taking quantum theory system as measurement unit, which makes a quantitative relationship with the material participating in photosynthetic reaction.

Although the weather situation affects the device's precision and limits its application, the device still has a good extensive application prospect in engineering applications that do not require high accuracy. It can be applied in light environment fast measurement outdoor or indoor shaded with colorless transparent material. In future studies, through the experimental method, corrected parameters for different weathers can be added to improve the device's accuracy.

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