Development of a canopy Solar-induced chlorophyll fluorescence measurement instrument

G Sun1,2,4, X Wang3, Zh Niu2, F Chen2

1 College of Engineering, China Agricultural University, Beijing 100083, China
2 State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
3 Beijing Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China

E-mail: bpesun@163.com

Abstract. A portable solar-induced chlorophyll fluorescence detecting instrument based on Fraunhofer line principle was designed and tested. The instrument has a valid survey area of 1.3 x 1.3 meter when the height was fixed to 1.3 meter. The instrument uses sunlight as its light source. The instrument is equipped with two sets of special photoelectrical detectors with the centre wavelength at 760nm and 771nm respectively and bandwidth less than 1nm. Both sets of detectors are composed of an upper detector which are used for detecting incidence sunlight and a bottom detector which are used for detecting reflex light from the canopy of crop. This instrument includes photoelectric detector module, signal process module, A/D convert module, the data storage and upload module and human-machine interface module. The microprocessor calculates solar-induced fluorescence value based on the A/D values get from detectors. And the value can be displayed on the instrument's LCD, stored in the flash memory of instrument and can also be uploaded to PC through the PC's serial interface. The prototype was tested in the crop field and the results demonstrate that the instrument can measure the solar-induced chlorophyll value exactly with the correlation coefficients was 0.9 compared to the values got from Analytical Spectral Devices FieldSpec Pro spectrometer. This instrument can diagnose the plant growth status by the acquired spectral response.

1. Introduction
Photosynthesis provides vegetation the base of all the material metabolism and energy metabolism. Chlorophyll fluorescence emission (The emission peak is of a longer wavelength than the excitation energy) is produced after the chlorophyll absorbs light due to direct competition with photochemical conversion. It is very valuable to quantify the amount of chlorophyll fluorescence emitted by a leaf or canopy under natural sunlight. Firstly, photosynthesis has close relationship with chlorophyll fluorescence under natural conditions. When plants are in a strong light conditions, fluorescence emission can avoid chloroplasts absorb the light over the digestive ability of photosynthesis. In this case, fluorescence plays a very important role in protecting the plants from burns. On the other hand, in general chlorophyll fluorescence and photosynthetic rate are negatively related. Hence, by measuring the yield of chlorophyll fluorescence, information about changes in the efficiency of photochemistry and heat dissipation can be gained. Secondly, fluorescence can give insights into the ability of a plant to tolerate environmental stresses and into the extent to which those stresses have damaged the photosynthetic apparatus. With the widely use of the laser-induced chlorophyll fluorimeter, the technology of active chlorophyll fluorescence was greatly used at the leaf level, which works as a probe to detect the plant's photosynthesis status. The difference of physical significance between the chlorophyll fluorescence induced by laser and that induced by sun is very

---

4 To whom any correspondence should be addressed

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
The solar-induced chlorophyll fluorescence is more intuitive to indicate the plant’s photosynthesis [1].

The amount of chlorophyll fluorescence emitted by a leaf under natural sunlight only accounts for up to 1% of the absorbed light in the visible part of the spectrum [2]. And the signal of fluorescence and the vegetation radiance are mixed together. So it is difficult to get the signal of fluorescence at the canopy level. Liangyun Liu reported that two standard Fraunhofer lines of the terrestrial oxygen absorption at 688 and 760nm are very obvious. And the chlorophyll fluorescence emission is high at this two wave bands[3]. Therefore, the two chlorophyll fluorescence emissions are possible to be measured under sunlight, and he give a method to detect the fluorescence with the spectral meter. The diurnal changes of chlorophyll fluorescence in the two experiments were primarily affected by the diurnal changes of photosynthetically available radiation (PAR). The correlation coefficients were greater than 0.9 for all the relationships between PAR and the solar-induced fluorescence of winter wheat and Japan Creeper at 688 and 760 nm based on Fraunhofer line-depth (FLD), suggesting that the solar-induced fluorescence could closely track the changes of PAR and chlorophyll fluorescence. The relative solar-induced fluorescence based on FLD was negatively related to Fv/Fm measured by an OS1-FL modulated chlorophyll fluorometer. Yongjiang Zhang et.al. studied the effects of water stress on maize leaf physiological status through passive chlorophyll fluorescence detection at the leaf level. This paper studied the method to detect the solar-induced chlorophyll fluorescence at 760nm based on the FLD at the canopy lever.

Fraunhofer lines are serials of spectral lines which were originally observed as dark features in the optical spectrum of the Sun. Those dark lines in the solar spectrum were caused by absorption by those elements in the upper layers of the sun. Some of the observed features are also caused by absorption in oxygen molecules in the Earth’s atmosphere. The principle of the FLD method is summarized and shown in Fig.1. The radiance of the target (pant) is compared to that of a sun irradiance in the same illumination condition. Parts a and b represent the detected irradiance from the sun in and out of the oxygen absorption feature, respectively. Similarly, c and d represent the detected radiance from the target at the border and at the bottom of the band. R is defined as the reflex ratio, f is the fluorescence flux. Assuming that R and f are constants in the vicinity of the band, they can be derived from the measurement of a, b, c and d. So, we can get the following formula

\[ f = d - R \times b \]  

\[ C = R \times a + f \]  

\[ d = R \times b + f \]  

\[ R = (c - d)(a - b) \]  

\[ f = d - R \times b \]

**Figure 1.** The Fraunhofer line principle of chlorophyll fluorescence.

Many absorption bands were observed in the solar irradiance spectrum including 486, 527, 589, 688 and 760nm. All these dark lines can be detected if the signal-to-noise ratio and the resolution of the spectral instrument are high enough. The 760nm and 688nm absorption bands are related with the chlorophyll fluorescence and the fluorescence radiation are strong at those two bands with the
2. Materials and methods

2.1. Instrument
The schematic diagram was shown in figure 2. The instrument was composed by incidence detecting module, the reflection detecting module and signal processing module. The incidence module is used to measure the radiance intensity of the sun at 760nm and 771nm band. Meanwhile, the reflection detecting module is used to detect the reflected spectrum which was a mixture of vegetation radiance spectrum and the fluorescence emission. The characteristic bands of 760nm and 771nm mentioned above are get through the narrow-band interference filters. The signal processing module can finish the following functions such as signal condition, A/D transfer and calculation of the intensity of the 760nm fluorescence. Moreover, the signal processing module have the functions of human machine interface, data storage and data transmission.

2.2. Incidence detecting module
The object of the incidence detecting module is to acquire the solar radiance intensity at the 760 and 771nm band. The bandwidth of the characteristic bands must be as narrow as possible, because the bandwidth of Fraunhofer line caused by absorption in oxygen molecules in the Earth’s atmosphere is less than 1nm. We selected the narrow-band filters from Andover company 010FC14-12.5 with the center band at 760 and 771nm, 1nm bandwidth and 12.5 diameter. Diffuser was mounted on the outside of the filter, which can eliminate the influence of the solar attitude to the result of the measurement. The incidence sensor was mounted on the inside of the filter. The light to digital sensor TSL2561 from TAOS was chosen. This sensor has high response from 400nm to 900nm. It has a IIC interface, which can interface with the controller to adjust the parameter of the sensor or to acquire the sensor data. In order to eliminate the effects of the stray light to the measurement precision, filter and light sensor are encapsulated in a top open solid-tube.

Figure 2. Schematic of measurement system
2.3. Reflection detecting module

Reflection detecting module faces the canopy of the object. It can measure the mix spectrum of the plant radiance spectrum and the fluorescence emission. This module composed of two detecting lens with the characteristic band at 760 and 771nm. Each detecting lens is composed by narrow-band filter, lens and silicon photoelectrical sensor. And the detecting lens is encapsulated in bottom open solid-tube. The silicon photoelectrical sensor has high response from 400nm to 1100 nm, and the peak wavelength is 850nm. What’s more important is that the short-circuit current of the sensor has good linear relationship with the light radiation. The lens is a double convex which can help to get simple imaging, and the focus and diameter are 12.7mm. Lens’s field angle is 45 digress.

2.4. Signal processing module

In this system, MSP430F1611 is the process core. It is ultra-low-power 16-bit RISC mixed-signal processor from TI. User can chose suitable working mode to reduce the power consume, so it is particularly suitable for battery application or handheld device.

Peripheral circuit includes power up circuit, storage circuit, LCD & keypad circuit, analogy signal processing circuit, serial interface and power et al. According the theory of weak signal detection, the precision, stability and sensitivity of the preamplifier determined the performance of the whole system. Therefore, the design of the preamplifier is the key of system design. Due to the large output impedance of the sensor, the I/U transform circuit is used in this design. In detail, as shown in Fig.3, the silicon photoelectrical sensor connected with the amplifier OPA2335 using current amplification manner, and the output signal connects with the port of the A/D input of the microcontroller to execute the A/D transform. In this circuit, the load resistance of the silicon photoelectrical sensor is R/A (the open-loop gain of the amplifier is A), so R/A is large enough than the output impedance. This circuit is good enough for this silicon photoelectrical sensor. This system also include a data flash AT45DB161D which have two Mbytes storage capacity. To provide a friendly human machine interface, LCD and keypad are installed in this instrument. It also has a serial interface, through which user can upload the measured data to PC.

2.5. Software design

The software was developed by modularization programming method. It comprises measuring and processing module, data storage module, serial interface module and keypad & LCD modules. Foreground and background method is this system’s event-handing mechanism. After the power up, initializer will be executed. Then, it will be into a waiting status. When it get the instruction from the user through the keypad or the serial interface, the instrument will start the measurement, and calculate the fluorescence value. The fluorescence data can be saved or upload to PC according the command from the interface.

3. Results and discussion

The following testing calibration has been carried out in the test field of Agriculture and forestry academy of sciences in Beijing. Canopy spectrum test was separately carried out to water body, clover, cement, lawn, wheat, naked soil, etc. Reflectance in 760nm and 771nm by the instrument were measured, and the reflectance data by ASD spectrometer were also got as contrast data. A 40 × 40 cm BaSO4 calibration panel was used to measure the solar irradiance at the canopy. The spectrometers works on radiance measurement mode, and calibration spectrum was measured before getting the radiance spectrum of the target. Then we can get the radiance spectrum of the target by measured radiance spectrum be divided by the reflex ratio of the calibration panel. Fig.4 and Fig.5 are the
relating result of instrument to result of ASD spectrum meter at 760nm and 771nm, respectively. The correlation coefficients of measured data between the developed instrument and ASD spectrometer are higher than 0.98.

A portable solar-induced chlorophyll fluorescence detecting instrument based on Fraunhofer line principle at the canopy level was designed and tested in this paper. By the contrast the data between this instrument with the data measured by ASD spectrometer, we can get the conclusion that this portable instrument can replace the ASD spectrometer to fulfill the task of measuring the solar-induced chlorophyll fluorescence. And the advantage of this instrument is low cost and the real-time measurement ability. And this method is possible to be adapted for remote sensing applications at aircraft or satellite altitude.

Acknowledgements
The authors would like to thank The Ministry of Science and Technology of the People's Republic of China for their financial support (2013CB733405).

References
[1] Schreiber U, Bilger W, Neubauer C 1994 Chlorophyll Fluorescence as a Non-Destructive Indicator for Rapid Assessment of in Vivo Photosynthesis *Ecological Studies*. 100 49-70
[2] Bolhar-Nordenkampf H R, Long S P, Baker N R 1989 Chlorophyll Fluorescence as a Probe of the Photosynthetic Competence of Leaves in the Field: a Review of Current Instrumentation *Functional Ecology*. 3 497-514
[3] Liangyun Liu, Yongjiang Zhang, Jihua Wang, Chunjiang Zhao 2005 Detecting Soar-Induced Chlorophyll Fluorescence From Field Radiance Spectra Based on the Fraunhofer Line Principle. *IEEE Transactions on Geoscience and Remote Sensing*. 43 827-832