SOLAR-INDUCED CHLOROPHYLL FLUORESCENCE EXTRACTION AND VALIDATION AT AIRBORNE LEVEL BASED ON AN UNMANNED AIRSHIP

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ABSTRACT

Passive remote sensing (RS) of solar-induced chlorophyll fluorescence (SIF) of vegetation is feasible at ground level, airborne level and space borne level with certain prototypes. Fraunhofer Line Discrimination (FLD) and its improved methods have been widely used to extract SIF. Unlike processing at ground level, these methods do not work so well since it is not easy to obtain the solar incident irradiance (SI) at airborne level, which is the key to calculating SIF. This paper adopts three strategies to extract SIF at airborne level. 1. Simultaneously measure SI at ground level. 2. Measure SI and acquire the hyperspectral image concurrently at airborne level. 3. Detect SIF with aFLD method which calculates SIF by comparing the radiance of the non-fluorescing target and vegetation. And then the validation and evaluation works were done with ground level measurements. The SIF values $F_{\text{airborne}}^{\text{SI}}$ calculated with airborne SI measurement are close to SIF at ground $F_{\text{ground}}$, about 30% higher. However, the SIF $F_{\text{airborne}}^{\text{SI, ground}}$ with ground based SI are mostly negative. As to aFLD method, cement ground, water and roof are used, the results $F_{\text{airborne}}^{\text{roof}}$ and $F_{\text{airborne}}^{\text{water}}$ based on the roof and water are all negative. Cement ground works better according to the same size relation of three crops with $F_{\text{ground}}$ ($F_{\text{soybean}} > F_{\text{millet}} > F_{\text{peanut}}$), while the SIF value $F_{\text{cement}}^{\text{airborne}}$ is much higher than the all crops’ $F_{\text{ground}}$ about 150%. The results show that the SI measured at ground level may have some problems for extracting SIF at airborne level. Method with SI measured at airborne level is best among these strategies. Also, this study proved that cement acted as the non-fluorescing target performs well in aFLD.

KEY WORDS Chlorophyll Fluorescence; Unmanned Airship; Hyperspectral; Validation

1. INTRODUCTION

Remote sensing has high potential in providing timely information on crop conditions during the growing season over large areas and it can be used in conjunction with crop models for predicting crop yields (Beeri and Peled, 2009). Interest in remote sensing (RS) of solar-induced chlorophyll fluorescence (SIF) by terrestrial vegetation is motivated by the link of F to photosynthetic efficiency which could be exploited for large scale monitoring of plant status and functioning (Meroni et al., 2009). Detection SIF from airborne level has been proved be an important and feasible way for precision agriculture.
All FLD-based methods require the incident solar irradiance (SI). However, unlike at ground level, Incident solar irradiance is hard to measure at ground level. Two strategies were widely used.

1. Simultaneously measure SI with spectrometer at ground level. Then, introduce into FLDs method to extracting SIF from airborne-level data.

2. Measure SI and acquire the hyperspectral image concurrently at airborne level by placing a recognizable reference object on the ground.

Zarco (2013) obtained the SI at ground level with HR2000 and retrieved SIF at airborne level. The SIF results are consistent with leaf steady state fluorescence (Fs). However, both two strategies have some disadvantages. Differences between instruments at ground and airborne level, including different spectral resolution, signal noise ratio (SNR) etc., are the main problem of the first strategy. In the second method, the reference object must be Lambert and its reflectance should be acknowledged. And most important, it should be large enough to be observed at airborne-level.

A convenient and feasible fluorescence retrieval method at airborne level was first adopted by comparing the radiance acquired from fluorescing and non-fluorescing targets, here referenced as aFLD(Maijer, 2002). This method was successfully tested at the leaf and canopy levels (Meroni et al., 2004, 2008a, 2008b; Moya et al., 2004). Zarco (2009) successfully extracted SIF at airborne level and linked SIF to water stress of fruiter.

All the three methods (two strategies in FLD and aFLD) were proved be feasible to extract SIF at airborne level, while, the performances has not be compared and valued.

In this article, an airborne experiment with corresponding measurements at ground level, which can adopt these three methods, was conducted. Based on the experiment, the comparison of these three methods was done.

2. MATERIALS AND METHODS

2.1 Airborne campaigns and field experiments

2.1.1 Study site

The study was conducted on 31st August 2013 at State Key Laboratory of Remote Sensing experimental site in Baoding, Hebei province (N 38°42′48″, E 115°27′51″). The region belongs to North China Plain, at an altitude of 40m above the sea level. The annual average temperature is 12℃, annual rainfall is 550 mm, belongs to the temperate monsoon climate. The major crops are corns, soybeans, millets and peanuts. Corns were matured and part has been harvested when the experiments carry out. A variety of other plants were in the exuberant growth period. By that time, the canopy heights of millets, soybeans and peanuts are less than 0.5m with full crops. The structures of the canopy can be considered as
horizontal homogeneous. The shadow and soil effects are negligible.

2.1.2 Airborne campaign

An unmanned airship platform FY-17 for remote sensing research was developed to carry a payload with hyperspectral imaging sensors and GPS/INS system. Considering the standing-air-time, security and reliability, the unmanned airship was chosen instead of other air vehicles. The platform is 17 m length with up to 3 hours and 40 kg payload (Fig.1). The unmanned airship filled with helium can reach 1 km flying height and 60 km/h ground speed. The platform is automatically controlled by flight operating system at ground, communicating by radio signal at 400 Hz (Fig.2b). The deviation from the flight line is about 5 m under the control of the ground station, which means the data acquired in the flight lines can be geometric rectified.

![Image of FY-17 airship](image)

Figure 1. FY-17 airship’s five parts: emages (direction and balance control), gasbag, pod (airship controller), holder (detection system) and propelling system

The hyperspectral imaging sensor (AisaEAGLET, Specim, Finland), operates with a full width at half maximum (FWHM) of 3.3 nm and ~1nm spectral sampling, ranging from 400 to 1000 nm. The hyperspectral imager was calibrated in April 2013 by Specim. The 18.5 mm focal length lens yielded an FOV 35°. Frame rate storage on board the airship was set to 30 fps with an integration time of 4ms. The energy of the two pixels is merged to avoid frame dropping by setting the spatial binning to 2. The precision of GPS/INS system (RT3100, Oxford Technical Solutions, England), which is designed for the AisaEAGLET and used for recording the position and pose of each pixel, can reach 0.5m for location and 0.1 degrees for attitude measuring. The hyperspectral image acquired was geometric rectified utilizing the GPS position and pose information. AisaEAGLET data were geometrically and radiometrically corrected using CALIGEO software (Specim, Finland) (Fig. 3). Finally, the radiance spectra were obtained for each pixel. These radiance spectra
were used for extracting the chlorophyll fluorescence by O\textsubscript{2} in-filling method.

**Figure 3. Hyperspectral image**

The length of the flight line is about 1.5 km from east to west at 400 m altitude. The original pixel resolution is about 0.32 m, resampled as 0.5 m at geometric correction with nearest neighbor algorithm. Besides the crops, some bare soils and buildings are in the flight line. A reflectance standard board was placed at the center of the flight line in a quite open area. The size of the board is 6 meters width and 10 meters length, made up by four small panels 1.5 m\texttimes10 m, more than 100 pixels in the airborne hyperspectral image. The board was designed and calibrated by the Institute of remote sensing application (IRSA) of China Academy Sciences. The board is considered as lambert reflector and the reflectance from 300nm-1000nm is approximate 0.6. The SI was calculated with the known reflectance of the board.

**2.1.3 Field experiments**

Measurements of ChlF at ground level were simultaneously taken by hyperspectral spectrometer HR4000 (Ocean Optics, USA) between twelve and half past twelve local time. The fiber-optics spectrometer with 0.05 nm FWHM provided spectral measurements range from 720 nm to 810 nm with 3648 channels. The spectrometer was specifically designed for fluorescence detection around 760 nm. The device was installed with 1.5 m long, 600 micron optical fiber using VIS-NIR cosine corrector-diffuser.

The spectrometer was used to measure the SIF of three crops, including soybeans, millet and peanuts. Besides, the incident solar irradiance was obtained every 5 minutes using a diffuse reflectance spectalon WS-1 (Ocean Optical, USA). The WS-1 diffuse reflectance standard is made of PTFE, a diffuse white plastic that provides a lambertian reference surface for reflectance experiments. It is >98% reflective from 700-900 nm, calibrated at National Institute of Metrology (China).

**2.2 Solar-induced fluorescence extraction methods**

Based on the assumption that the fluorescence emission and ground reflectance standard are lambert, the vegetation apparent radiance \( L(\lambda) \) at band \( \lambda \) is composed by two parts: Reflectance of incoming light and fluorescence emitted by vegetation:

\[
L(\lambda) = r(\lambda) \times \frac{E(\lambda)}{\pi} + F(\lambda)
\]

(1)

Where \( F(\lambda) \) is the fluorescence at band \( \lambda \), \( r(\lambda) \) is the actual reflectance which is fluorescence free, \( E(\lambda) \) is
solar incident irradiance interacting with the plant. The SIF signal, which contributes less than 3% of the reflected light energy near infrared part of the spectrum, is too weak to detect under natural light (Moya et al., 2004). Reduced by the atmospheric absorption, the solar spectrum at ground level has many dark lines whose band widths are between 0.1nm and 10 nm (which are so-called Fraunhofer lines). Meanwhile, fluorescence signal is highlight and plant reflectance of incoming is weak inside Fraunhofer Line, which makes it possible to extract SIF.

In Fraunhofer Line, the reflection signals fail in and fluorescent information highlighted. O2-A dark line has been regarded as the best choice in ChlF detecting due to the wider, deeper absorption valley, also it is closer to fluorescence emission peak than O2-B and Hα dark line which are main absorption lines in red and near infrared (Moya et al., 2004).

2.2.1 FLD

The FLD relies on two flux measurements, one inside and one outside a Fraunhofer line. The magnitude of ChlF is deduced by comparing the signal measured inside the dark line with the signal measured in a nearby wavelength that contains the entire solar background irradiance (Plascyk, 1975; Meroni et al, 2009).

SIF signal is calculated by comparing apparent radiance and irradiance in (λin) and out (λout) of Fraunhofer line. It is assumed that the reflectance and fluorescence are constant. Then we can get the value of ChlF and actual reflectance (without the influence of ChlF).

$$r(\lambda) = \frac{F(\lambda_{\text{out}})E(\lambda_{\text{in}})}{\pi} + F(\lambda_{\text{in}})$$

$$F = \frac{E(\lambda_{\text{out}})E(\lambda_{\text{in}}) - L(\lambda_{\text{out}})E(\lambda_{\text{in}})}{E(\lambda_{\text{out}}) - E(\lambda_{\text{in}})}$$

Where r (λ) represents the actual reflectance of target, L (λin) and L (λout) are the target radiance in and out of Fraunhofer Line. E (λin) and E (λout) represent the solar irradiance in and out of O2-A Fraunhofer Line.

When it comes to detecting SIF at airborne level, two strategies are used to obtain the solar incident irradiance. Due to the recognizable reflectance standard board at ground, we can extract the spectrum of SI through the hyperspectral image without auxiliary measurements. Another strategy is obtaining SI by ground hyperspectral spectrometer. In our study, the HR4000 is used to acquire SI.
To match the spectral resolution of the radiance imagery acquired by the hyperspectral airborne sensor, the high-resolution irradiance spectra measured with the HR4000 instrument was resampled through Gaussian convolution.

\[
L_{\lambda, \text{FWHM}_d} = \int_{-\infty}^{\infty} L_{\lambda, \text{FWHM}_o} \cdot K_{\lambda-\hat{\lambda}} d\hat{\lambda}
\]  

(4)

\[
K_{\lambda} = \frac{2\sqrt{\pi}}{\text{FWHM}_o \cdot \text{FWHM}_d} e^{-\frac{4(\text{ln2})^2}{\text{FWHM}_o \cdot \text{FWHM}_d}}
\]

(5)

Where FWHMo is the original FWHM of HR4000, FWHMd is the targeted FWHM of the AisaEAGLET, \(L_{\lambda, \text{FWHM}_o}\) is the original radiance, \(L_{\lambda, \text{FWHM}_d}\) is the targeted radiance, \(K_{\lambda-\hat{\lambda}}\) is the Gaussian function.

Meanwhile, \(\int_{-\infty}^{\infty} K_{\lambda-\hat{\lambda}} d\hat{\lambda} = 1\) (Alexander.Damm et al., 2011).

### 2.2.2 aFLD

Because of the difficulty to get the solar radiance at airborne level, aFLD method is proposed (Maier, 2002). This method regards a non-fluorescing target as the reference body, such as horizontal roof and cement ground, of which the reflectance are basically unchanged. Then the relationship between solar radiance and non-fluorescing target is expressed in Eq. (6).

\[
\frac{E(\lambda) r_u(\lambda)}{\pi} = L_u(\lambda)
\]

(6)

Where \(L_u(\lambda)\) is the apparent radiance of non-fluorescing target. Then we can use non-fluorescing target’s reflectance \(r_u\) and its apparent radiance \(L_u\) to present solar incident irradiance \(E\). In this way, Eq (6) could be introduced in Eq (1), here comes the new equation (7).

\[
L(\lambda) = \frac{L_u(\lambda)}{r_u(\lambda)} \times r + F
\]

(7)

Where \(L(\lambda)\) is target apparent radiance, \(r\) is target reflectance, \(F\) represent the value of SIF.

Same as FLD, aFLD takes two bands of non-fluorescing target in and out of Fraunhofer Line. It is assumed that their reflectance is constant (\(r_u(\lambda_{\text{in}}) = r_u(\lambda_{\text{out}})\)), then we could get the value of SIF.

\[
F = \frac{L_u(\lambda_{\text{out}}) L_u(\lambda_{\text{in}}) - L_u(\lambda_{\text{in}}) L_u(\lambda_{\text{out}})}{L_u(\lambda_{\text{out}}) - L_u(\lambda_{\text{in}})}
\]

(8)

In this article, the cement ground, roof, artificial pond are regards as the non-fluorescing target. Their radiance were obtain from the hyperspectral image and used in the aFLD method.

### 3. Results

#### 3.1 Solar incident radiance

To extract SIF signal from the hyperspectral image with FLD method, it is essential to obtain the solar incident spectrum. As mentioned, in the study, both ground based instrument HR4000 and airborne-level hyperspectral sensor are used. The airborne campaign was carried out during the local time 12:14 to 12:20. The spectrum of the solar incident is taken during the campaign with the reflectance standard, and then transferred from digital signal to radiance.
In order to introduce the spectrum acquired by HR4000 to FLD method, calculating SIF value in the hyperspectral image at airborne level. The high-resolution radiance spectra measured was resampled through Gaussian convolution (Fig. 5). After degrading, the details in the absorb line is disappear. Also, the width and depth of the absorb line are diminish. In this study, the bottom of absorb dark line around 760 nm is lifted significantly, from 3 to 14 (mW cm\(^{-2}\) str\(^{-1}\) um\(^{-1}\)). At the same time, the solar incident radiance was collected at airship platform with AisaEAGLET. More than 50 pixels were selected in the reflectance standard board to obtain the solar incident radiance at airborne level. The degraded spectrum from HR4000 has the same FWHM (3.3 nm) with the solar incident radiance spectrum at airborne level.

![Figure 5. Solar incident radiance. The green curve represents the original spectrum by HR4000, the red curve is the spectrum degraded through Gaussian and the blue curve is SI from airborne level](image)

The airborne-derived fluorescence quantification was compared with ground measurements of canopy-level fluorescence. In this study, due to the horizontal homogeneous structures of the canopy, soybeans, peanuts and millets were choose to extracting SIF both at airborne and ground level. The SIF at 760nm are calculated based on FLD. The wavelength (761.27002 nm) with the lowest radiance near 760nm is regarded as the inside band of the O2-A feature. To assess the difference of the original spectra obtained by HR4000 with 0.05 nm FWHM and the degraded spectra with 3.3 nm FWHM, the SIF values are derived through FLD method with the same inside band and outside band (Fig. 6). The results show that after degrading, the SIF values of millets, soybeans and peanuts reduce slightly, 3.18%, 3.46% and 4.58% respectively. In both two spectral resolutions, the quantitative relation is coherent enough, which is \( F_{\text{soybean}} \gg F_{\text{millet}} \gg F_{\text{peanut}} \). With 0.05 nm and 3.3 nm FWHM, the variances for the three crops changes little. The standard deviations are 0.029, 0.040 and 0.017 for the SIF results with 0.05nm FWHM and 0.028, 0.039 and 0.017 (mW cm\(^{-2}\) str\(^{-1}\) um\(^{-1}\)) for the values with 3.3 nm FWHM. According to the comparison, we can believe that the differences of SIF derived from the spectral measurements with these two spectral resolutions are negligible.

3.2 SIF at ground level and airborne level
Two methods were used to extract SIF at airborne level, FLD and aFLD. When it comes to FLD method, the solar incident radiance is necessary. The degraded solar incident radiance spectrum and the spectrum obtained through AisaEAGLET are introduced to the FLD to calculate the fluorescence in the hyperspectral image. The plots of millets, soybeans and peanuts are adjacent to each other (Fig. 3). The average fluorescence of the plots are listed and compared with the ground based measurements (Fig. 7).

Solar-induced fluorescence estimates at the O$_2$-A band made with different instruments under different illumination intensities vary from near 0 to 17 W m$^{-2}$sr$^{-1}$µm$^{-1}$ (Meroni et al., 2009) (0 to 1.7 mW cm$^{-2}$ sr$^{-1}$µm$^{-1}$). All the positive values are within the scope. The SIF values $F_{\text{airborne}}^{SI}$ calculated with airborne SI measurement are close to the ground SIF values $F_{\text{ground}}$, only about 30% higher. However, the SIF values $F_{\text{ground}}^{SI}$ with ground based SI are mostly negative. Millets’, soybeans’ and peanuts’ fluorescence is 0.036, -0.044 and -0.116 (mW cm$^{-2}$sr$^{-1}$µm$^{-1}$).

In the aFLD method, cement ground, water and color steel roof are used, the results $F_{\text{airborne}}^{\text{roof}}$ and $F_{\text{airborne}}^{\text{water}}$ based on the roof and water are all negative. The negative values are abnormal, since the plots are full crops and the soil has little effect on the SIF signal. The SIF values $F_{\text{airborne}}^{\text{cement}}$ are much higher than the all crops’ $F_{\text{ground}}$. For millets, the value derived at airborne level is 0.840 and the ground result is 0.281. Similarly, 0.978 and 0.349 are the SIF of the soybeans. The peanuts’ values
are 0.786 and 0.243. All fluorescence signals extracted through aFLD with cement as the non-fluorescence reference are three times than the signal measured with HR4000 at ground level. Compare to water and the color steel roof, cement ground works better according to fact that the quantity relation of three crops is the same with $F_{\text{ground}} (F_{\text{soybean}} > F_{\text{millet}} > F_{\text{peanut}})$.

4. DISCUSSION AND CONCLUSION

Different fluorescence signals are derived from the same hyperspectral image with FLD and aFLD. According to the values in aFLD method, three non-fluorescence references have totally different performances. Both FLD and aFLD, SIF are extracted by comparing the reflected energy of the vegetation with the solar incident radiance or the references’ reflected energy. When the solar incident radiance can acquire whether with ground based or airborne-level measurements, the FLD is feasible. However, in many cases, such supplementary measurements or materials are not available during the airborne campaign. aFLD works in this situation since this method could derive ChlF just based on the remote sensing image.

<table>
<thead>
<tr>
<th>reflectance</th>
<th>Reflectance standard</th>
<th>Cement ground</th>
<th>Roof</th>
<th>water</th>
</tr>
</thead>
<tbody>
<tr>
<td>761.27nm</td>
<td>59.23%</td>
<td>24.41%</td>
<td>7.49%</td>
<td>2.52%</td>
</tr>
<tr>
<td>755.79nm</td>
<td>62.36%</td>
<td>24.70%</td>
<td>8.57%</td>
<td>3.17%</td>
</tr>
<tr>
<td>Out-In</td>
<td>3.13%</td>
<td>0.29%</td>
<td>1.08%</td>
<td>0.65%</td>
</tr>
</tbody>
</table>

Extracting SIF from the hyperspectral image at airborne level, the spectrum of the solar incident radiance or the three non-fluorescence references are introduced to the FLD and aFLD methods.

As the Fig.5 shows that when SI obtained at ground was degraded, the depth of the $O_2$-A feature was decrease. When we introduce the degraded SI as the apparent reflected energy to the reflectance calculation, the result will not be 0.6 constantly. The degraded SI measured at ground was error contained. The error may come from the degrading method. However, other differences except FWHM between two spectrometers were not considered in our case, which happen to many airborne-level SIF experiments.

The SI obtained at airborne level was regarded as the real solar incident radiance due to the better result. Based on it, the reflectance of non-fluorescing target and reflectance standard can be calculated. Only two relevant bands (761.27nm and 755.79nm) were listed in Tab.1.

The differences of reflectance between in-band and out-band are ordered by \( \text{reflectance standard} > \text{cement ground} > \text{roof} > \text{water} \). In aFLD, we assume that the reflectance of in-band and out-band of the non-fluorescing target is constant. In this case, only cement ground’s is consistent with hypotheses. It is the main reason that the performances of other references are not so satisfactory.
In conclusion, it is error favor that introducing the solar incident irradiances obtained at ground level into airborne level image for extracting SIF. Measuring solar incident irradiances at airborne level with the hyperspectral sensor which is simultaneously used to get the radiances of vegetation perform best for SIF detection at airborne level. As to aFLD, different non-fluorescing targets have various performances. The roof and water is not feasible, because the reflectance inside and outside the Fraunhofer Line changes too much. Even though the SIF value extracted with the cement ground is about 150% to the ground based measurements, it performs better according to the same size relation of three crops with $F_{\text{ground}} \geq F_{\text{soybean}} \geq F_{\text{millet}} \geq F_{\text{peanut}}$.

REFERENCE


