Effects of spectral resolution and SNR on the vegetation solar-induced fluorescence retrieval using FLD-based methods at canopy level

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Abstract
The accuracy of solar-induced chlorophyll fluorescence (SIF) retrieval is dependent on the specifications of the sensor used. Here, we present a quantitative accuracy assessment of the SIF retrieval for different spectral resolution (SR) and signal-to-noise ratio (SNR) at five potential bands (Hα, O_{2}-B, Fe, O_{2}-A, and KI). Firstly, the sensitivities of the SIF retrieval to the correction factors in the FLD algorithm or the radiance noise increased rapidly when the SR decreased, especially for the O_{2}-B band. Then, the dominant factor influencing the SIF retrieval was the SNR for the narrow bands, while was the SR for the broad band. Finally, the accuracy assessment of the SIF retrieval for the potential space-based hyperspectral sensors, including GOSAT TANSO-FTS, SCIAMACHY, OCO-2, Metop GOME-2, and FLEX FLORIS, showed a large error (>35%) for GOSAT, and relative small errors from 5% to 20% for other sensors.

Keywords: Solar-induced chlorophyll fluorescence (SIF), Fraunhofer Line Discrimination (FLD), accuracy assessment, spectral resolution (SR), signal-to-noise ratio (SNR).

Introduction
A characteristic spectral emission known as solar-induced chlorophyll fluorescence (SIF) can be observed in the red and far-red spectral regions under excitation by solar radiation. The use of SIF is a very promising approach in the detection of the physiological status of vegetation as it can be a reliable and observable indicator of the actual photosynthetic activity of terrestrial vegetation [Lichtenthaler and Rinderle, 1988; Liu et al., 2013]. However, the retrieval of SIF values is difficult because the SIF represents only a small amount of the reflected radiance and about 1% of the total light absorbed [Maxwell and Johnson, 2000]. Although the observed vegetation radiance inevitably includes contributions from both reflected and fluoresced radiation, it is possible to separate SIF radiation from the observed apparent vegetation reflectance. The Fraunhofer Line Discrimination (FLD) principle [Plascyk, 1975; Plascyk and Gabriel, 1975] allows the retrieval of the SIF at the solar Fraunhofer lines or at the strong telluric atmospheric absorption bands, where the intensity...
of the emitted fluorescence is comparable to the intensity of the incoming radiation [Carter et al., 1990; Carter et al., 1996; Liu et al., 2005; Joiner et al., 2011]. The standard FLD method assumes that the reflectance and SIF are wavelength independent within the narrow absorption band and employs two channels (one within the absorption band and the other outside the absorption band) to separate the SIF signal. However, the assumption is weak for broad absorption bands. Especially for exploitation of sFLD at O$_2$-B band, the major limitation is mostly due to the highly variable spectral behaviour of both reflectance and SIF in this spectral window. To overcome the limitations caused by the assumptions inherent in FLD, Maier et al. [2003] proposed a 3FLD method that uses three channels (left shoulder, inside valley and right shoulder of the absorption band) to retrieve SIF values. This method can account for the linear variation of the SIF and reflectance in the region of the absorption bands. Alonso et al. [2008] presented an improved FLD (iFLD) method that improved the accuracy of the estimation of SIF based on the incorporation of two correction coefficients intended to include the spectral characteristics of both reflectance and fluorescence in the region of the absorption band. In general, the standard FLD method strongly overestimates SIF, while the 3FLD and iFLD methods provide a more accurate estimation [Meroni et al., 2009].

The SIF spectrum covers the spectral wavelength range from about 650 to 850 nm, with two peaks at approximately 685 and 740 nm [Lichtenthaler and Rinderle, 1988; Franck et al., 2002]. Within this spectral window, there are several solar Fraunhofer lines and telluric atmospheric absorption bands [Moya and Cerovic, 2004]. The O$_2$-A band at 761 nm and the O$_2$-B band at 687 nm have been widely employed for SIF retrieval because they are relatively broad and can be easily detected using hyperspectral data with a spectral resolution (SR) of about 1 nm [e.g. Liu et al., 2005; Guanter et al., 2007; Mazzoni et al., 2008; Guanter et al., 2010; Mazzoni et al., 2012]. However, as telluric atmospheric absorption bands, the O$_2$-A band and O$_2$-B band are strongly disturbed by atmospheric radiation transfer, which make it difficult to retrieve SIF from space. In contrast, the solar Fraunhofer lines (such as the KI line at 770.1 nm and the Fe line at 758.8 nm) are less affected by the disturbance due to the atmosphere [Frankenberg et al., 2011; Guanter et al., 2013], but they are much narrower and can only be detected when the SR is better than 0.1 nm. In addition, the broader H$\alpha$ band centered at 656.5 nm has also been employed for SIF detection [McFarlane et al., 1980; Carter et al., 1990].

In recent years, as high spectral resolution data from several space-based sensors has become available, many studies on SIF retrieval from space have been carried out. Band 1 of GOSAT TANSO-FTS covers the spectral region 758-775 nm with an SR of about 0.022 nm. Kuze et al. [2009] showed that the O$_2$-A band, together with the KI and Fe lines, were observable in the 0.022 nm resolution spectra. Joiner et al. [2011], Frankenberg et al. [2011] and Guanter et al. [2012] have employed GOSAT hyperspectral data for global SIF retrieval. The SCIAMACHY instrument on board ENVISAT is a grating spectrometer that operates from ultraviolet to near-infrared wavelengths (212–2386 nm) in eight separate channels. SIF retrieval using channel 4 (595-812 nm) of this spectrometer, which has an SR of 0.48 nm, was explored by Joiner et al. [2013]. Similarly, GOME-2 is an operational nadir-viewing UV/visible cross-track scanning spectrometer [Munro et al., 2006]. Joiner et al. [2013] employed channel 4 of GOME-2, which covers the wavelengths 590-90 nm with an SR of approximately 0.5 nm, for the global mapping of SIF. The recently launched
OCO-2 can provide hyperspectral data in the $\text{O}_2$-A band with an SR of 0.042 nm and a relatively high spatial resolution, which is promising for space-based SIF retrieval. The potential of OCO-2 for SIF retrieval has been investigated by Frankenberg et al. [2014]. In addition, the Fluorescence EXplorer (FLEX) mission has been selected as one of the two candidates for ESA’s Earth Explorer 8 mission. If this mission is finally selected, the FLuORescence Imaging Spectrometer (FLORIS) will fly in formation with Sentinel-3 to monitor global SIF with a spatial resolution of 300 m [Kraft et al., 2014].

The configurations of the sensors mentioned above are quite different. The SR and signal-to-noise ratio (SNR) of sensors are two important factors that influence the accuracy of SIF retrieval. According to the basic principle of the FLD-based method, the robustness of the SIF retrieval relies on the absorption depth. Cao et al. [2013] found that the SIF retrieval accuracy substantially decreased in higher-altitude areas when using the standard FLD and 3FLD methods at the $\text{O}_2$-A band. The reason for this was the decrease in the absorption depth of the $\text{O}_2$-A band. As shown by Meroni et al. [2009], the shapes of these absorption bands are affected by the sensor’s SR. Therefore, it is important to quantify the impact of the sensor characteristics on the accuracy of SIF retrieval at different bands. Damm et al. [2011] showed that the accuracy of SIF retrieval (at the $\text{O}_2$-A band) was mostly affected by the SNR, while about 40% of the error was related to the SR. Liu and Liu [2014] assessed the sensitivity of the five potential bands to atmospheric radiation transfer under different SR conditions. Due to the different shapes and widths of these five bands, the effect of the SR or SNR on the different bands will not be the same. To the best of our knowledge, there is still no work analyzing the accuracy of SIF retrieval at all five potential bands for different SR and SNR conditions and the theoretical retrieval accuracy of the potential satellite sensors has not been investigated or compared.

In this paper, the FLD-based methods for SIF retrieval are investigated using the simulated spectral dataset at canopy level, and the aims are: 1) to analyze the sources of uncertainty sources for SIF retrieval for the FLD-based methods; 2) to quantify the influence of the SR and SNR on SIF retrieval at different bands; 3) to present some preliminary investigation on the theoretical retrieval accuracy of SIF for potential satellite sensors, including GOSAT, OCO-2, GOME-2 and SCIAMACHY and also the planned FLORIS.

**Materials and Methods**

**Data simulation**

The SIF and reflectance spectra used in this paper were simulated by the SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes) model. The SCOPE model is an integrated model of soil-canopy spectral radiance, photosynthesis, fluorescence, temperature and energy balance [Van der Tol et al., 2009]. It has been proved able to reproduce realistic radiance spectra for SIF retrieval studies and applications.

In the simulation experiment, the leaf chlorophyll content (Cab) was set as 20–80μg/cm², based on the 120 samples in the LOPEX’93 dataset; the Leaf Area Index (LAI) was set at values of 1, 2, 4 and 6; and the fluorescence quantum efficiency (FQE) was set as 0.02 and 0.04 [Damm et al., 2011]. All the other parameters required by SCOPE were set at their default values—the details are listed in Table 1. In total, 32 datasets, which included SIF and top-of-canopy (TOC) reflectance spectra, were simulated with different Cab, LAI and FQE values.
Table 1 - Leaf and canopy parameters used in the SCOPE model [Van der Tol et al., 2009].

| Parameter | Value          | Unit     | Description                        |
|-----------|----------------|----------|------------------------------------|
| PROSPECT  |                |          |                                    |
| Cab       | 20, 40, 60, 80 | μg cm⁻²  | Chlorophyll AB content             |
| Cdm       | 0.012          | g cm⁻²   | Dry-matter content                 |
| Cw        | 0.009          | cm       | Leaf-water-equivalent layer        |
| Cs        | 0              | fraction | Scenecent material fraction        |
| N         | 1.4            |          | Leaf-thickness parameters          |
| Canopy    |                |          |                                    |
| LAI       | 1, 2, 4, 6     | m² m⁻²   | Leaf area index                    |
| hc        | 2              | M        | Vegetation height                  |
| LIDFa     | -0.35          | -        | Leaf inclination                   |
| LIDFb     | -0.15          | -        | Variation in leaf inclination      |
| leafwidth | 0.1            | M        | Leaf width                         |
| Fluorescence |          |          |                                    |
| FQE       | 0.02, 0.04     | -        | Fluorescence quantum yield efficiency at photosystem level |

The solar irradiance arriving at the TOC was simulated by MODTRAN5 [Berk et al., 2005] with an SR of 0.005 nm. The solar zenith angle (SZA) was set as 30° and the view zenith angle as 0°. The TOC upwards radiance could then be calculated using equation [1]:

\[
L_{TOC} = \frac{(E_{dir} \mu_s + E_{dif}) \rho_s}{\pi} + SIF \quad [1]
\]

where \(E_{dir}\) and \(E_{dif}\) are the direct and diffuse fluxes of solar irradiance arriving at the surface, \(\mu_s\) is the cosine of the solar zenith angle and \(\rho_s\) is the surface reflectance.

**Spectra re-sampling and noise simulation**

In order to assess the uncertainties in SIF retrieval caused by sensor configurations, the irradiance and radiance spectra at the TOC were simulated using different values of the SR and SNR. To obtain the irradiance and radiance spectra for different SRs, a Gaussian function with different values of the Full Width at Half Maximum (FWHM) was employed to simulate the spectral response function of different sensors. Then, the Gaussian filters with different FWHM values were convolved with the reference high-resolution spectra (with an SR of 0.005 nm). Finally, the smoothed spectra were re-sampled using an interval that was half the size of the SRs.

In addition, the radiance spectra with different SNR levels were simulated by adding a random Gaussian-distributed noise that had a mean value of 0 and a standard deviation that was dependent on the SNR level. The SNR is defined as the ratio of the reference signal
intensity to the standard deviation of the random Gaussian-distributed noise. In this study, radiance spectra with ten different SNR levels (50, 100, 200, 300, 500, 1,000, 2,000, 5,000, 10,000, and 100,000) were simulated. The reference signal intensity was set as the intensity at the outside channel of a canopy radiance spectrum with an LAI value of 4, under solar irradiance with an SZA of 30°. Therefore, the absolute noise intensity was different for the five potential bands, because the reference radiance is smaller at red band, and higher at NIR band.

![Figure 1 - TOC solar irradiance spectra with different SRs in five potential absorption bands used for SIF retrieval.](image)

There are five mainly absorption bands employed here. Figure 1 shows the solar irradiance spectra at different SRs in five potential bands (Hα, O₂-B, Fe, O₂-A and KI) for FLD-based SIF retrieval, which was derived from the irradiance spectrum with an SR of 0.005 nm simulated by MODTRAN5. It is clear that the absorption depth and absorption shape are dependent on the SR, and that the absorption depth increases with higher SR.

**Specifications of the potential satellite sensors for SIF retrieval**

In recent years, many studies on space-based SIF retrieval have been carried out using hyperspectral data acquired by satellite sensors. The potential sensors for SIF retrieval include GOSAT TANSO-FTS, SCIAMACHY, OCO-2, Metop GOME-2, and FLEX FLORIS, and their spectral and SNR specifications are listed in Table 2.

| Sensor             | SR (nm) | SNR  | Reference                  |
|--------------------|---------|------|---------------------------|
| GOSAT TANSO-FTS    | 0.022   | 300  | [Kuze et al., 2009]       |
| OCO-2              | 0.042   | 1000 | [Frankenberg et al., 2014]|
| GOME-2             | 0.5     | 1000 | [Callies et al., 2000]    |
| SCIAMACHY          | 0.48    | 2800 | [Lichtenberg et al., 2006]|
| FLEX FLORIS        | 0.3@O₂; 3@Ha | 3000 | @ O₂-B & Hα; 200-1200@O₂-A | [Kraft et al., 2013] |
**Methods of SIF retrieval**

**The standard FLD method (sFLD)**
The solar-induced fluorescence signal overlaps with the reflected light and can be separated out at the Fraunhofer lines or strong atmospheric absorption bands, where the amount of incident irradiance is comparable to the amount of fluorescent emission [Plascyk, 1975; Plascyk and Gabriel, 1975]. According to the standard Fraunhofer line discrimination (sFLD) method, the solar-induced fluorescence can be retrieved as [Plascyk and Gabriel, 1975]:

\[
F_{in} = \frac{I_{out}L_{in} - I_{in}L_{out}}{I_{out} - I_{in}} \quad [2]
\]

where \(I_{in}\) and \(I_{out}\) represent the irradiance inside and outside the absorption feature, respectively, and \(L_{in}\) and \(L_{out}\) represent the reflected radiance inside and outside the absorption feature, respectively.

**The three-channel FLD method (3FLD)**
The 3FLD method was proposed by Maier et al. [2003]. It assumes that the variation in the SIF and the reflectance over the spectral range is linear. The irradiance and radiance of a single reference channel (\(I_{out}, L_{out}\)) are replaced by the weighted averages for two channels at the left and right shoulders of the absorption band.

**The improved FLD method (iFLD)**
According to Alonso et al. [2008], an improved FLD method (iFLD) was derived by employing two correction factors to account for the variations in reflectance and fluorescence inside and outside the Fraunhofer line. The iFLD was defined as:

\[
F_{in} = \frac{\alpha_R \times L_{in} \times I_{out} - L_{out} \times I_{in}}{\alpha_R \times I_{out} - \alpha_F \times I_{in}} \quad [3]
\]

where \(\alpha_R\) is the ratio of the reflectance value outside the absorption feature to that inside it, and \(\alpha_F\) is defined similarly for the fluorescence values.
The correction factors \(\alpha_R\) and \(\alpha_F\) cannot be directly obtained from spectroradiometric measurements under natural conditions. In order to solve this problem, Alonso et al. [2008] proposed a set of “apparent” reflectance and fluorescence factors \(\{\alpha_{R*}, \alpha_{F*}\}\) to approximate the real factors \(\{\alpha_R, \alpha_F\}\). In this study, simulated datasets were employed, and the true values of \(\alpha_R\) and \(\alpha_F\) could be calculated using the simulated reflectance and SIF spectra. Therefore, the real correction factors \(\alpha_R\) and \(\alpha_F\) were employed for the iFLD method in this study.

**Channel-setting for the FLD-based methods for different spectral resolutions**
The SR of a sensor has a large influence on the shape of the observed spectra at the absorption bands, especially for broad telluric atmospheric absorption bands such as the
**O₂-A and O₂-B bands** because these bands consist of a large number of absorption lines with different depths (see Fig. 1). With the variation of spectral shape caused by different SRs, the positions of channels inside and outside the absorption bands will also change. Channels used in FLD-based SIF retrieval methods must be carefully selected to adapt to the specific spectral shapes corresponding to different SRs.

The channels inside each absorption feature were set to the position of the minima in each of the absorption bands. The reference channels outside the absorption feature were set according to the following rules: 1) the irradiance should be relatively steady around the channels (which means the channels are on the “shoulders” of the absorption valleys); and 2) the channels should be as near to the inside channels as possible. For the O₂-A bands, there is a further special consideration. When the SR is higher than 1 nm, the absorption band should be regarded as a combination of two absorption valleys (see Fig. 1). This means that the reference channel at the right-hand side is set at the peak between the two absorption valleys when the SR is sufficiently high. When the SR is lower than 1 nm, the middle peak cannot be detected and so the reference channel at the right-hand side must be set at the right shoulder of the whole absorption band. Therefore, the position of the longer-wavelength reference channel for the O₂-A band will change significantly when the SR is lower than 1 nm.

![Figure 2 - Spectral position of the channels used in FLD-based methods. These positions are dependent on the SR at the five potential bands.](image)

Figure 2 shows the spectral positions of selected channels at each potential band for FLD-based SIF retrieval for different values of the SR. For all bands, the distance between the channels inside and outside the absorption valleys increases when the SR decreases. As the estimation errors in FLD-based methods are mainly caused by the SIF and reflectance differences between the channels inside and outside the absorption bands, the FLD-based methods should be more robust when the outside channels outside are nearer to the inside channels. Hence, the SR is a significant factor influencing the accuracy of FLD-based SIF retrieval.
Uncertainty analysis for FLD-based SIF retrieval

As mentioned above, the SIF estimation errors for the iFLD method are caused by the errors in the estimated values of $\alpha_R$ and $\alpha_F$. Alonso et al. [2008] analyzed the contribution of the errors in the determination of the coefficients $\Delta \alpha_R$ and $\Delta \alpha_F$ to the uncertainty in the calculated fluorescence, $\Delta F_{\text{in}}$. These contributions are accounted for by the terms $(\partial F_{\text{in}} / \partial \alpha_R) \times \Delta \alpha_R$ and $(\partial F_{\text{in}} / \partial \alpha_F) \times \Delta \alpha_F$, respectively [Alonso et al., 2008]:

$$\Delta F_{\text{in}} = \frac{\partial F_{\text{in}}}{\partial \alpha_R} \times \Delta \alpha_R + \frac{\partial F_{\text{in}}}{\partial \alpha_F} \times \Delta \alpha_F \quad [4]$$

$$\frac{\partial F_{\text{in}}}{\partial \alpha_R} = \frac{-I_{\text{out}} \times I_{\text{in}} \times L_{\text{in}} \times \alpha_F + I_{\text{out}} \times I_{\text{in}} \times L_{\text{out}}}{(\alpha_R \times I_{\text{out}} - \alpha_F \times I_{\text{in}})^2} = k \times \frac{-L_{\text{in}} \times \alpha_F + L_{\text{out}}}{(\alpha_R - \alpha_F \times k)^2} \quad [5]$$

$$\frac{\partial F_{\text{in}}}{\partial \alpha_F} = \frac{I_{\text{out}} \times I_{\text{in}} \times L_{\text{in}} \times \alpha_R - I_{\text{in}}^2 \times L_{\text{out}}}{(\alpha_R \times I_{\text{out}} - \alpha_F \times I_{\text{in}})^2} = k \times \frac{L_{\text{in}} \times \alpha_F - k \times L_{\text{out}}}{(\alpha_R - \alpha_F \times k)^2} \quad [6]$$

where $k = I_{\text{in}} / I_{\text{out}}$ is the ratio of the irradiance inside the absorption band to that outside, which can indicate the depth of the absorption band.

Similarly, we analyzed the contribution of the noise in observed radiance ($\Delta L_{\text{in}}$ and $\Delta L_{\text{out}}$) to the retrieved SIF:

$$\Delta F_{\text{in}} = \frac{\partial F_{\text{in}}}{\partial L_{\text{in}}} \times \Delta L_{\text{in}} + \frac{\partial F_{\text{in}}}{\partial I_{\text{in}}} \times \Delta I_{\text{in}} \quad [7]$$

$$\frac{\partial F_{\text{in}}}{\partial L_{\text{out}}} = \frac{-k}{\alpha_R \times I_{\text{out}} - \alpha_F \times I_{\text{in}}} = \frac{-k}{\alpha_R - \alpha_F \times k} \quad [8]$$

$$\frac{\partial F_{\text{in}}}{\partial L_{\text{in}}} = \frac{\alpha_R \times I_{\text{out}}}{\alpha_R \times I_{\text{out}} - \alpha_F \times I_{\text{in}}} = \frac{\alpha_R}{\alpha_R - \alpha_F \times k} \quad [9]$$

Equations 5-9 show that value of $k$ (or the absorption depth) is the main factor that determines the contributions of $\Delta \alpha_R$, $\Delta \alpha_F$, $\Delta L_{\text{in}}$ and $\Delta L_{\text{out}}$ to the errors in the SIF retrieval. This indicates that the FLD-based SIF retrieval methods would be more robust and reliable with a smaller value of $k$ (or a bigger absorption depth).

The depth of the absorption bands is very different for different SRs. The absorption depth can be defined as
For a specific band, the absorption depth is mainly determined by the SR. We, therefore, analyzed the variation of the absorption depths of the five potential bands with different SRs, as listed in Figure 3.

\[
Depth = \frac{I_{\text{out}} - I_{\text{in}}}{I_{\text{out}}} = 1 - k \quad [10]
\]

The absorption depth of all five tested bands decreases significantly as the SR decreases. Most of the narrow absorption lines in the \(O_2\)-A band have an FWHM of about 0.05 nm to 0.1 nm. The absorbance of the deepest line is almost 1. However, as the SR decreases, these narrow and deep absorption lines are smoothed. As a result, the depth of the \(O_2\)-A and \(O_2\)-B bands decreases rapidly when the SR is higher than 0.1 nm (as Fig. 3 shows).

To keep the absorption depth greater than about 0.2, data with an SR higher than 0.05 nm is needed for the KI and Fe lines, 0.5 nm for the \(O_2\)-B band and \(H\alpha\) band, and 10 nm for the \(O_2\)-A band.

**Results**

**Robustness of FLD-based methods for different SRs**

**Sensitivity to the estimation errors in the correction factors for the FLD-based method**

The estimation errors for the FLD-based SIF retrieval method are mainly caused by the errors in the estimated values of \(\alpha_F\) and \(\alpha_R\). Therefore, the sensitivity of the iFLD method to systemic errors can be quantified as being the partial derivatives of \(F_{\text{in}}\) with respect to \(\alpha_F\) and \(\alpha_R\), \(\frac{\partial F_{\text{in}}}{\partial \alpha_F}\) and \(\frac{\partial F_{\text{in}}}{\partial \alpha_R}\), which can be regarded as the amplification coefficients of the errors in the estimated \(\alpha_F\) and \(\alpha_R\).

Figure 4 shows the variation with the SR of the sensitivity of the iFLD method to the
estimated errors in the two correction coefficients at the five potential bands. In general, the sensitivity increases as the SR decreases.

Among the three broad bands (H\(\alpha\), O\(_2\)-B and O\(_2\)-A), the O\(_2\)-B band is the most sensitive. The O\(_2\)-B band consists of many absorption lines with quite different widths and depths and so the shape of this band varies a lot as the SR changes, especially at the longer-wavelength side. In addition, the shape of the reflectance spectra within the O\(_2\)-B band is also complex because this band is located near the “red-edge” of the vegetation reflectance spectrum and the contribution of SIF is relatively large. As a result, the values of \(\frac{\partial F_\text{in}}{\partial \alpha_R}\) and \(\frac{\partial F_\text{in}}{\partial \alpha_F}\) in the O\(_2\)-B band are very unstable. The retrieved SIF value at the O\(_2\)-A band is also very sensitive to the errors in the estimated values of \(\alpha_F\) and \(\alpha_R\), but the variation in the sensitivity with the SR is more stable because of the more regular spectral shape compared with the O\(_2\)-B band. The SIF estimation error at the H\(\alpha\) band is much more stable than at the O\(_2\)-B and O\(_2\)-A bands when the SR decreases. However, as the intensity of the SIF signal at
the Hα band is very low (less than 10% of the SIF at the O2-B band), the relative error in the estimated SIF could still be high. For the two narrow bands (Fe and KI), the Fe line, which has the smaller absorption depth, is more sensitive to the SR.

It can also be seen that the errors in $\alpha_R$ contribute much more to the accuracy of the iFLD method than the errors in $\alpha_F$—the value of $\left( \frac{\partial F_{in}}{\partial \alpha_R} \right)$ is much larger than that of $\left( \frac{\partial F_{in}}{\partial \alpha_F} \right)$ . The intensity of the reflected radiation is much higher than the SIF emission and so the SIF estimation error is dominated by the errors in the estimated $\alpha_R$.

**Sensitivity to noise in the radiance spectra for the FLD-based method**

In a similar way, we analyzed the sensitivity of the iFLD method to the noise in the radiance spectra, by calculating the partial derivatives of $F_{in}$ with respect to $L_{in}$ and $L_{out}$ using datasets with different SRs. The partial derivatives in equation [8] and [9], as illustrated in Figure 5, can be regarded as the amplification coefficients of the noise in the observed radiance for the SIF retrieval.

![Figure 5 - Sensitivities of FLD-based methods to the noise in the TOC radiance ($L_{in}$ and $L_{out}$). The sensitivity is dependent on the SR at the five potential bands.](image-url)
The results were similar to those found for the analysis of the sensitivity of the estimation errors to the two correction factors in the iFLD method. The sensitivity to noise in the radiance spectra is different for different absorption bands, which increases as the SR decreases. Among the three broad absorption bands, the O₂-B band was found to be the most sensitive to the noise in the radiance spectra because of its complex and inconstant reflectance shape in different SR, which causes it to be very unstable. The partial derivatives (the amplification coefficients of the noise) at the Hα band are small for all values of the SR. For the two narrow Fraunhofer lines, the sensitivity to noise increases steadily as the SR decreases; the Fe line is a little more sensitive to the noise.

Accuracy of SIF retrieval for different SRs and SNRs

In this study, the accuracy of the SIF retrieval was quantified by using the relative root mean square error (RRMSE). We calculated the RRMSE of the SIF signals retrieved by the iFLD, 3FLD and sFLD methods at the five potential bands using the simulated datasets with different SRs and SNRs. Contour maps were employed to illustrate the variation in the RRMSE with the changes in the SR and SNR (Fig. 6).

In the contour maps shown in Figure 6, the accuracy of the SIF retrieval algorithms is more sensitive to the SR than to the SNR if the contours appear more vertically distributed. Conversely, the accuracy is more sensitive to the SNR where the contours appear more horizontally distributed.

For the two narrow bands (KI and Fe), the performance of the three SIF retrieval methods was similar. The SNR was the dominant factor influencing the accuracy of the SIF retrieval. When the SR was relatively low, the accuracy of the sFLD method decreased significantly while the 3FLD and iFLD methods were more accurate.

The error analysis results for the three broader bands (Hα, O₂-B and O₂-A) were different to those for the two narrow bands, as illustrated in Figure 6. As the true correction factors (α_R and α_F), which were dependent on the SR, were used, the dominant factor influencing the accuracy of the iFLD method at the three broad bands was the SNR. However, in the case of the 3FLD and sFLD methods, the assumptions about the reflectance and fluorescence variations became more important, and hence both the SR and SNR had an important influence on the SIF retrieval accuracy. The sFLD method appeared to be more sensitive to the SR than the 3FLD method, and the accuracy of the 3FLD method was significantly higher than that of the sFLD method for the same SR and SNR, especially for the O₂-A band.

In addition, Figure 6 illustrates that the five bands have different sensor configuration requirements for SIF retrieval. For example, if the aim is to keep the RRMSE of the retrieved SIF value lower than 20% using the 3FLD method and spectral data with an SNR of 1000, the SR should be higher than 1 nm and higher than 2 nm for the O₂-B band and O₂-A band, respectively.
Figure 6 - RRMSE (%) for SIF retrieval using datasets with different SRs and SNRs at the five potential bands.
**Performance of potential satellite sensors for SIF retrieval**

In recent years, many studies on space-based SIF retrieval have been carried out using hyperspectral data acquired by satellite sensors. Based on the accuracy analysis carried out in this study (Fig. 6), the SIF retrieval accuracy of some potential space-based hyperspectral sensors can be assessed according to their spectral and SNR specifications if the atmospheric radiation transfer is neglected. The sensors included GOSAT TANSO-FTS, SCIAMACHY, OCO-2, Metop GOME-2, and FLEX FLORIS.

Table 3 - RRMSE in retrieved SIF values obtained using simulated hyperspectral data with the SR and SNR of GOSAT and OCO-2 at the KI, Fe and O\(_2\)-A bands if the atmospheric radiation transfer was neglected.

| Sensor                  | RRMSE (%) | KI | Fe | O\(_2\)-A |
|-------------------------|-----------|----|----|------------|
|                         |           | iFLD | 3FLD | sFLD | iFLD | 3FLD | sFLD | iFLD | 3FLD | sFLD |
| GOSAT TANSO-FTS         |           | 89.48 | 87.31 | 119.20 | 93.68 | 87.80 | 93.36 | 34.65 | 34.70 | 34.65 |
| OCO-2                   |           | 46.20 | 44.79 | 46.39 | 46.13 | 41.90 | 45.79 | 10.50 | 10.58 | 10.68 |

Table 4 - RRMSE in retrieved SIF values obtained using simulated hyperspectral data with the SR and SNR of GOME-2, SCIAMACHY and FLORIS at the H\(\alpha\), O\(_2\)-B and O\(_2\)-A bands if the atmospheric radiation transfer was neglected.

| Sensor                  | RRMSE (%) | H\(\alpha\) | O\(_2\)-B | O\(_2\)-A |
|-------------------------|-----------|-------------|-----------|-----------|
|                         |           | iFLD | 3FLD | sFLD | iFLD | 3FLD | sFLD | iFLD | 3FLD | sFLD |
| GOME-2                  |           | 34.73 | 40.37 | 90.34 | 4.65 | 6.72 | 39.96 | 13.78 | 14.55 | 18.52 |
| SCIAMACHY               |           | 15.73 | 17.15 | 79.09 | 1.968 | 5.163 | 39.69 | 5.618 | 7.555 | 15.39 |
| FLEX FLORIS             |           | 109.3 | 571.2 | 1629.2 | 12.37 | 14.01 | 22.57 | 12.91 | 13.59 | 16.94 |

Table 3 shows the performance of the SIF retrieval using GOSAT and OCO-2 spectral data. The SRs were high enough for the detection of narrow solar Fraunhofer lines such as the KI line and Fe line, but the H\(\alpha\) and O\(_2\)-B bands were not covered. The performance of OCO-2 was much better than that of GOSAT at all the three bands due to its higher SNR. Table 4 shows the performance of the SIF retrieval using GOME-2, SCIAMACHY and FLORIS spectral data. Compared with the GOSAT and OCO-2 data shown in Table 3, the SRs were much lower and hence only the broader H\(\alpha\), O\(_2\)-B and O\(_2\)-A bands were significant and observable. The results show that the accuracy of the SIF retrieved using the SCIAMACHY and GOME-2 data was the highest because it had the highest SNR in Table 3 and Table 4, with a retrieval error about 5% if the 3FLD method was employed for O\(_2\)-B band and the atmospheric radiation transfer was neglected.

However, the noise intensity was determined by the SNR and also related to the reference signal intensity. In this paper, the reference signal intensity was set as the radiance intensity at the outside channel of a canopy radiance spectrum, and hence the absolute noise intensity was different for the five potential bands even when the SNR was the same. In fact, the SNR of a measured spectral dataset should be wavelength-dependent. For GOME-2 and SCIAMACHY, the spectral range covers the H\(\alpha\), O\(_2\)-B and O\(_2\)-A bands, but only a single
fixed SNR value was used for all the bands. Furthermore, the reflectance is very low at the red bands (Hα and O2-B) but high at the NIR band (O2-A). For a dense canopy under solar irradiance as described in section 2.2, the TOC irradiance is about 35 mWm⁻²nm⁻¹sr⁻¹ at the Hα and O2-B bands, and 95 mWm⁻²nm⁻¹sr⁻¹ at the O2-A band. Compared to the O2-A band, the absolute noise intensity was also smaller at the Hα and O2-B bands in the simulation experiment if the same SNR was given. Therefore, the SIF retrieval accuracy at the Hα and O2-B bands may have been overestimated for GOME-2 and SCIAMACHY and should be adjusted using the wavelength-dependent SNR values of GOME-2 and SCIAMACHY if these were available. If the absolute noise intensity simulated for the Hα and O2-B bands had been the same as for the O2-A band, the SIF retrieval error at the Hα and O2-B bands, as listed in table 3, would increase to 2.7 times the value obtained. Furthermore, it must be noted that the impact of atmospheric radiation transfer was not taken into account in this study because we aimed only to investigate the uncertainties caused by the sensor configurations. Ignoring the impact of atmospheric radiation transfer, the broader O2-A and O2-B bands performed better than the narrower solar Fraunhofer lines given similar sensor specifications. The optimal RRMSEs in the SIF values retrieved using OCO-2, GOME-2 and FLORIS data by the 3FLD method were less than 15%. The performance of the SIF retrieval using GOSAT data was somewhat worse (the RRMSE was about 35%) due to its lower SNR of about 300. If the impact of atmospheric radiation transfer were taken into account, the performances would be rather different. Liu and Liu [2014] showed that the solar Fraunhofer lines are much more sensitive to the disturbance due to atmospheric radiation transfer and thus have more potential for space-based SIF retrieval if the SR is sufficient.

Discussion
In this study, we produced a theoretical assessment of the accuracy of SIF retrieval for some potential satellite sensors based on their SRs and SNRs. The results obtained should be helpful in the design of sensors for SIF monitoring. However, after this study, some uncertainties remain. This work focused on the influence of sensor configurations and so the effect of atmospheric radiation transfer was not taken into account. Although the broad O2-A and O2-B bands do not require a high SR, they are much more sensitive to atmospheric disturbance [Liu and Liu, 2014]. Therefore, in practice, the accuracy of the atmospheric correction also needs to be considered when choosing the optimal band for SIF retrieval. Both the disturbance due to atmospheric effects and the theoretical accuracy of the SIF retrieval should be investigated in future work so that optimum guidance for space-based SIF retrieval can be produced. As all the investigations were carried out with simulated data, only the variations in the SR and SNR were considered. Other factors, such as the influence of the spectral sampling interval (SSI) and the spectral shift (SS) were excluded. According to the study by Damm et al. [2011], the SSI accounts for less than 12% of the error while the SS accounts for less than 7%. Compared with the SR and SNR (which account for more than 80% of the error), the influence of the SSI and SS is relatively small. In the analysis of the error due to the noise, only the noise in the upward radiance was considered. The error or noise in the downward irradiance was neglected. For space-based observations, the error in the upward radiance is caused mainly by the sensor noise if the
atmospheric radiation transfer is neglected, and the noise is random in the spectral domain. The downward irradiance is usually estimated using an atmospheric radiation transfer model, and its accuracy is dominated by the atmospheric radiation correction, which is not random in the spectral domain. The results of this study show that the systematic bias in the radiance ($L_{\text{in}}$ and $L_{\text{out}}$) can be balanced out to some extent, as illustrated in Figure 5. Therefore, the atmospheric correction error in both the radiance and irradiance spectra would be mostly balanced out by the negative sensitivity of the inside and outside radiation as shown by Equations [8] and [9] and Figure 5. Therefore, the SIF retrieval error due to the uncertainty in the atmospheric correction would have a similar relative amplitude to that for the radiance or irradiance spectra.

In addition, the FLD-based method is only one among several SIF retrieval approaches: other methods include the spectral fitting method [Meroni and Colombo, 2006; Liu et al., 2015] and the singular vector decomposition method [Joiner et al., 2011; Guanter et al., 2012, 2013]. Investigations into other SIF retrieval methods were not included in this study. The performance of other SIF retrieval methods may be somewhat different.

Conclusions

Based on the Fraunhofer Line Discrimination (FLD) principle, the weak signal of SIF can be detected using hyperspectral data. In this paper, we presented a quantitative assessment of the accuracy of solar-induced chlorophyll fluorescence retrieval at five potential bands (Hα, O₂-B, Fe, O₂-A, and KI). Three FLD-based methods (sFLD, 3FLD, and iFLD) were employed for this retrieval and assessed. Firstly, the sensitivities of the SIF retrieval to the correction factors and the radiance noise for different values of the SR and SNR were quantified by a partial derivative analysis. The sensitivity increased rapidly when the SR decreased, especially for the O₂-B band. When the noise was neglected, the retrieval error was found to be mainly due to the error in the estimation of reflectance correction factor ($\alpha_R$) rather than the error in the fluorescence correction factor ($\alpha_F$). When the two correction factors could be accurately estimated or neglected, the retrieval error also increased with the noise level in the radiance spectra and the sensitivity to noise was also greatest for the O₂-B band.

Next, the distribution of the errors in the retrieved SIF values at the five bands for different SRs and SNRs was obtained using simulated datasets with the SCOPE and MODTRAN models. The results showed that the five potential bands have different sensor configuration requirements for SIF retrieval. In cases where it was possible to accurately estimate or to approximate the reflectance and fluorescence correction factors using the 3FLD or sFLD method, such as in the case of the narrow KI and Fe absorption lines, the SNR was the dominant factor influencing the SIF retrieval accuracy. If the two correction factors could not be approximated or accurately estimated, the SR became the dominant factor, as in the case of the three broad bands (Hα, O₂-B and O₂-A).

Finally, the SIF retrieval accuracy of the FLD-based methods for the potential space-based hyperspectral sensors GOSAT TANSO-FTS, SCIAMACHY, OCO-2, Metop GOME-2, and FLEX FLORIS, was investigated. The results showed that the SIF retrieval error for GOSAT data was unacceptably large (>35%) due to its low SNR of 300 but that it was acceptable for other sensors that had a high SNR, with the error varying from 5% to 20%.
at the optimal bands. Therefore, if the atmospheric radiation transfer are neglected, according to the above analysis, the sensor specifications could be improved for SIF retrieval. If an RRMSE lower than 20% is required for the SIF retrieval using the FLD-based methods, the SNR should be higher than 2500 and the SR higher than 0.05 nm for the two narrow Fraunhofer lines (KI and Fe). For the Hα band, the SNR should be higher than 1000 with an SR higher than 0.25 nm. For the O$_2$-B band, the SNR should be higher than 300 with an SR higher than 0.5 nm. Finally, for the O$_2$-A band, the SNR should be higher than 1000 with an SR higher than 2 nm.

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References
Alonso L., Gomez-Chova L., Vila-Frances J., Amoros-Lopez J., Guanter L., Calpe J., Moreno J. (2008) - Improved Fraunhofer Line Discrimination method for vegetation fluorescence quantification. IEEE Geoscience and Remote Sensing Letters, 5: 620-624. doi: http://dx.doi.org/10.1109/LGRS.2008.2001180.

Berk A., Anderson G.P., Acharya P.K., Bernstein L.S., Muratov L., Lee J., Fox M., Adler-Golden S.M., Chetwynd J.H., Hoke M.L., Lockwood R.B., Gardner J.A., Cooley T.W., Borel C.C., Lewis P.E. (2005) - MODTRAN (TM) 5, a reformulated atmospheric band model with auxiliary species and practical multiple scattering options: Update. In: Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XI, S.S. Shen and P.E. Lewis (Eds.), pp. 662-667. doi: http://dx.doi.org/10.1117/12.606026.

Callies J., Corpaccioli E., Eisinger M., Hahne A., Lefèbvre A. (2000) - GOME-2-Metop’s second-generation sensor for operational ozone monitoring. ESA bulletin, 102: 28-36.

Cao R., Chen X., Chen J., Yang W. (2013) - An Inherent Limitation of Solar-Induced Chlorophyll Fluorescence Retrieval at the Absorption Feature in High-Altitude Areas. IEEE Geoscience and Remote Sensing Letters, 10: 1567-1571. doi: http://dx.doi.org/10.1109/LGRS.2013.2262106.

Carter G.A., Jones J.H., Mitchell R.J., Brewer C.H. (1996) - Detection of solar-excited chlorophyll a fluorescence and leaf photosynthetic capacity using a Fraunhofer Line Radiometer. Remote Sensing of Environment, 55: 89-92. doi: http://dx.doi.org/10.1016/0034-4257(95)00192-1.

Carter G.A., Theisen A.F., Mitchell R.J. (1990) - Chlorophyll fluorescence measured using the Fraunhofer line-depth principle and relationship to photosynthetic rate in the field. Plant Cell and Environment, 13: 79-83. doi: http://dx.doi.org/10.1111/j.1365-3040.1990.tb01302.x.

Damm A., Erler A., Hillen W., Meroni M., Schaepman M.E., Verhoef W., Rascher U. (2011) - Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence. Remote Sensing of Environment, 115: 1882-1892. doi: http://dx.doi.org/10.1016/j.rse.2011.03.011.

Damm A., Guanter L., Verhoef W., Schläpfer D., Garbari S., Schaepman M.E. (2015)
Impact of varying irradiance on vegetation indices and chlorophyll fluorescence derived from spectroscopy data. Remote Sensing of Environment, 156: 202-215. doi: http://dx.doi.org/10.1016/j.rse.2014.09.031.

Franck F., Juneau P., Popovic R. (2002) - Resolution of the photosystem I and photosystem II contributions to chlorophyll fluorescence of intact leaves at room temperature. Biochimica et Biophysica Acta (BBA)-Bioenergetics, 1556: 239-246. doi: http://dx.doi.org/10.1016/S0005-2728(02)00366-3.

Frankenberg C., Butz A., Toon G.C. (2011) - Disentangling chlorophyll fluorescence from atmospheric scattering effects in O2-A band spectra of reflected sun-light. Geophysical Research Letters, 38. doi: http://dx.doi.org/10.1029/2010gl045896.

Frankenberg C., Pollock R., Lee R.A.M., Rosenberg R., Blavier J.F., Crisp D., O’Dell C.W., Osterman G.B., Wennberg P.O., Wunch D. (2014) - The Orbiting Carbon Observatory (OCO-2): spectrometer performance evaluation using pre-launch direct sun measurements. Atmospheric Measurement Techniques Discussions, 7: 7641-7670. doi: http://dx.doi.org/10.5194/amtd-7-7641-2014.

Guanter L., Alonso L., Gómez-Chova L., Amorós-López J., Vila J., Moreno J. (2007) - Estimation of solar-induced vegetation fluorescence from space measurements. Geophysical Research Letters, 34. doi: http://dx.doi.org/10.1029/2007gl029289.

Guanter L., Alonso L., Gómez-Chova L., Meroni M., Preusker R., Fischer J., Moreno J. (2010) - Developments for vegetation fluorescence retrieval from spaceborne high-resolution spectrometry in the O2-A and O2-B absorption bands. Journal of Geophysical Research, 115. doi: http://dx.doi.org/10.1029/2009jd013716.

Guanter L., Frankenberg C., Dudhia A., Lewis P.E., Gómez-Dans J., Kuze A., Suto H., Grainger R.G. (2012) - Retrieval and global assessment of terrestrial chlorophyll fluorescence from GOSAT space measurements. Remote Sensing of Environment, 121: 236-251. doi: http://dx.doi.org/10.1016/j.rse.2012.02.006.

Guanter L., Rossini M., Colombo R., Meroni M., Frankenberg C., Lee J.-E., Joiner J. (2013) - Using field spectroscopy to assess the potential of statistical approaches for the retrieval of sun-induced chlorophyll fluorescence from ground and space. Remote Sensing of Environment, 133: 52-61. doi: http://dx.doi.org/10.1016/j.rse.2013.01.017.

Joiner J., Guanter L., Lindstrøt R., Voigt M., Vasilkov A., Middleton E., Huemmrich K., Yoshida Y., Frankenberg C. (2013) - Global monitoring of terrestrial chlorophyll fluorescence from moderate spectral resolution near-infrared satellite measurements: methodology, simulations, and application to GOME-2. Atmospheric Measurement Techniques Discussions, 6: 3883-3930. doi: http://dx.doi.org/10.5194/amtd-6-3883-2013.

Joiner J., Yoshida Y., Vasilkov A.P., Corp L.A., Middleton E.M. (2011) - First observations of global and seasonal terrestrial chlorophyll fluorescence from space. Biogeosciences, 8: 637-651. doi: http://dx.doi.org/10.5194/bg-8-637-2011.

Kraft S., Bézy J.L., Del Bello U., Berlich R., Drusch M., Franco R., Gabriele A., Harnisch B., Meynart R., Silvestrin P. (2013) - FLORIS: phase A status of the fluorescence imaging spectrometer of the Earth Explorer mission candidate FLEX. SPIE Remote Sensing,International Society for Optics and Photonics, 88890T.

Kraft S., Bello U.D., Drusch M., Gabriele A. (2014) -FLORIS: The Fluorescence Imaging Spectrometer of the Earth Explorer Mission Candidate FLEX. In: 5th International
Workshop on Remote Sensing of Vegetation Fluorescence, Paris, France.

Kuze A., Suto H., Nakajima M., Hamazaki T. (2009) - *Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring*. Applied Optics, 48: 6716-6733. doi: http://dx.doi.org/10.1364/AO.48.006716.

Lichtenthaler H.K., Rinderle U. (1988) - *The role of chlorophyll fluorescence in the detection of stress conditions in plants*. CRC Critical Reviews in Analytical Chemistry, 19: S29-S85. doi: http://dx.doi.org/10.1080/15476510.1988.10401466.

Liu L.Y., Zhang Y.J., Wang J.H., Zhao C.J. (2005) - *Detecting solar-induced chlorophyll fluorescence from field radiance spectra based on the Fraunhofer line principle*. IEEE Transactions on Geoscience and Remote Sensing, 43: 827-832. doi: http://dx.doi.org/10.1109/TGRS.2005.843320.

Liu L., Zhao J., Guan L. (2013) - *Tracking photosynthetic injury of Paraquat-treated crop using chlorophyll fluorescence from hyperspectral data*. European Journal of Remote Sensing, 46: 459-473. doi: http://dx.doi.org/10.5721/EuJRS20134627.

Liu X., Liu L. (2014) - *Assessing Band Sensitivity to Atmospheric Radiation Transfer for Space-Based Retrieval of Solar-Induced Chlorophyll Fluorescence*. Remote Sensing, 6: 10656-10675. doi: http://dx.doi.org/10.3390/rs6110656.

Liu X., Liu L., Zhang S., Zhou X. (2015) - *New Spectral Fitting Method for Full-Spectrum Solar-Induced Chlorophyll Fluorescence Retrieval Based on Principal Components Analysis*. Remote Sensing, 7: 10626-10645. doi: http://dx.doi.org/10.3390/rs70810626.

Maier S.W., Günther K.P., Stellmes M. (2003) - *Sun-induced fluorescence: A new tool for precision farming*. In: Digital imaging and spectral techniques: Applications to precision agriculture and crop physiology. McDonald M., Schepers J., Tartly L., Toai T.V., Major D. (Eds.), ASA Special Publication, pp. 209-222.

Maxwell K., Johnson G.N. (2000) - *Chlorophyll fluorescence - a practical guide*. Journal of experimental botany, 51: 659-668. doi: http://dx.doi.org/10.1093/jexbot/51.345.659.

Mazzoni M., Falorni P., Del Bianco S. (2008) - *Sun-induced leaf fluorescence retrieval in the O-2-B atmospheric absorption band*. Optics Express, 16: 7014-7022. doi: http://dx.doi.org/10.1364/OE.16.007014.

Mazzoni M., Meroni M., Fortunato C., Colombo R., Verhoef W. (2012) - *Retrieval of maize canopy fluorescence and reflectance by spectral fitting in the O_2–A absorption band*. Remote Sensing of Environment, 124: 72-82. doi: http://dx.doi.org/10.1016/j.rse.2012.04.025.

McFarlane J., Watson R., Theisen A., Jackson R.D., Ehrler W., Pinter Jr P., Idso S.B., Reginato R. (1980) - *Plant stress detection by remote measurement of fluorescence*. Applied Optics, 19: 3287-3289. doi: http://dx.doi.org/10.1364/AO.19.003287.

Meroni M., Rossini M., Guanter L., Alonso L., Rascher U., Colombo R., Moreno J. (2009) - *Remote sensing of solar-induced chlorophyll fluorescence: Review of methods and applications*. Remote Sensing of Environment, 113: 2037-2051. doi: http://dx.doi.org/10.1016/j.rse.2009.05.003.

Meroni M., Colombo R. (2006) - *Leaf level detection of solar induced chlorophyll fluorescence by means of a subnanometer resolution spectroradiometer*. Remote Sensing of Environment, 103: 438-448. doi: http://dx.doi.org/10.1016/j.rse.2006.03.016.

Moya I., Cerovic Z.G. (2004) - *Remote sensing of chlorophyll fluorescence: instrumentation...*
and analysis. Chlorophyll a Fluorescence, Springer, pp. 429-445. doi: http://dx.doi.org/10.1007/978-1-4020-3218-9_16.

Munro R., Eisinger M., Anderson C., Callies J., Corpaccioli E., Lang R., Lefebvre A., Livschitz Y., Albiñana A.P. (2006) - GOME-2 on MetOp: from In-Orbit Verification to Routine Operations. Proceedings of the 2006 EUMETSAT Meteorological Satellite Conference, Helsinki, Finland, pp. 12-16.

Plascyk J.A. (1975) - The MK II Fraunhofer line discriminator (FLD-II) for airborne and orbital remote sensing of solar-stimulated luminescence. Optical Engineering, 14: 339-346. doi: http://dx.doi.org/10.1117/12.7971842.

Plascyk J.A., Gabriel F.C. (1975) - Fraunhofer line discriminator Mk II - Airborne instrument for precise and standardized ecological luminescence measurement. IEEE Transactions on Instrumentation and Measurement, 24: 306-313. doi: http://dx.doi.org/10.1109/TIM.1975.4314448.

Van der Tol C., Verhoef, W., Timmermans J., Verhoef A., Su Z. (2009) - An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy balance. Biogeosciences, 6: 3109-3129. doi: http://dx.doi.org/10.5194/bg-6-3109-2009.

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