Fluorescence estimation in the framework of the CEFLES2 campaign

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Fluorescence estimation in the framework of the CEFLES2 campaign

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Chlorophyll fluorescence (ChF) is a relevant indicator of the actual plant physiological status. In this article different methods to measure ChF from remote sensing are evaluated: the Fraunhofer Line Discrimination (FLD), the Fluorescence Radiative Method (FRM) and the improved Fraunhofer Line Discrimination (iFLD). The three methods have been applied to data acquired in the framework of the CarboEurope, FLEX and Sentinel-2 (CEFLES2) campaign in Les Landes, France in September 2007. Comparing with in situ measurements, the results indicate that the methods that provide the best results are the FLD and the iFLD with root mean square errors (RMSEs) of 0.4 and 0.5 mW m⁻² sr⁻¹ nm⁻¹, respectively, while the FRM provides an error of 0.8 mW m⁻² sr⁻¹ nm⁻¹.

1. Introduction

Vegetation is a fundamental part of the biosphere. It regulates energy exchange between the land biosphere and the atmosphere, determines the hydrological processes and, through photosynthesis, fixes atmospheric carbon dioxide in the biomass. For this reason, the remote sensing of vegetation is acquiring great interest, since the leaves of plants have the largest surface of all biological organisms and can be detected from far away. When green leaves are illuminated, chlorophyll molecules are excited. This excitation energy drives the photosynthesis. Some energy is also dissipated as heat and as chlorophyll fluorescence (ChF). ChF in photosynthesis represents that portion of absorbed radiant energy that is not converted into chemical energy (or heat) but is re-emitted as radiation. Therefore, the ChF is related to the photosynthesis process (Schreiber and Bilger 1987) and is an indicator of the actual plant physiological status. It consists of low intensity radiation placed in the red and near infrared spectral regions (approximately between 650 and 800 nm), which is emitted by the chlorophyll-\(a\) when it is excited by the solar irradiance. ChF can provide an early and
more direct approach for detecting sub-optimal conditions before significant reductions in chlorophyll content or leaf area index (LAI) have occurred (Meroni et al. 2009). In fact, a more accurate assessment of the terrestrial vegetation’s carbon budget can be obtained directly by measuring ChF emissions (Entcheva Campbell et al. 2008). Additionally, ChF is a pre-visual indicator of water stress, that is, before the onset of stress (Zarco-Tejada et al. 2009).

Under natural illumination, the low intensity of the ChF compared to the solar radiation reflected by the plant in the same spectral range makes its detection with remote sensing sensors a challenging problem. As a consequence, it is necessary to make use of some of the absorption bands of the solar spectrum, also known as Fraunhofer lines, situated in the red and near infrared spectral regions (where the ChF radiation is placed). In this interval, the solar irradiance presents three main absorption bands as can be seen in figure 1: the line Hα at 656 nm due to the absorption of the hydrogen in the solar atmosphere and the bands situated at 687 (oxygen-B) and 760 nm.

Figure 1. (a) Reflectance (dotted line) and fluorescence (continuous line) in arbitrary units of a vine leaf excited at 355 nm (adapted from Moya et al. 2004a). (b) Solar irradiance at sea level. The circles indicate the absorption bands on the oxygen and the hydrogen absorption bands.
Fluorescence estimation

(oxygen-A), which are due to the molecular absorption of the oxygen in the terrestrial atmosphere.

The Hα absorption band is far from the maximum emission of the fluorescence. Therefore, oxygen absorption bands are mostly considered in the fluorescence measurement. As the plant reflectance is at 760 nm between 5 and 10 times greater than at 687 nm, the fluorescence signal is more masked by the reflectance at 760 nm. However, the oxygen-A absorption band (760 nm) is deeper and wider than the oxygen-B absorption band. As a result, the oxygen-A band appears to be the most suitable for fluorescence estimation with remote sensing sensors (Moya et al. 2004a). This article consequently is centred on the analysis of the fluorescence in the oxygen-A absorption band.

There are several methods for measuring fluorescence from remote sensing (Meroni et al. 2009). In this article, we investigate three of them: the Fraunhofer Line Discrimination (FLD), the Fluorescence Radiative Method (FRM) and the improved Fraunhofer Line Discrimination (iFLD). The three methods have been applied in the framework of the CarboEurope, FLEX and Sentinel-2 (CEFLES2) campaign. This campaign was proposed to characterize the vegetation in a large area of southern France including part of Les Landes forest and surrounding agricultural fields during three different periods, April, June and September 2007. During this campaign, several airborne and *in situ* measurements were performed.

2. Theoretical background

In this section, three different methods for estimating fluorescence through remote sensing are described. The main difference between them is the approximation considered on the surface reflectance and fluorescence spectral dependence inside and outside the absorption band. The FLD method considers that these parameters are constant within the nearby wavelengths. However, the FRM and the iFLD consider a linear approach of the surface reflectance and fluorescence. In the first case, the coefficients of proportionality are constant through every pixel of the image and in the second the coefficients are estimated for each pixel.

2.1 FLD method

The FLD is based on the use of the Fraunhofer lines or their immediacy for the fluorescence estimation and it is applied to atmospherically corrected data. In this way, the radiance reflected by a reference panel is compared with the radiance reflected by vegetation under equal illumination conditions.

The radiance coming from the illuminated target emitting fluorescence, $L_{\text{in}}(\lambda)$, is given by:

$$L_{\text{in}}(\lambda) = R_{\text{in}}(\lambda)I_{\text{in}}(\lambda) + F_{\text{in}}(\lambda)$$

where $R_{\text{in}}(\lambda)$ is the reflectance (without the emission contribution), $I_{\text{in}}(\lambda)$ is the incident radiance and $F_{\text{in}}(\lambda)$ is the fluorescence. From this equation, a linear system of two equations can be derived considering both the signal measured inside the Fraunhofer line ($L_{\text{in}}(\lambda)$) and the signal measured outside the Fraunhofer line but in the vicinity of it ($L_{\text{out}}(\lambda)$).
The FLD method considers that both the reflectance and the fluorescence remain constant inside and outside the absorption band (Plascyk 1975, Plascyk and Gabriel 1975, Moya et al. 2004a), that is, $R_{\text{in}} = R_{\text{out}}$ and $F_{\text{in}} = F_{\text{out}}$. Considering this approach in equations (2) and (3), the fluorescence and reflectance can be written as:

$$R = \frac{L_{\text{out}} - L_{\text{in}}}{I_{\text{out}} - I_{\text{in}}}$$  \hspace{1cm} (4)$$

$$F = \frac{I_{\text{out}}L_{\text{in}} - L_{\text{out}}L_{\text{in}}}{I_{\text{out}} - I_{\text{in}}}$$  \hspace{1cm} (5)$$

### 2.2 FRM method

The FRM is based on the estimation of fluorescence by including it in the radiative transfer equations as an emission term, so in this case the atmospheric correction is included in the equations and they are applied to raw data. Figure 2 shows the contributions of the atmosphere and the surface to the top of the atmosphere signal that have been taken into account in the visible and near infrared (VNIR) spectral range.

With these different contributions and considering the surface as uniform and Lambertian (Nicodemus et al. 1977), the radiative transfer equations for the atmosphere can be written as (Verhoef and Bach 2003):

$$E_s(b) = \tau_{ss}E_s(t)$$  \hspace{1cm} (6)$$

$$E^-(b) = \tau_{sd}E_s(t) + \rho_{dd}E^+(b)$$  \hspace{1cm} (7)$$

$$E_o(t) = \rho_{so}E_s(t) + \tau_{do}E^+(b) + \tau_{oo}E_o(b)$$  \hspace{1cm} (8)$$

$$E^+(b) = \rho_{\text{surf}}[E_s(b) + E^-(b)] + \pi F$$  \hspace{1cm} (9)$$

![Figure 2. Contributions of the atmosphere and the surface to the top-of-atmosphere irradiance.](image-url)
where (b) and (t) indicate the bottom and the top of the atmosphere irradiance, respectively. In equation (6), the attenuation of direct sunlight by direct transmittance $\tau_{ss}$ is described through the whole atmospheric layer, equation (7) reflects the generation of diffuse downward flux (sky irradiance) by diffusely transmitted direct solar flux and upwelling diffuse flux from the surface that is reflected back by the atmosphere. Here, the term $\rho_{dd}$ is the atmospheric spherical albedo, $\tau_{sd}$ is the diffuse transmission, $\rho_{surf}$ is the surface reflectivity and $E_s$ is the solar irradiance. Equation (8) describes how the top-of-atmosphere radiance that reaches the sensor ($E_o$) is generated from atmospherically scattered direct sunlight via the term $\rho_{so}$ (which can be considered a bi-directional reflectance of the atmospheric layer), the diffuse upwelling flux that is scattered into the direction of view via the transmittance term $\tau_{do}$ and the directly transmitted radiance from the target via the direct transmittance $\tau_{oo}$. Finally, equation (9) describes the reflection of radiance by a Lambertian surface.

Solving these equations and with $E_o(t) = \pi L_{sensor}(t)$ then $L_{sensor}(t)$ is given by:

$$L_{sensor} = \left( \rho_{so} + \frac{(\tau_{ss} + \tau_{sd}) (\tau_{do} + \tau_{sd} \rho_{surf})}{1 - \rho_{surf} \rho_{dd}} \right) \frac{E_s}{\pi} + \frac{(\tau_{do} + \tau_{oo}) F}{1 - \rho_{surf} \rho_{dd}}$$  \hspace{1cm} (10)

considering $L_0 = \rho_{so} E_s / \pi$ and $T = (\tau_{do} + \tau_{oo}) (\tau_{ss} + \tau_{sd})$ equation (10) can be simplified:

$$\frac{L_{sensor} - L_0}{T} = \frac{1}{1 - \rho_{surf} \rho_{dd}} \left( \frac{E_s \rho_{surf}}{\pi} + \frac{(\tau_{do} + \tau_{oo}) F}{T} \right)$$ \hspace{1cm} (11)

Introducing the spectral dependency, the linear system to be solved is:

$$\frac{L_{sensor} - L_0}{T} = \frac{1}{1 - \rho_{surf} \rho_{dd}} \left( \frac{E_s \rho_{surf}}{\pi} + \frac{(\tau_{do} + \tau_{oo}) F}{T} \right)$$ \hspace{1cm} (12)

$$\frac{L_{sensor} - L_0}{T} = \frac{1}{1 - \rho_{surf} \rho_{dd}} \left( \frac{E_s \rho_{surf}}{\pi} + \frac{(\tau_{do} + \tau_{oo}) F}{T} \right)$$ \hspace{1cm} (13)

From this equation, it is necessary to know $\rho_{surf}^{out}$, $F^{out}$, $\rho_{surf}^{in}$ and $F^{in}$. In figure 1, it can be visualized that in the spectral range of the oxygen-A absorption band the slope of the reflectance and fluorescence spectrum remains more or less constant. Therefore, it is considered a linear approach of the reflectance and fluorescence:

$$\rho_{surf}^{in} = \beta_R \rho_{surf}^{out}$$ \hspace{1cm} (14)

$$F^{in} = \beta_F F^{out}$$ \hspace{1cm} (15)

Then, substituting equations (14) and (15) in (12) and (13), the fluorescence can be expressed as:

$$F^{in} = \frac{A^{in} \left( \frac{E_s^{out}}{\beta_R \pi} + \frac{A^{out} \rho_{dd}^{out}}{\beta_R} \right) - A^{out} \left( \frac{E_s^{in}}{\pi} + A^{in} \rho_{dd}^{in} \right)}{C^{in} \left( \frac{E_s^{out}}{\beta_R \pi} + \frac{A^{out} \rho_{dd}^{out}}{\beta_R} \right) - C^{out} \left( \frac{E_s^{in}}{\pi} + A^{in} \rho_{dd}^{in} \right)}$$ \hspace{1cm} (16)
where $A_{\text{in/out}} = \frac{L_{\text{in/out}}}{T_{\text{in/out}}}$ and $C_{\text{in/out}} = \frac{(\tau_{\text{in/out}} + \tau_{\text{oo}})}{T_{\text{in/out}}}$.

In equation (15), it is assumed that $\beta_F = 0.8$ in the spectral zone of the oxygen-A absorption band (Moya et al. 2004b).

Regarding $\beta_R$, we propose the following expression:

$$\beta_R = \frac{A_{\text{in}} \left( \frac{E_{\text{out}}}{\pi} + A_{\text{out}} \rho_{\text{dd}}^{\text{out}} \right)}{A_{\text{out}} \left( \frac{E_{\text{in}}}{\pi} + A_{\text{in}} \rho_{\text{dd}}^{\text{in}} \right)}$$

To obtain this equation, it has been considered that in equation (12) the surface reflectance does not include the fluorescence emission. The methodology proposed considers the pixels where the Normalized Difference Vegetation Index (NDVI) is less than 0.2. Therefore, the fluorescence should be equal to zero as the pixels correspond to bare soils. In equation (16), this fact implies that the terms in the numerator must be equal. In application to real data, $\beta_R$ will be the average through the pixels of bare soil.

2.3 iFLD method

The iFLD method (Alonso et al. 2008) allows the limitations of considering the reflectance and fluorescence constant inside and outside of the oxygen absorption band to be avoided. It is based on the FLD method and it is also applied to atmospherically corrected data. This method considers the variation of these parameters describing it by two coefficients $\alpha_R$ and $\alpha_F$ defined as:

$$R_{\text{out}} = \alpha_R R_{\text{in}}$$

$$F_{\text{out}} = \alpha_F F_{\text{in}}$$

In this way, equations (2) and (3) can be rewritten:

$$L_{\text{in}}(\lambda) = R_{\text{in}}(\lambda) I_{\text{in}}(\lambda) + F_{\text{in}}(\lambda)$$

$$L_{\text{out}}(\lambda) = \alpha_R R_{\text{in}}(\lambda) I_{\text{out}}(\lambda) + \alpha_F F_{\text{in}}(\lambda)$$

Therefore, the reflectance and fluorescence are now expressed as:

$$R_{\text{in}} = \frac{L_{\text{in}} - F_{\text{in}}}{I_{\text{in}}}$$

$$F_{\text{in}} = \frac{\alpha_R I_{\text{out}} L_{\text{in}} - L_{\text{out}} I_{\text{in}}}{\alpha_R I_{\text{out}} - \alpha_F I_{\text{in}}}$$

The difficulty in obtaining the coefficients $\alpha_R$ and $\alpha_F$ from spectrometric measurements in natural conditions should be noted. This is due to the fact that the measured radiance also includes the fluorescence contribution. Therefore, only the apparent reflectance ($\hat{R}$), contaminated by fluorescence (see equation (24)), can be estimated from direct measurements.
Fluorescence estimation

\[ \hat{R} = \frac{L}{I} = R + \frac{F}{I} \] (24)

As a result, the apparent coefficient is defined as:

\[ \hat{\alpha}_R = \frac{\hat{R}_{\text{out}}}{\tilde{R}_{\text{in}}} \] (25)

where \( \hat{R}_{\text{out}} = L_{\text{out}}/I_{\text{out}} \) and \( \tilde{R}_{\text{in}} \) are obtained using spline interpolation to estimate the apparent reflectance in \( \lambda_{\text{in}} \) (the wavelength of the absorption band). \( \tilde{R}_{\text{in}} \) is equivalent to the reflectance that would be retrieved in the absence of the atmospheric absorption on the radiance and irradiance but still affected by fluorescence.

With these elements the fluorescence can be expressed in terms of measurable quantities:

\[ \hat{F}_{\text{in}} = \frac{\hat{\alpha}_R I_{\text{out}} \cdot L_{\text{in}} - L_{\text{out}} I_{\text{in}}}{\hat{\alpha}_R I_{\text{out}} - \hat{\alpha}_F I_{\text{in}}} \] (26)

where \( \hat{\alpha}_F \) is determined considering \( \hat{F}_{\text{in}} = F_{\text{in}} \) (Alonso et al. 2008):

\[ \hat{\alpha}_F \approx \frac{I_{\text{out}}}{I_{\text{in}}} \cdot \hat{\alpha}_R \] (27)

with \( I_{\text{in}} \) determined by interpolating the irradiance in \( \lambda_{\text{in}} \) to remove the atmospheric absorption in the same way as \( \tilde{R}_{\text{in}} \).

3. Experimental development

In this section, the experimental campaign is described that has been considered to analyse the different methods of fluorescence estimation.

3.1 Field campaign

CEFLES2 was a multi-objective campaign that exploited the synergies between several airborne and ground measurements performed in coordination with the CarboEurope Regional Experiment Strategy (CERES). In this way, the CEFLES2 campaign provided the validation of photosynthesis estimation based on ground and airborne eddy flux measurements of plant-mediated exchange processes (photosynthetic CO\(_2\) uptake, evapotranspiration and energy budget). The campaign also supported the development of the Fluorescence Explorer (FLEX) mission, which was presented in the framework of Earth Explorer in the European Spatial Agency, by providing airborne measurements of solar-induced fluorescence and extensive ground-based measurements of leaf-level processes, and the Sentinel-2 mission, which is a multispectral optical imaging mission for global land observation at high resolution. Airborne and ground measurements were acquired in the Les Landes region of France in April, June and September 2007 to capture different growth stages of vegetation. Airborne measurements taken covered the visible, near-, shortwave- and thermal-infrared wavelengths. Ground measurements included rates of photosynthetic carbon
dioxide uptake, efficiency of light reaction, evapotranspiration, LAI, leaf chlorophyll content, emissivity and temperature (Rascher et al. 2009).

3.2 Study area

CEFLES2 measurement activities were developed within a rectangle stretching from Bordeaux to Toulouse in Southwest France. The majority of sites lay in the Les Landes forested area and the adjacent intermediate zone, in the transition between forested and cultivated areas. The Sentinel-2 experiment required as first priority agricultural and natural vegetation test sites. An area of agricultural fields near Marmande was the main focus of FLEX measurement activities during all three campaigns as well as the site of the most intensive CERES and Sentinel-2 measurements. The site comprised large fields of different agricultural crops, mainly winter wheat and corn on flat land in the Garonne valley bottom. Additionally, measurements were also carried out around Clairac, in an undulating agricultural cultivated area. Other measurements were carried out in evergreen (pine) forest and deciduous forest sites, as well as in vineyard and grassland sites, though data acquired in these areas were not used in this work.

3.3 Airborne data: Airflex

Airflex is an interference-filter based airborne sensor (Moya et al. 2006) developed in the framework of the Earth Observation Preparatory Programme of the European Space Agency. Basically, it is a six channel photometer aimed to measure the in-filling of the atmospheric $O_2$ bands. A set of three different channels (each with a specific interference filter) is used to characterize each absorption band: one at the absorption peak and two others immediately before and after the $O_2$ absorption feature. The filters used in the Airflex sensor are shown in table 1.

The use of two filters out of the band allows interpolating the reflectance within the band. The Full Width Half Maximums (FWHMs) are 0.5 and 1.0 nm for the $O_2$B and $O_2$A band, respectively. During the CEFLES2 campaign, the Airflex sensor was fixed on the floor of the Piper Seneca airplane of the IBIMET (Istituto di Biometeorologia of the CNR).

The data considered in this work were acquired in a straight line at an altitude of 465 m with a resulting ground spatial resolution of 16 m. We have centred the attention in the oxygen-A absorption band and in the September campaign as this month presented more heterogeneity of crops. In fact, in the results section the study will be centred in two different crops where the in situ measurements were retrieved: a corn and a bean field. There were a total of four Airflex overpasses over these fields. In UTC the overpasses over the bean field were at 9:17, 9:28, 11:40 and 11:49 a.m. and over the corn field at 9:53, 11:24, 11:40 and 11:49 a.m.

<table>
<thead>
<tr>
<th>Band</th>
<th>Outside band (nm)</th>
<th>Inside band (nm)</th>
<th>Outside band (nm)</th>
<th>Full Width Half Maximum (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2$B</td>
<td>685.541</td>
<td>687.137</td>
<td>694.114</td>
<td>0.5</td>
</tr>
<tr>
<td>$O_2$A</td>
<td>757.191</td>
<td>760.39</td>
<td>770.142</td>
<td>1.0</td>
</tr>
</tbody>
</table>
3.4 **Airborne data: AHS**

The Airborne Hyperspectral Scanner (AHS) (Sobrino *et al.* 2008), is an 80-band airborne imaging radiometer, developed and built by SensyTech Inc. (currently Argon ST, and formerly aedalus Ent. Inc.) and operated by the Spanish Institute for Aerospace Technology (INTA). It has 63 bands in the reflective part of the electromagnetic spectrum, 7 bands in the 3–5 μm range and 10 bands in the 8–13 μm region. However, our study will be centred on the first 20 bands, covering a spectral response of 0.4 to 1.1 μm (400 to 1100 nm).

The AHS is a linescanner with a concept shared with classical airborne line-scanners, such as the Airborne Thematic Mapper (ATM), the Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator (MAS). The AHS has been installed in a CASA-212 200 Series aircraft and integrated with a GPS/INS POS-AV 410 from Applanix.

The data used in this work have been acquired in a straight line at an altitude of 2865 m with a resulting ground spatial resolution of 6 m.

3.5 **In situ data**

*In situ* measurements retrieved by an OceanOptics HR4000 spectrometer (Ocean Optics, Dunedin, FL, USA) at nadir have been considered to estimate *in situ* fluorescence. These measurements were performed by the group from UNIMIB (University of Milano-Bicocca). Two crops have been considered: a corn and a bean field. Measurements were retrieved on 13 and 15 of September, respectively.

In the case of the corn field, the spectrometer was installed on top of a two-floor scaffolding tower of 3.2 m height, resulting in an observed circular area of 49 cm radius. However, the bean field was observed from a height (above ground) of 150 cm and its mean height was 45 cm, resulting in an observed circular area of 23 cm radius (CEFLES2 Data Acquisition Report).

4. **Results**

The analysis of Airflex data is centred on the oxygen-A absorption band and in September as this month presented more heterogeneity of crops. Airflex data have been calibrated considering the *in situ* measurements simultaneous to the airborne overpasses of two kinds of surface, bare soil and vegetation (corn). With this aim, atmospheric correction has been inverted over *in situ* data estimating the reflectance that would be measured by the sensor using the radiative transfer code MODTRAN 4.3 (Berk *et al.* 1998). A linear regression has been performed for each band representing the value measured by the sensor versus the one estimated from the atmospheric correction inversion over *in situ* data, where the slope and the intercept are the calibration coefficients. In table 2, the calibration coefficients are summed corresponding to the three Airflex bands centred in the oxygen-A absorption band.

The surface reflectance is then obtained by applying these coefficients to every raw data and performing the atmospheric correction with MODTRAN 4.3 following Verhoef and Bach (2003) methodology. As *in situ* data have been considered in the calibration of the sensor the surface reflectance from Airflex has been compared with the one estimated with the AHS sensor following the same methodology of atmospheric correction. In figure 3, the mean values over a corn field are represented, where
the errors refer to the spatial variation of the surface reflectance through the field. It can be seen that the calibrated data fit well with the AHS estimated spectrum.

The three different methods described in the methodology section have been considered: FLD, FRM and iFLD. In figure 4, the fluorescence estimated with the different methods is represented and the NDVI through one Airflex flight line over the study area.

As a general view, the fluorescence profile is similar to the NDVI. Comparing the different results of fluorescence obtained, it can be observed that the FRM involved the higher values, and the profile seems to be noisier. Intermediate values of fluorescence are estimated considering the FLD method, obtaining the lowest values with the iFLD method.

With the aim of evaluating the method closest to the real values, the results have been compared with *in situ* measurements. These ones were centred in a corn (the left star in figure 4) and a bean field (right star). The measurements were performed by the group from the University of Milano-Bicocca (UNIMIB) using an OceanOptics HR4000 spectrometer as explained in the previous section.

Fluorescence *in situ* measurements were performed in the corn field on 13 September and in the bean field on 15 September. Therefore, only measurements acquired in the bean field were simultaneous to the Airflex overpass, which was performed on 15 September. However, we also consider the 13 September *in situ* measurements in the test since data were atmospherically corrected and also both days were very clear.

The band position, width and depth of the oxygen absorption bands strongly depend on the spectral resolution with which they are observed (Meroni *et al.* 2009).

Table 2. Calibration factors of the Airflex sensor where \( R(\text{in situ}) = a \cdot R(\text{Airflex}) + b \).

<table>
<thead>
<tr>
<th>Airflex bands</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>B760 (757 nm)</td>
<td>0.39</td>
<td>0.03</td>
</tr>
<tr>
<td>F760 (760 nm)</td>
<td>0.55</td>
<td>0.01</td>
</tr>
<tr>
<td>R770 (770 nm)</td>
<td>0.42</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Figure 3. Comparison of the Airflex surface reflectance calibrated with the surface reflectance estimated from an Airborne Hyperspectral Scanner (AHS) image simultaneous to the Airflex overpass.
Fluorescence estimation

Figure 4. (a) Airflex flight line over an Airborne Hyperspectral Scanner (AHS) image (the stars point to the place where in situ measurements were performed). (b) Normalized Difference Vegetation Index (NDVI) and fluorescence estimated considering the Fraunhofer Line Discrimination (FLD) method, using the radiative transfer equation and the improved Fraunhofer Line Discrimination (iFLD) method through Airflex flight line 1.

Therefore, in order to compare in situ and airborne measurements, spectra measured in situ were band averaged using Airflex spectral response functions. Then we applied the FLD and iFLD methods to these data. The FRM method cannot be applied to in situ measurements as it includes the atmospheric correction. Table 3 shows the comparison of in situ and airborne fluorescence estimated with the same method. The airborne fluorescence estimated with the FRM method has been compared to in situ fluorescence estimated with the FLD. The errors in the table refer to the standard deviation of the value due to its spatial variation.

5. Discussion

From table 3, at first we can observe that the standard deviations of the in situ measurements in the bean field are (in most cases) higher than the corn field independently of the method. This can be a consequence of the lower observed circular area in the bean field measurements, affecting more the structural effects and the shadows. We can also remark that the fluorescence values in the bean field are higher than in the corn field, which agree with the NDVI values. Figure 5 shows the temporal evolution of the NDVI and the fluorescence estimated at airborne level with the different methods in the case of the bean field.

In this graph we can observe that while the NDVI does not change significantly through time, the fluorescence, independently of the method, increases from 9 to
Table 3. Fluorescence values (in mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$) estimated with the different methods from Airflex data and compared to in situ measurements.

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>NDVI</th>
<th>Airflex</th>
<th>In situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLD Bean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9:17</td>
<td>0.84 ± 0.02</td>
<td>1.16 ± 0.06</td>
<td>1.37 ± 0.12</td>
</tr>
<tr>
<td>9:28</td>
<td>0.85 ± 0.02</td>
<td>1.45 ± 0.07</td>
<td>2.15 ± 0.05</td>
</tr>
<tr>
<td>11:40</td>
<td>0.84 ± 0.06</td>
<td>2.7 ± 0.3</td>
<td>2.92 ± 0.13</td>
</tr>
<tr>
<td>11:49</td>
<td>0.83 ± 0.05</td>
<td>2.6 ± 0.3</td>
<td>2.5 ± 0.5</td>
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<td>0.55 ± 0.04</td>
<td>1.02 ± 0.13</td>
<td>1.12 ± 0.01</td>
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</table>

Note: FLD, Fraunhofer Line Discrimination; iFLD, improved Fraunhofer Line Discrimination; FRM, Fluorescence Radiative Method.

12 a.m. This agrees with Amoros-Lopez et al. (2008) where some experiments show that the fluorescence emission is directly related to the photosynthetically active radiation (PAR) intensity, which means that the maximum fluorescence radiance can be measured around noon.

Centring the attention on the comparison between in situ and airborne fluorescence, the FLD sub-estimates and the iFLD and FRM overestimates the fluorescence value. The lowest root mean square error (RMSE) in the case of the bean field is reached considering the FLD method. However, in the corn field (which presents less standard deviation) the RMSE is lowest with the iFLD. The FRM presents the worst error. On the one hand, it could be due to the comparison with in situ fluorescence estimated with another methodology (the FLD). On the other hand, the FRM method overestimates significantly the fluorescence, which is caused by the assumption of the $\beta_R$ (equation (17)) constant and equal to the corresponding value of bare soils. Consequently, as the soil spectrum slope is lower than the vegetation spectrum (in the oxygen-A absorption band spectral range) $\beta_R$ is lower than it should be and, according to equation (16), the fluorescence values are overestimated.

Therefore, the methods that provide better results when compared to in situ fluorescence are the FLD and iFLD with RMSEs of 0.4 and 0.5 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$, respectively, while the error committed with the FRM is 0.8 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$. These errors could be associated with the structural effects of the vegetation, which
are less important in airborne data than *in situ* measurements due to the different spatial resolution.

Comparing the fluorescence at airborne level obtained with the different methods we can see in table 3 that the FRM estimates the highest values while the iFLD estimates the lowest ones. The overestimation of the FRM method has already been discussed. However, the difference between the FLD and iFLD fluorescence values is due to the assumption of considering the reflectance and fluorescence constant (in the case of the FLD) or variable (in the case of the iFLD) inside and outside of the oxygen absorption band. The results agree with Alonso *et al.* (2008), who demonstrate that the assumption of spectrally-constant fluorescence and reflectance of FLD actually leads to fluorescence overestimation at the oxygen-A absorption band.

### 6. Conclusions

In this article, three different methods for estimating the fluorescence have been investigated: the FLD, the FRM and the iFLD. They have been applied to Airflex airborne data in the framework of the CEFLES2 campaign, and have been evaluated through its comparison with *in situ* measurements. In the comparison with *in situ* measurements, the methods that provide the best results are the FLD and the iFLD with RMSEs of 0.4 and 0.5 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$, respectively, while the FRM provides an error of 0.8. Further data are needed, both *in situ* and airborne, in order to develop a more extensive study. In June 2009 the Sentinel-3 Experiment (SEN3EXP) campaign was performed over different zones of Spain and Italy providing more *in situ* and airborne data.
Acknowledgements

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References


