ABSTRACT

A characteristic spectral emission is observed in vegetation chlorophyll under excitation by solar radiation. This emission, known as solar-induced chlorophyll fluorescence, occurs in the red and near infra-red spectral regions. In this paper a new methodology for the estimation of solar-induced chlorophyll fluorescence from spaceborne and airborne sensors is presented. The fluorescence signal is included in an atmospheric radiative transfer scheme so that chlorophyll fluorescence and surface reflectance are retrieved consistently from the measured at-sensor radiance. This methodology is tested on images acquired by the Medium Resolution Imaging Spectrometer (MERIS) on board the ENVironmental Satelllite (ENVISAT) taking advantage of its good characterization of the O₂-A absorption band. Validation of MERIS-derived fluorescence is carried out by applying the method to data acquired by the Compact Airborne Spectrographic Imager (CASI-1500) sensor concurrently to MERIS acquisitions. CASI-derived fluorescence is in turn compared with ground-based fluorescence measurements. A correlation coefficient $R^2$ of 0.85 is obtained.

Key words: Solar-induced chlorophyll fluorescence, Remote sensing, Atmospheric correction, Vegetation indices.

1. INTRODUCTION

Vegetation photosynthesis is a key factor driving the different biochemical cycles and CO₂ exchanges occurring between the biosphere and the atmosphere. The monitoring of vegetation state and biological activity is one of the key objectives of remote sensing. This has traditionally relied on vegetation indices that characterize the amount and spatial distribution of vegetation. An indicator of the actual plant physiological state is the solar-induced chlorophyll fluorescence emission ($F_s$). The emission of light as fluorescence (namely, in the 650 to 800 nm spectra range) is produced after absorption of light by a mechanism in direct competition with the photochemical conversion. The $F_s$ signal has been widely reported to be of 0.85 is obtained.

A sensitivity analysis performed using typical remote sensing acquisition geometry and atmospheric conditions showed that factors such as the illumination and observation angles, target elevation and orientation, atmospheric turbidity or sensor spectral calibration do have a crucial impact on the depth of absorption features. In this framework, a new technique for estimating $F_s$ from space measurements is presented in this work. The $F_s$ retrieval is coupled to an atmospheric correction scheme, where surface elevation, aerosols, surface reflectance and the sensor spectral calibration are properly modelled. The $F_s$ signal at 760 nm in radiance units is provided as output. MERIS [8] has been selected to test the method at a satellite scale, because its spectral configuration enables a good characterization of the O₂-A absorption feature. MERIS images are acquired in 15 bands covering the 400-900 nm spectral region at a spatial resolution up to 300 m. In particular, bands 10 and 11 offer an optimal configuration as reference/measuring channel pair to be used by the FLD technique. The O₂-A absorption is well defined by band 11, centered at 760.6 nm around the detection of solar-induced vegetation fluorescence from MERIS FR data.
the bottom of the absorption feature (apart from intrinsic instrumental spectral shifts) with a small bandwidth of 3.75 nm, and band 10 (around 753.8 nm) is separated only by 7 to 8 nm, and is nearly free from absorption. No other spaceborne instrument presents such a good spectral resolution around the O₂ absorption at a spatial scale finer than the 300 m per pixel of MERIS Full Resolution (FR) mode. This size is a reasonable upper limit for the pixel dimensions to which the interpretation of the fluorescence signal is feasible, as pure vegetation targets can still be detected. At coarser spatial resolutions, the appearance of non-fluorescent targets at sub-pixel level would lead to weakening the fluorescence signal, so that the estimation of \( F_s \) could become impossible. In addition to the spectral configuration, MERIS presents a reliable radiometric and spectral calibration after a number of specific calibration and validation activities. Validation of MERIS-derived \( F_s \) is carried out by comparing with equivalent retrievals from airborne CASI data at 13 m spatial resolution, which in turn are intercompared with ground-based fluorescence measurements acquired during the SENTinel-2 and FLuorescence EXPERiment (SEN2FLEX) ESA campaign. It was deployed in 2005 for the observation of solar-induced fluorescence signal over multiple agricultural and forest targets to verify signal suitability for observations from space, as proposed for example by the Fluorescence Explorer (FLEX) Earth Explorer mission of the ESA Living Planet Programme.

2. ALGORITHM DESCRIPTION

The \( F_s \) signal is included in the whole radiative transfer scheme as an additive term adding up over the reflected flux at the target level. If the fluorescence emission is assumed to be isotropic [9] and the surface reflectance to be Lambertian, the radiative transfer equation giving the at-sensor radiance is

\[
L_{\text{TOA}} = L_0 + \frac{[E_{\text{dir}} + E_{\text{diff}}] \rho_s + \mu_s F_s] T}{1 - S} \tag{1}
\]

where \( L_{\text{TOA}} \) is the TOA radiance, \( L_0 \) is the atmospheric path radiance; \( \mu_s \) is the cosine of the illumination zenith angle \( \theta_s \), measured between the solar ray and the surface normal; \( E_{\text{dir}} \), \( E_{\text{diff}} \) are the direct and diffuse fluxes arriving at the surface, respectively; \( S \) is the atmospheric spherical albedo, reflectance of the atmosphere for isotropic light entering it from the surface; \( T \) is the total atmospheric transmittance (for diffuse plus direct radiation) in the observation direction, and \( \rho_s \) is the surface reflectance.

For the calculation of \( F_s \) the atmospheric functions in Eq. 1 (\( L_0 \), \( E_{\text{dir}} \), \( E_{\text{diff}} \), \( T \) and \( S \)) must be known. This is achieved by an atmospheric correction method [10] which is coupled to the fluorescence retrieval. It is based on the estimation of aerosol optical thickness (AOT) and columnar water vapor (CWV) from the at-sensor radiance. The atmospheric parameters are calculated on a per-pixel basis accounting for the surface elevation, which is provided by a Digital Elevation Model (DEM) overlapped to the images. The DEM is also employed in the calculation of the actual illumination angle to be used in correction of topographic effects in rough terrain. The sensor spectral calibration is also assessed in the evaluation of atmospheric absorptions. A MODTRAN4-based look-up table (LUT) enables fast but accurate computation of the atmospheric parameters. Once these are known, a problem of 2 unknowns, \( \rho_s \) and \( F_s \), and one equation must be solved.

The FLD principle is used to decouple the emitted and reflected contributions. MERIS bands 10 and 11 are used as reference/measuring band, as it has been discussed previously. Theoretically, any other pair of bands in the red and NIR spectral regions could be used in order to provide the necessary information for the separation of \( \rho_s \) and \( F_s \), but the low weight \( F_s \) would have in the radiance outside a strong absorption band would cause the fluorescence signal to be too low to be separated from the reflected radiation. Writing the spectral dependence explicitly, the system to be solved is

\[
\begin{align*}
L_{\text{TOA}}^{10} &= L_0^{10} + \frac{[E_{\text{dir}}^{10} + E_{\text{diff}}^{10}] \rho_s^{10} + \mu_s^{10} F_s^{10}] T^{10}}{1 - S^{10} \rho_s^{10}} \\
L_{\text{TOA}}^{11} &= L_0^{11} + \frac{[E_{\text{dir}}^{11} + E_{\text{diff}}^{11}] \rho_s^{11} + \mu_s^{11} F_s^{11}] T^{11}}{1 - S^{11} \rho_s^{11}}
\end{align*}
\]

The problem consists then of two equations being defined by 4 variables, \( \rho_s^{10} \), \( F_s^{10} \), \( \rho_s^{11} \), and \( F_s^{11} \). It is closed-up by assuming a linear spectral dependence in \( \rho_s \) and \( F_s \) between bands 10 and 11, which are thus related by

\[
\begin{align*}
\rho_s^{11} &= A \rho_s^{10} \\
F_s^{11} &= B F_s^{10}
\end{align*}
\]

This simplistic modelling is justified by the spectral proximity of MERIS bands 10 and 11, which is around 8 nm. It is a refinement against just assuming \( \rho_s^{11} \approx \rho_s^{10} \) and \( F_s^{11} \approx F_s^{10} \), as it was done in an earlier version of the method. The \( A \) coefficient is calculated on a per-pixel basis, using \( \rho_s^{10}, \rho_s^{11} \) as provided by the atmospheric correction module neglecting the fluorescence contribution. On the other hand, a universal value is selected for the \( B \) coefficient. Most of the variability in the fluorescence emission spectrum due to external parameters is expected in the 670-740 nm range, while the shape of the two wings at the sides of this interval remains constant for a wide range of canopy conditions and vegetation types. In particular, the literature shows that a value around \(-0.8\) for the spectral slope of the \( F_s \) emission at the 760 nm region can be adopted as representative of a wide range of those cases. From Eq. 2 and Eq. 3 and a little algebra, an analytical expression for the fluorescence emission is derived. An effective transmittance factor correcting for possible inaccuracies in the computation of the O₂-A absorption is calculated in the last place. Linear spectral patterns around the 760 nm spectral region in non-fluorescent targets is assumed for that purpose.
3. RESULTS

3.1. Results from MERIS data

The method was tested on MERIS FR data acquired over the Barrax study site (39.05°N, 2.10°W, La Mancha, Spain) during the ESA-sponsored Spectra bARRx Campaign (SPARC) and SEN2FLEX activities. The Barrax study site offers a unique case for testing the performance of fluorescence retrieval algorithms. Extensive green vegetation fields are present in different phenological states and stress levels, either irrigated or not. The flatness of the terrain practically avoids the influence of surface elevation, as it is nearly constant around 700 m above sea level. Moreover, a large MERIS FR data set has been acquired along the last years over the Barrax study site, with a number of images in coincidence with dedicated field campaigns. For the analysis of the results, a 90 km-side square area centered at the Barrax site is chosen. Possible errors associated to changes in the MERIS spectral calibration and in the atmospheric state are minimized by working in a reduced area.

A sample of $F_s$ map from the Barrax area is shown in Fig. 1. It has been extracted from a MERIS FR image acquired on 14 July 2004. The Normalize Difference Vegetation Index (NDVI) [11] map from the same area is also displayed in order to give an idea of the vegetation cover in the area. Equivalent maps have been generated from other MERIS acquisitions in the summer months of 2003, 2004 and 2005. Overall, similar fluorescence levels of around 2–4 Wm$^{-2}$sr$^{-1}$µm$^{-1}$ are detected in all the cases, although some local deviations are found in certain areas. It must be remarked that the fluorescence intensity estimated from MERIS data compares well with the approximated range of variation published in the literature for the chlorophyll fluorescence emitted under natural conditions (e.g. [12, 13]).

Those $F_s$ maps have been compared with other biophysical products derived from MERIS data. In particular, maps of fractional vegetation cover, Leaf Area Index (LAI), LAI times the leaf chlorophyll content, fraction of absorbed photosynthetically active radiation and the MERIS Terrestrial Chlorophyll Index [14] were derived from MERIS images. The comparison with the corresponding $F_s$ maps does not lead to solid conclusions about the correlation between fluorescence and the other biophysical parameters. Although the same vegetation patterns can be recognized within the different products, the 300 m spatial resolution is too coarse for a quantitative analysis. It was also found that the chlorophyll-related products do not present a clear correspondence with $F_s$, although the correlation is higher than for the other biophysical parameters. This fact suggests that the fluorescence emission is more related to the pigment concentration than to the amount of vegetation, what indicates the link between fluorescence and vegetation photosynthetic activity. These results support the ability of the proposed methodology to estimate vegetation fluorescence from MERIS FR data. However, it is difficult to attempt a robust quantitative validation of the results at a 300m per pixel resolution, as the crops where ground truth is available can not be clearly distinguished, nor pure vegetation pixels can be isolated. For this reason, the same methodology has been applied to data acquired at the time of MERIS acquisitions during the SEN2FLEX campaign by the airborne sensor CASI-1500. The in situ measurements of solar-induced fluorescence taken during the campaign enable the quantitative assessment of the $F_s$ signal retrieved from remote sensing data.

3.2. Results from CASI-1500 data

CASI-1500 is a pushbroom airborne sensor acquiring hyperspectral images during the SEN2FLEX campaign in the 370 to 1050 nm spectral region with a spectral resolution up to 2.2 nm (288 bands). The nominal spatial resolution is 3 m per pixel. CASI provides a nearly-continuum spectrum in the entire spectral range, with very fine observation channels that are able to reproduce any small spectral absorption feature due to surface or atmospheric components. A detailed characterization of the O$_2$-A absorption band at 760 nm is also provided. These features enable the use of CASI for the estimation of $F_s$ signal at a much finer spatial resolution than MERIS.

As in the case of MERIS, the fluorescence retrieval is coupled to an accurate atmospheric correction algorithm [15]. It is specifically designed for ultra-fine spectral resolution (bandwidth from 2 to 10 nm) and spatial resolution (pixel size less than 10 m) imaging spectrometers. The assessment of the spectral calibration is coupled to the removal of the atmospheric distortion so that maps of surface reflectance are derived, as well as CWV maps, estimations of AOT and updated sensor gain coefficients and spectral calibration. The $F_s$ term is included in the atmosphere/surface radiative transfer according to Eq. 1, and the same steps for the estimation of the fluorescence signal than in the case of MERIS are carried out.

Reflectance and fluorescence images were obtained as final product. The reflectance images were used, in turn, for the derivation of Normalize Difference Vegetation Index (NDVI) [11] and PRI. RGB composites showing the imaged area and the retrieved $F_s$ image from the 288-bands spectral mode are plotted in Fig. 2. The circular shapes of some fields are due to the irrigation system consisting in a pivot system spinning around the crop. It was observed that different information is provided by the three vegetation indicators. For example, the NDVI normally presents a low variation within the same field, while PRI and $F_s$ show noticeable variations. Indeed, $F_s$ shows spatial patterns within the fields in areas where the NDVI looks homogeneous. This is a new proof of the decoupling between the green vegetation amount, as given by the NDVI, and the actual plant photosynthetic activity, indicated by the fluorescence signal. Indeed, the correlation between PRI and $F_s$ reported by some authors work-
ing at the laboratory level [12, 13, 16, 17] has not been proved, as the PRI decreases gradually towards the edges of the image in vegetation targets. This may be explained by the large dependence of the PRI on the canopy structural parameters, and so on the view angle, described by Barton and North [18].

Moreover, the range of \( F_s \) values compares well with those estimated from MERIS data. For a quantitative validation of the CASI-derived \( F_s \) signal, it has been compared with ground-based fluorescence measurements taken simultaneously to CASI acquisitions. The radiance measured by an ASD FieldSpec FR spectroradiometer on different crops over the Barrax study site was converted into chlorophyll fluorescence at 760 nm by applying the FLD principle. These ground-based fluorescence measurements are compared with CASI-derived \( F_s \) signal in Fig. 3. A high linear correlation with a coefficient \( R^2 = 0.854 \) between ground-based and remote sensing \( F_s \) retrievals can be noted. However, further investigation is still needed to analyze the deviations found between CASI-derived fluorescence and ground-based measurements. In any case, the ability of the method for the remote discrimination of high and low levels of fluorescence emissions has been demonstrated, and so of plant photosynthetic activity. This can be considered an important step in the field of monitoring vegetation activity from space.

4. SUMMARY AND CONCLUSIONS

A new method for the estimation of chlorophyll fluorescence from space- and airborne sensors with a proper characterization of the atmospheric \( O_2-A \) absorption feature has been presented. The fluorescence retrieval is coupled to an atmospheric correction scheme in order to account for the impact of different factors, both environmental (aerosol loading, surface elevation, reflectance) and technical (instrument spectral calibration) over the

\[ O_2-A \text{ absorption depth}. \] The method has been tested on MERIS FR and CASI-1500 data. The MERIS-based \( F_s \) maps showed a good correspondence with the typical variation ranges published in the literature. The \( F_s \) signal is not redundant with other vegetation indicators, although it has a better correlation with indicators representing pigment concentrations rather than vegetation amount. Quantitative validation was achieved by comparing MERIS \( F_s \) retrievals with those from airborne CASI-1500 data. The latter were taken at a 3 m spatial scale, so the intercomparison with ground-based fluorescence measurements is meaningful. A clear linear correlation \( (R^2 = 0.854) \) was found, although only 5 points were used. A systematic overestimation of CASI retrievals against ground-based measurements must be investigated.

Solar-induced chlorophyll fluorescence signal is a promising indicator of the vegetation conditions, closer to actual photosynthesis than other vegetation indices. Even though the fluorescence signal is very weak compared to
other contributions, a first step towards its quantitative detection has been presented in this work. Further research in that direction could open new perspectives in the monitoring of vegetation from the space.

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