Terrestrial Plant Fluorescence as seen from Satellite Data

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***Abstract*—Elevated atmospheric CO$_2$ concentration is shown to be partially compensated by additional CO$_2$ uptake from land and ocean. Increasing the CO$_2$ solubility in the ocean is known to be a reason of ocean acidification. Yet, biological cycles related to CO$_2$ assimilation over land and in ocean are mainly carried by the photosynthetic organisms. Fluorescence generated by these organisms can be an integrating tool that might be used directly to obtain information on photosynthetic performance. Therefore, measuring fluorescence is potentially an indicator for carbon uptake by both land and ocean photosynthetic processes. The main focus of this study is on terrestrial Solar Induced Fluorescence (SIF) retrieval from space-borne measurement data, which is also important for global forest monitoring and agricultural purposes. SIF (being emitted between 600-800 nm) is a small fraction of the reflected light in visible and near infrared spectral region. However, it can be quantified within a certain wavelength regions of satellite data from top of the atmosphere. In our study, a newly developed retrieval scheme is used to identify SIF from non-invasive satellite measurements and has been shown to be closely related to ocean remote fluorescence retrieval as well. The first results from our SIF retrieval method for 10 years of data from SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Chartography) and first results from GOME-2 (Global Ozone Monitoring Experiment-2) are promising and show reasonable correlation to previous studies.**

I. INTRODUCTION

Space-borne chlorophyll fluorescence retrieval is a potential way to estimate vegetation carbon-related processes that are of interest for agricultural purposes, forest management, and assessment of the terrestrial carbon budget. During the last years, there have been several successful attempts to retrieve Solar Induced plant Fluorescence (SIF) using satellite based data globally (e.g. Joiner et al., 2013 [1]) using data from different space-borne instruments e.g. GOSAT (Greenhouse gases Observing SATellite) or GOME-2 (Global Ozone Monitoring Experiment II).

In principle the used methods take advantage of the fact that plant leaves absorb sunlight mainly within the visible spectral range and use it either for chemical work (photosynthesis) and/or release it as heat or fluorescence (in red and Near Infra Red, NIR, spectral region) back to the atmosphere. Therefore, SIF can be considered to be an additive signal on top of the ground reflectance reaching TOA (Top Of Atmosphere). Chlorophyll fluorescence is emitted mainly in the spectral range of red to the near-infrared with two pronounced peaks at 690 and 740 nm. (Figure 1) The additive signal emitted as SIF at canopy level within this wavelength range affects the TOA radiance.

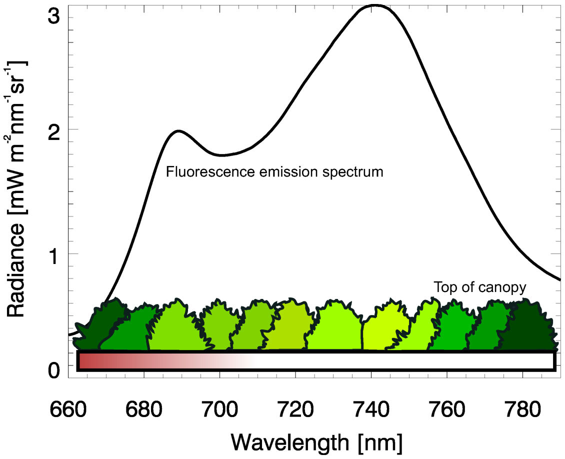

Fig. 1. The fluorescence spectral feature as it is measured over canopy layer from FluorMOD data [4].

Emitted between 600-800 nm, this additive signal is affected by gaseous absorption, and scattering processes in the atmosphere. Although it is a very weak signal and two orders of magnitude smaller than the received radiance at TOA, it is feasible to retrieve it within spectral wavelength windows in the NIR.

II. METHOD AND DATA

The developed retrieval method ([2]) is based on a modeled assumption of the emitted fluorescence spectrum at canopy level as it would be seen at TOA.

The sun-normalized radiance, I_n, at TOA in presence of terrestrial plant fluorescence, can be written as:

$$I_n(\lambda) = I^{+}(\lambda)/I_0(\lambda),$$

with I^+ and I_0 being the measured radiance at wavelength λ influenced by SIF and extra-terrestrial solar irradiance, respectively. Furthermore, the measured radiance also can be described as:

$$I^{+}(\lambda) = I^{-}(\lambda) + \varepsilon(\lambda)\ ,$$

where $I^{-}(\lambda)$ is the radiance in absence of SIF and $\varepsilon(\lambda)$ is a fluorescence spectrum as reaches the TOA level. However, SIF as a weak signal, is sensitive to atmospheric gaseous absorption. In order to avoid this impact we selected a narrow wavelength range where practically no gaseous absorption can play a role. Additionally we will need to take in to account the atmospheric and measurement spectral broadband effects such as aerosol and molecular scattering and surface reflectance. As a result, the natural logarithm of the measured radiance can be written as following:

$$\ln I_n(\lambda) = \ln I^-(\lambda)/I_0(\lambda) + \ln I^+(\lambda)/I^-(\lambda). \qquad (1)$$

The optical depth is defined as the natural logarithm of the sun-normalized radiance (hereafter referred to as τ). Accordingly τ^+, as optical depth influenced by fluorescence can be written as the optical depth free of SIF (τ^-), and a spectrum containing the information about SIF at TOA. We refer to the latter quantity as fluorescence reference spectrum (F).

The simulated radiance at TOA, affected by fluorescence, I^+, and when no fluorescence is present, I^-, is shown in Figure 2 (a). As τ^-, shown in Figure 3 (a), is not affected by any atmospheric gaseous absorption or additive SIF, it presents a broadband spectral feature. However, τ^+, as it can be seen from Figure 3 (b), still free of absorption, but influenced by SIF as an additive signal, exhibits features due to the Fraunhofer line infilling effect. It can be shown that τ^+, is constructed by summing over τ^- and fluorescence reference spectrum F, shown in Figure 2 (b). Thus, F is defined as:

$$F(\lambda) = \ln I^+(\lambda)/I^-(\lambda).$$

Eq. 1 is transformed to:

$$\tau^+(\lambda) \;=\; \tau^-(\lambda) \;+\; f\,F(\lambda)\,.$$

As it can be seen from Figure 2 and 3, τ^- can be represented by a polynomial due to its broadband feature.

Fluorescence has been retrieved using least squared fitting method to fit F to the measured optical depth of the atmosphere:

$$\left\|\,\tau^+(\lambda) - f\,F(\lambda) - P(\lambda)\,\right\|^2 \rightarrow min,$$
$$\text{with} \quad P(\lambda) = \sum_{i=1}^{N} a_i \lambda^i\ ,$$

with f being the fit factor for the modeled F spectrum and a_i the polynomial coefficients.

SIF is intended to be retrieved globally. To create F for each location, we would have to find one measurement in presence of SIF and one in absence of it. Both measurements, need to be done under the same conditions (atmospheric and geometrical) which is feasible in principle but in reality but not for every measurement situation. Thus, The fluorescence reference spectrum, F, is decided to be simulated and computed by a Radiative Transfer odel (RTM). We selected a well established, comprehensive RTM, called SCIATRAN v3 [3].

A fluorescence emission spectrum, φ, at canopy layer as the fluorescence emission source for the radiative transfer equation has been added to SCIATRAN. The utilized SIF emission spectrum has been selected through FluorMOD ("Development of a Vegetation Fluorescence Canopy Model") (for instance see Zarco-Tejada et al. (2006) [4]). As it has been mentioned before, the simulated F, using φ can be only used in some specific spectral wavelength ranges.

There are two main requirements for corresponding spectral window selection which are:

- The fluorescence signal contribution to the TOA radiance should be significant enough to achieve accurate retrievals;
- The chosen wavelength range should be free of surface or telluric absorption features to be used in our method.

Therefore, we selected a narrow spectral window between 748.5 and 753 nm which meets both requirements. However, we ensured that there are enough spectral Fraunhofer lines within this range which are necessary to characterize the spectral retrieval features.

Nadir measurements from the SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric Chartography) instrument aboard ENVISAT (ENVIromental SATellite), which provides a long-term data record has been used for this study.

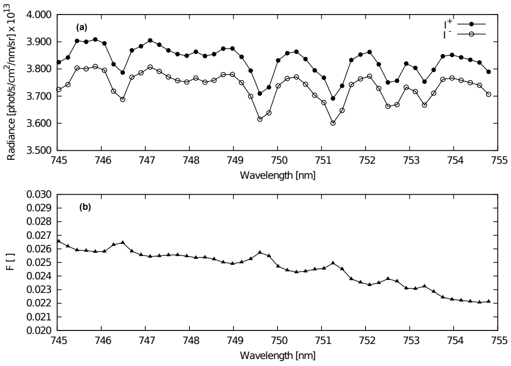

Fig. 2. (a): The radiance modeled as it is received at TOA, with and without SIF in the wavelength region used in this study. The fluorescent (I^+) radiance is biased with respect to I^-, due to the SIF effect. (b): The fluorescence reference spectrum, F, calculated with radiances shown in (a).

A. Data source: SCIAMACHY

SCIAMACHY is a grating spectrometer on board the ENVIromental SATellite (ENVISAT) [5]. and has the spectral resolution with FWHM of 0.48 nm in and spatial resolution of 30 km by 240 km the selected channel for this study.

B. Zero-offset correction

[6] discussed the zero-offset effect, as the amount of additive radiation not originating from SIF but rather other

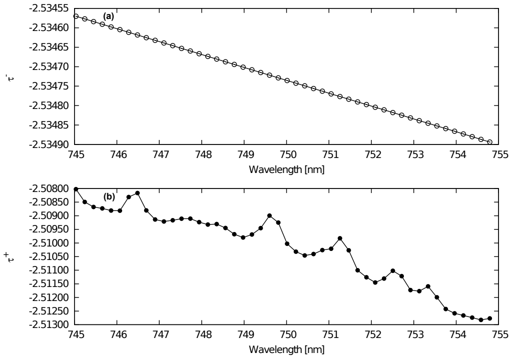

Fig. 3. (a): The optical depth excluding SIF τ^- in the wavelength region used in this study. (b): The optical depth including SIF τ^+ for the same wavelength range as in (a).

sources, that can affect fluorescence retrieval. According to Joiner et al. (2013 and 2014) [7], [1] the non-linearity of instrumental signal can be a source of such additive radiation. It has been shown that the zero-offset effect is a significant source of error in the retrievals. Correcting the retrieval method for this effect, which can be instrumental was an important step for the SIF retrieval progress, shown in this paper. For brevity the correction method is not explained here. However, for further reading please see Vountas et al. (2014) [2].

III. RESULTS AND DISCUSSION

The retrieved SIF is presented as fluorescent power P_f which is obtained as bellow:

$$P_f = \hat{f} * \varphi$$

and is the fluorescent power at canopy level in [mW m^{-2} sr^{-1} nm^{-1}].

The global P_f has been retrieved based on fully consolidated SCIAMACHY level 1 nadir data (consolidation degree "W"). In order to cope with cloudy pixels from the SCIAMACHY measurements we removed them using MICROS (MerIs Cloud fRation fOr Sciamachy) cloud fraction data set [8].

Retrieval of P_f can be seen in Fig. 4, for seasonally resolved averages of all available years (2003-2012), gridded to 80 arc minutes.

Larger values of P_f are retrieved over densely vegetated areas, as expected and are shown by Joiner et al. (2013), Guanter et al. (2013 and 2014) [1], [9], [10]. The original spatial resolution of our results is 240 x 30 km^2 and therefore, the SIF retrieval is likely to be influenced by water, especially near the coasts.

The well pronounced fluorescence average power over "corn-belt" is qualitatively in analogy with the research of Guanter et al. (2014) [10]. The differences between the two studies can also be due to different spatial resolution of the GOME-2 (80 km x 40 km) and SCIAMACHY.

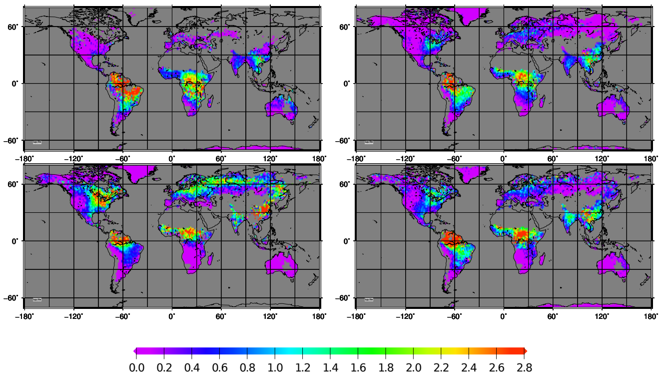

Fig. 4. Global values of fluorescent power at canopy level in mW m^{-2} sr^{-1} nm^{-1} based on SCIAMACHY data. (Left top) For Northern winter (DJF); (Right top) For spring (MAM); (Left bottom) For summer (JJA) and (Right bottom) For autumn (SON) months.

A. *Comparison with NASA fluorescence data*

SIF data, derived from GOME-2 by Joiner et al. (2013) [1] (labeled as "version 25" and henceforth called GSFC-data), has been used for comparison. Both SIF retrieval results were grided to 80 arc minutes. SCIAMACHY achieves in its nadir-mode global coverage at the equator in six days. However, for GOME-2 this time is approx. 1.5 days. As a result the SCIAMACHY data set is sparser.

Similarly, there is an overall analogy between the global data sets over typical hot spots such as US corn-belt. The differences could be due to different spatial resolution and local overpass time of the instruments. Different retrieval wavelength window is another reason for different *average* fluorescence retrieval. Therefore, identical results cannot be expected.

GSFC values vary within a narrower data interval between 0 and 2 mW m^{-2} sr^{-1} nm^{-1} and the data from this study are up to 4 mW m^{-2} sr^{-1} nm^{-1}.

A possible source of difference between both data sets might also be the low sampling of our retrieval results over regions where persistent clouds disturb the measurement for the SCIAMACHY large pixels. For instance in northern parts of South America some of the averaged values are made of five individual observations only, due to this problem while in less cloudy regions more than 30 individual observations were used to average one year of data.

IV. CONCLUSION

A novel method for the retrieval of Solar Induced Fluorescence (SIF) has been developed. The application of it to 10 years of SCIAMACHY data showed promising results. comparing our SIF retrieval with results from J. Joiner [1] showed that SIF values of our retrieval vary within a broader value range up to 4 mW m^{-2} sr^{-1} nm^{-1}], while Joiner et al.'s results are limited to maximum values of about 2 mW m^{-2} sr^{-1} nm^{-1}. Our approach is of generic nature and therefore, could be applied to other data sets as well. We plan to apply the method to GOME-2 level 1 data, as the instrument has a better spatial resolution (in the wavelength range needed) and a better global coverage.

ACKNOWLEDGMENT

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