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Retrieval of maize canopy fluorescence and reflectance by spectral fitting in the O_2–A absorption band

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ABSTRACT

Canopy level chlorophyll fluorescence and reflectance of maize were retrieved simultaneously by using spectral fitting (SF) techniques applied to canopy and reference upwelling radiances measured on the ground in the O_2–A atmospheric absorption band by means of a ground-measurements-based (GMB) method, using a white reference panel. This method was inspired by the Fluorescence Experiment (FLEX) mission concept, which is expected to provide the user community with a top-of-canopy radiance product, as well as sufficient data on atmospheric conditions to enable the simulation of a white reference panel radiance, after which the ground-based method can also be applied by the users of FLEX data. For the retrieval, a coupled surface–atmosphere radiative transfer model was also used to simulate the canopy radiance in specific atmospheric conditions and to quantify fluorescence and reflectance variables by using a second method based on the canopy radiance simulation (CRS), which uses the canopy radiance measurements only. The CRS method does not require any cross calibration of reference measurements, and is extremely useful when a reliable reference cannot be found. Part of the mathematical functions that modeled reflectance and fluorescence were recently used by the authors to perform simulations of observations from space. Simulations of the retrievals for both methods were performed at two different spectral band widths of 9 nm and 20 nm to evaluate the accuracy limits for a signal to noise ratio equal to 300:1. These simulations demonstrated an enhanced accuracy as compared to previously reported retrievals on the ground, and indicated that the CRS model can indeed be successfully applied for the retrieval of fluorescence. In the retrievals from measurements, the two intervals were compared to better evaluate the combined influence of the atmospheric conditions and forward modeling spectral accuracy on the CRS method. The 20 nm interval was also used to evaluate the possibility of retrieving the bi-directional and hemispherical–directional reflectances in the viewing direction of the canopy and surroundings. Lastly, the narrower 9 nm interval delivered the most accurate simulations and was chosen for comparing the retrievals obtained by means of the two different methods. From this comparison fluorescence retrieved by means of the CRS method resulted higher (about 5%) than that retrieved with the GMB method by means of the same mathematical functions, while the retrieved reflectances were very similar. The methods presented here demonstrate that fluorescence can be retrieved even when atmospheric and surface information is limited.

1. Introduction

The analysis of vegetation fluorescence has benefitted from multidisciplinary investigations involving several scientific communities such as those of eco-physiologists and ecologists, instrumentalists, and remote-sensing and radiative transfer modeling experts. In recent years, the development of dedicated instruments for sensing fluorescence has required a continuous review of the algorithms that could exploit the possibilities of emerging instruments in meeting the interests of a heterogeneous scientific community.

Different methods for retrieving fluorescence that have been proposed in the literature differ depending on their radiance and reflectance-based approaches, the number of channels and the type of techniques employed (Alonso et al., 2008; Maier et al., 2003; Meroni & Colombo, 2006; Moya et al., 2006). Recent studies have proposed a novel approach for chlorophyll fluorescence and reflectance retrievals on the ground (Mazzoni et al., 2008; Meroni et al., 2010), by exploiting spectral fitting (SF) techniques in the two atmospheric oxygen (O_2) absorption bands in the red and far-red spectral regions centered at 688 and 760 nm, respectively. SF is still a rather new

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technique for people working in this field, especially those more familiar with vegetation indices determined from measurements performed at low resolution. When the Fraunhofer-line-depth (FLD) principle (Plascyk, 1975; Plascyk & Gabriel, 1975) is applied, only a single value of fluorescence intensity, with reference to a given wavelength, or wavelength interval, is computed. Historically, this technique was applied to the narrow solar Fraunhofer lines (e.g., <1 nm) and implemented with filtered detection, but could be considered reliable when applied to isolated narrow lines. Recently, the FLD principle was also used to retrieve chlorophyll fluorescence in the solar potassium (K, 770 nm) lines close to the O_2–A absorption band by combining measurements with retrieval techniques at a very high resolution (J. Joiner et al., 2011). However, the FLD method has been widely used over the past decade by researchers studying *in situ* steady state fluorescence retrievals of vegetation outdoors, within the O_2 bands (e. g., see references in Meroni et al., 2010). Effectively, the use of this method could have been prompted by the low resolution of the instruments used, which automatically limited the number of data collected within the absorption lines. In many cases, when low spectral resolution instruments are used (e.g. ASD FieldSpec, USA), the FLD or FLD-like methods (Meroni et al., 2010) are the only viable option because only one spectral observation is collected within the absorption band.

Developing methods to retrieve chlorophyll fluorescence from satellite data, such as will be available from the proposed FLEX mission concept under development by the European Space Agency (ESA), provides the rationale for studies such as this one to investigate the feasibility of applying complex equations to the problem. The goal of this mission is to provide to the user community atmospherically corrected data at such a level that spectra of top-of-canopy radiance and total surface irradiance are of a quality comparable to that of measurements in the field. Frankenberg et al. (2011) found that the effects of vegetation fluorescence on TOA radiance spectra are hard to distinguish from those of aerosol variations when considering only limited spectral windows of the order of 20 nm. However, it is expected that combining data over larger portions of the spectrum will enable separation of the atmospheric signal from the typical fluorescence spectral signature.

A detailed comparison of SF and FLD approaches for distinguishing the fluorescence signal within the atmospheric oxygen absorption bands was reported in a recently published simulation by Meroni et al. (2010). This comparison has been extremely useful for understanding the causes of the different results obtained when using these two approaches. The superiority of the SF method as compared to the FLD method in wider (e.g., non solar line) spectral features such as the O_2–A band was outlined in a simulation study that compared the accuracies of the methods in practical situations in which noise was also considered, in order to make this comparison more realistic. Noise level was found to be a key factor in determining the most accurate formulation of SF functions. In the red and far-red O_2 absorption bands, SF enables very accurate retrievals of fluorescence. The main difficulty of this technique is the correct solving of numerous equations, namely one for each sampled wavelength (wave-number), and in the appropriate selection of specific spectroscopic functions. However, many tasks in remote sensing require the same level of computational complexity, and this problem can typically be solved by using standard routines, such as those in Mazzoni et al. (2008, 2010), and implemented with graphical user interfaces.

Recently, Meroni et al. (2010) conducted ground simulations by using upwelling radiances derived from MODTRAN 5 (Berk et al., 2005) for the irradiance spectra and by disregarding adjacency effects (at-sensor radiance signals coming from surface elements outside the target). At the top of the canopy (TOC), this is a reasonable approximation. For applications from space, this compromise negatively influences the accuracy of the fluorescence retrieval, because the adjacency effects are not negligible. As a proof of this, in Mazzoni et al. (2010) many simulations of canopy radiance were performed with the help of a coupled surface-atmosphere radiative transfer model (Milton & Rolling, 2006; Verhoef & Bach, 2007), which has been upgraded for the incorporation of fluorescence and the use of high-resolution MODTRAN5 (beta version) data. Although the FLEX mission does not endorse this approach, the future possibility of the FLEX mission (or other satellite missions) may take advantage of this method.

In this paper, we first show the results obtained by adopting a simplified method for the retrieval using a ground-measurements-based GMB method that only requires the measured *in situ* radiance data, both of the reference panel and the canopy. This method was used to analyze measurements that were performed at different times during the day, and compared to simulations of the retrievals performed with the upgraded version of the coupled atmospheric canopy-radiance model described in Verhoef (2010). This was done to establish the accuracy limits of the retrievals at ground-level, and to correct the spectral calibration of the measurements. In order to quantify fluorescence and reflectance from the same *in situ* canopy radiance data set, a second retrieval method, the canopy radiance simulation CRS method, was necessary. The second method used simulations of the canopy radiance in place of the reference panel radiance measurements.

In this way, retrievals of both reflectance and fluorescence were possible by avoiding all the sources of experimental uncertainty linked to the cross-calibration procedure of the reference panel. On the other hand, since the atmospheric conditions were only presupposed, the reflectance quantification by means of the GMB method applied to the cross-calibrated data was a necessary confirmation of the reflectance retrieved by means of the CRS method.

The paper is organized so as to describe the two retrieval methods and the functions that model the canopy fluorescence and reflectance. Simulations of the retrievals and the retrievals from measurements are reported separately for both methods. Furthermore, the retrievals of both of these were combined in order to compare the results.

2. Materials and methods

The measurements that we analyzed were performed with a spectral resolution comparable to the one proposed for FLORIS, the FLuORescence Imaging Spectrometer, which is the core instrument of the FLEX mission.

2.1. Spectral measurements

The measurements, which were conducted in a cornfield (maize) during the CEFLES2 campaign (Rascher et al., 2009), were obtained as a daily cycle, under clear sky conditions using a portable spectrometer (HR4000, OceanOptics, USA) that was characterized by a Full Width at Half Maximum (FWHM) of 0.13 nm (corresponding to the spectral resolution of the instrument) and a 707–805 nm spectral range for estimating fluorescence within the O_2–A band (centered at 760 nm). The spectrometer was housed in a Peltier thermally-regulated box (model NT-16, Magapor, Zaragoza, Spain) in which the internal temperature was maintained at 25 °C in order to reduce dark current drift. The instrument had been calibrated beforehand in the laboratory, and the lab and field spectrometers were spectrally and radiometrically calibrated with known references (CAL-2000 mercury argon lamp, OceanOptics, USA) as well as by cross-calibration with a recently factory-calibrated ASD FS FR spectrometer (ASD, USA). In the following sections, the calibration curve for the spectrometer has been indicated as *calw*.

The measurements were acquired by using bare fiber optics with an angular field of view of 25°. The average top of the canopy (TOC) plane was observed from nadir at a distance of 2.2 m. The spectrometer fibers were mounted on top of a scaffolding tower placed in the