A Comparison of Different Techniques for Passive Measurement of Vegetation Photosynthetic Activity: Solar-Induced Fluorescence, Red-Edge Reflectance Structure and Photochemical Reflectance Indices

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***Abstract*—Measurement of vegetation photosynthetic activity from space has been an objective for the development of new techniques. Among the different existing techniques, passive fluorescence measurements, specific reflectance indices such as the PRI (Photochemical Reflectance Index), and derivative of high spectral resolution reflectance in the red-edge (680-750 nm) are the three methods than can be used as remote sensing techniques from airborne and space sensors and that have proven to give consistent and reliable information about canopy photosynthetic activity.**

Keywords: Photosynthesis, fluorescence, PRI, red-edge, remote sensing, boreal forest.

I. INTRODUCTION

The measurement of vegetation photosynthetic activity from space has been an objective for the development of new techniques and methods that have been used first at the field level, then in airborne sensors and ultimately in satellite systems in some cases. Optical methods based on high spectral resolution reflectance measurements have been demonstrated successful in the case of agricultural fields, but for application to global scale measurements by future satellite systems, methods need to be defined general enough that can be applied to any vegetation type and conditions.

Among the different existing techniques, passive fluorescence measurements (by using oxygen absorption lines located in 687 nm and 760 nm and line-depth measuring method), specific reflectance indices such as the PRI (Photochemical Reflectance Index) by using reflectances at 531 and 570 nm, and derivative of high spectral resolution reflectance in the red-edge (680-750 nm) are the three methods than can be used as remote sensing techniques from airborne and space sensors and that have proven to give consistent and reliable information about canopy photosynthetic activity.

A. Solar-Induced Fluorescence

Chlorophyll fluorescence emission is produced right after light absorption, by means of a mechanism in direct competition with photochemical conversion. Although this emission is very low (<1% of absorbed light) it is commonly used for tracking photosynthetic activity in laboratory. In field conditions fluorescence can be measured from a distance of some meters using active methods (laser and telescope), but this technique is not applicable for measurements from aircrafts or satellites. Passive remote sensing allows to measure fluorescence signal out of the vegetation radiance without the use of an artificial source of light. To achieve this, it is necessary to use those wavelengths where irradiance is significantly low due to absorption by the atmosphere, either terrestrial or solar (Faunhofer lines).

A new instrument (PMFD: Passive Multi-wavelength Fluorescence Detector) was developed at LURE [1] for continuous measurement of chlorophyll fluorescence based on the Fraunhofer line principle, applied in the atmospheric oxygen absorption A and B bands (760nm and 687nm, respectively) [2].

The fluorescence at 687nm (F687) and at 760nm (F760) are both due to Photosystem II, with some contribution from Photosystem I [3]. Thus, the measurements at both oxygen absorption bands provide information on different processes of the photochemical activity.

To estimate the fluorescence, PMFD measures the radiation coming from the target, as well as from a white-reference panel, at two narrow-band wavelengths for each of the absorption bands, one centered at the absorption feature λ_0, the other located outside the absorption to use as a reference baseline, as shown in Fig. 1.

The wavelengths, at which **a**, **b** and **c**, **d** are measured, are assumed to be close enough to consider that the vegetation

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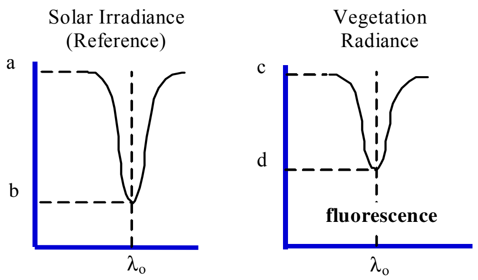

Figure 1. Variation on the depth of the oxygen absorption line due to chlorophyll fluorescence.

reflectance R(λ) and the fluorescence F(λ) are constant. Then the vegetation reflectance at the absorption band would be

$$R(\lambda_0) = (c - d) / (a - b) \quad (1)$$

and the passive fluorescence flux at λ_0 can be derived with

$$f(\lambda_0) = d - R(\lambda_0) \cdot b. \quad (2)$$

B. Photochemical Reflectance Index

The xanthophyll cycle provides a way of dissipating the excess of energy that cannot be used for carbon assimilation. PRI is an index, first introduced by Gamon [4], derived from narrow band reflectance at 531nm and 570nm used to estimate relative changes in the xanthophyll cycle, thus an indicator of efficiency of the photosynthetic activity.

It is defined as

$$PRI = (R531-R570)/(R531+R570) \quad (3)$$

With two additional channels available on the PMFD sensor, at 531 and 570 nm, it is also possible to monitor the PRI simultaneously with the fluorescence emission detection.

C. Red-edge structure

The red-edge region (from 650 to 800 nm) of vegetation spectra contains information about the molecular structure of the plant's cells, and conformational changes introduce variations in the shape of the red-edge. Besides, chlorophyll emits fluorescence within the range of the red-edge, so both contributions (chemical structure and fluorescence) are mixed [5].

The first derivative of this region presents a double peak feature. In a previous controlled experiment in laboratory conditions the shape of this double-peak was found to track variations in steady state fluorescence in response to changes in environmental conditions of the vegetation under study [6].

We have performed a double-gaussian fit to adjust the shape of the reflectance first derivative, as a means to quantify the variations in the shape, while capturing the double-peak structure. For the fitting we allow all three gaussian parameters (central wavelength, amplitude and FWHM) to change, i.e. a total of six parameters are fitted. This is illustrated in Fig. 2.

For the evolution of the red edge reflectance derivative during the day we found that only the amplitude of the peaks varied significantly, while the other two parameters remained almost constant. Thus, to reflect the changes in the vegetation

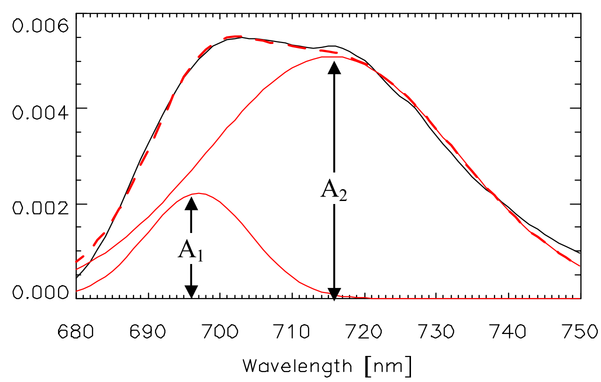

Figure 2. First derivative of the reflectance at the red-edge region showing a double peak feature. Also shown the two gaussian fit as dashed line.

status, we have considered only the amplitude of the two gaussians A_1 and A_2 as a ratio:

$$DPR = A_1/A_2 \quad (4)$$

An ASD FR/FS spectroradiometer has been used for the measurement of target spectral reflectance in the range from 350nm to 2500nm with 1nm spectral resolution in the VIS/NIR region. From these measurements we were able to derive the Double-Peak Ratio as well as PRI. The spectral resolution of this instrument is not narrow enough to use the oxygen absorption bands for fluorescence measurements.

II. FIELD MEASUREMENTS

In order to test such methods in a natural environment, a field campaign was carried out in summer 2002 in a boreal forest of Scots pine (*Pinus sylvestris*) in Sodänkyla, North Finland (26° 38' longitude East, 67° 22' latitude North). The campaign period covered the spring recovery of pine trees from winter dormancy to the summer fully active state of photosynthesis. In the SIFLEX (Solar-Induced Fluorescence Experiment) campaign, a complete set of measurements was acquired, including the three vegetation photosynthetic activity indicators previously reported, as well as all the necessary ancillary information (meteorological data, solar radiation inputs, plant architectural information, leaf pigments content) and CO_2 fluxes.

The PMFD and ASD instruments were placed at the top of a 20m high tower. The target was a portion of the canopy located at an horizontal distance of 55m northwards from the tower, and at a height of about 10m. The reference panels were located at the tower for practical reasons.

Both instruments were pointing to the same spot, with a FoV (field of view) of approximately 4º (the FoV of the ASD was slightly smaller).

The measurements took place from 10:00 to 16:00 in 15 minutes intervals with the ASD, and continuously with the PMFD. They were repeated on a daily basis, whenever the weather allowed it, from the 29th of April to the 6th of June.

III. TIME SERIES ANALYSIS

The results derived from the time series of data have allowed to study both diurnal cycles for sunny and cloudy days

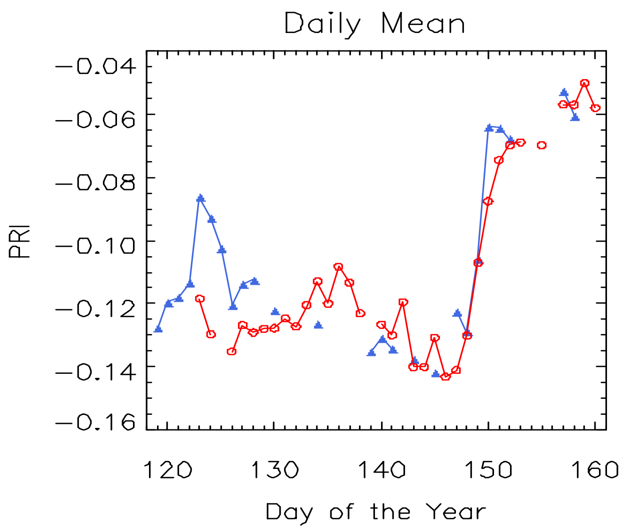

Figure 3. Evolution of PRI along the SIFLEX campaign, as measured with PMFD (circles) and ASD (triangles).

and varying meteorological conditions, and also the secular variation along the measurement campaign following vegetation growth.

For the duration of the campaign, the vegetation passed from a dormant state, with very low activity, to a fully active state. Both states were expected to be reflected in the selected indicators. This transition is clearly seen in PRI daily mean values, shown in Fig. 3, around DoY (day of the year) 150.

During the week previous to the campaign the weather conditions were exceptionally good, with high temperatures and clear skies that caused the snow to melt earlier. The higher temperatures and the availability of water provided the forest appropriate conditions to start activation. The following days, weather returned to normal, with lower temperatures, that slowed down the recovery of photosynthetic activity. This is clearly reflected in the PRI evolution through the campaign. The different, although similar, results from PMFD and ASD are considered mainly due to the differences in the FoV and the spectral resolution.

DPR response is more variable, but presents a similar tendency of receding activity in the first part of the campaign, with a large increase towards the end, but presents more local variations. Examining the diurnal cycle, we found that DPR is mainly driven by solar irradiance (radiation forcing), and especially in very clear days the canopy bi-directional reflectance effects become relevant. In any case, the long term evolution of the plant activity is captured by this indicator.

Daily mean values of F687 present an almost linear relationship with PAR, as expected when vegetation is using solar radiation efficiently. The combination of F687 with F760 should provide information about changes in the activity of the Photosystems I and II. Unfortunately, the signal coming from the target at 760nm was affected by multiple scattering within the forest deepening the absorption feature, while the reference panel (located at the top of the tower) was not; therefore the measurements cannot be directly used, and need a more detailed study and processing to compensate for this effect.

Within the diurnal cycle, the F687 measurements record sudden fluorescence changes which adjust the photochemical activity for strong changes of illumination.

PRI presents the best correlation with CO_2 assimilation of all three indicators. This is a promising result, although a relationship between CO_2 fluxes and these photochemical activity indicators is still far from being determined, as other physical considerations must still be taken into account.

The correlation between the three indicators is very low, indicating that each contains particular information, that could be used in combination. This is important, as each one of them is based in different processes of the photochemical activity of the plants.

IV. Conclusions

The results clearly indicate a high correlation for the overall variation along the whole campaign. The daily cycle is dominated by meteorological conditions (radiation forcing) and canopy structural effects as varying solar illumination conditions and geometry.

The three indicators do not correlate between them, but at the same time, all follow the expected tendency for the vegetation reactivation, thus complementing each other.

DPR and F760 suffer from canopy structural effects, particularly in sunny days, and it needs more detailed analysis to be able to interpret the signal variations in the diurnal cycle.

The red-edge is shaped by the contribution of molecular conformation changes as well as fluorescence. These contributions are coupled, so an accurate model of the photochemical activity of the plants is necessary to better understand behavior of the red-edge. Such a model is currently under development under the sponsorship of the European Space Agency [7]

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