

FLuorescence EXplorer (FLEX): mapping vegetation photosynthesis from space

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ABSTRACT - *The FLuorescence EXplorer (FLEX) mission proposes to launch a satellite for the global monitoring of steady-state chlorophyll fluorescence in terrestrial vegetation. Fluorescence is a sensitive probe of photosynthetic function in both healthy and physiologically perturbed vegetation, and a powerful non-invasive tool to track the status, resilience, and recovery of photochemical processes and moreover provides important information on overall photosynthetic performance with implications for related carbon sequestration. The early responsiveness of fluorescence to atmospheric, soil and plant water balance, as well as to atmospheric chemistry and human intervention in land usage makes it an obvious biological indicator in*

improving our understanding of Earth system dynamics. The amenability of fluorescence to remote, even space-based observation qualifies it to join the emerging suite of space-based technologies for Earth observation. FLEX would encompass a three-instrument array for measurement of the interrelated features of fluorescence, hyperspectral reflectance, and canopy temperature. FLEX would involve a space and ground-truthing program of 3-years duration and would provide data formats for research and applied science.

1. INTRODUCTION

The increase in atmospheric CO₂ due to terrestrial emissions, and the corresponding global warming and associated climate changes, are modulated by the dynamical component of the Earth: the living organisms, in particular vegetation dynamics, and the induced consequences and feedbacks in biodiversity of animal species and human activities. Given the relationship between vegetation photosynthesis and global CO₂ cycle through carbon assimilation, and with the global water cycle, due to the strong coupling between photosynthesis rates and canopy water transpiration, improved knowledge of global vegetation photosynthesis becomes clearly a priority in research about the Earth System.

Vegetation monitoring continues being a key issue in global Earth Observation. Despite the fact of the several mission already dedicated directly (i.e. VEGETATION) or indirectly (i.e. MERIS) to global terrestrial vegetation monitoring, the derived information is mostly related to the amount of vegetation (Leaf Area Index, Fractional Vegetation Cover, Biomass) or to the potential photosynthetic activity (APAR, Chlorophyll Content). A remaining topic to be covered in global vegetation monitoring is the measurement of the actual photosynthetic function.

Until now, most of the information that has been acquired by remote sensing of the Earth's surface about vegetation conditions has come from "reflected" light in the solar domain. There is, however, one additional source of information about vegetation gross primary production (GPP) in the optical and near-infrared wavelength range that has not yet been exploited by any satellite mission, related to the "emission" of fluorescence from the chlorophyll of assimilating leaves: part of the energy absorbed by chlorophyll is not used for carbon fixation, but re-emitted at longer wavelengths as fluorescence (Buschmann et al., 1998; Seaton and Walker, 1990), as illustrated in Fig. 1.

Solar-induced fluorescence can be measured by passive techniques, making use of the so-called Fraunhofer bands and of O₂ absorption of radiation in narrow regions of the spectrum, where apparent vegetation reflectance is mostly contributed by chlorophyll fluorescence (Carter et al., 1996; Liu et al., 2005). New modelling and data assimilation tools make it possible to derive meaningful information from the measured fluorescence signal. Recent studies have also demonstrated that the weak fluorescence

signal is indeed detectable from a satellite system at relevant spatial resolution and with the accuracy required by ecosystem models.

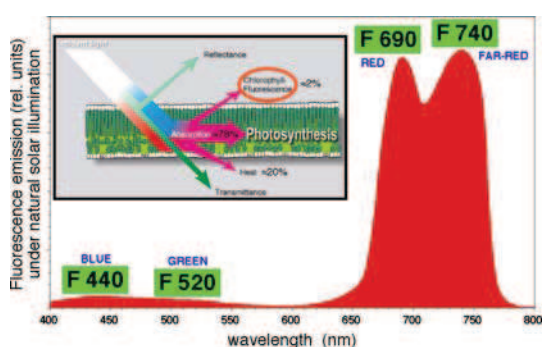


Fig. 1 Typical leaf fluorescence emission spectrum, showing also the typical energy balance within a leaf, fluorescence emission representing about 2% of absorbed light

Active excitation techniques (laser induced, with modulated light or saturating pulses) have been extensively used in laboratory studies to carry out detailed studies about plant photosynthesis (Cecchi et al., 1994), but the use of active techniques in observations from space has serious technological difficulties, while natural solar excitation (solar-light induced fluorescence) is a proper way of addressing fluorescence measurements from space. Passive techniques have also the advantage that they give the actual functioning of vegetation under the true natural illumination conditions.

In addition to fluorescence measurements, reflectance indicators such as the Photochemical Reflectance Index (PRI), by looking at reflectance in the range 500-570 nm and the spectral shape of reflectance derivatives in the range in the range 670-740 nm, have been shown to provide additional, complementary information to fluorescence measurements, as they may be related to non-photochemical fluorescence quenching and/or antioxidant pigment status for the avoidance of photo-damage (Gamon et al. 1992). Thus, significant information about plant functioning can be obtained by looking at such physiological indicators by means of dedicated optimised spectral reflectance measurements. Given the fact that there is a need to know basic vegetation variables -such as LAI, fCover, leaf chlorophyll, leaf dry matter, leaf water- in order to properly understand the measured fluorescence signal, reflectance measurements which allow characterisation of such canopy properties seem to be mandatory together with the fluorescence measurements. Leaf chlorophyll content information

is especially relevant, and this information is potentially retrievable from reflectance systems with high spectral resolution, that would be an ideal complement to fluorescence measurements.

It has been demonstrated that the spectrum of fluorescence emission is dependent on leaf temperature, thus there is a need for thermal information in order to interpret fluorescence signals. Temperature is also related to transpiration and stomata closure, which affects CO₂ uptake and fluorescence. Therefore temperature measurements help to confirm the trends observed in fluorescence measurements. While fluorescence is immediately and uniquely related to photosynthesis, temperature provides additional information about plant status and instantaneous energy/water fluxes between plants and the atmosphere.

A number of activities have been carried out in the last years to consolidate the concept by addressing two key issues: (a) to demonstrate that the (weak) fluorescence signal is indeed detectable from a satellite system at relevant spatial resolution and with enough accuracy to feed models with inputs derived from such measurements, and (b) to demonstrate the existing knowledge and modelling/data assimilations tools to make use of the measured fluorescence signal in such a way that meaningful information is derived and current capabilities are improved with the help of such new type of measurements.

2. OBSERVATIONAL REQUIREMENTS

FLEX focuses on the exploitation of the innovative fluorescence measurements, and uses additional reflectance and temperature measurements to help interpret the fluorescence signal and to provide the needed complementary information.

2.1. Fluorescence spectral bands

The fluorescence of green vegetation consists of the blue-green fluorescence (maxima at 440 and 520 nm) and of the red and far-red chlorophyll fluorescence (maxima at 690 and 740 nm). The major part of the blue-green fluorescence is emitted from the epidermis whereas the red and far-red chlorophyll fluorescence is emitted from the mesophyll, the photosynthetically active part of the leaf tissue. To monitor vegetation photosynthesis, we need to look at the chlorophyll fluorescence (red and far-red fluorescence). Blue-green fluorescence is addressed as a secondary objective as it can provide additional information about the status (and health) of vegetation. A combination of Fraunhofer lines and O₂ lines would make it possible to measure all the main fluorescence bands (see Fig. 2). The two O₂ bands (A and B) and the H α and H β bands are considered mandatory. The fluorescence signal in both H α and H β is quite low, but both bands have a favourable depth and shape, and both are particularly

well located, with H β providing access to blue-green fluorescence emission. The two FeI bands are desirable but they are spectrally very narrow. The band at 396.8 nm (H Ca II) is of too low intensity and too contaminated by Raman scattering to be used for fluorescence measurements from space. The final selection of the number of fluorescence bands will be determined as a function of technical feasibility and associated risks and costs, given some margins in technical design.

2.2. Reflectance spectral bands

Spectral reflectance measurements are considered mandatory to complement fluorescence measurements:

- (1) To determine the light that is effectively absorbed by chlorophyll versus the total light absorbed by the plant
- (2) To validate of the fluorescence measurements made by the Fraunhofer and O₂ line in-filling methods
- (3) To characterise basic vegetation variables essential for the interpretation of fluorescence measurements.
- (4) For vegetation species identification, and identification of plant functional types.
- (5) For a good characterisation of atmospheric status in the atmospheric correction of the data.
- (6) To determine instantaneous spectral illumination conditions.
- (7) For scene identification and cloud screening.

2.3. Target users community

Fluorescence measurements represent a unique capability for the global monitoring of the actual vegetation photosynthesis, as no other measurement protocol applicable to space measurements allows retrieving such a direct indicator of actual canopy photosynthesis and thus a quantitative mapping of the terrestrial carbon sinks. In this context, the regional up-scaling of detailed point measurements at eddy-covariance towers and the spatial analysis of the correlation between plant physiological performances and stress factors can be addressed (Lichtenthaler, 1996), providing useful forcing for existing global climate models through the link between carbon and water fluxes.

2.4. Spatial coverage and temporal resolution

The objective is a global coverage mission, monitoring vegetation photosynthesis along the seasonal cycles and the activation/deactivation of the photosynthetic mechanisms (photochemistry being adjusted to a lesser or greater level of activity). Global coverage should be achieved with a periodicity of a week in final products. Temporal resolution is important to track key physiological phenomena, but cloud cover prevents the ability of daily observations. The use of models to interpret the data reduces temporal requirements, making the mission viable with derived weekly information.

2.5. Spatial resolution

Combining the requirements driven by validation activities with field measurements and the resolution demanded by derived applications, a resolution in the order of 250-300 m would be reasonable and in line with other data sources and modelling efforts.

2.6. Time of observation

On sunny days, because of the influence of non-photochemical fluorescence quenching, steady-state chlorophyll fluorescence is usually highest in early morning and typically starts to decrease by about 10 am local solar time, reaching minimum between noon and early afternoon, then possibly recovering by evening (sometimes not until next day or later). According to eco-physiological research, the success in capturing the clearest signals would likely be around 8 to 9 am local solar time. As a balance between maximum fluorescence emission and maximum solar illumination, observation time must be around 9:30-10:00 local solar time. Time of acquisition will be optimised according to the data assimilation strategy, to address the scaling from instantaneous measurements to daily-integrated estimates.

2.7. Mission duration

In the scientific use of FLEX data, a 3-years mission has been considered a minimum to demonstrate the usefulness of fluorescence measurements from space: at least 3 full vegetation growing cycles are needed to get significance in inter-annual variability. A target mission duration of 5 years would provide more statistical relevance to seasonal cycles.

2.8. Relation / dependence / complementarity with other missions

In the context of fluorescence data assimilation into global vegetation dynamics models addressing global CO₂ fluxes, complementary satellite sources are identified, but co-located observations are not strictly necessary, and data integration from different sources would be accommodated through a data assimilation scenario. However, the different instruments onboard FLEX are conceived in such a way that self-consistent measurements are provided to make possible the retrieval of basic final products (vegetation photosynthesis) without absolute need of external reference data.

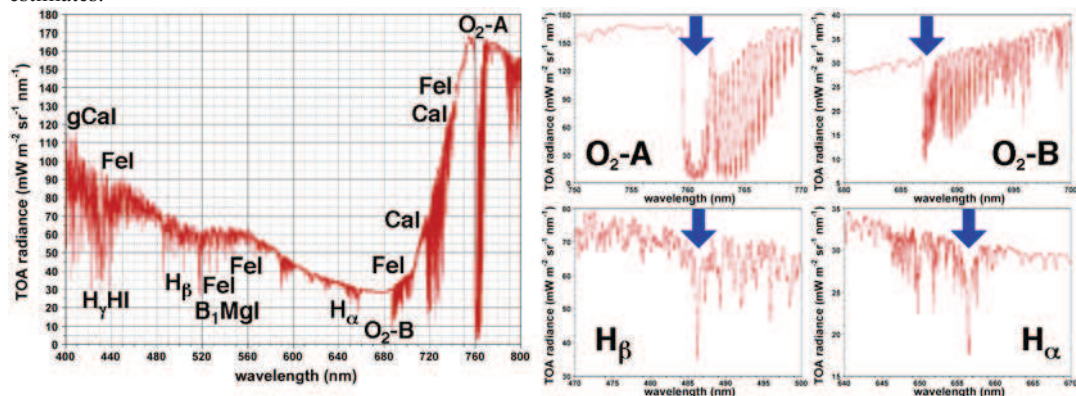


Fig. 2 Location of absorption bands across the spectrum of fluorescence emission, for a typical top-of-atmosphere vegetation radiance spectra, with a more detailed view of the four main bands addressed in FLEX

3. TECHNICAL CONCEPT

3.1. Principle of measurements: spectral absorption line fluorescence detection technique

Under natural sunlight illumination, the amount of chlorophyll fluorescence emitted by a leaf represents (in its steady state) a very small fraction of the reflected light in the visible part of the spectrum. However, at certain wavelengths where the solar spectrum is attenuated (Fraunhofer lines or atmospheric absorption lines), the fluorescence signal can be quantified. The formation of these sharp absorption lines is due to resonances in ionized metals or atomic hydrogen in the solar chromosphere excited by electromagnetic radiation emanating from the

underlying photosphere, or strong gaseous molecular absorption (i.e. oxygen) in the terrestrial atmosphere. These lines largely overlap with the chlorophyll fluorescence emission spectrum of plants. One way to obtain information on natural fluorescence (i.e. solar excited) from the whole reflectance signal is to use the FLD (Fraunhofer Line Discrimination) method. James Plascyk was the first to introduce the FLD method in 1975 (Plascyk, 1975). In short, this method compares the depth of the line in the solar irradiance spectrum to the depth of the line in the radiance spectrum of the plant: would a spectral absorption line be completely dark, the fluorescence (a broad band phenomenon) would introduce some light at the line position visible on a black background. In such lines the otherwise

much stronger reflectance background is significantly reduced, and fluorescence can be decoupled from the reflected signal when measuring in spectral channels close enough so that it can be assumed that both reflectance and fluorescence vary smoothly with wavelength (Moya and Cerovic, 2004). Consideration of multiple scattering and spectral derivatives of both fluorescence and reflectance can be added to the basic retrieval method by means of perturbative corrections. Atmospheric effects contribute to the measured signal and have to be assessed and corrected for. Interpretation of the retrieved fluorescence radiance emanating from the canopy would benefit from additional spectral reflectance and leaf temperature information to account for the dependence on solar irradiation and environmental conditions.

3.2. Orbit and platform description

A single satellite in a sun-synchronous orbit is considered as the baseline for the mission design. While a geostationary mission would appear interesting in order to resolve the diurnal cycle, spatial resolution requirements and the low signal level, plus the fact that a single geostationary mission does not provide global coverage, favours a low-altitude sun-synchronous orbit. A dedicated instrument for multi-spectral solar induced fluorescence measurements is the core of the mission, while additional spectral reflectance and temperature measurements are required for a proper exploitation of the signal. The platform should be able to support the three instruments, while no off-track platform pointing is required (nominal nadir looking).

3.3. Instrument description

The instrument concept being considered for a mission dedicated to map canopy photosynthetic activity at global scale is derived from a number of studies performed by industry in the last few years. A baseline set of instruments would consist of a core instrument:

- A Fraunhofer and Atmospheric Lines Imaging Spectrometer (FALIS), measuring individual line parameters between 480 nm and 760 nm. This main fluorescence instrument is conceived as a modular system, to allow optimisation of each individual module for each associated fluorescence band, and two secondary, dual-view angle instruments, consisting of:

- A Multi-Angle Vegetation Imaging Spectrometer (MAVIS), being the ground observed area the same for each view angle by adjusting each telescope. The spectral coverage would be from 400 to 2400 nm for additional reflectance information, with well defined priorities to choose between different imaging spectrometer alternatives and particular spectral coverage options.

- A Surface TIR Spectrometer (STIRS), operating in the thermal infrared and using micro-bolometer technology, with three channels in the 8.8 to 12 μm spectral range.

4. FEASIBILITY

Feasibility of the fluorescence measurement approach based on FLD method has been largely confirmed by means of dedicated field experiments (Moya et al., 1998), over agricultural areas and boreal forest targets, such as the SIFLEX (Solar Induced Fluorescence Experiment) campaigns (Louis et al., 2005), and the use of the AirFLEX airborne demonstrator recently built by LURE, Paris, France, and the laboratory developments of a $H\alpha$ instrument based on Fabry-Perot filters, also developed at LURE. Moreover, feasibility has also been demonstrated by using MERIS data in the context of retrieving fluorescence from TOA radiance measurements. MERIS has two dedicated spectral bands, inside and outside the O_2 -A absorption at 760 nm, plus high spatial resolution (300 m) and enough radiometric resolution to allow separation of fluorescence from the reflected signal. Although MERIS only provides fluorescence in one spectral band (not useful to derive biophysical indicators) and MERIS is not optimised for such purpose (smiling effects, multi-cameras normalisation, and spectral stability) still MERIS data has been used to demonstrate the feasibility of fluorescence measurements from space: both MERIS RR data in spectral calibration campaign mode, and MERIS FR data in flat areas with a mixture of large vegetated areas and bare soils, optimal to validate such fluorescence retrievals, accounting for effects due to varying surface pressure in O_2 absorption (Moreno et al., 2004). On the other hand, a direct link between photochemical indicators derived spectral reflectance measurements and carbon fluxes was demonstrated by the dedicated SIFLEX (Solar-Induced Fluorescence Experiment) carried out in Sodankyla, Finland, in summer 2002, confirming the capability to use such type of information as inputs to terrestrial carbon models (Louis et al., 2005).

5. MISSION PRODUCTS

Combination of fluorescence measurements and photochemical indices (i.e., PRI), plus the integration of fluorescence information with biophysical indicators derived from the complementary spectral reflectance and temperature measurements, allow the retrieval of biophysical products with direct physical meaning such as the "Light Use Efficiency" (LUE) product and the "Photosynthesis Activation Index" (PAI) product, together with the Photosynthetic Resilience Rating that quantifies recovery from stress events, and a Photosynthetic Stability Rating that

serves for general change detection. A completely new way of addressing land photosynthesis and carbon assimilation by terrestrial vegetation will be made possible by the use of such innovative information provided by FLEX.

Several data exploitation strategies have been analysed in detail, from the direct use of relative fluorescence as "vegetation index", the exploitation of spatio-temporal absolute fluorescence variability as a quantitative measurement of plant photosynthesis, up to data assimilation methods in dynamical vegetation models, with "change detection analysis" a key element in most applications. Mission products have been identified and algorithms to derive such products are being developed, with some of them already available.

Particular aspects already considered are: exploitation of spatio-temporal absolute fluorescence variability as a quantitative measurement of plant photosynthesis, estimation of Absorbed Photosynthetically Active Radiation, exploitation of spatio-temporal absolute fluorescence variability as a quantitative measurement of plant water status and stresses, long-term trends in steady-state chlorophyll fluorescence yields and data assimilation methods in Dynamical Vegetation Models.

6. PERSPECTIVES

The FLEX mission fits perfectly into the main research objectives of ESA and related international programmes, with impact on global carbon cycle studies and vegetation photosynthesis, water resources research and anthropogenic impacts associated to land-use changes and varying spatial patterns of vegetation species. All these research objectives are of high relevance for the research programme of the European Commission, the World Climate Research Programme and the International Geosphere-Biosphere Programme.

Out of the 24 candidates, FLEX is now one of the six missions in Pre-Phase A development within the ESA Earth Explorer Programme. A decision will be made in 2008 to move to Phase-A and later on a selection process will decide which missions will be actually implemented.

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