IAC-06-B1.3.4

FLUORESCENCE EXPLORER (FLEX): AN OPTIMISED PAYLOAD TO MAP VEGETATION PHOTOSYNTHESIS FROM SPACE

Jose F. Moreno
Dept. Earth Physics and Thermodynamics, Faculty of Physics-University of Valencia
Dr. Moliner, 50, 46100 Burjassot, Valencia, Spain.
Tel. +34 96 3543112, Fax +34 96 3543385, Email: Jose.Moreno@uv.es
and

Gregory P. Asner [1], Heike Bach [2], Tomas Belenguer [3], Andrew Bell [4], Claus Buschmann [5], Alfonso Calera [6], Javier Calpe [7], Petya Campbell [8], Giovanna Cecchi [9], Roberto Colombo [10], Lawrence A. Corp [11], Andrew Court [12], Mike A. Cutter [13], Mathias Disney [14], Alexander Dudelzak [15], Guido D'Urso [16], Richard Fernandes [17], Jaume Flexas [18], Peter Gege [19], Birgit Gielen [20], Anatoly Gitelson [21], Emanuel U. Gloor [22], Jim Gower [23], Robert O. Green [24], Joachim Hill [25], Stephane Jacquemoud [26], Li Jia [27], Mathias Kneubühler [28], Tuomas Laurila [29], Philip Lewis [14], Dan Lobb [13], Federico Magnani [30], Stefan W. Maier [31], Michal V. Marek [32], Alfonso Martinez [33], Pablo Martinez-Cobo [34], Piero Mazzinghi [35], Massimo Menenti [36], Ray Merton [37], Elizabeth Middleton [8], Eduardo de Miguel [3], John Miller [38], Gina Mohammed [39], Edward J. Milton [40], Fermin Morales [41], Ismael Moya [42], Ladislav Nedbal [43], Wolfgang Knorr [44], Catherine Ottlé [45], Albert Olioso [46], Stefania Pace [47], Antonio Palucci [48], Roberto Pedros [49], Jouni Peltoniemi [50], Josep Peñuelas [51], Antonio Plaza [34], Jan Polcher [52], Uwe Rascher [53], Rainer Reuter [54], Andries Rosema [55], Jean-Louis Roujean [56], Yasunori Saito [57], Bernard Saugier [58], Michael Schaepman [59], Jesus B. Serrano [60], Jeff J. Settle [61], Mercedes Sierra [62], Jose Sobrino [63], Marc-Philippe Stoll [36], Z. Bob Su [64], Carsten Tobehn [65], Nicolas Tremblay [66], Roland Valcke [67], Wout Verhoef [68], Frank Veroustraete [69], Michel Verstraete [70], Pablo Zarco-Tejada [71]

[1] Carnegie Institution of Washington, Stanford, CA, USA; [2] VISTA GmbH, Munich, Germany; [3] INTA, Madrid, Spain; [4] EMS Technologies Canada Ltd., Ottawa, Ontario, Canada; [5] Universität Karlsruhe - Botanik II, Karlsruhe, Germany; [6] University of Castilla-La Mancha, Albacete, Spain; [7] Electronics Dept. - Engineering School, Valencia, Spain; [8] NASA Goddard Space Flight Center, Greenbelt, MD, USA; [9] Applied Physics Institute / CNR, Florence, Italy; [10] Dept. Environmental Sciences, Univ. Milano-Bicocca, Italy; [11] USDA ARS Hydrology and Remote Sensing Lab., Beltsville, MD, USA; [12] TNO Science and Industry, The Netherlands; [13] Sira Technology Ltd, Chislehurst, Kent, UK; [14] NERC CTCD - UCL, London, UK; [15] CSA, Montreal, Canada; [16] Dept. Agricultural Engineering, University of Naples Federico II, Naples, Italy; [17] CCRS, Ottawa, Ontario, Canada; [18] UIB-CSIC, Universitat de les Illes Balears, Palma de Mallorca, Baleares, Spain; [19] Remote Sensing Technology Institute, DLR Oberpfaffenhofen, Germany; [20] Department of Biology, University of Antwerp, Wilrijk, Belgium; [21] University of Nebraska, Lincoln, Nebraska, USA; [22] Univ. Princeton, USA; [23] Institute of Ocean Sciences, Canada; [24] NASA Jet Propulsion Laboratory, Pasadena, California, USA; [25] University of Trier, Germany; [26] University Paris 7, Paris, France; [27] Alterra - Wageningen University, The Netherlands; [28] Remote Sensing Laboratories, University of Zurich, Switzerland; [29] FMI, Helsinki, Finland; [30] DCA, University of Bologna, Italy; [31] Satellite Remote Sensing Services, Dep. Land Information, Floreat, WA, Australia; [32] Laboratory of Ecological Physiology, Brno, Czech Republic; [33] EADS-CASA Espacio, Madrid, Spain; [34] GRNPS, University of Extremadura, Spain; [35] INOA, Florence, Italy; [36] LSIIT, Université Louis Pasteur, Strasbourg, France; [37] Centre for Remote Sensing & GIS, University of New South Wales, Sydney, Australia; [38] York University, Toronto, Canada; [39] P&M Technologies, Canada; [40] School of Geography, University of Southampton, UK; [41] Department of Plant Nutrition, EEAD-CSIC, Zaragoza, Spain; [42] LURE-CNRS, Paris, France; [43] Inst. Landscape Ecology - Physical Biology, Nové Hrady, Czech Republic; [44] Department of Earth Sciences, QUEST - University of Bristol, Bristol, UK; [45] CETP-IPSL-CNRS, Vélizy, France; [46] INRA, Avignon, France; [47] ENEA Centro Ricerche Trisaia, Policoro, Italy; [48] ENEA C.R. Frascati, Italy; [49] Solar Radiation Unit, University of Valencia, Valencia, Spain; [50] Finnish Geodetic Institute, Helsinki, Finland; [51] CREAF-CSIC, Barcelona, Spain; [52] Laboratoire de Météorologie Dynamique du CNRS, Paris, France; [53] Institute of Chemistry and Dynamics of the Geosphere, Research Center Jülich, Germany; [54] Institute of Physics, University of Oldenburg, Germany; [55] EARS, Delft, The Netherlands; [56] CNRM/GMME/MATIS, Meteo-France, Toulouse, France; [57] Faculty of Engineering, Shinshu University, Nagano, Japan; [58] Université Paris-Sud, Paris, France; [59] Centre for Geo-Information, Wageningen University, The Netherlands; [60] GMV, Madrid, Spain; [61] Environmental Systems Science Centre, University of Reading, Reading, UK; [62] SENER, Madrid, Spain; [63] Global Change Unit, University of Valencia, Valencia, Spain; [64] ITC, Enschede, The Netherlands; [65] OHB-System AG, Bremen, Germany; [66] Agriculture and Agri-Food Canada, Canada; [67] Limburgs Universitair Centrum, Diepenbeek, Belgium; [68] NLR, The Netherlands; [69] VITO, Belgium; [70] JRC, Italy; [71] IAS-CSIC, Cordoba, Spain

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.

INTRODUCTION

The increase in atmospheric CO_2 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 CO_2 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 [1] [2], as illustrated in Fig. 1.

Solar-induced fluorescence can be measured by passive techniques, making use of the so-called Fraunhofer bands and of O_2 absorption of radiation in narrow regions of the spectrum, where apparent vegetation reflectance is mostly contributed by chlorophyll fluorescence [3] [4]. 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.

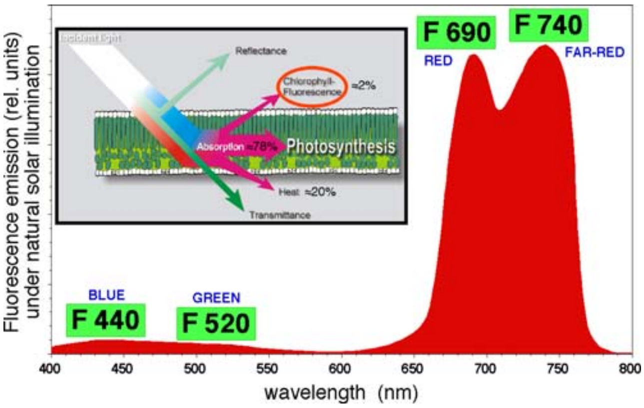

Fig. 1 Typical leaf fluorescence emission spectrum, showing also the typical energy balance within a leaf, fluorescence emission representing about 2% of absorbed light

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 [5] [6], 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 [7]. 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 CO_2 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.

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.

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 O_2 lines would make it possible to measure all the main fluorescence bands (see Fig. 2). The two O_2 bands (A and B) and the Hα and Hβ bands are considered mandatory. The fluorescence signal in both Hα and Hβ is quite low, but both bands have a favourable depth and shape, and both are particularly well located, with Hβ 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.

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 O_2 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.

Target users community

Fluorescence measurements represent a unique capability for the global monitoring of the actual vegetation photosynthesis [8], 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 [9] [10], providing useful forcing for existing global climate models through the link between carbon and water fluxes.

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.

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.

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.

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.

Relation/dependence/complementarity with other missions

In the context of fluorescence data assimilation into global vegetation dynamics models addressing global CO_2 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.

Table 1. Overview of mission objectives, measurements and functional requirements

Primary science mission objectives	**Measurement requirements**	**Mission / instrument functional requirements**
(a) Global vegetation photosynthesis, CO_2 fluxes, carbon assimilation: - Photosynthetic function mapping - Photochemical indicators (PRI) - Activation/deactivation status of photosystems - Total light absorbed by the canopy - Photosynthetic Activation Index - Photosynthetic Resilience Rating - Photosynthetic Stability Rating	Vegetation fluorescence in multiple spectral bands: *Mandatory bands:* O_2 A (760.5), O_2 B (687.0) Hα (656.3), Hβ (486.1) *Desirable bands:* Fe I (738.9), Fe I (685.5) *Optional bands:* g Ca I (422.7), Hγ HI (434.0), b1 MgI (518.4) Spectral reflectance measurements associated to photochemical indicators: 500-800 nm range with 5 nm resolution. Key bands located at 531 and 570 nm. Leaf temperature decoupled from soil temperature.	Imaging spectrometer (either dispersive or interference filters) modularly accommodated to each spectral fluorescence line to be observed. Time of observation compatible with maximum photosynthesis activity and illumination conditions. Imaging spectrometer, covering such spectral range plus additional spectral information for cloud screening and atmospheric corrections. Thermal radiometer with multiple spectral bands (3 bands between 8.8 and 12 μm) Data assimilation
(b) Coupling of photosynthesis (carbon) and transpiration (water) at a global scale: Light use efficiency and water use efficiency - coupling of carbon and water cycles	Canopy water status. Leaf / soil temperatures for derivation of surface-atmosphere heat and water fluxes as coupled to photosynthesis by stomatal behaviour.	Spectral bands around 970 and 1200 nm). Multiangular data needed to decouple canopy structural effects in energy /water/ carbon fluxes. Thermal measurements (decouple leaf and soil temperatures)
(c) Vegetation stress monitoring (agricultural, food and forestry applications): - Early indicators of environmental stresses	Monitoring fluorescence temporal changes with enough temporal resolution (weekly information). Decoupling of photoprotective mechanisms. Recovery after stress conditions.	Relative high spatial resolution compatible with global coverage (≈300 m) Multi-annual data needed for looking at seasonal changes
(d) Anthropogenic impacts associated to land use changes and varying management practices for land vegetation induced by human activities	Spectral reflectance bands needed to identify key land-use changes associated to human activities and to identify changes in vegetation species	Imaging spectrometer covering key spectral intervals (500-1000 nm and 2000-2300 nm with key relevance) Assimilation of photosynthesis maps with other information sources.

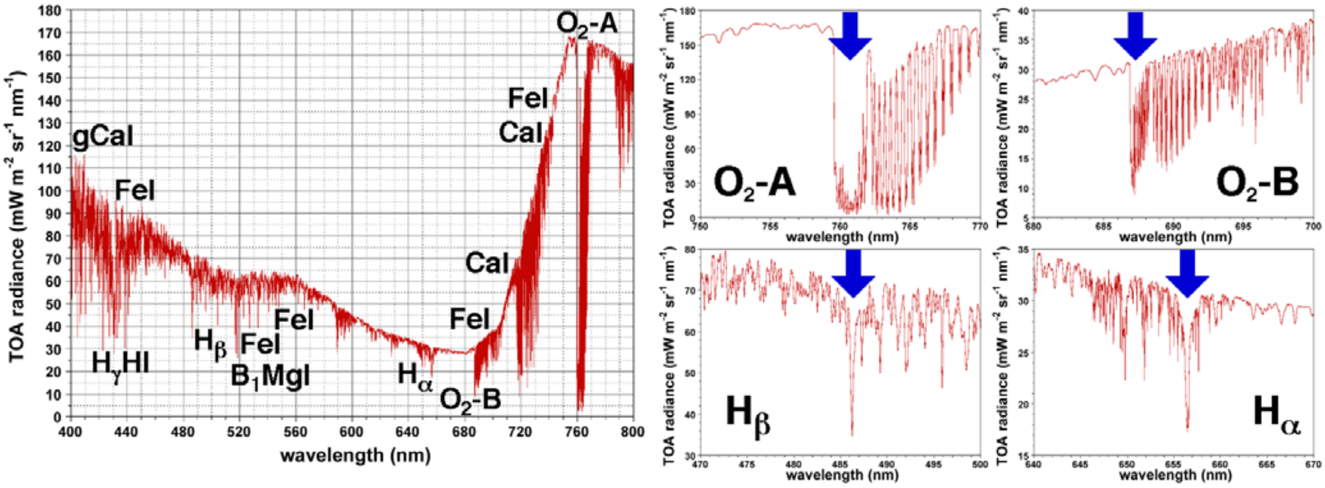

Fig. 2 Location of absorption bands across the spectrum of fluorescence emission, for a typical top-of-atmosphere vegetation radiance spectra, with a more detailed view of the four main bands addressed in FLEX

TECHNICAL CONCEPT

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 Plascyck was the first to introduce the FLD method in 1975 [11]. 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 [12] [13]. 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.

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).

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 [14], [15] [16]. 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.

Fraunhofer and Atmospheric Lines Imaging Spectrometer (FALIS)

The main fluorescence instrument is conceived as a modular system, with a dedicated module (spectrometer) for each fluorescence band to be measured. This allows optimisation of each individual module for each associated band, with more modules added as more fluorescence bands are to be measured. A minimum baseline concept can be defined with additional bands as optional, and the final decision on how many bands to be observed can be made later depending on overall mission optimisation without compromising the baseline for the mandatory fluorescence bands which are strictly needed.

The FALIS instrument consists of a set of narrow band channels selected to provide direct access to the vegetation fluorescence component present in Fraunhofer or atmospheric absorption lines. The basic configuration consists of a telescope to image the target area on the entrance slit of the spectrometer and a grating spectrometer, which provides a spectral image of the lines on the detector. The imaging spectrometer has a ground FOV of about 0.35 × 220 km (assuming a satellite altitude of 800 km). The spectral resolution is about 0.1 nm. The FOV of the instrument can be directed to the Earth or to a diffuser, which is irradiated by the Sun for calibration purposes.

Preliminary designs of an imaging spectrometer concept and a filter spectrometer concept have been made in recent years as part of industrial FLEX feasibility studies, including image freezing options for a limited field of view for individual spectral lines. Since image-freezing options are not compatible with the requirement of global coverage, alternative options have been considered by accommodating spatial resolution requirements and taking into account the possibility of using spectral lines (such as oxygen absorption bands) where signal levels make unnecessary the image-freezing options.

The main limitation for the FALIS concept comes from the fact that a quite large field of view will be required to guarantee global coverage, while high spectral resolution and spectral stability (absolute spectral position) is required all across the field of view (all along the ground swath). Placing the dispersive element in a telecentric beam makes the ray cone the same for each point of the field of view but leads to an inhomogeneous illumination of the pupil, also dependent on the spectral shape of the input light in the transmitted band pass. This is of particular importance when observing within a spectral line, as in the case of FALIS. Placing the dispersive element in a collimated beam, due to the dependence of the transmitted wavelength on the incidence angle, a wavelength variation from the centre to the edge of the field of view appears. The optical design should accommodate some extra optics in order to assure the collimated beam incidence over the dispersive optical component. The optical quality requirements in this kind of configurations are more demanding because the total clear aperture of the dispersive component is working for each field of view. Different optical locations could be included to accommodate the telecentric configuration or the collimated configuration in the same optical layout as some compromise between optical quality and spectral resolution should be considered. A concept based on Spatial Heterodyne Spectrometer (SHS) has been also considered as a potential alternative for the type of measurements required in the FLEX mission, to provide an instrument with high spectral resolution and spectral stability across a large field of view.

The case of the FALIS instrument for FLEX -high resolution spectrometry of targeted bands- is particularly well suited to a field-widened SHS imager solution. While the slab-waveguide SHS option is not appropriate for such imaging applications, the monolithic glass SHS will provide much better SNR than other solutions and much better calibration stability than the filter solution. A separate monolithic glass SHS Michelson can be constructed for each waveband of interest, with associated dichroics and a narrow bandpass filter for each spectrometer to prevent aliasing. This design will allow full 2-D imaging in pushbroom operation in each waveband. The monolithic glass design lacks moving parts and thus allows maximum stability of spectral calibration over the mission life. The SHS does not need a slit to discard light, and can be designed to image a square or slightly rectangular footprint on the ground. The tilted grating design will turn one of the spatial dimensions into a "spectral" dimension on the detector, tracing out an interferogram along one dimension of the detector as the satellite motion scans over any particular fixed spot on the ground. Given comparable optical étendue at R~6500, a field-widened SHS will have a throughput-resolution product ~170 x larger than an air-spaced etalon spectrometer, and ~1000 x larger than a standard grating spectrometer. The optical configuration for such an instrument would likely consist of a telecentric imaging system focussed onto the Michelson grating arms, then re-imaged at appropriate magnification onto a CCD detector. A field-widened SHS in this mode can accept ray bundles no faster than ~f/10 - f/15 without degrading fringe contrast, but will image the full cross-track field. At a spectral resolution of 0.1 nm, the 687, and 656.3 nm bands can both be imaged with the same SHS, assuming a 640×480 pixel CCD with 640 spatial pixels at 300 m per bin and 480 spectral bins at 0.1 nm per bin. A more detailed simulation will be necessary, however, to determine whether the background noise limit of such a wide band would have an adverse affect on the SNR at the regions of interest, while it would not be difficult to significantly increase the spectral resolution over a narrower bandwidth.

Since we need to work with very high spectral resolution (up to 0.1 nm in some specific bands), and we require stability in the spectral position of the bands all across the Field of View, we need to address the problem of field widening while keeping high spectral resolution for specific spectral bands (at least four spectral lines: 760 nm, 687 nm, 656 nm and 486 nm imaged over a large field of view). The large Field of View is needed to get global coverage within few days. A possible alternative is to align several instruments across-track, thus making each individual instrument less demanding. This solution is similar to the one adopted for MERIS on ENVISAT (multi-cameras in parallel). In this case new technologies currently under development, as MEMS spectrometers and interferometers, could help in keeping mass and cost of the whole instrument within the foreseen limits.

Multi-Angle Vegetation Imaging Spectrometer (MAVIS)

Regarding the instrument dedicated to (multi-angular) spectral reflectance measurements, several options have been considered, all of them with strong heritage from previous developments in the context of different missions. The Compact High Resolution Imaging Spectrometer (CHRIS) is a low-cost, size and mass (<14 kg / 79×26×20 cm / 8 W power) already flown in PROBA-1. An extension of CHRIS capabilities to cover the SWIR part of the spectrum has been considered as a potential candidate for the MAVIS concept for FLEX. Alternative designs have been considered (i.e. developments towards MERIS-type extensions for GMES Sentinel-3 or the AVIRIS-heritage design for the FLORA mission). A dual spectrometer concept (one covering the 400-1000 nm and another covering the SWIR part) has been also considered. If a full spectral coverage is required, implementation of a multi-prisms imaging spectrometer, such as in the SPECTRA concept, could be adapted. The requirement of global coverage means that platform pitch cannot be used to increase integration time, and this has an impact on system size requirements. In order to guarantee global coverage, some relaxed requirements in other respects are required, particularly in spatial resolution, which is always the most significant parameter controlling instrument size.

Multi-angle reflectance (dual-angle at least) measurements are needed to improve atmospheric corrections and to characterize vegetation structural effects. Reflectance spectral bands detection with multi-angular possibility can be achieved in different ways. A dual-angle dual-telescope approach is preferred to guarantee same field of view for the two observation angles (similar to the Terra/MISR concept) while variants from the scanning concepts already used in AATSR can be also considered. The best alternative is to decouple the multi-angle requirements from the spectral requirements, limit multiple angles to a few spectral bands (preferably in the range 400 nm to 1000 nm, given the relatively high cost of SWIR) and make the ground sampling distance less demanding for the multi-angle case. In this situation, the multi-angle parts may be relatively small, without introducing major constraint on other components of the mission. Alternatively, a system with two telescopes feeding a common spectrometer can be designed, using separate parts of the entrance slit, but this would tend to limit the across-track spatial resolution for each field.

Dedicated spectrometers for each spectral range -with different spectral resolutions and SNR optimised for each spectral range- and different alternatives for the nadir looking case and for the multi-angular case can be accommodated, given the well-defined priorities in terms of observational requirements.

Surface TIR Spectrometer (STIRS)

Canopy temperature information must be acquired simultaneously with fluorescence (same FOV and spatial resolution). The thermal instrument should have a highly precise calibration in order to detect canopy temperature differences relevant for interpretation of fluorescence changes (accurate enough to resolve temperature effects in canopy fluorescence), and with multi-angular capabilities: two observation angles are requested to allow separation between soil and foliage temperatures. Alternatives such as derivations from the MIBS (Micro-Bolometer Spectrometer), operating in the TIR, between 8.8 to 12 μm, for which an instrument breadboard is available, can be used, based on the technology of new micro-bolometers arrays. For systems that have medium NEΔT (Noise Equivalent Temperature Difference) requirements and can operate with high-speed optics (<1.5), room temperature micro-bolometer performance has increased enough to enable the design of multi-spectral instruments based on this new detector technology, so that the cost and complexity of the instrument is reduced with respect to standard instruments operating in the TIR.

The micro-bolometer spectrometer consists of a telescope that focuses the scene of interest on a slit, by means of a mirror which can be rotated to point to either the scene or the calibration blackbody's, the actual telescope mirror and a folding mirror which is used to compact the system. A collimator made by folding mirrors transforms the slit image into a parallel beam going to the ZnSe prism, that disperses the light and a high-speed thermal camera (f/0.8) images the dispersed signal on the detector. Given the high reflectance for TIR radiation, the use of folding mirrors only marginally influences the throughput of the system, with a mechanically compact system, stray-light rejection and spectral purity. The same approach as for the VNIR/SWIR instrument can be taken: use of independent modules (telescope + spectrometer) per observation direction. Here again an important issue is the requirement on the spatial resolution relative to the different observation angles, as it is required that the ground observed area is the same for each view angle, by adjusting the focal length of each telescope.

All the three concept instruments presented here, FALIS, MAVIS and STIRS, have a strong heritage coming from feasibility studies (FALIS with feasibility studies for FLEX), operating instruments (MAVIS with CHRIS, MERIS and SPECTRA developments) and breadboard (STIRS with MIBS). Spectrometer concepts such as CHRIS on PROBA, and derived designs for APEX, the SPECTRA mission and for the FLORA mission (based on AVIRIS heritage) can serve as reference for the technical design of the FLEX spectrometer. For FALIS several alternative concepts exist, including designs made within FLEX industrial feasibility studies and derivation for airborne concepts such as AirFLEX, and miniature spectrometer developed for planetary missions can be adapted to meet the requirements of FALIS. High spectral resolution technologies with field-widening have been developed by using rugged monolithic wide-field imaging tunable filters, Michelson, Fourier-Transform and Fabry-Perot interferometers and spatial heterodyne spectrometers, to provide simultaneously high spatial and spectral resolution over wide fields of view. Developments in the frame of the WINDII instrument on UARS, the SWIFT field-widened Michelson instrument, and DYNAMO, SHIMMER, SHOW or GLORIA can serve as heritage for the development of advanced FLEX instruments such as FALIS.

FEASIBILITY

Feasibility of the fluorescence measurement approach based on FLD method has been largely confirmed by means of dedicated field experiments [17], over agricultural areas and boreal forest targets, such as the SIFLEX (Solar Induced Fluorescence Experiment) campaigns [18], and the use of the AirFLEX airborne demonstrator recently built by LURE, Paris, France, and the laboratory developments of a Hα 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 [19].

After the recent development of several instruments measuring passive fluorescence in the oxygen absorption bands at the canopy level but at short distances (< 50 meters), a new instrument able to measure from an aircraft has been developed to increase both the distance of measurement and the target size, then achieving the landscape or the regional level. Named AirFLEX, to serve as an airborne demonstrator for FLEX, it was used for the first time in a measurement campaign dedicated to the comparison of multiple targets under similar sun illumination conditions (nadir viewing). The campaign took place in La Mancha, Spain, during June and July 2005 over different cultivated fields, natural vegetation and forested areas, using also bare soil fields as reference targets.

Consecutive measurements along different days showed a good reproducibility of the data even for the basic measurement of absorption depths. As a second step, actual fluorescence yields (in relative units) have been computed taking bare fields as a reference, showing the capability of the Red/FarRed fluorescence ratio to discriminate behaviours among different vegetation species (see Fig. 3), even for fields that show similar values of standard vegetation indices as NDVI.

The different peaks in Fig. 3 correspond to different vegetation types along the flight line, while areas with near zero values correspond to soils. It must be emphasised the different information provided by the two fluorescence wavelengths (at 687 nm and at 760 nm). The ratio between these two values provides additional biophysical indicators about vegetation status.

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 [18].

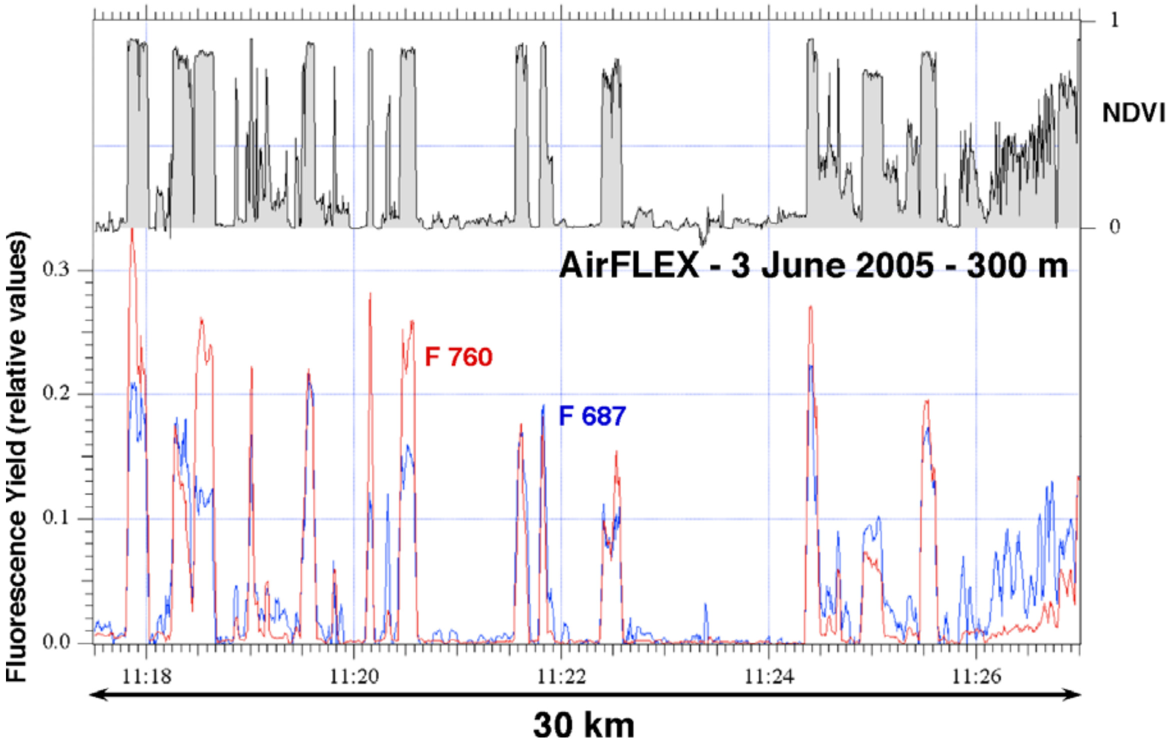

Fig. 3 Fluorescence yield values at 687 nm (O2B, in blue) and 760 nm (O2A, in red) measurement bands, as derived from AirFLEX for a 30 km transept along several vegetated areas and bare soil fields, La Mancha, Spain, June 2005.

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:

(a) Exploitation of spatio-temporal absolute fluorescence variability as a quantitative measurement of plant photosynthesis

(b) Estimation of Absorbed Photosynthetically Active Radiation

(c) Exploitation of spatio-temporal absolute fluorescence variability as a quantitative measurement of plant water status and stresses

(d) Long-term trends in steady-state chlorophyll fluorescence yields

(e) Data assimilation methods in Dynamical Vegetation Models

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.

REFERENCES

[1] C. Buschmann and H. K. Lichtenthaler, "Principles and characteristics of multi-color fluorescence of plants". J. Plant Physiol., vol. 152, pp.297-314, 1998.

[2] G. G. R. Seaton and D. A. Walker, "Chlorophyll fluorescence as a measure of photosynthetic carbon assimilation", Proc. Roy. Soc. London, vol.B242, pp.29-35, 1990.

[3] Carter G. A., J.H. Jones, R. J. Mitchell and C. H.Brewer, "Detection of solar-excited chlorophyll-a fluorescence and leaf photosynthetic capacity using a Fraunhofer line radiometer". Rem. Sensing Environ. 55, 89-923, 1996.

[4] L. Liu, Y. Zhang, J.Wang, and C. Zhao, "Detecting solar-induced chlorophyll fluorescence from field radiance spectra based on the fraunhofer line principle", IEEE Trans. Geosci. Remote Sensing 43(4), pp. 827–832, 2005.

[5] Cecchi G., P. Mazzinghi, L. Pantani, D. Tirelli and P. De Angelis, "Remote sensing of chlorophyll-a fluorescence of vegetation canopies:1 Near and far field measurements techniques". Remote Sens. Envir. 47:18-28, 1994.

[6] A. Rosema, J. H. F. Snel, H. Zahn, W. F. Buurmeijer and L. W. A. Van Hove, "The relation between laser-induced chlorophyll fluorescence and photosynthesis". Rem. Sens. Environ. , vol.65, pp.143-154, 1998.

[7] J.A. Gamon, J. Penuelas and C.B. Field, "A narrow-waveband spectral index that tracks diurnal changes in photosynthetic efficiency", Remote Sensing of Environment 41(1), pp. 35–44, 1992.

[8] G. Papageorgiou, "Chlorophyll fluorescence: an intrinsic probe of photosynthesis". In: Bioenergetics of Photosynthesis (G. Govindjee, Ed) NY, Academic Press, pp. 313-371, 1975

[9] H.K. Lichtenthaler, "Vegetation stress: An introduction to the stress concept in plants", J. Plant Physiol. 148, pp. 4–14, 1996.

[10] McFarlane J.C., R.D. Watson, A.F. Theisen, R.D. Jackson, W.L. Ehrler, P.J. Pinter Jr., S.B. Idso and R.J. Reginato "Plant stress detection by remote measurement of fluorescence". Applied Optics 19:3287-3289, 1980.

[11] J. Plascyk, "The MKII Fraunhofer Line Discriminator (FLD-II) for airborne and orbital remote sensing of solar stimulated luminescence", Optical Engineering, vol. 14(4), pp. 339–346, 1975.

[12] R.D. Watson, "Proposed design for an aircraft and space shuttle compatible Fraunhofer Line Discriminator", in Workshop on applications of luminescence techniques to Earth resources studies, edited by W.R. Hemphill and M. Settle, LPI Tech. Rep. 81-03, pp62, Lunar and Planetary Institute, Houston, 1981.

[13] I. Moya and Z.G. Cerovic, "Remote sensing of chlorophyll Fluorescence: Instrumentation and analysis", in Chlorophyll a Fluorescence: A Signature of Photosynthesis, Series: Advances in Photosynthesis and Respiration, vol. 19, G.C. Papageorgiou and Govindjee (Eds.), pp. 429-445, 2004.

[14] M.-P. Stoll. et al., "FLEX-Fluorescence Explorer – a space mission for screening vegetated areas in the Fraunhofer lines", Europto conference on Remote Sensing for Earth Science Applications, Florence, Italy; SPIE vol.3868, pp.108-119, 1999.

[15] Bazalgette Courrèges-Lacoste G., A. Court, C. Smorenburg, H. Visser, M.P. Stoll and C. Buschmann; "FLEX instrument feasibility study", Final report ESA contract 14385/00/NL/DC, 108p. TNO-TPD, Delft, The Netherlands, 2001.

[16] C.E. Sioris, G. Bazalgette Courrèges-Lacoste and M.P. Stoll, "Filling-in of Fraunhofer lines by plant fluorescence: Simulations for a nadir-viewing satellite-borne instrument", J. of Geophys. Res.-D, vol.108-D4, pp. 4133-4138.

[17] Moya, I., L. Camenen, G. Latouche, C. Mauxion, S. Evain and Z. C. Cerovic; "An instrument for the measurement of sunlight excited plant fluorescence", in Photosynthesis: Mechanisms and Effects, edited by G. Garab, Kluwer Acad. Pub.: Dordrecht, pp. 4265-4270, 1998.

[18] J. Louis, A. Ounis, J.M. Ducruet, S. Evain, T. Laurila, T. Thum, M. Aurela, G. Wingsle, L. Alonso, R. Pedros and I. Moya, "Remote sensing of sunlight-induced chlorophyll fluorescence and reflectance of Scots pine in the boreal forest during spring recovery", Remote sensing of environment 96(1), pp. 37-48, 2005.

[19] Moreno J., L. Alonso, L. Guanter, S. Gandia, "Using MERIS Data to test 02 Differential Absorption Technique for Passive Fluorescence Measurements from Space", Proceedings of the2nd Workshop on Remote Sensing of vegetation Fluorescence, 17-19 November 2004, Montreal, Canada, ESA WPP-242, 2004.