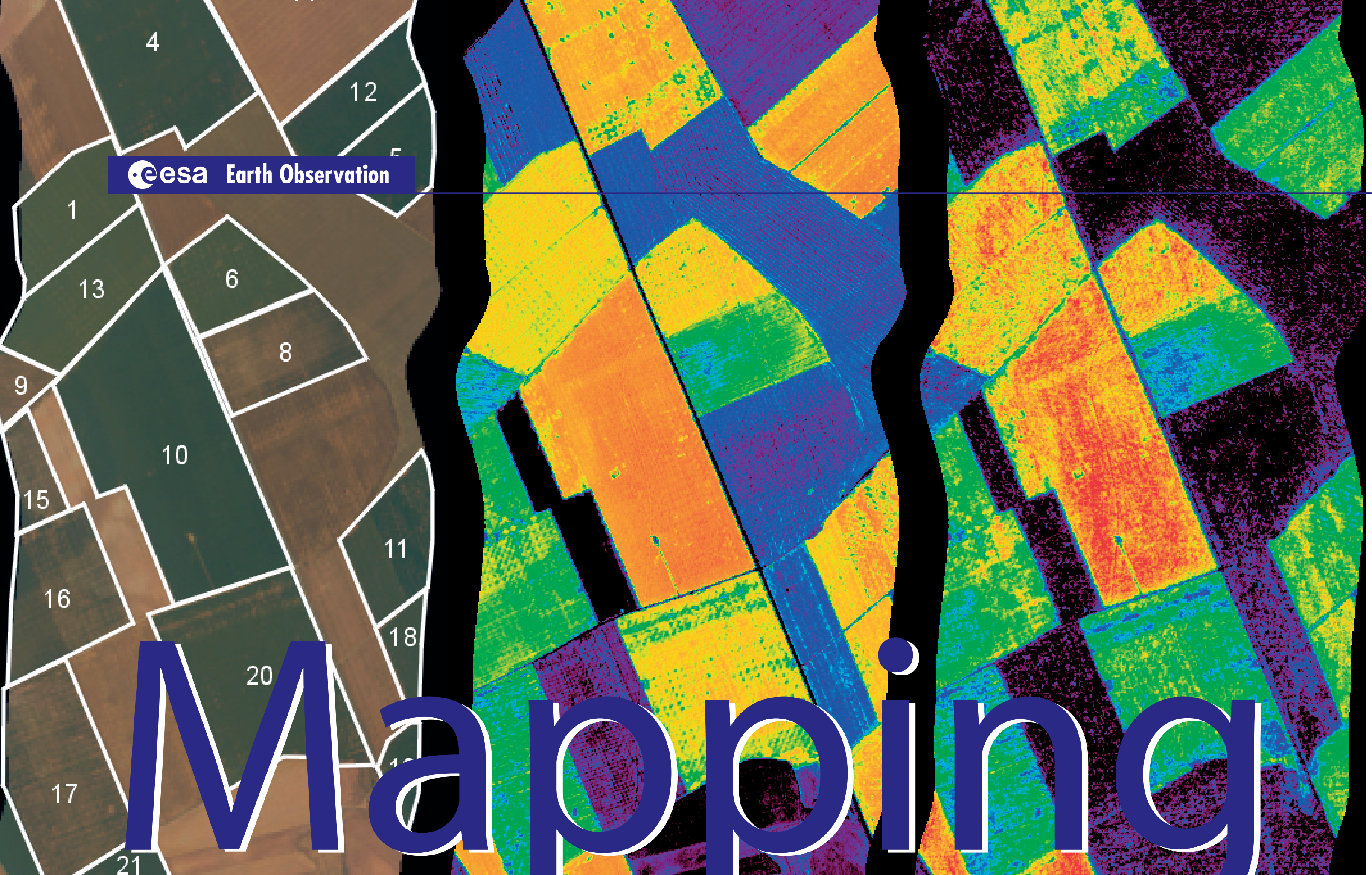

Mapping Photosynthesis from Space

- a new vegetation-fluorescence technique

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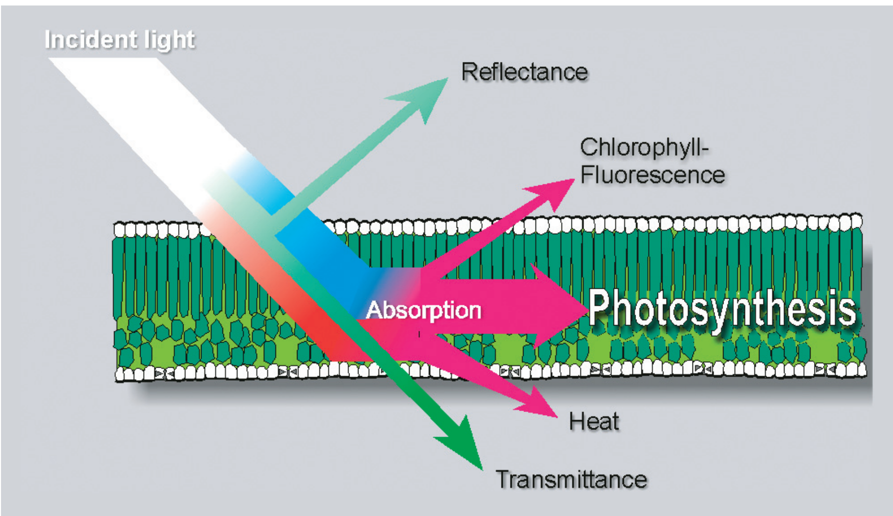
Most of the information that has been acquired so far by remote sensing of the Earth's surface has come from the analysis of reflectance data. Typically, the information provided by the sensors carried by satellites is embedded in either reflected sunlight, at optical and near- to mid-infrared wavelengths, in reflected radar pulses in the microwave domain, or in radiation emitted by the surface itself (thermal and passive microwave). There is, however, one additional source of information about the Earth in the optical and near-infrared wavelength range that has not yet been exploited by any satellite mission, namely 'vegetation fluorescence'.

Our interest in vegetation fluorescence in terms of observing the Earth stems from the fact that it provides unique information about the photosynthetic activity of the vegetation. Unlike conventional reflectance measurements, which are affected by numerous processes, fluorescence represents a specific observable of the fundamental physical processes occurring within the plant. Extensive experimental and theoretical studies have demonstrated that vegetation fluorescence serves as a proxy for the actual photosynthesis.

An Earth Observation mission based on fluorescence thus has the potential to provide valuable large-scale information about photosynthetic activity, which in turn would significantly improve estimates of carbon-dioxide uptake and provide a means for screening and monitoring vegetation vigour over large areas. This information would be complementary to that provide by current and planned optical remote-sensing satellites.

The topic of vegetation fluorescence is not new. The fluorescence signal has been studied for years and is routinely used in laboratories to study photosynthetic activity. The extension of passive fluorescence-measuring techniques to space, however, is highly innovative. Motivated by the potential of fluorescence to map photo-synthetic activity at large scales, two experimental missions have been proposed in the past: Flex (ESA) in 1998 and Flexsat (NASA) in 1999. In terms of ESA programmes, the Fluorescence Explorer (Flex) was proposed within the framework of the First Announcement of Opportunity for Earth Explorer Opportunity missions. Although the proposal was not selected, it received a positive assessment and was on a short list of missions judged to have very high scientific merit. As a consequence, ESA's Earth Observation Science Advisory Committee (ESAC) recommended the initiation of scientific and technical studies furthering a satellite mission concept.

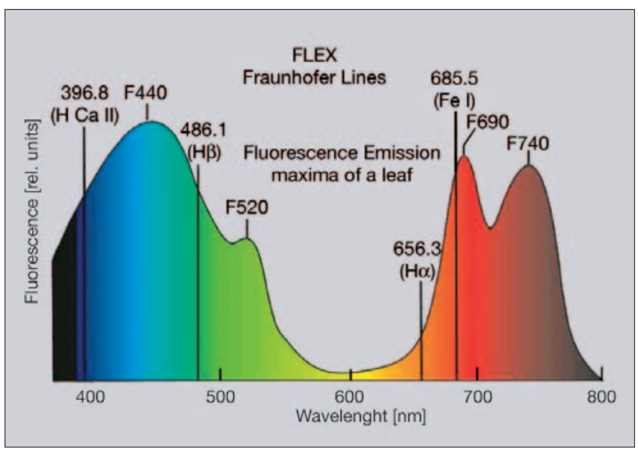
In response to this recommendation, ESA has initiated several activities over the last few years addressing key challenges in exploiting the fluorescence signal at satellite level. These include:
– an instrument feasibility study
– campaign activities
– scientific studies, and
– workshops.



How light energy falling on a leaf is partitioned. About 78% of the incident radiation is absorbed, while the rest is either transmitted or reflected at the leaf's surface. About 20% is dissipated through heat and only 2% emitted as fluorescence, as a by-product of photosynthetic reactions occurring within the leaf itself.

The main objectives of the Flex instrument-feasibility study were to refine the instrument concept for the detection of vegetation fluorescence from space, to identify potential bottlenecks, and to estimate the accuracy of the retrieval of the fluorescence signal from a spaceborne platform. The study was led by TNO-TPD, Delft (NL), with participation by the University Louis Pasteur (ULP), Strasbourg (F), the University of Karlsruhe, Karlsruhe (D) and York University, Toronto (Can.).

The Flex study addressed a critical technical challenge characteristic of vegetation fluorescence: the weakness of the fluorescence signal itself, whose level represents only a very small fraction of the total reflected visible light (less than 2% in most cases). This requires special observation methods based on measurements in very narrow spectral bands for which the reflected background signal is strongly depressed (the so-called 'Fraunhofer-line method'). The study examined various imaging concepts and performed extensive signal modelling to determine an acceptable sensor concept. One result of the study was to show that atmospheric effects on the signal could generally be corrected for through modeling, and that the retrieval of fluorescence radiance appears feasible from space with an overall accuracy of 10%. The study also identified the need to document the fluorescence signal over real vegetation canopies, as only a theoretical estimate could be used during the Flex study.



The fluorescence emission spectrum of a leaf as derived from laboratory measurements. The peaks in emission at 440, 520, 690 and 740 nanometres are clearly visible in spectrum.

The experimental setup during the ESA SIFLEX campaign which took place above the Arctic Circle, in Sodankyla, Finland. Observations of solar-induced fluorescence were made from the top of a 20 m tower overlooking the Boreal forest canopy.

To address these issues, an ESA field campaign known as SIFLEX (Solar Induced FLuorescence EXperiment) was initiated in 2002 in northern Finland. The aim was to establish and document fluorescence signal levels over Boreal forests, in specific bands of interest for spaceborne fluorescence sensors. The participating scientists collected 6 weeks worth of fluorescence data, covering the spring recovery of the forest from winter dormancy, through to its fully active summer state when photosynthesis was at its maximum. These measurements were made from an instrument, specially developed by the LURE photosynthesis and remote-sensing team in Paris, which was pointed at the forest canopy from the top of a 20 m tower erected especially for the campaign. Coinciding with the fluorescence data acquisition, a wide range of additional measurements were performed by the Finnish Meterological Institute, the University of Valencia, and York University. These included CO_2 flux measurements to establish a linkage between the fluorescence signal and the carbon cycle, and reflectance measurements and thermal measurements for canopy-modelling purposes.

Overall the ESA SIFLEX campaign represented a significant step forward as, for first time, it was possible to detect and observe the chlorophyll fluorescence signal and its fluctuations in the natural environment over a long period of time. As a result, more realistic simulations can be made of the performance requirements for future spaceborne fluorescence sensors. Initial simulations based on campaign data show that the chlorophyll fluorescence signal is detectable by means of remote sensing even under the difficult low-light conditions that are typical in Arctic regions.

As part of the coordinated efforts, a study was also launched in 2002 by ESA to advance the underlying science of a possible future vegetation-fluorescence space mission through the development of integrated canopy-fluorescence models. The aim of this study is to incorporate the fluorescence signal into existing canopy models in order to simulate the total signal, consisting of both reflectance and fluorescence emission components. The final model will be validated using SIFLEX and other campaign data. In the future, it will serve as a basic tool with which to develop accurate quantitative approaches to extract information from fluorescence and reflectance data and form a basis for the development of retrieval algorithms.

In addition to existing activities, a number of future activities have been initiated to address the remaining open issues associated with an eventual space fluorescence mission. Of prime importance is the documentation of the fluorescence signal over different types of land-cover and under a variety of conditions. This follows a key recommendation made by the scientists attending the First FLEX Workshop help in June 2002 at ESTEC (NL). To meet this challenge, an airborne fluorescence instrument is currently under development. It will be flown next year over a test site in Spain during the 2003 ESA AIRFLEX (Airborne Fluorescence Experiment) campaign. This campaign is expected to provide important information about fluorescence signal sensitivity, spatial variability and scaling effects, and will complement the initial field activities initiated with SIFLEX.

Additional investigations are also currently underway based on airborne and spaceborne hyperspectral images. Recent results have shown that narrow imaging spectrometers are sensitive to the fluorescence signal in spectral bands where reflectance is strongly attenuated by atmospheric absorption. Different analysis methods based on hyperspectral data are under investigation.

It is interesting to note that, a quarter of a century after satellite detection of fluorescence was first envisaged, no operational system has yet been developed. For a long time, fluorescence studies have remained confined to the laboratory and have not attained the status of an operationally exploitable remote-sensing technique. A number of steps are required to transform the laboratory results into an operational space mission. The activities undertaken at present by ESA and other agencies have strongly contributed to this bridging phase. The feasibility of detecting fluorescence from space has been demonstrated through dedicated campaigns and instrument studies. The unknowns regarding the measurement, analysis and exploitation of the fluorescence signal are being addressed by the development of appropriate canopy radiative models and assessed using campaign measurements. Together these activities contribute to furthering the concept for a spaceborne fluorescence mission and open new ways for the global monitoring of vegetation, with improved estimates of vegetation photosynthetic activity and direct implications for carbon flux estimation.

The complementarity between indices derived from conventional reflectance measurements and from fluorescence. All images were derived from airborne hyperspectral data acquired with DLR's ROSIS sensor. The leftmost image represents a true colour image of the Barrax test site, near Albacete in Spain. The middle image represents an estimate of vegetation fluorescence derived using a novel technique applicable to hyperspectral data. The rightmost image represents the commonly used Green NDVI index, which is derived from reflectance data and generally provides information about greenness and vegetation vigour. The different spatial patterns and levels of the vegetation fluorescence image with respect to the NDVI image illustrate the additional information captured by fluorescence and the complementarity of reflectance and fluorescence measurements.
(Courtesy of S. Maier, Satellite Remote Sensing Services, Australia)