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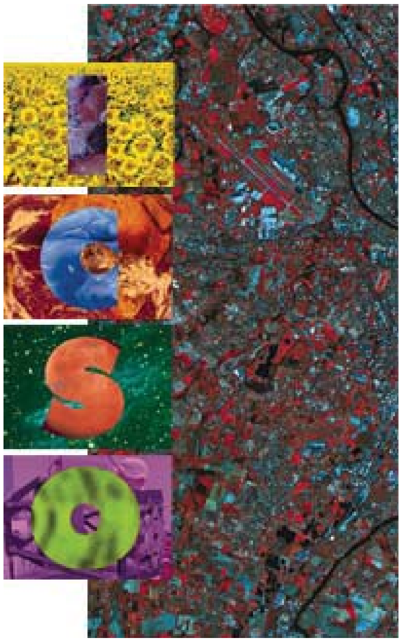

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FLEX: AN IMAGING SPECTROMETER FOR MEASUREMENT OF VEGETATION FLUORESCENCE

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ABSTRACT

Detection of vegetation fluorescence gives information about plant functioning, stress and vitality. During the past decades several ground based laser fluorosensors have been developed to investigate these processes and to demonstrate the value of this technique.
FLEX (= FLuorescense EXplorer) is a space mission to measure the fluorescence of vegetation on earth over large areas from space. Such a mission would greatly improve the understanding and enhance the capability to quantify e.g. the role of terrestrial vegetation in global carbon sequestration. Because the fluorescence signal, which is excited by solar irradiation is low with respect to the reflected sunlight the signal from a satellite is proposed to be measured in the solar Fraunhofer lines, where the reflection signal is much reduced.
The heart of FLEX is a high resolution imaging spectrometer with 2 channels: channel 1 around the Fraunhofer lines at $\lambda = 397$ nm, $\lambda = 423$ nm and/or $\lambda = 434$ nm and channel 2 around the Fraunhofer line at $\lambda = 656$ nm. The required spectral resolution will depend on the linewidth (0.02-0.3 nm).
A first definition of the field of view is 8.4 degrees, leading from an 800 km satellite altitude to a swath of about 120 km. For detection a 1024x1024 pixel frame transfer CCD detector is proposed, with a pixel dimension of 13 x 13 μm2.The maximum footprint is about 500x500m^2.
The optical configuration contains a scan mirror for solar calibration, for pointing the FOV in swath direction and for freezing the observed ground scene up to a few seconds to increase the signal to noise performance.
At this moment the concept of FLEX is elaborated in a feasibility study. Both the scientific and instrument requirements are updated and the concept is studied in detail. Besides a development plan for FLEX is made.
In this paper the idea and the headlines of FLEX are described.

Keywords: Fluorescence, imaging spectrometer, Fraunhofer line detection.

1. INTRODUCTION

The fluorescence of vegetation is an indicator of stress and vitality. Since several decades both in laboratories and in the field studies has been performed to investigate at one hand the fundamental mechanisms of the fluorescence in relation to the photosynthesis and the functioning of the vegetation and on the other hand to explore the possibilities of this type of measurement for remote sensing purposes.
Concerning the science related aspects many studies have been published and the relation between fluorescence intensity and vitality of the vegetation is clearly demonstrated.
Since more than 20 years Laser Induced Fluorosensors have been developed for studies in laboratory and in the field. These sensors are using pulse lasers for excitation and detect the fluorescense signal in a short time window to obtain a sufficient S/N performance.

For example about 10 years ago in the Netherlands a sensor called LEAF (= Laser Environmental Active Fluorosensor) was developed both for field measurements (distance $\leq$ 100 m) and conditioned laboratory investigations[3, 4].

Herewith the first steps for remote sensing application have been made, albeit for application at a moderate distance.

For application from space detection of solar induced fluorescence (so called “natural” fluorescence) is the only realistic possibility. Contrary to Laser Induced Fluorescence with monochromatic excitation natural fluorescence results from broadband (solar) excitation. However the basic fluorescence phenomena are the same, only the relative distribution of the emission may be different.

Practically observation and measurement of the solar induced vegetation fluorescence is difficult because of the weakness of the signal relative to the reflected signal. The only feasible method is sensing the fluorescence using the Fraunhofer lines in the solar spectrum, where the irradiance is low enough so that the fluorescence signal is not too small in comparison to the reflected signal.

This technique has already been explored more than 25 years ago by Plascyk e.a., who developed a Fraunhofer Line Discriminator (FLD), based on a solid etalon Fabry-Perot filter[5, 6].

In later years investigations with the FLD have been continued especially in the US on a low level scale[7, 8, 9, 10].

The FLEX instrument is an European initiative, that is based on high resolution spectroscopy, making use of advanced 2-dim. detector arrays[11, 12]. FLEX is proposed in 1998 for a space mission and is being studied at this moment w.r.t. a more detailed definition of the science – and instrument requirements, demonstration of feasibility by a more elaborated instrumental design and performance estimate and additional laboratory experiments.

The present study is being performed by TNO Institute of Applied Physics (instrumental aspects) and the University of Strasbourg and of Karlsruhe (scientific aspects).

2. SCIENTIFIC REQUIREMENTS

The primary goal of the FLEX mission is the quantative measurement from space of plant fluorescence by measurements at defined (Fraunhofer) wavelengths. These measurements of course must provide information about the state of the observed vegetation w.r.t. factors such as stress and vitality, which affect plant function.

For FLEX this leads to:

1. Measurement of fluorescence.
   This fluorescence is measured at the bottom of the Fraunhofer line. The Fraunhofer lines itself are carefully selected, at least one in the red (in the chlorophyl fluorescence region) and one in the blue. Extensive information from short range remote sensing demonstrates, that proper usage of fluorescence measurements relies on more than one wavelength and on ratios of intensities.
2. Combination of data.
   Additional data such as reflectance, temperature, atmospheric transmission etc. will increase the value of interpretation of the fluorescence measurements.
   These additional data can be provided by various sources: measuring the total Fraunhofer line profile (“shoulders” + bottom), additional sensors (thermal module to FLEX), hyper-spectral and/or broadband measurements from other satellites etc.
3. Ground truth measurements.
   Elaboration and interpretation of FLEX (and FLEX related) measurements must be correlated with on ground verification, especially during the development period of this fluorescence technique.

3. INSTRUMENTAL REQUIREMENTS.

For the FLEX instrument design the main starting points are:

1 Selection of Fraunhofer lines.

Table 1 gives a list of usable Fraunhofer Lines

name	H Ca II	g Ca I	Hγ HI	Hβ HI	b1 MgI	HαHI	FeI	FeI
λ (nm)	396.8	422.7	434.0	486.1	518.4	656.3	685.5	738.9
width (nm) FWHM	1.44	0.15	0.35	0.132	0.16	0.144	0.012	0.021

Table 1: Fraunhofer lines.

The primary choice is:

- HγHI: $\lambda = 434.0$ nm
  FWHM = 0.35 nm
- HαHI: $\lambda = 656.3$ nm
  FWHM = 0.144 nm

The measurement in more lines will give additional imformation. Adding more lines will be considered for the final instrument design.

2. Spectral resolution
The required spectral resolution will depend on the width of the Fraunhofer line.
A first estimate is:

- $\lambda = 434.0$ nm $\Delta\lambda \leq 0.17$ nm
- $\lambda = 656.0$ nm $\Delta\lambda \leq 0.07$ nm

3. Field of view (FOV)
The wish is to cover a reasonable large FOV in swath direction (≥ 50 km) in combination with a ground pixel size of larger than 50 x 50 m^2.
The maximum allowable pixel size for scientific study shall be no more than 500 x 500 m^2.

Besides these starting points the following factors determine to a great extent the optical instrumental design of FLEX.

- Choice of detector
  A first choice is a frame transfer CCD detector from EEV with 1024 x 1024 pixels of 13 x 13 μm^2. For the spectral image 900 x 900 pixels are available. Residual pixels are used for dark current measurement, straylight correction etc. By this choice the limitations concerning spectral and spatial possibilities are determined.
- Fluorescence radiance
  The inensity level of the fluorescence is low and varies with wavelength. Most reliable measurements have been performed with monochromatic excitation. From these measurements an extrapolation can be made for simulated solar excitation. This gives for the Hα line flux a radiance lower than 7 mW m^{-2} nm^{-1}, which is the weakest signal level of the overall fluorescence spectrum.
- Scanning
  FLEX must have a scanning possibility for several purposes
  - Calibration (pointing the instrument via a reflection diffuser to solar radiation)
  - Extension of view reange in cross direction.
  - Extention of observation time (to improve S/N performance).

4. CONCEPT DESIGN

Based on the starting points as mentioned in chapter 3 a concept design of FLEX is made.
The schematic configuration is given in figure 1.

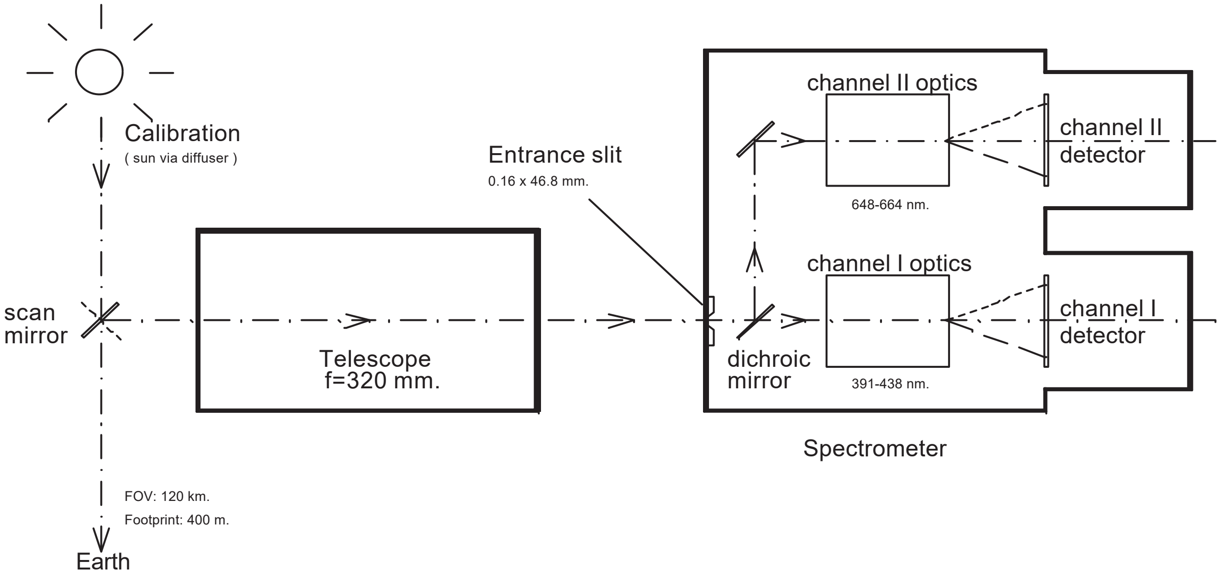

Figure 1: Schematic configuration of FLEX

FLEX is an imaging spectrometer, that consists essentially of a telescope and a spectrometer.
Via a scan mirror in front of the telescope the observation or the calibration mode can be selected.

The various elements in the configuration are:

The telescope
The telescope images the earth (or solar radiation) on the entrance slit of the spectrometer.
It consists of a single mirror with a focal length of 320 mm.
A telescope exit slit (= spectrometer entrance slit) of 0.16 x 46.8 mm^2 leads to a FOV of 0.03° (flight direction) x 8.4° (swath direction).

The spectrometer
The (imaging) spectrometer consists of 2 spectral channels. In each channel after dispersion by a grating a (limited) spectral range is imaged in one direction on the detector.
In perpendicular direction the FOV of 8.4° is imaged on the detector.
The components of the spectrometer are:

- Entrance slit (0.16 x 46.8 mm^2)
- Dichroic mirror for separation of the 2 spectral channels.

  - Channel 1:
    - spectral range: 391 – 438 nm
    - resolution: 0.14 nm
    - Fraunhofer lines: 396.6 nm, 422.7 nm and 434.0 nm
    - grating: 2400 gr/mm (1st order)
    - fused silica imaging optics (f ≈ 100 mm)
    - monochromatic image of entrance slit: 0.033 x 11.7 mm^2 (= 2.5 x 900 pixels)

The spectral resolution is more than sufficient to measure the relative broad Fraunhofer line at 396.6 nm. Also for the HγHI line (434.0 nm) it seems good enough, however for the g CaI line (422.7 nm) this resolution is marginal.

For this preliminary concept channel 1 contains 3 Fraunhofer lines, which seems atttractive.

More detailed study in a later phase however may show, that a limiatation to e.g. 2 Fraunhofer lines with considerable high resolution may be preferred.

These changes in the optical concept are relatively easy to imply.

- Channel 2:
  - spectral range: 648 – 664 nm
  - resolution: 0.06 nm
  - Fraunhofer line: 656.3 nm
  - grating: 450 gr/mm (6th order)
  - imaging optics: f ≈ 130 mm
  - monochromatic image of the entrance slit 0.033 x 11.7 mm^2.

The choice of the HαHI Fraunhofer line for this channel is obvious.Although not close to the maximum,it is still in the chlorophyll fluorescence domain, while the FWHM is a factor larger than that of the FeI lines at 685.5 nm and 738.9 nm.

The grating of this channel is used in the 6th order at an angle of incidence and diffraction around 60 degrees. The grating order is selected by a spectral filter.

The scanmirror

With the scanmirror in front of the telescope FLEX can be set in 2 modes:

- Observation mode

  Starting point for the FLEX mission is a sunsynchronous orbit with an observation time between 10.00 – 14.00 hrs. Another interesting possibility is observation from a geostationary orbit. Herewith the variation of fluorescence during the day can be measured and a longer integration time, while observing a scene, is possible.The scan mirror can be pointed in 2 directions in order to increase in swath direction the viewing range. The FOV in swath direction is 8.4 degrees (≈ 117 km from an 800 km satellite attitude).By extending in cross direction the viewrange to ± 8 degrees a selection of the FOV within a range of 340 km is possible.
- Calibration mode

  FLEX has to be calibrated in space at regular intervals. Therefore at some point in the satellite orbit a diffuser is irradiated directly by the sun. With the scanmirror the telescope is pointed to this diffuser. During earth observation the sun aperture in front of the diffuser is closed by a shutter mechanism to protect the instrument from solar straylight during normal earth observation and to protect the diffuser from degradation.

In table 2 an overview is given of the main data of the FLEX concept.

Spectral		Range	Resolution
	Channel 1 Channel 2	391-438 nm 648-664 nm	0.14 nm 0.06 nm
	Fraunhofer lines: 396.6 nm, 422.7 nm, 434.0 nm, 656.3 nm		
Spatial	FOV: 0.03° (flight) x 8.4° (swath) IFOV: 0.5 x 0.5 km^2 Scan range: ± 8° (= 340 km)		
Detector	Nr of pixels: 1024 x 1024 Pixel dimension: 13 x 13 μm^2		
Camera	FOV: 1.8° x 9.0°		
Dimension	500 x 250 x 200 mm^3		
Mass	20 kg		

Table 2: FLEX data

5. CONCLUDING REMARKS

In this paper the concept design of an instrument for measurements of fluorescence from space is described. After study of the potential and possibilities of the fluorescence technique as tool for diagnostics of the vitality of vegetation during the last decades both in Europe and US the possibilities for application from space are being explored now, where in the US the interferometric techniques are studied and in Europe high resolution spectroscopy is being explored. At this moment a feasibility study of FLEX is being performed, which will bring us a step further to the realisation of a spaceborne mission.
This will be a first step for future development of a new generation of sensors for earth observation.

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