FLEX - Fluorescence Explorer

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ABSTRACT

FLEX is a scientifically driven space mission to provide demonstration/validation of the instrumentation and technique for measuring the natural fluorescence of vegetation in the Fraunhofer lines. The payload consists of high spectral resolution (0.1-0.3 nm) CCD imaging grating spectrometer with two channels: one in the red (648-664 nm)and one in the blue (391-438 nm) for working with several Fraunhofer lines. The across track FOV is 8.4°; ground spatial resolution is better than 0.5x0.5km2. To increase the S/N ratio a steering mirror will be used, if necessary, to "freeze" the image and also to provide ± 4° across track depointing. Calibration is made by viewing the sun via a diffuser plate switched into the telescope field of view. A separate CCD camera will allow cloud detection and scene identification. A TIR radiometer will provide simultaneous surface temperature measurements.

The spacecraft, overall mass estimated at 200kg, is derived from the ASI-MITA bus which provides all the necessary subsystems and stabilized platform. By use of on-board storage, ground requirements for satellite control and data link are minimized; the possibility of local stations for real time reception/distribution is also envisaged. Provisional orbit characteristics are: LEO sun synchronous, 500-900km altitude. Priority will be given to highest revisit frequency on a sufficient number of selected test sites.

Keywords: Fraunhofer line detection, imaging spectrometer, fluorescence.

1 - INTRODUCTION

Fluorescence of vegetation is directly linked to photosynthesis and thus to light transformation and utilization for biomass production. Since many factors act on photosynthesis efficiency and photosynthetic capacity, at short term (stress factors: temperature, water, nutrients, ..) and long term (environmental factors: global air temperature, available PAR radiation, atmospheric composition, ..) fluorescence signal is thus highly specific of vegetation function, stress and vitality [1, 2, 3, 4, 5]. Observation and measurement of fluorescence from space would significantly enhance our capability to monitor vegetation state and quantify biosphere processes and interactions. Although solar induced fluorescence is a very weak signal, its detection is possible using the Fraunhofer lines of the solar spectrum, a method that can be used from a satellite, as was already suggested some 25 years ago [6, 7, 8, 9]. Since this time, development in optical imaging spectrometers and space technology makes this technique feasible. In a companion paper (this conference) the rationale and scientific motivations for a fluorescence space mission - FLEX - Fluorescence Explorer - recently proposed in response to ESA call for Earth Explorer Opportunity Missions, are discussed. This paper addresses the technical characteristics and mission elements: instrument concept / spacecraft/ mission operations and implementation of the FLEX project, focussing on the Fraunhofer imaging spectrometer.

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2 - GENERAL MISSION CHARACTERISTICS

2.1 Scientific requirements: the scientific payload senses the surface fluorescence intensity, which implies appropriate calibration of the signal, and its spectral distribution over the solar spectrum, which means operation at least in the red and blue regions. Proper usage of the signal would require that the mission, beside fluorescence, also acquire key vegetation variables directly available from space: reflectance data and vegetation temperature.
Additional means for cloud detection and scene identification are mandatory for data processing.
The mission being an exploratory mission for validation of the technique and method, acquisition of the data from space must be contemporary with ground data at selected sites. Strong scientific motivations require special attention to be paid to boreal forest biomes [10, 11, 12]. Frequent observations at northern latitudes are thus required. High spatial resolution is not mandatory, although it should be better than 0.5x0.5 km2.

2.2 Space segment: no global coverage is envisaged; rather, priority will be given to frequent revisit of selected study areas mostly distributed between 30° and 70° Northern latitudes, with overpass time between 11h and 13h . A mission duration of 2 to 4 years is appropriate. Provisional orbit is LEO sun-synchronous circular orbit, altitude 500 to 900 km .
An important feature for accurate measurement of the fluorescence signal is a well-stabilized platform. The proposed spacecraft is derived from the ASI-MITA bus, providing all the necessary subsystems. The overall mass is estimated at some 200Kg, compatible with small or medium class launchers.

2.3 Mission operations: in order to minimize costs, the mission will use only a single ground control command / receiving station. Extended on-board data processing will minimize data link constraints. In order to allow a wide community to access this new data type, the possibility of direct transmission to Earth (NOAA/HRPT-like protocol), using low cost local receiving stations is also envisaged.
Data processing, archiving and data distribution will be under the responsibility of a FLEX scientific and management steering committee.

3 - FRAUNHOFER SPECTROMETER DESIGN CONCEPT

3.1 Technical and observation requirements: Instrument concept and technical characteristics are dictated by the characteristics of the fluorescence response of vegetation and its observation in Fraunhofer lines.
The fluorescence is a very weak signal [6, 13]: for non-stressed vegetation, fluorescence represents at most 1% to 2% of total PAR energy. This would correspond to the signal amplitude of a hypothetical surface with constant reflectance of 1-2% over the 400-700nm domain. Except in the red where vegetation, and in particular some forested areas, have a reflectance as low as 2% or so, the reflectance is usually higher. On the other hand, the observed fluorescence may be actually much less than the rough estimate above because of re-absorption (up to 90% reabsorbed in some cases) and other effects and its unequal distribution over the spectrum [14].
Contrarywise, for stressed vegetation, significantly higher levels of fluorescence signals can be expected. Figure (3.1) illustrates the matter.

A convenient factor to characterize the florescence is the fluorescence index *"f"* equal to the ratio of the fluorescence emitted in the Fraunhofer line to the background solar irradiance (i.e. at a wavelength just outside the Fraunhofer line).
Would the Fraunhofer line be completely dark, any signal observed in the Fraunhofer line of the light from the surface would come from fluorescence (assuming no inelastic atmospheric scattering). Actually, the minimum in the trough is in the order of a few to 15%, depending on the particular line, so that the fluorescence signal competes with a residual reflectance signal. The spectral resolution of the spectrometer has thus to be very high, typically less than 0.1nm.
Assuming no atmosphere, it is easy to show that

$$f = \frac{S_f - kS_b}{(1-k)I_0} \quad \text{and} \quad r = \frac{S_b - S_f}{(1-k)I_0}$$

Where r is the background surface reflectance, S_f (resp. S_b) the signal in the Fraunhofer line (resp. background), I_0 the background irradiance and kI_0 the residual irradiance in the Fraunhofer line. I_0 and k can be obtained from the Fraunhofer line profile in the direct Sunlight.

Among different Fraunhofer lines in the visible region, for instance

396.85nm	422.67nm	434.05nm	486.13nm	518.36nm	656.3nm

the Hα line at 656.3nm is mandatory since it is closest to the maximum of chlorophyll-a emission fluorescence around 680nm. Estimate of the minimum (no stressed vegetation) fluorescence index in the Hα line leads to $f \sim$ a few 10^{-4}. This calls for a high S/N ratio together with high dynamical range.

The second Fraunhofer line, which was chosen to illustrate the optical system concept, is the 396.85nm. This choice is subject to modification according to the outcome of further studies on solar induced fluorescence and atmospheric contribution to the signal.

Baseline for observation direction is nadir or nearly nadir (TBC); a direct view to the sun is necessary for calibration purposes.

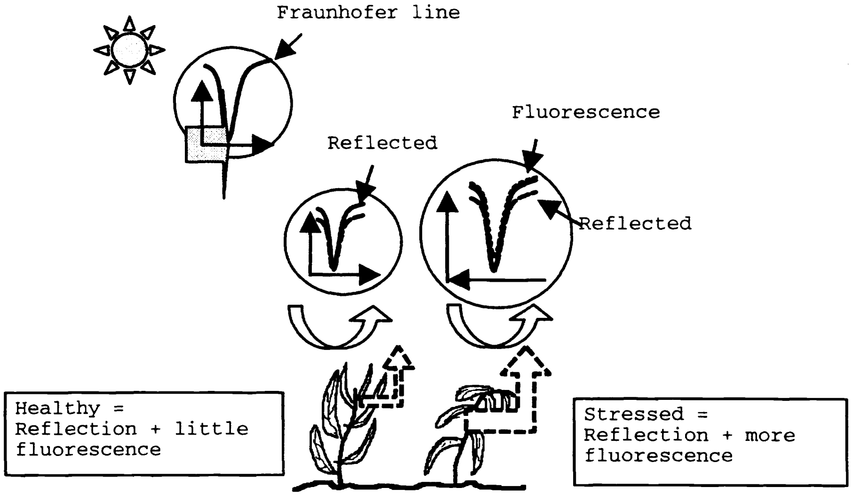

Figure (3.1): Fraunhofer line method to observe the fluorescence in full sunlight.

3.2 Spectrometer concept

3.2.1. Design drivers

The optical configuration of FLEX is based on the following starting points:

1. **Spectral**

- Channel 1: λ=391-438 nm.
  $\Delta\lambda$=0.14 nm.

  This channel contains the Fraunhofer lines: λ=396.6 nm, λ=422.7 nm and/or λ=434.0 nm.

- Channel 2: λ= 648-664 nm.
  Δλ= 0.06 nm.
  This channel contains the Fraunhofer line: λ=656.3 nm.

The required spectral resolution is determined by the width of the Fraunhofer line.
This means, that normally a spectral resolution of 0.1 nm or better is required, except for the λ=396.6 nm line, for which a spectral resolution of about 0.3 nm is sufficient.
The spectral values of channel 1 is a compromise between spectral range (the wish to detect more than 1 Fraunhofer line), the minimum required spectral resolution and the detector capabilities (=number of detector elements).

2. **Spatial**

Linear FOV (Field of View) in swath direction: 8.4 degrees (≈ 117 km from an 800 km satellite altitude).
Geometrical FOV in flight direction: 0.03 degrees (≅ 0.4 km).
IFOV (Instantaneous FOV)= about 0.5x0.5 km^2 (footprint).
The wish is to cover a reasonable large swath (FOV perpendicular to the flight direction) together with a footprint in nadir direction of about 0.5 x 0.5 km^2. Also here the possibilities are determined by the choice of the detector (=number of detector elements).

3. **Detection**

A preliminary choice for FLEX is the frame transfer CCD detector from EEV with 1024 x 1024 pixels of 13x13 μm^2. (EEV 47-20). This choice sets the limitations for the spectral and spatial possiblities mentioned before. For the spectral image 900 x 900 pixels are used. Residual pixels are used for dark current measurement, straylight correction etc.

4. **Scanning.**

FLEX is supplied with a scan mirror system for 3 purposes:

- Calibration possibilities (pointing the instrument to solar radiation, via a reflection diffuser).
- Extending in cross direction the view-range to ± 8 degrees (≈340 km).
- To extend the observation time to a few seconds by "freezing" the observed ground scene. This time period might be necessary to accumulate sufficient photons to obtain an adequate signal to noise performance of the detector from the selected scene.

3.2.2. General layout.

A schematic layout of the system is given in figure (3.2).

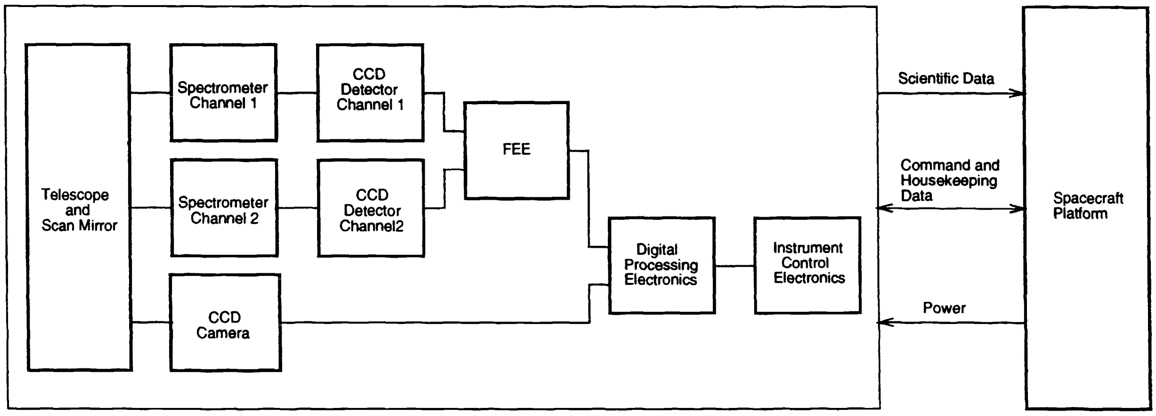

Figure (3.2): General layout of the scientific payload.

The payload consists of the instrumental part, the spacecraft platform and the interfaces.

The instrument itself is an imaging spectrometer consisting of a telescope + scan mirror, 2 spectrometers + detectors + electronics and a camera for scene identification and cloud detection. Besides the camera will be used for scan-mirror control purposes ("freezing of the scene). The FOV of the camera is about 1.8^0 x 9.0^0, centred with respect to the FOV of the main instrument of 0.03^0 x 8.4^0.

The total optical design concept of FLEX can be realised in a unit with overall dimensions of about 500x250x200 mm^3.

A mass estimate of the optical/mechanical unit is about 20 kg.

3.2.3. Optical configuration.

Figure (3.3.) presents a schematic layout of the optical configuration of the main instrument of FLEX

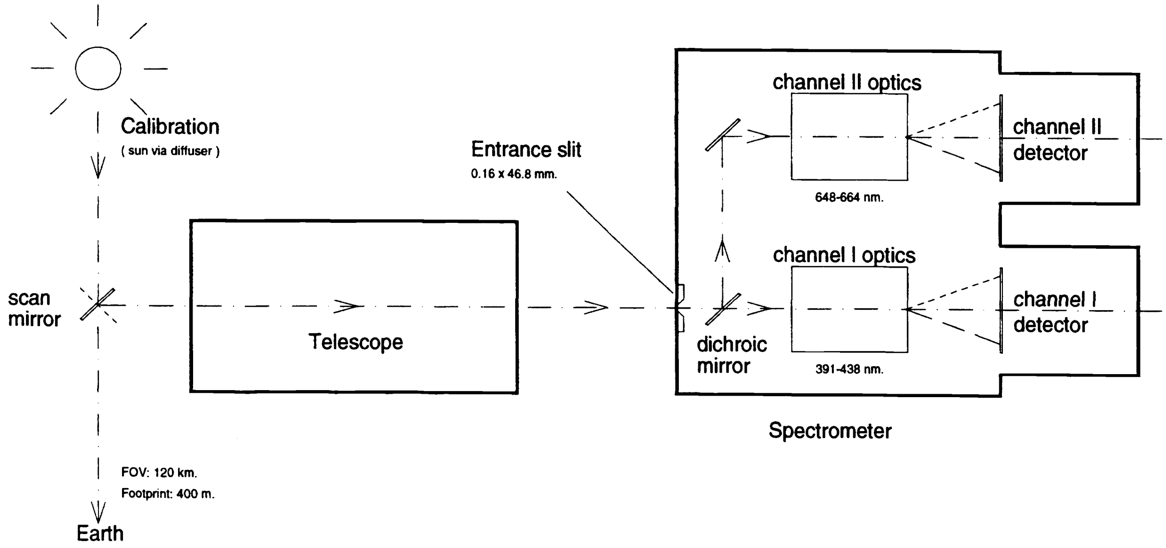

Figure (3.3): Schematic Optical Configuration (Camera not included).

As mentioned earlier FLEX is an imaging spectrometer. This means, that on a matrix detector in one direction a linear FOV is imaged (on 900 pixels), while at the same time in perpendicular (flight) direction the linear FOV is spectrally dispersed. Scanning of the earth is performed by the movement of the spacecraft.

The basic elements of the configuration are:

Scan mirror system

Herewith the FOV is pointed to the earth for measurements or to the sun (via a diffuser) for calibration. The scan mirror system consists of 2 separate mirrors in series. These mirrors can be rotated around single axes, that are orthogonal. The size of the mirrors is limited to about 25 mm diameter.

The telescope

Herewith the earth or the solar radiation is imaged on the entrance slit of the spectrometer. The telescope consists of a single mirror with a focal length of 320 mm.

In combination with the FOV of 0.03^0 x 8.4^0 this leads to a dimension of the telescope exit slit (=spectrometer entrance slit) of 0.16 x 46.8 mm^2.

The spectrometer.

This "heart of the instrument" consists of an entrance slit, a dichroic mirror for separation of the spectral channels, the channel optics (collimating optics, grating, and spectral imaging optics) and the CCD detectors.

The dichroic mirror reflects the short wavelength (channel 1) and transmits the long wavelength (channel 2).

Channel 1 consists of a collimating mirror (∅= 30 mm), a 2400 gr/mm plane reflection grating (used in 1st order) and a fused silica lens system with a focal length of about 100 mm.

The entrance slit of the spectrometer is monochromatically imaged on the detector surface as 0.033 x 11.7 mm^2 (=2.5 x 900 pixels). The spectral resolution of this channel, which is mainly determined by the 2.5 pixels width of this monochromatic image of the entrance slit is about 0.14 nm.

This is more than sufficient to measure the relatively broad Fraunhofer line at 396.6 nm. For the other lines in the wavelength range of channel 1 this spectral resolution is only marginally sufficient.

Channel 2 contains only one interesting Fraunhofer line (at 656.3 nm). For this reason the spectral resolution of this channel has been optimized to measure only this line.

The collimating mirror creates a beam of ∅=40 mm, that falls on a 450 gr/mm echelle type grating, that is used in the sixth order at an angle of incidence and diffraction around 60 degrees. The grating order is selected by a spectral filter. The focal lengths of the spectral imaging lens is about 130 mm.

Also for this channel the monochromatic image of the entrance slit at the detector is 0.033 x 11.7 mm^2, corresponding to a spectral resolution of 0.06 nm.

The polarisation sensitivity of the FLEX optical instrument is kept < 3% (around 400 nm) thanks to proper design and a limited wavelength range per channel.

Calibration

At some point in the satellite orbit the diffuser can be irradiated directly by the sun. With a mesh the amount of radiation to the diffuser can be reduced to the desired level (no saturation).

A shutter mechanism is used to close the sun aperture to protect the instrument from solar straylight during normal earth observation and to protect the diffuser from degradation.

A summary of the main instrumental data is given in table (3.1)

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: 0.03^0 (flight) x 8.4^0 (swath). IFOV: 0.5 x 0.5 km^2 Scan range: ± 8^0 (=340 km).		
Detector:	Nr of pixels: 1024x1024. Pixel dimension: 13x 13 μm^2.		
Camera:	FOV: 1.8^0 x 9.0^0		
Dimension:	500 x 250 x 200 mm^3		
Mass:	20 kg.		

Table 3.1: Key spectrometer data

3.2.4. Signal level estimate

Concerning the signal level estimate 2 factors are important:

- Maximum earth signal

  Assuming a maximum albedo of 1.0, an instrument efficiency of 20% and a detector quantum efficiency of 60% the maximum signal of FLEX will be about $2x10^5$ electrons per detector pixel per second integration time. This means , that these max. signal levels can be handled by FLEX until an integration time of about 0.5 sec. (the full well capacity is about 1×10^5 electrons)

- Fluorescence signal

  The fluorescence signal is very weak. It is estimated, that the spectral radiance of the fluorescence signal (in the rather broad fluorescence wavelength ranges) will be about 10^{-3} of that of a perfect diffuser (in the same wavelength range).

  This means, that the fluorescence signal will usually be larger than the photon noise in the dip of a Fraunhofer line for an average earth signal level.

  Fortunately the most interesting scenes (forests) have a low reflectance, so the performance of the instrument will be sufficient to measure the fluorescence signal well above the photon noise of the "normal" (without fluorescence) earth reflectance.

  The detection of the weak fluorescence signal is a point for further elaboration and experimental verification.

4 - TEMPERATURE MEASUREMENTS

It may be important to measure the temperature of the vegetation simultaneously with the fluorescence measurements.
Some reasons are

- There is existance of a threshold temperature for photo synthetic activity $\cong 5^0C$)
- Temperature can be a stress factor.
- Temperature influences evaporation.
- The fluorescence mechanism is temperature dependent

Therefore adding a TIR radiometer to the FLEX instrument for simultaneous measurement of the surface temperature is considered.
The required accuracy will be ± 1 K, the spectral band between 10-12 μm.

5 - CONCLUDING REMARKS

The Fraunhofer line method calls for a high resolution, high quality imaging spectrometer with high S/N and high immunity to stray light. Scientific usage of the fluorescence signal also calls for simultaneous acquisition of high-resolution spectral reflectance and temperature data. However, since reflectance does not vary rapidly over time, it could be obtained from other missions. To lower the costs and relax the constraints, a first exploratory space mission could be focussed on fluorescence measurements only (plus additional camera, as described above). This would result in a reasonably simple space mission that is perceived as feasible and timely with respect to the development of ambitious Earth observation programs and the growing need for very specific information type from space.
In the meantime an optical bread-board instrument must be produced to allow acquiring a large amount of real natural fluorescence data, together with scientific studies addressing open questions which should be undertaken and conducted in the spirit of a future space mission.

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