FLUORESCENCE EXPLORER (FLEX)

ESA EARTH EXPLORER-8 CANDIDATE MISSION
ESA’s Earth Explorers

GOCE
Gravity Field and Steady-State Ocean Circulation Explorer
17 MAR 2009

SMOS
Soil Moisture and Ocean Salinity
2 NOV 2009

CryoSat-2
Polar Ice Monitoring
8 APR 2010

ADM-Aeolus
Atmospheric Dynamics Mission
Mid 2015

SWARM
The Earth Magnetic Field And Environment Explorer
Nov 2013

EarthCARE
Earth Clouds and Radiation Explorer
Nov 2016

SWARM
The Earth Magnetic Field And Environment Explorer
Nov 2013

EarthCARE
Earth Clouds and Radiation Explorer
Nov 2016

BIOMASS
Biomass Establishment
2019

BIOMASS
Biomass Establishment
20XX

FLEX / CarbonSat
Explorer 8
**Net Ecosystem Production (NEP)**

**Net Biome Production (NBP)**

**Net Primary Production (NPP)**

**Gross Primary Production (GPP)**

- Large uncertainties and discrepancies in outputs from different models
- Variations correlated with both light absorption and efficiency of light use

![Diagram of Terrestrial carbon cycle](image)

- Photons to absorbed light
- Absorbed light to light use efficiency
- Light use efficiency to GPP
- GPP to NEP
- NEP to NBP

**Key Data Points**

- **GPP**: $\approx 120$ Gt / yr
- **NPP**: $\approx 60$ Gt / yr
- **NEP**: $\approx 10$ Gt / yr
- **NBP**: $\approx 1$ Gt / yr
Science objectives

(a) Global vegetation fluorescence, and derived photosynthesis, CO$_2$ fluxes, carbon assimilation:
- Mapping photosynthetic efficiency
- Activation/deactivation status of photosystems

(b) Coupling of photosynthesis (carbon) and transpiration (water) at a global scale:
- Coupling of carbon and water cycles (light use efficiency versus water use efficiency)

(c) Vegetation stress monitoring:
- Early indicators of environmental stresses

(d) Anthropogenic impacts associated to land use changes and varying management practices (food security)
De-excitation pathways

PHOTOSYNTHESIS

EXCITED STATE

Photochemistry

Fluorescence

Constitutive heat dissipation

Regulated heat dissipation

REGULATION FACTORS

Incident sunlight

GROUND STATE

Ch

Ch*

Absorption

Fluorescence emission

lower energy

Absorption (a.u.)

Fluorescence (a.u.)

absorption

excitation

300 400 500 600 700
wavelength (nm)

300 400 500 600 700
wavelength (nm)
DYNAMICS OF REFLECTANCE AND FLUORESCENCE
Fluorescence versus water stress

Peak ratio changes through the day and between days as stress increases, changing the shape of the emission spectrum.

Fluorescence versus air pollution stress

Van Wittenbergh et al., 2013  http://dx.doi.org/10.1016/j.envpol.2012.10.003.
Vegetation stress

Photosynthetic Strain

Water deficit
Freezing
Chilling
Heat
Salinity
Weeds
High light
Ozone
Heavy metal toxicity
Acid rain
UV
Pollutants
Insecticides
Herbicides
Elevated CO2
Nutrient deficit
Pests

Fluorescence tracks actual photosynthesis as regulated by vegetation stress

Direct impact on agricultural production, food security and optimization of food resources for the growing population
Determination of fluorescence from apparent reflectance

**Apparent reflectance**

\[ F_{S/L}^{WLR} \]

**Actual reflectance**

\[ r_o \]

0.3 FWHM / 0.1 nm sampling

300 m spatial resolution

**Fluorescence Emission**

- \( O_2-B \)
- \( O_2-A \)

**Atmospheric Transmittance**

**Radiance (W/m²/nm/sr)**

- True Reflectance (free of fluorescence)
- Apparent Reflectance

**Wavelength (nm)**

- 755 to 775
Initial SIF estimates at O$_2$ absorptions

**Requires** (from Atmospheric Correction):

- TOC Total Irradiance $E_{tot}$ and $\hat{E}_{tot}$ (modelled with no O$_2$)
- TOC Apparent Reflectance $\rho_{app}$ (includes SIF)

$$F_S = (\rho_{app} - \hat{\rho}_{app}) \cdot \frac{E_{tot} \cdot \hat{E}_{tot}}{\pi(E_{tot} - \hat{E}_{tot})}$$

No assumptions about true reflectance $\rho$
(large source of error in other retrieval methods)
The FLEX retrieval scheme produces as output the full shape of the actual reflectance plus the full spectral curve of fluorescence emission.

This is a key element because it allows:
(a) To derive fluorescence integral energy, peak-ratios, etc.
(b) Biophysical parameters such as chlorophyll, LAI, etc. from the actual reflectance (actual red-edge)
Light-limited vs. carbon-limited fluorescence-photosynthesis relationship.
Orbit selection taking into account instantaneous illumination conditions and previous history of illumination at the time of overpass.
DYNAMICAL APPARENT REFLECTANCE CHANGES

Fluorescence emission

Actual measurements done under varying illumination conditions

Rad(t_f) - Rad(t_i) = R \cdot I + f(t_f) - R \cdot I - f(t_i) = f(t_f) - f(t_i)

Xanthophyll cycle

violaxanthin

zeaxanthin

Fluorescence emission
Spectral sampling of FLORIS + Sentinel 3/OLCI-SLSTR

- Improved quantification of aerosol effects
- Determination of atmospheric water vapor content (940 nm absorption band)
- Cloud screening, including cirrus (1375 nm dedicated band)
- Improved vegetation biophysical parameter estimation (Ca, LAI, fCover)

<table>
<thead>
<tr>
<th>Spectral region</th>
<th>Central Wavelength [nm]</th>
<th>FWHM [nm]</th>
<th>Spectral Sampling [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRI</td>
<td>500 – 600</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Chl</td>
<td>600 – 677</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>O₂-B</td>
<td>677 – 686</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td>O₂-A</td>
<td>686 – 697</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Red-edge</td>
<td>697 – 740</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>O₂-A</td>
<td>740 – 755</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>755 – 759</td>
<td>0.7</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>759 – 762</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>762 – 769</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>769 – 780</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Altitude: ~815 km
Local solar time: 10:00 LTDN
Temporal co-registration: < 6s (G) / 15s (T)

FLORIS (150 km)
OLCI NADIR (1270 km)
SLSTR ‘NADIR’ (1420 km)
SLSTR backward (750 km)
The combined use of satellite data and models remains of crucial importance to interpret the data in a data assimilation scenario.
FLEX Level-2 products

Target scientific community and levels of data users.

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<th>LEVEL-2 PRODUCTS</th>
<th>COMMENTS</th>
</tr>
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<tbody>
<tr>
<td>• Total fluorescence emission (spectrally integrated value)</td>
<td>Integrated values at canopy level are the ones required by models. $e(F) \leq 0.2 \text{ mW m}^{-2}\text{sr}^{-1}\text{nm}^{-1}$ for instantaneous observations. 300 m original spatial resolution.</td>
</tr>
<tr>
<td>• Peak values (F680 and F740)</td>
<td></td>
</tr>
<tr>
<td>• PSI – PSII contributions</td>
<td>Regulated energy dissipation, accounts for the fraction of light absorbed by non-photochemical pigments (carotenoids / chlorophyll ratio and violaxanthin / zeaxanthin ratio, anthocyanin).</td>
</tr>
<tr>
<td>• Non-photochemical energy dissipation</td>
<td></td>
</tr>
<tr>
<td>• Fluorescence quantum efficiency</td>
<td>Ratio between energy emitted as fluorescence versus actual chlorophyll specific absorption.</td>
</tr>
<tr>
<td>• Photosynthesis rate</td>
<td>Effective charge separation at PSII, interpreted as actual electron current.</td>
</tr>
<tr>
<td>• Vegetation stress</td>
<td>Defined as “actual photosynthesis / potential photosynthesis”</td>
</tr>
<tr>
<td>• Vegetation productivity (GPP)</td>
<td>Defined at Level-2, but recommended usage as Level-3 product</td>
</tr>
</tbody>
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<thead>
<tr>
<th>LEVEL-3 PRODUCTS</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Spatial mosaics</td>
<td>Regional / continental / global maps</td>
</tr>
<tr>
<td>• Temporal composites</td>
<td>Monthly / seasonal / annual composites</td>
</tr>
<tr>
<td>• Activation / deactivation of photosynthetic machinery</td>
<td>Determines length of the growing season</td>
</tr>
</tbody>
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<th>LEVEL-4 PRODUCTS</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Dynamical vegetation stress</td>
<td>Derived by data assimilation with dynamical vegetation model</td>
</tr>
<tr>
<td>• Gross Primary Productivity (GPP)</td>
<td>Derived by data assimilation with usage of external inputs (meteo data, land cover maps)</td>
</tr>
</tbody>
</table>
FLORIS Concept 1

Launcher: Vega

Coverage
- Global (land + major islands, -56 to 75 degree latitude, coastal zones 50 km
- Revisit time up to 19 days

S/C
- ‘Small satellite’ recurrent S/C bus
- Wet mass <1000 kg
- Power consumption <500 W

FLORIS Concept 2

P/L
- Power consumption ~120W
- Weight ~120 kg
- Data rate ~150 Mbps
FLORIS breadboards well advanced,
Detector breadboard – CCD being manufactured
1. Configuration of simulation run and selection of target location/epoch.

2. Parallel execution of S3 and FLEX geometries:
   - Tandem → delay between platforms.
   - Instrument pointing over scene.

3. Generation of synthetic TOA radiance scenes from a common uniform grid.
   - Distribution of biophysical and atmospheric parameters.
   - Execution of RTM: fluorescence, reflectance and TOA radiance.

4. Instrument & L1 processing chains for each instrument and generation of L1b data.
   - Simplified S3 Instrument+L1 chain.
   - Detailed simulation of FLORIS instrument characteristics (optics, electronics and noises).

5. L2R performs synergy between S3 and FLEX.

FLEX E2ES SCENE GENERATION

Geometry-Scene interaction:
Input: Geometry module output data:
- Acquisition time of each line (or SLSTR scan).
- Platform real orbit position at each acquisition line.
- Sensor real Line-Of-Sight (LOS) per pixel and acquisition line.
- Instrument spectral technical specs. (range, resolution, sampling interval,...).

Output:
- Latitude/longitude of each image pixels considering surface topography.
- Observation/illumination zenith/azimuth angles.
- Binary mask for shadows by topography or clouds.

Scene Definition:
1. Land-cover map over the scene grid: 1) Corine, 2) external, 3) simulated.
2. Definition of a biophysical parameters database (or reference spectra) for each land-cover class.
3. Distribution of atmospheric parameters according to location and epoch. Cloud binary mask.

\[ L_{TOA} = L_{p0} + L_{BOA} \tau_{oo} + L_{adj} \tau_{do} \]
FLEX E2ES DATA PROCESSING MODULE

- **Pre-processing**: process L1b data from FLEX and S3 to set them on a common grid, radiometrically cross-calibrated and corrected from non-uniformity effects.
- **Atmospheric correction**: characterizes atmospheric status and retrieves at-ground surface irradiance and apparent reflectance.
- **FLEX products retrieval**: retrieves fluorescence emission as well as additional biophysical parameters for a complete understanding of photosynthesis processes.
• Aerosol retrieval
• Cloud screening techniques
• Algorithm development for advanced vegetation parameters
• Cross calibration and validation of products

FLEX

Cal / Val sites

tower sites & validation networks

other satellites (Sentinels, MSG, etc.)

• Land cover maps at high spatial resolution
• Meteorological products from geostationary satellites
• Rainfall and water availability
• Soil moisture products
• Vegetation water content

Innovative optical tools for proximal sensing of ecophysiological processes (OPTIMISE)
Passive-Active FLEX sensor (PA-FLEX) sensor mounted on the top of scaffolding at the SIRTA site at Palaiseau, France
HyPlant

Module 1: Imaging spectrometer (380 – 2500 nm) with 3nm (VIS) and 10nm (SWIR) spectral resolution

Module 2: Fluorescence module (670 – 780 nm) with 0.25nm (FWHM) and 0.11nm (SSI)

DUAL (VNIR-SWIR)

FLUOR
Chlorophyll fluorescence map from HyPlant
Current products:
- different SIF wavelengths
- different overpass times
- no single measurements, but spatial and temporal averages

**GOSAT** (Greenhouse gases Observing SATellite)
Local sun time at equator crossing around 12:45 – 13:15 PM.

**GOME-2**
Global Ozone Monitoring Experiment 2 (GOME-2/MetOp)
spatial resolution of 80 km×40 km, swath width of 1920 km
equator crossing time of 09:30 LT
**OCO-2**
(launched in 2014)

O$_2$ A-band
0.757–0.775 μm
FWHM = 0.042 nm

Fraunhofer lines at 758.6 and 758.8 nm and 770.1 nm

Single-measurement precision of about 0.3–0.5 Wm$^{-2}$sr$^{-1}$ μm$^{-1}$ at 755 nm

Ground-pixel size: 1.3 × 2.25 km$^2$

Local overpass time: 1:30 p.m.

Frankenberg et al., *Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2*, RSE, 2014
ESA Sentinel-5 Precursor
TROPOMI
(to be launched in 2015)

LTAN: 13:30 h
Fly in formation with U.S. NPP mission
Spectral range: 675–775 nm
Spectral resolution: 0.5 nm
Spectral sampling: 0.1 nm

CONCLUDING REMARKS

- Plant photosynthesis is a key component of the global carbon cycle: fluorescence provides actual (not just potential) photosynthesis rates to constraint models of CO₂ assimilation (GPP)

- Great potential for applications in agriculture / food production

- New field instruments / airborne demonstrator (HyPlant) theoretical models (leaf/canopy - ecosystem - global), end-to-end mission simulator, ground validation networks

- Many on-going activities involving a large science community, Welcome to join!

FLEX Earth Explorer, tandem mission with Sentinel-3, Phase A / B1, Final decisión in 2015, launch for 2020+…
PERSPECTIVES:

- While FLEX data become available, on-going activities using GOSAT, GOME-2, and soon OCO-2, S5P

- Synergy with SMAP applications (vegetation stress, *actual* versus *potential* photosynthesis and coupling to evapotranspiration, Net Ecosystem Carbon Exchange)
Thank you for your attention!

Questions?