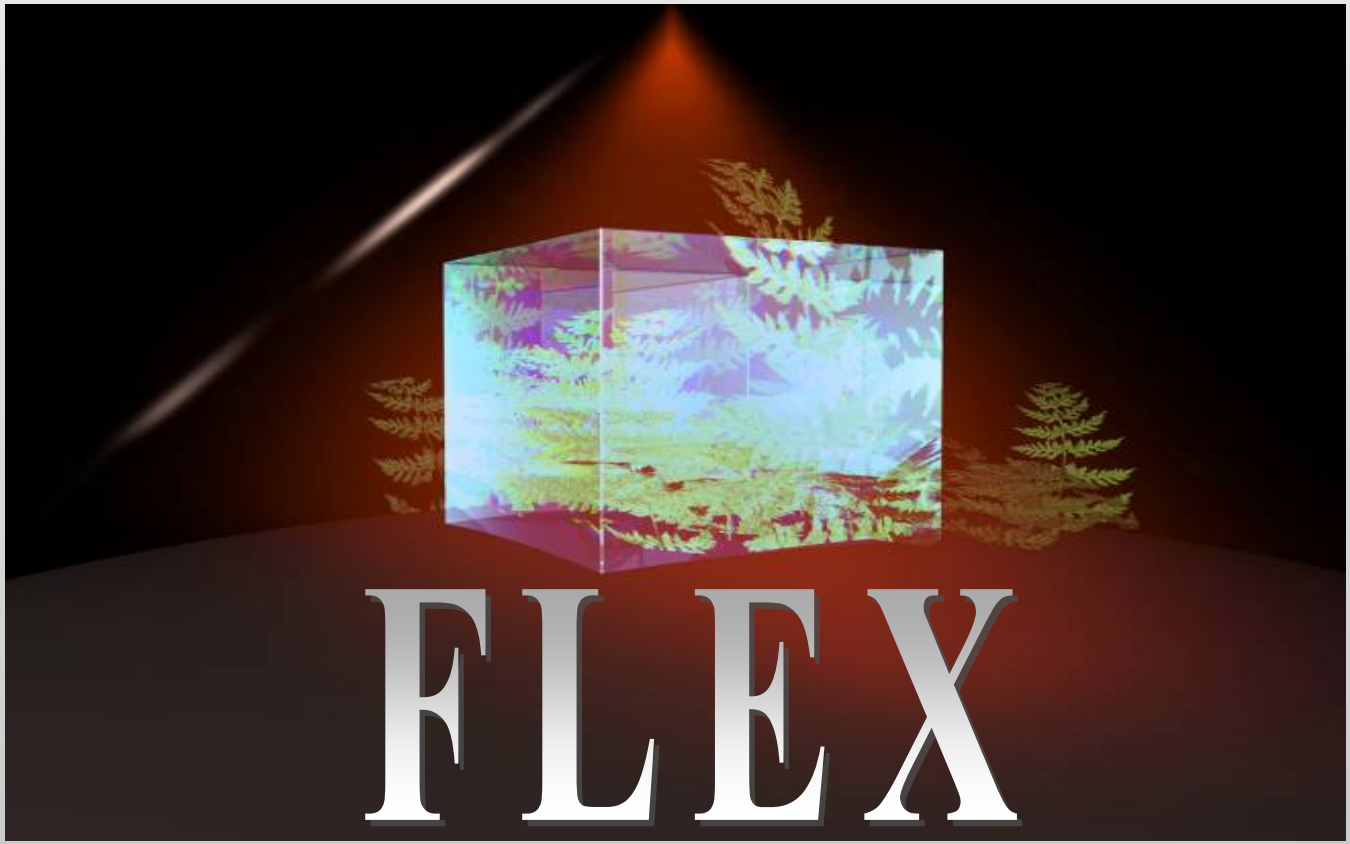


NCEO/CEOI-ST Joint Science Conference. University of Sheffield, June 25, 2014

FLEX Mission: Measuring Fluorescence from Space

Luis Alonso, Jose Moreno

LEO Group, LPI, University of Valencia (Spain)

and **the FLEX Team**

ESA's living planet programme

Explorer 8 mission candidates under study since 2012

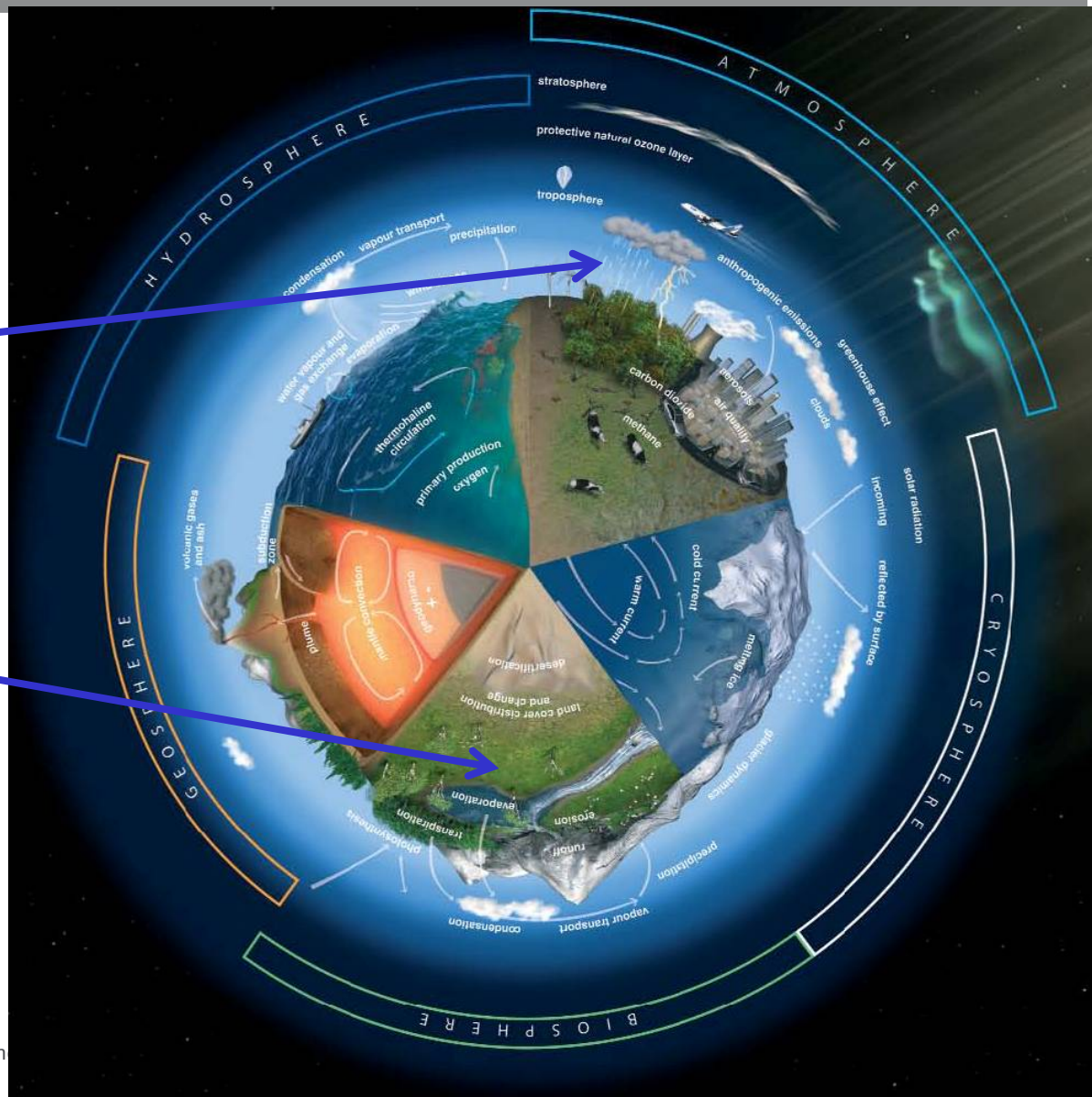
- **CarbonSat**

  Monitoring CO_2 content of the atmosphere (sources, sinks, hot spots)

- **FLEX**

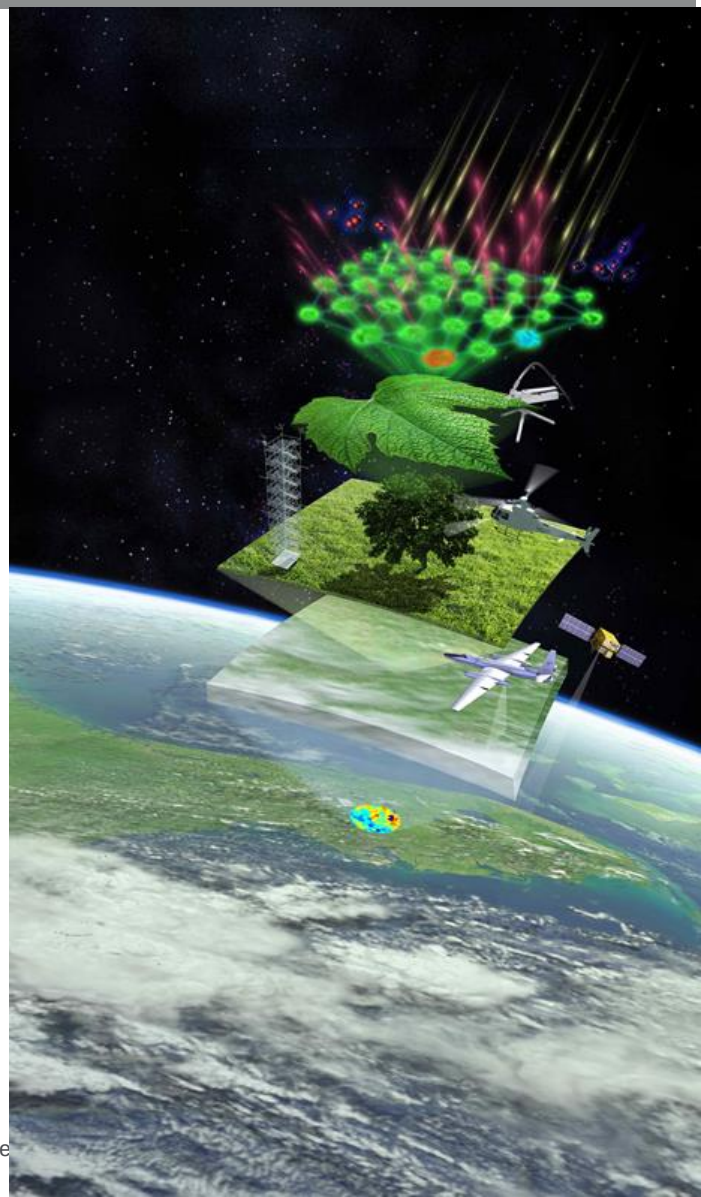
  FLuorescence **EX**plorer

  Monitoring vegetation fluorescence – the breath of the Earth



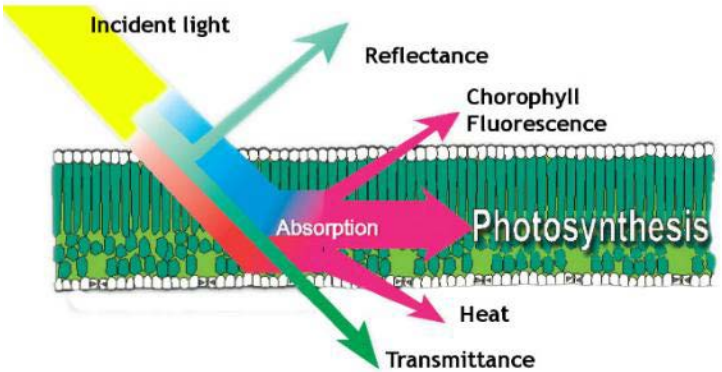
FLEX – mission objectives

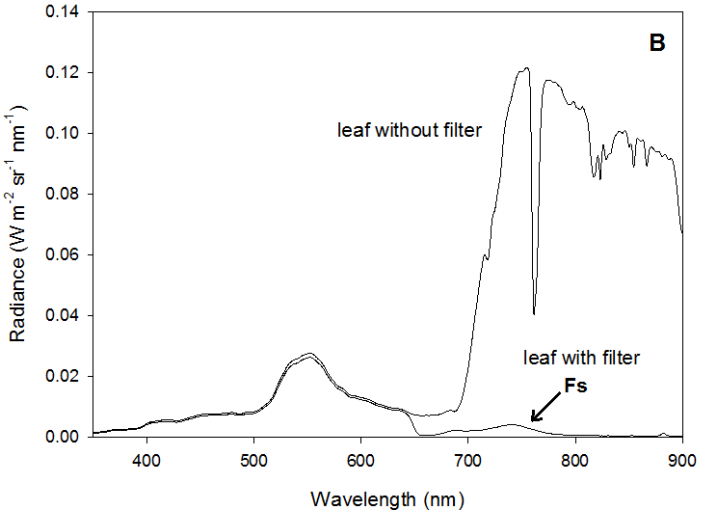
- **Primary scientific objectives**
  - Accurate global mapping of vegetation fluorescence (emission spectrum)
  - Estimate the actual global photosynthetic activity via related light absorption and emission
  - Vegetation health status / stress identification
  - Enhance knowledge on anthropogenic impacts associated to land use changes
- **Secondary scientific objectives**
  - Understanding of the terrestrial component of the CO_2 cycle
  - Improvement of GPP modelling



What is fluorescence?

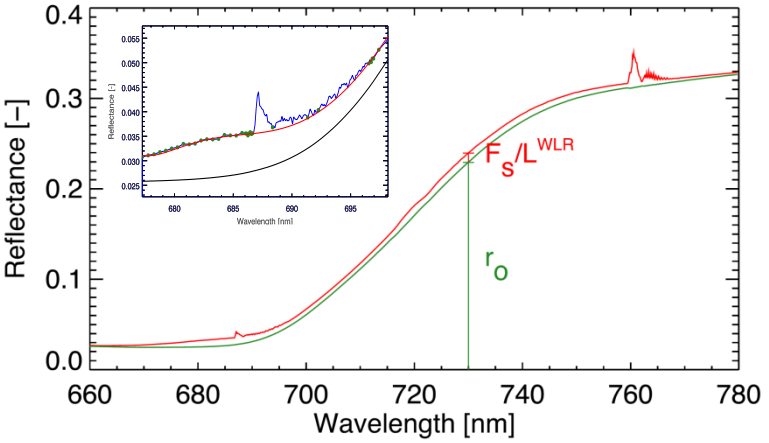
Incident solar light can be either reflected, **absorbed** or transmitted by a leaf.





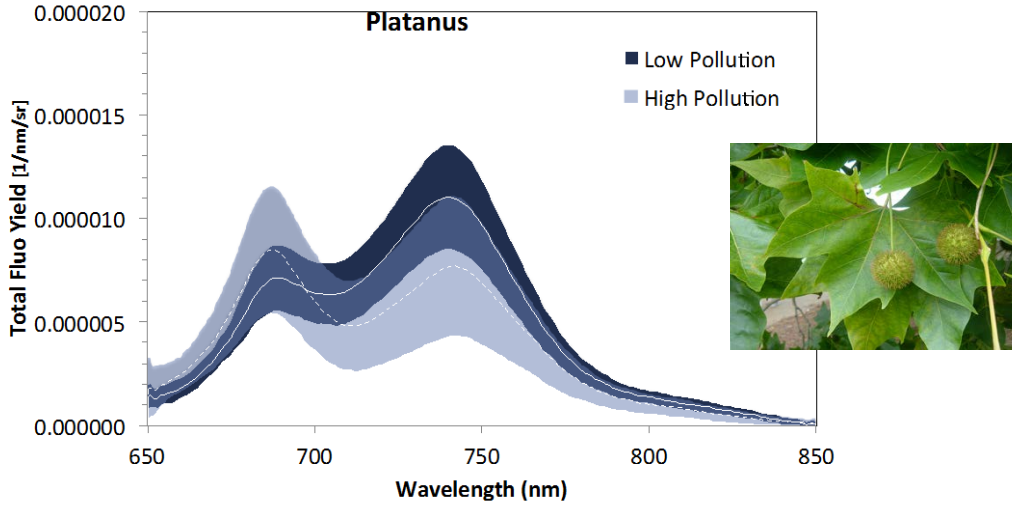
The absorbed light photons can be used for **photosynthesis** or can be dissipated.

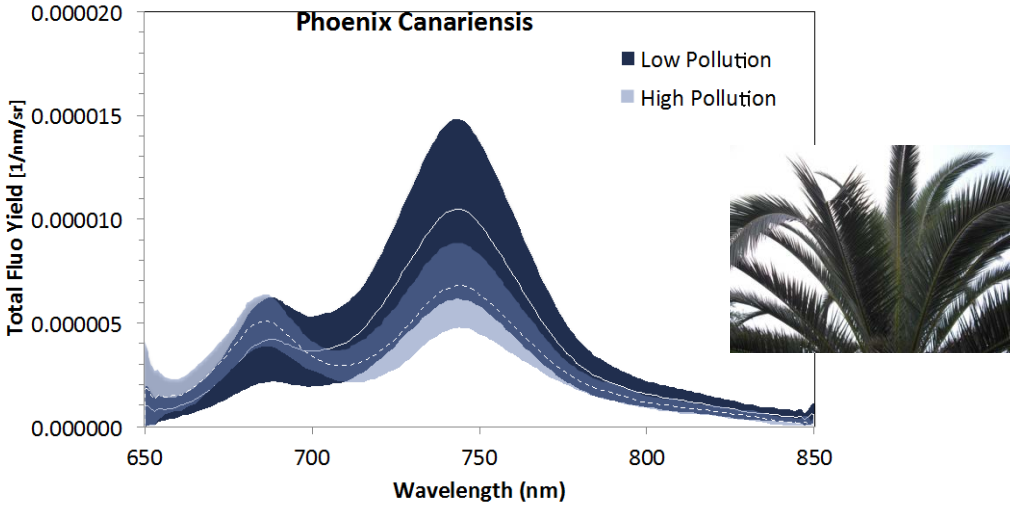
Dissipation can occur as Non-Photochemical Quenching (e.g. heat) or emitted as **fluorescence** (SIF) photons.



Dynamical fluorescence emission

Fluorescence emission spectra from two different species exposed at two levels of air pollution





- Fluorescence is influenced by
  - Environment
  - Plant structure
  - Stress
- Two peaks of the fluorescence emission are highly variable
- Difference in shape between pollution levels, but also between species

Ref: Van Wittenberghe et al. **Upward and downward solar-induced chlorophyll fluorescence yield indices of four tree species as indicators of traffic pollution in Valencia**

Environ Pollut, Vol 173, 2013

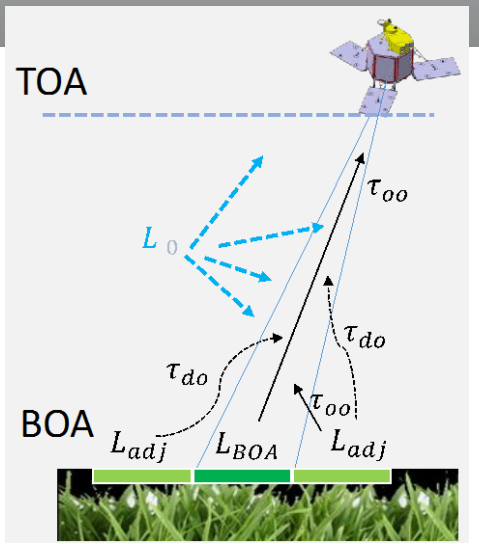
http://dx.doi.org/10.1016/j.envpol.2012.10.003.

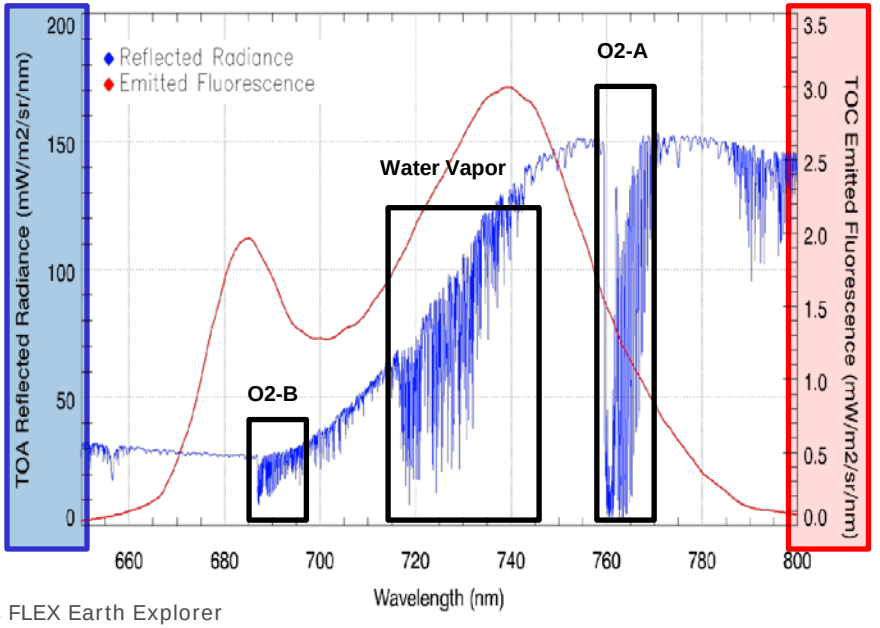
Measuring a faint signal F_{SIF}

- L_{TOA}
  - Light seen at the **top of the atmosphere** (instrument input radiance)

$$L_{TOA} = L_0 + \frac{\left[\frac{(E_{dir}\cdot\cos(\vartheta_{ill}) + E_{diff})\cdot\rho_{Surf}}{\pi} + F_{SIF}\right]\cdot\tau_{atmosphere}}{1 - S_{albedo}\cdot\rho_{Surf}}$$

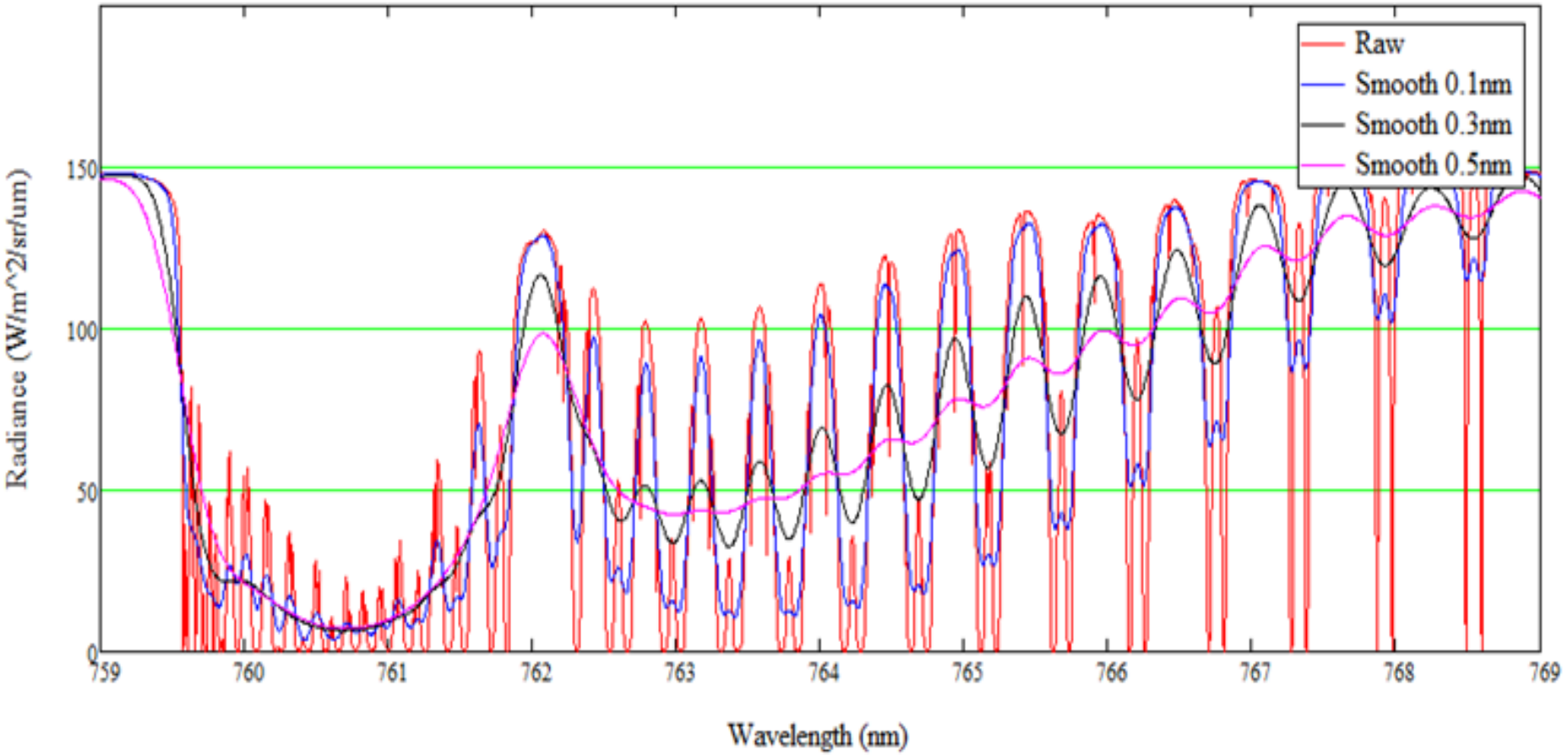
- L_0
  - Atmospheric path radiance
- $E_{dir/diff}$
  - Diffuse and directly flux reflected by Earth and transmitted through the atmosphere
- ρ_{Surf}
  - Signal is modulated by the Earth surface reflectance
- $\tau_{atmosphere}$
  - Sensitivity to atmospheric changes
- S_{albedo}
  - Atmospheric pherical albedo



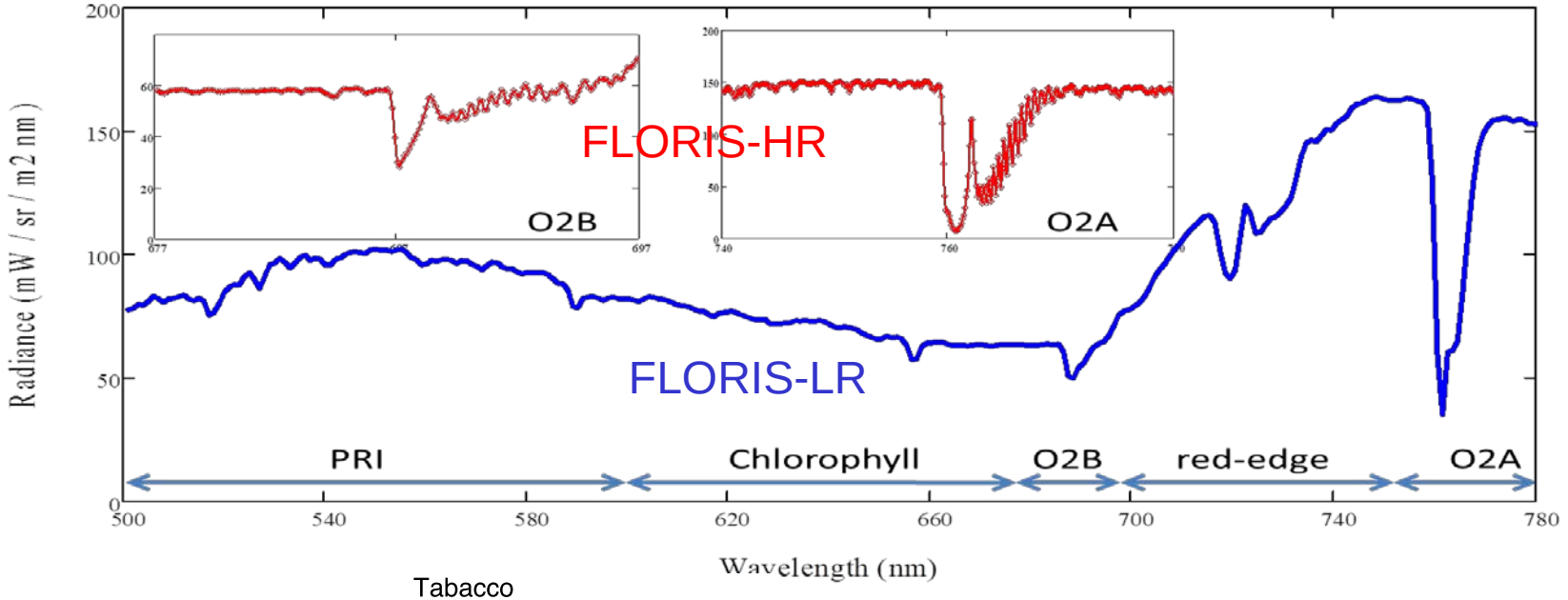


Spectral resolution

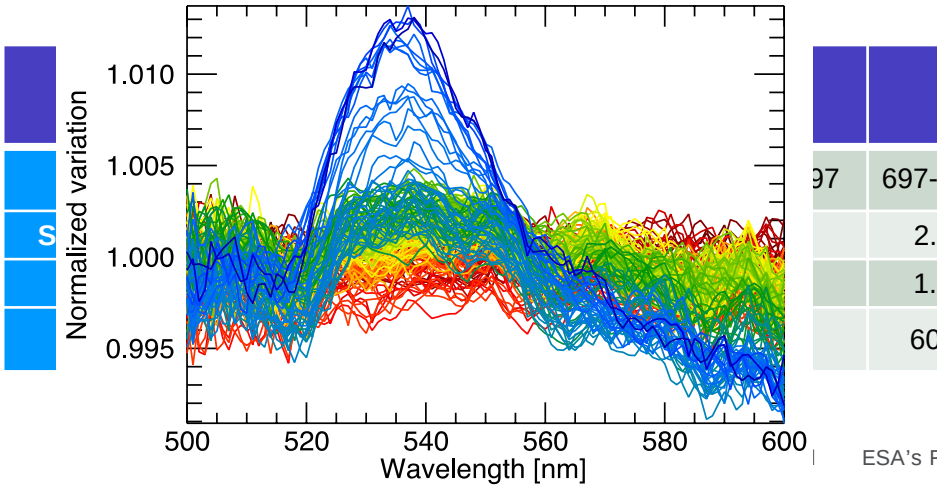
Finer resolution: lower SNR
Coarser resolution: loss of spectral features

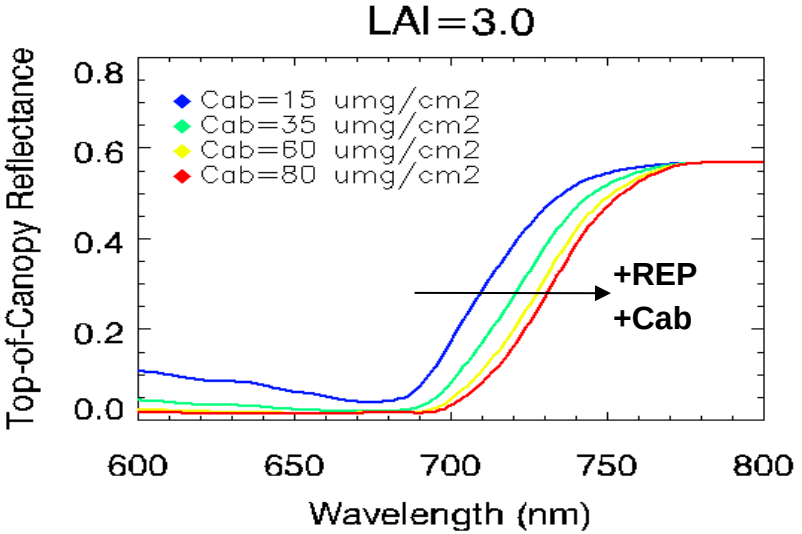


FLORIS band configuration



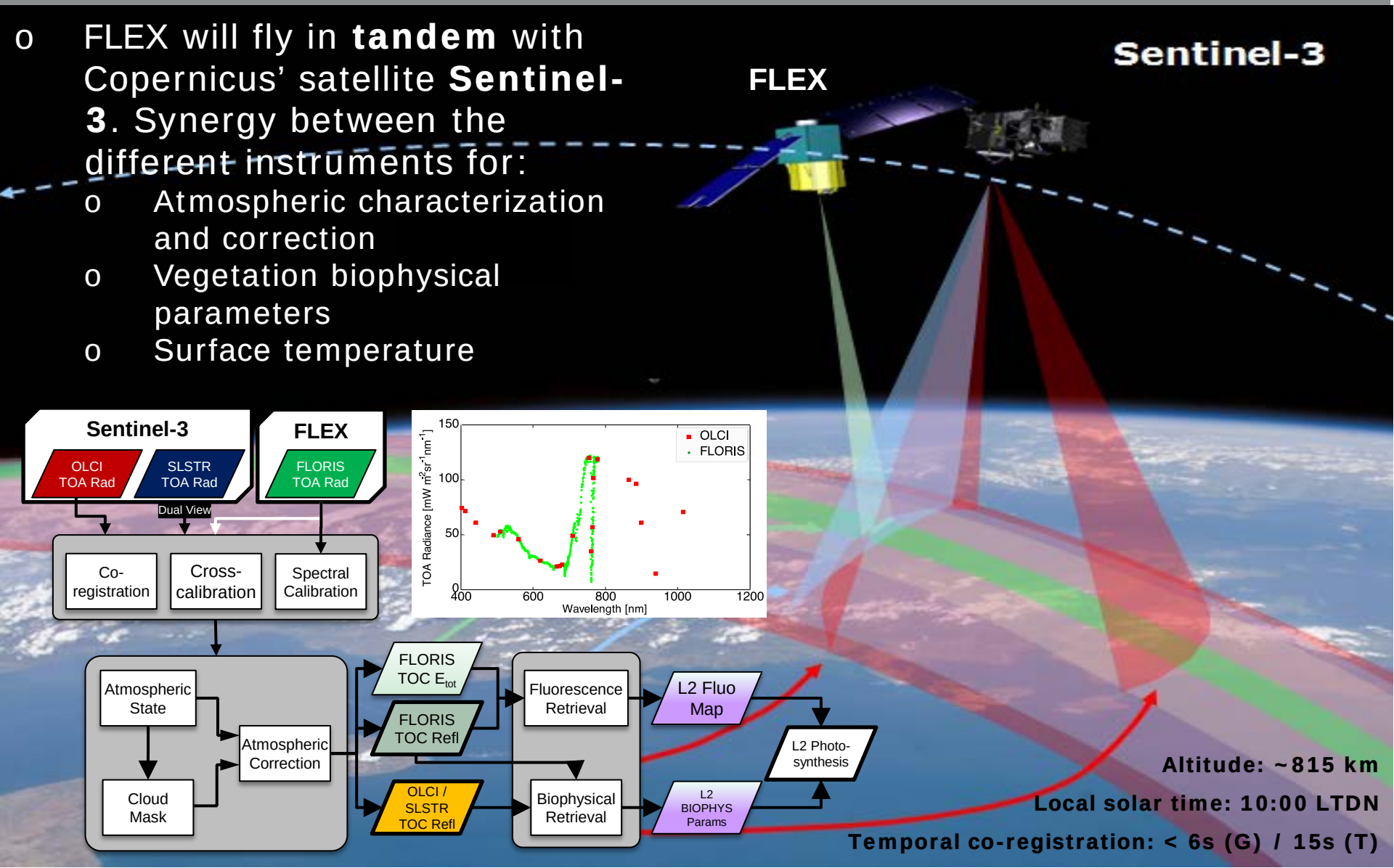
Tabacco



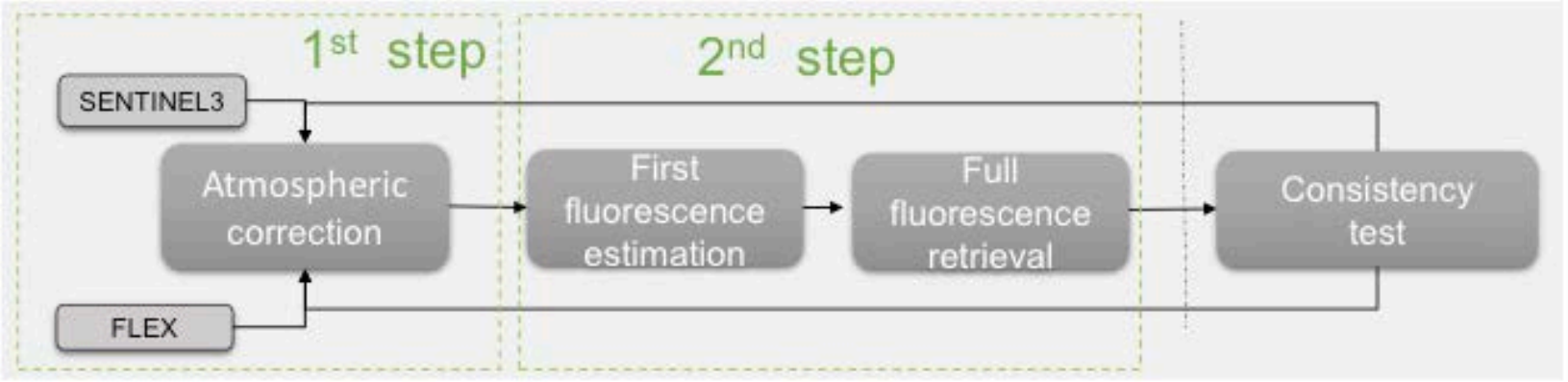


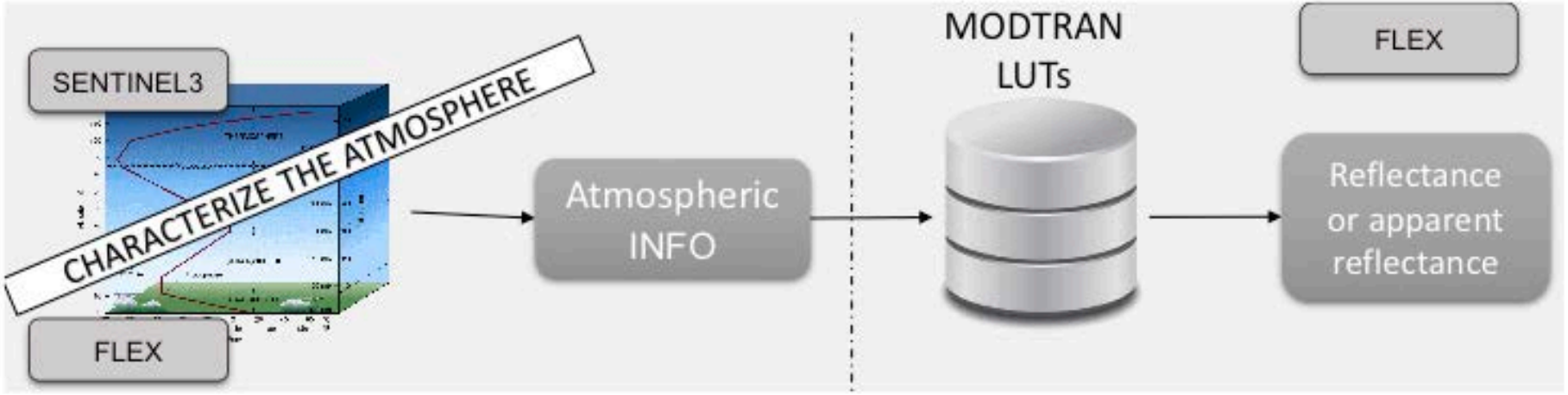
FLEX / S3 tandem concept

- FLEX will fly in **tandem** with Copernicus' satellite **Sentinel-3**. Synergy between the different instruments for:
  - Atmospheric characterization and correction
  - Vegetation biophysical parameters
  - Surface temperature

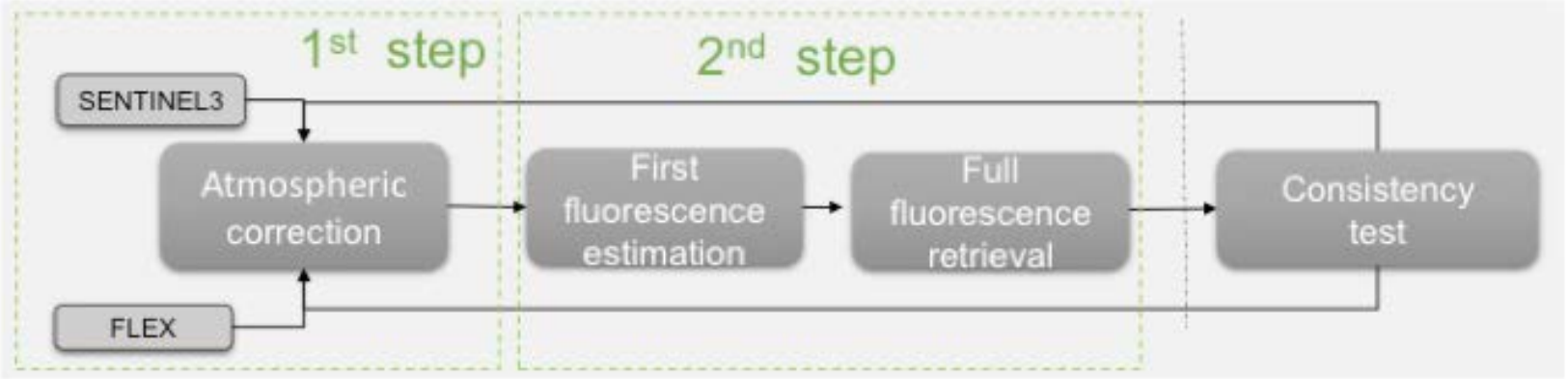


Two-Step full-spectrum fluorescence retrieval





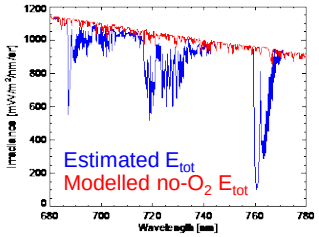
Two-Step full-spectrum fluorescence retrieval

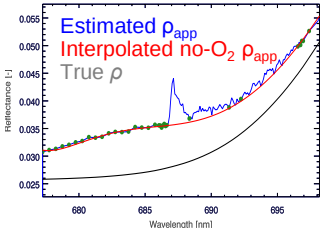


Initial SIF estimates at O_2 absorptions

Requires (from Atmospheric Correction):

- TOC Total Irradiance $\mathbf{E_{tot}}$ and $\hat{\mathbf{E}}_{\mathbf{tot}}$ (modelled with **no O_2**)
- TOC Apparent Reflectance $\boldsymbol{\rho}_{\mathbf{app}}$ (includes SIF)



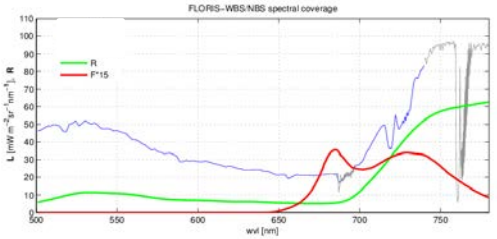


$$F_s = (\rho_{app} - \hat{\rho}_{app}) \cdot \frac{E_{tot} \cdot \hat{E}_{tot}}{\pi(E_{tot} - \hat{E}_{tot})}$$

No assumptions about true reflectance $\boldsymbol{\rho}$
(large source of error in other retrieval method)

SIF_{687} & SIF_{760}
ρ_{687} , ρ_{760}

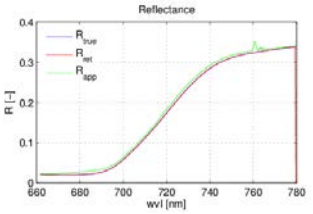
Full Spectrum Retrieval

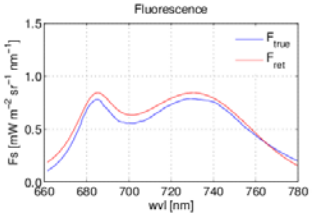


Fluorescence
True Reflectance

n-parameters to be fitted
initialization is required

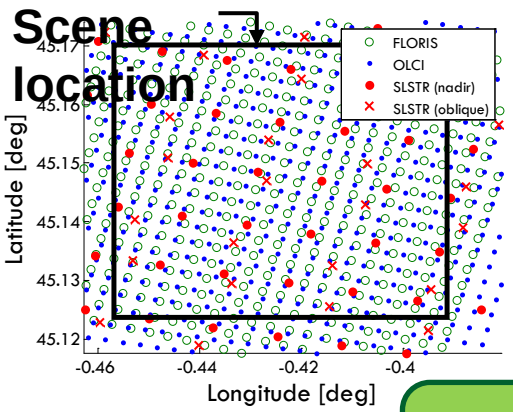
$$min \sum_{\lambda} (L_{TOC}(\lambda) - F(\lambda) - \rho(\lambda)E_{tot}(\lambda))^2$$





ρ **errors** <1% and SIF **errors** <10%

End-to-End Mission Simulator



FLORIS Instrument Module

SEN3 Instrument Module

Scene Generator

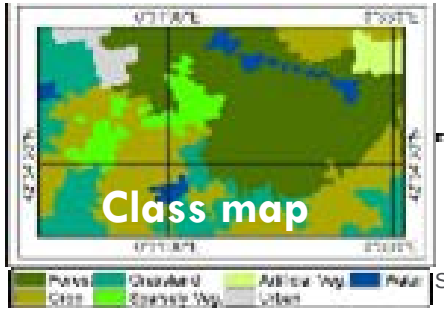
Level-1 Processing

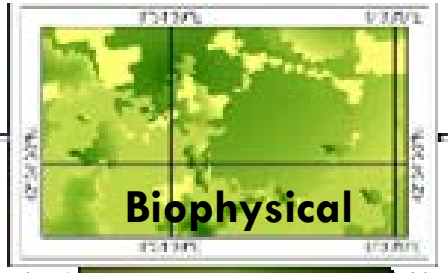
Performance Module

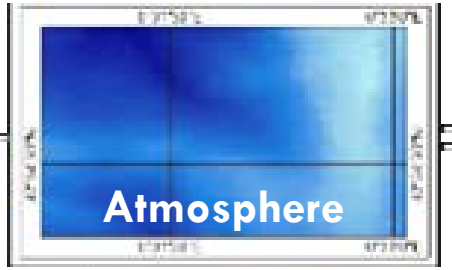
SEN3 Geometry Module

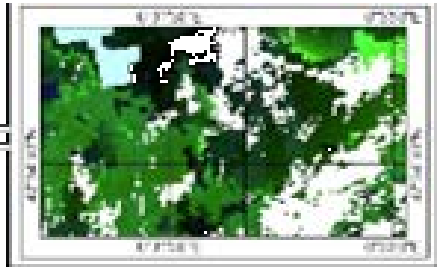
FLORIS Geometry Module

Level-2 Retrieval



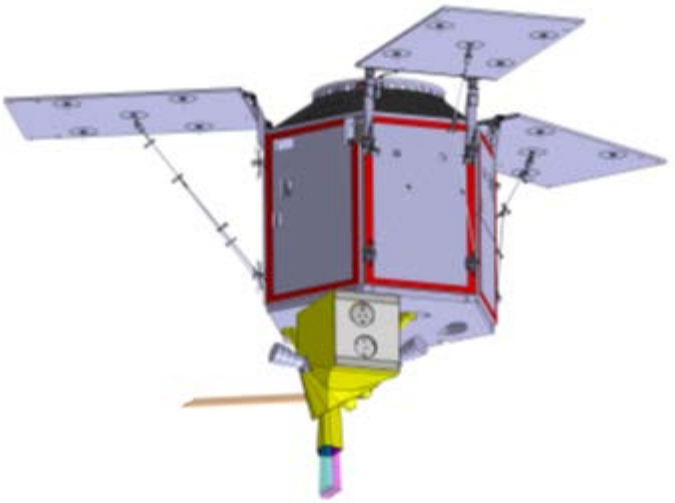


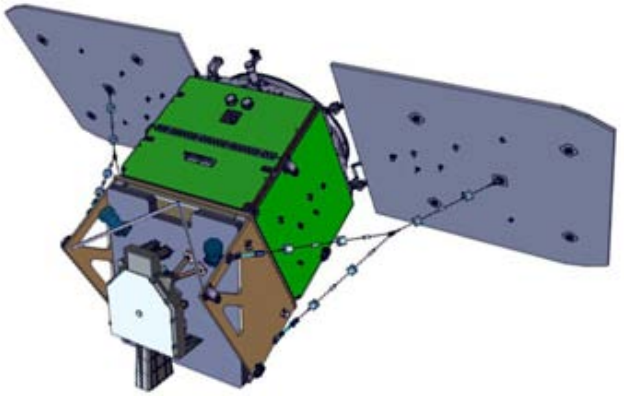




Spacecraft and payload accommodation

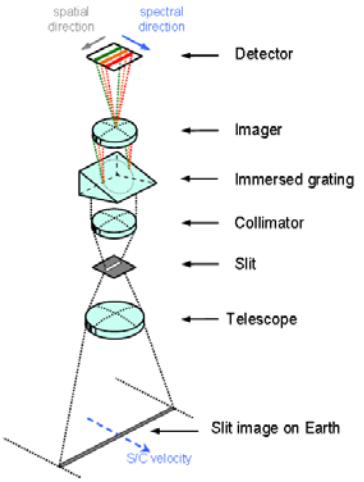
- S/C
  - ‘Small satellite’ – recurrent S/C bus
  - Wet mass <1000 kg
  - Power consumption <500 W
- P/L
  - Power consumption ~120W
  - Weight ~120 kg
  - Data rate ~150 Mbps
- Launcher
  - Vega
- Coverage
  - Global (land + major islands, -56 to 75 degree latitude, coastal zones 50 km
  - Revisit time up to 19 days



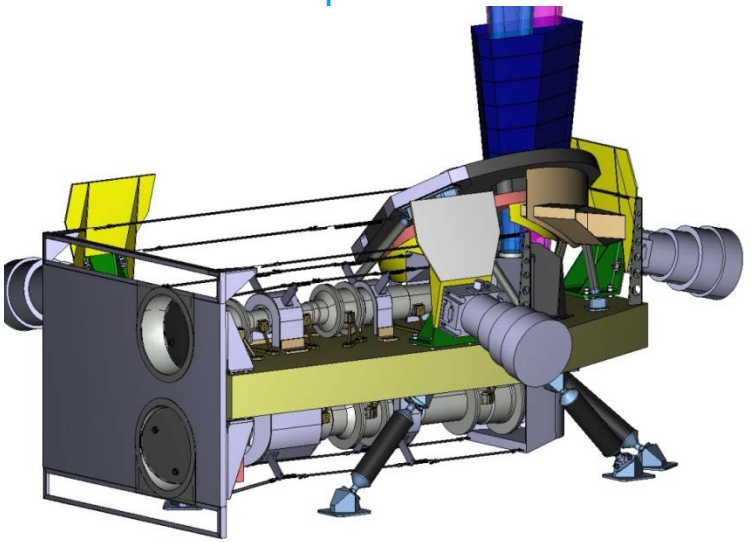


Instrument configurations

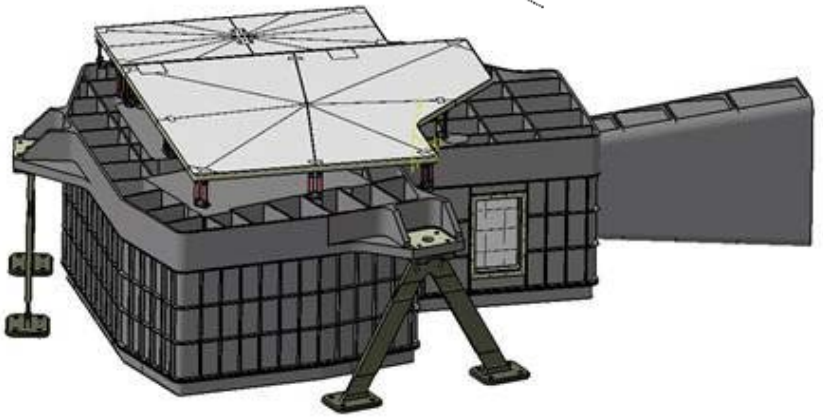
- Phase B1 running
  - Instrument concepts frozen
  - Spectrometer refractive or catadioptric
  - Reflective or transmissive grating
  - One or two telescopes or spectrometers



FLORIS Concept 1



FLORIS Concept 2



AIRBUS

SURREY SATELLITE TECHNOLOGY LTD

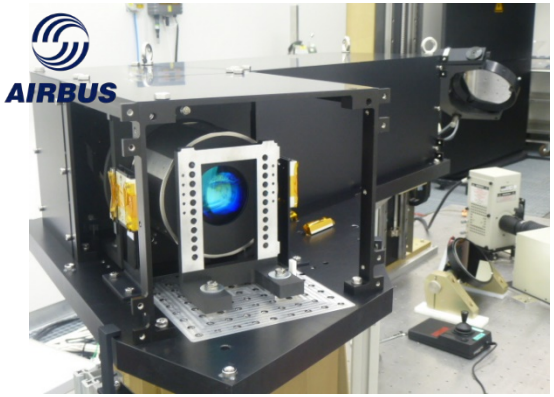
ThalesAlenia Space

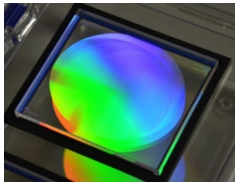
Selex ES A Finmeccanica Company

FLORIS breadboards: Objectives

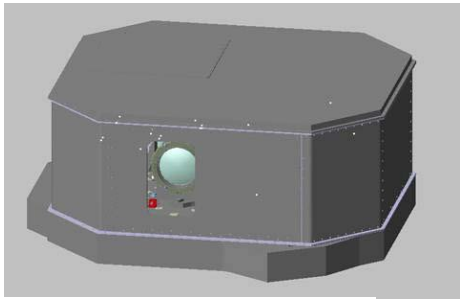
- Demonstration of the **manufacturability** of the flight representative optical elements (lenses, mirrors, coatings, filters, gratings, slits) according to the specifications
- Demonstration of the **assembly accuracy** of the optical elements according to the accuracies as defined in the tolerance analysis
- Verification of the **alignment** concept, contamination budget, general accuracies and adequacy of the measurement signals
- Demonstration/measurement of **the imaging & spectral performance** at focal plane
- Tolerance of the instrument to thermal cycling

FLORIS Concept 1





FLORIS Concept 2



Summary

- FLEX will provide global mapping of terrestrial vegetation fluorescence at moderate spatial resolution
- Retrieval and measurement configuration will make use of full information content provided by FLORIS and Sentinel-3
- End-to-End Simulator with detailed implementation of every aspect of the mission, allowing to test performance of each module
- Accuracy of fluorescence measurement expected to be 10% (as demonstrated by campaigns and by simulations)
- FLORIS breadboards in construction and under testing
- Phases A/B1 of FLEX to be completed ~03/2015

Thanks to the FLEX Mission Advisory Group

- Yves Goulas
- Andreas Huth
- Gina Mohammed
- Franco Miglietta
- Jose Moreno
- Ladislav Nedbal
- Wouter Verhoef
- Uwe Rascher
- Betsy Middleton (observer)

Questions?

Would you like to know more?

www.esa.int

FLEX / PARCS

http://ipl.uv.es/flex-parcs/

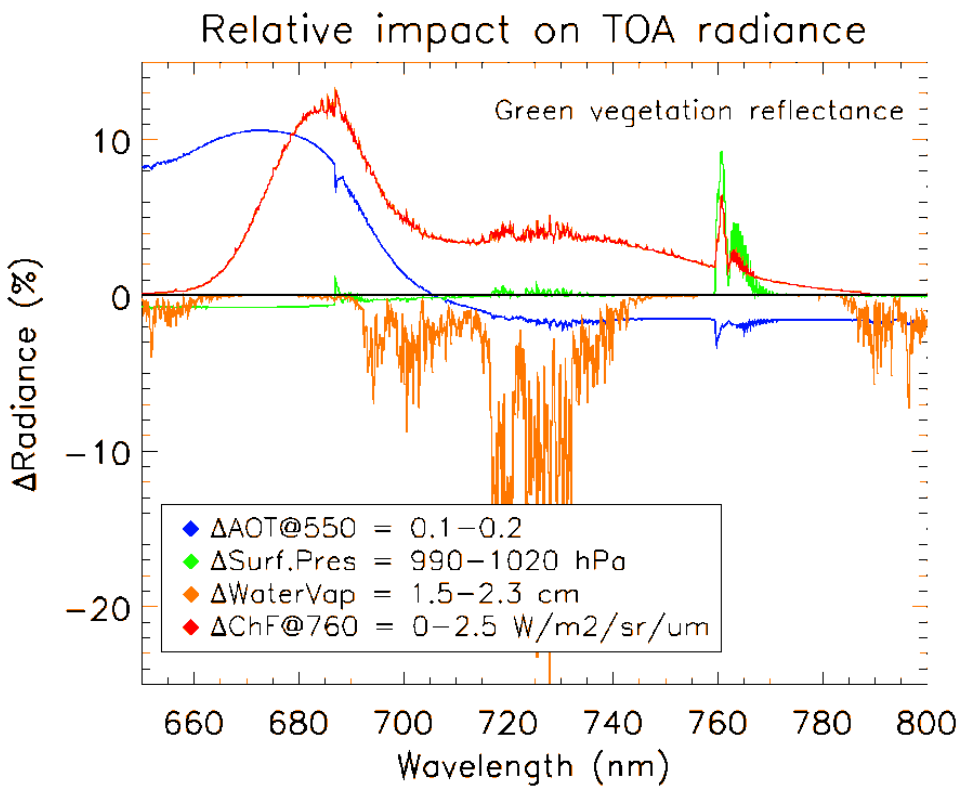
FLEX / PHOTOSYN

http://www.flex-photosyn.ca/

System / instrument requirements

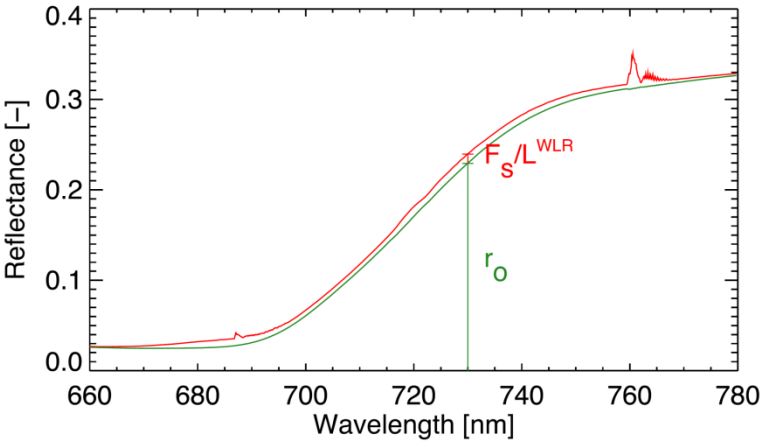
Requirement	Specification	Comment
Instrument type	Pushbroom Imaging Spectrometer	
Mission lifetime	3.5 years (T) / 5 years (G)	
Data latency	5 h (T) / 24 h (G)	
Coverage	-56º < latitude < 75º	Sun Zenith Angle < 75º Observation Zenith Angle < 15º Land area including coastal zones (50km)
Pitch angle	<5º	Preferably Nadir pointing
Swath width	150 km	Enables global coverage
Spatial Sampling Distance	300 m	@ Nadir
Integrated energy	>70% over an area of 1.1 SSD	
Spectral band coverage	500 nm – 780 nm	
Spectral Resolution and Sampling	0.3 nm / 0.1 nm (HR) 2 nm / 0.65 nm (LR)	
Signal to noise ratio	> 200 at 761 nm	
Spectral stability	1nm 10 pm for FLORIS-HR 0.1 SSI nm for FLORIS-LR	Over mission lifetime During observational time of 1 orbit
Straylight sensitivity	Specified for black & white scene	To maintain radiometric requirement
Spectral co-registration	<0.1 SSD	Smile
Spatial co-registration	<0.1 SSD	Keystone
Knowledge of ISRF	Better than 1%	
Absolute radiometric accuracy	2% (G) 3% (T)	Excluding uncertainty of Sun radiance
Relative accuracy	1%	Spectral and spatial
Polarisation sensitivity	2% (FLORIS-LR) 1% (FLORIS-HR)	
Temporal co-registration	6s (G) / 15s (T)	To avoid significant cloud movements
Inter-channel temporal co-registration	<2s	
Geo-location accuracy	0.3 SSD (with ground control points	

Disentangling fluorescence from TOA radiance



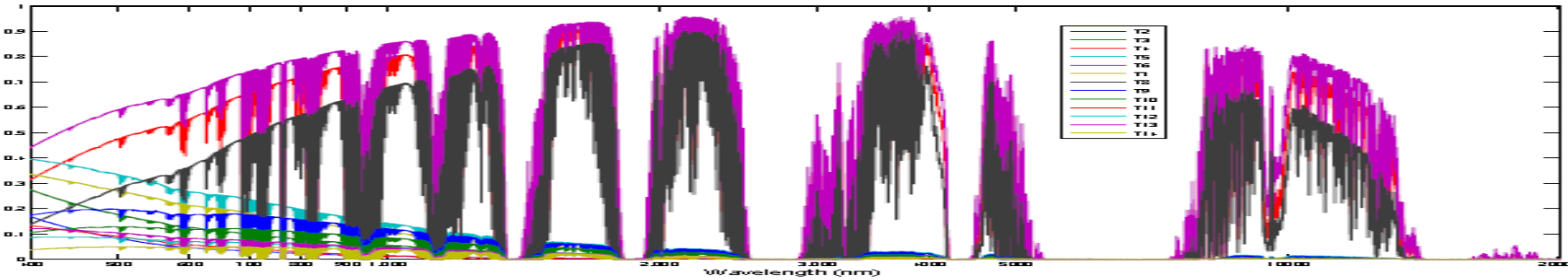
- Sensitivity analysis performed to establish spectral ranges and spectral resolutions
- Competing effects
  - Atmospheric state variables
    - Aerosol Optical Thickness (AOT)
    - Aerosol height and model
    - Surface Pressure
    - Water Vapor
  - Vegetation reflectance
- Disentanglement requires
  - High resolution for Oxygen B and Oxygen A
  - Medium resolution red-edge
  - Medium resolution elsewhere

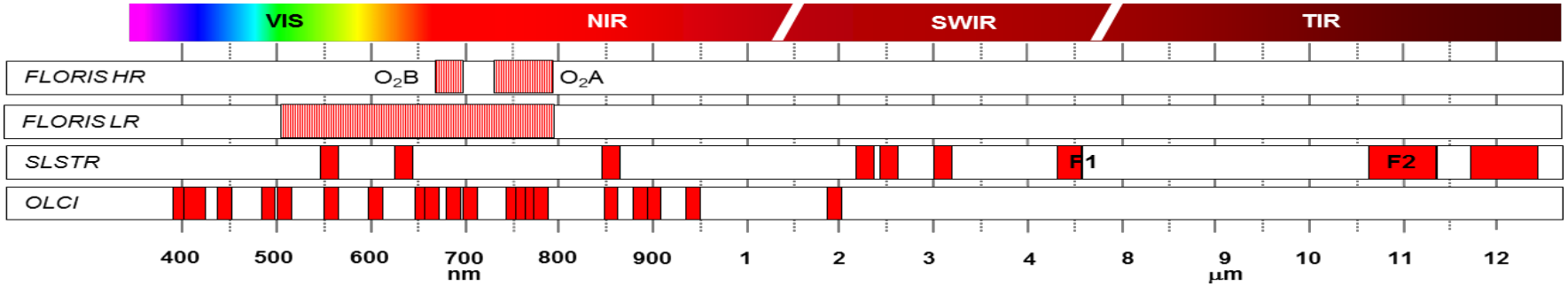
Retrieval evolution



- Promising method for fluorescence retrieval:
  - independent decoupling of reflectance/fluorescence effects and atmospheric/topographic effects
  - Apparent reflectance
    - $r_o' = r_o + F_s / L^{WLR}$
    - true reflectance derived by elimination of the Oxygen absorption (no free fitting parameter anymore)
    - Incoming radiance L^{WLR} from radiative transfer programs
- Other retrieval methods, where reflectance is a free model parameter, are currently under investigation
- Reflectance expected to be a smooth function of wavelength
- Retrieval accuracy expected to be about 10% for both
  - relative accuracy at the two emission peaks
  - total integral of the fluorescence radiance across the whole spectral range (total energy emission)

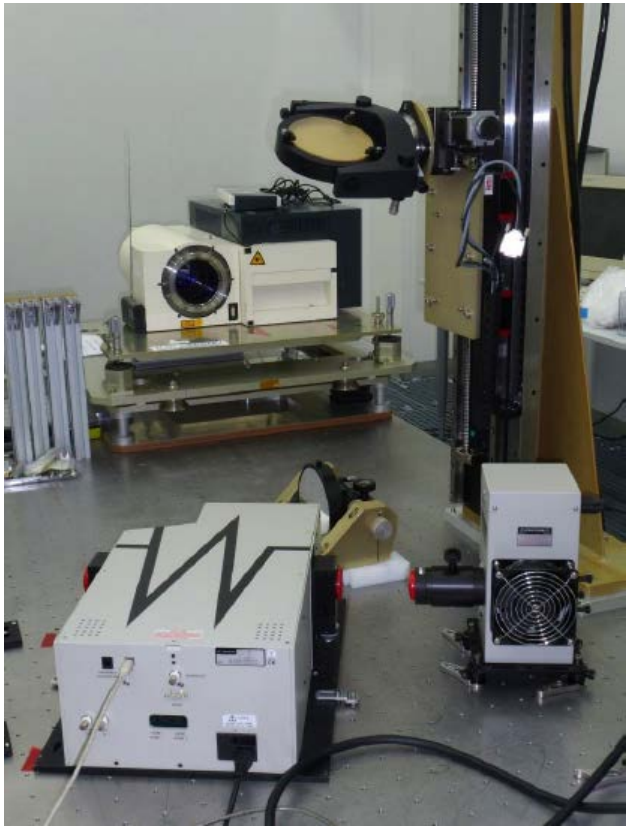
FLORIS / S-3 band configurations

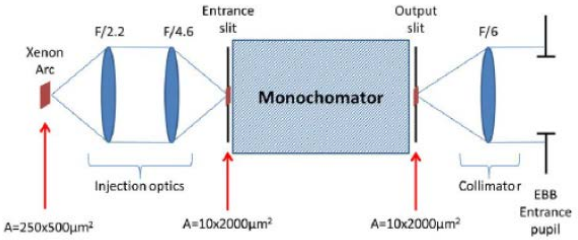


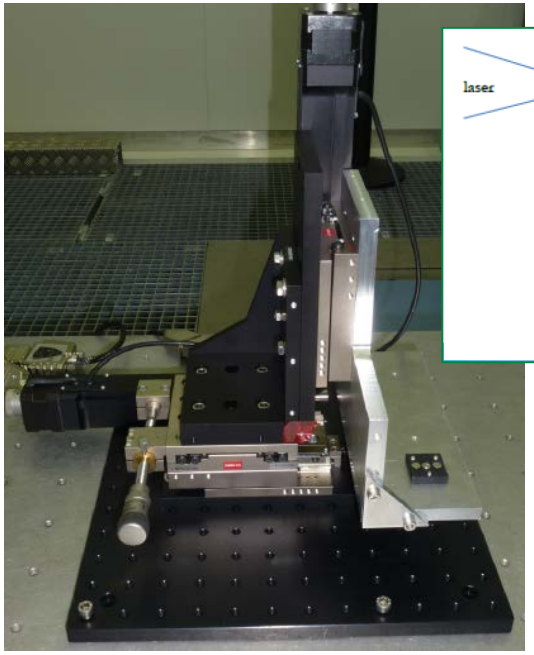


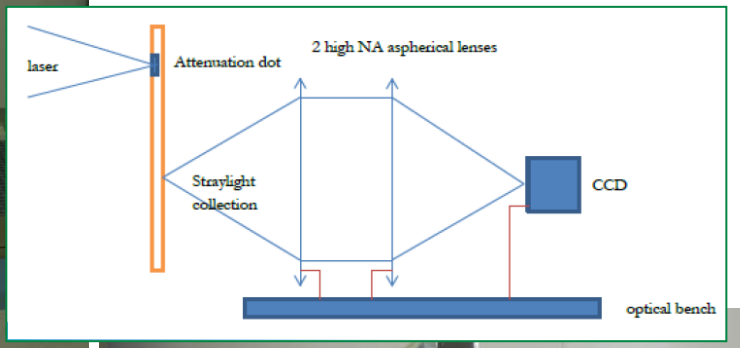
- FLORIS (**300 m** SSD)
  - **Fluorescence**
  - PRI
  - Atmospheric correction
  - Apparent reflectance
- S-3 OLCI (300 m SSD)
  - **Camera 4 – 250 km swath**
  - O1 to O4 (400 to 490 nm)
    - **Aerosols**
    - Chlorophyll
    - Reflectance
  - O9 to O16 (510 to 779 nm)
    - Cross calibration
  - **Context information**
- SLSTR (500m – 1 km SSD)
  - VIS S1 to S3 and F1/F2
    - **Aerosols**
  - SWIR S4 to S6
    - Reflectance
  - TIR S7 to S9
    - Temperature
    - **Clouds** (water vapour)

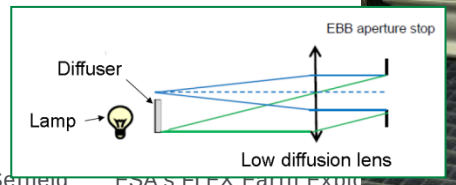
Breadboard 1: system test equipment









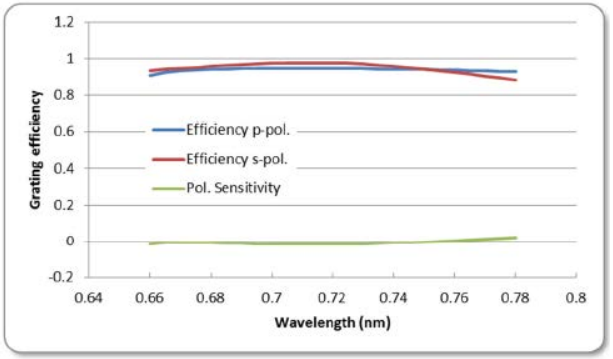


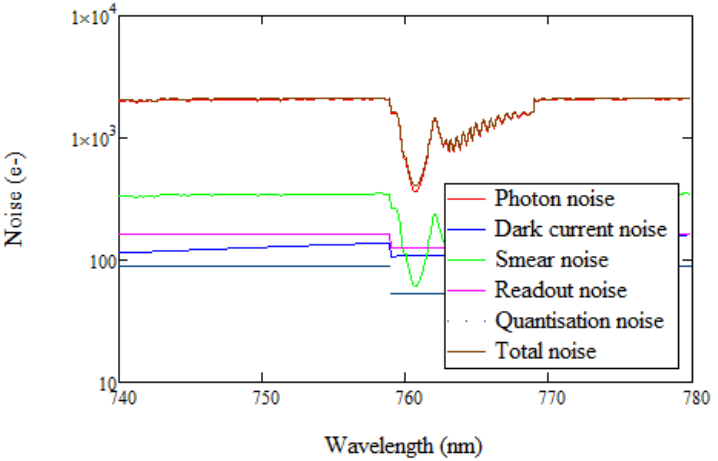
Radiometric performance

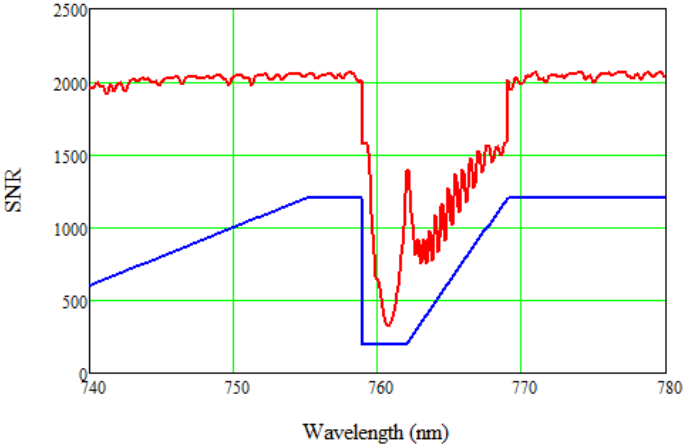
- High signal to noise (SNR) required → large aperture (~80 mm)
- Due to relatively large aperture, the system is photon noise limited
- Other contributors have been minimised

$$SNR_{Sample} = \frac{N_{ph}(\lambda) \cdot b_{ana} \cdot b_{dig}}{\sqrt{(N_{ph}(\lambda) + N_{dark} + N_{smear}) \cdot b_{ana} \cdot b_{dig} + (N^2_{readout} + N^2_{quant}) \cdot b_{dig}}}$$

- Grating efficiency is essential

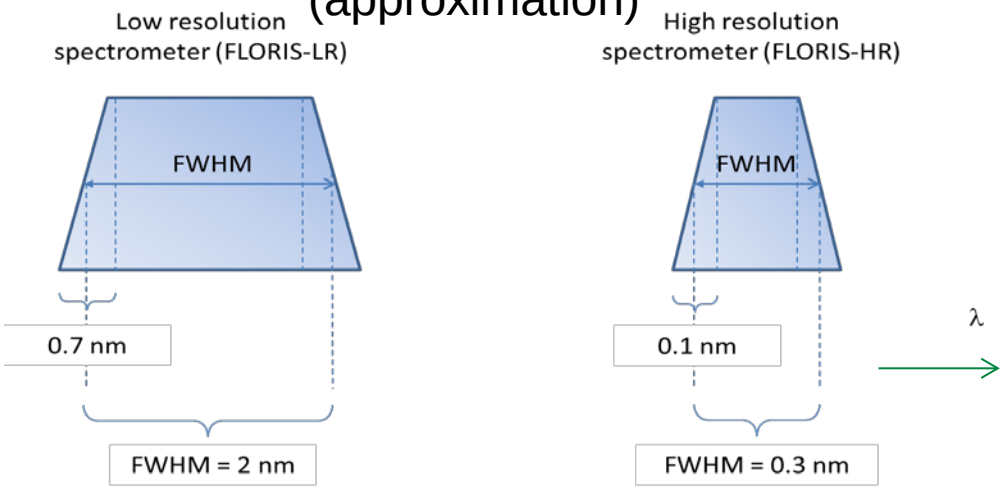




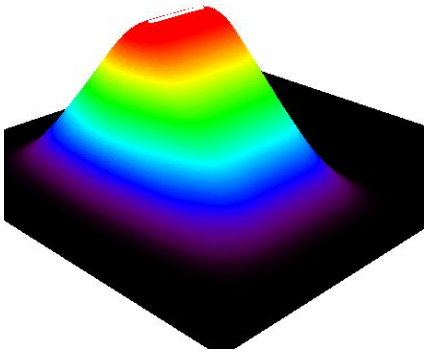


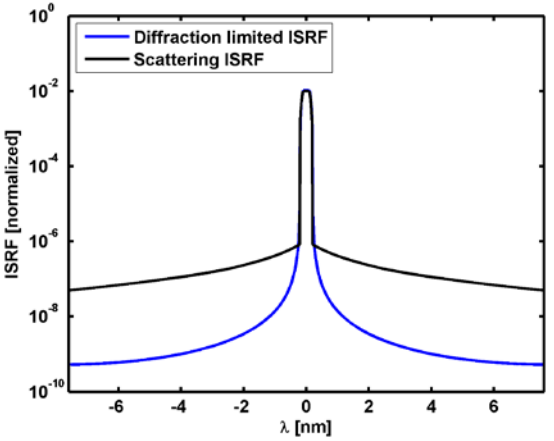
Instrument response function

Spectral (approximation)



Spatial



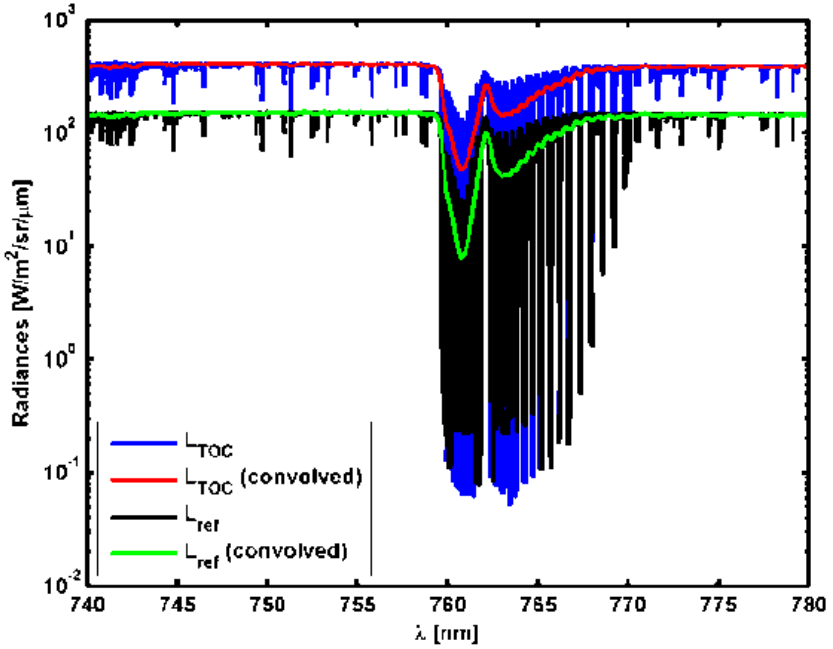


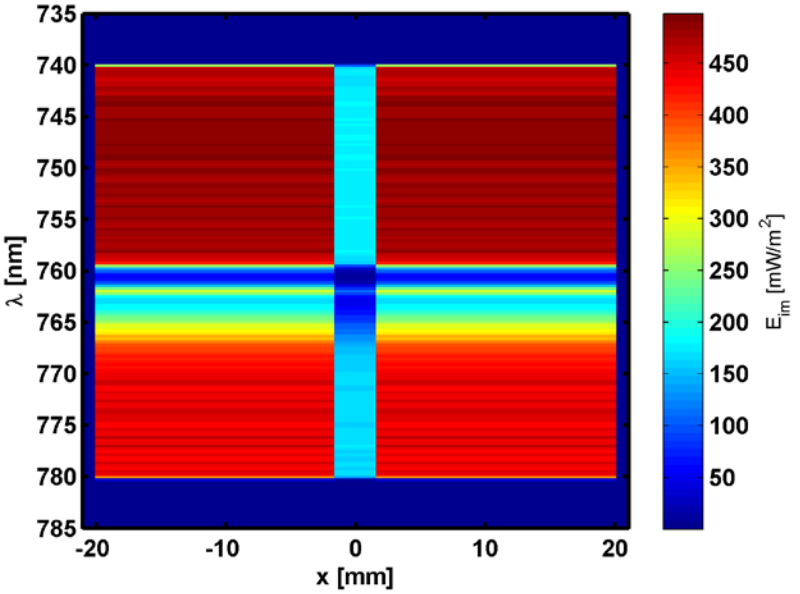
- Due to scattering of the optics and optical elements, the IRF is more sophisticated
- Finite response at larger angles

Straylight behavior – test case

- Test of straylight sensitivity on black & white scene (L_{ref} & L_{TOC})

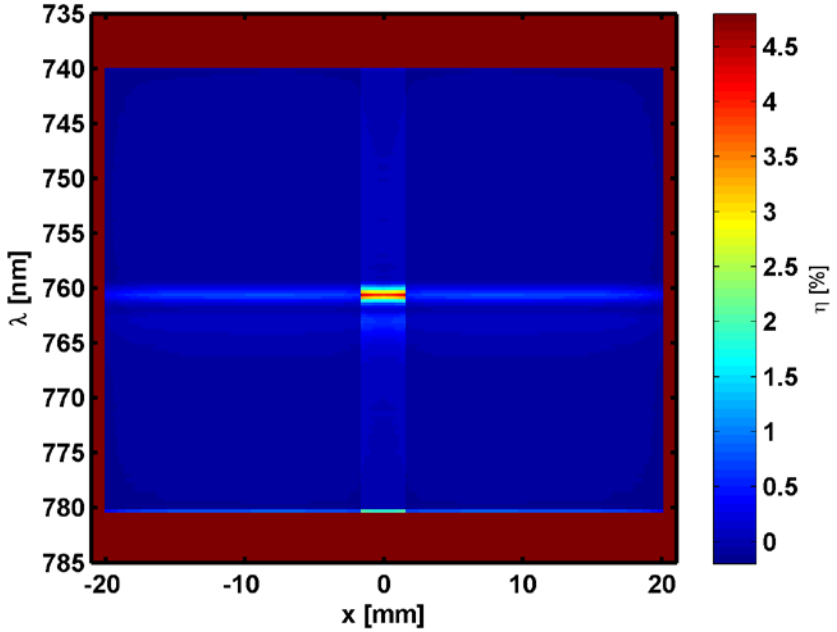
Slit

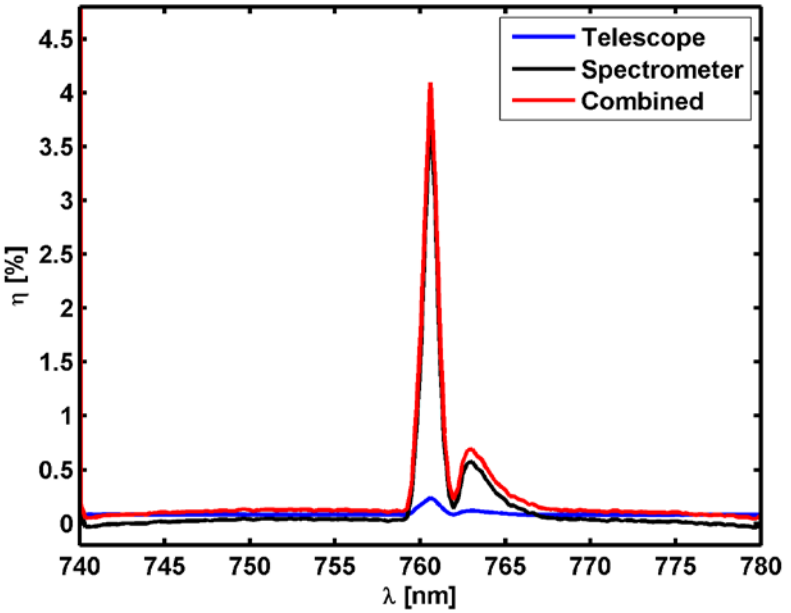




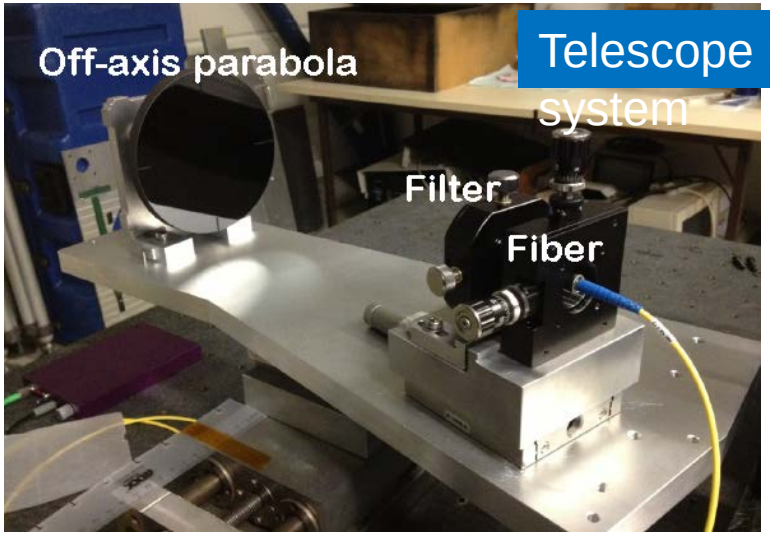
Radiometric error due to straylight

- Radiometric error ~4% at absorption line
- Without correction

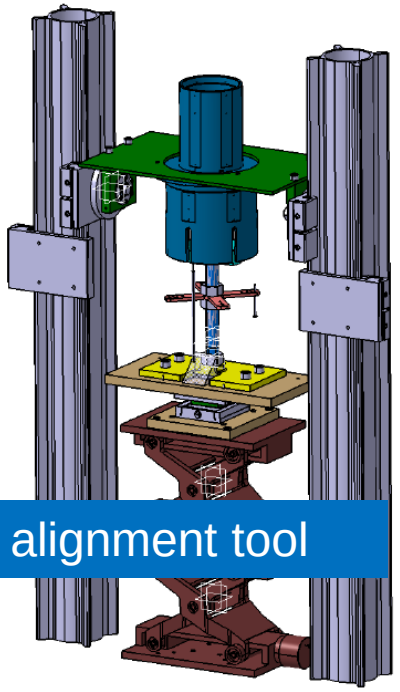




Breadboard 1: telescope test equipment

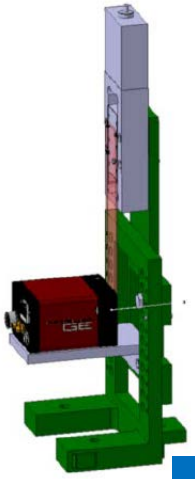


Telescope illumination system

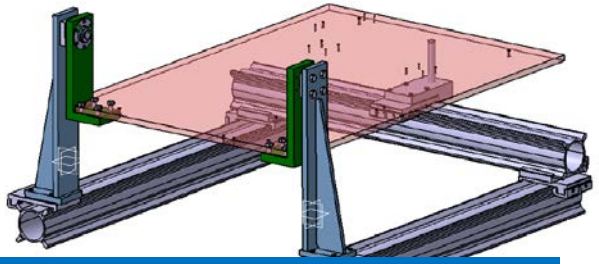


Lens barrel alignment tool

First lens under inspection

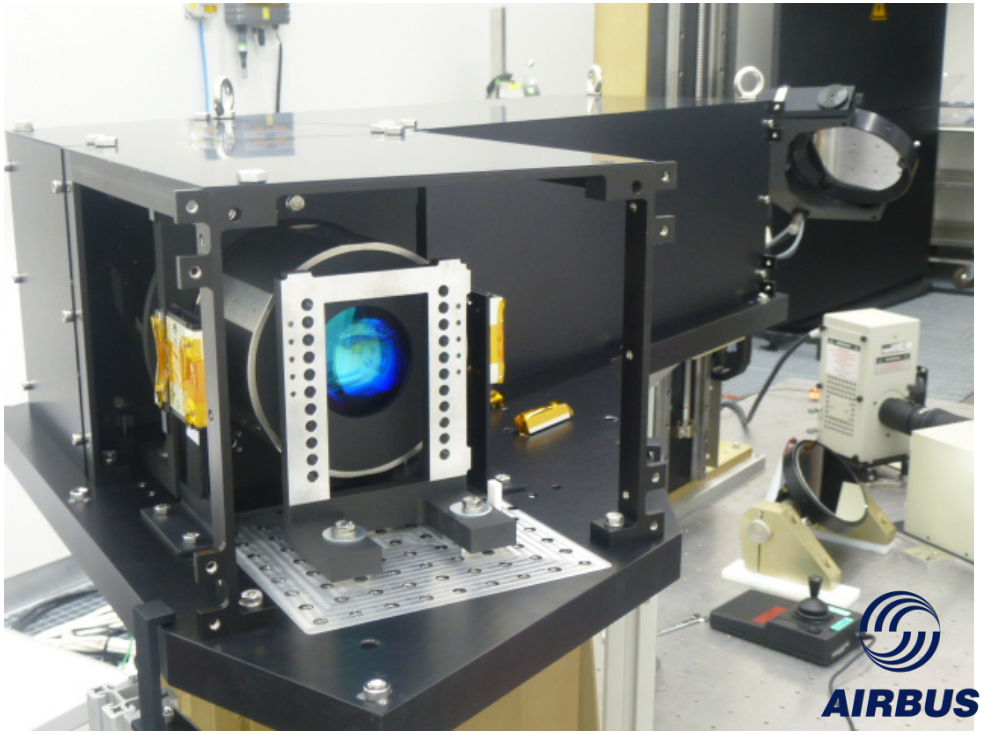


Knife edge scanner

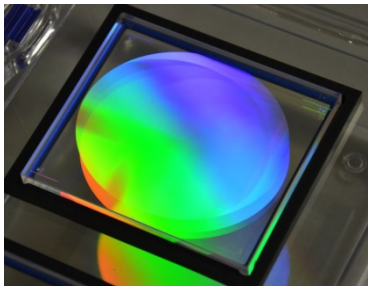


Field scan mechanism

Breadboard 1: manufacture completed

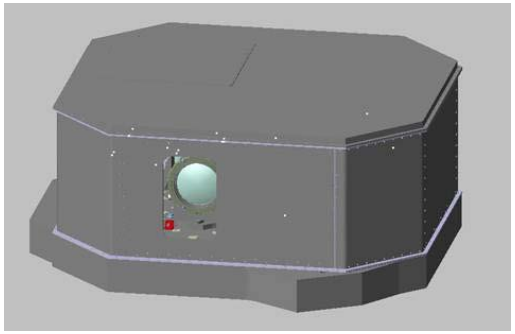


- BB fully assembled
- Telescope and spectrometer line shapes measured
- Very good performance achieved so far

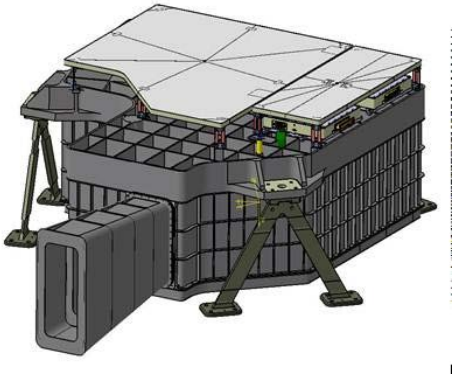


Fraunhofer IOF

Breadboard 2: system test equipment

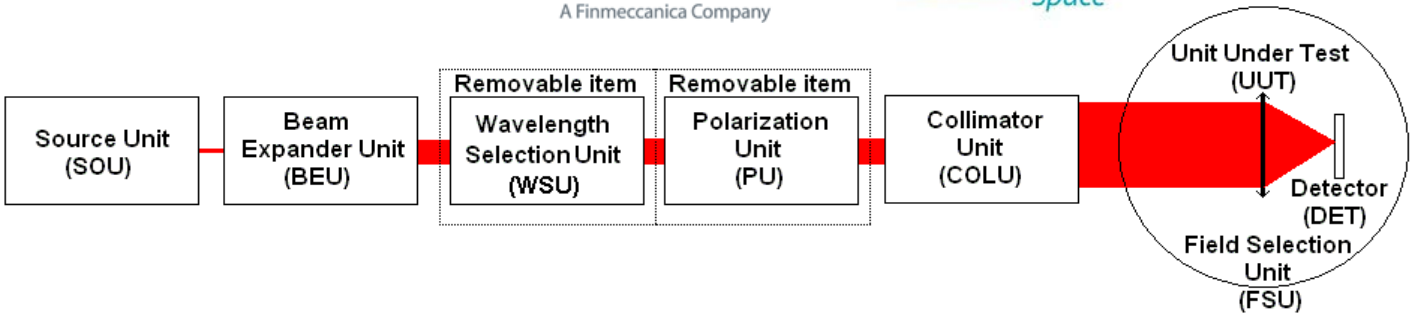


BB optics fully representative



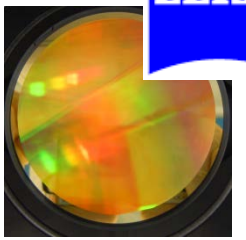
Selex ES
A Finmeccanica Company

ThalesAlenia Space



- BB and test equipment OGSE under definition
- First grating samples tested
- Detailed design review approaching

ZEISS



Detector breadboard - CCD

- Same detector for Concepts 1 and 2
- **Split frame transfer CCD**, 1020 x 440 pixels (TBC)
- Line transfer times of ~1.25 µs, frame time of 45.8 ms
- Pixel size 28 µ m x 42 µ m, full well capacity ~2 Me-
- Operating temperature 263 K, dark current of ~0.1 nA/cm^2
- Read noise <20e$^-$, 2.5 MHz readout rate
- ITT issued, under evaluation, start expected in June