Toward consistent observations of sun-induced fluorescence and reflectance from field-spectroscopy to FLEX: instruments and retrieval algorithms

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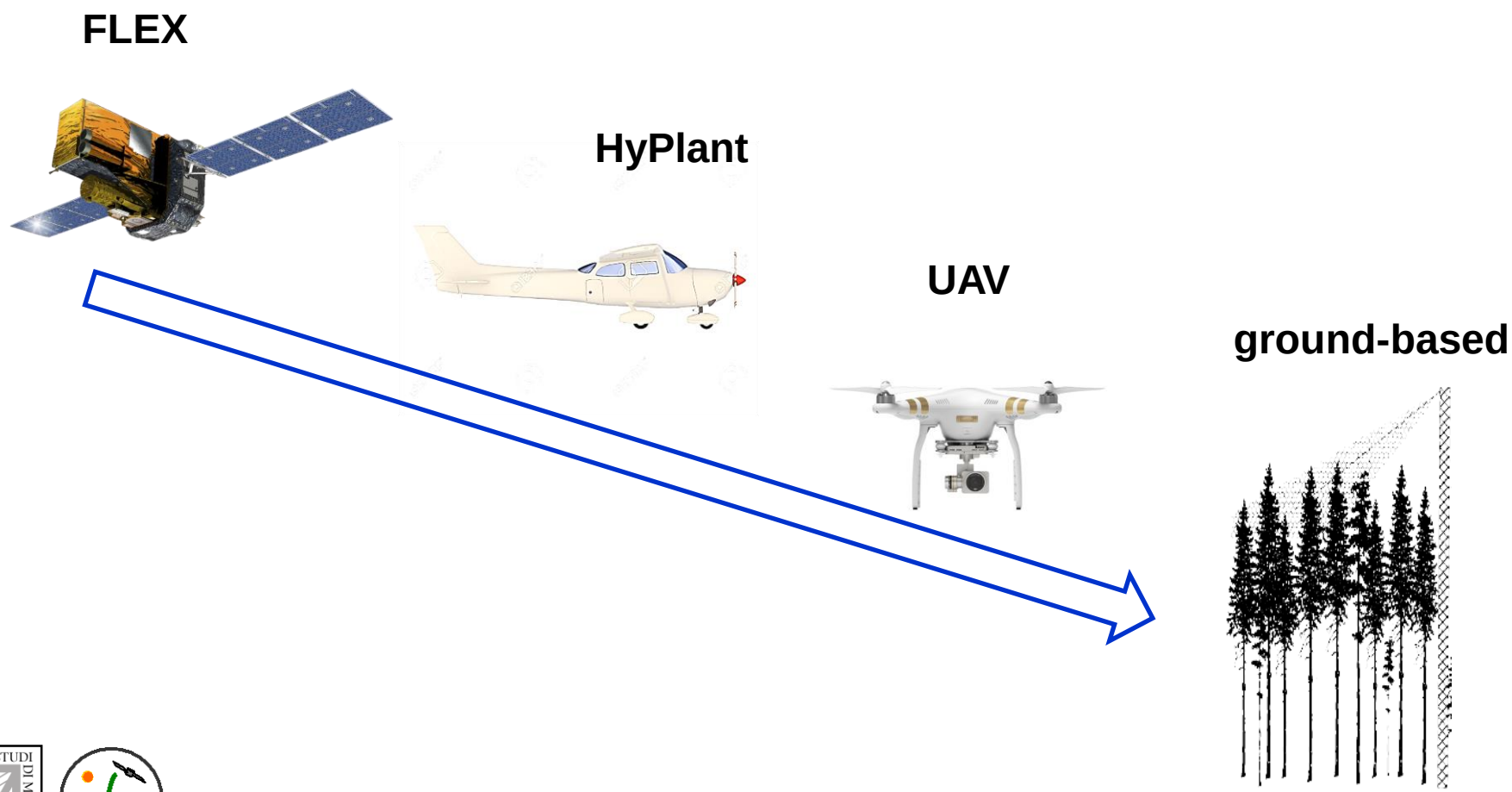
FLEX Cal/Val

credits: U. Rascher, FLEX2017

- the Cal/Val plan of FLEX Level-1/Level-2 products involves high-resolution spectrometer measurements (FLEX-like conf.) at different scales (ground-based; UAV; airborne)
- the Cal/Val plan is much more articulate including: i) selection of test sites (observational requirements), ii) different ecosystems; iii) spatial sampling scheme to upscale observations to FLEX

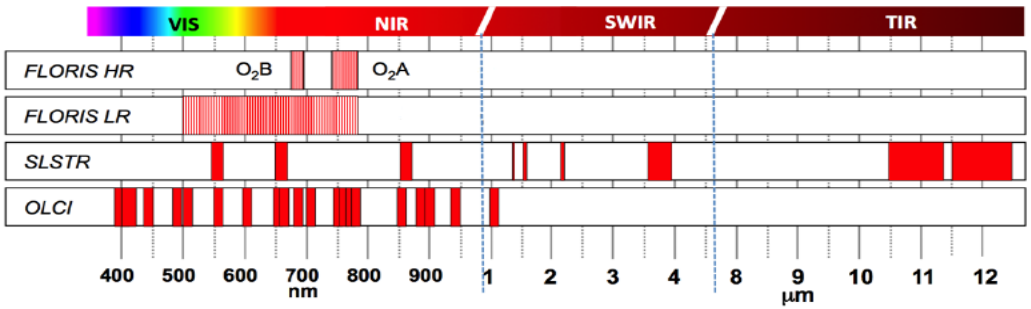
Objective

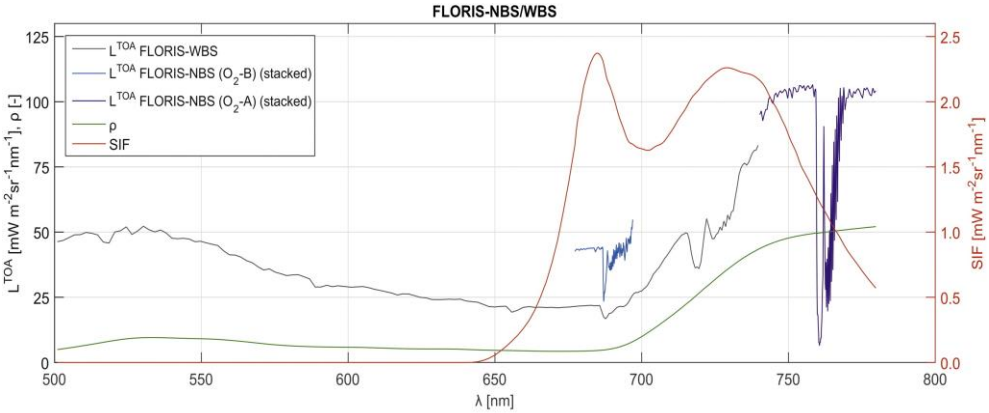
- Current development of fluorescence retrieval algorithm based on *Spectral Fitting* and high-resolution spectrometers for observations at different scales:

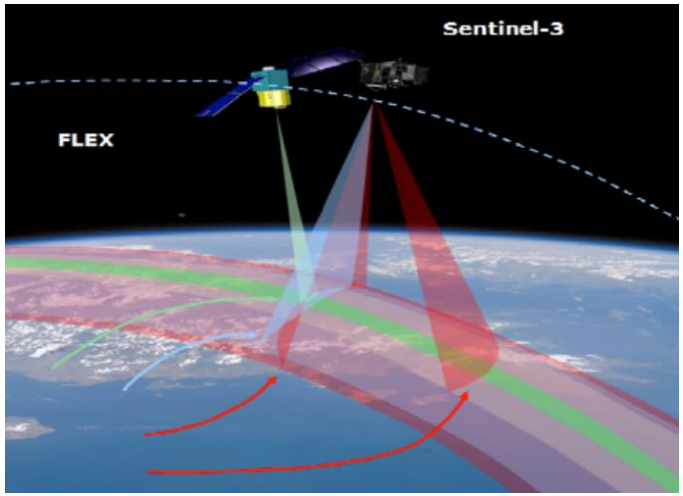


FLEX-S3 tandem mission

***FLOR**escence **I**maging **S**pectrometer (FLEX)*







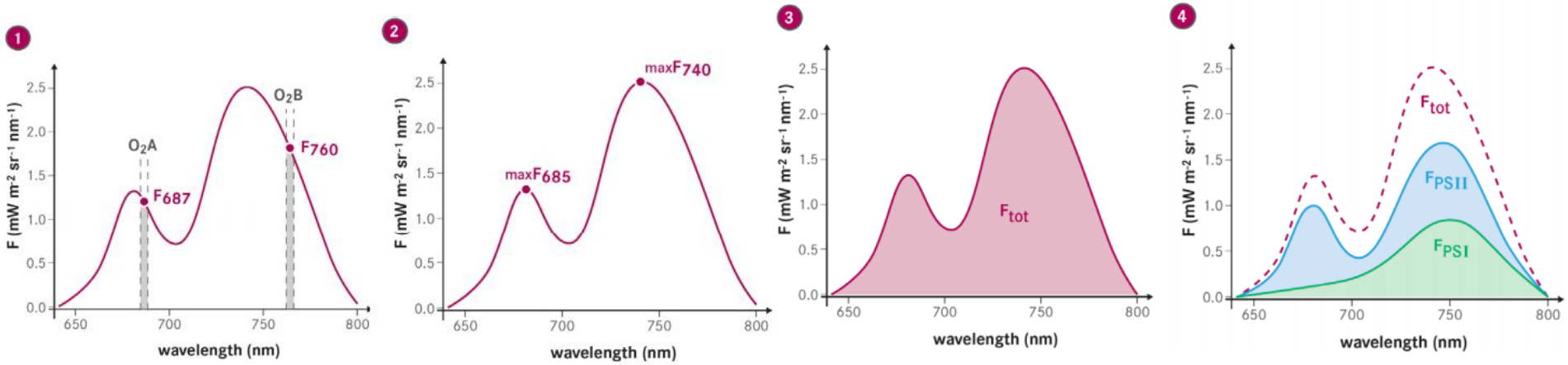
FLORIS technical specifications

Spectral Region	Visible	SIF_{red}		red-edge		$SIF_{far-red}$			
λ (nm)	500-677	677-686	686-697	697-740	740-755	755-759	759-762	762-769	769-780
SR (nm)	3.0	0.7	0.3	2.0	0.7		0.3		0.7
SSI (nm)	2.0	0.5	0.1	1.0	0.5		0.1		0.5
SNR	245	340	175	425	linear from 510 to 1015	1015	115	linear from 115 to 455	1015

- Spectral range 500-780nm
- NBS 0.3 nm spectral resolution (0.1 nm sampling) around O_2 bands
- WBS 0.5-2 nm sampling in PRI, Chlorophyll absorption and red-edge
- 300 m spatial resolution

FLEX Level2 products

canopy fluorescence

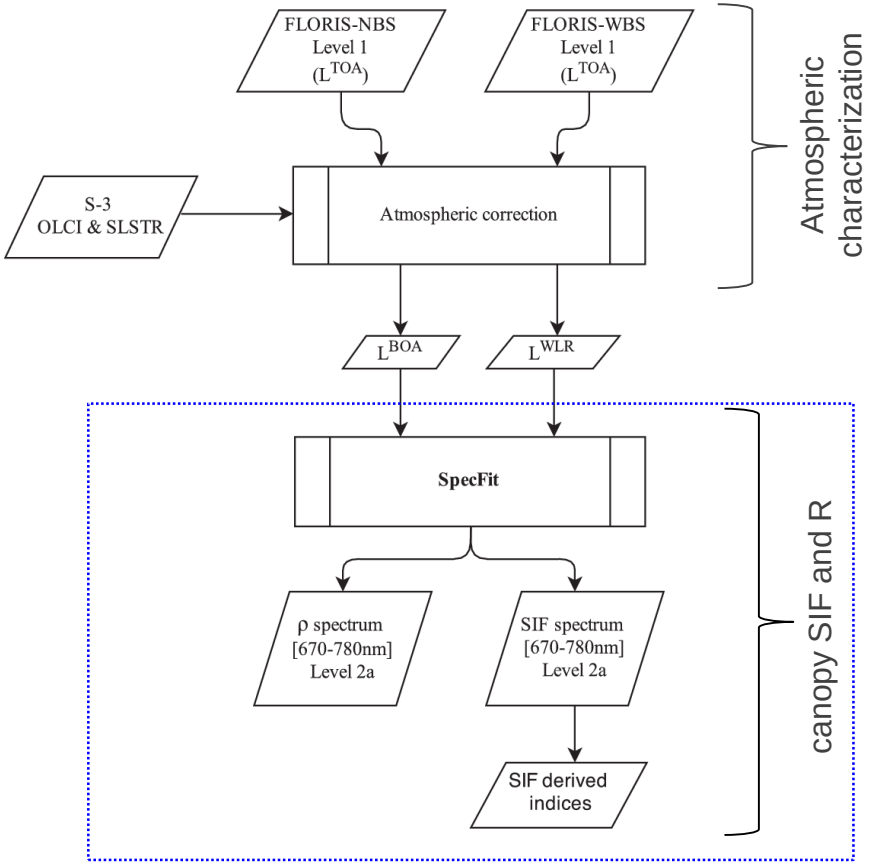


Additional information

- Non-photochemical quenching (PRI)
- Vegetation biophysical parameters (LAI, LCC, APAR…)
- Head dissipation (surface temperature)
- All information needed for fine atmospheric correction

SIF retrieval for FLEX

FLEX-S3 data flow (simplified)



Spectral Fitting

1) Atmospheric characterization exploits FLEX and S3 (AOD, alfa, G, CWV)

2) *Spectral Fitting* algorithms to decouple canopy **SIF** and **R**

- **high resolution** spectra at O_2 bands;
- **broader spectral window** covering the full fluorescence emission spectrum [660-780nm]

canopy radiance at TOA (forward model)

- Coupled canopy/surface and atmospheric RT

$$L^{TOA}$$

$$= \rho_{so}\frac{E_s^0 cos\theta_0}{\pi}$$ atmospheric path radiance

$$+\left[\frac{\tau_{ss}r_{so}E_o^s cos\theta_s}{\pi} + SIF_s + \frac{(\tau_{sd} + \tau_{ss}\overline{r_{sd}}\overline{\rho_{dd}})\,E_s^0 cos\theta_s/\pi + \overline{SIF_d}\,\rho_{dd}}{1-\overline{r_{dd}}\rho_{dd}}r_{do}\right]\tau_{oo}$$ target's surface radiance

$$+\left[\frac{(\tau_{sd}\overline{r_{dd}} + \tau_{ss}\overline{r_{sd}})E_s^0 cos\theta_s/\pi + \overline{SIF_d}}{1-\overline{r_{dd}}\rho_{dd}}\right]\tau_{do}$$ adjacency

Canopy terms

$\boldsymbol{r_{so}}\,(BRF)$, $\boldsymbol{r_{sd}}\,(DHRF)$, $\boldsymbol{r_{do}}\,(HDRF)$, $\boldsymbol{r_{dd}}\,(\mathrm{BHRF})$

$\boldsymbol{SIF_s}, \boldsymbol{SIF_d}$

Atmospheric terms

$\boldsymbol{\tau_{ss}}, \boldsymbol{\tau_{sd}}, \boldsymbol{\tau_{oo}}, \boldsymbol{\tau_{do}}, \boldsymbol{\rho_{sd}}, \boldsymbol{\rho_{dd}}$

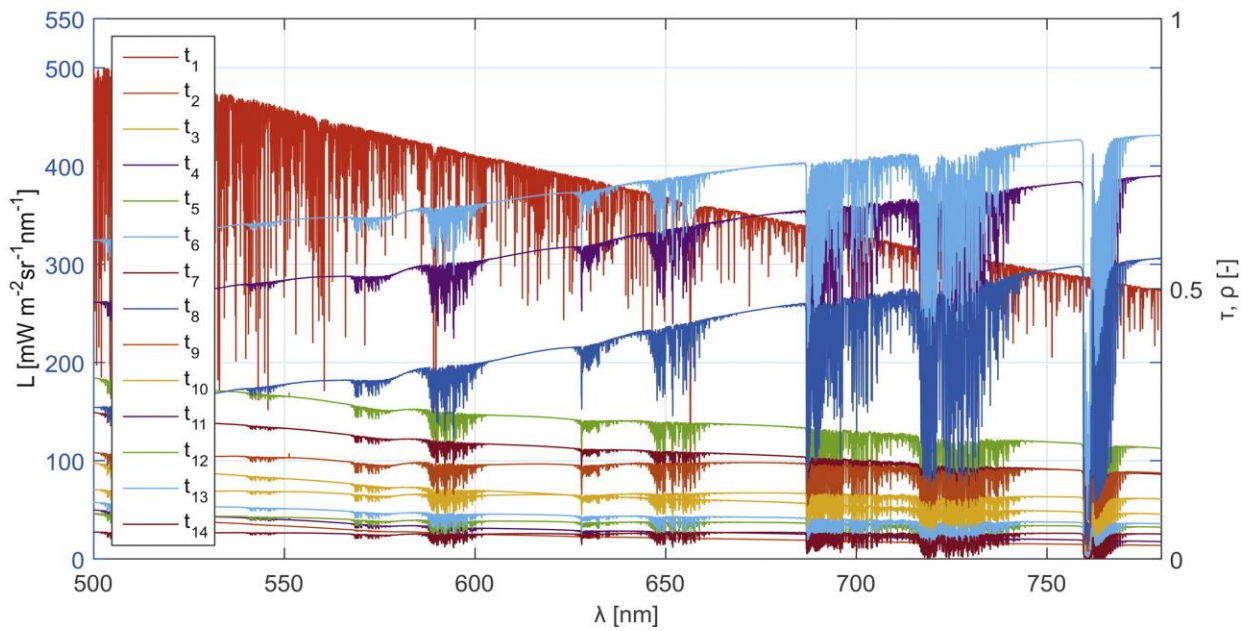
Atmosphere RTM

- MIT widely used technique to derive atmospheric functions from MODTRAN
- set of 14 (18 including thermal) atmospheric functions (surface-atmosphere coupled RT)

$$L^{TOA} = t_1\left[t_2 + t_8 r_{so} + \frac{t_9 + t_{14}\overline{r_{sd}}}{1-\overline{r_{dd}}\,t_3} r_{do} + \frac{t_{10}\overline{r_{sd}} + t_{11}\overline{r_{dd}}}{1-\overline{r_{dd}}\,t_3}\right] + t_6 SIF_s + \left[\frac{\overline{SIF_d}(t_7 + t_{13} r_{do})}{1-\overline{r_{dd}}\,t_3}\right]$$

Atmospheric Functions	*Name*
$\langle E_s^0 \rangle \cos\theta_s / \pi$	t_1
$\langle \rho_{so} \rangle$	t_2
$\langle \rho_{dd} \rangle$	t_3
$\langle \tau_{ss} \rangle$	t_4
$\langle \tau_{sd} \rangle$	t_5
$\langle \tau_{oo} \rangle$	t_6
$\langle \tau_{do} \rangle$	t_7
$\langle \tau_{ss}\tau_{oo} \rangle$	t_8
$\langle \tau_{sd}\tau_{oo} \rangle$	t_9
$\langle \tau_{ss}\tau_{do} \rangle$	t_{10}
$\langle \tau_{sd}\tau_{do} \rangle$	t_{11}
$\langle \tau_{ss}\rho_{dd} \rangle$	t_{12}
$\langle \rho_{dd}\tau_{oo} \rangle$	t_{13}
$\langle \tau_{ss}\rho_{dd}\tau_{oo} \rangle$	t_{14}

Atmospheric functions



FLEX SIF retrieval at O_2 bands

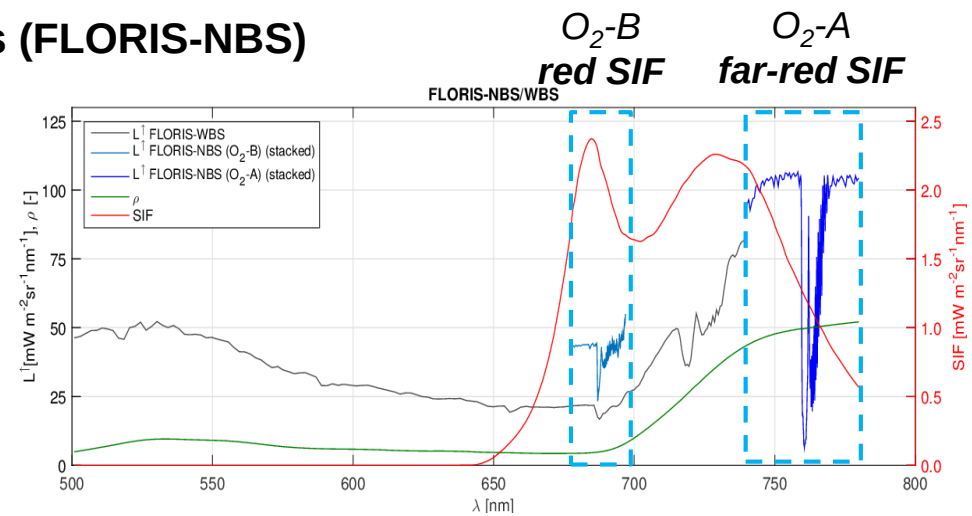
Spectral Fitting Methods (SFM) at O_2 bands (FLORIS-NBS)
[684-696nm] [740-780nm]

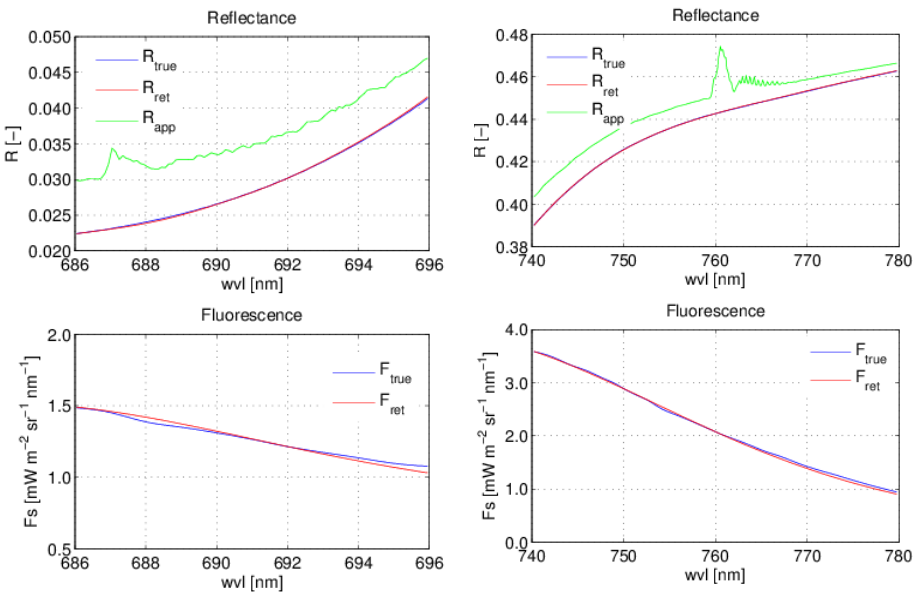
$$SIF = p - voigt$$

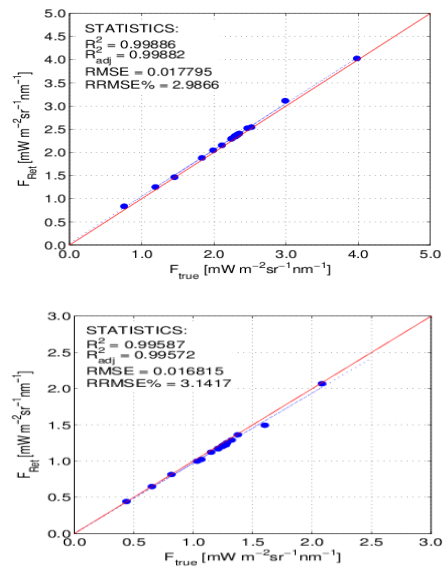
$$R = spline$$

<u>COST FUNCTION</u>

$$\min \sum \left(L_{mod}(\lambda) - L_{obs}(\lambda)\right)^2 + J + p$$







FLEX SIF spectrum retrieval - SPECFIT_V1

SPECtrum FITting [670-780 nm] (FLORIS-NBS + WBS)

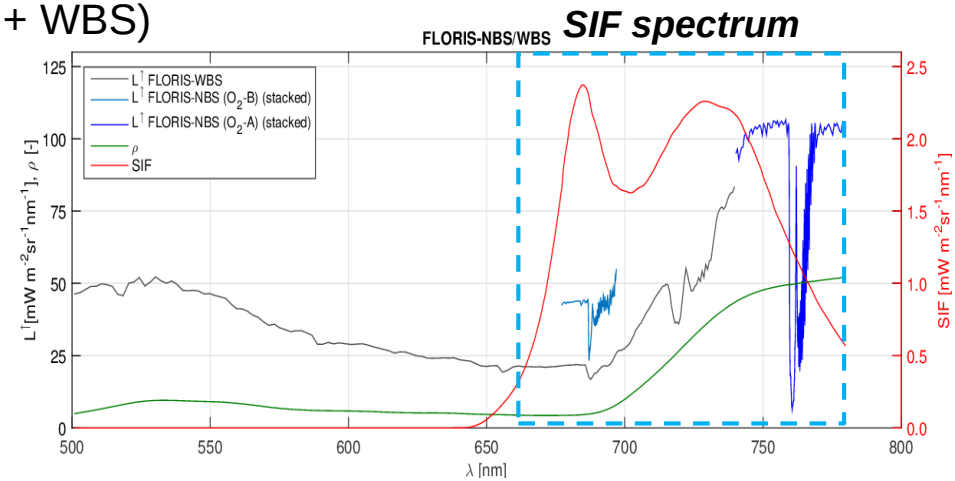
<u>1) p-voigt method</u>

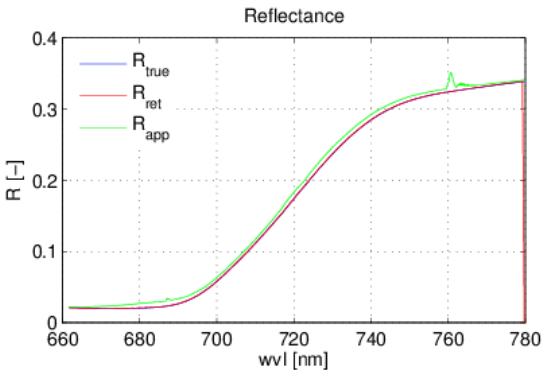
$$R = piecewise\ spline\ (15\ kts)$$

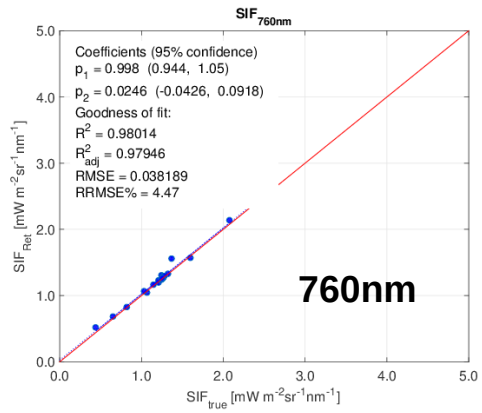
$$SIF(\lambda) = SIF_{far-red}(\lambda) + SIF_{red}(\lambda)$$

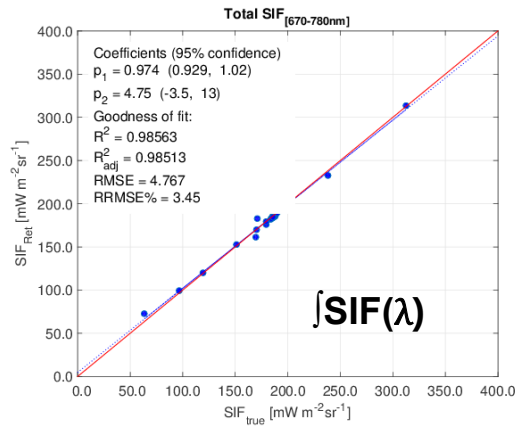
$$SIF_{red}(\lambda) = p - voigt$$

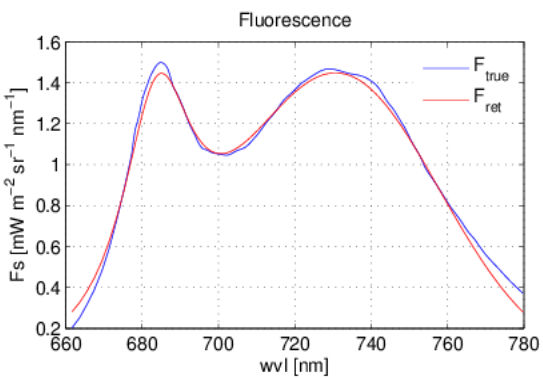
$$SIF_{far-red}(\lambda) = p - voigt$$

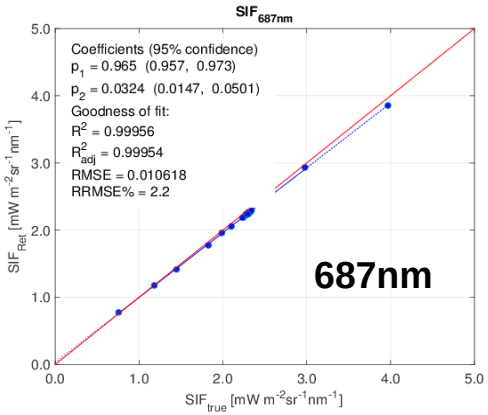












PS_{II} & PS_{I} spectra retrieval - SPECFIT_V2 (experimental)

SPECtrum FITting [670-780 nm]

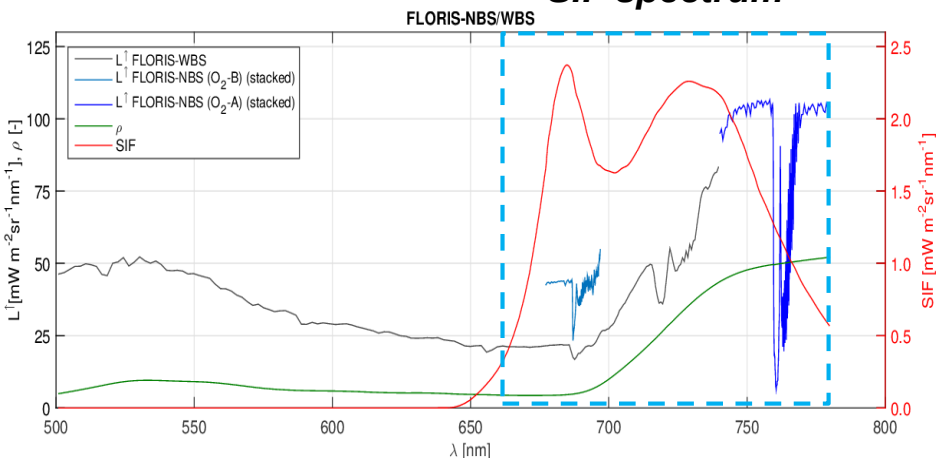
2) PS_{II}-PS_{I} method

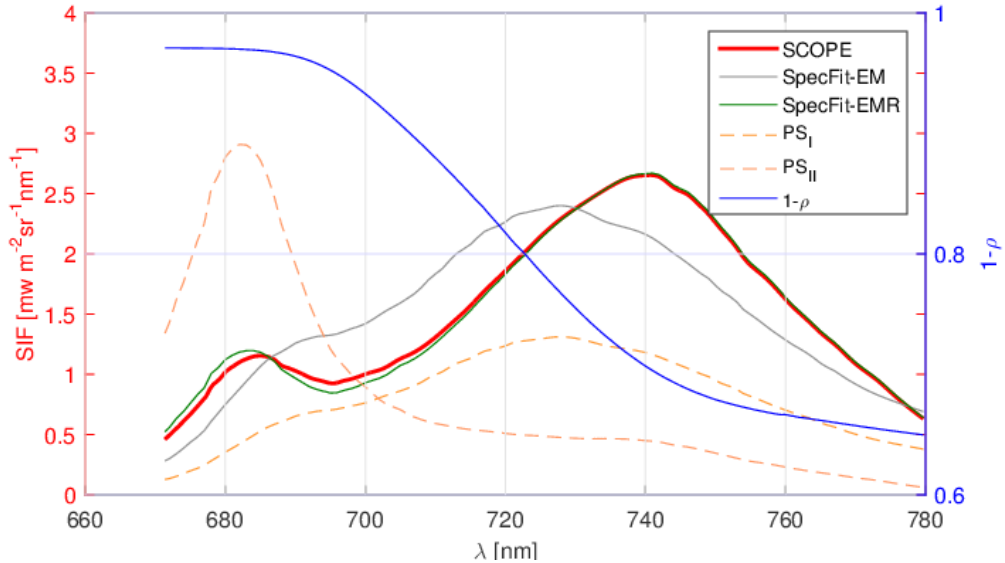
$$PS_I'(\lambda) = \Phi_I PS_I(\lambda) \; * \; [\overbrace{1-(1-\rho(\lambda))}^{\text{approx.}}]$$

$$PS_{II}'(\lambda) = \Phi_{II} PS_{II}(\lambda) * [1-(1-\rho(\lambda))]$$

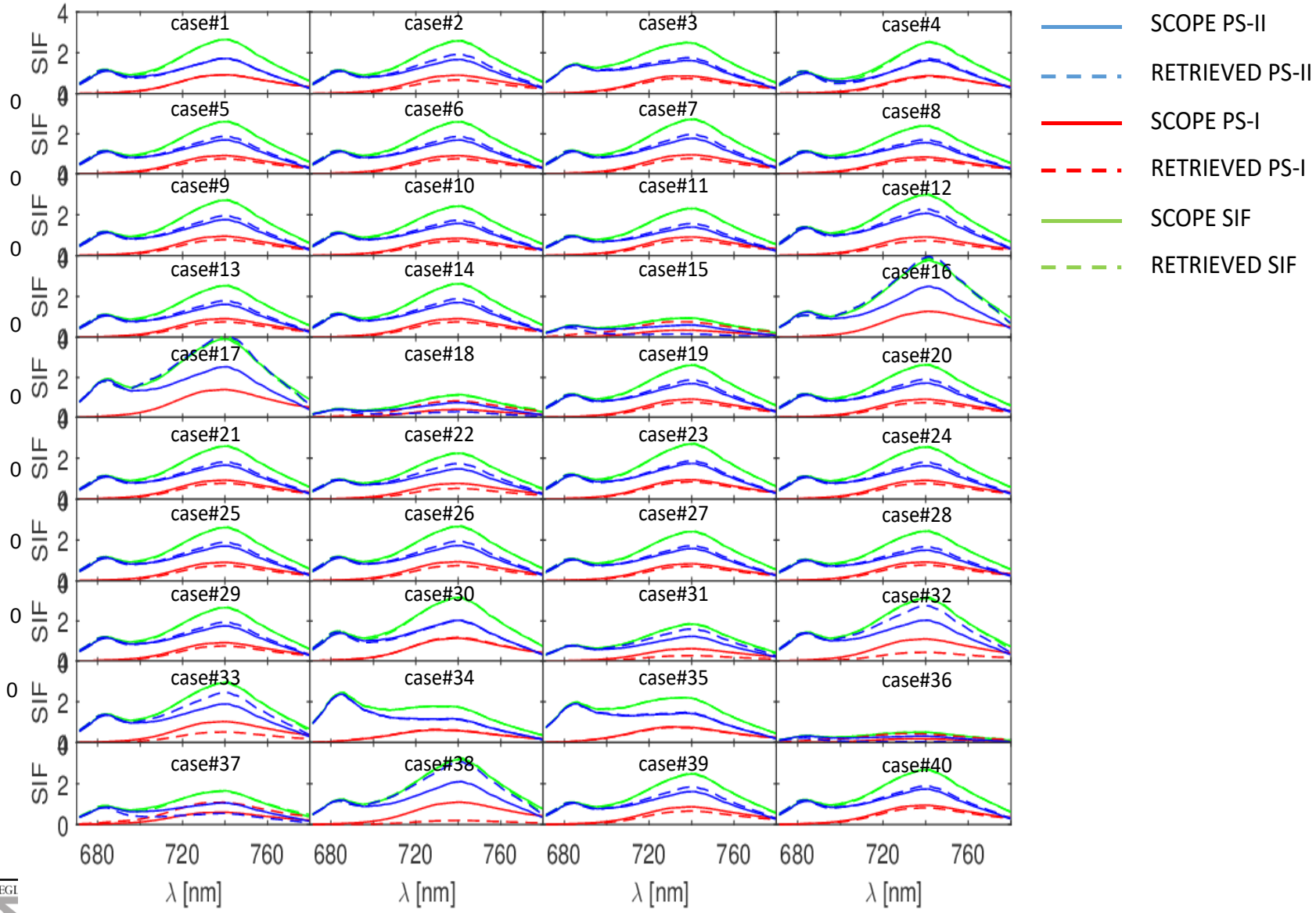
$$SIF(\lambda) = PS_I'(\lambda) + PS_{II}'(\lambda)$$

SIF spectrum



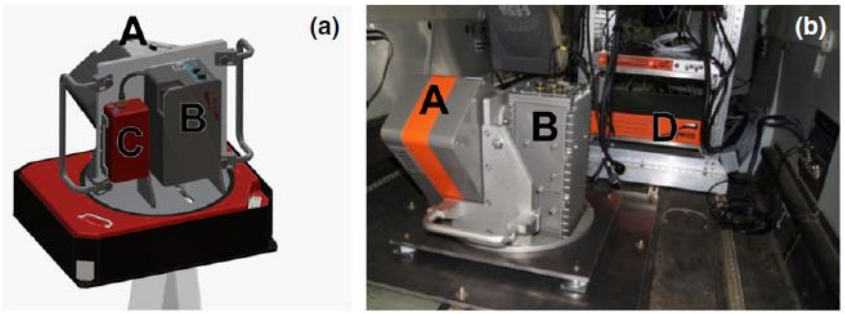


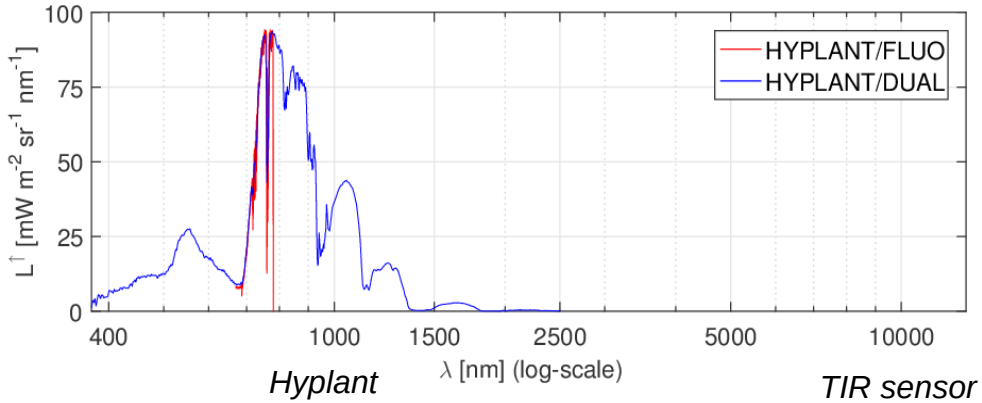
FLEX SIF spectrum & PS_I & PS_{II}

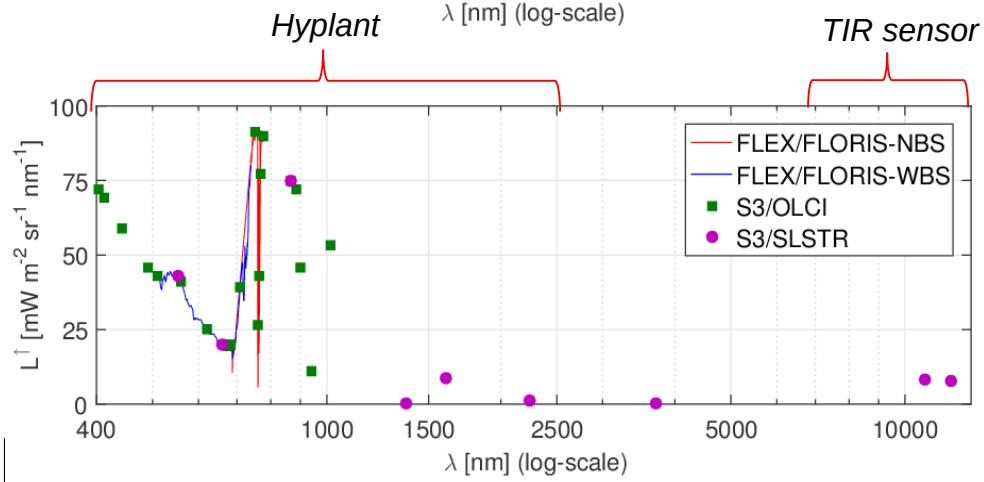


HyPlant - FLEX airborne demonstrator

HyPlant high performance spectrometer optimized to measure **sun-induced fluorescence** and VNIR/SWIR optical properties







HyPlant VS FLEX:

+ spectral resolution comparable to FLEX

+ extended spectral range for PRI, vegetation properties retrieval

- Airborne viewing angles are different compared to satellite

- SNR lower than FLEX

HyPlant SIF retrieval

$$L_{mod} = t_1 \left[t_2 + t_8 r_{so} + \frac{t_9 + t_{14}\overline{r_{sd}}}{1 - \overline{r_{dd}}\, t_3} r_{do} + \frac{t_{10}\overline{r_{sd}} + t_{11}\overline{r_{dd}}}{1 - \overline{r_{dd}}\, t_3} \right] + t_6 SIF_s + \left[\frac{\overline{SIF_d}(t_7 + t_{13} r_{do})}{1 - \overline{r_{dd}}\, t_3} \right]$$

1) t_i atmospheric transfer functions → MODTRAN5 RTM

- Sunphotometer (+ fine tuning)
- Model inversion

Challenges:

- fine estimation of ISRF
- atmospheric parms.

2) rdd rsd (spatially filtered) → average value over the image

3) Lambertian

rso (direct) = rdo (diffuse)

$SIF_s = SIF_d$

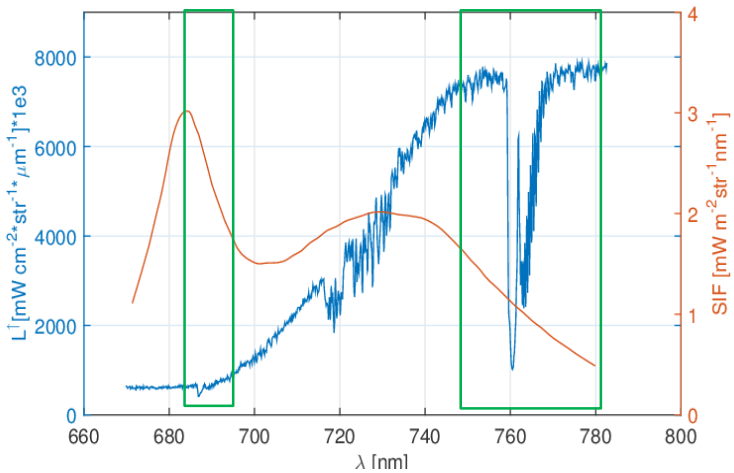
4) Spectral Fitting:

$$\min \sum \omega(\lambda)\left(L_{mod}(\lambda) - L\ (\lambda)\right)^2$$

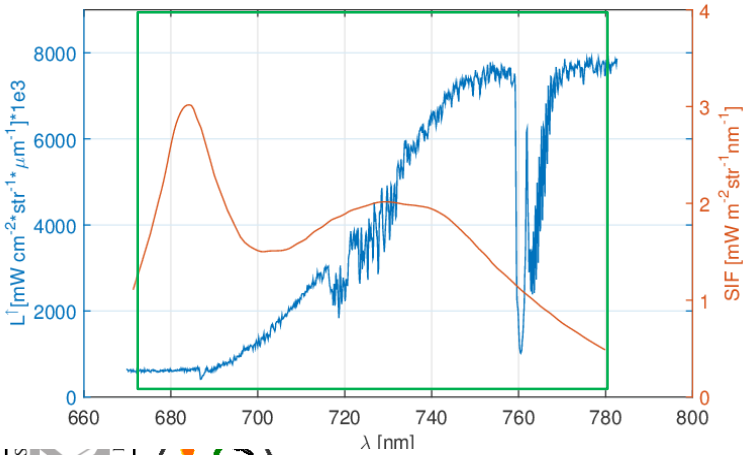
rso & SIF spectra

HyPlant SIF retrieval

$$L_{mod} = t_1\left[t_2 + t_8 r_{so} + \frac{t_9 + t_{14}\overline{r_{sd}}}{1-\overline{r_{dd}}\,t_3} r_{do} + \frac{t_{10}\overline{r_{sd}} + t_{11}\overline{r_{dd}}}{1-\overline{r_{dd}}\,t_3}\right] + t_6 SIF_s + \left[\frac{\overline{SIF_d}(t_7 + t_{13} r_{do})}{1-\overline{r_{dd}}\,t_3}\right]$$



SFM ⇨ Implemented and under testing

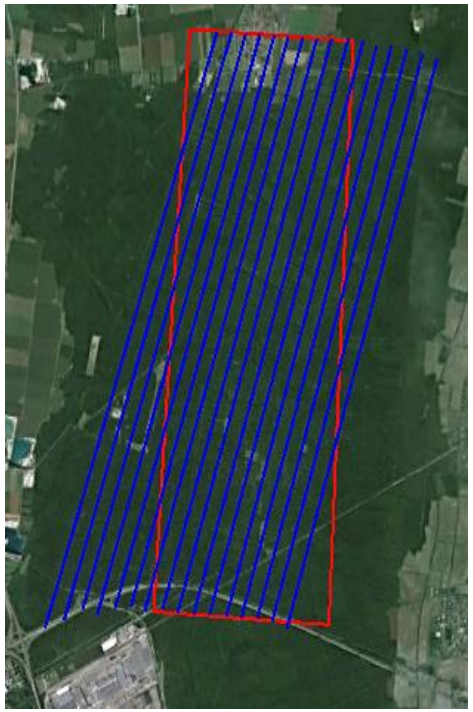


SpecFit ⇨ Under implementation

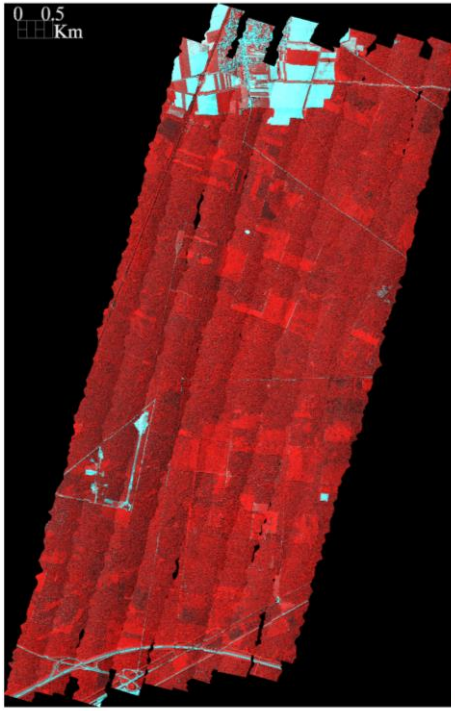
HyPlant – large spatial scale

- Sen2ExpFL (June 16th 2013), Harth forest Mulhouse (FR) (mixed forest)

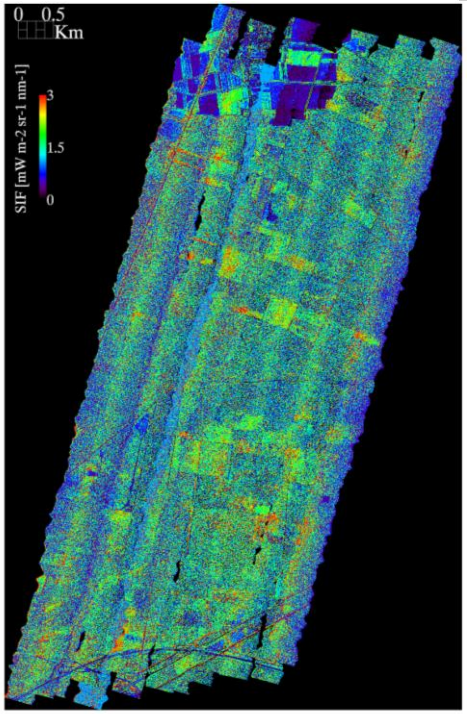
Flight lines



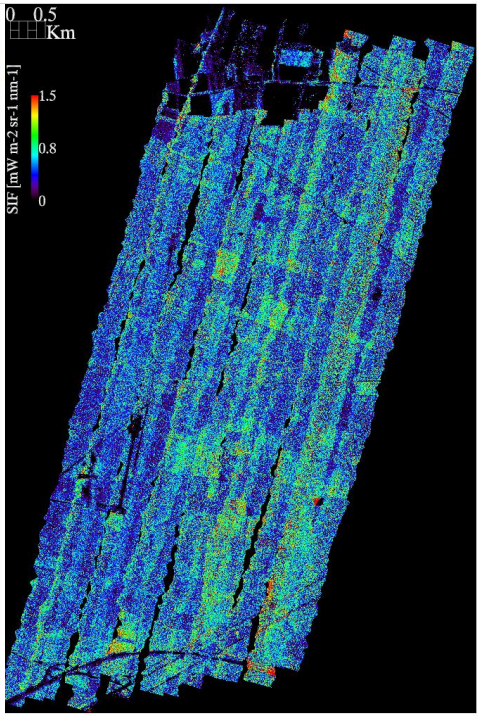
False color



SIF 760nm

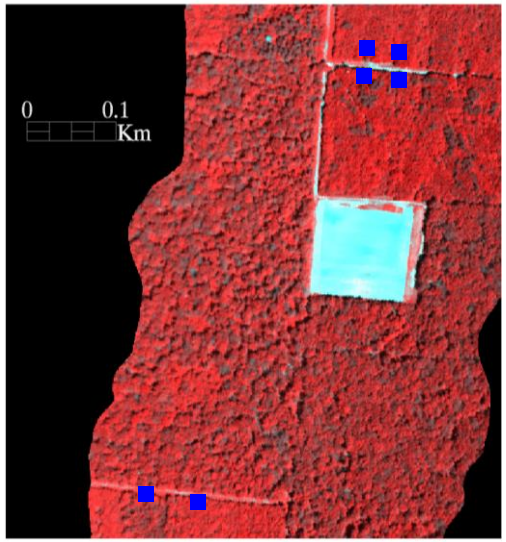


SIF 687nm

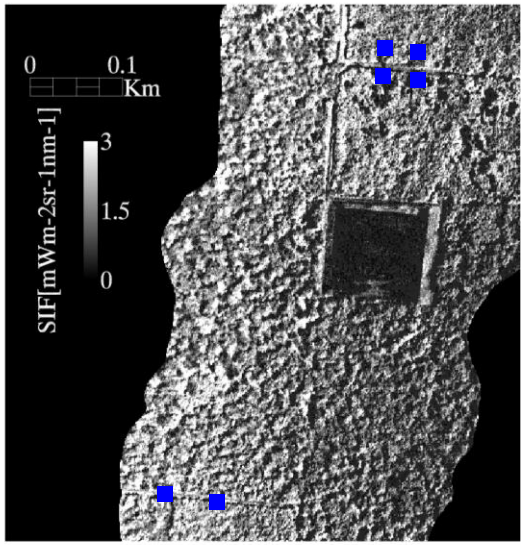


HyPlant – SIF maps validation (1)

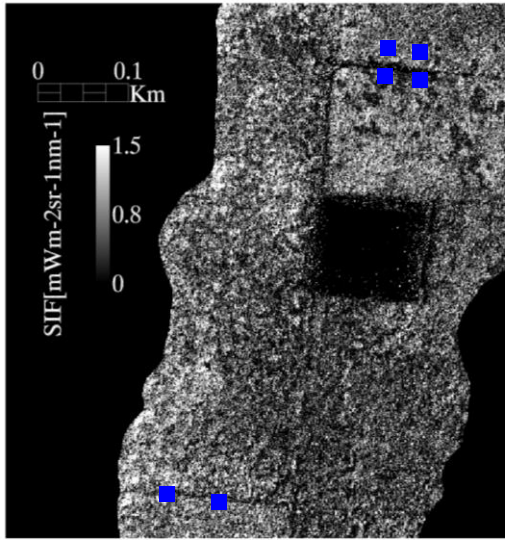
False color



SIF 760nm



SIF 687nm



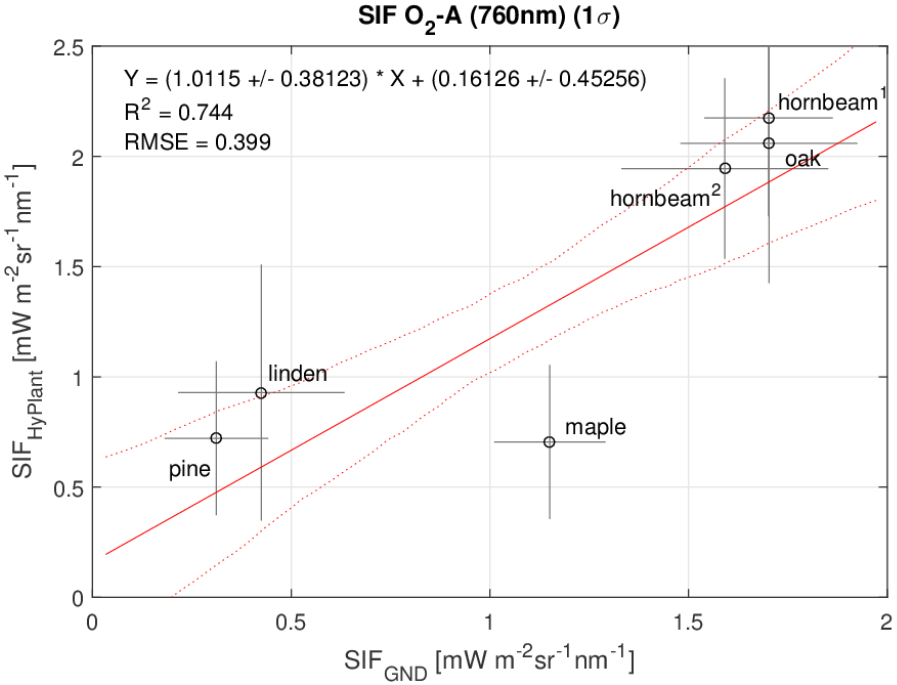
ROI

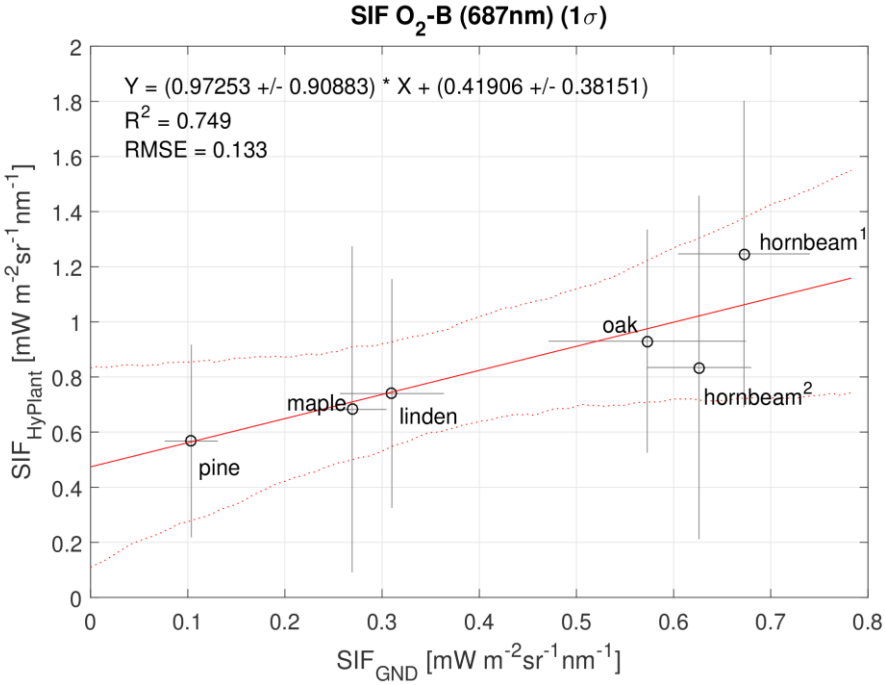
Ground based measurement set-up

TOC measurements on different plant species

Date	Species
June, 16th	Oak
June, 16th	Hornbeam
June, 17th	Pine
June, 17th	Maple
July, 2nd	Larch
July, 2nd	Linden

HyPlant – SIF maps validation (2)





UAV – UNIMIB experience on HyUAV

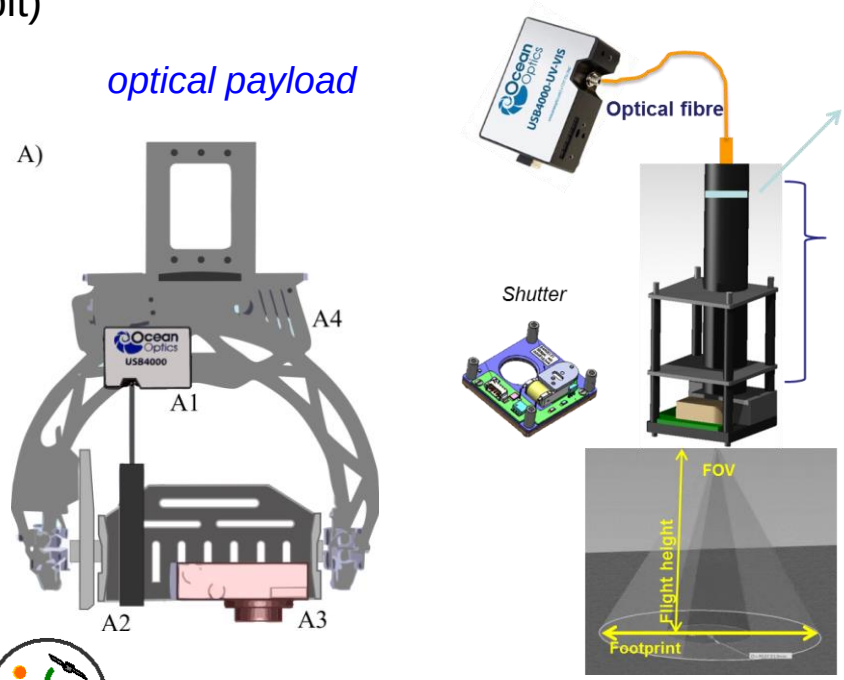
Anteos platform

- Four-rotor platform, maximum payload of 2 Kg and flight time of 20 min
- GPS/IMU, radio connection to GCS

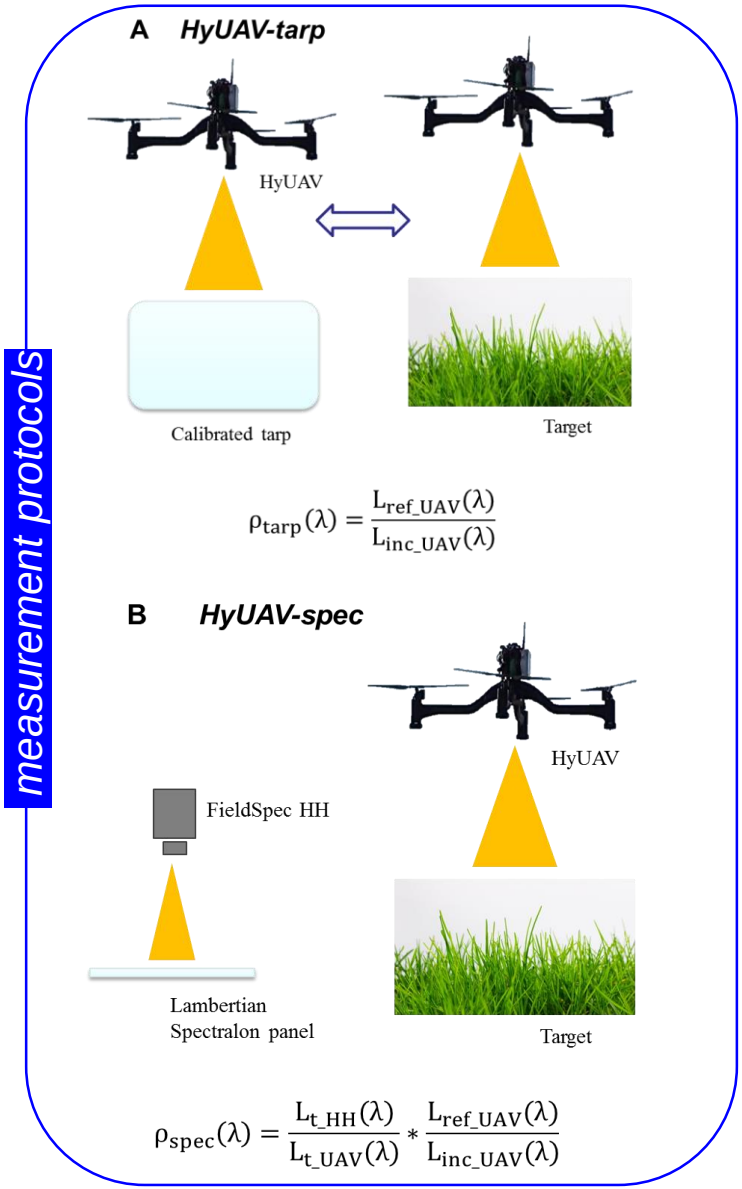
Optical payload

- RGB digital camera (Canon S100)
- Ocean Optics USB4000 VNIR non-imaging spectrometer (350 -1000nm, 1.5 nm FWHM, 16bit)

optical payload



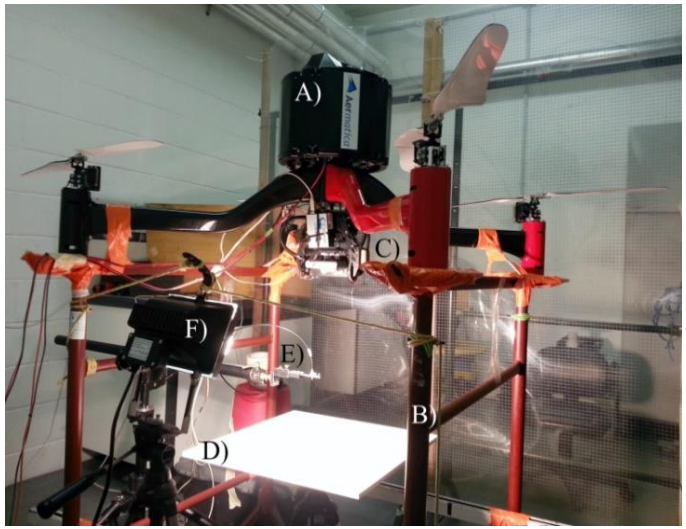
measurement protocols



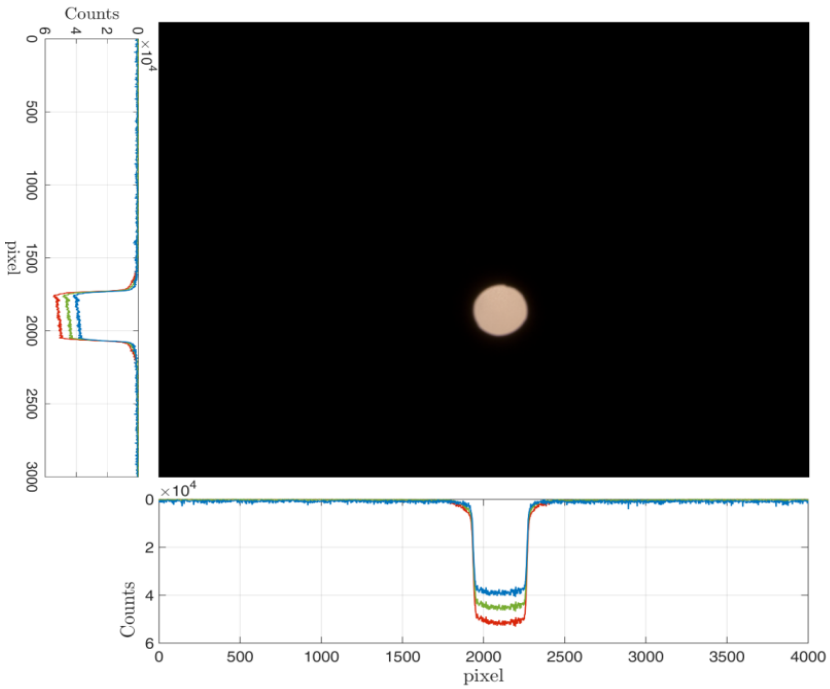
UAV – Lab. characterization (vibrations)

Assessing platform vibrations on spectra stability: geometric, radiometric and spectral

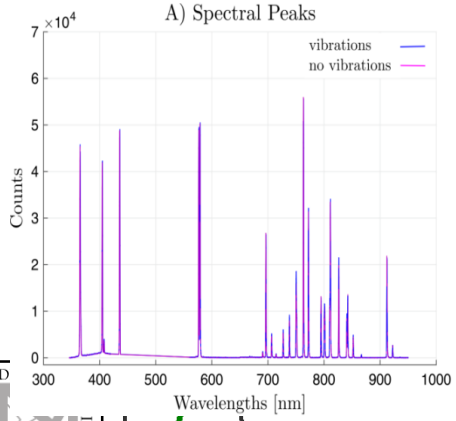
Lab. Test-bed

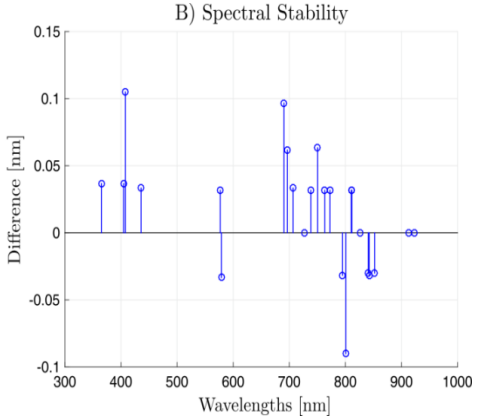


Geometric: to derive size and position of spectrometer FOV within RGB imagery → vector between UAV and spectrometer barycenter

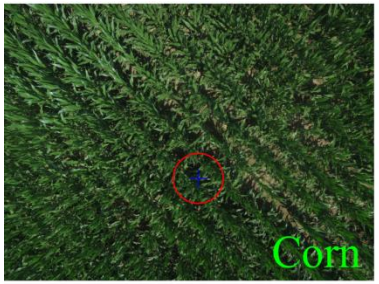


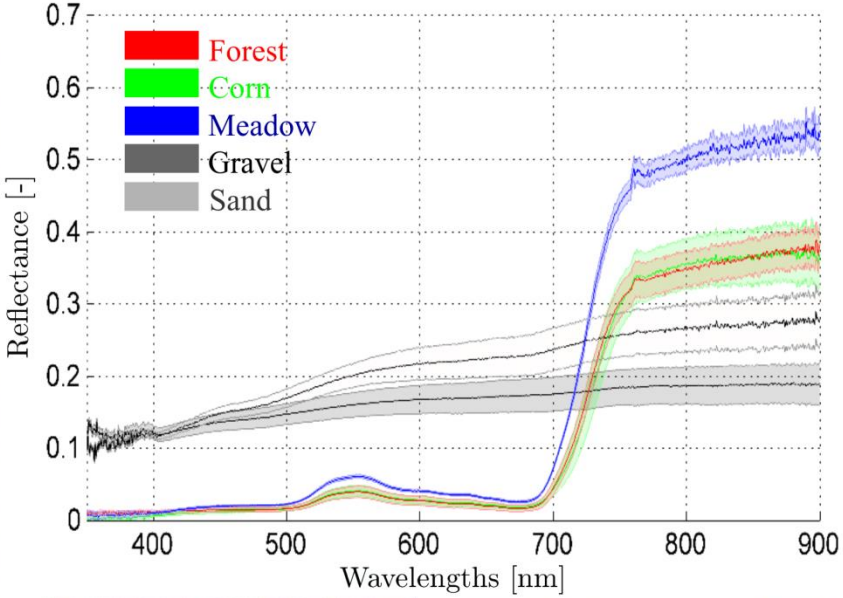
Regular radiometric and spectral characterization



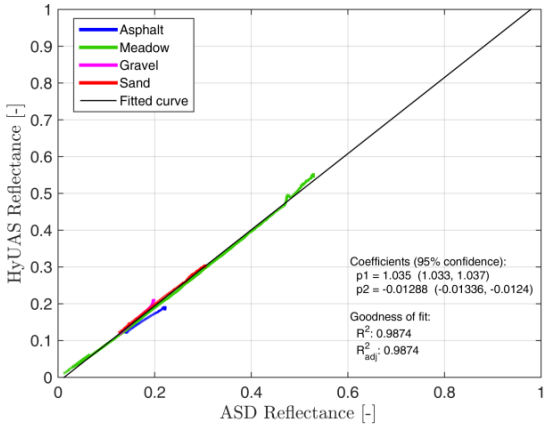


UAV – comparison with ground-based meas.





HyUAS Vs. ASD

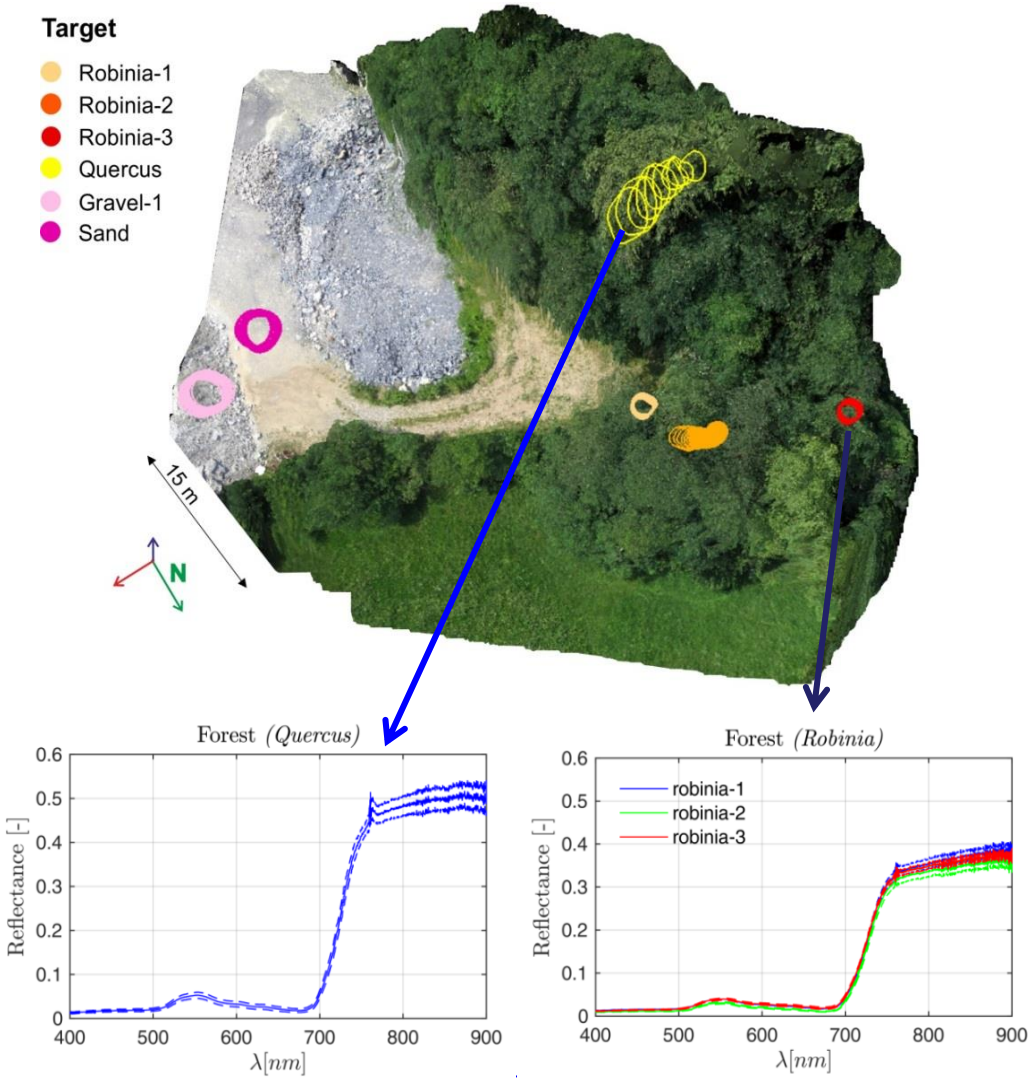


- Reflectance measured with the **HyUAS** exhibits a **high correlation** with those measured with the **ASD FieldSpec** (R^2 = 0.98).

- **Reflectance signatures** calculated for each sample describe the **typical features** of the different land covers

UAV - Photogrammetric analysis

Heterogeneous and/or 3D structurally complex targets (i.e. forest) require very accurate location of spectrometer sampling area



Some issues:

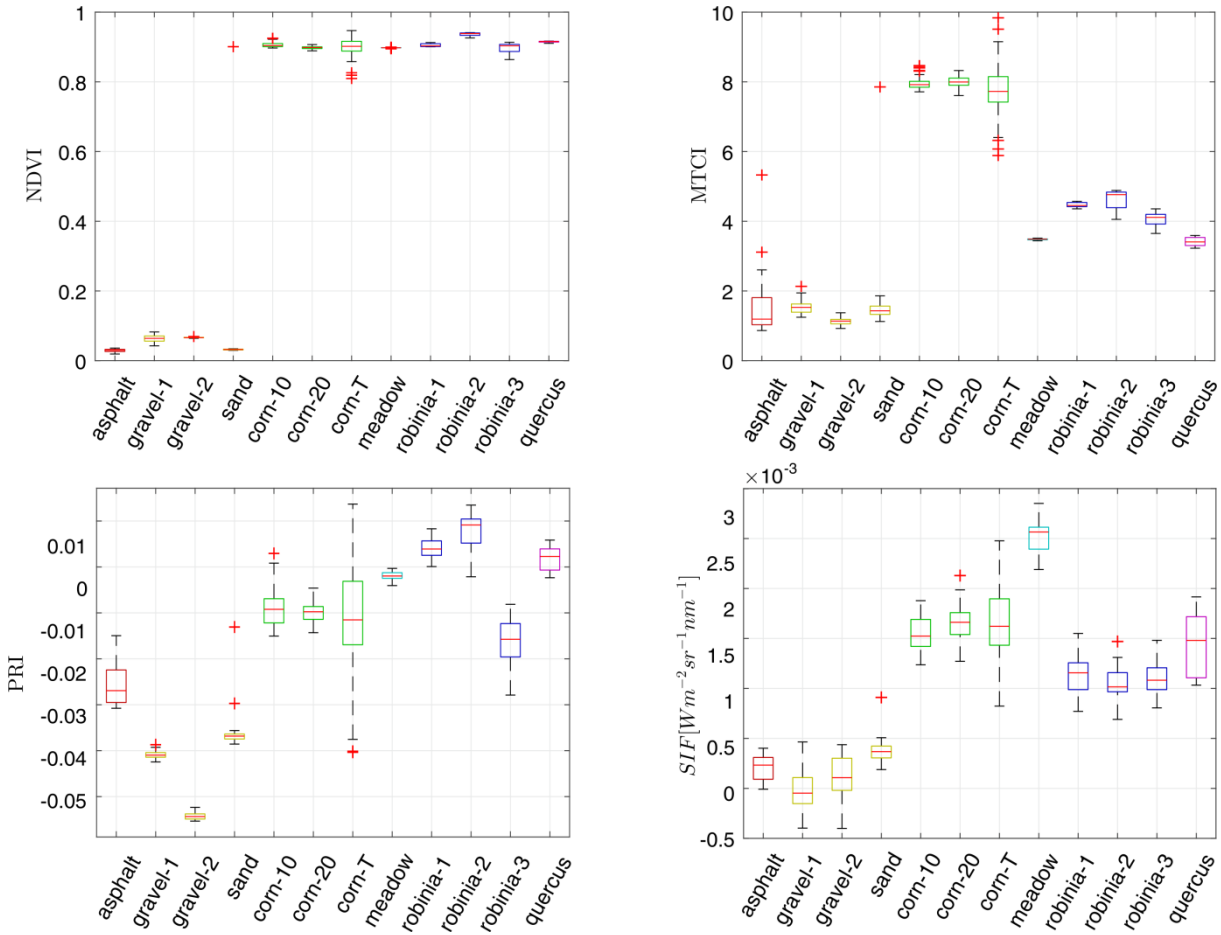
- Spectrometer FOV size depends on sensor-target distance → low flying UAV
- The FOV shape (circular) from nadir over a flat surface, becomes ellipsoid (or irregular) shape due to platform roll/pitch Vs. canopy 3D shape
- Canopy directional effects are even more evident in such "close range" configuration

Geometric processing:

- Structure from motion algorithms used to derive DSM from RGB
- Orthophoto draped on the DSM
- Spectrometer footprint are overlaid on the model considering nav data and DSM

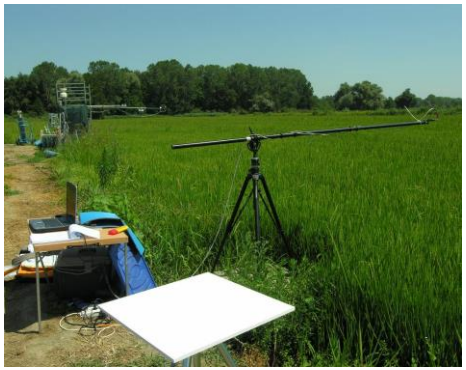
UAV – VIs and SIF

- Boxplots of NDVI, MTCI, PRI and SIF (O2-A) derived from HyUAS reflectance spectra for the different targets.



field spectroscopy – UNIMIB instruments

1. Manual spec system (2004)



2. HSI, Hyper**S**pectral **I**rradiometer (2007)

3. MRI, Multiplexer **R**adiometer/**I**rradiometer (2009)

4. FLOX

(2016)

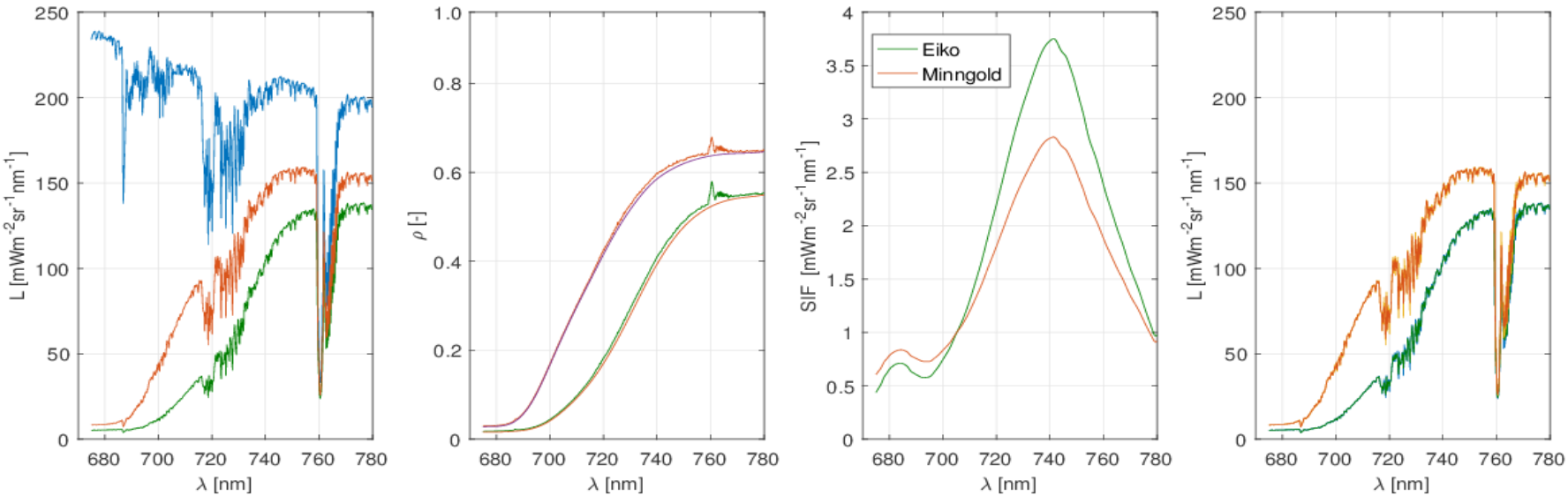
Each spectral system hosts two or three spectrometers (OceanOptics, USA)

Spectrometer	FWHM (nm)	Sampling interval (nm)	Spectral range (nm)	Application
1	1	0.25	350-1050	Irrad. measurements, ρ and VIs computation
2	0.1	0.02	700-800	Sun-induced Chl fluorescence at O_2-A
3	0.2	0.04	670-850	Sun-induced Chl fluorescence at O_2-A & O_2-B
4	0.25	0.07	657-740	Sun-induced Chl fluorescence at O_2-B

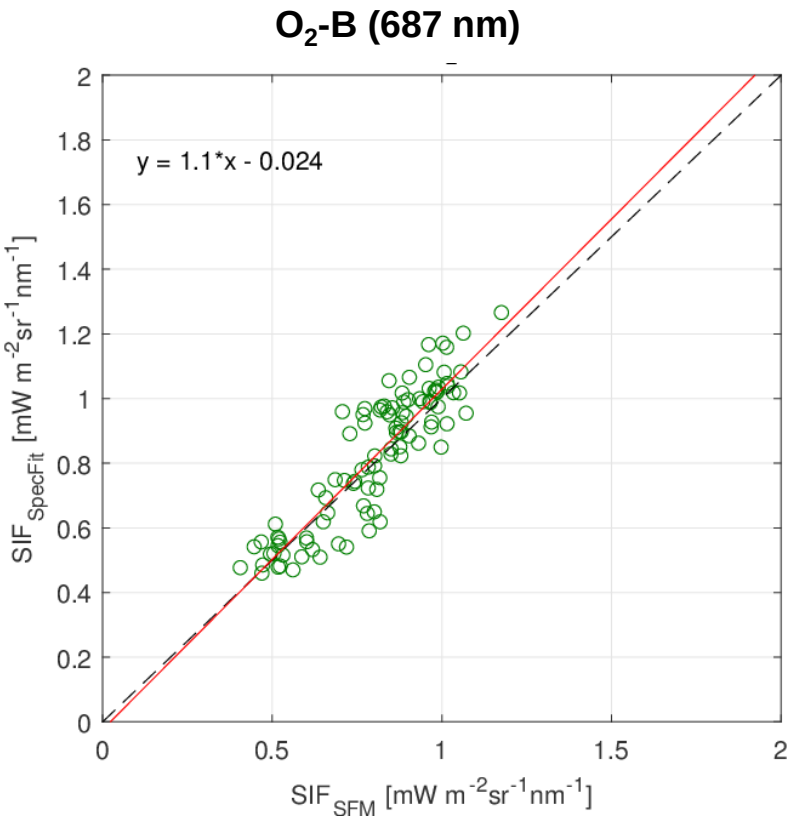
Field Spectroscopy - SIF spectrum retrieval

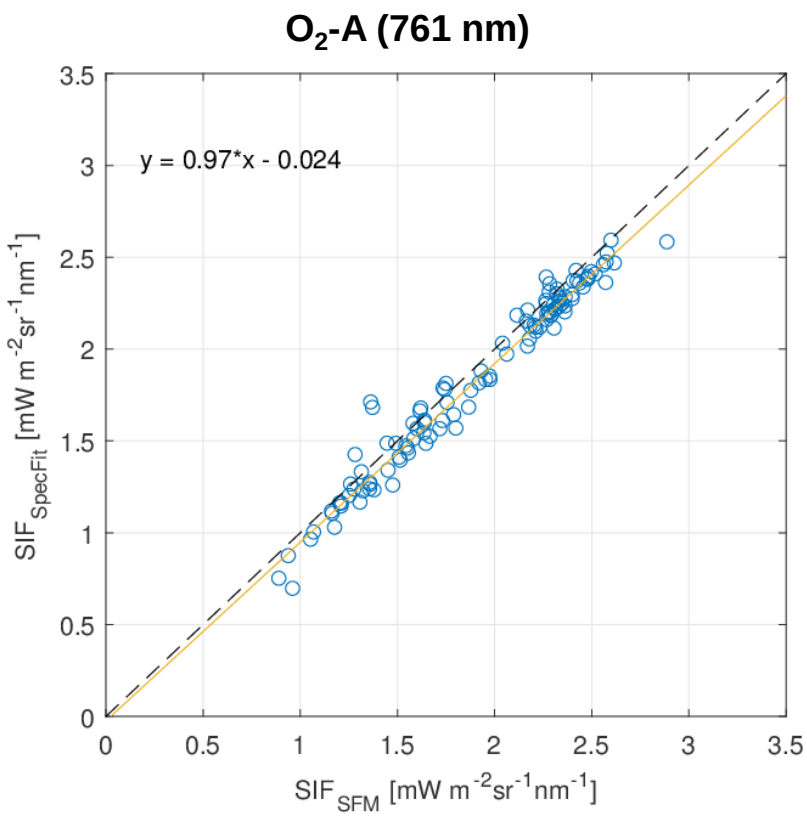
Eiko Minngold

SOYFLEX campaign 2016

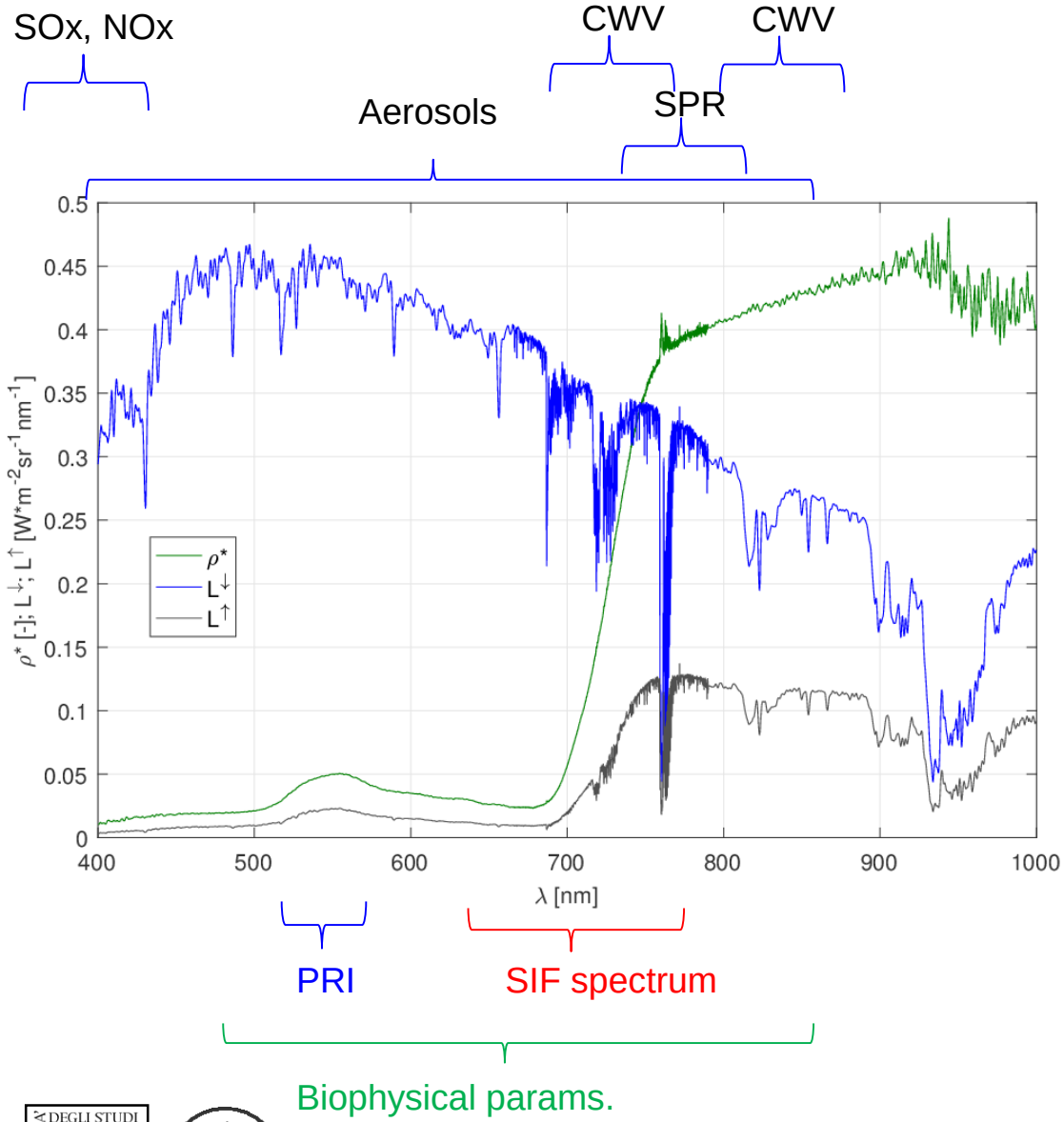


SpecFit VS SFM





Recommendations for spectral measurements



Atmospheric vars.

Retrieval algorithm from atmospheric community must be adapted/tested to our conf.

Spectrum Fitting

Model inversion for biophysical parms. retrieval (van der tol et al., 2016, RSE)

STSM of M. Celesti; host: University of Twente

canopy vars.

Concluding remarks

- The interest on Spectrum Fitting is the capability of retrieving fluorescence spectral behavior
- The R and SIF spectral signature provide unprecedented opportunity to gain more information: i) canopy re-absorption (red SIF) and multiple-scattering (far-red); ii) decoupling PSII and PSI spectra
- The algorithms have been implemented for processing high-resolution measurements at different scales: from ground to airborne/satellite
- Suggested instrument spectral configuration: 1 spectrometer covering SIF emission range [650-800nm] + 1 VNIR spectrometer for PRI, biophysical params. and potentially atmospheric parms.
- In general, ground-based observations are the most reliable from retrieval algorithm point of view: incoming radiation is well-know (measured) and ISRF does not play any role; interpretation of the signal could be tricky because directional effects (sampling area size VS leaves size and canopy structure)
- Ground-based measurements from high towers (i.e. > 10m) must be carefully considered because potential atmospheric effects → we need to investigate this topic better, proposing an easy, fast and reliable correction (i.e. O2 absorption cross-section scaled by surface pressure??)
- similar considerations can be applied to low-flighting UAV observations, close range measurements (< 10m) are favorite because they should not require complex atmospheric correction

Thank you