MULTI-FLEX

Towards a strategy for fluorescence monitoring at multiple scales within the context of the FLEX/S-3 tandem mission

Marco Celesti (University of Milano-Bicocca)

LIVING PLANET FELLOWSHIP

BIOSPHERE

Outline

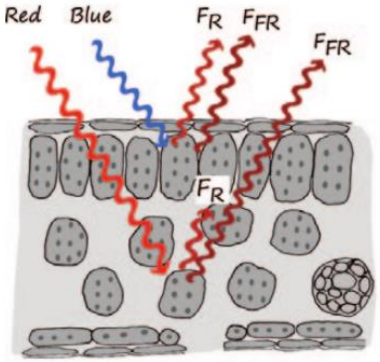
- Scientific context of the research
- Experimental data collection
- Project overview/summary
- Methods and Results (WP1-5)
- Highlights and scientific output

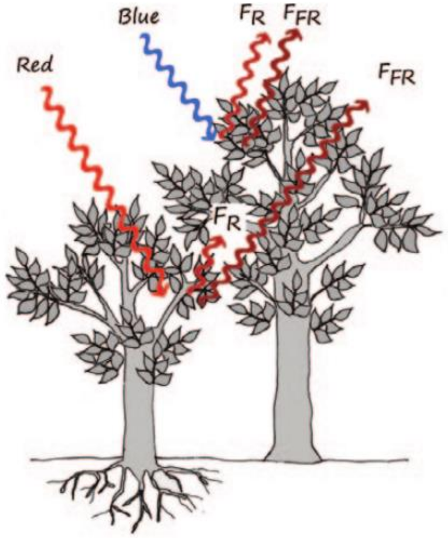
Context of the research

ESA EE8 FLEX mission

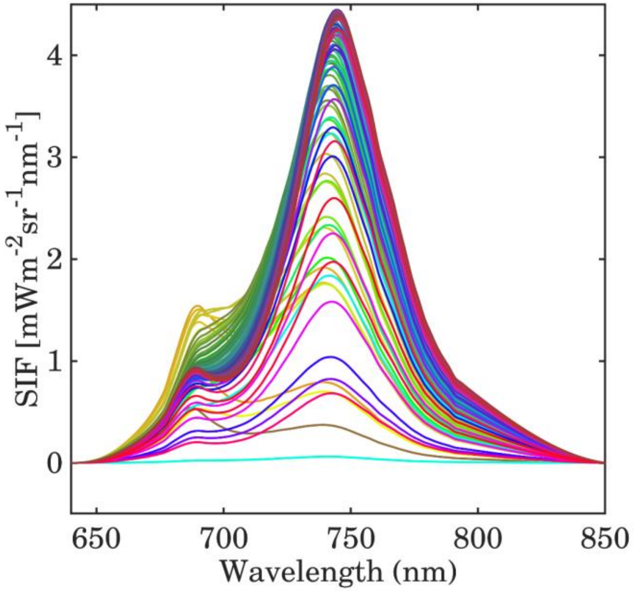
First mission conceived for global SIF retrieval at 300m x 300m spatial resolution

- Solar-induced chlorophyll fluorescence (SIF) is emitted at photosystem level as a function of absorbed excitation energy (APAR) and SIF quantum efficiency (Φ_F)
- Propagates through the leaf and the canopy → top of canopy fluorescence (→ RS measurements – O_2 bands + full spectrum)
- Inherently linked to the functioning of the photosynthetic machinery
- Highly dynamic in time and space





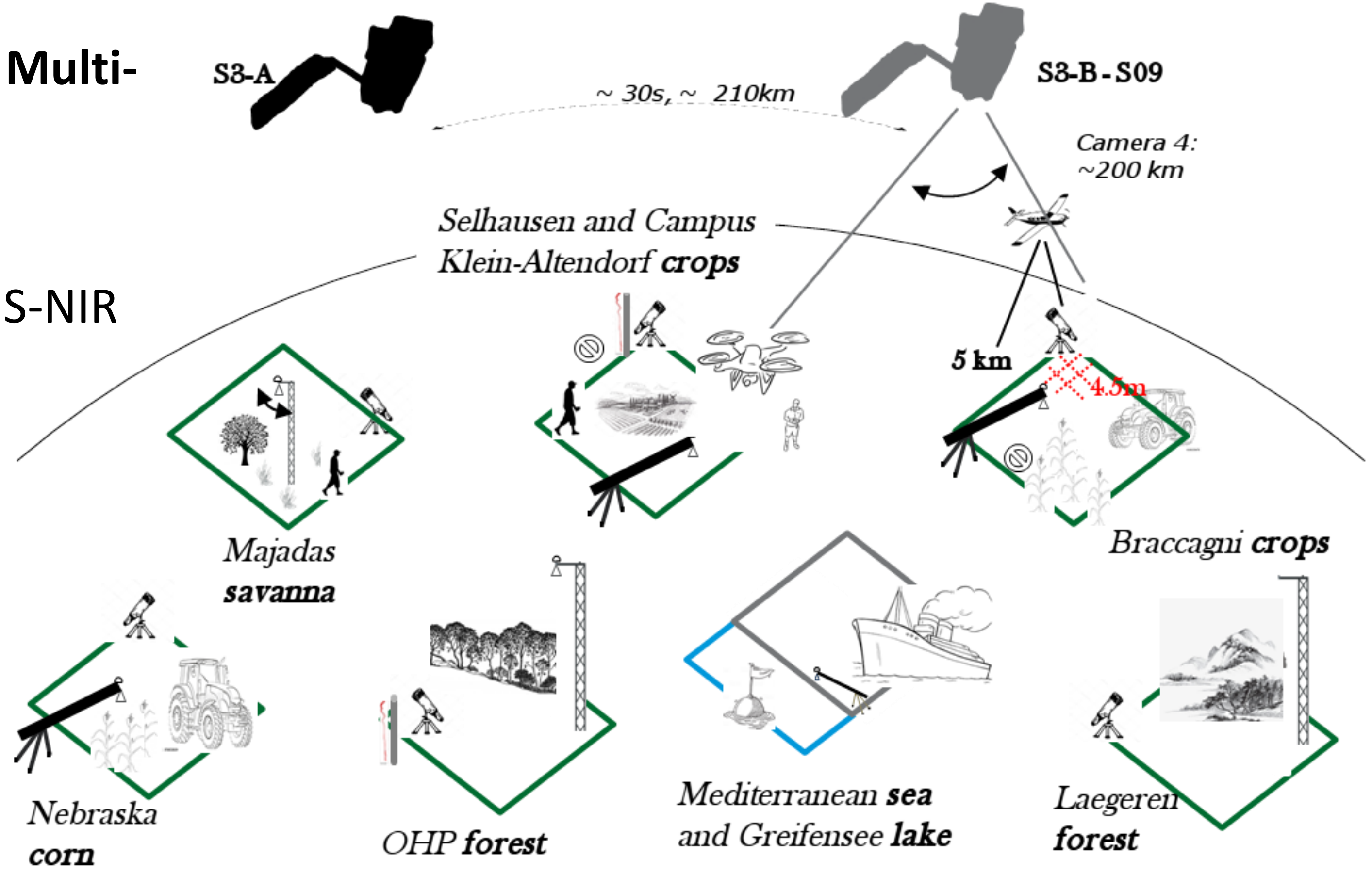
Porcar-Castell et al. (2014) *Journal of Experimental Botany*



Experimental data collection

ESA FLEXSense + **ATMO-FLEX** campaign → **Multi-scale** dataset acquired in Summer 2018

- Long term ground based hyperspectral VIS-NIR measurements (FLOX)
- Airborne overpasses (HyPlant → FLEX demonstrator)
- S-3B OLCI "FLEX mode" acquisitions
- Ancillary data (site specific)



Project overview

MULTI-FLEX: TOWARDS A STRATEGY FOR FLUORESCENCE MONITORING AT MULTIPLE SCALES WITHIN THE CONTEXT OF THE FLEX/S-3 TANDEM MISSION

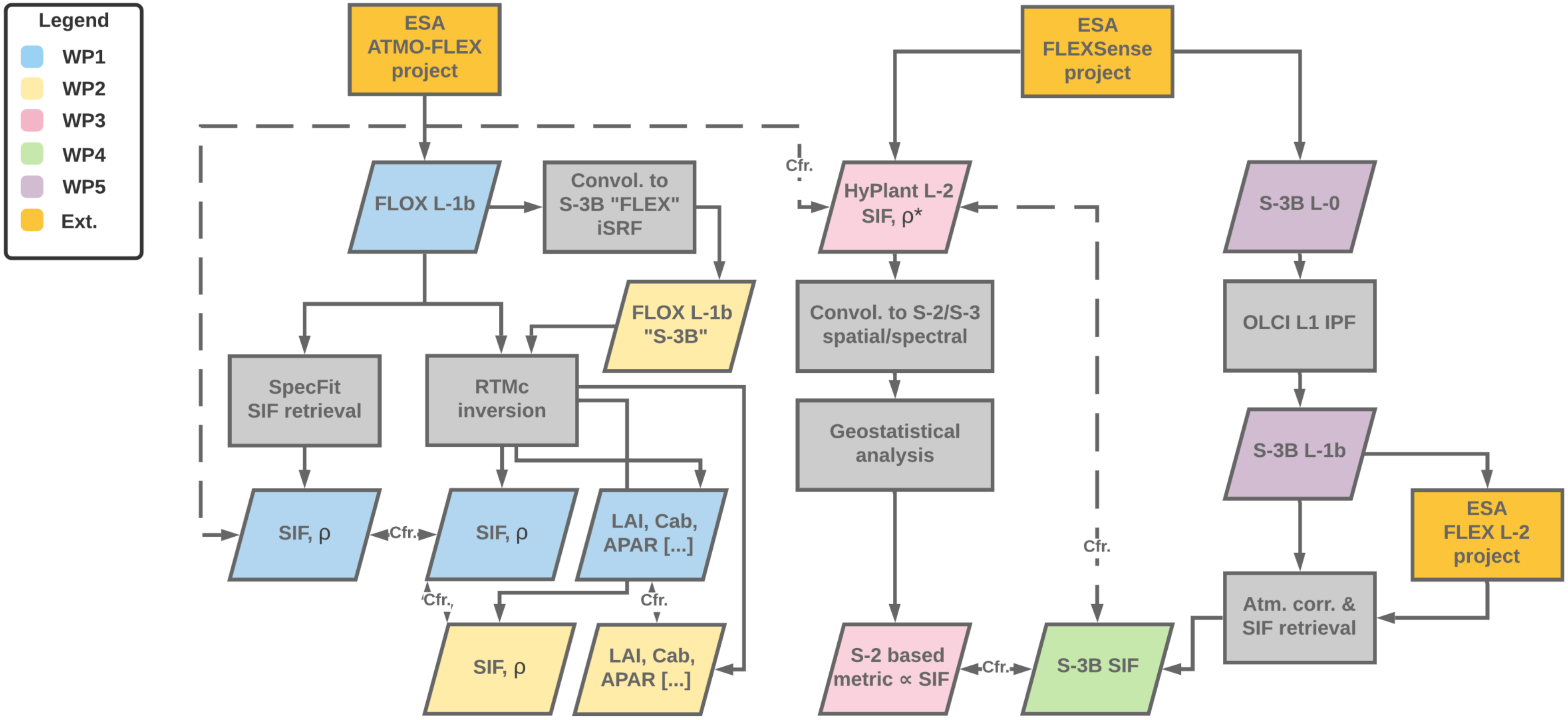
Duration: 1 Dec 2018 – 30 Nov 2020

Main objective: to explore the spectral, temporal and spatial variability of fluorescence for plant status monitoring exploiting multi-source remote sensing optical data

Specific objectives:

- to develop a processing chain for coupled retrieval of fluorescence and vegetation parameters from continuous ground hyperspectral measurements in FLEX-like spectral configuration;
- to adapt and test this inversion scheme to the spectral resolution of the reconfigured Sentinel-3B OLCI;
- to exploit HyPlant (TOC) products to test reflectance-based metrics capable of tracking the spatial heterogeneity of fluorescence
- to test these approaches on fluorescence products derived from the reconfigured Sentinel-3B OLCI data

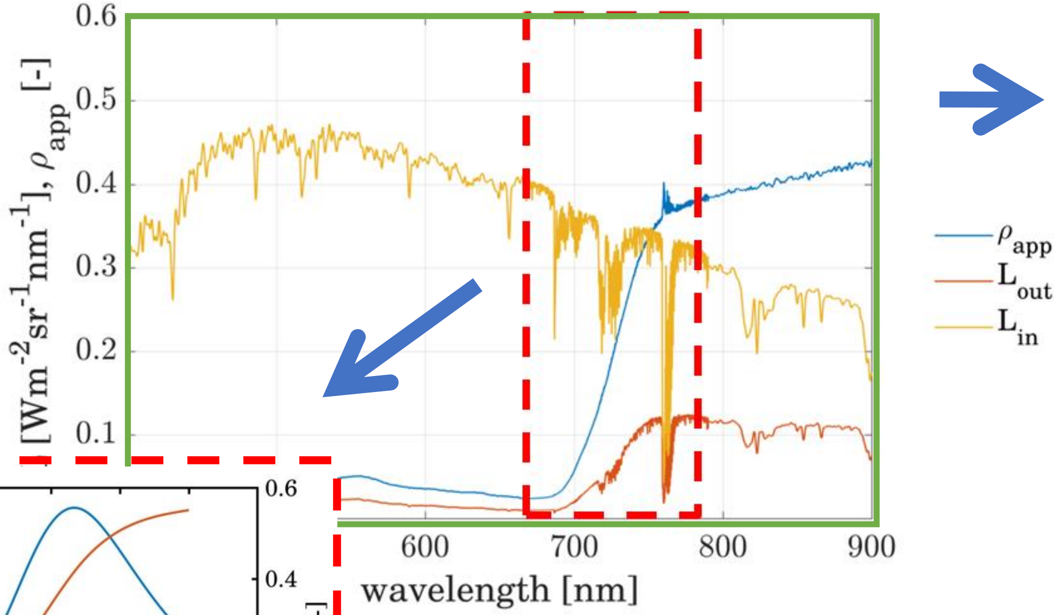
Project workflow

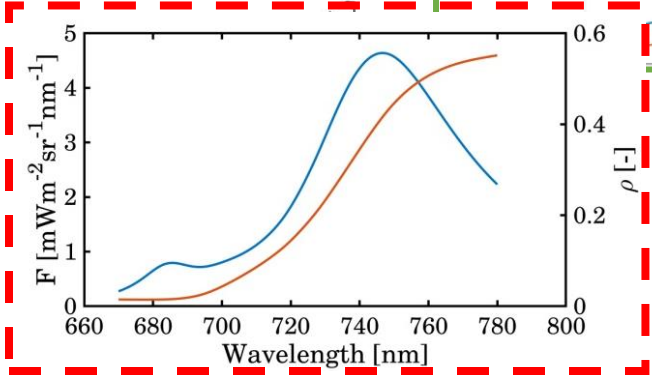


Data & Methods [WP1]

Coupled retrieval of fluorescence and vegetation parameters from continuous ground hyperspectral measurements

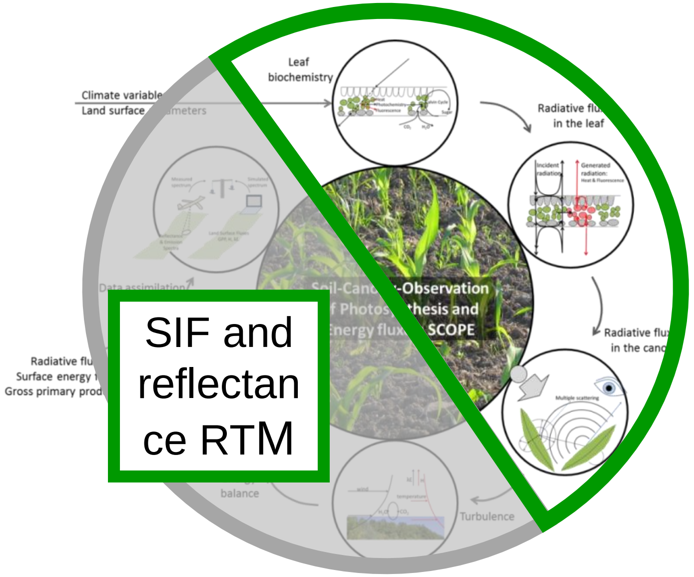
FLOX VIS-NIR data





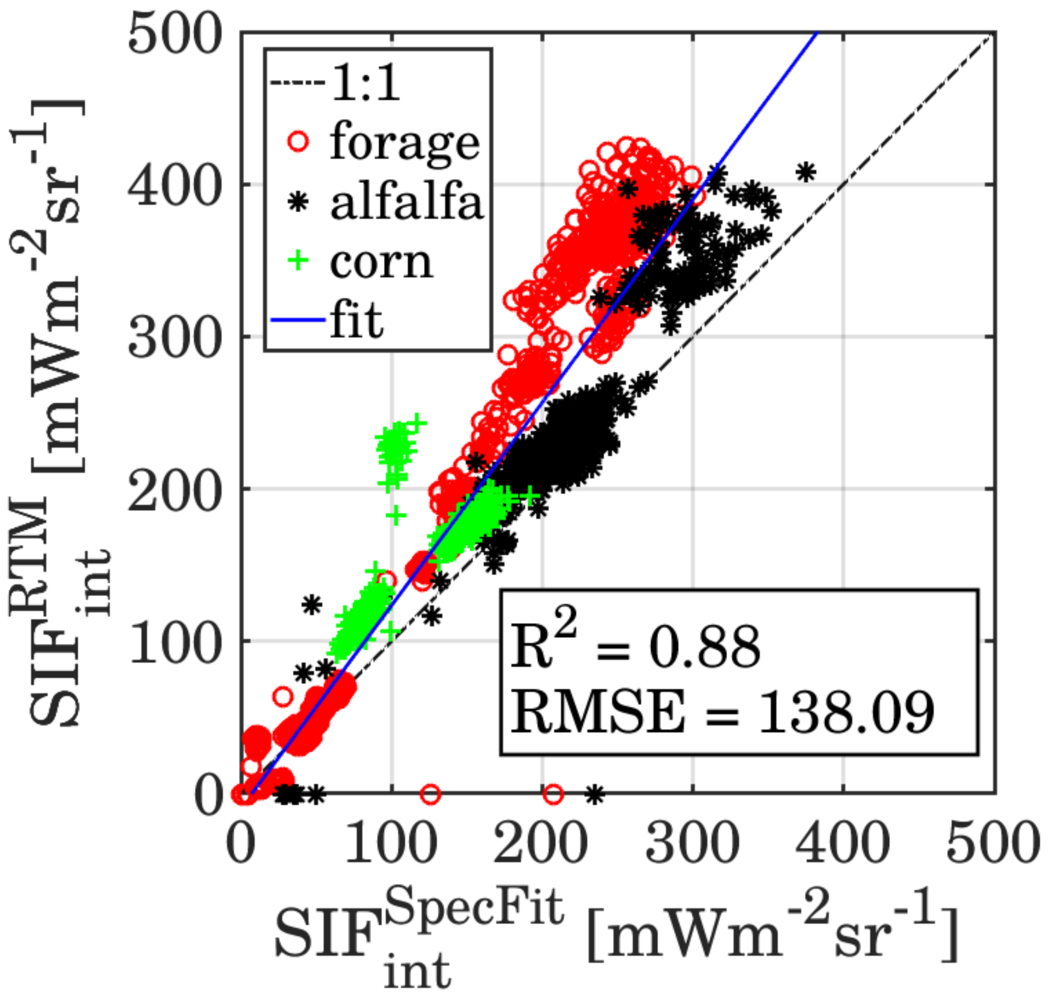
SpecFit (after Cogliati et at., 2019)

SCOPE model (RTM + fluxes)



Non-linear Least Square NO:
Cab, Cca, Cdm, Cw …
LAI, APAR …
Φ_F → fluorescence quantum efficiency

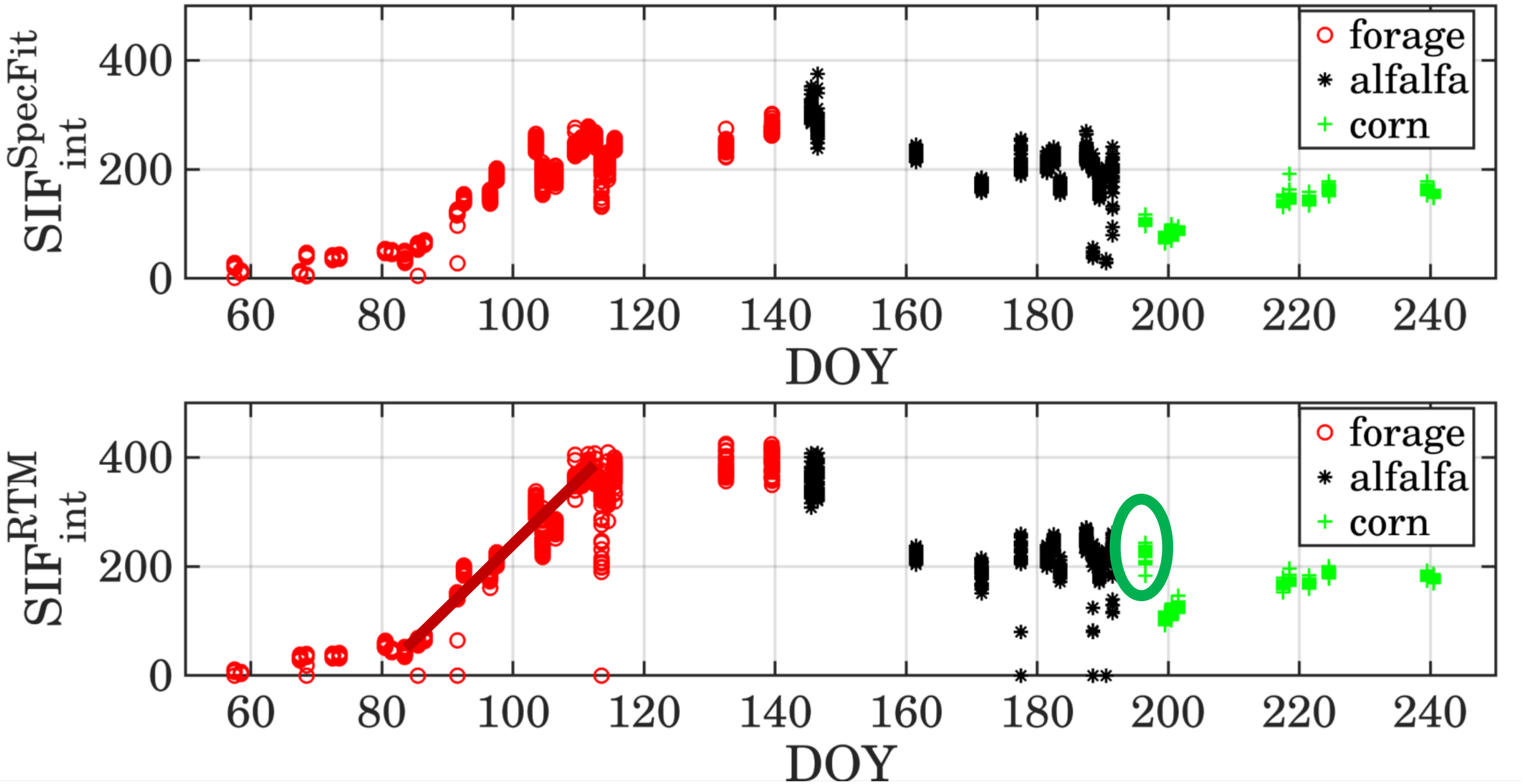
Results [WP1]



- Overestimation due to uncertain retrieval of SIF-driving parameters (e.g., LAI, Cab)
- Crop specific trends suggest potential incorrect representation of different leaf angle distribution functions (LADf)
- Soil contribution to apparent reflectance might play a confounding role for low LAI

Results [WP1]

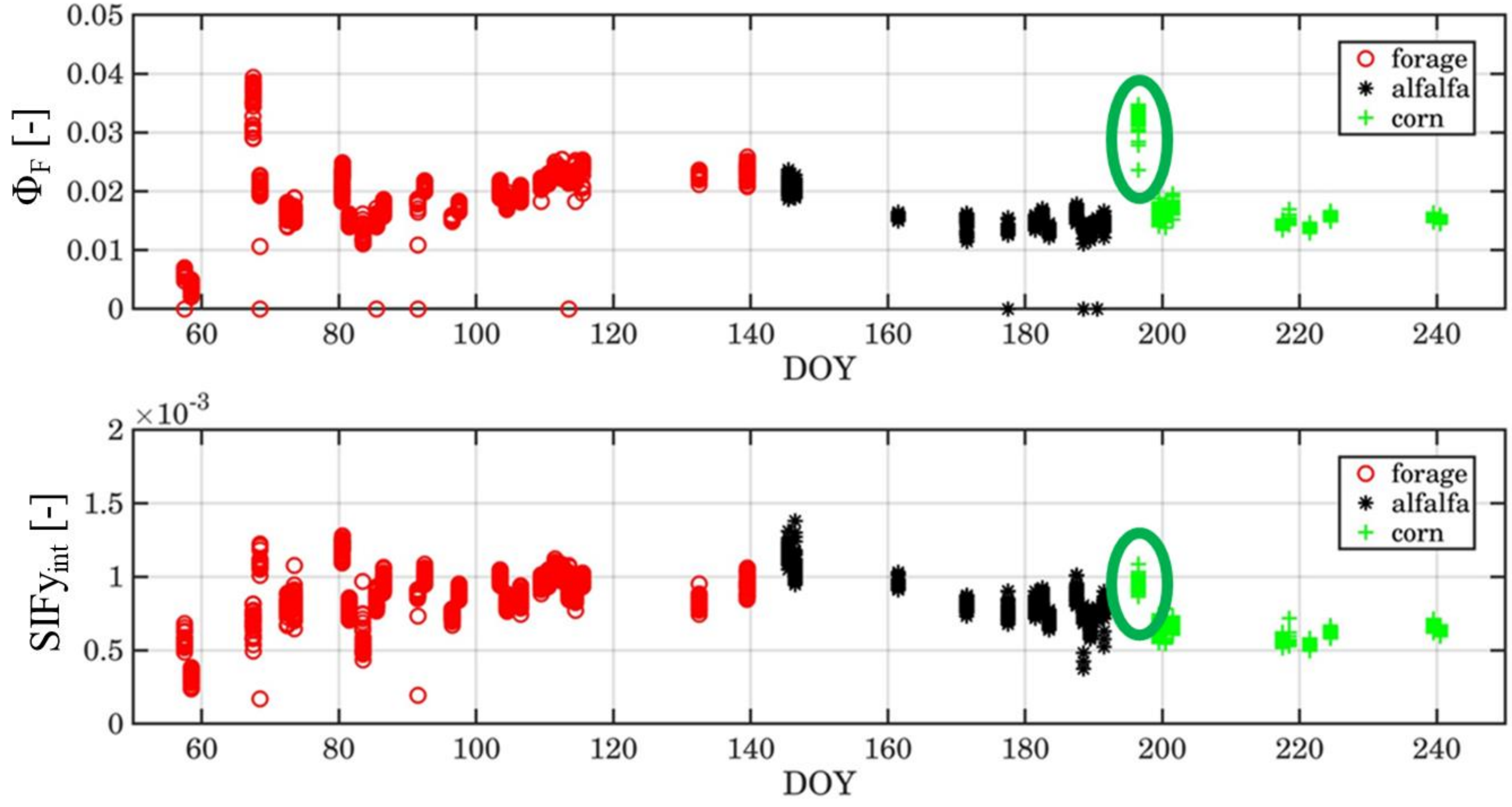
Time series of full spectrum SIF integral retrieved with SpecFit and with RTM inversion



- Trends are generally maintained
- Absolute values are overestimated

- Largest discrepancy during forage growing phase and beginning of corn growth

Results [WP1]



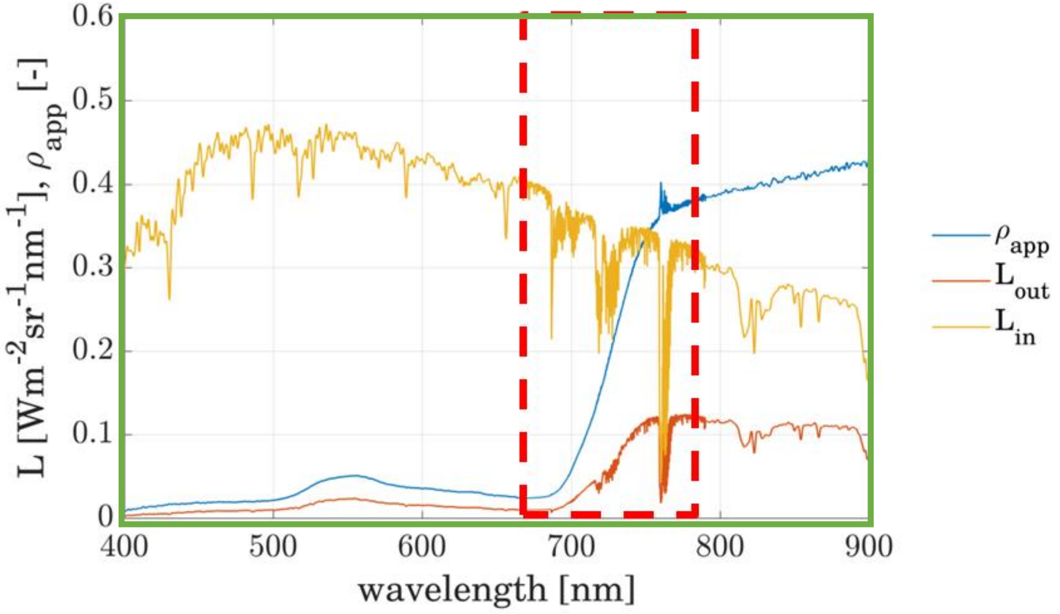
Nevertheless, the retrieved Φ_F values are coherent with what shown by the most widely used normalized SIF metric → APAR is relatively much lower than SIF

$$SIFy_{int} = \frac{F_{int}}{APAR}$$

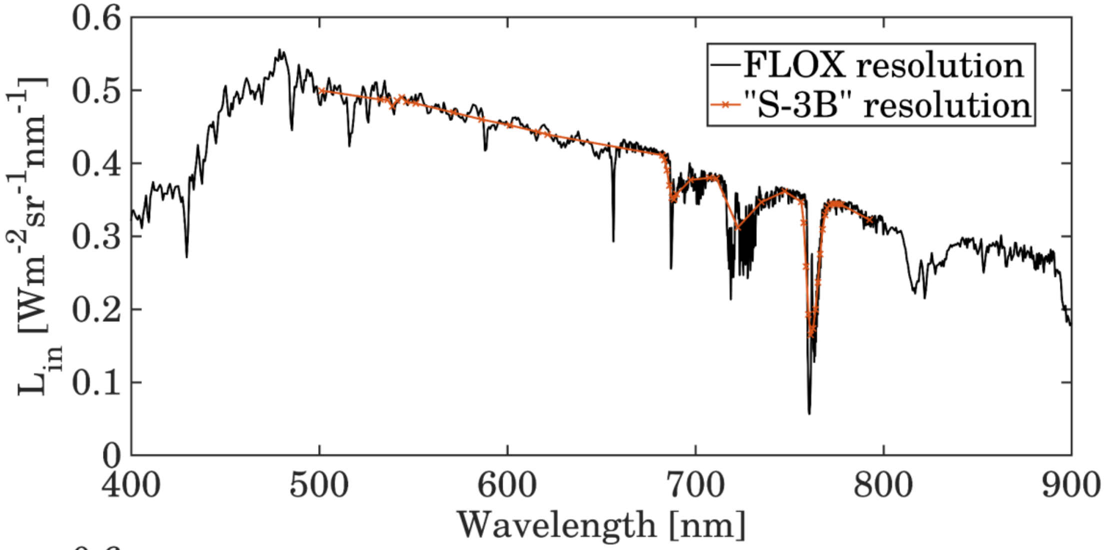
Data & Methods [WP2]

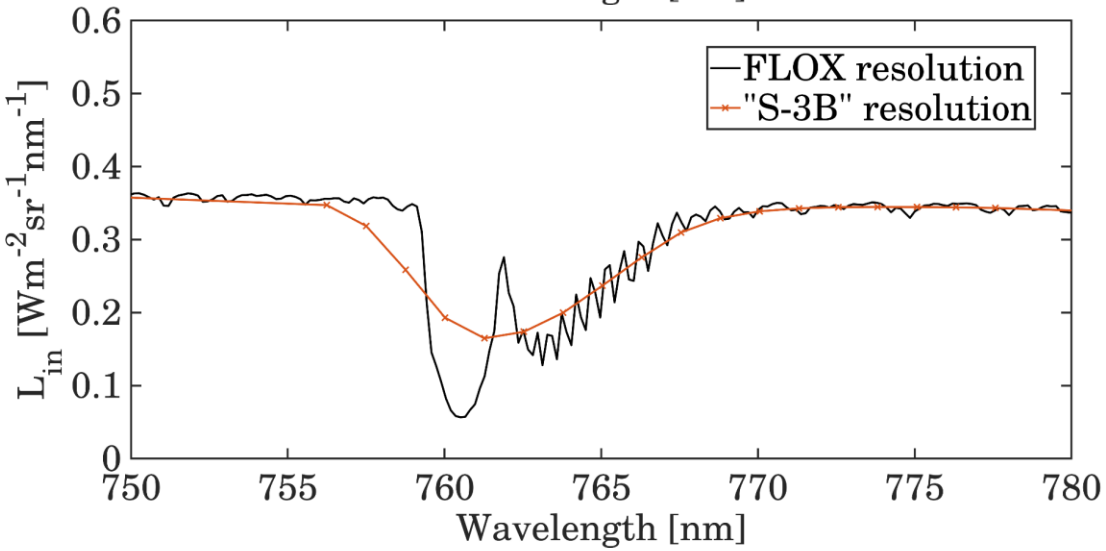
Testing SIF retrieval on reconfigured S-3B OLCI data (convolved FLOX data)

FLOX VIS-NIR data

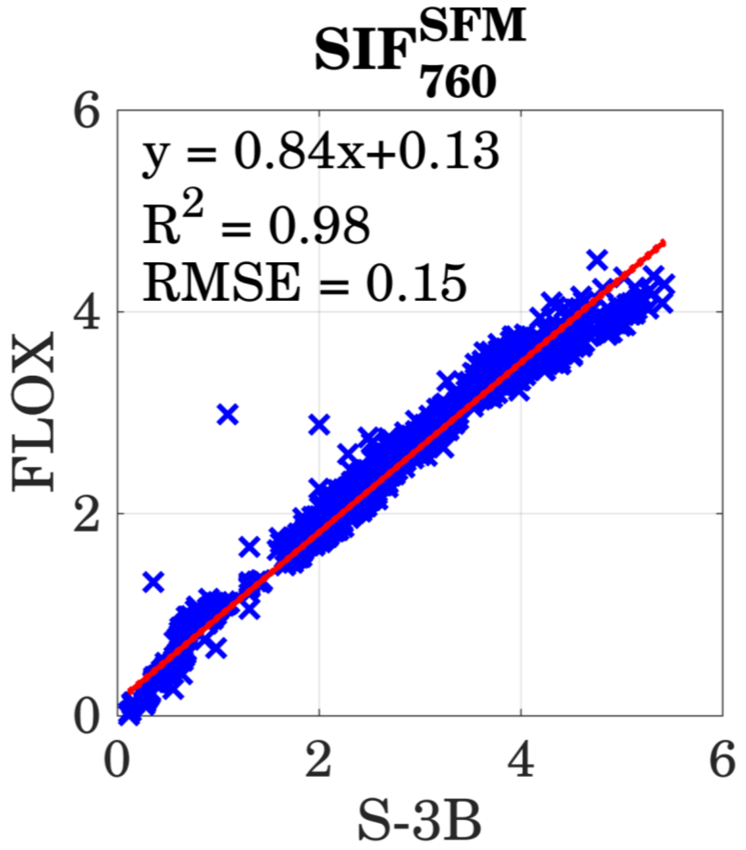


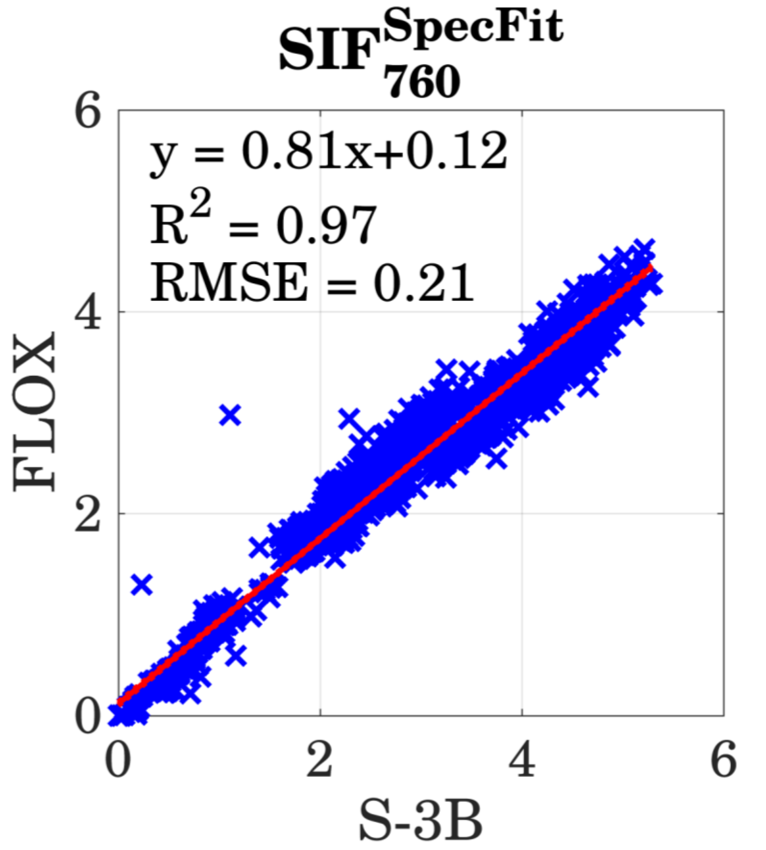
+ iSRF of the reconfigured S-3B OLCI





Results [WP2]





S-3B data reconstructed from FLOX data

SFM/SpecFit retrieval from S-3B "FLEX mode" data and cf. with reference data

- Overestimation due to the different spectral resolution (critical in the absorption bands where SIF is retrieved) but good overall relative agreement in the O_2-A band (SIF_{760})
- Simple retrieval approaches (e.g., FLD) do not work well in the O_2-B band while a higher spectral resolution is required for complex methods. SFM did not converge, SpecFit did but values not comparable with reference

Data & Methods [WP3]

Evaluation of proximal sampling approaches and S-2 based metrics towards SIF cal/val

Data

- Hyplant SIF_{760} maps – agricultural landscapes
  - Selhausen (Germany): 1-3m spatial res.
  - Braccagni (Italy): 4.5m spatial res.
  - All resampled to 9m grid
- Land cover map
  - Selhausen: **31 «homogeneous» fields** (ie a single crop) and 11 FLEX pixels (potentially more than one crop)
  - Braccagni: 30 «homogeneous» fields and 48 FLEX pixels
- 200 random points for each polygon
  - Minimum distance imposed so that a pixel is never sampled twice

Selhausen (Germany) 26 June 2018 – homog. fields

Data & Methods [WP3]

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Selhausen (Germany) 26 June 2018 – FLEX pixels

Data & Methods [WP3]

Evaluation of proximal sampling approaches and S-2 based metrics towards SIF cal/val

- SIF values extracted from random points (9m x 9m) simulate proximal sensing measurements
- Aggregated SIF at 300m x 300m simulates the FLEX pixel value

→Only the uncertainty linked to the spatial sampling is assessed

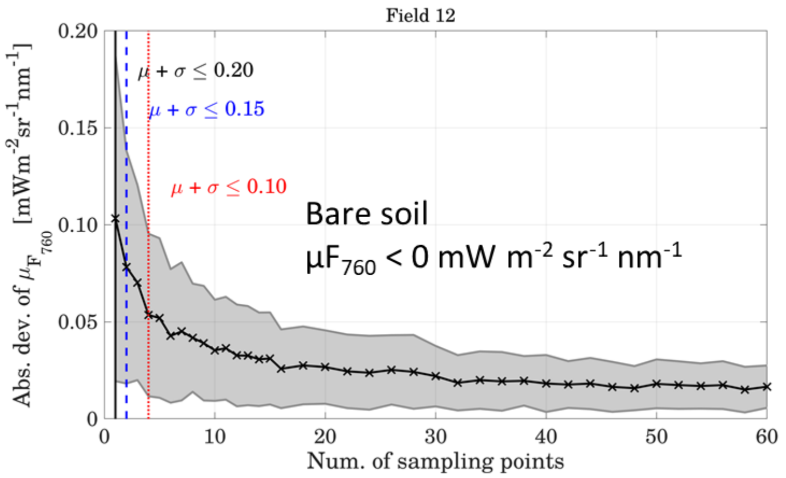
- ADM was calculated for increasing number of sampling points following a bootstrap approach

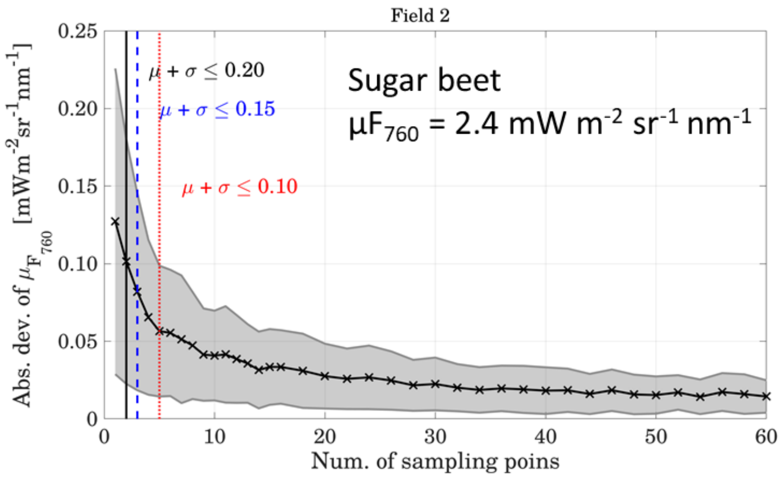
$$ADM = \left| \frac{\sum_{n=1}^{npts} SIF_{760,n}^{points}}{npts} - \mu_{SIF_{760}^{field}} \right|$$

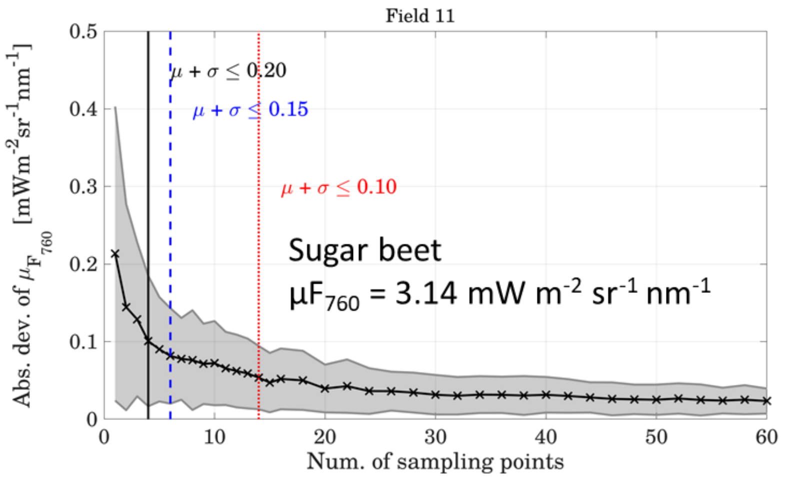
Selhausen (Germany) 26 June 2018 – FLEX pixels

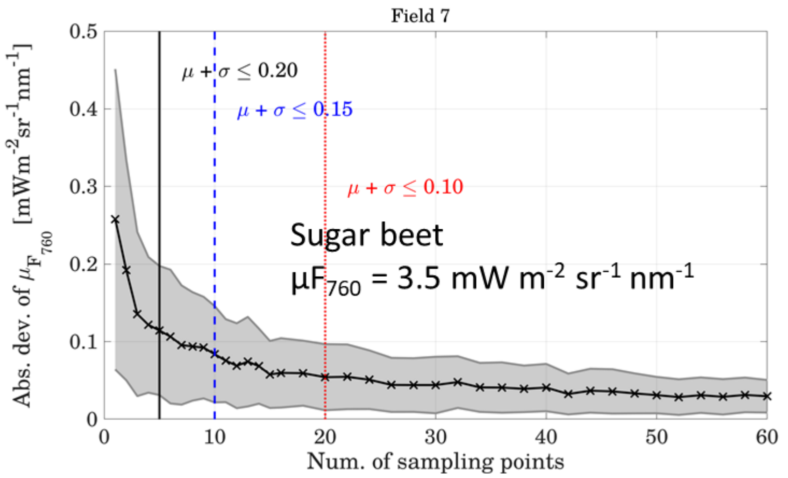
Results [WP3]

Homogeneous fields

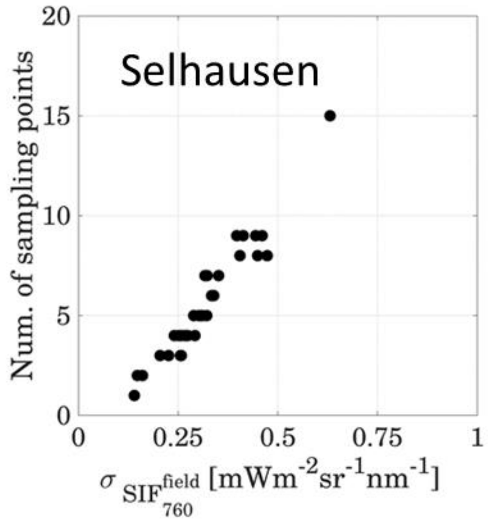


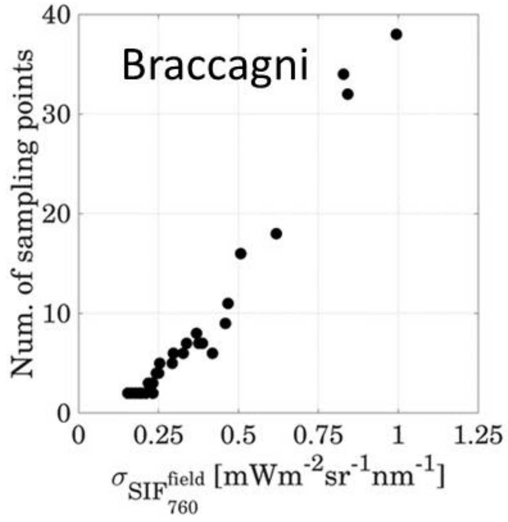






Threshold 0.2 mW m-2 sr-1 nm-1

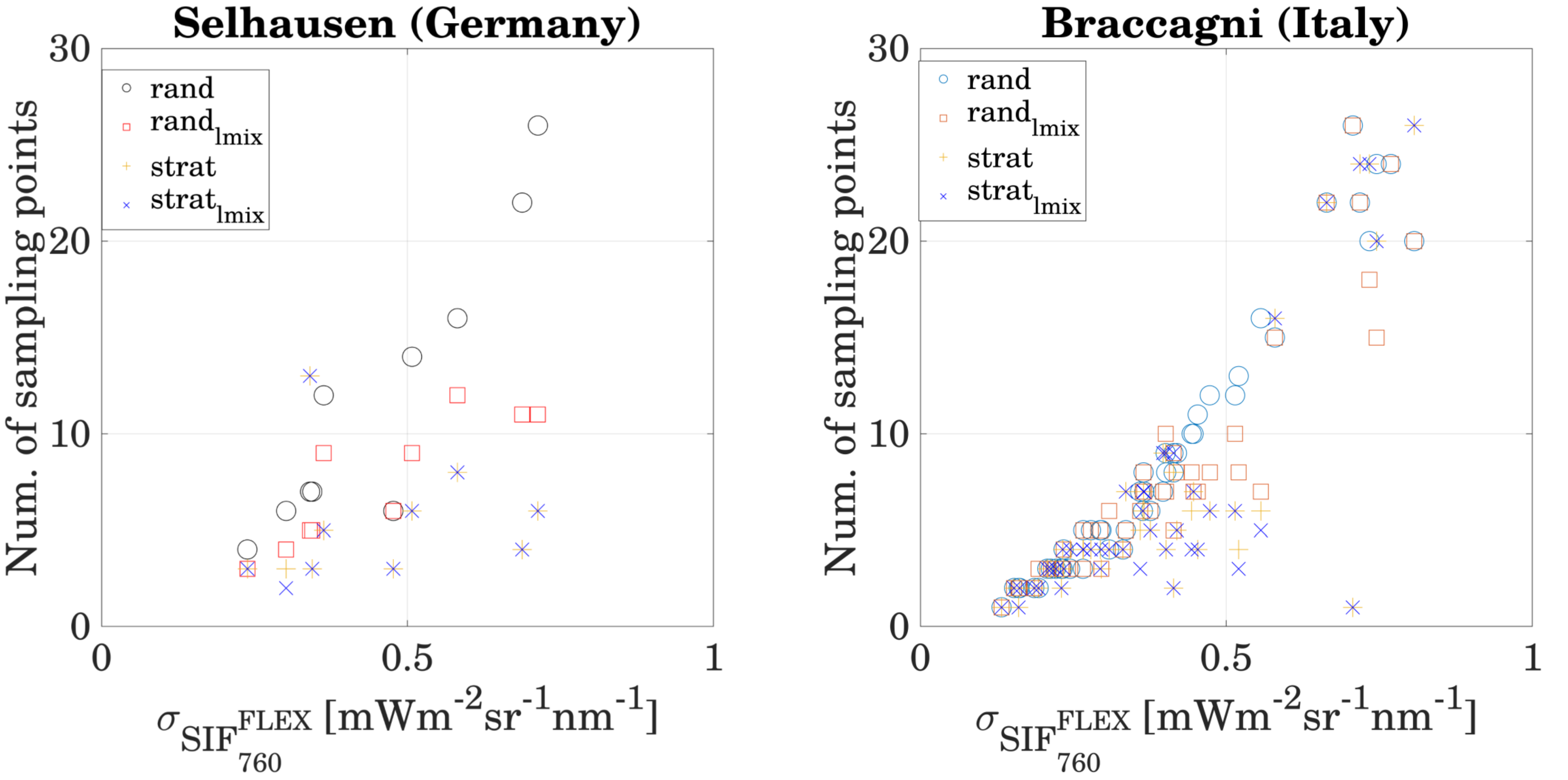




Results [WP3]

Threshold 0.2 mW m-2 sr-1 nm-1

FLEX pixels



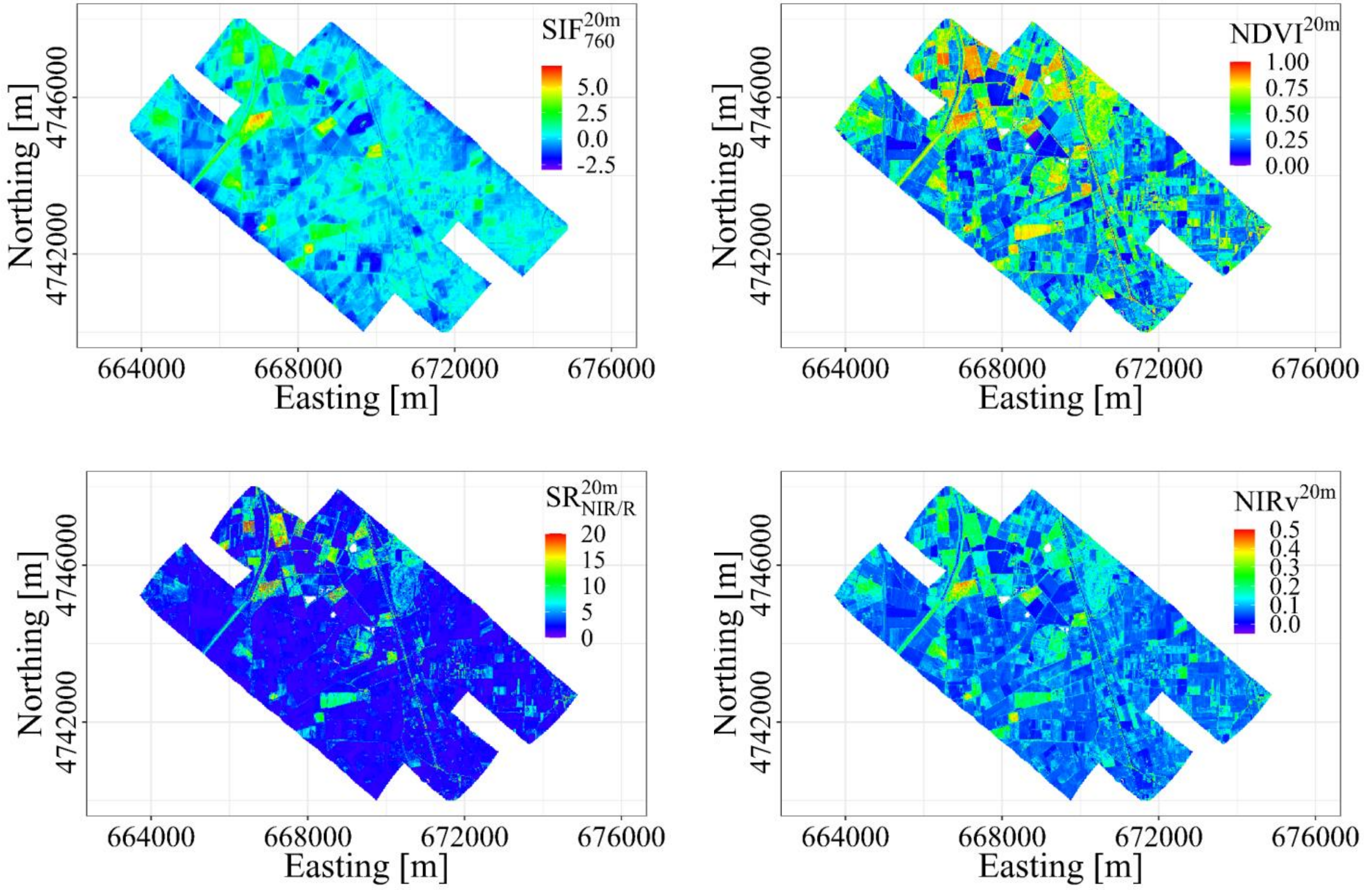
Data & Methods [WP3]

Evaluation of proximal sampling approaches and S-2 based metrics towards SIF cal/val

Data

- HyPlant SIF_{760} maps
  - Resampled to 20m and 300m grid
- HyPlant surface reflectance (370-2500nm) maps
  - Convolved to Sentinel-2 bands
  - Resampled to 20m and 300m grid
  - Several VIs calculated on spectrally convoluted data (e.g. NDVI, SR, ARVI, EVI, NIRv)
  - Per-pixel CV of spectral reflectance

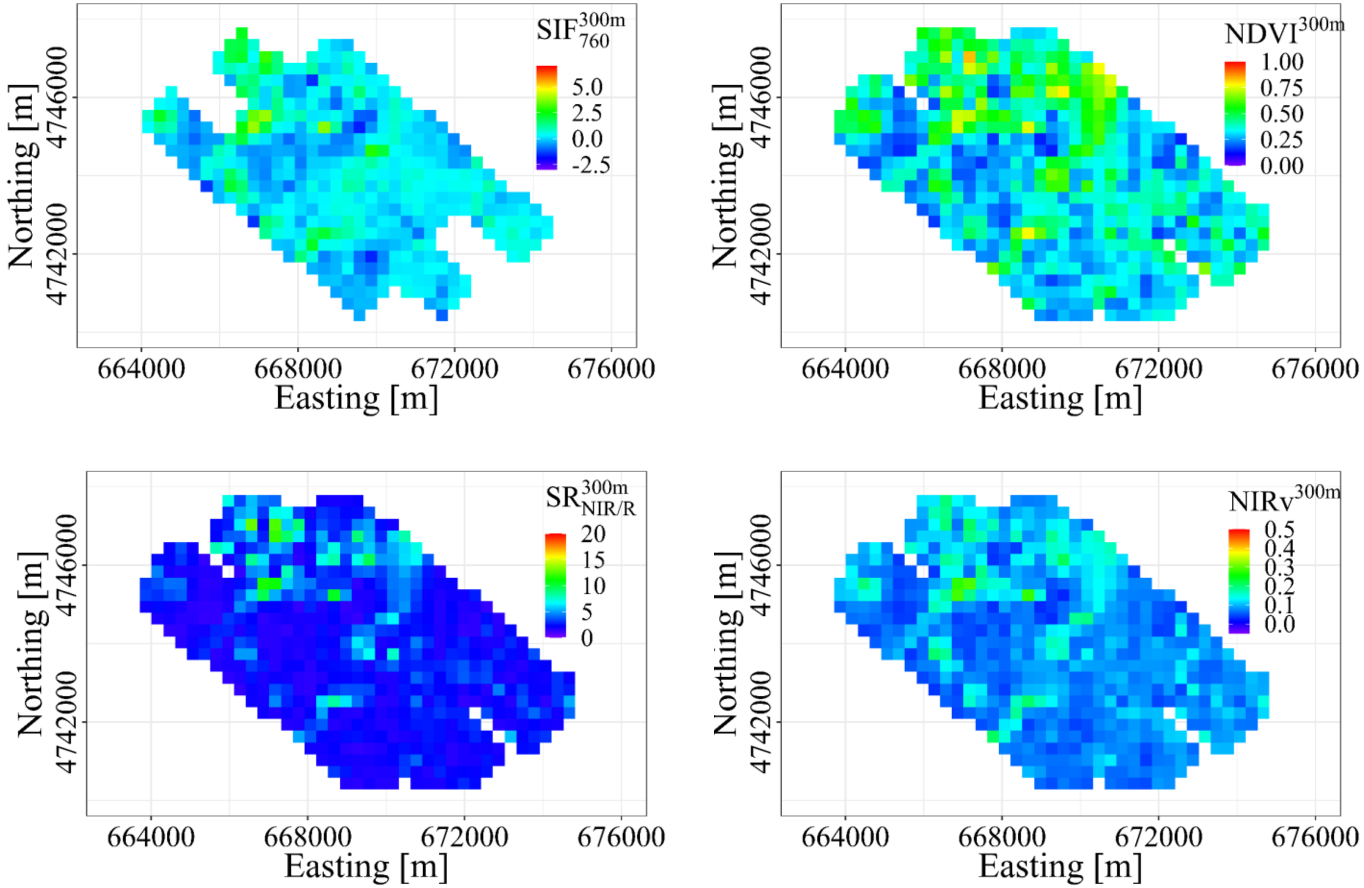
Braccagni (Italy) 26 June 2018 – 20m



Data & Methods [WP3]

Evaluation of proximal sampling approaches and S-2 based metrics towards SIF cal/val

Braccagni (Italy) 26 June 2018 – 300m



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  - Resampled to 20m and 300m grid
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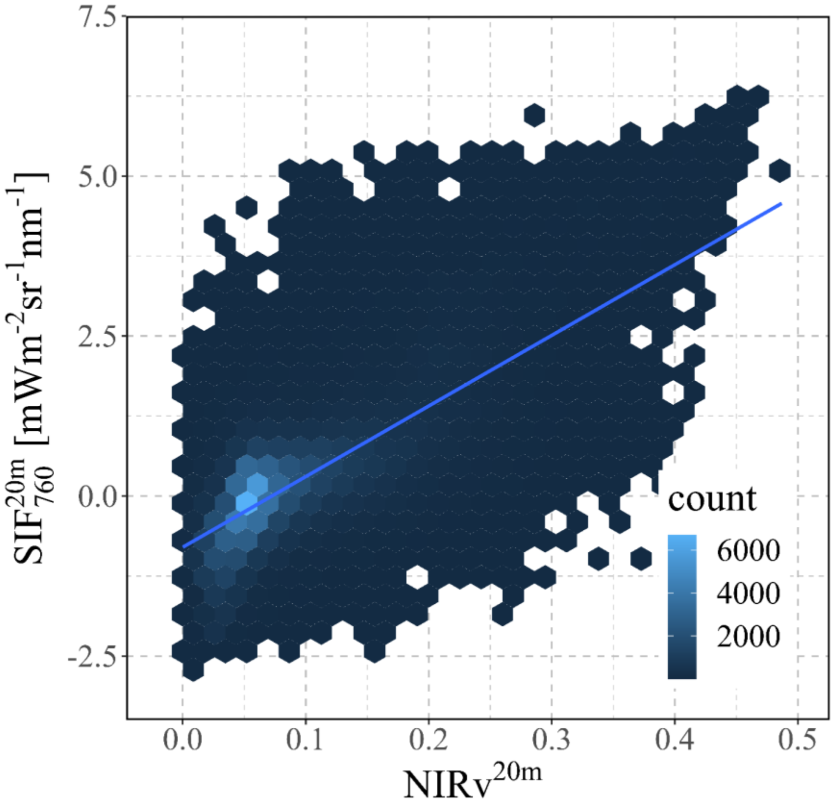
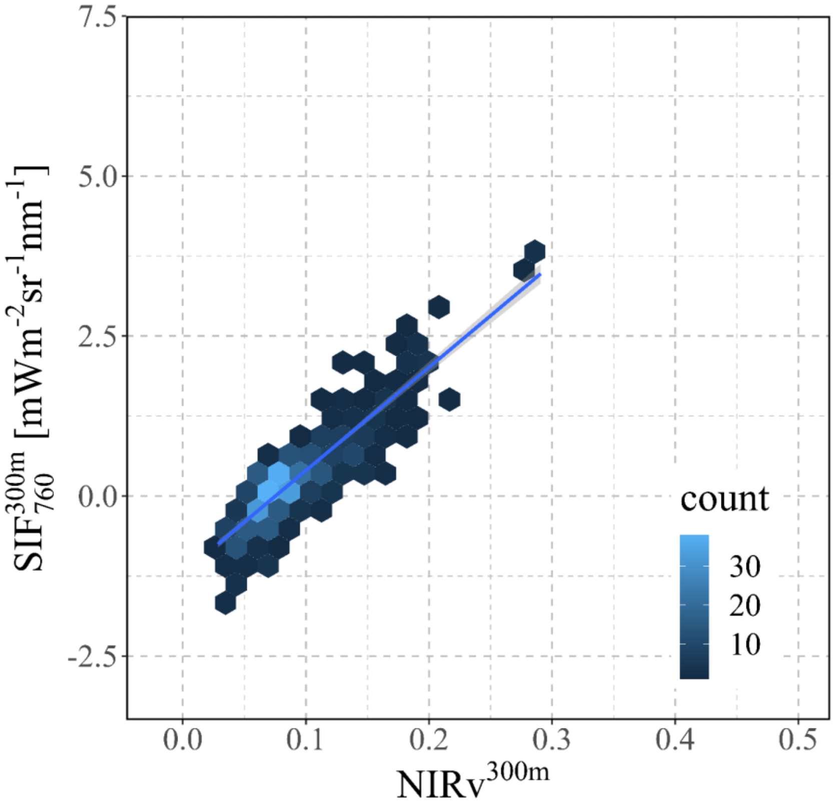
  - Several VIs calculated on spectrally convoluted data (e.g. NDVI, SR, ARVI, EVI, NIRv)
  - Per-pixel CV of spectral reflectance

Results [WP3]

20m x 20m

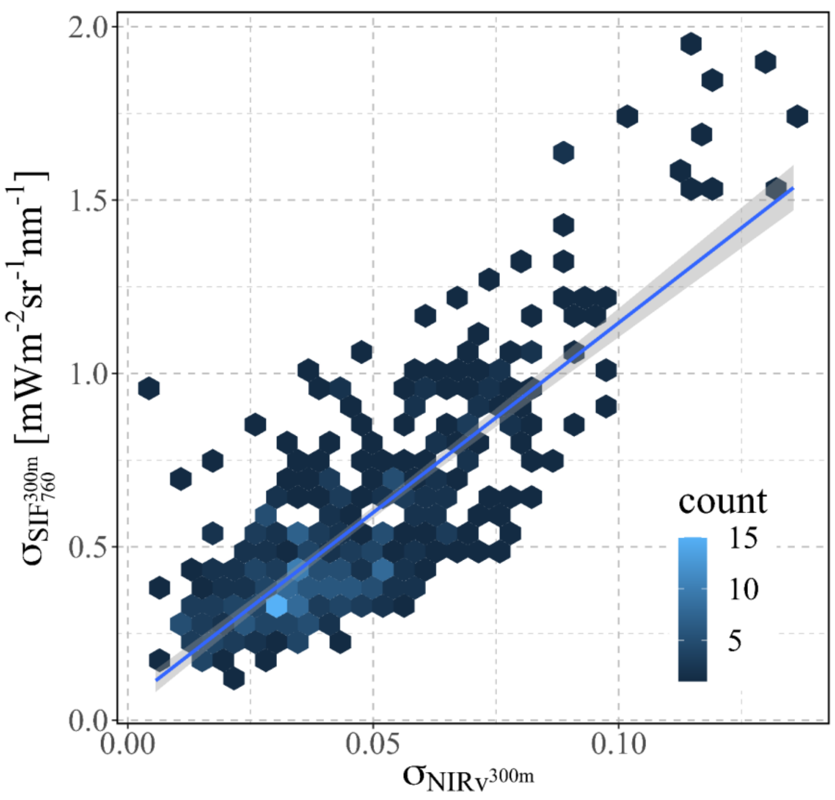


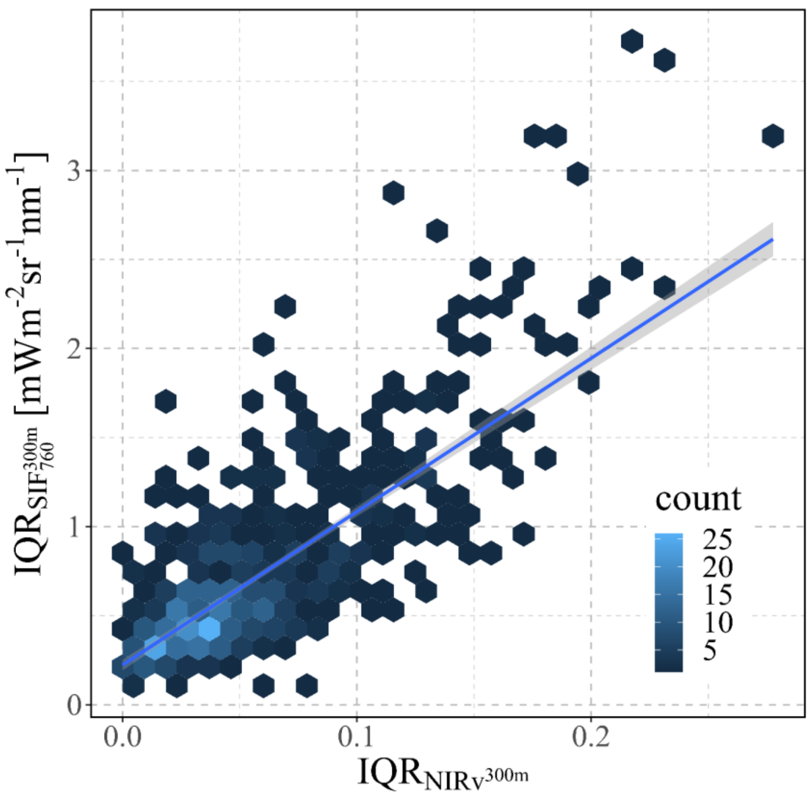
300m x 300m



- Among the tested VIs, NIRv showed highest correlation with SIF_{760} (particularly at 300m x 300m)
- Strong linearization when comparing spatially aggregated data

Results [WP3]





- A linear relationship can also be observed for standard deviation and interquartile range of SIF_{760} and NIRv computed at 300m x 300m

→ Potential use as a proxy for FLEX pixel SIF_{760} standard deviation to drive cal/val sampling strategy

Data & Methods [WP5]

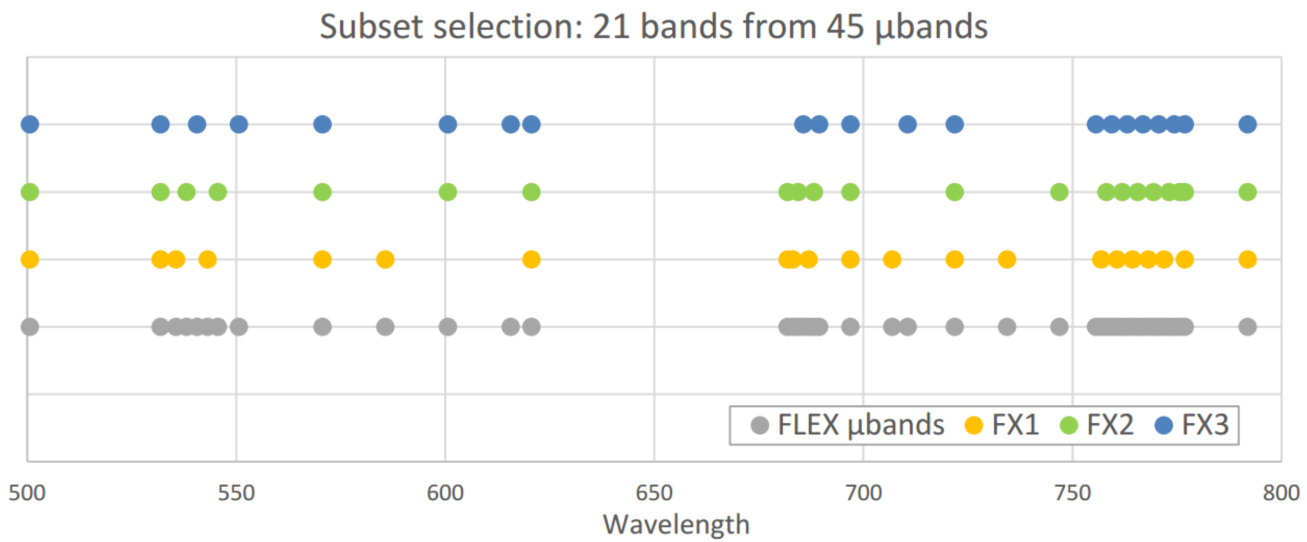
Processing of the reconfigured Sentinel-3B OLCI data to L1b TOA radiances

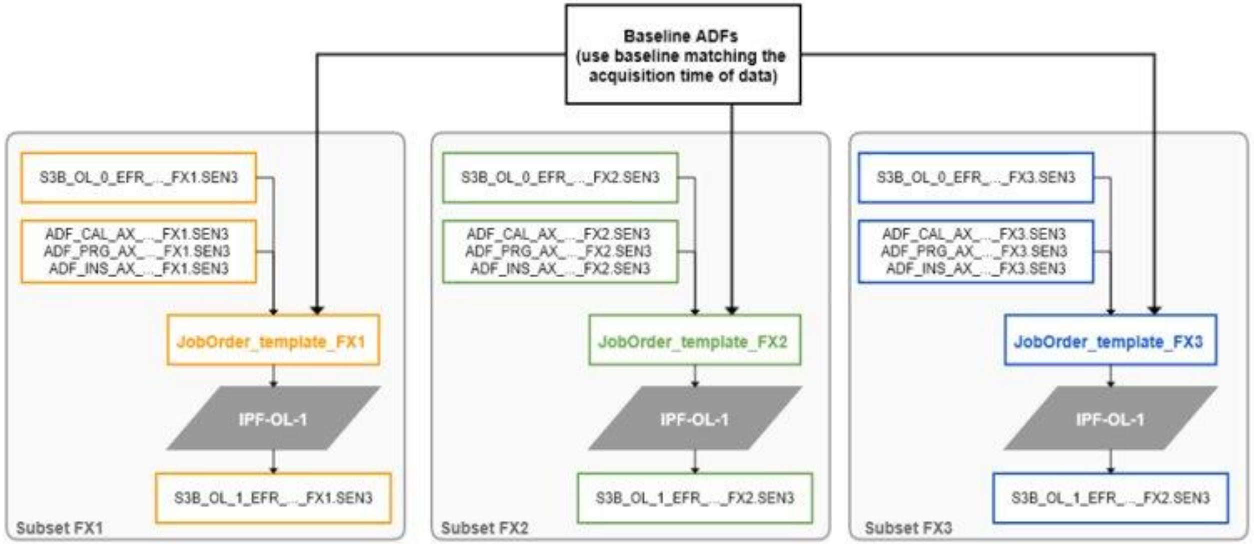
S-3B OLCI "FLEX-mode" = Modified S09 configuration:

- 45 µbands
- Focus on O_2-A and O_2-B

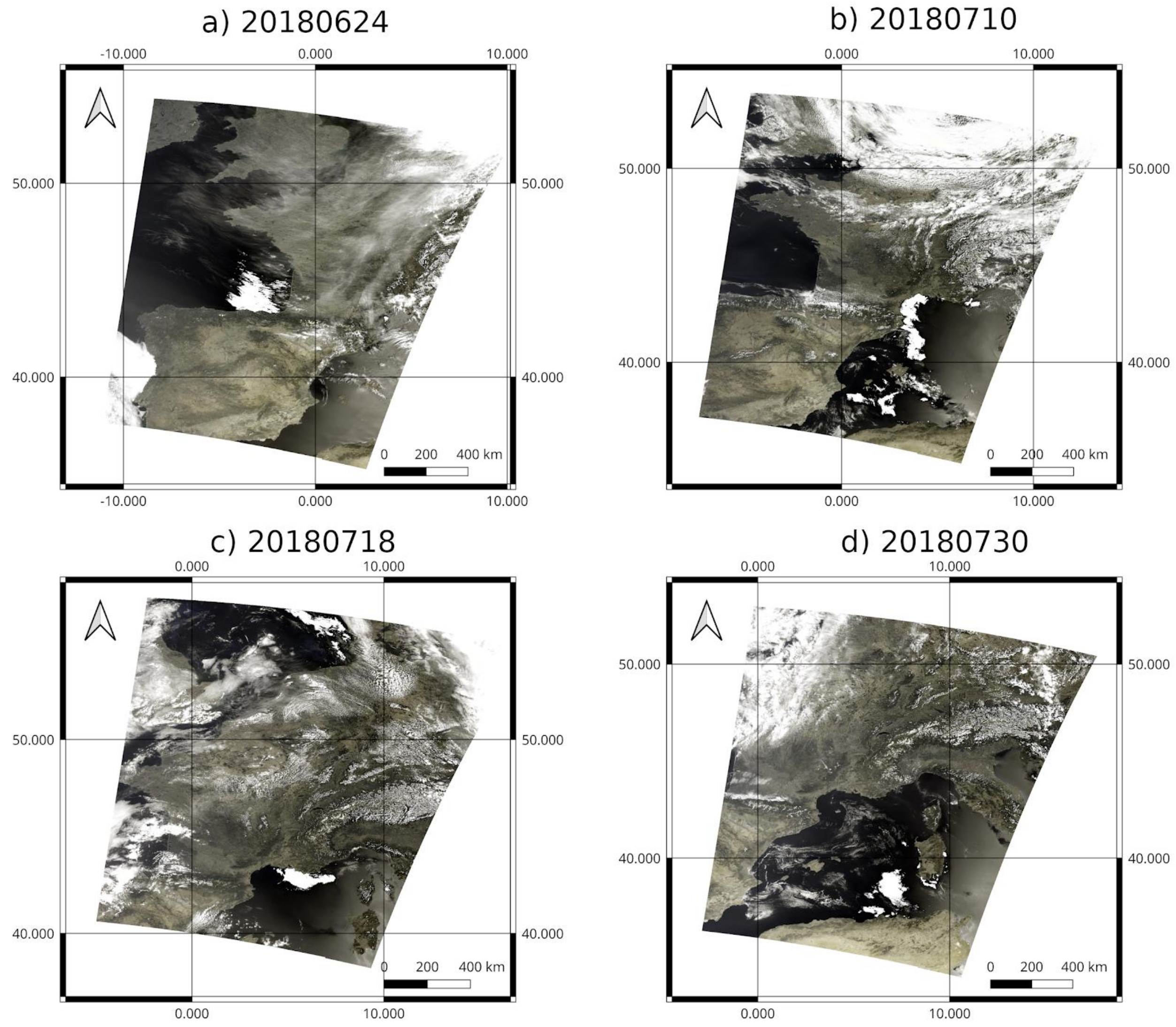
No ground processor capable of dealing directly with S09 data

- Preparation of Level-0 ISPs + ADFs in order to be processed with EO standard processor (i.e., three 21-bands subsets)





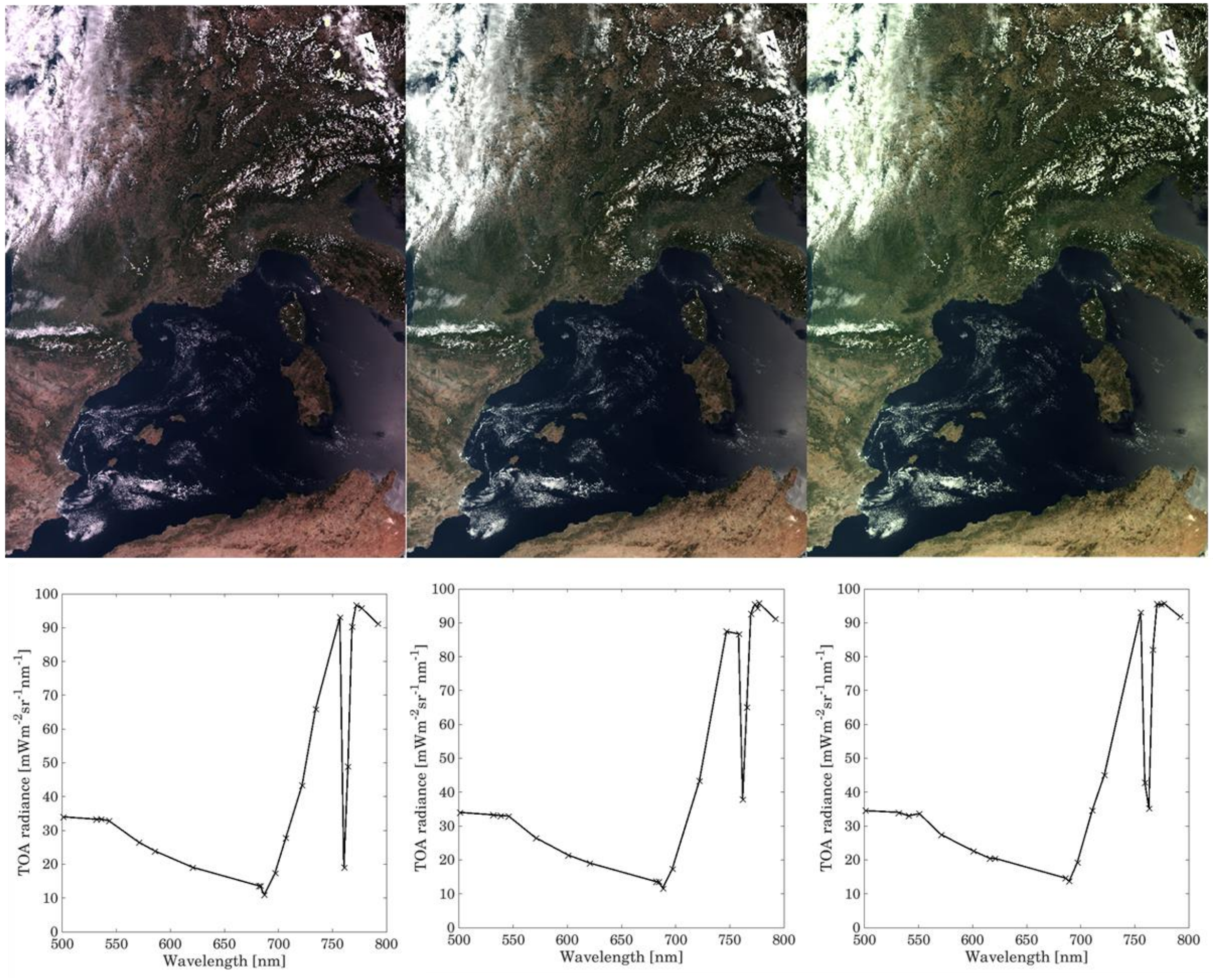
Results [WP5]



- All 24 S-3B “FLEX mode” acquisition were successfully processed up to L-1B TOA radiance
- Data were formatted into standard OLCI L-1B products
- Freely accessible through the ESA Earth Online data portal https://earth.esa.int/eogateway/campaigns/olci-tandem + scientific paper on processing and quality check (Celesti et al., under review in Scientific Data)

Results [WP5]

FX1 FX2 FX3



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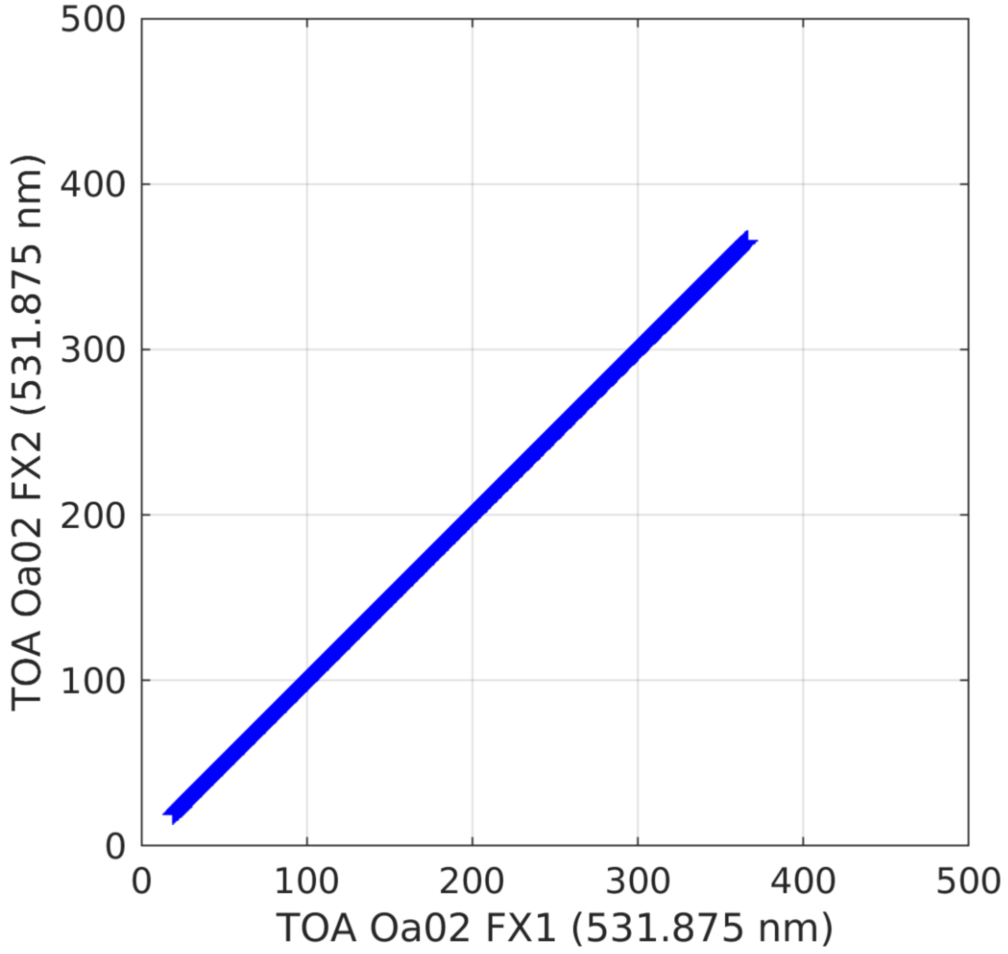
- How to quantitatively evaluate the performance of the processor with non-relaxed bands? Critical part is most likely stray-light correction…

Results [WP5]

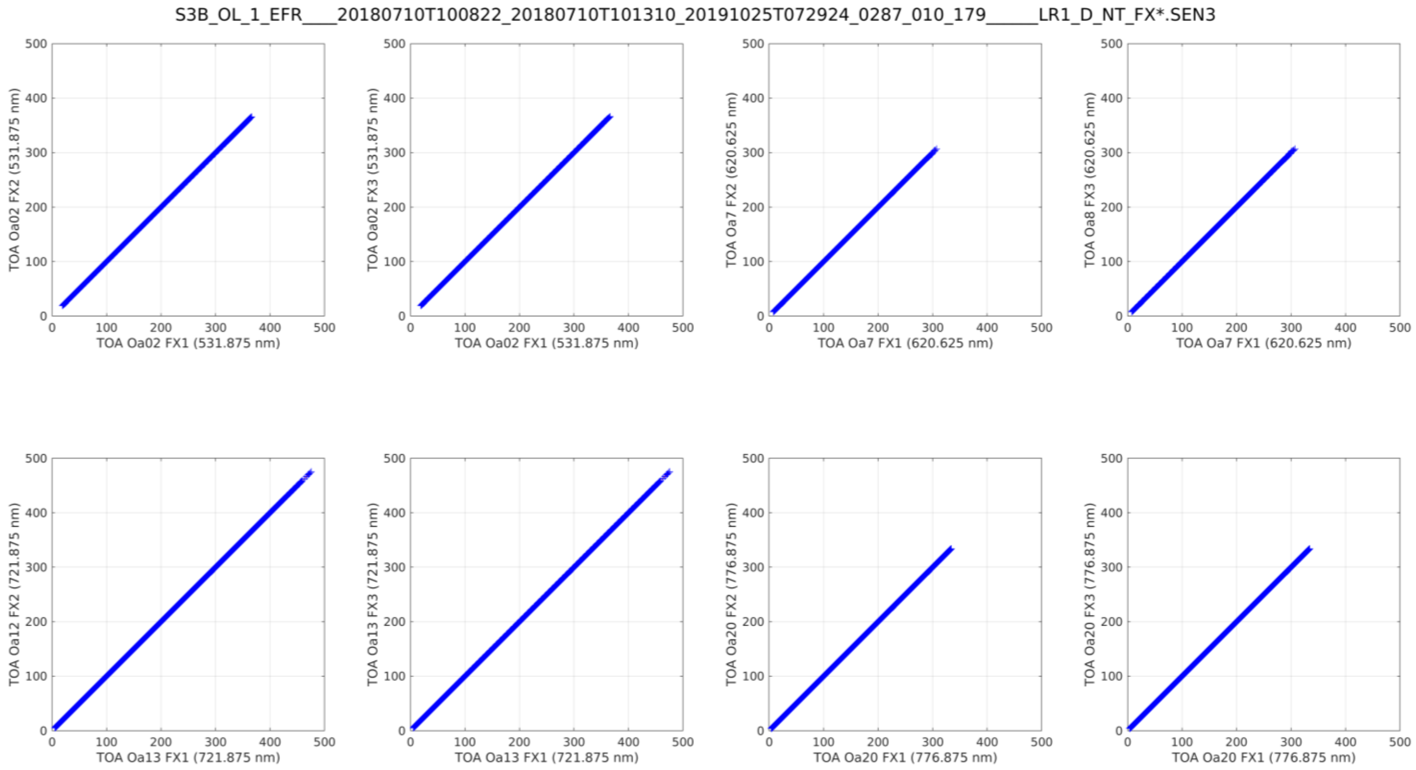
Q-Q plot between two subsets (same microband)



- How to quantitatively evaluate the performance of the processor with non-relaxed bands? Critical part is most likely stray-light correction…
- Comparison of common bands between FX1, FX2 and FX3 → very good match after removing saturated pixels

Results [WP5]

Q-Q plots between all common microbands



(Modified from Celesti et al., under review in Scientific Data)

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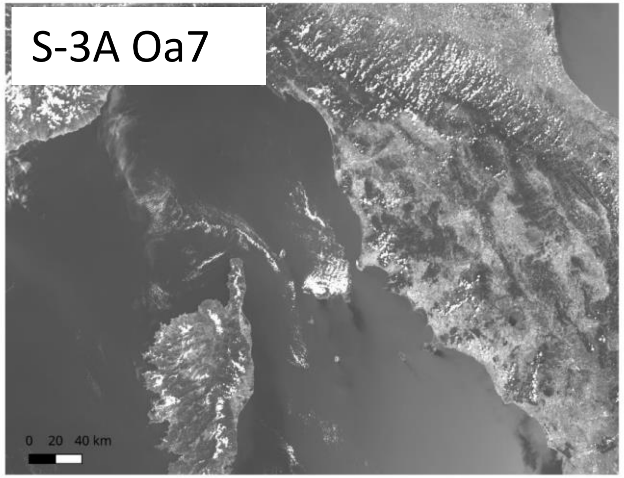
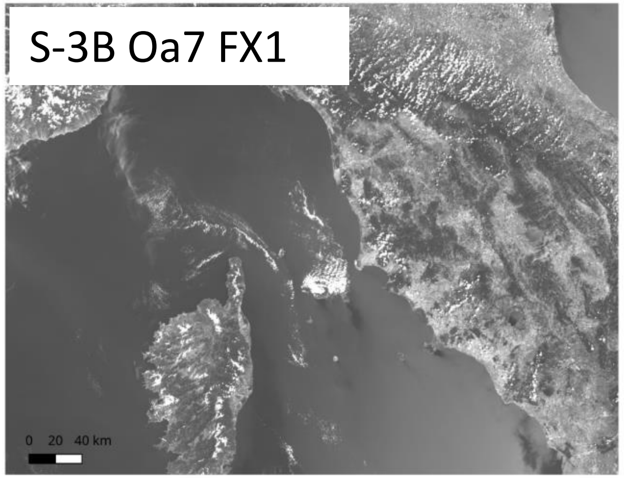
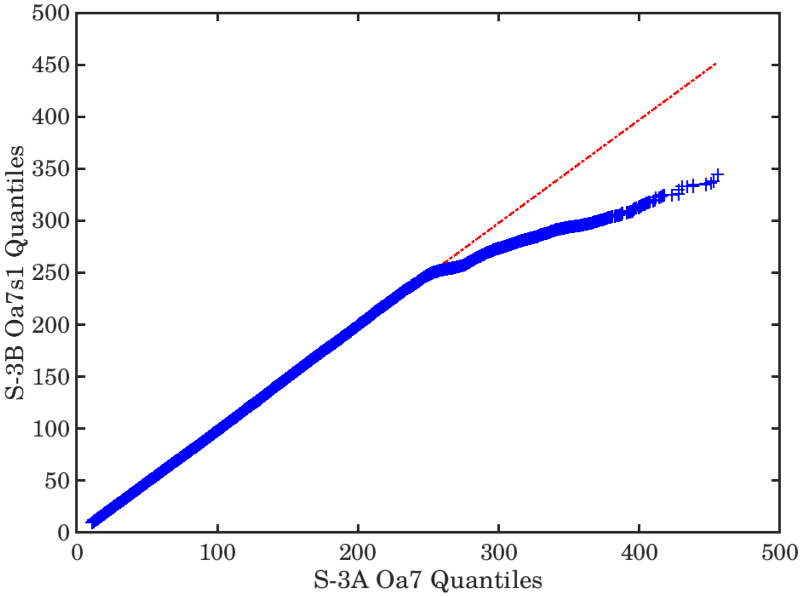
Results [WP5]



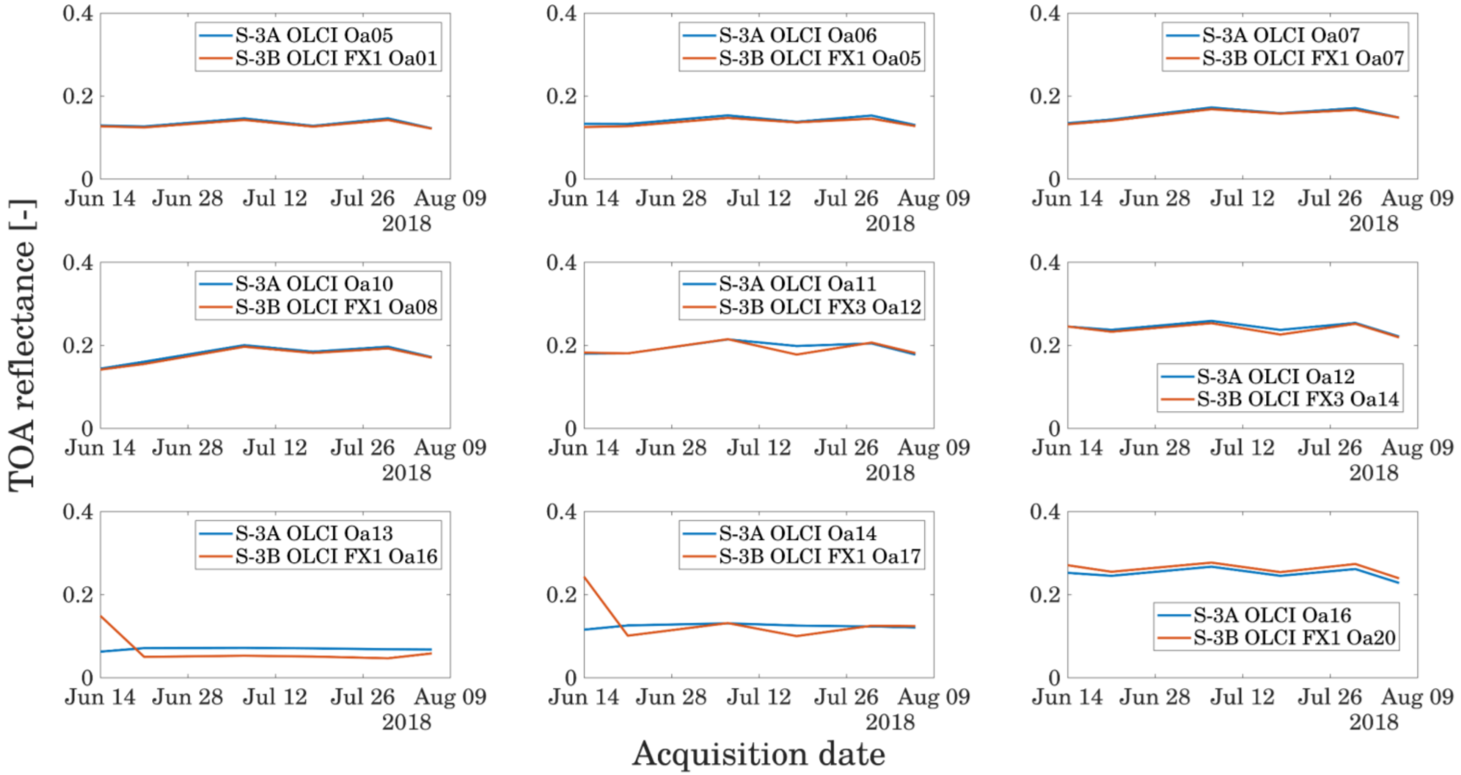




- How to quantitatively evaluate the performance of the processor with non-relaxed bands? Critical part is most likely stray-light correction…
- Comparison of common bands between FX1, FX2 and FX3 → very good match after removing saturated pixels
- Comparison with S-3A OLCI → very good agreement given the spectral discrepancy of the two products

Results [WP5]

Temporal trend of TOA reflectance over
La Crau (43.558 85° N, 4.864 472° E)



(Modified from Celesti et al., under review in Scientific Data)

- How to quantitatively evaluate the performance of the processor with non-relaxed bands? Critical part is most likely stray-light correction…
- Comparison of common bands between FX1, FX2 and FX3 → very good match after removing saturated pixels
- Comparison with S-3A OLCI → very good agreement given the spectral discrepancy of the two products
- “SF-TAPE” project (FUB) → characterize the uncertainty of S-3B “FLEX mode” L-1B data from S-3A + RTMs

Data & Methods [WP4]

Towards the exploitation of S-3B “FLEX mode” data: a bottom-up approach

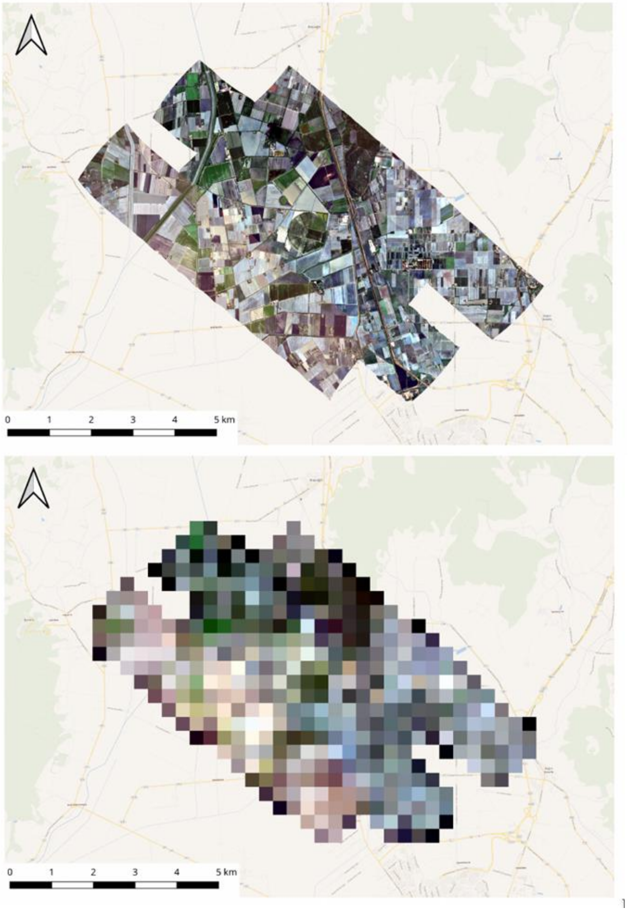
- A full atmospheric correction of the S-3B “FLEX mode” data was not yet performed
- A very good characterization of the atmospheric properties is needed to run SIF retrieval

→ First attempt: reconstruct S-3B “FLEX mode” L-1B TOA radiance coupling MODTRAN and HyPlant surface reflectance

$$L_{TOA}^{sim} = t_1 \left[t_2 + t_8 r_{so} + \frac{t_9 r_{so} + t_{10} r_{sd}}{1 - r_{dd} t_3} + \frac{t_{11} r_{dd}}{1 - r_{dd} t_3} \right]$$

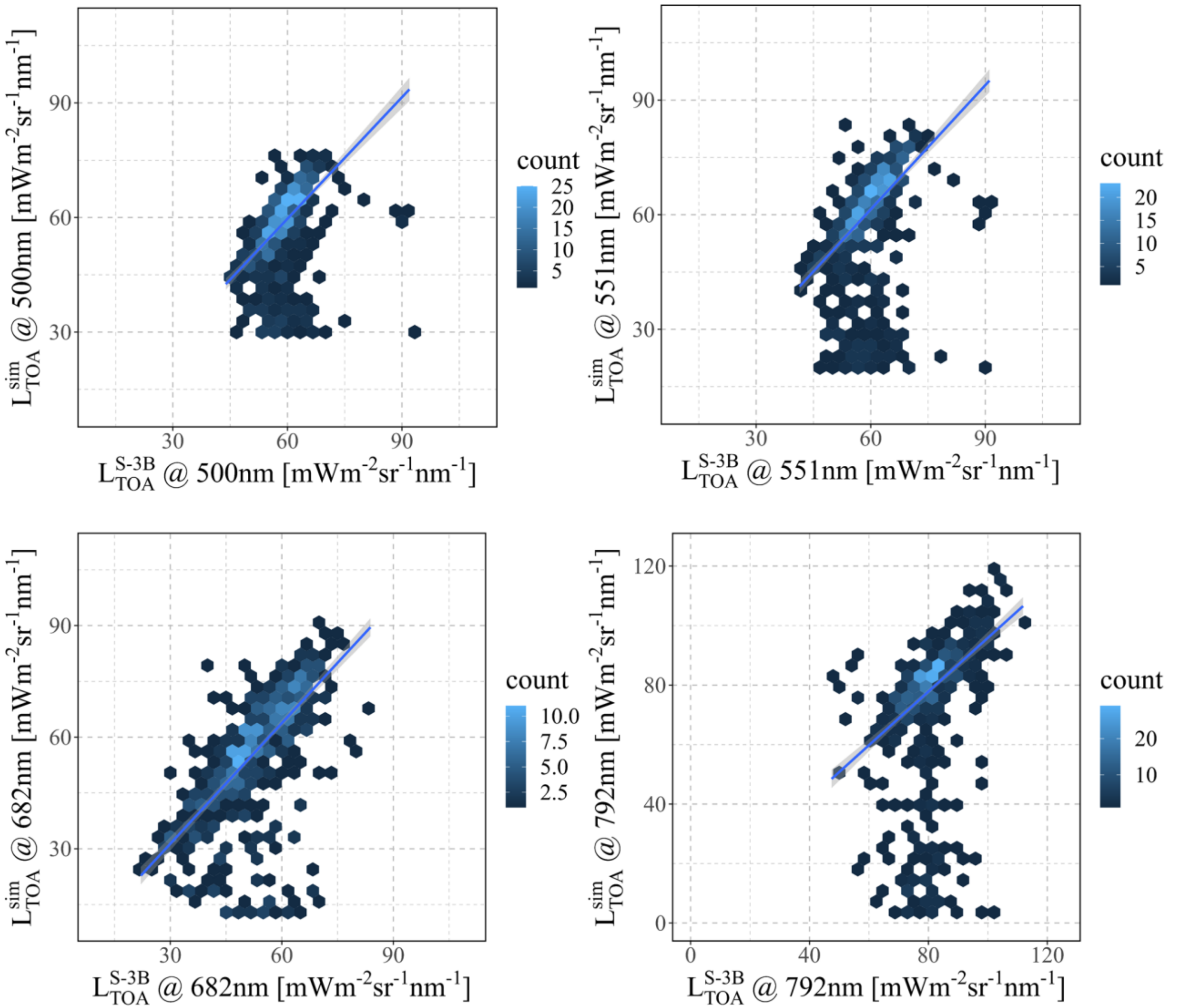
Modified from Cogliati et al. (2015)
Remote Sensing of Environment

HyPlant surface reflectance



Results [WP4]

Decent overall agreement between TOA radiance data from S-3B ($L_{TOA}^{S\text{-}3B}$) and bottom-up propagation of HyPlant surface reflectance (L_{TOA}^{sim})



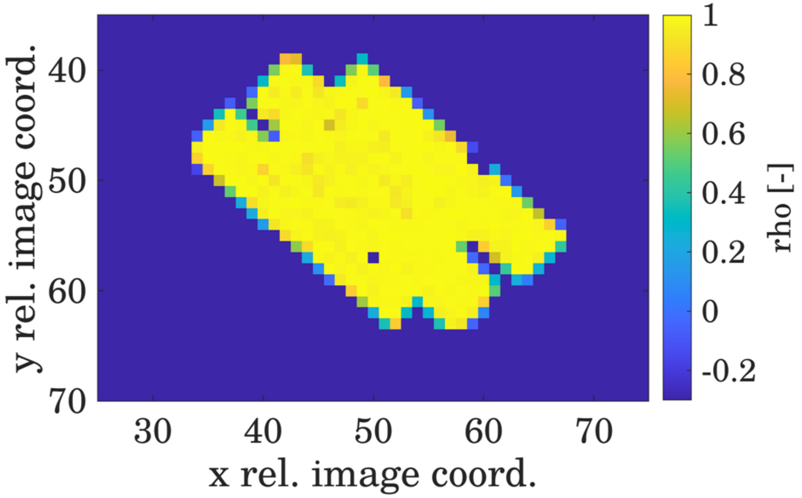
Results [WP4]

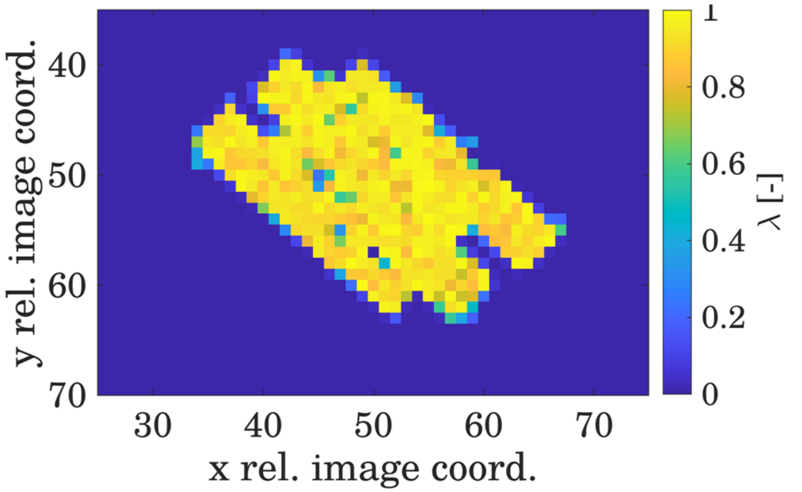
Decent overall agreement between TOA radiance data from S-3B ($L_{TOA}^{S\text{-}3B}$) and bottom-up propagation of HyPlant surface reflectance (L_{TOA}^{sim})

→ Very high values of per-pixel Pearson's correlation coefficient (rho) between the two TOA radiance spectra

→ High values of lambda agreement index (λ): an extension to rho that downregulates its value according to the bias

→ Code for applying SFM is ready and was tested. Atmospheric and instrument characterization still to be improved for SIF retrieval, further refinements will come from the collaboration with FLEX L-2 study team and FUB (SF-TAPE project)





Highlights

- Successful retrieval of SIF and vegetation parameters from “FLEX like” ground data → encouraging towards higher level products from FLEX

- Very good agreement between SIF values retrieved in the O_2-A (SIF_{760}) from simulated S-3B “FLEX mode” data and reference values

- Quantitative guidelines for SIF validation at the FLEX pixel scale (adaptable to other products)

- Initial (encouraging) steps towards the exploitation of S-2 surface reflectance data for characterization of SIF heterogeneity within the 300m x 300m pixel

- High-quality, standardly formatted S-3B OLCI “FLEX mode” L-1B data made available to the scientific community for further exploitation

Scientific output

Projects linked to MULTI-FLEX

- "Optical synergies for spatiotemporal SENsing of Scalable ECOphysiological traits" (SENSECO) COST Action CA17134
- ESA "SF-TAPE" project (Lena Janicke, Ph.D. student at the Free University of Berlin);
- "Algorithms development for chlorophyll fluorescence signal evaluation generated from inland waters and terrestrial vegetation using hyperspectral remote sensing and radiative transfer models" (Ilaria Cesana, Ph.D. student at the University of Milano-Bicocca)
- ESA "ATMO-FLEX", "ATMO-FLEX CCN“ and “FLEXSense" projects

Peer reviewed papers

- Biriukova, K., Celesti, M. et al. (2020) Effects of varying solar-view geometry and canopy structure on solar-induced chlorophyll fluorescence and PRI. *ISPRS Journal of Photogrammetry and Remote Sensing*. Corresponding author, https://doi.org/10.1016/j.jag.2020.102069
- Hao, D., [. . .] Celesti, M. et al. (In press) Practical approaches for normalizing directional solar-induced fluorescence to a standard viewing geometry. *Remote Sensing of Environment*
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- Celesti, M. et al. A data driven approach to define proximal sensing protocols towards the validation of medium resolution SIF products. In preparation
- Celesti, M. et al. Exploring continuous time series of vegetation hyperspectral reflectance and solar-induced fluorescence through radiative transfer model inversion. In preparation

Scientific output

Conferences and workshops

- Celesti, M. (2020) Sentinel-3B OLCI in “FLEX mode” during the tandem phase: a novel dataset towards the future synergistic FLEX/S-3 mission. To be presented at the Sentinel-3 Validation Team meeting, 15-17 December 2020, online.
- Celesti, M. (2020) Exploring continuous time series of vegetation hyperspectral reflectance and solar-induced fluorescence through radiative transfer model inversion. Presented at the EGU 2020 general assembly, 4-8 May 2020, online.
- Celesti, M.,et al.(2019) Exploring the Physiological Information of Solar-Induced Chlorophyll Fluorescence Through Radiative Transfer Model In-version: a Multi-Scale Approach From Ground to Airborne Data. ESALiving Planet Symposium, 13-17 May 2019, Milan, Italy;
- Celesti, M.,et al.(2019) Sentinel-3B OLCI in “FLEX mode” during the tandem phase: a new opportunity for fluorescence retrieval from space. ESA Living Planet Symposium, 13-17 May 2019, Milan, Italy;
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- Celesti, M. (2019) “MULTI-FLEX” Living Planet Fellowship: Concurrentretrieval of Solar-induced fluorescence and plant traits from multi-scalehyperspectral data. Presented at the ESA FLEX Mission Advisory Groupmeeting, 25 June 2019, ESA-ESTEC, The Netherlands;
- Celesti, M. (2019) Solar-induced fluorescence (SIF) scaling: an issue withmany contributors. Presented at the SENSECO COST action WG1 workshop,26 September 2019, Budapest, Hungary;
- Celesti, M. (2019) Satellite based imagery from the 2018 campaign – overviewon the S-2 and S-3 data and the processing of the S-3B reprogrammeddata. Presented at the ESA ATMO-FLEX/FLEXSense progress meeting, 14-17September 2019, ESA-ESRIN, Italy;
- Hueni, A. and Celesti, M. (2019) FLUOSPECCHIO: a spectral informationsystem in support of the FLEX mission calibration/validation activities. Presented at the SENSECO COST action WG1-WG2-WG3-WG4 joint work-shop, 28-30 October 2019, Lanzarote, Spain;
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Thanks for your attention!

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