living planet symposium | BONN 23–27 May 2022

TAKING THE PULSE OF OUR PLANET FROM SPACE

A novel hybrid machine learning phasor-based approach to retrieve a full set of solar-induced fluorescence metrics and biophysical parameters from model simulations and field data

Prof. Laura Sironi

June 26TH 2022

Background

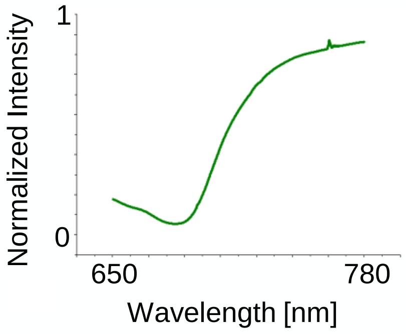
Signal acquired by spectrometers:

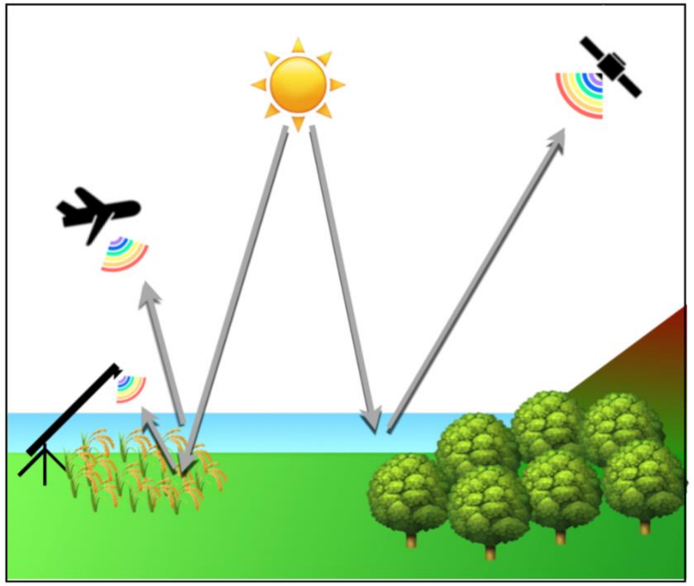
$$R_{APP}(\lambda) = \frac{L^{\uparrow}(\lambda)}{L^{\downarrow}(\lambda)} = R(\lambda) + \frac{F(\lambda)}{L^{\downarrow}(\lambda)}$$

$$L^{\uparrow}(\lambda) = R(\lambda)L^{\downarrow}(\lambda) + F(\lambda)$$

Top of canopy total radiance
Canopy reflectance
at-surface downwelling radiance
Fluorescence signal

R_{app} spectrum





Our targets:

1- Retrieving of F spectrum from R_{app}
2- Estimation of other fluorescence-related variables

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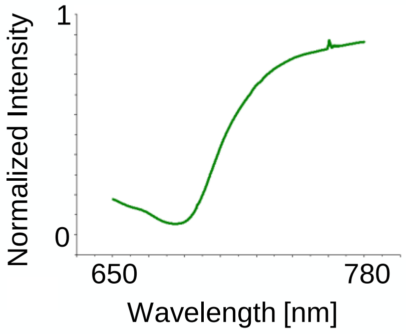

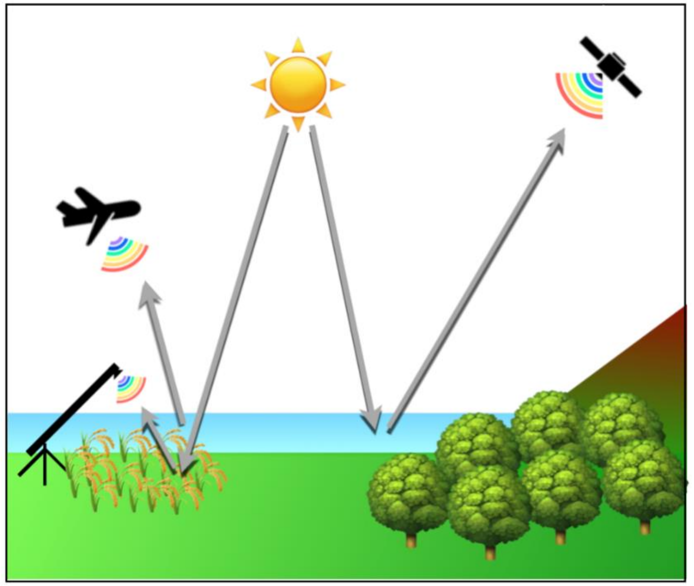

- Leaf Area Index (LAI)
- Chlorofyll Content (Cab)
- F Quantum Yield (Fqe)
- Absorbed Photosynthetic Active Radiation (APAR)
- F and F at photosystem level (F_{RC})

SOLUTION:

Machine Learning + Phasor Approach =

i-φ-MaLe

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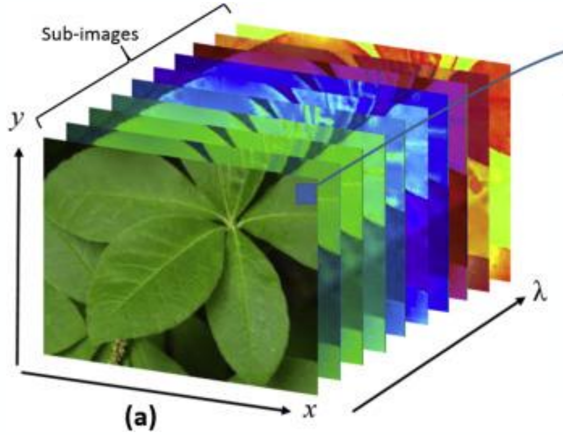
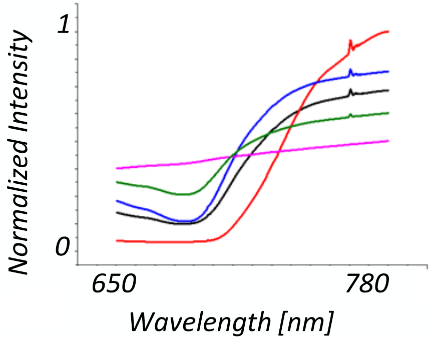
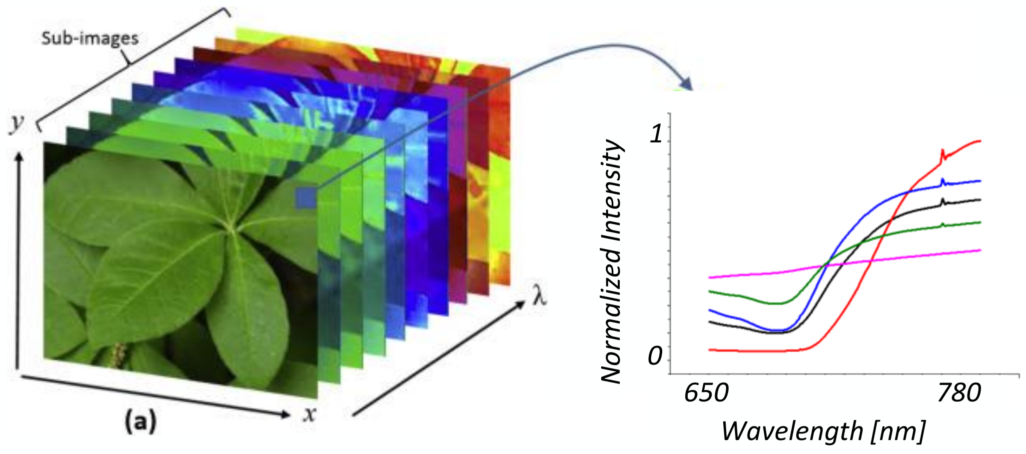
Standard Phasor Approach



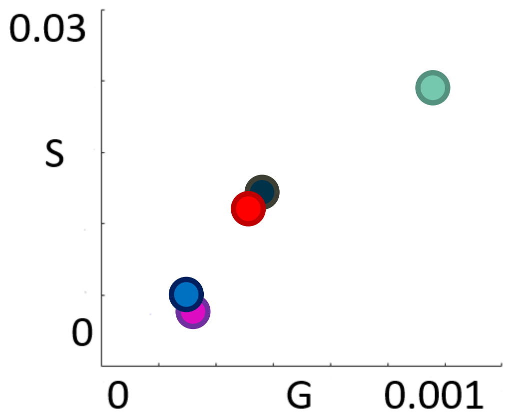


- *In hyperspectral images, each pixel is associated to a single spectrum*

Standard Phasor Approach



DFT



Discrete Fourier Transform (DFT)

$$g = ReA_k = \frac{\sum_{n=1}^{N} R_{app}^{n} \cos(\frac{-2\pi kn}{N})}{\sum_{n=1}^{N} R_{app}^{i}}$$

$$s = ImA_k = \frac{\sum_{n=1}^{N} R_{app}^{n} \sin(\frac{-2\pi kn}{N})}{\sum_{n=1}^{N} R_{app}^{i}}$$

N = # R_{app} points
k = harmonic ($k = 1$)

- *Each spectrum is transformed in a single point (g,s) on the phasor plot.*

- ***(g,s) position is dependent on the spectrum functional shape.***

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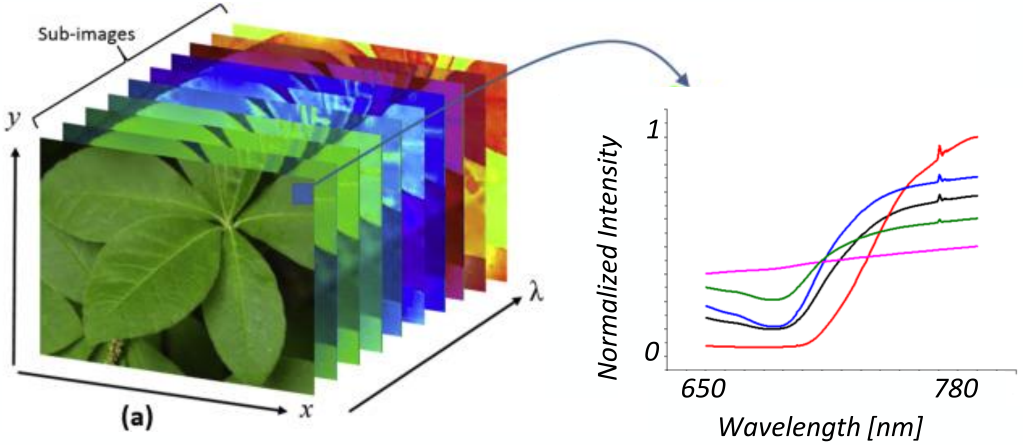

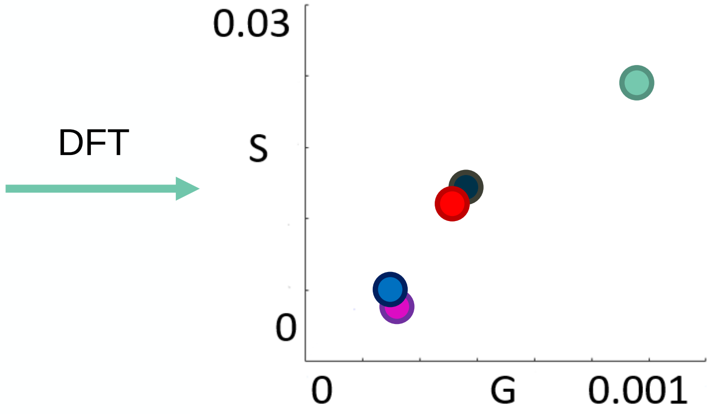

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*Transforming phasor approach in a **predictive model**:*

*#1 Training set of **R_{app} spectra, simulated** through a RT model*
*#2 R_{app} divided in spectral windows **(windowed phasor approach)***
*#3 Statistical-based **retrieval phase***

Novelty #1: R_{app} simulations for Training set

esa

RT model Input Data

Solar Zenith Angle (SZA)
Leaf Area Index (LAI)
Chlorophyll Content (Cab)
Fluorescence Quantum Yield (Fqe)

Scope + MODTRAN5***
RT model

RT model Output Data

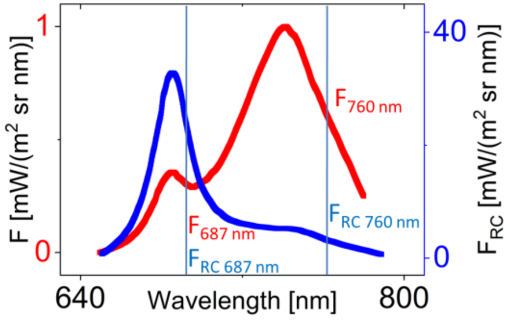
R_{app}, F & F_{RC} spectra, Absorbed Photosynthetic Active Radiation (APAR)

Dataset: $3x10^6$ different scenarios (R_{app})

Each R_{app} is associated to:

- LAI [0 8]
- Cab [0 80]
- Fqe [0.010 0.024]
- SZA [20 60]
- APAR
- F
- F_{RC}

LAI + Cab + APAR + Fqe
+



** Van der Tol et al. (2019). The scattering and re-absorption of red and near-infrared chlorophyll fluorescence in the models Fluspect and SCOPE. Remote Sensing of Environment.*

*** Berk et al. (2011). MODTRAN 5.2.1 User's Manual. Air Force Research Laboratory, Space Vehicles Directorate, Air Force Materiel Command, Hanscom AFB, MA 01731- 3010: Spectral Sciences, Inc.*

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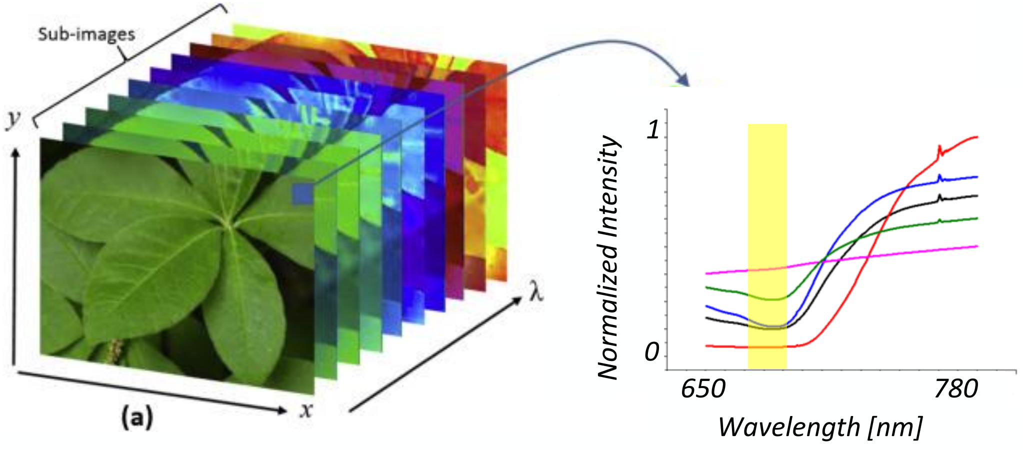
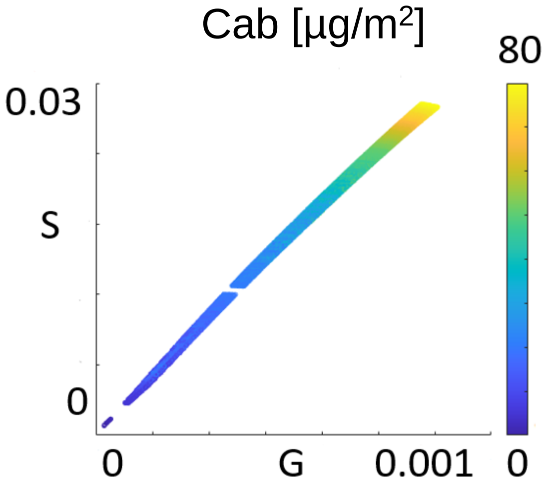
Novelty #2: Windowed phasor approach



DFT



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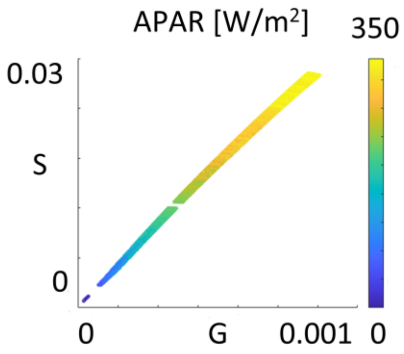
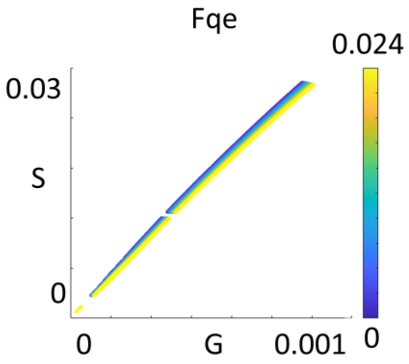
N = # R_{app} points
k = harmonic (k = 1)

- *This property is valid for every considered variable.*
- *R_{app} spectra with near projection positions are associated to similar parameter values.*





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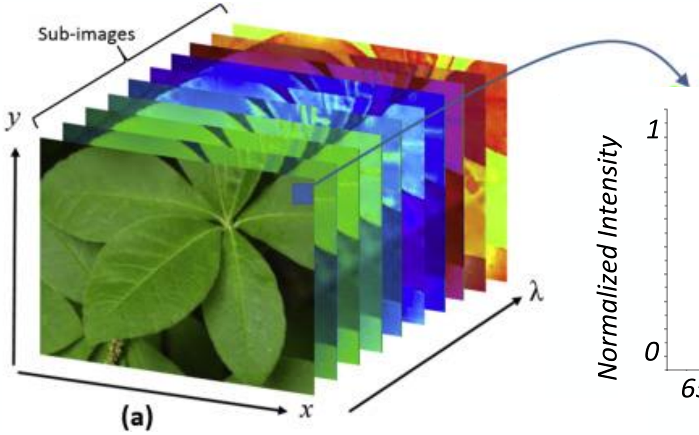

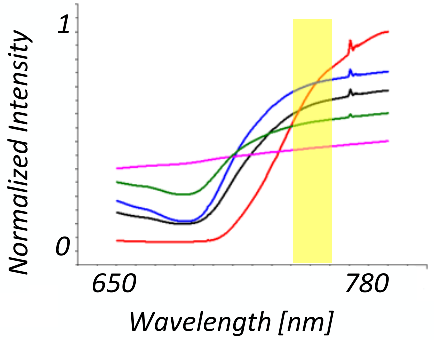

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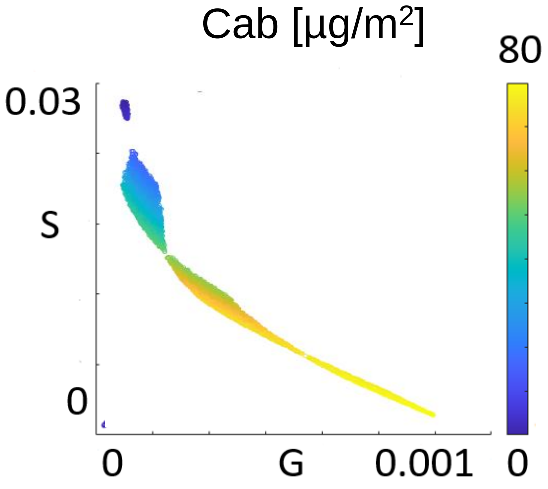

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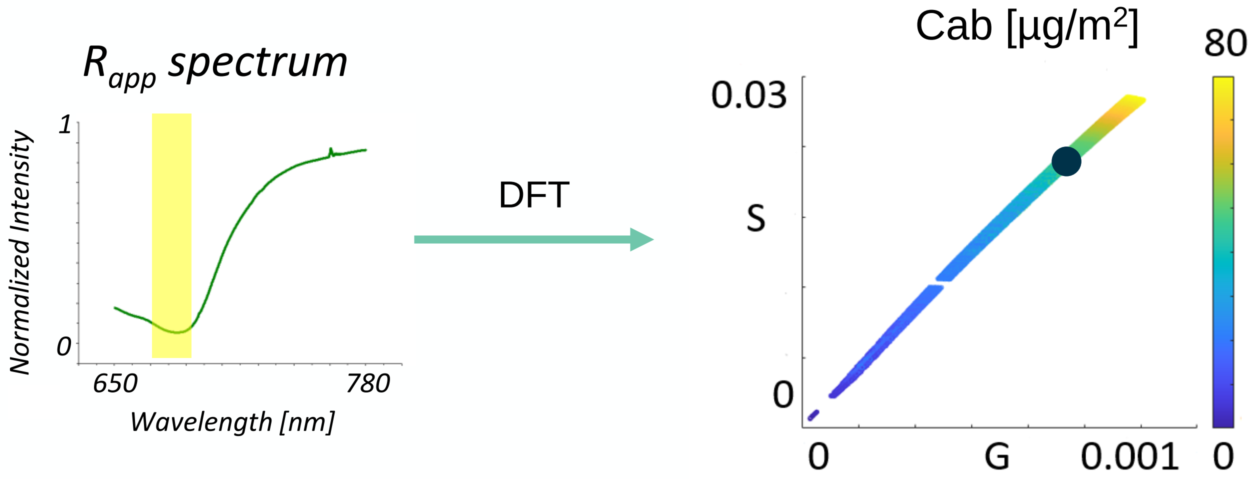
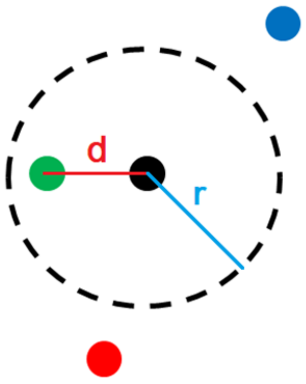
N = # R_{app} points
k = harmonic (k = 1)

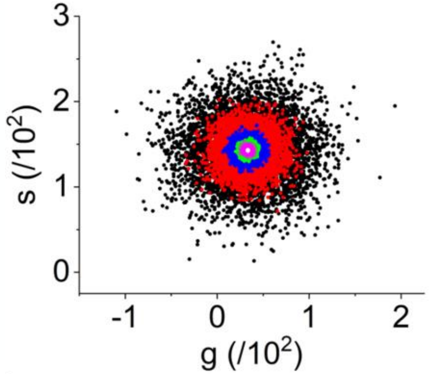
- *Each (g,s) projection color-codes for the parameter value associated to the related R_{app}*

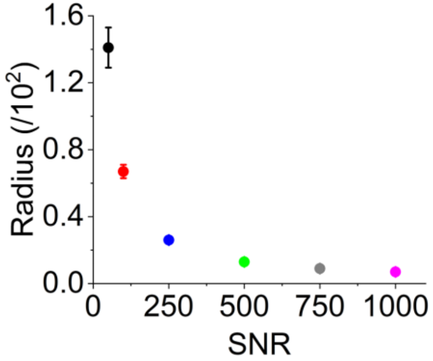
- *Relative positions on the phasor plot change in each spectral window.*

Novelty #3: Retrieval Phase





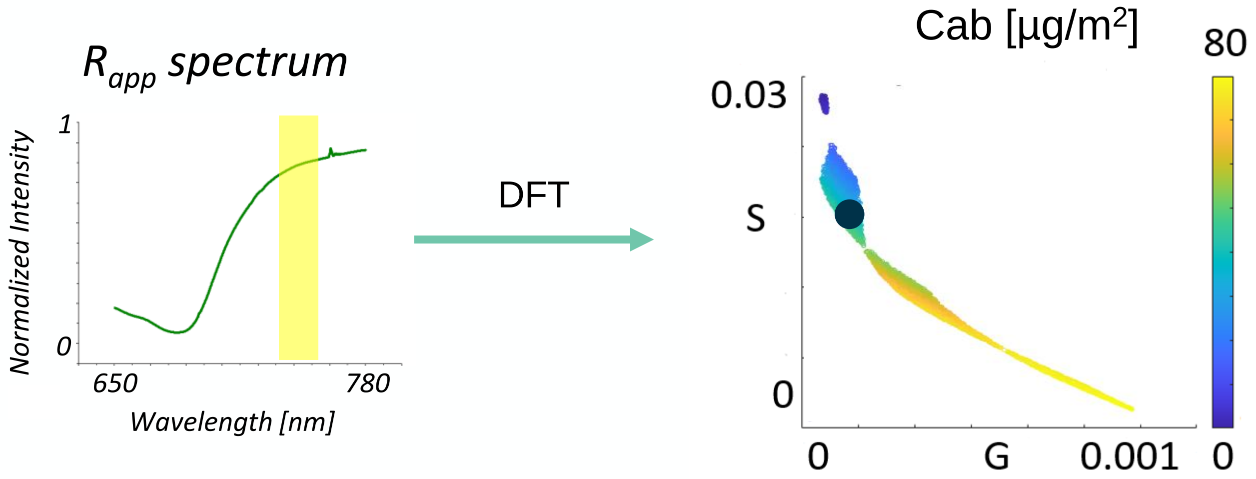


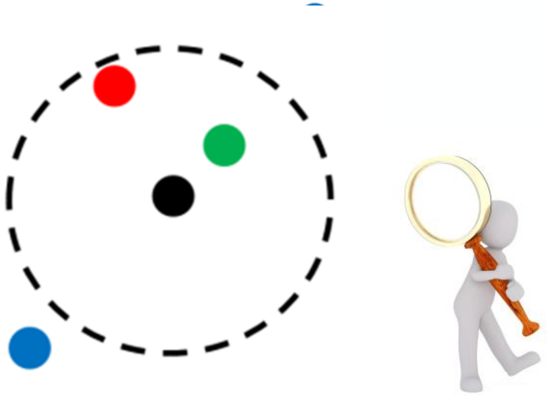


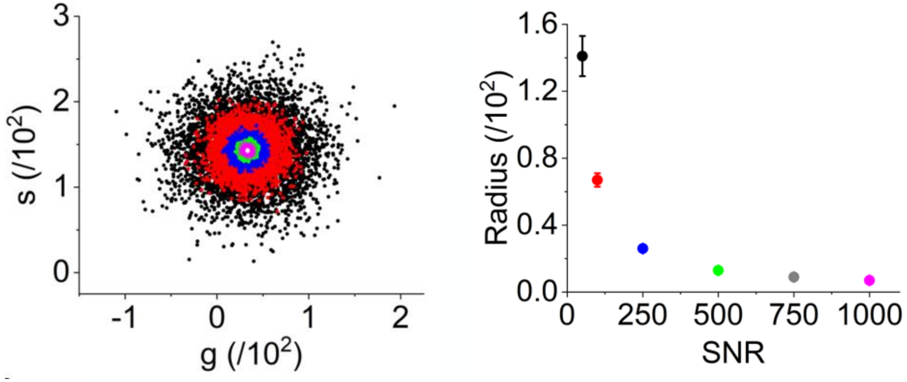
- *A circle of radius r is considered around the (g,s) point, including only the training set points, whose distance is d < r.*

$$r \propto \sqrt{\frac{1}{SNR}}$$

Novelty #3: Retrieval Phase



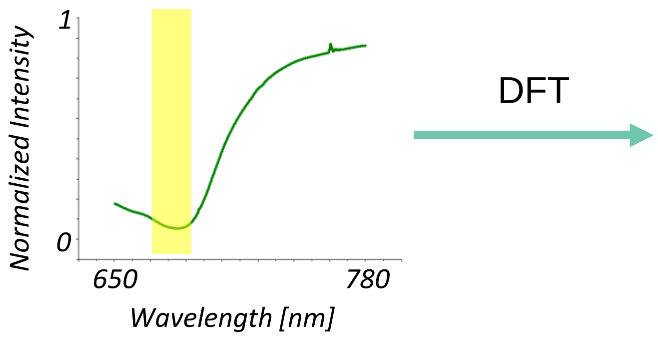


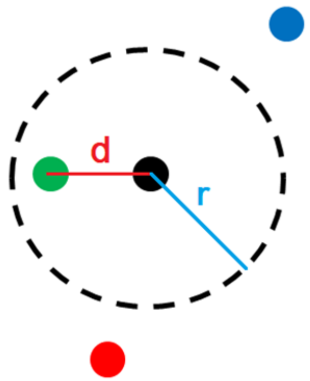


- *For each window, a different phasor plot is obtained.*
- *Reciprocal position of (g,s) points changes in the phasor plots, strongly mitigating the ill-posed problem.*

Novelty #3: Retrieval Phase

R_{app} spectrum





Ranking

Training Spectrum	*Occ*	*D*
Training #1	*0+0*	*0+0*
Training #2	*0+1*	*0+2.3*
Training #3	*0+0*	*0+0*

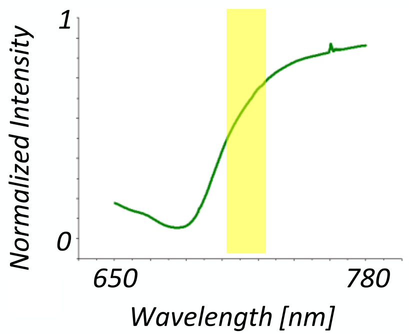
- *Occ. and D are computed for N spectral windows.*

$$Occ. = \sum_{i=1}^{N} \alpha_i \qquad D = \sum_{i=1}^{N} \left(\frac{r}{d_i}\right) \alpha_i \qquad \alpha_i = \begin{cases} 1 \ \ if \ \ d_i \leq r \\ 0 \ \ if \ \ d_i > r \end{cases}$$

N = # of selected spectral windows

Novelty #3: Retrieval Phase

R_{app} spectrum



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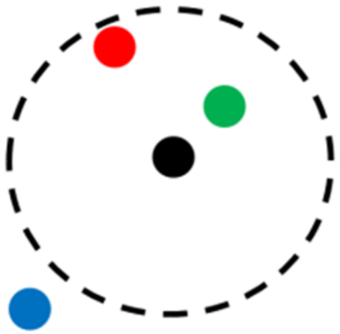

Ranking

Training Spectrum	*Occ*	*D*
Training #1	*0+1*	*0+1.8*
Training #2	*1+1*	*2.3+3.4*
Training #3	*0+0*	*0+0*

- *Occ. and D are computed for N spectral windows.*

$$Occ. = \sum_{i=1}^{N} \alpha_i \qquad D = \sum_{i=1}^{N} \left(\frac{r}{d_i}\right) \alpha_i \qquad \alpha_i = \begin{cases} 1 & if \;\; d_i \leq r \\ 0 & if \;\; d_i > r \end{cases}$$

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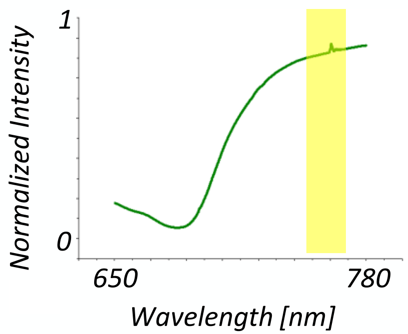
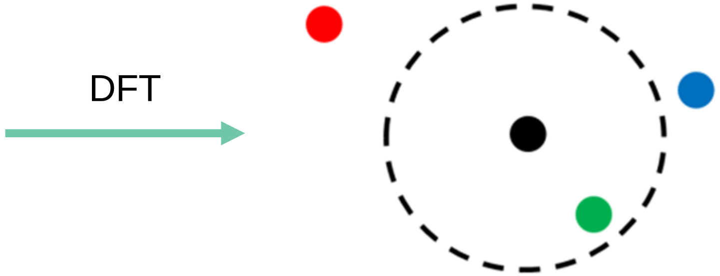
Novelty #3: Retrieval Phase

R_{app} spectrum





Ranking

Training Spectrum	*Occ*	*D*
Training #1	*1*	*1.8*
Training #2	***3***	***7.2***
Training #3	*0*	*0*

Analyzed R_{app} is associated to the biophysical/fluorescence variables of the training spectrum characterized by:

1) Highest Occ;

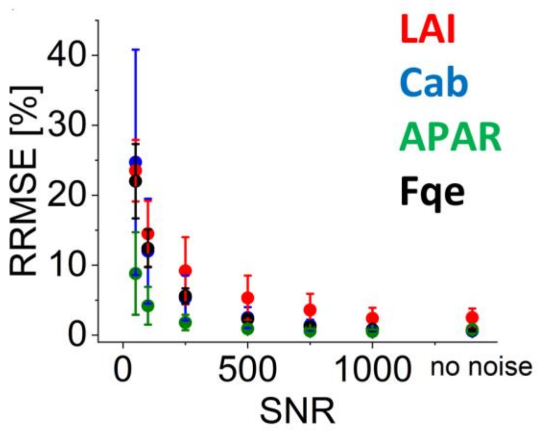
2) Highest D;

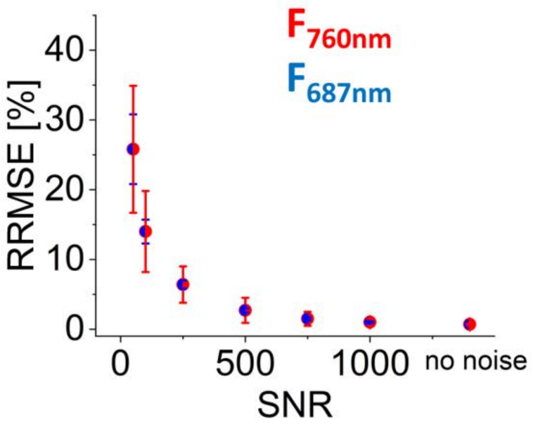
3)Average of training spectra with highest Occ and D

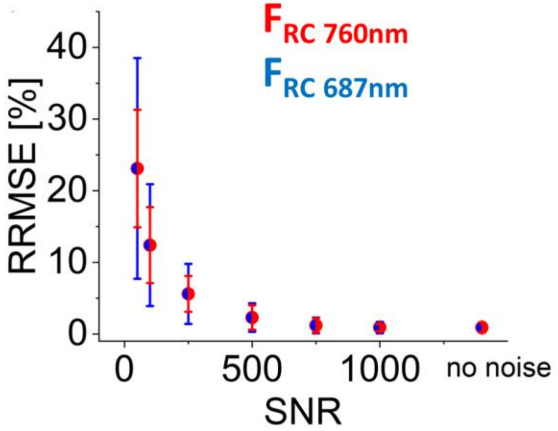
$$Occ. = \sum_{i=1}^{N} \alpha_i \qquad D = \sum_{i=1}^{N} \left(\frac{r}{d_i}\right) \alpha_i \qquad \alpha_i = \begin{cases} 1 \ \ if \ \ d_i \leq r \\ 0 \ \ if \ \ d_i > r \end{cases}$$

N = # of selected spectra windows

Algorithm Validation







No Noise

Parameter	CON1 – RRMSE (%)
Cab	0.6 ± 0.3
LAI	2.0 ± 1.0
APAR	0.8 ± 0.6
Fqe	0.7 ± 0.1
F (687 nm)	0.7 ± 0.6
F (760 nm)	1.0 ± 0.8
F_{RC} (687 nm)	0.9 ± 0.7
F_{RC} (760 nm)	0.9 ± 0.7

Ideal scenario (NO noise)
RRMSE < 2%

Experimental scenario
RRMSE < 10%

Test Set Data:

- *20% test spectra*
- *<2ms per R_{app} spectrum*
- *Increasing noise (SNR = [50 1000])*

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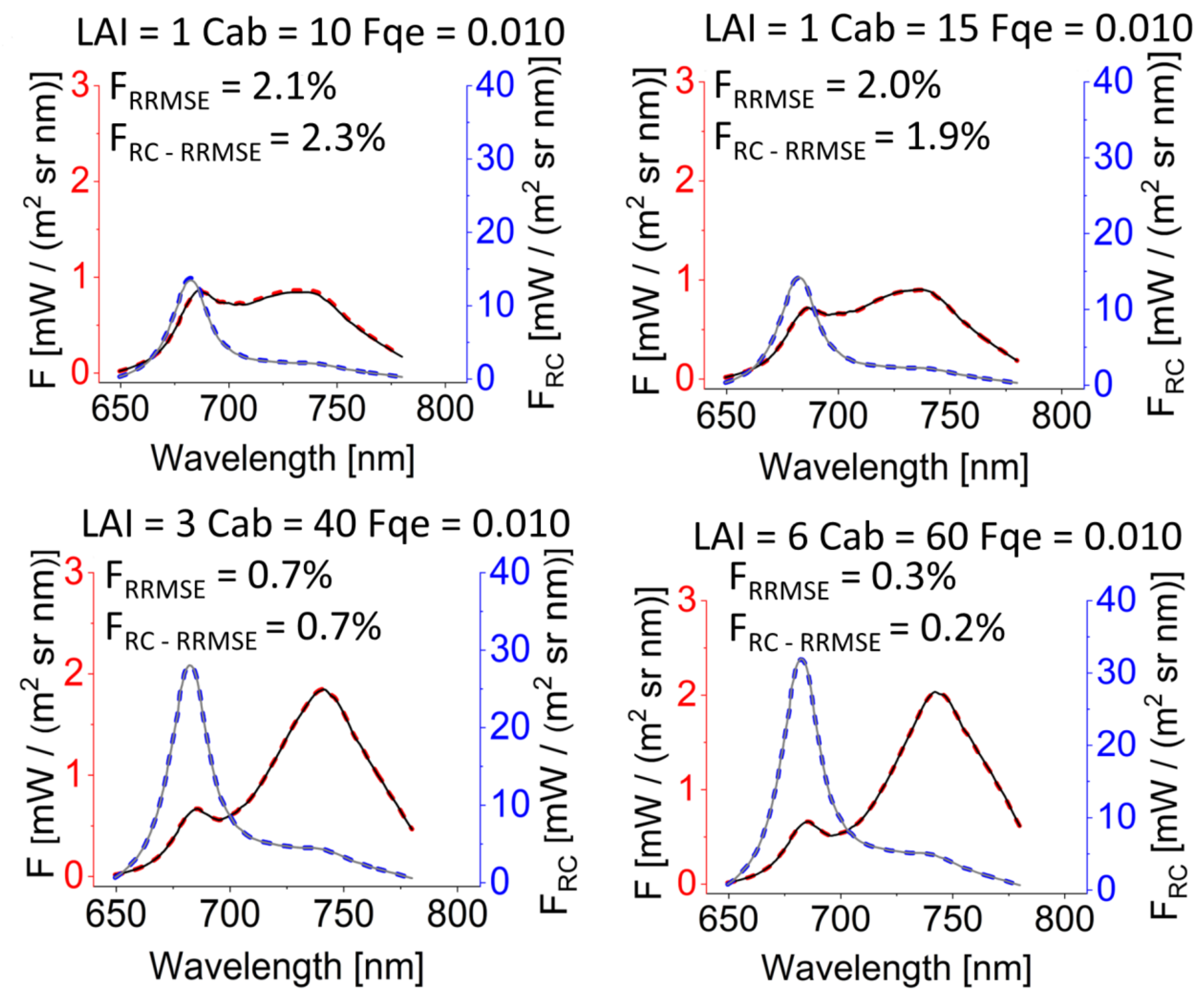

Graphs Color-Code

F_{true} — $F_{estimated}$

$F_{RC - true}$ — $F_{RC - estimated}$

Ideal scenario (NO noise)

RRMSE < 2%

Experimental scenario

RRMSE < 10%

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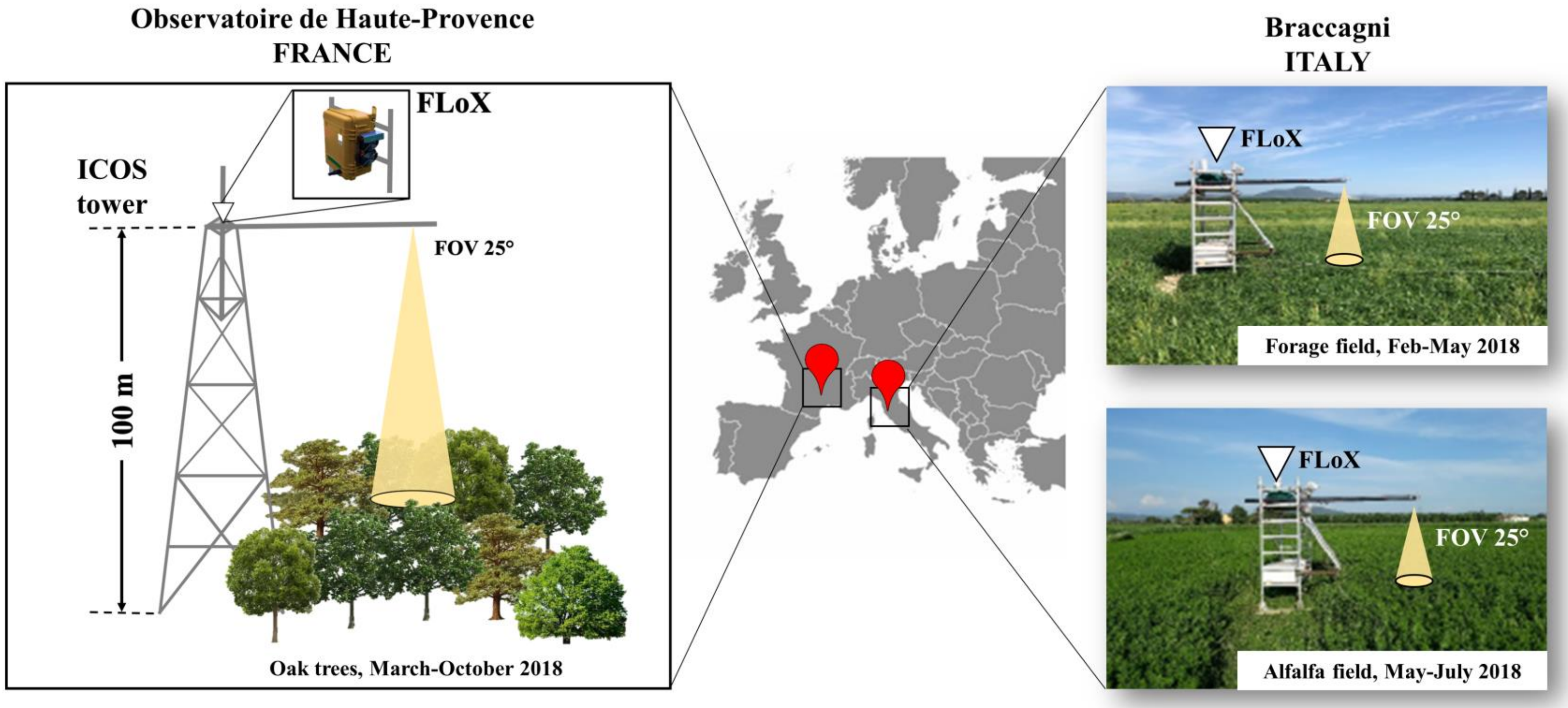
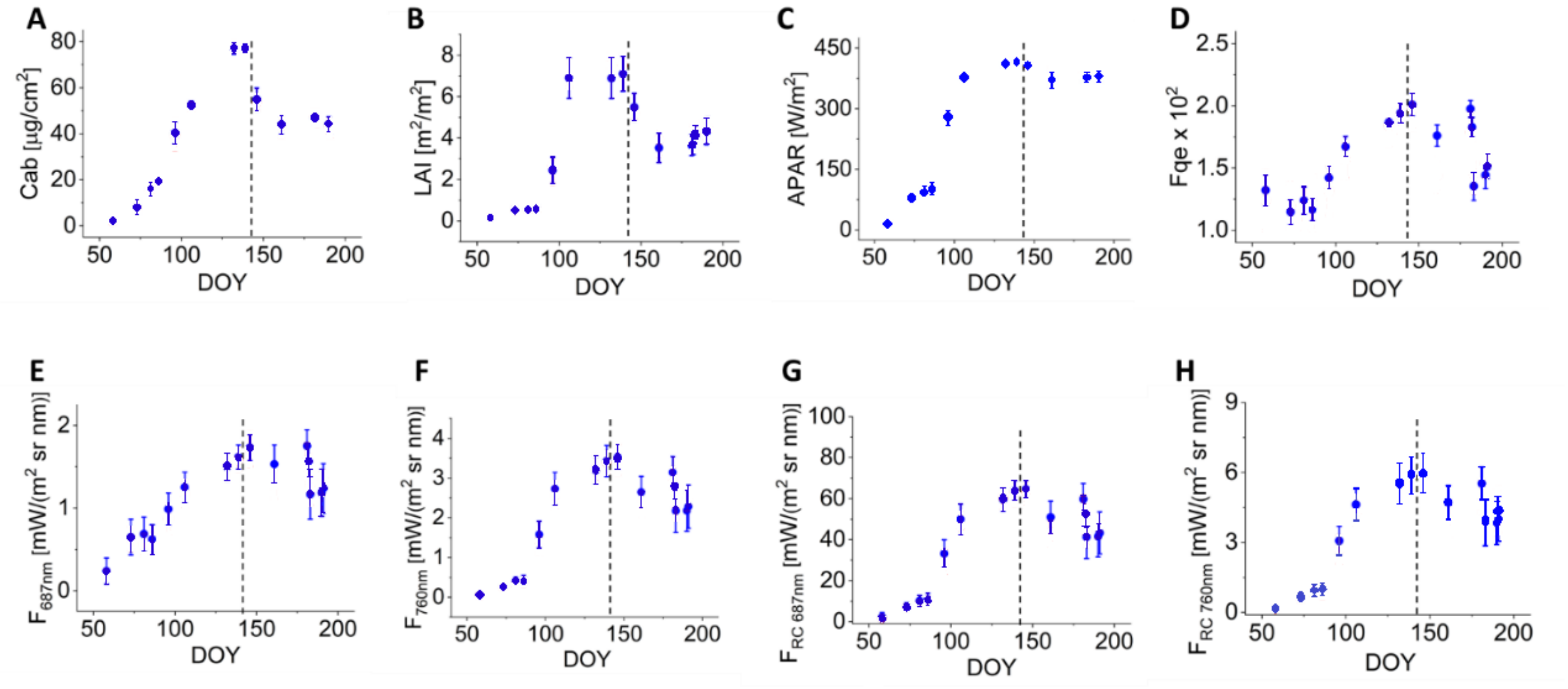
Field Measurements



Both ***Canopy and Tower-level*** *experimental data have been analyzed*

Canopy-level Field Measurements

Seasonal Trends



Trends are ***comparable to the experimentally monitored vegetation status***

Vegetation Status

DOY 57 - 146 : Forage growth

DOY 146 – 150: Alfalfa growth
DOY 150: cut of Alfalfa
DOY 150 – 192: Alfalfa growth

Data Processing

Each point is the mean ± std. dev. of 40 R_{app} acquired at solar noon ± 15min

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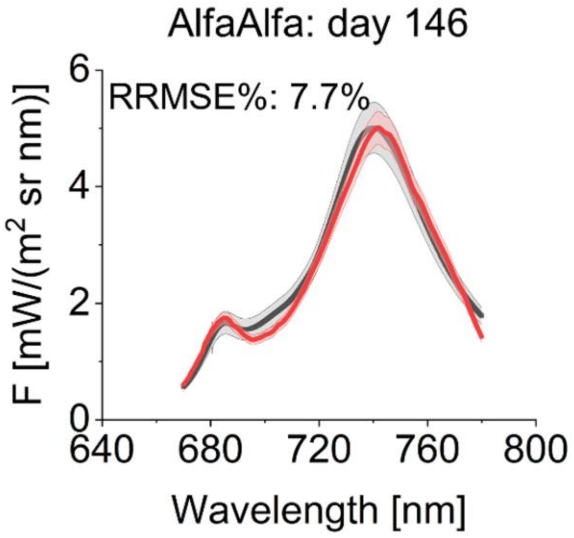
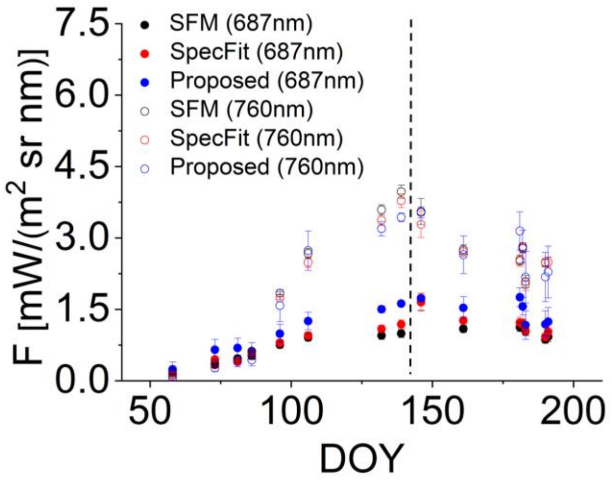
Canopy-level Field Measurements

Seasonal Trends





i-φ-MaLe F trends are ***compatible with SFM* and SpecFit***** *results*

Vegetation Status

DOY 57 - 146 : Forage growth

DOY 146 – 150: Alfalfa growth
DOY 150: cut of Alfalfa
DOY 150 – 192: Alfalfa growth

Data Processing

Each point is the mean ± std. dev. of 40 R_{app} acquired at solar noon ± 15min

** Cogliati et al. (2015). Retrieval of sun-induced fluorescence using advanced spectral fitting methods. Remote Sensing of Environment.*

*** Cogliati et al. (2019). A Spectral Fitting Algorithm to Retrieve the Fluorescence Spectrum from Canopy Radiance. Remote Sensing.*

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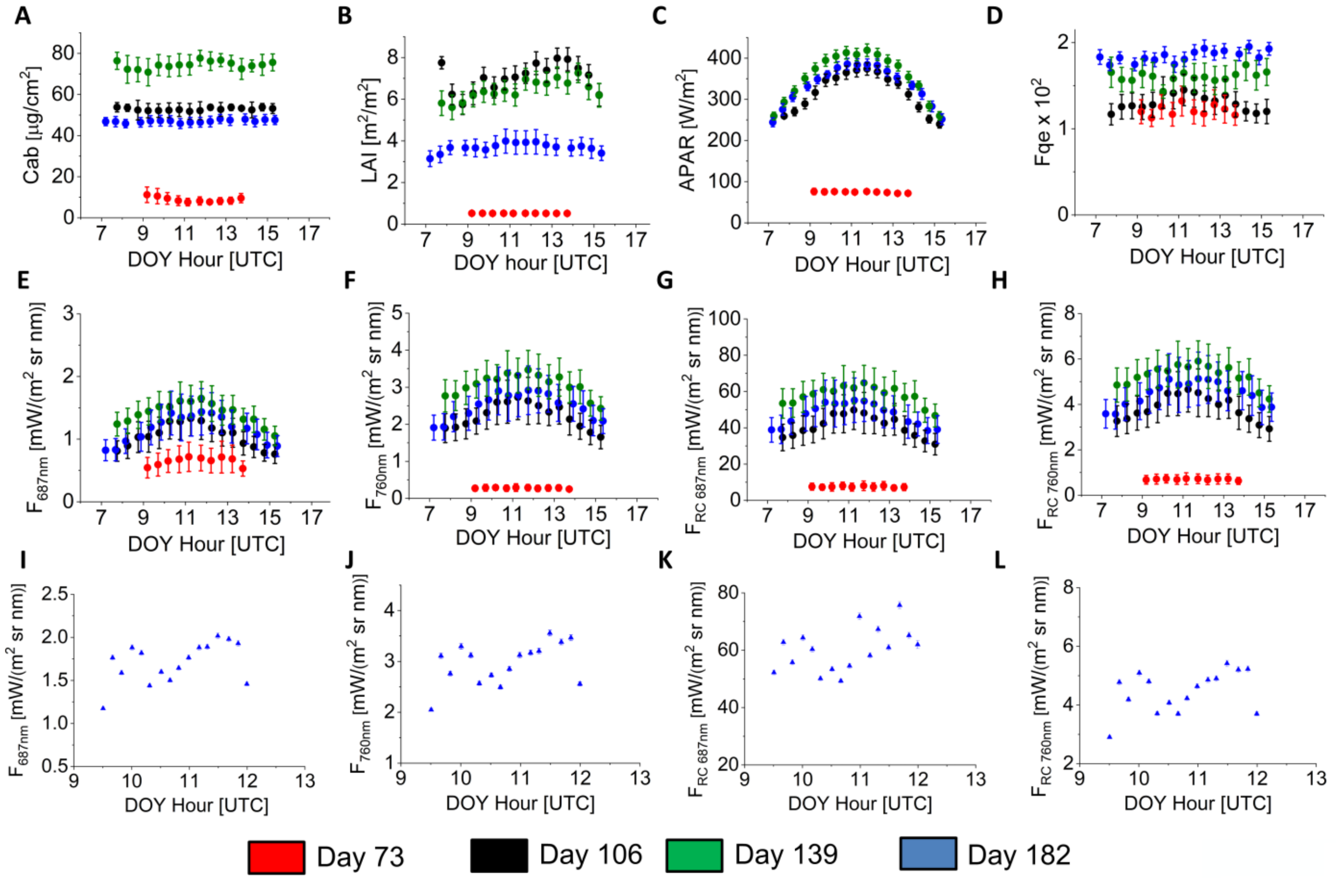
Canopy-level Field Measurements

Daily Trends



Results

- Cab, LAI and Fqe constant trends
- APAR trend dependent on cos(SZA)
- Midday depression detected for some F and F_{RC} spectra
- Trends comparable to state-of-the-art literature*

Data Processing

Each point is the mean ± std. dev. of R_{app} acquired at DOY Hour ± 15min

** Campbell et al. (2019). Diurnal and Seasonal Variations in Chlorophyll Fluorescence Associated with Photosynthesis at Leaf and Canopy Scales. Remote Sensing.*

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Main Achievements

*i-φ-MaLe is the **first algorithm** to successfully and simultaneously retrieve:*

- *Fluorescence **Quantum Yield***
- *Fluorescence spectrum at **photosystem level***

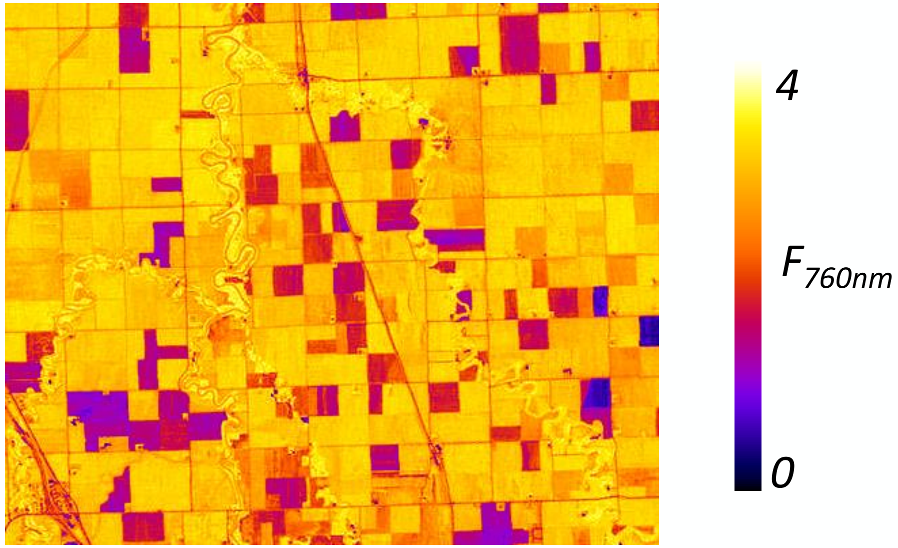
Moreover, it also estimates:

- *Fluorescence spectrum at canopy level*
- *Crucial biophysical parameters (LAI, Cab, APAR)*

*Experimental analysis are performed in **real time** (< 2ms per spectrum), from **Top-of-Canopy** level measurements (1-3m) to **Tower-level** acquisitions (~100m – not shown)*

Future Perspectives

- *Exploitation of* ***3D Radiative Transfer Models***
- *Wide training set to simulate more experimental scenarios (e.g. varying* ***LIDF****)*
- *Application to* ***hyperspetral images*** *and* ***satellite-level measurements***



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Scodellaro et al. (2022), A novel hybrid machine learning phasor-based approach to retrieve a full set of solar-induced fluorescence metrics and biophysical parameters. Remote Sensing of Environment (under review).

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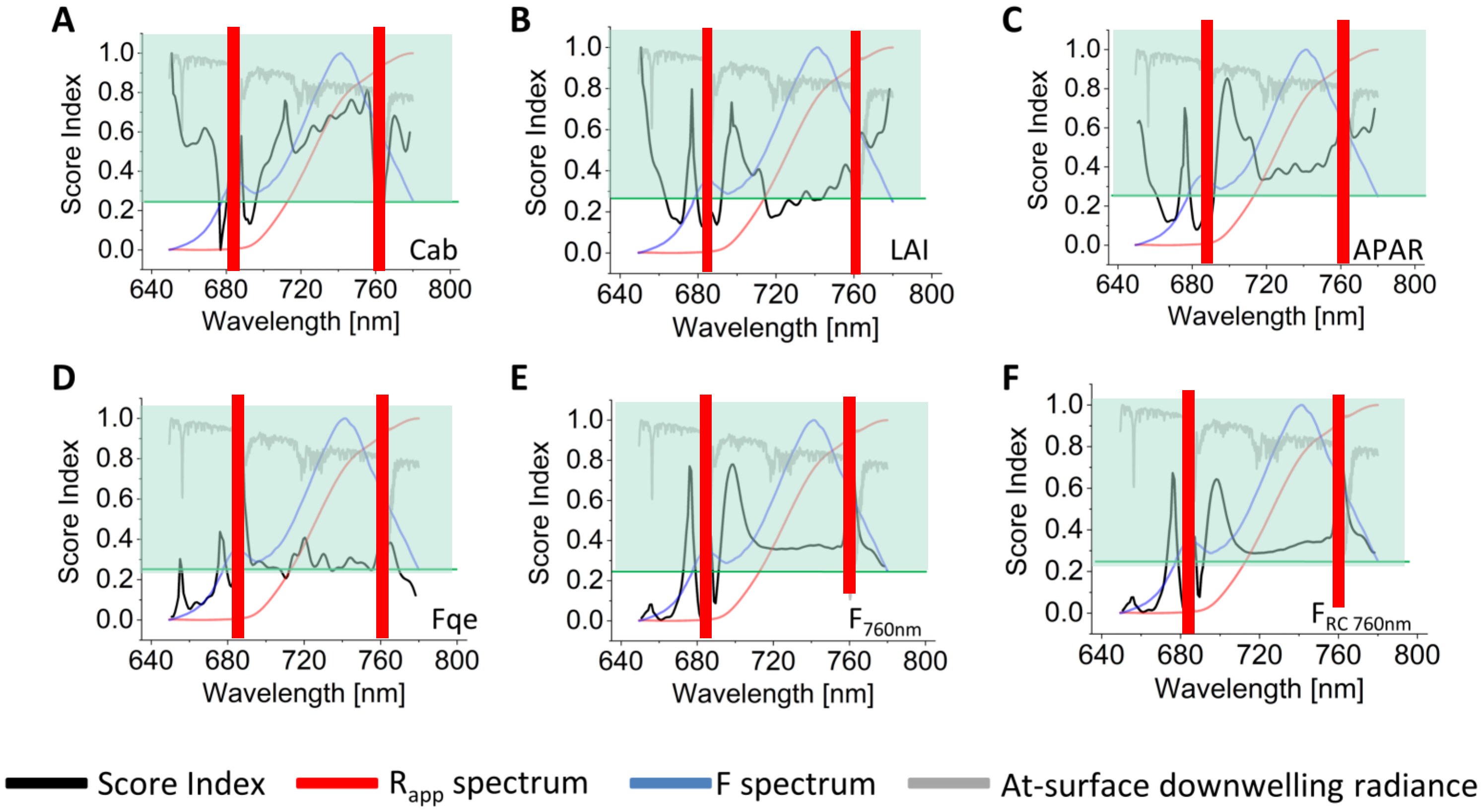
i-φ-MaLe method



Score Index

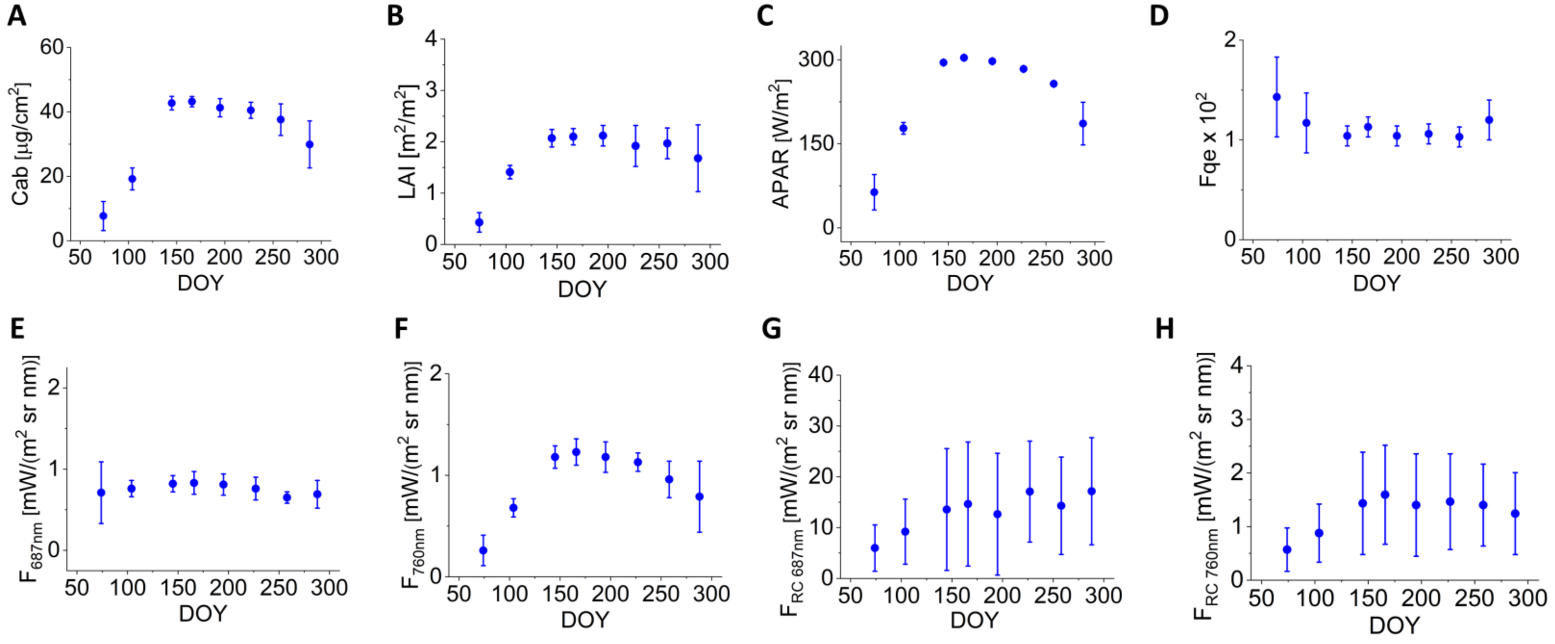
Amount of informative content characterizing the spectral window

Configuration 2

***O_2 bands are excluded**, in order to avoid atmospheric oxygen absorption effects on the Rapp spectra.*

Tower-level Field Measurements

Seasonal Trends



No negative F values *(differently from inversion-based methods)*

Algorithm Configuration 2

- O2 bands exclusion

- Higher uncertainties in F and F_{RC} retrievals (lower fluorescence contribute in Solar Fraunhofer Lines)*

Data Processing

mean ± std. dev. of R_{app} acquired at solar noon ± 15min

** Mohammed et al. (2019). Remote sensing of solar-induced chlorophyll fluorescence (SIF) in vegetation: 50 years of progress. Remote Sensing of Environment.*

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