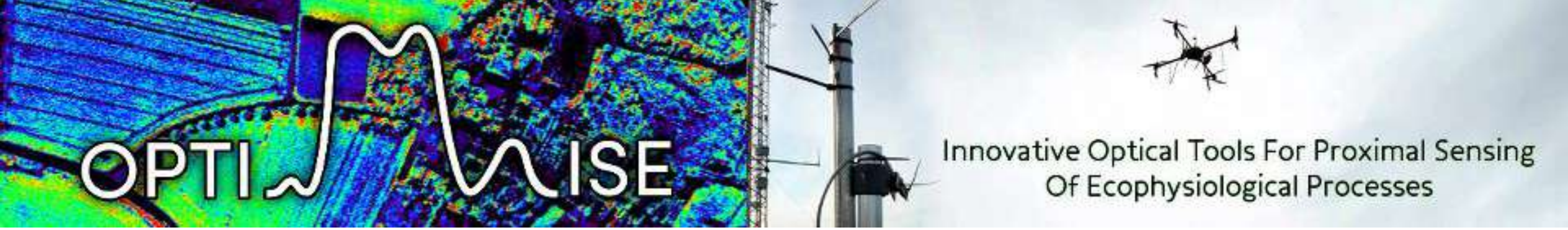

Ground measurements of Solar-induced chlorophyll fluorescence: **retrievals methods and practical cases**

MaPi Cendrero-Mateo, **Sebastian Wineke**, Helge Aasen, Javier Pacheco-Labrador, Alasdair McArthur, Alex Damm, Francisco Pinto, Jose Moreno, Luis Alonso, Luis Guanter, Marco Celesti, Micol Rossini, Nues Sabater, Roberto Colombo, Sergio Cogliatti, Uwe Rascher, and Yves Goulas.

COST is supported by the EU Framework Programme Horizon 2020

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Motivation

→ Update

- State of the art retrieval methods
- State of the art spectrometers which allow the retrieval of F at both O2B and O2A bands

REVIEW

Remote sensing of solar-induced chlorophyll fluorescence: Review of methods and applications

M. Meroni [a,*], M. Rossini [a], L. Guanter [b], L. Alonso [c], U. Rascher [d], R. Colombo [a], J. Moreno [c]

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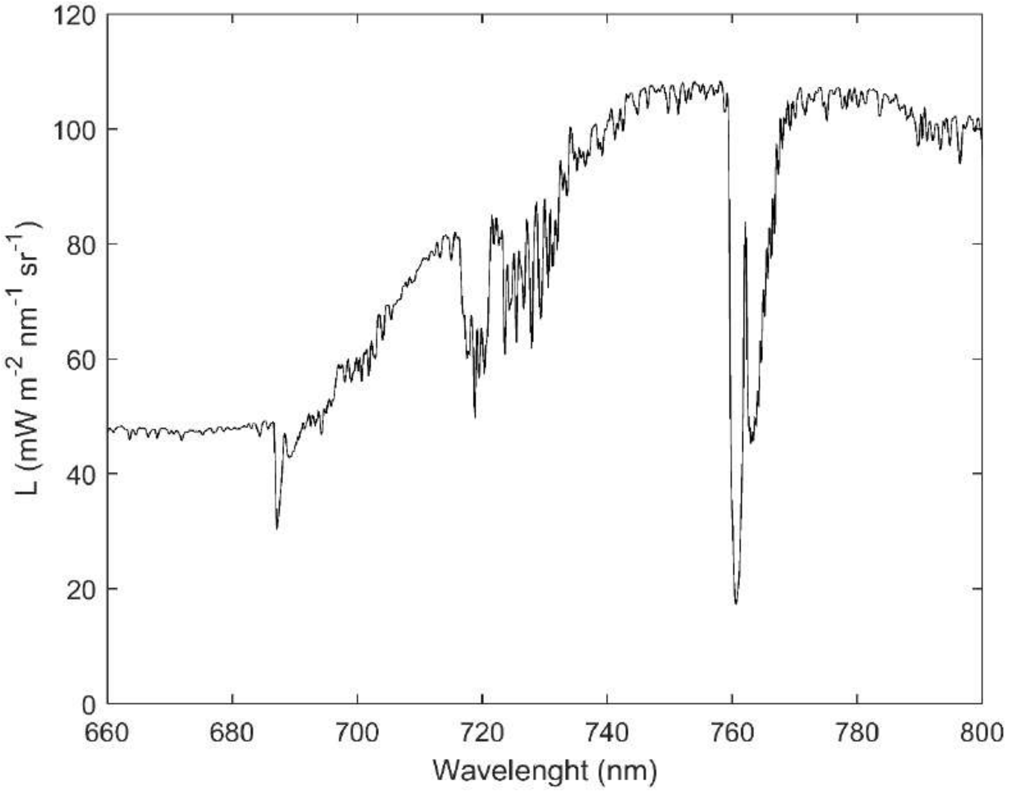
[b] GFZ German Research Centre for Geosciences, Telegrafenberg A17, 14473, Potsdam, Germany
[c] Image Processing Laboratory, LPI, University of Valencia, P.O. Box 22085, Valencia, Spain
[d] Institute of Chemistry and Dynamics of the Geosphere, ICG-3: Phytosphere, Forschungszentrum Jülich, Leo-Brandt-Str, 52425 Jülich, Germany

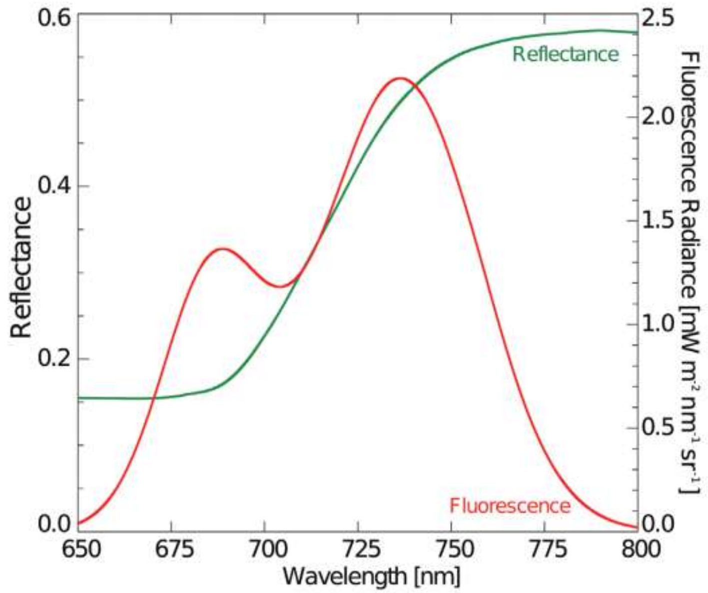
Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence

Alexander Damm [a,*], André Erler [b], Walter Hillen [c], Michele Meroni [d], Michael E. Schaepman [a], Wout Verhoef [e], Uwe Rascher [b]

[a] Remote Sensing Laboratories, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland
[b] Institute of Bio- and Geosciences, IBG-2: Plant Sciences, Forschungszentrum Jülich, Stetternicher Forst, 52425 Jülich, Germany
[c] Aachen University of Applied Sciences, Campus Juelich, Medical Informatics, Heinrich-Mussmann Str. 1, 52428 Jülich, Germany
[d] European Commission, DG-JRC, Institute for Environment and Sustainability, Monitoring Agricultural Resources Unit, Via Fermi 2749, 21027 Ispra, Italy
[e] University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC), P.O. Box 6, 7500 AA Enschede, The Netherlands

Under sun-light condition

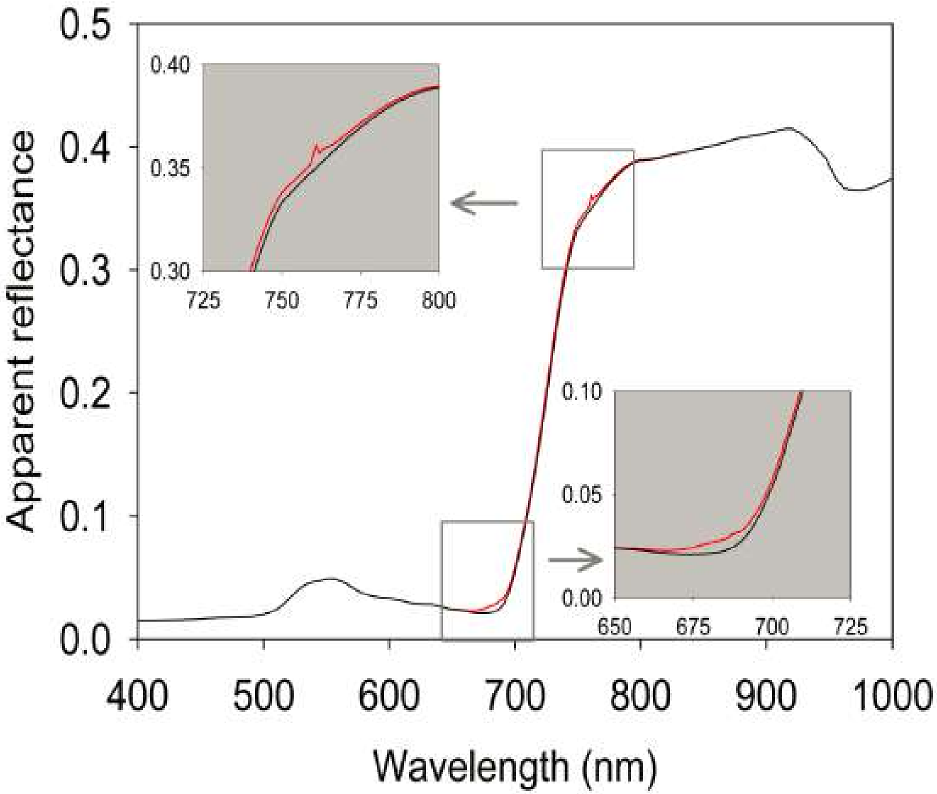




L = target radiance
E = solar irradiance
r = reflectance
F = Fluorescence

$$L(\lambda) = \frac{E(\lambda) \cdot r(\lambda)}{\pi} + \boldsymbol{F}(\lambda)$$

Under sun-light condition



Real reflectance (ρ)
Apparent reflectance (ρ_{app})

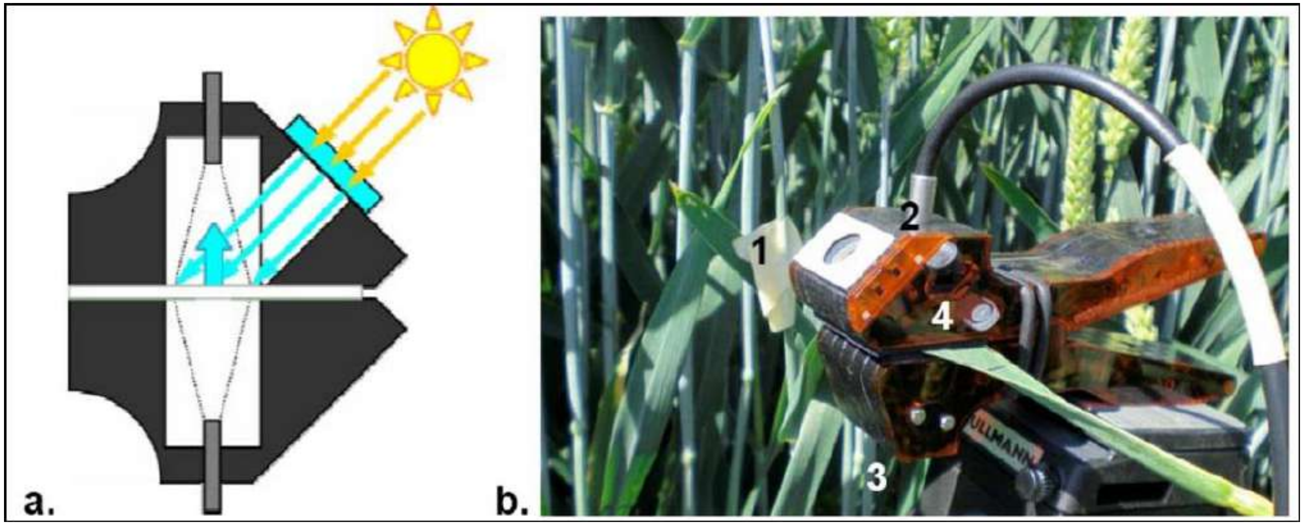
$$\boldsymbol{r}(\lambda) = \frac{\boldsymbol{L}(\lambda)\boldsymbol{\pi}}{\boldsymbol{E}(\lambda)}$$

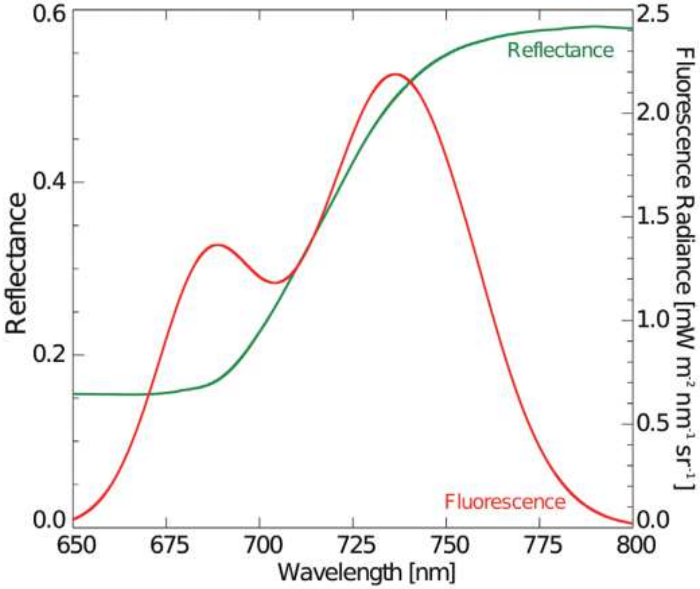
$$\boldsymbol{r}_{app}(\lambda) = \boldsymbol{r}(\lambda) + \frac{\boldsymbol{F}(\lambda)\boldsymbol{\pi}}{\boldsymbol{E}(\lambda)}$$

L = target radiance
E = solar irradiance
r = reflectance
r_{app} = apparent reflectance
F = Fluorescence

Credits: Meroni et al., 2009 & Jullita 2014

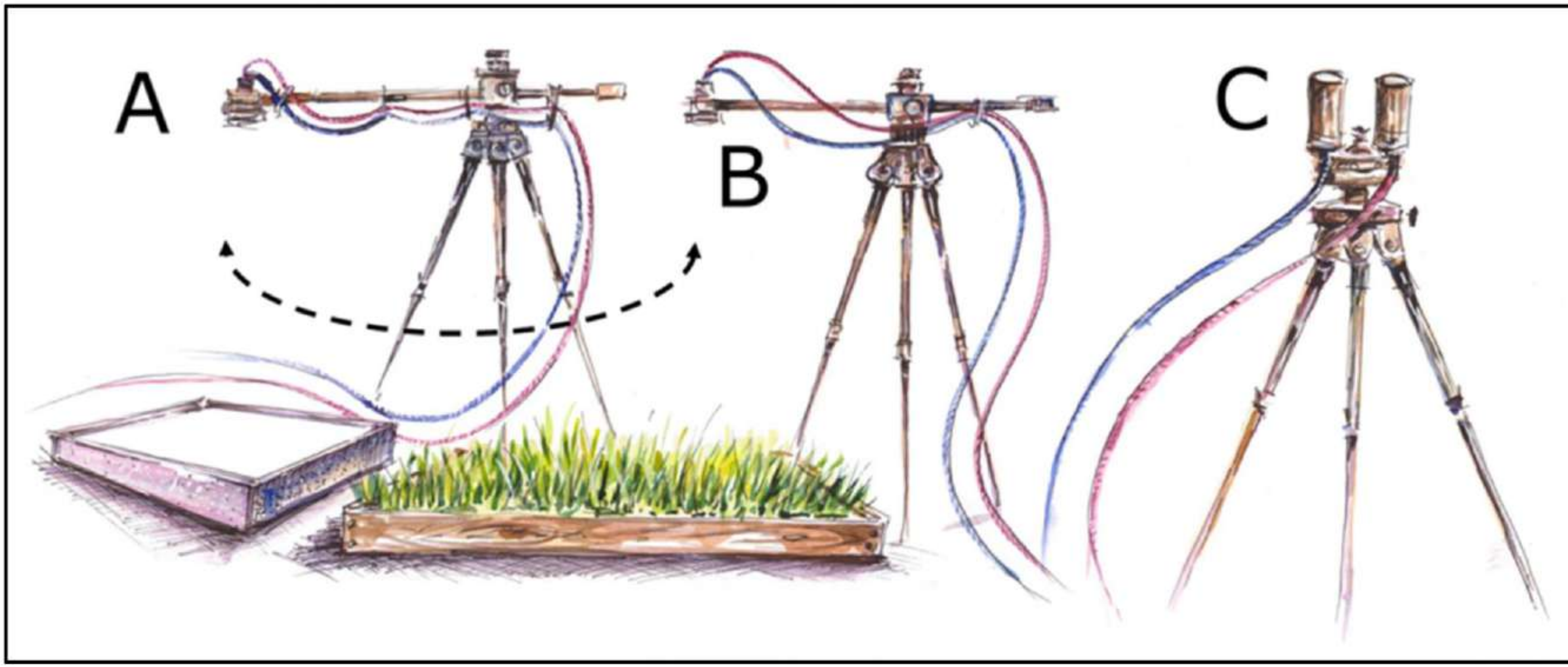
Field measurements - Leaf





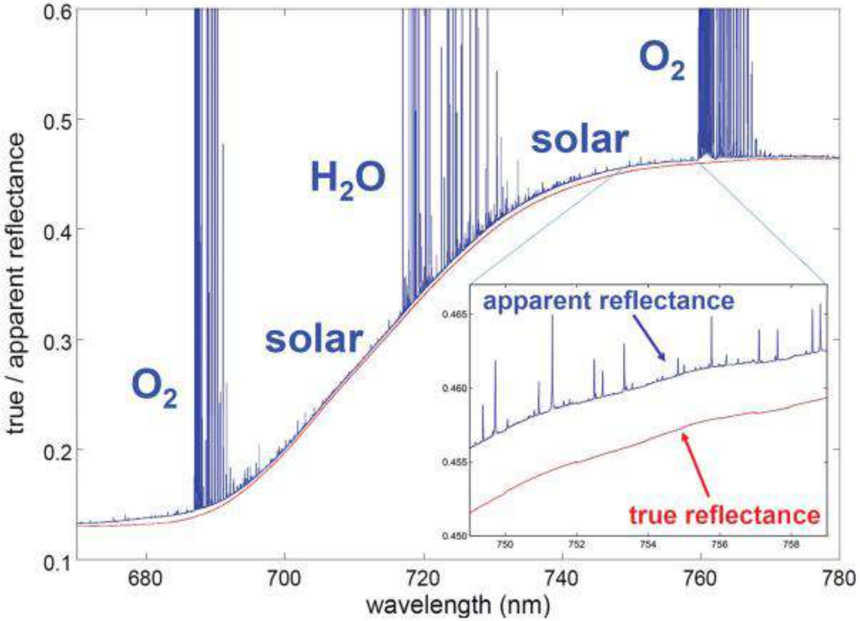
Credits: Luis Alonso

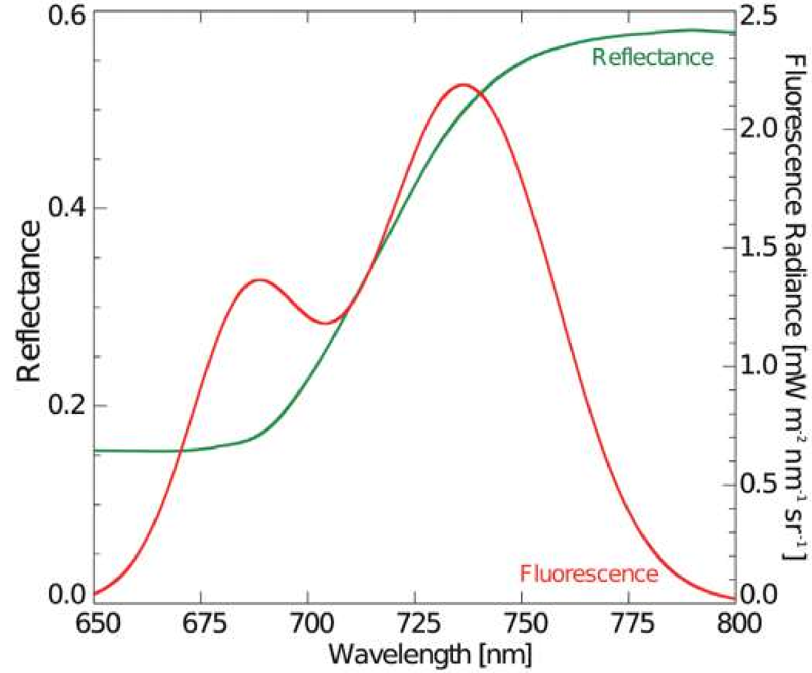
Field measurements – Top of Canopy



Credits: Julitta et al. 2016

Under sun-light condition

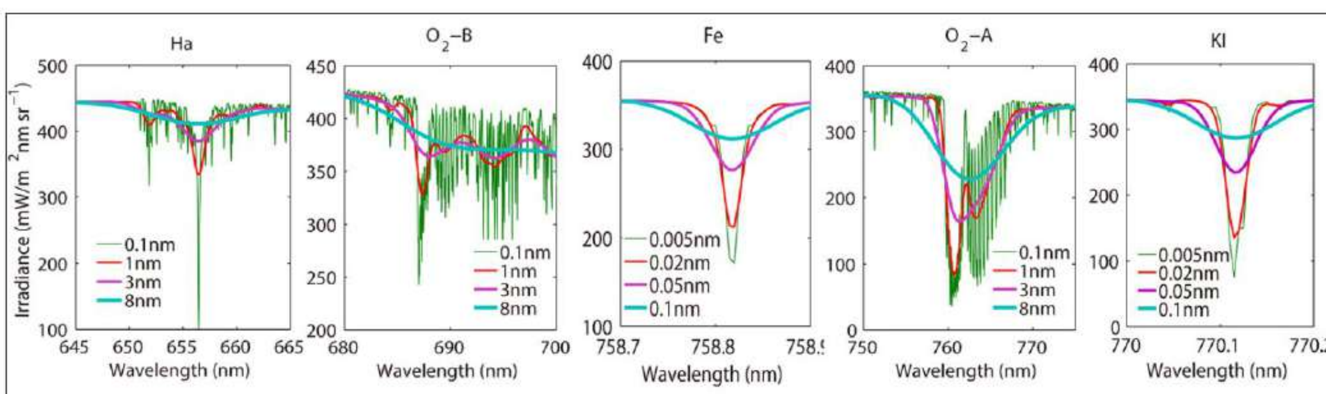




Credits: FLEX selection report

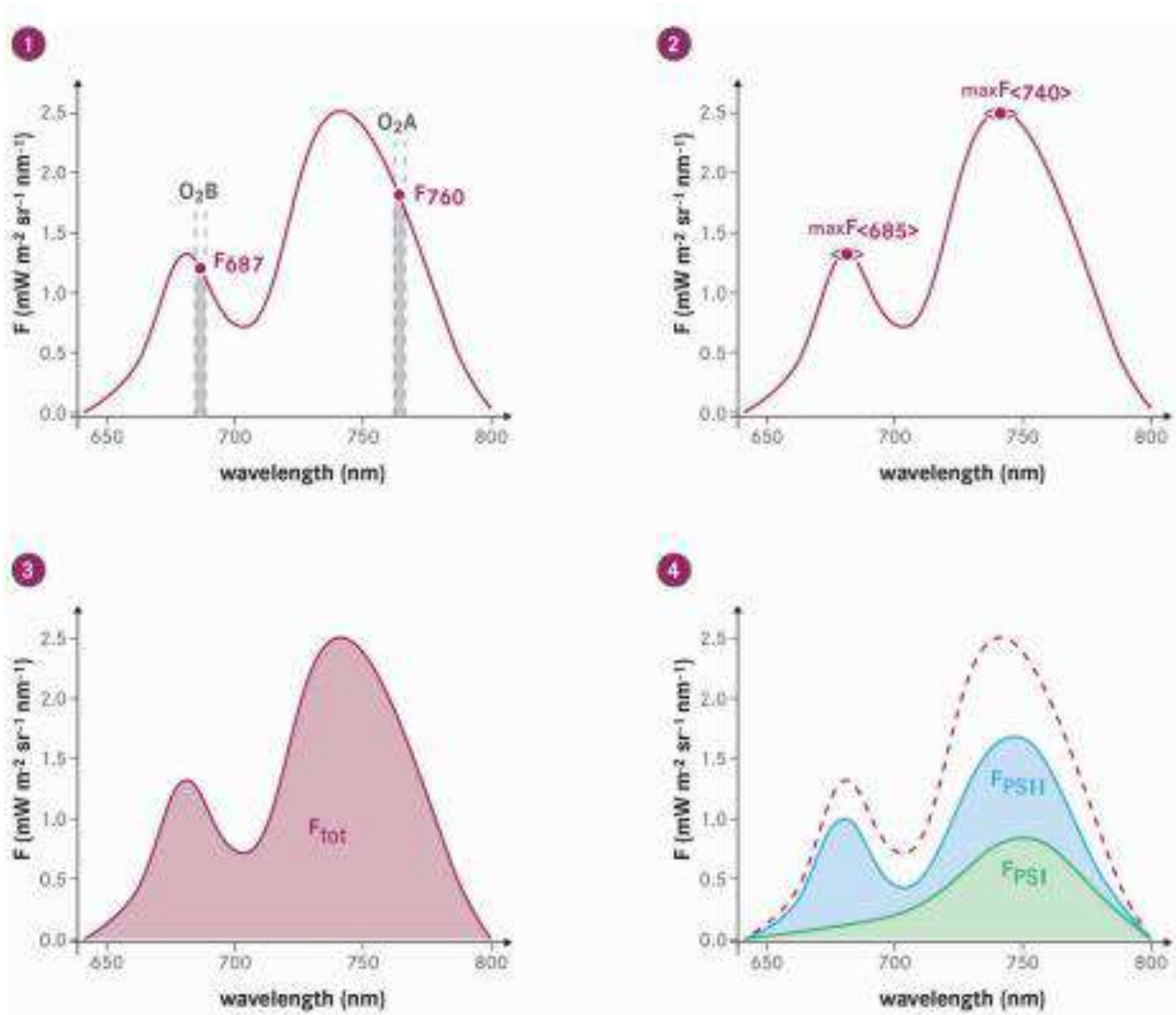
Solar and atmospheric absorption bands used to retrieve F:

- Hα [645-665 nm]
- O_2-B [680-700 nm]
- Fe [758.7-758.9]
- O_2-A [750-770 nm]
- KI [770-770.2 nm]



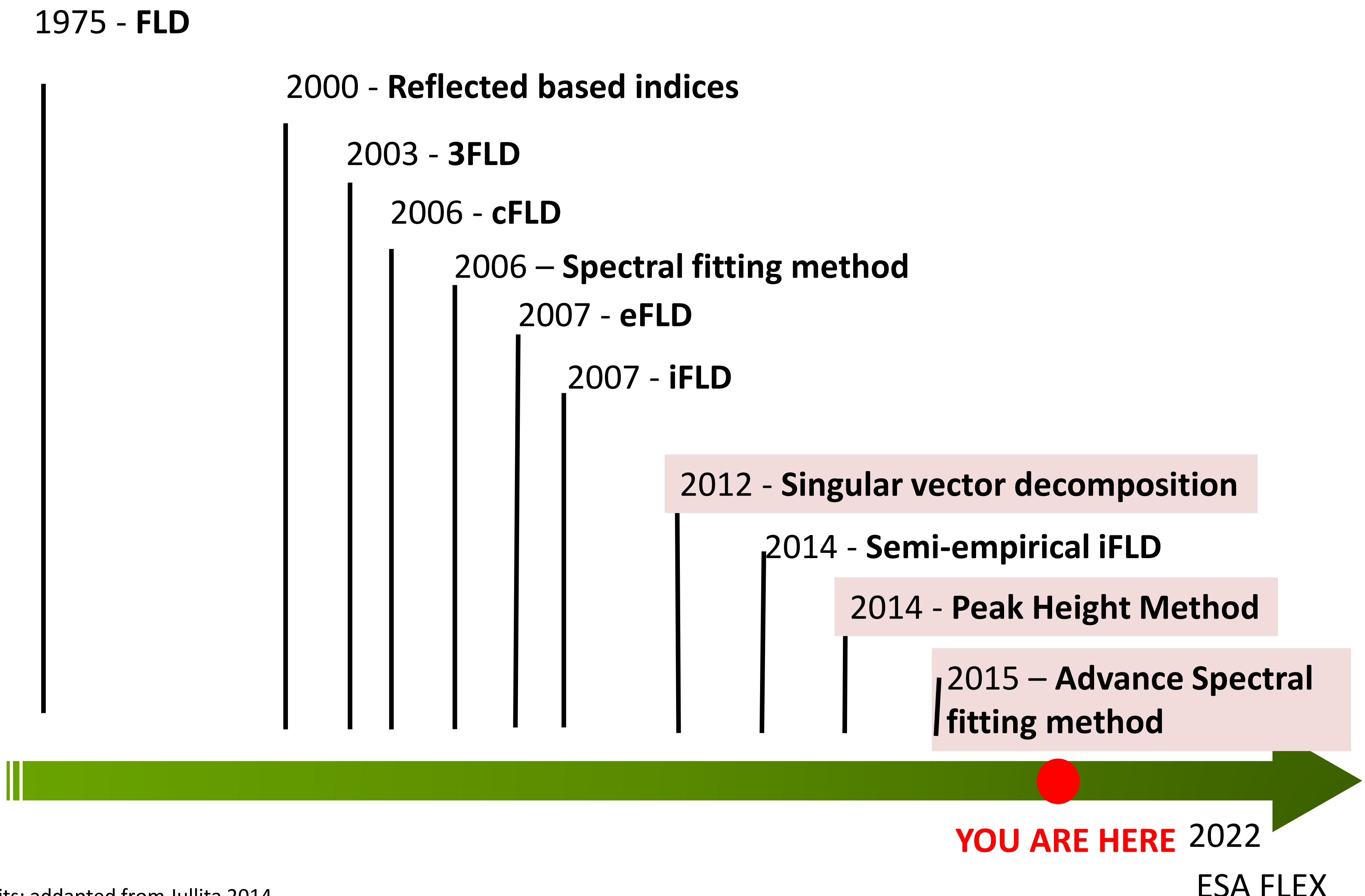
Credits: Liu et al., 2015

Sun-Induced Chlorophyll Fluorescence



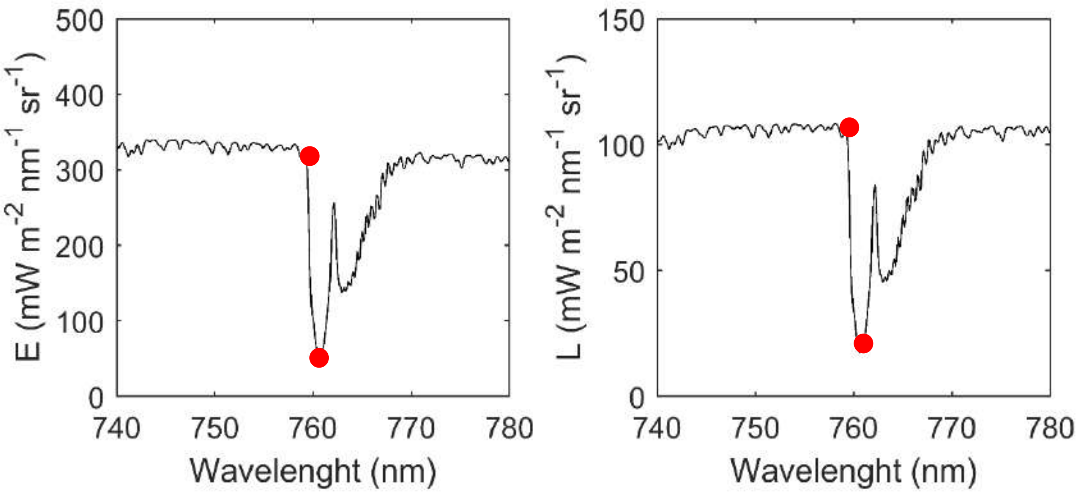
Credits: FLEX mission selection final report

Brief history of top of canopy sun-induced Cholorphyll fluorescence retrieval methods



Credits: addapted from Jullita 2014

Fraunhofer Line Depth (sFLD)



$$L(\lambda_{in}) = \frac{r(\lambda_{in})E(\lambda_{in})}{\pi} + F(\lambda_{in})$$

$$L(\lambda_{out}) = \frac{r(\lambda_{out})E(\lambda_{out})}{\pi} + F(\lambda_{out})$$

$$\boxed{\begin{aligned} r &= \frac{L(\lambda_{out}) - L(\lambda_{in})}{E(\lambda_{out}) - E(\lambda_{in})} \cdot \pi \\ F &= \frac{E(\lambda_{out}) \cdot L(\lambda_{in}) - L(\lambda_{out}) \cdot E(\lambda_{in})}{E(\lambda_{out}) - E(\lambda_{in})} \end{aligned}}$$

ASSUMPTION:

- Only use two bands – one inside and one outside the absorption band
- Fluorescence and reflectance are **considered constant** inside and outside the absorption band

$r(\lambda_{in}) \approx r(\lambda_{out})$ $F(\lambda_{in}) \approx F(\lambda_{out})$

1975 – Plascyk, 1975

Credits: addapted from Jullita 2014

Sun Induced Chlorophyll Fluorescence (SIF) reflectance based Indices

Ratio indices:

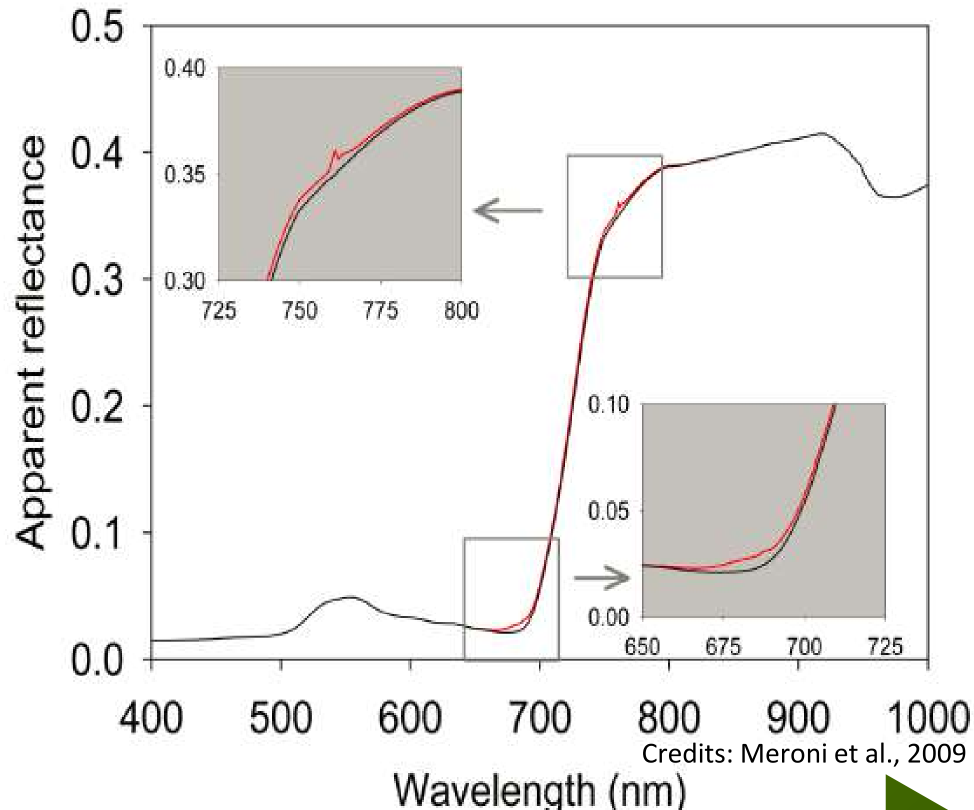
R750/R800 ; R685/R630 ; R680/R630 ;
R690/R630; R750/710; R683^2/ (R675*R691)
[Zarco-Tejada et al., 2000]

Derivative index:
(D688*D 710)/D697^2
[Zarco-Tejada et al., 2000]

In-filling index:
760.59-759.5
[Pérez-Priego et al., 2005]

Not in physical unit

Affected by atmospheric changes

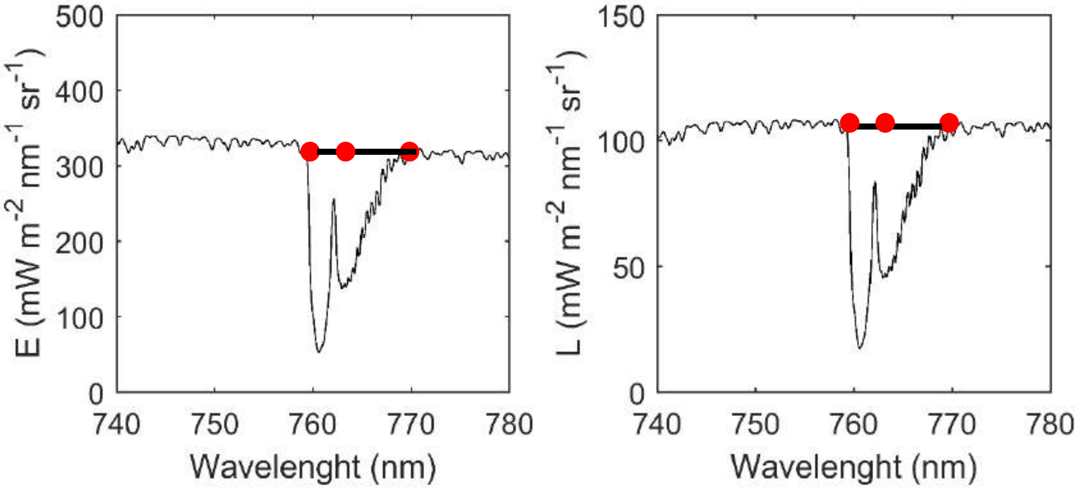


Credits: Meroni et al., 2009

2000

Credits: addapted from Jullita 2014

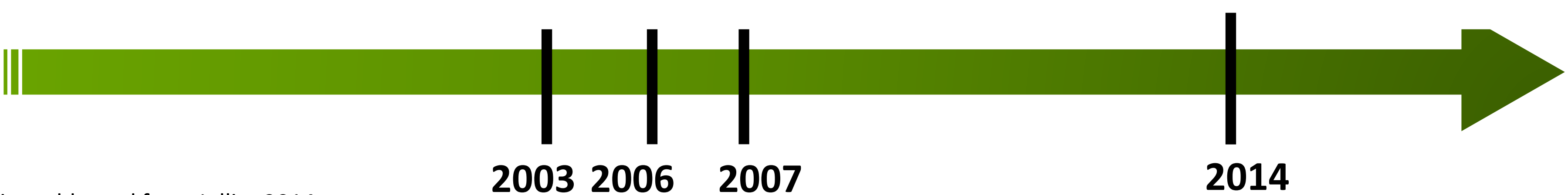
FLD like approach



$$r = \frac{L(\lambda_{\text{out}}) - L(\lambda_{\text{in}})}{E(\lambda_{\text{out}}) - E(\lambda_{\text{in}})} \cdot \pi$$

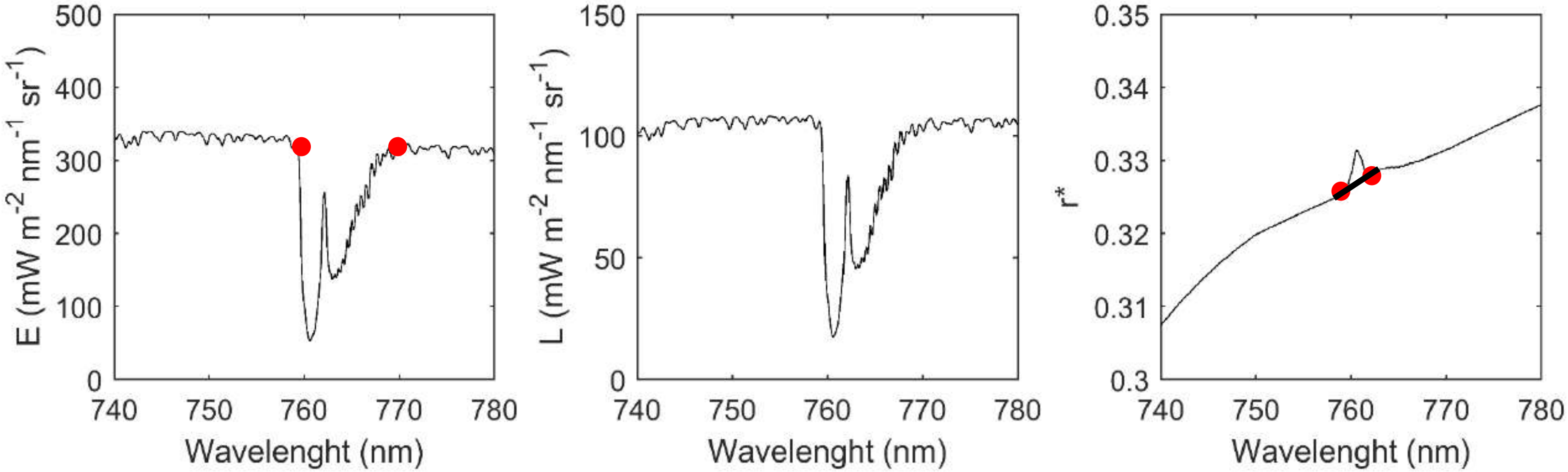
$$F = \frac{E(\lambda_{\text{out}}) \cdot L(\lambda_{\text{in}}) - L(\lambda_{\text{out}}) \cdot E(\lambda_{\text{in}})}{E(\lambda_{\text{out}}) - E(\lambda_{\text{in}})}$$

Method	Assumption
3FLD - Maier et al., 2003	Reflectance and fluorescence vary linearly – 1 band inside and 2 outside
cFLD - Gomez-Chova et al., 2006	**Reflectance** varies according to **polynomial functions**, **fluorescence** according to **leaf emission** – 1 band inside and 2 outside
eFLD - Mazzoni et al., 2007	**Reflectance** varies according to **polynomial functions** and **fluorescence is determined based on the calculated apparent reflectance** – bands inside and 2 outside
iFLD - Alonso et al., 2007 & Damm et al., 2014.	**Reflectance** varies according to **cubic splines functions**, and **coefficients compensate** for using **aRFL** instead of **true RFL** – 1 band inside and 2 outside



Credits: addapted from Jullita 2014

FLD like approach



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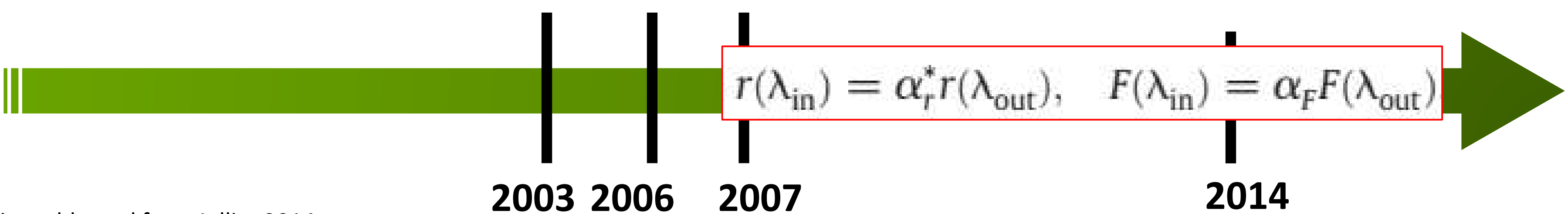
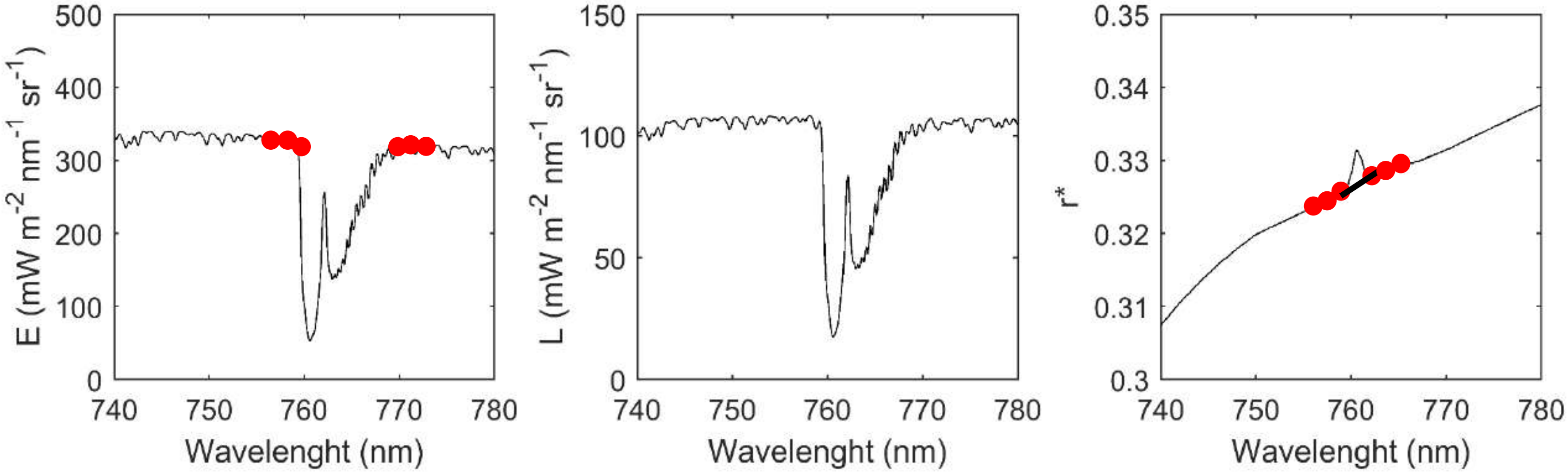


$$r(\lambda_{in}) = \alpha_r^* r(\lambda_{out}), \quad F(\lambda_{in}) = \alpha_F F(\lambda_{out})$$

Credits: addapted from Jullita 2014

FLD like approach



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iFLD - Alonso et al., 2007 & Damm et al., 2014.	**Reflectance** varies according to **cubic splines functions**, and **coefficients compensate** for using **aRFL** instead of **true RFL**

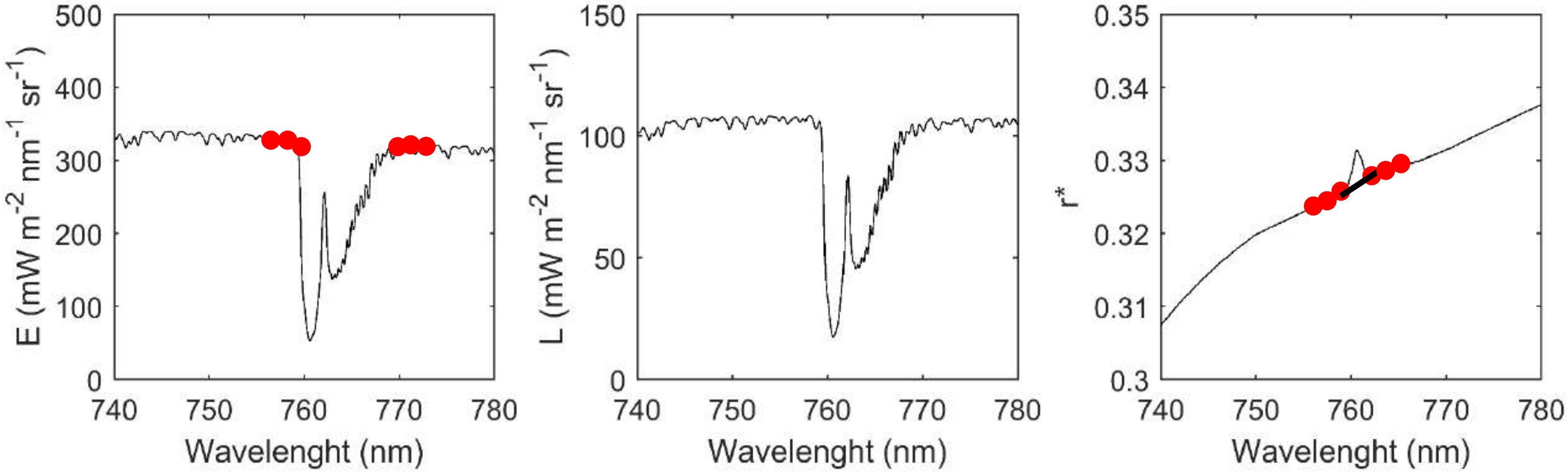
$$F(\lambda) = L(\lambda) - FIT(r^*(\lambda))E(\lambda) / \pi$$

2003 2006 2007

2014

Credits: addapted from Jullita 2014

FLD like approach



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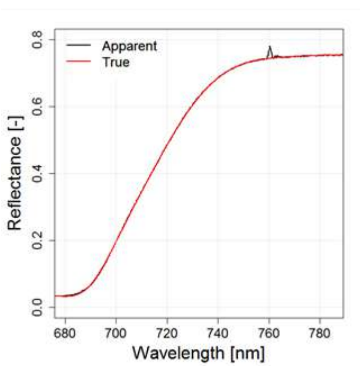
$$\alpha_F^* \approx \frac{E(\lambda_{\text{out}})}{\tilde{E}(\lambda_{\text{in}})} \alpha_r^*$$

Credits: addapted from Jullita 2014

Singular vector decomposition (SVD)

Theory: $$L(\lambda) = \frac{r(\lambda)E(\lambda)}{\pi} + F(\lambda)$$

Modeled reflected radiance



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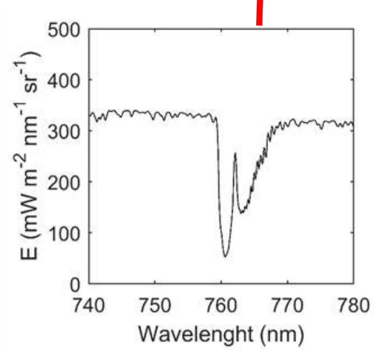

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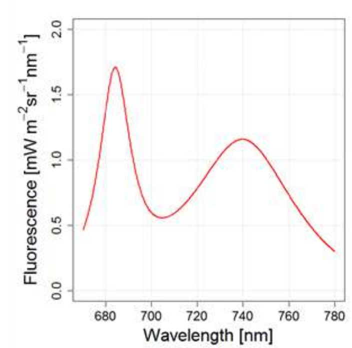

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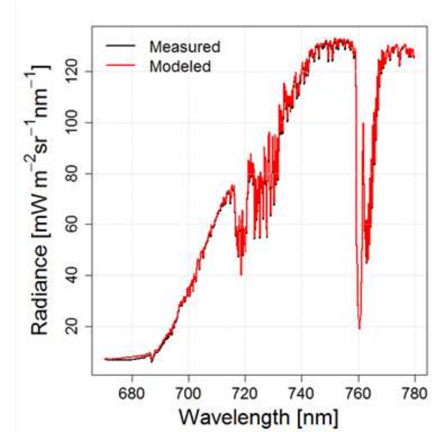


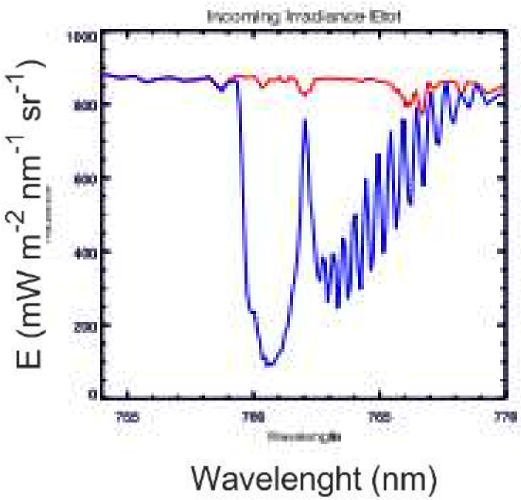
Fluorescence free radiance spectrum

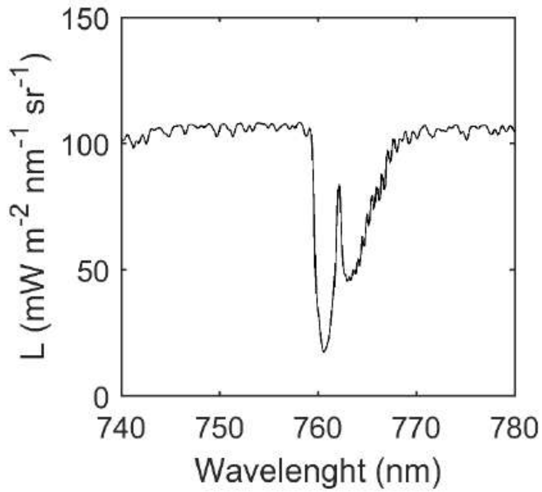
Fluorescence spectrum

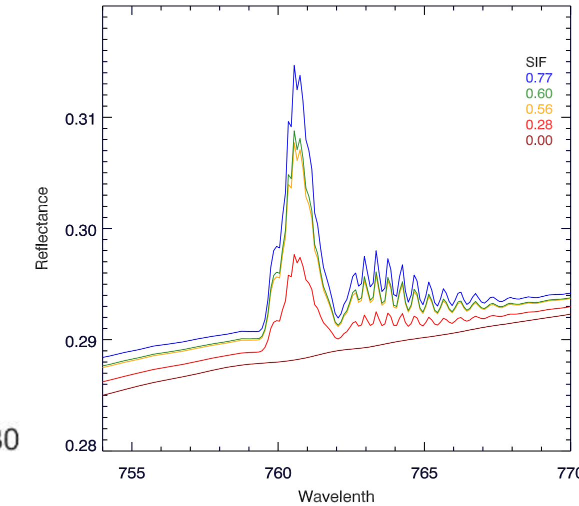
Linear combination of singular vectors
(principal components)

2012

Peak Height Method

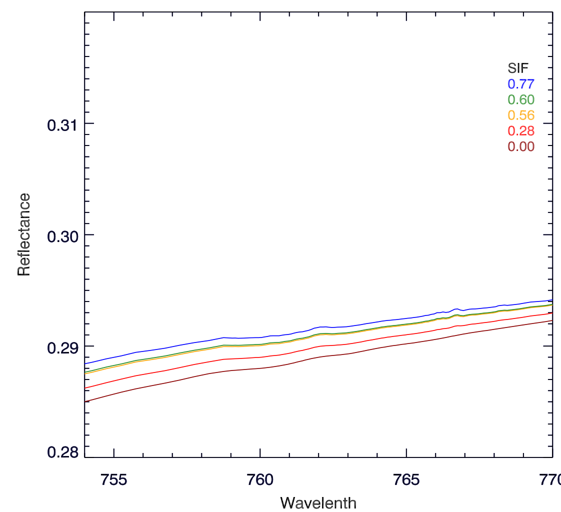




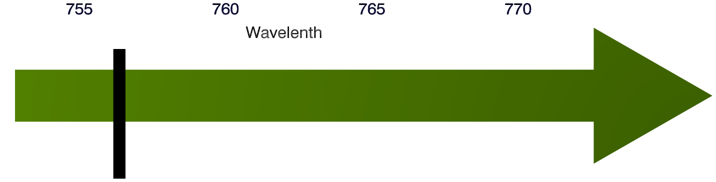


$$\rho_{app}-\tilde{\rho}_{app}=\left(\cancel{\rho}+\frac{\pi}{E_{tot}}F\right)-\left(\cancel{\rho}+\frac{\pi}{\tilde{E}_{tot}}F\right)$$

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



- Avoids making assumptions about true reflectance
- Limited to absorption bands



2014

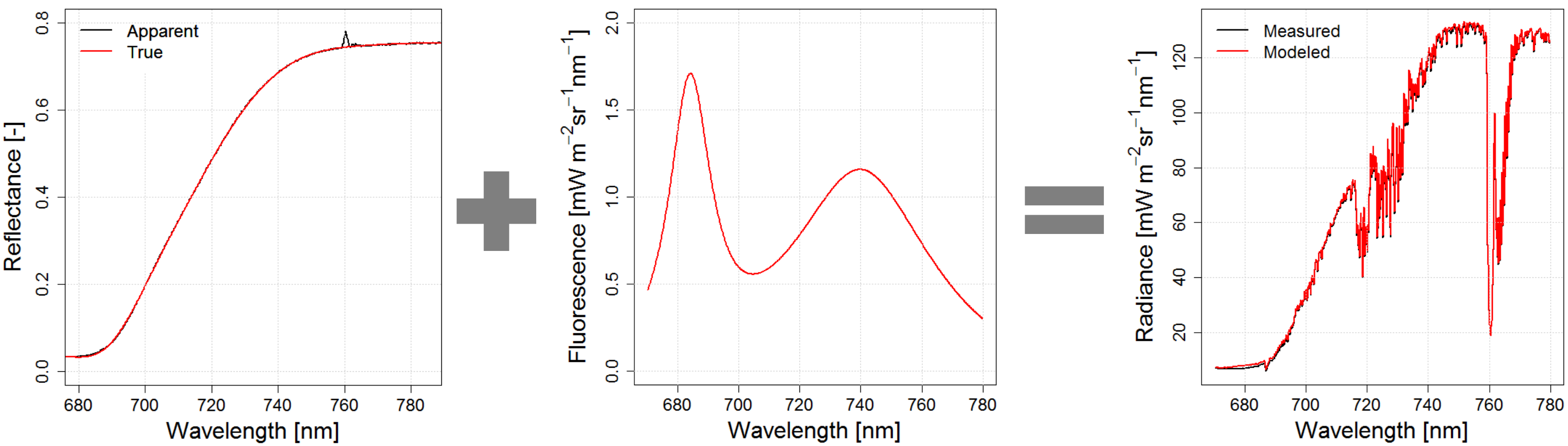
Spectral Fitting Methods (SFM)

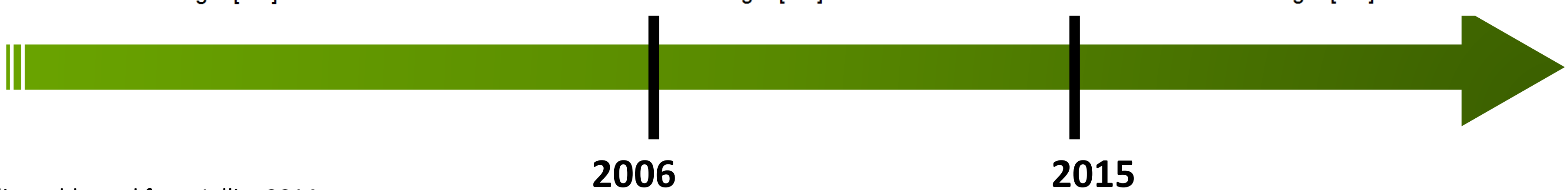
Theory: $$L(\lambda) = \frac{r(\lambda)E(\lambda)}{\pi} + F(\lambda)$$

True reflectance is
modelled as cubic spline
Based on on iFLD estimates

Fluorescence emission is
modelled as Voigt function
Based on iFLD estimates

Modeled reflected radiance



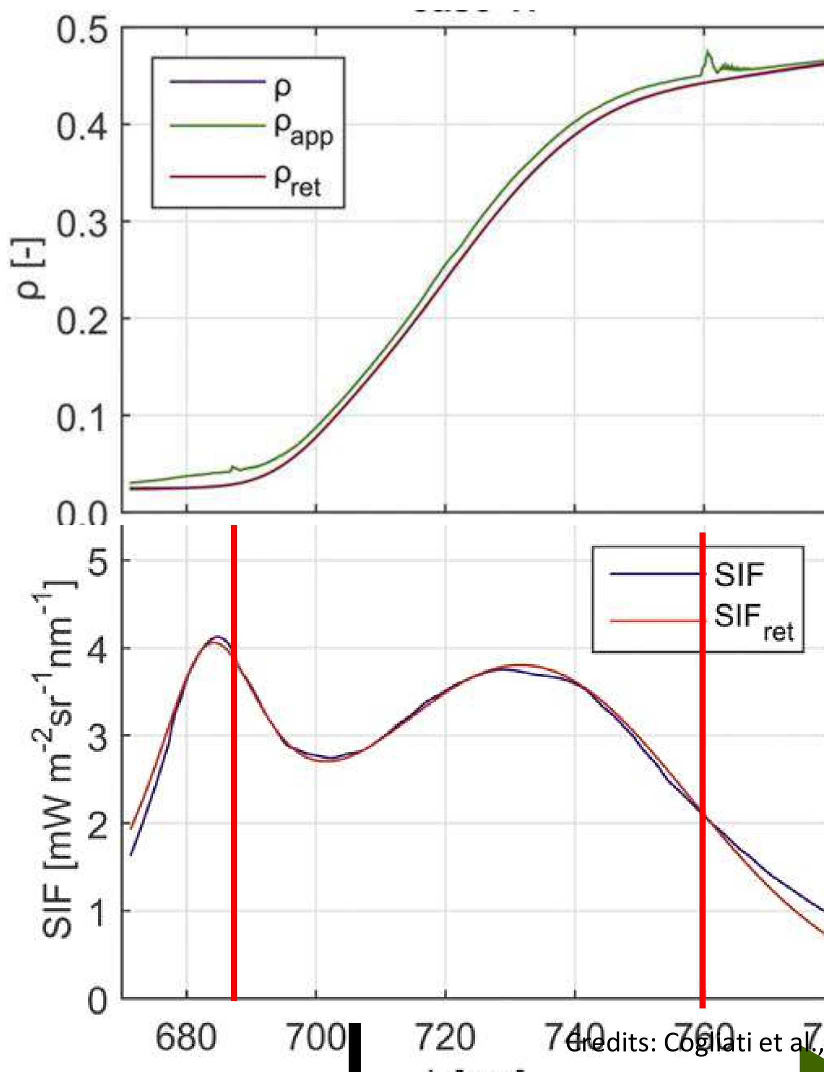


Credits: addapted from Jullita 2014

Spectral Fitting Methods (SFM)

Cost function optimization:

$$min \sum (L - L_{mod})^2$$



Credits: Cogliati et al., 2015

2006

2015

Credits: addapted from Jullita 2014

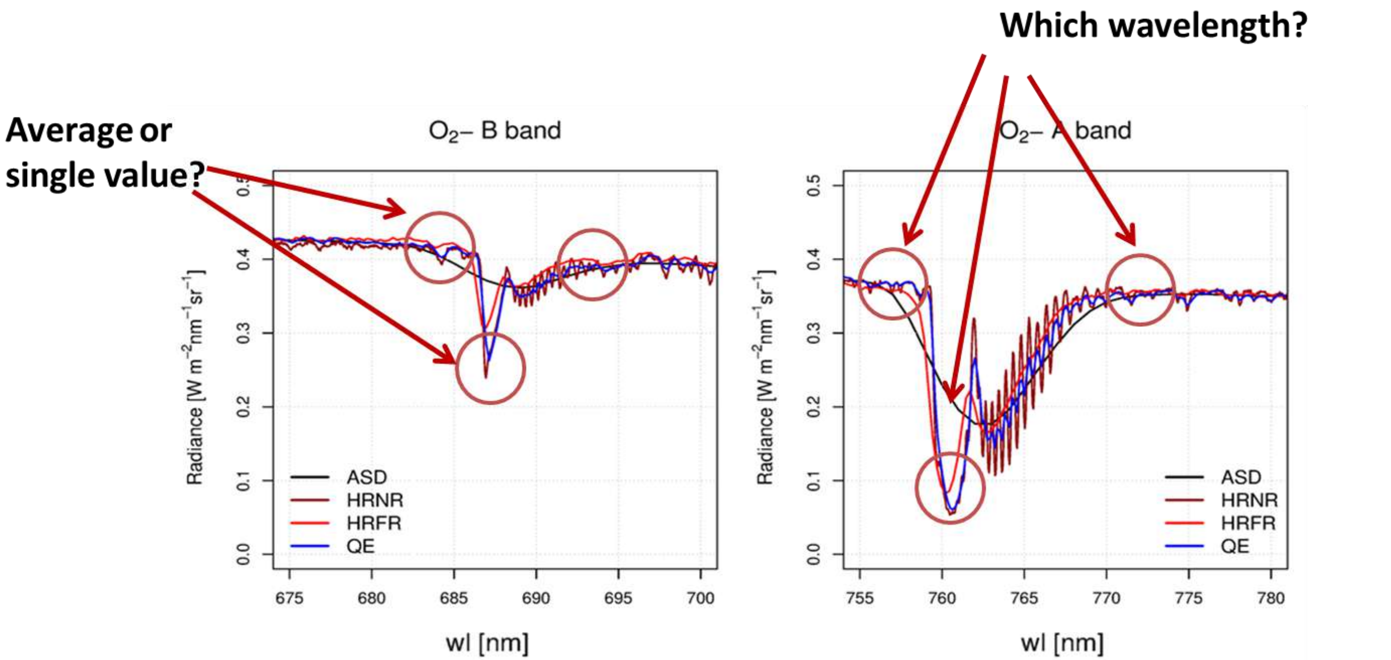
From theory to practice

How to apply these methods to measured data?

Not always easy to translate the method into an algorithm

Research questions:

1. **Sensitivity to Spectral resolution and SNR**
2. **Sensitivity to Spectral shift**
3. **Wavelength selection in and out the absorption band**



Model data

Table 1 - Spectrometer characteristics:

Spectrometer	Range [nm]	SSI [nm]	FWHM [nm]	SNR
HR4000	650-840	0.05	0.28	300:1
MAYA	650-803	0.08	0.44	450:1
QEPRO	651-803	0.13	0.38	1100:1
ASD	350-1000	1.4	3	4000

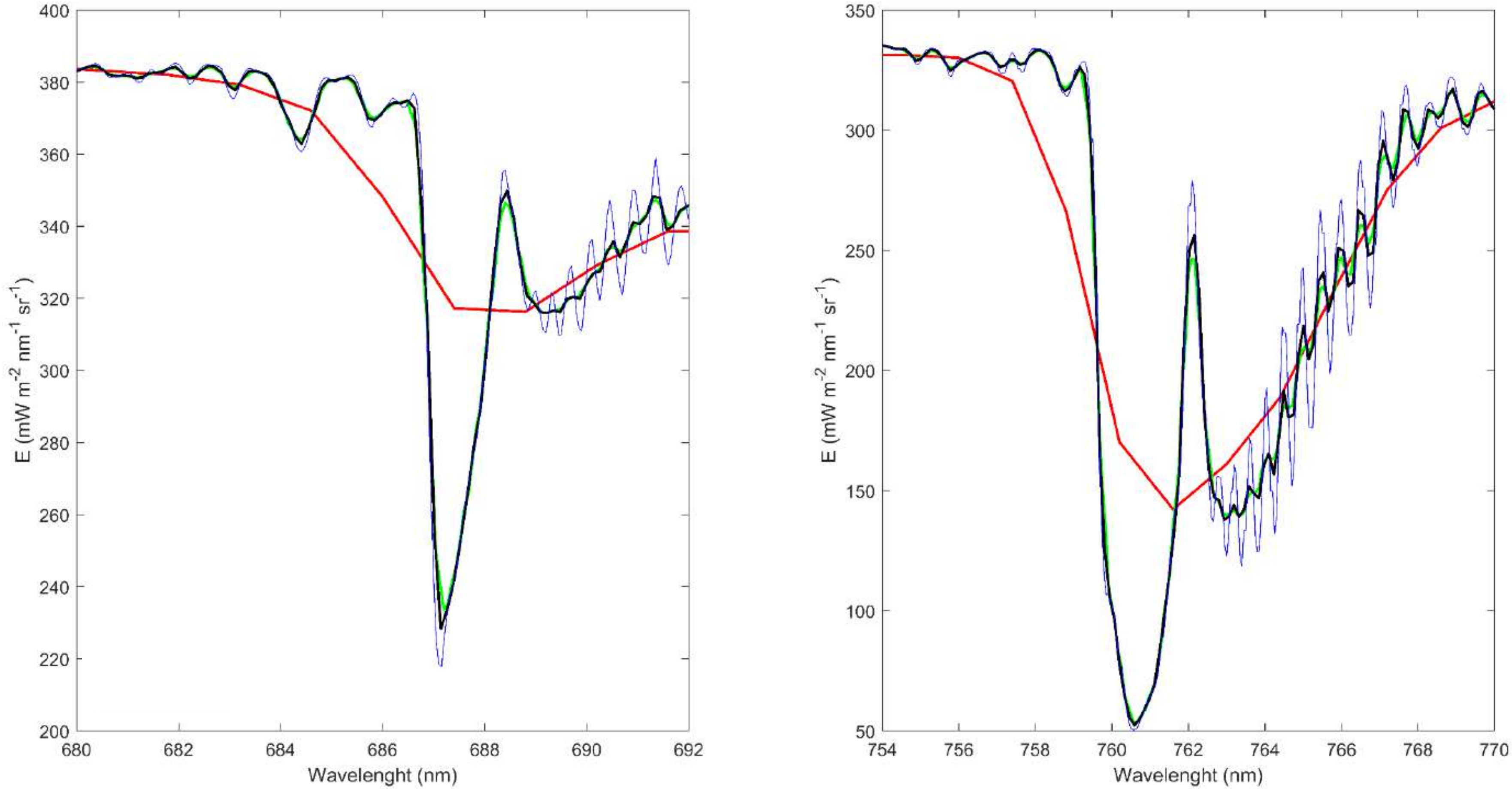
*adapted from: Celesti et al. 2016. Comparison of sun-induced chlorophyll fluorescence estimates from commercial spectrometers: an optimal setup for field measurements and aerial product validation

Spectra

- The 1600 spectra per spectral library comprise the following:
  - 16 vegetation types
  - each vegetation type is simulated 100 times
  - the first spectra per set of 100 spectra is without noise
  - the following 99 spectra are replicates but with noise

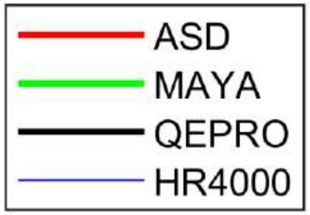
Spectra	Name	LAI	LIDF	CAB	f-eff	SIF685	SIF760
1	L1_E_20_2.txt	1	Erectophile	20	2	0.7617	0.3383
2	L1_E_20_4.txt	1	Erectophile	20	4	1.5234	0.6766
3	L1_E_80_2.txt	1	Erectophile	80	2	0.5589	0.402
4	L1_E_80_4.txt	1	Erectophile	80	4	1.1178	0.8039
5	L1_P_20_2.txt	1	Planophile	20	2	0.6378	0.6378
6	L1_P_20_4.txt	1	Planophile	20	4	2.9226	1.2756
7	L1_P_80_2.txt	1	Planophile	80	2	1.1293	0.76
8	L1_P_80_4.txt	1	Planophile	80	4	1.52	1.52
9	L4_E_20_2.txt	4	Erectophile	20	2	1.167	0.5164
10	L4_E_20_4.txt	4	Erectophile	20	4	2.3339	1.0329
11	L4_E_80_2.txt	4	Erectophile	80	2	0.8428	0.595
12	L4_E_80_4.txt	4	Erectophile	80	4	1.6856	1.1899
13	L4_P_20_2.txt	4	Planophile	20	2	1.921	0.8378
14	L4_P_20_4.txt	4	Planophile	20	4	3.842	1.6757
15	L4_P_80_2.txt	4	Planophile	80	2	1.4659	0.9826
16	L4_P_80_4.txt	4	Planophile	80	4	2.9318	1.9652

1. Sensitivity to Spectral resolution and SNR

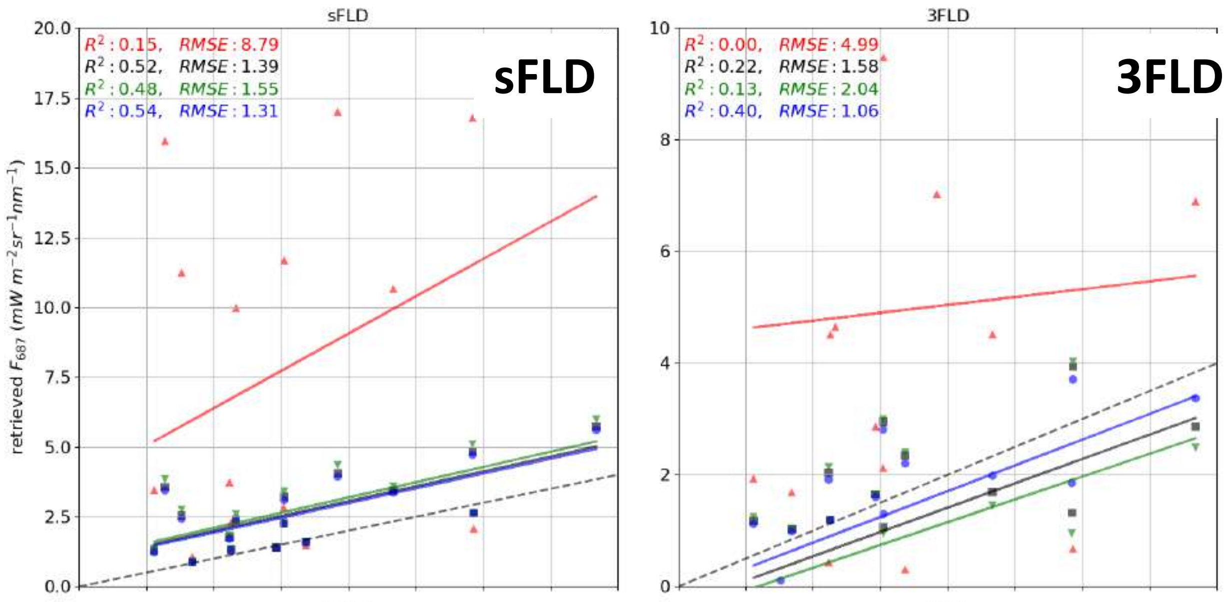


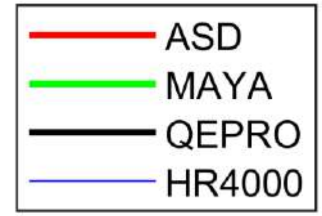
Retrieval methods

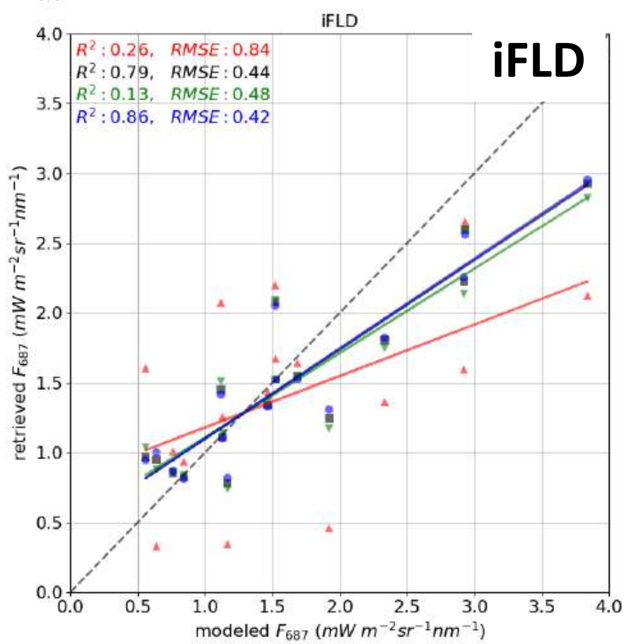
- sFLD, 3FLD, iFLD (done!)
- SFM, Peak Height (next…)



O$_2$-B band results (F687) – all 16 vegetation types WITHOUT noise

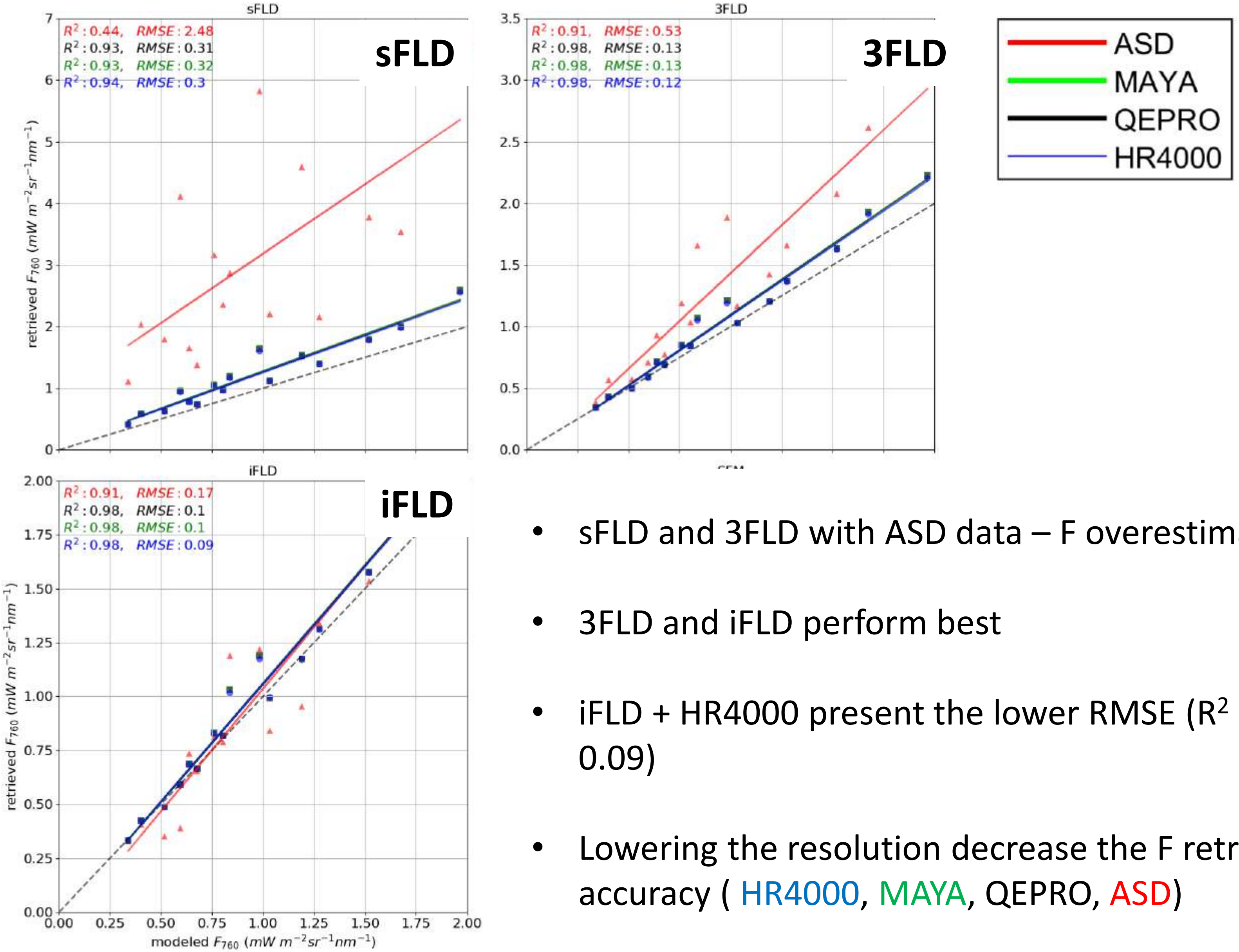






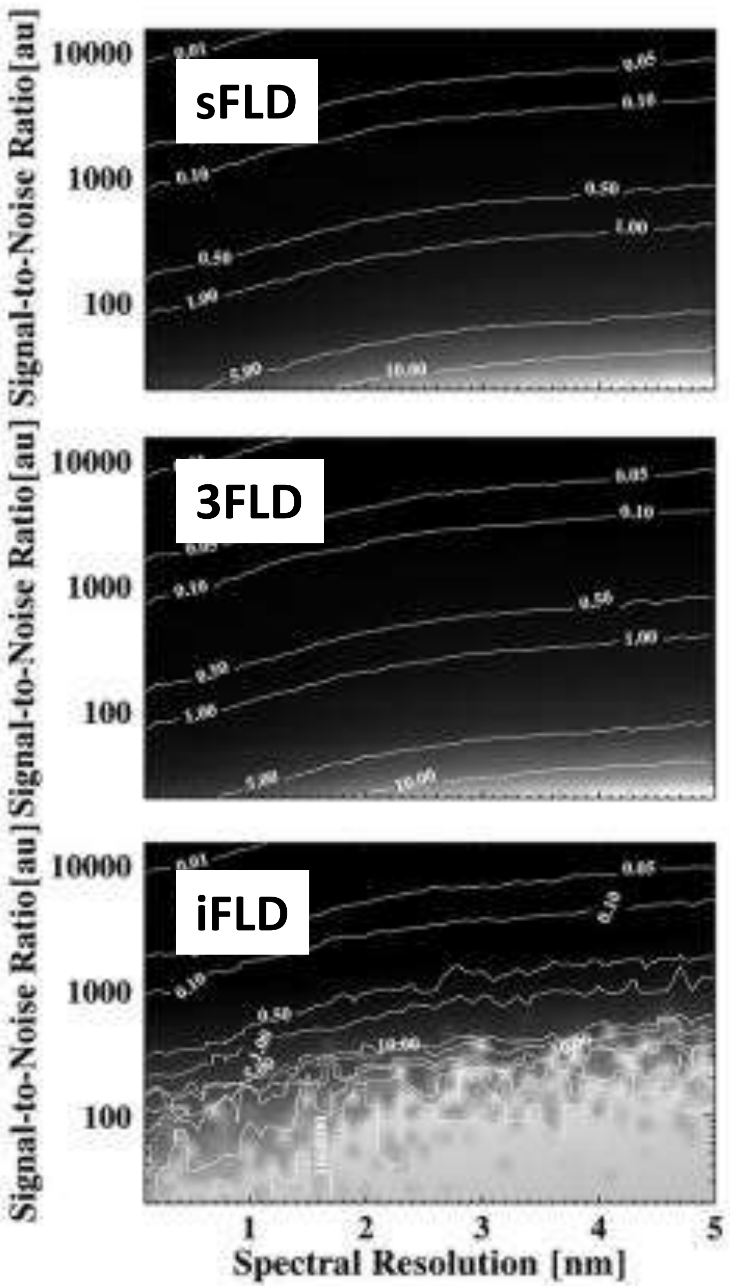
- None of the retrievals used perform really good in the O$_2$B band
- iFLD with HR400 performs “best” (R^2 0.70 & RMSE 0.42)
- Lowering the resolution decrease the F retrieval accuracy (HR4000, MAYA ~ QEPRO, ASD)
- Improve results when using Peak Height and SFM

O_2-A band results (F760) – all 16 vegetation types WITHOUT noise



- sFLD and 3FLD with ASD data – F overestimation
- 3FLD and iFLD perform best
- iFLD + HR4000 present the lower RMSE (R^2 0.98 & RMSE 0.09)
- Lowering the resolution decrease the F retrieval accuracy (HR4000, MAYA, QEPRO, ASD)

O_2-A band results (F760) – all 16 vegetation types WITH noise

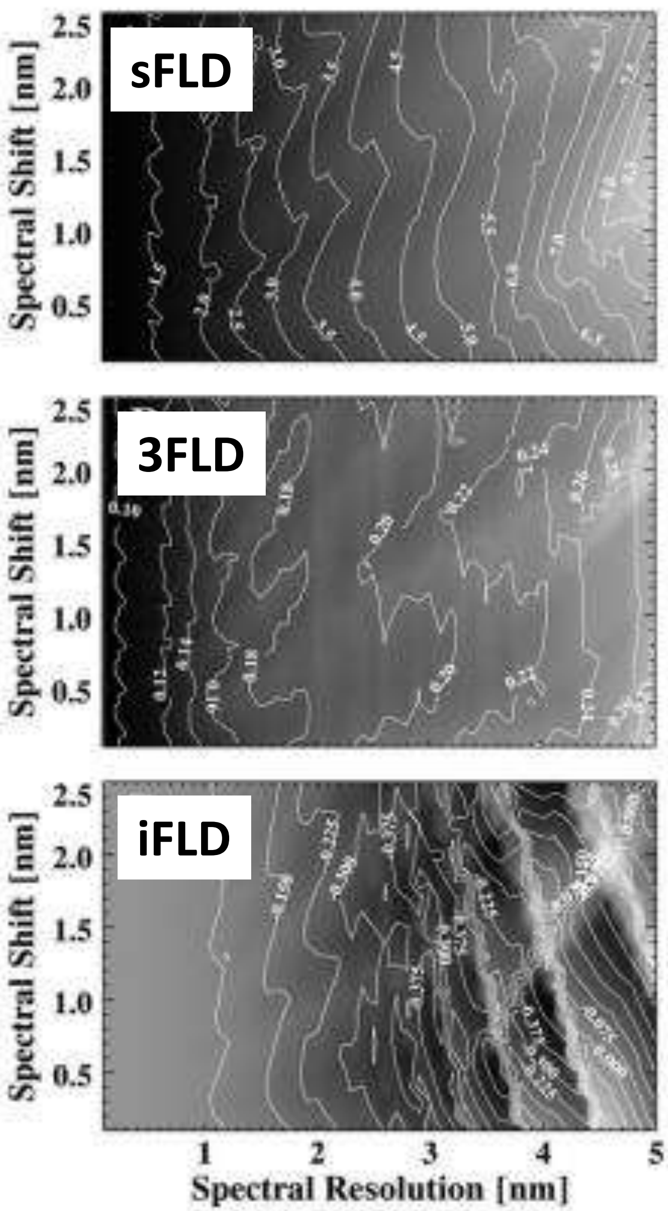


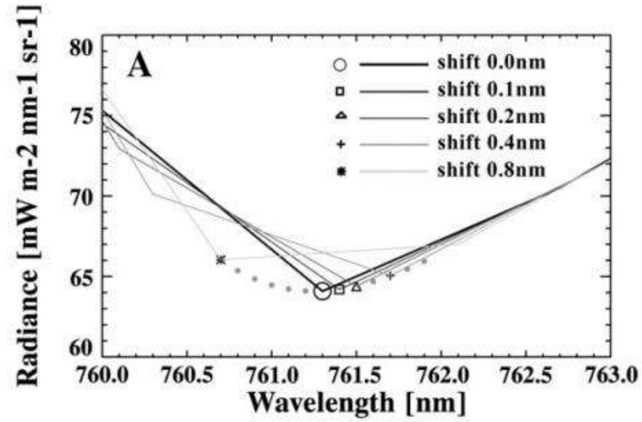
→ Plot - Average standard deviation of retrieved F

- Low SNR levels (10-200) led to a high fluctuation of the measured radiance signals and consequently to high F retrieval error.
- sFLD insensitive to noise – reached stable signal SNR ~ 200
- 3FLD – reached stable signal SNR ~ 1000
- iFLD sensitive to noise – no stable error value was fond even SNR ~ 10000
- Next – similar analysis with O_2B band and peak height and SFM methods.

Credits: Damm et al. 2010

2. Sensitivity to Spectral shift





→ **Spectral miscalibration** of the up looking and down looking channel.

→ **Plot - Average absolute difference between reference F and retrieved F**

- sFLD most affected by spectral shift
- **Lower spectral resolution – higher the influence of the spectral shift in F** (spectral shift = 0.5 spectral resolution)

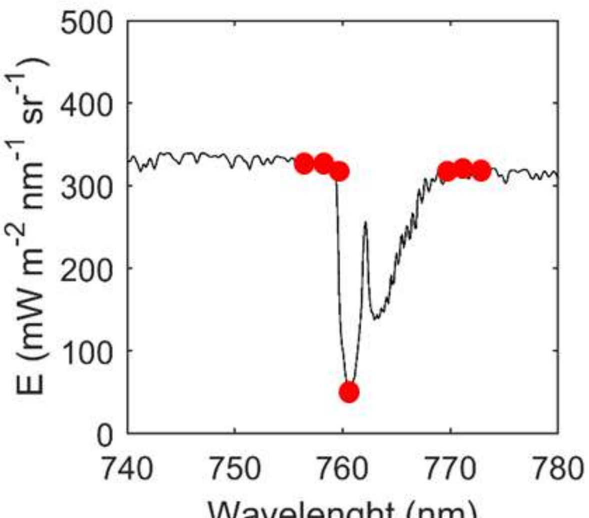
Credits: Damm et al. 2010

3. FLD like approaches: Wavelength selection in and out the absorption band

Recommendations

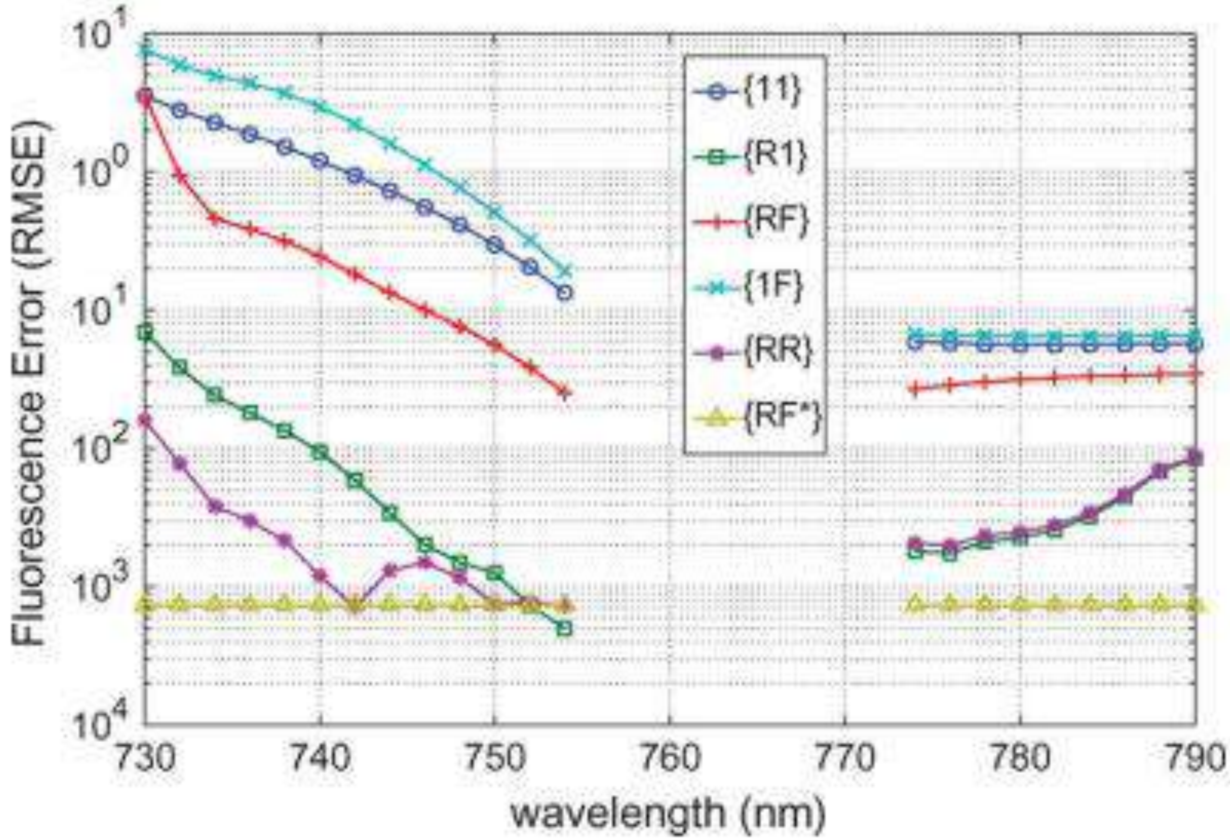
Channel inside:
- set to the position of the minimal in each of the absorption bands.

Channel outside:
- the irradiance should be relatively steady around the channels (which means the channels are on the “shoulders” of the absorption valleys)
- the channels should be as near to the inside channels as possible.



Credits: Liu et al., 2015

O_2-A band results (F760) – iFLD



- The error in the FLD-based methods are mainly caused by the F and reflectance different between the bands inside and outside the absorption bands.
- The RMSE increase when the distance between in the inside and outside absorption band increase (it is lower spectral resolution higher RMSE)

Credits: Alonso et al. 2008

Conclusions and future work

General conclusions (O_2B and O_2A band)

- When no noise is taking into account ASD-Low spectral resolution worst results and HR400-High spectral resolution best results.

- When noise is taking into account QEPRO lower spectral resolution compare to HR400 but better SNR 1100:1 best performance.

- FLD-bases method – band selection,
  - Inside the absorption band – lower point
  - Outside the absorption band – maximum points ~ avoid absorption valleys
  - Selection of bands ~ reduce distance between inside and out side bands

O_2B band (F680)

- Non of the FLD-based method provide an accurate estimation of F680
- Future – we need to evaluate peak height and SFM performance

O_2A band (F760) ~ Damm et al 2010.

sFLD

- Strongly overestimate F
- Sensitive to small signal variations
- 1- Spectral resolution
- 2- then spectral shift and SNR

3FLD

- Best compromise between robustness and accuracy
- 1- SNR
- 2- then spectral resolution and spectral shift

iFLD

- Best performance but highly influence by noise
- 1 – SNR
- 2 – then spectral resolution and spectral shift

O_2B band (F680)

- Non of the FLD-based method provide an accurate estimation of F680
- Future – we need to evaluate peak height and SFM performance

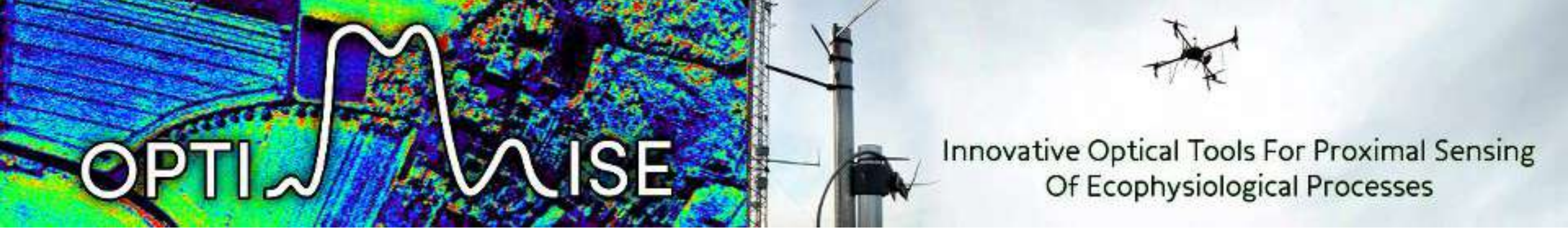
O_2A band (F760) ~ Damm et al 2010.

sFLD
- Strongly overestimate F
- Sensitive to small signal variations
- 1- Spectral resolution
- 2- then spectral shift and SNR

3FLD
- Best compromise between robustness and accuracy
- 1- SNR
- 2- then spectral resolution and spectral shift

iFLD
- Best performance but highly influence by noise
- 1 – SNR
- 2 – then spectral resolution and spectral shift

Future – we need to evaluate peak height and SFM performance



Thanks for your attention!!