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PhotoSpec - Ground-based Remote Sensing of Solar-Induced Chlorophyll Fluorescence

***K. Grossmann**[a,b], C. Frankenberg[c,d], U. Seibt[b], S. Hurlock[a,b], A. Pivovaroff[e], J. Stutz[a,b]

[a]Joint Institute For Regional Earth System Science and Engineering (JIFRESSE), University of California Los Angeles, Los Angeles, CA, 90095, USA; [b]Department of Atmospheric and Oceanic Sciences, University of California Los Angeles, Los Angeles, CA 90095, USA; [c]California Institute of Technology, Pasadena, CA, USA; [d]Jet Propulsion Laboratory, Pasadena, CA, USA; [e]La Kretz Center for California Conservation Science, University of California Los Angeles, Los Angeles, CA, USA

***contact**: kgrossmann@atmos.ucla.edu*

1. SIF as a constraint for photosynthesis

Solar-Induced Chlorophyll Fluorescence (SIF) emitted from vegetation can be used as a constraint for photosynthetic activity and is now observable on a global scale from space[1,2]. SIF observations have the potential to provide new and unique insights into Gross Primary Production (GPP) of vegetation and thus the global carbon budget[3].

The dependence of the SIF signal on environmental conditions, such as water stress, radiation, etc. remains poorly understood on a leaf-to-canopy scale, thus limiting our ability to explore the full potential of SIF observations.

We report on the development of an automated remote sensing system for ground-based SIF measurements (http://www.kiss.caltech.edu/study/photosynthesis/technology.html) and show initial results of the test measurements of the SIF signal with the new instrument.

2. Background of SIF

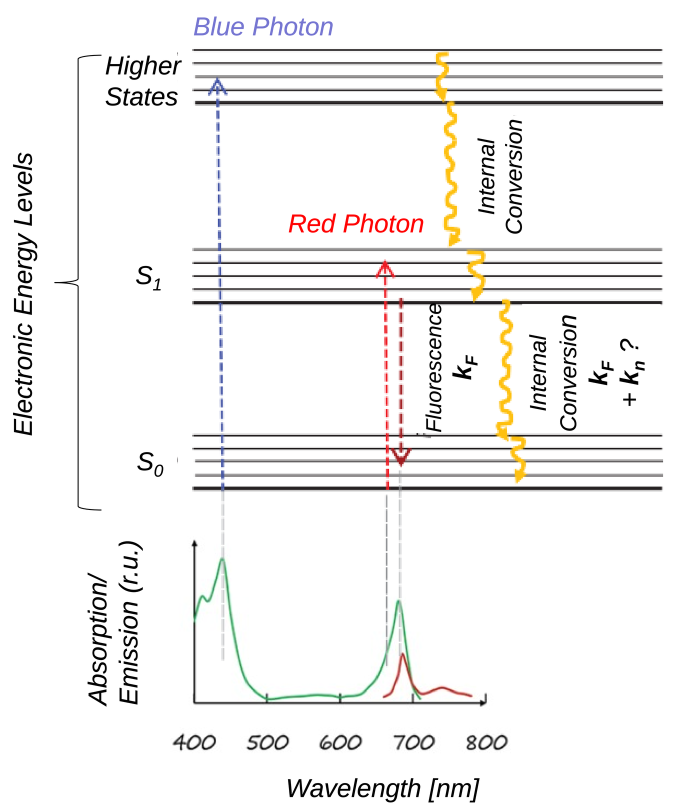


Figure 1: Idealized diagram illustrating the possible energy levels of absorbed photons in a Chl-a molecule[5].

- SIF has been used in photosynthesis studies for several decades[4].
- SIF is an electromagnetic signal emitted between ≈ 690 – 800 nm by chlorophyll-a (Chl-a) leaf pigments during photosynthesis[3]:

Chl-a absorbs photons of blue and red light very efficiently;
Absorption of a blue photon by Chl-a raises an e^- from S_0 to an orbital of a highly excited state;
Absorption of a red photon produces the state S_1 directly; from there the e^- can relax to the ground state via emission of a chlorophyll fluorescence photon[5].

- Probability of photons being emitted as chlorophyll fluorescence is directly proportional to the product of absorbed photosynthetic radiation and the fluorescence yield Φ_f[1]:

$$\Phi_f = \frac{k_f}{k_f + k_d + k_p + k_n}$$

rate constants:
k_f: fluorescence
k_d: radiationless decay
k_p: photochemistry
k_n: heat quenching

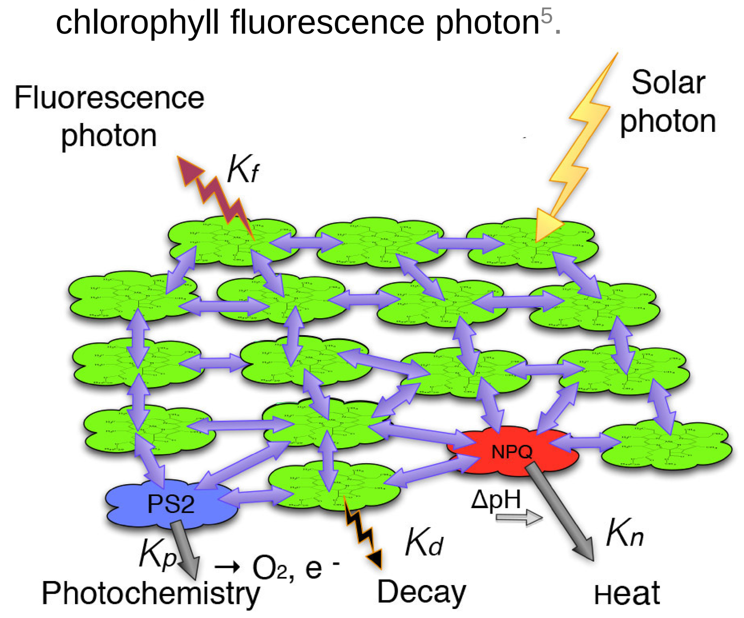


Figure 2: Schematic of SIF on a chloroplast level: arrays of chlorophyll molecules absorb and process solar photons in plant leaves, a small fraction Φ_f (≈ 0.5 – 2%) comes out as fluorescent photons[6].

3. Method

- The optical depth change within solar Fraunhofer lines and the O_2-A-band due to SIF is used to detect SIF via remote sensing in the red region of the solar spectrum (Figure 3).
- The SIF measurement technique used here is based on decades of experience using Differential Optical Absorption Spectroscopy (DOAS)[7], an established method to measure atmospheric trace gases.
- The SIF signal can be retrieved in the DOAS fitting procedure using an additive polynomial P. The optical density τ, which is the logarithmic ratio of the incident

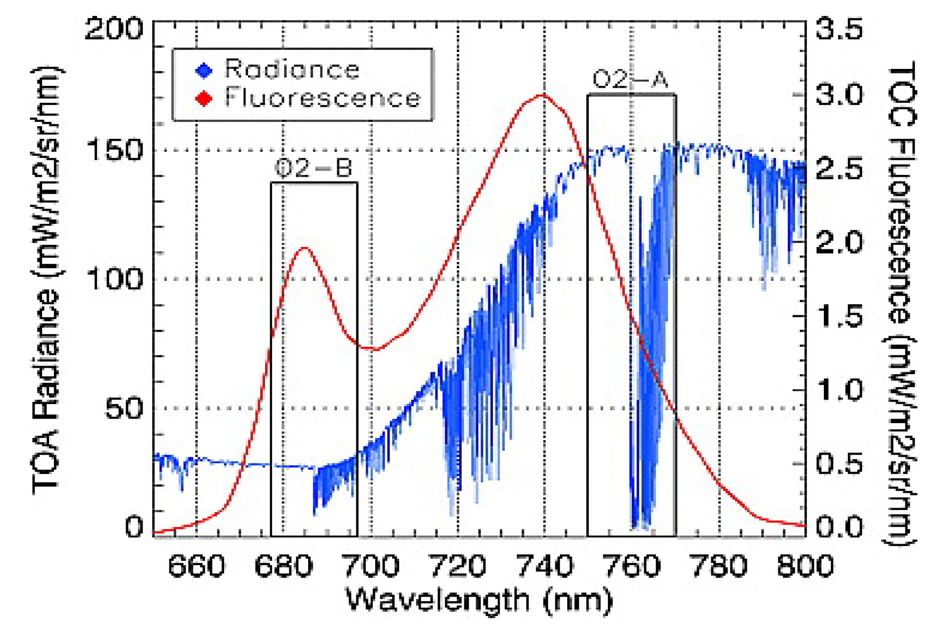


Figure 3: Chlorophyll fluorescence spectrum (red) and top-of-atmosphere (TOA) radiance spectrum simulated from a green vegetation target (blue)[8].

and attenuated intensity $I_0(\lambda)$ and $I(\lambda)$ and can be written as:

$$\tau(\lambda) = \ln\frac{I_0(\lambda) + P}{I(\lambda)}$$

4. Instrumental set-up

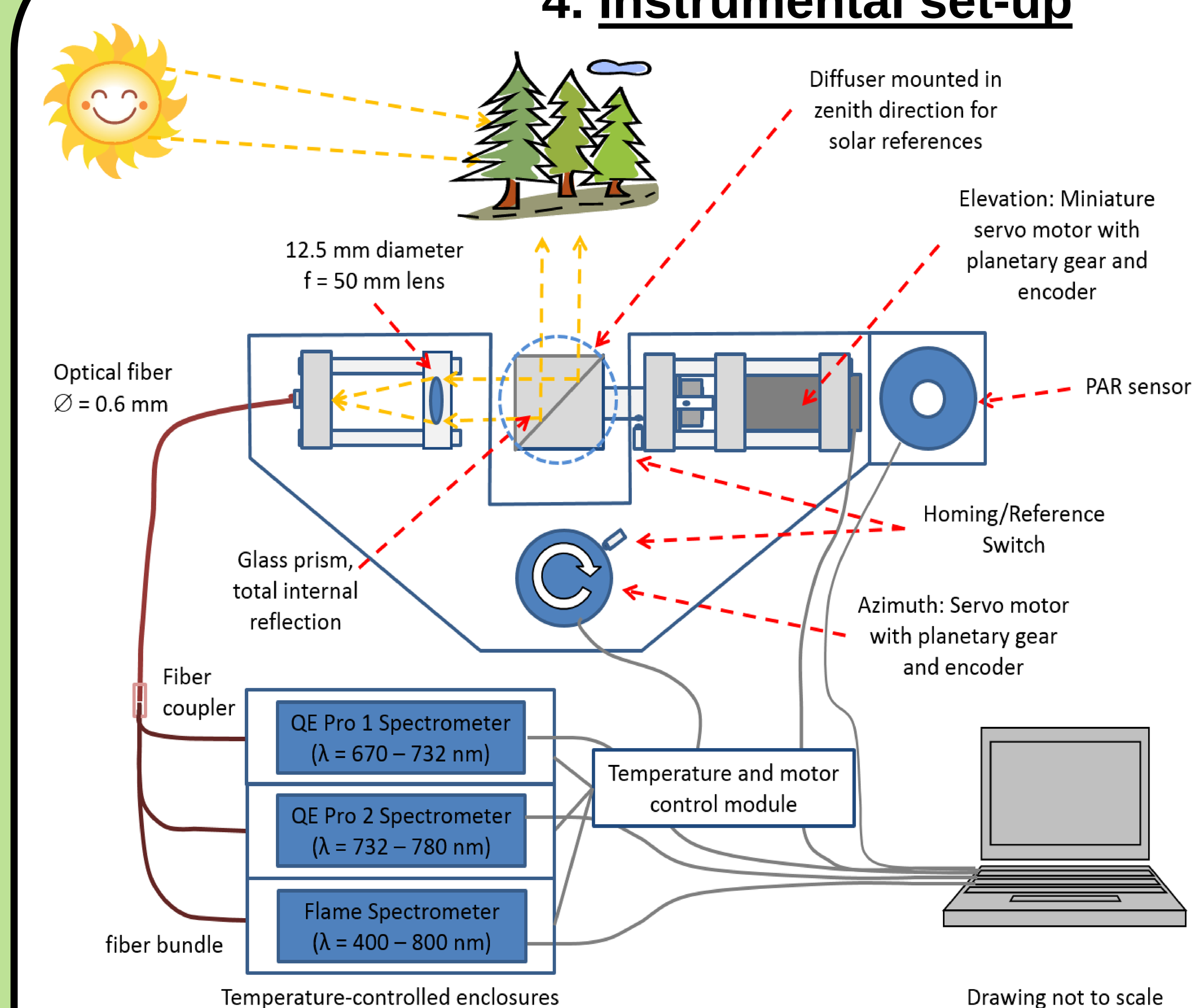


Figure 4: Top-view sketch of the instrument with the option to change azimuth and elevation viewing angles using a 2D scanner driven by servo motors.

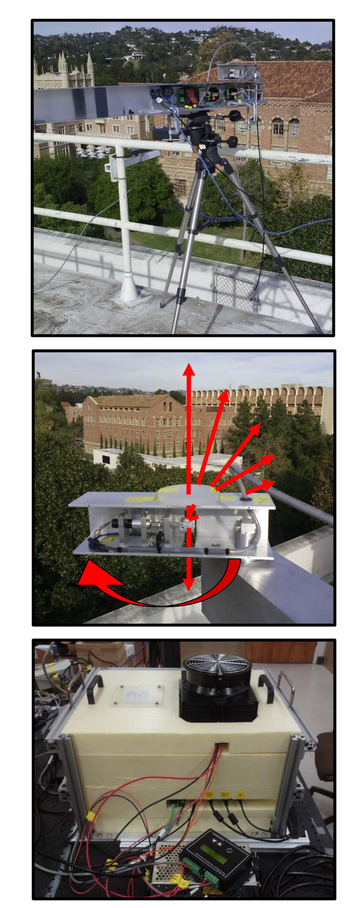


Figure 5: Images of the preliminary prototype instrument: a) 2D scanning telescope unit, b) telescope viewing directions, c) temperature-controlled enclosure.

Instrument description: The instrument consists of three thermally stabilized commercial spectrometers that are linked to a 2D scanning telescope unit via optical fiber bundles. The spectrometers cover an SIF retrieval wavelength range at high spectral resolution, but also provide moderate resolution spectra in order to retrieve vegetation indices and the photochemical reflectance index (PRI) (Table 1).

Table 1: Characteristics of the commercial spectrometers used for the SIF instrument.

Spectrometer	Wavelength range [nm]	Resolution [nm]
Ocean Optics QE Pro 1	670 - 732	0.1
Ocean Optics QE Pro 2	732 - 780	0.1
Ocean Optics Flame	400 - 800	1.5

The telescope set-up also includes a commercial photosynthetic active radiation (PAR) sensor (LICOR LI-190) to provide this quantity as an independent measurement, as incoming PAR is the driver of photosynthesis.

Scanning strategy: The 2D scanning telescope unit is able to point to a wide range of locations in the vegetation field at user selectable azimuth and elevation angles. A diffuser plate is mounted on top of the instrument to allow measurements of solar reference spectra (diffuser spectra). A typical measurement sequence starts with a list of different azimuth and elevation angle combinations, followed by the measurement of a diffuser spectrum with a time resolution of approximately 30-60 sec per measurement.

5. First SIF measurements with test instrument on the rooftop of the UCLA Mathematical Sciences building

a) Theoretical study and numerical uncertainty analysis

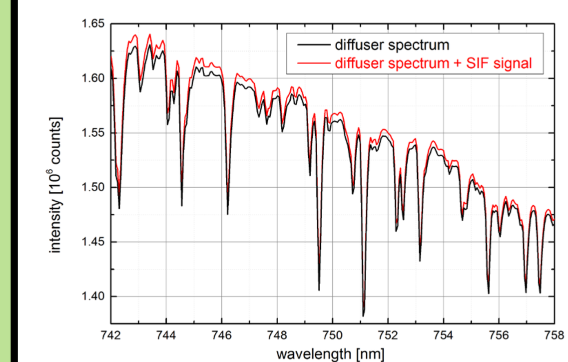


Figure 6: Example for a reference diffuser spectrum (black) and a diffuser spectrum plus an artificial SIF signal (red).

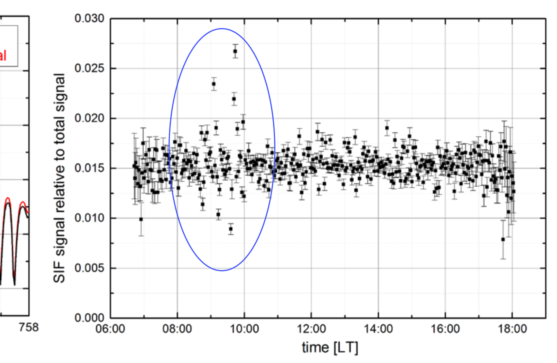


Figure 7: SIF signal retrieved with the SIF DOAS fitting routine.

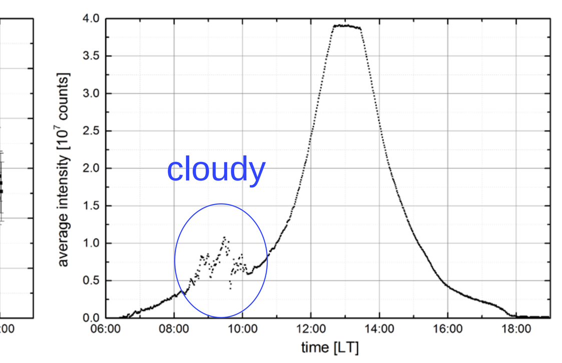


Figure 8: Average intensity of one day (08/08/2015) of diffuser measurements.

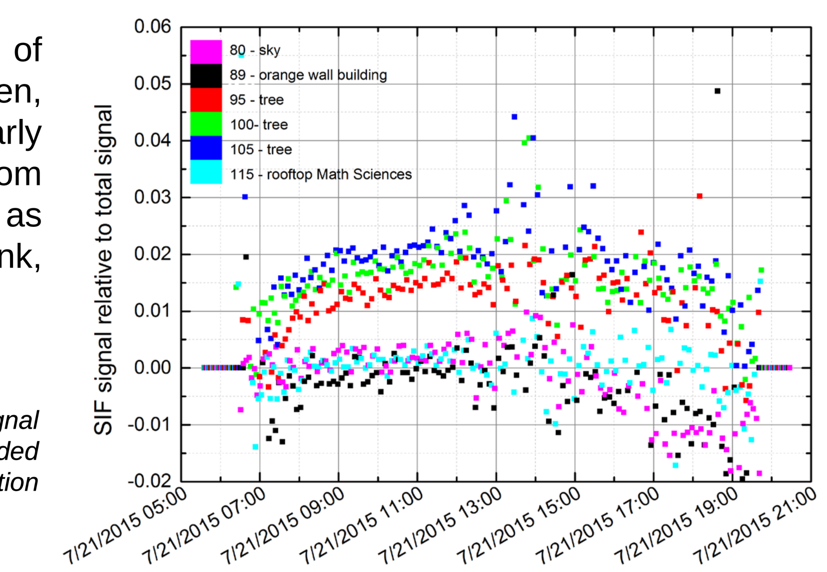
In order to test the SIF DOAS fitting retrieval and to determine the uncertainty of this retrieval, an artificial SIF signal (≈ 1.5% at 750 nm, see red line in Figure 3) is added to the diffuser spectra (Figure 6). One spectrum is then analyzed using the subsequent diffuser spectrum as a reference spectrum recorded one minute later. Figure 7 shows the retrieved SIF signal with a retrieval uncertainty of approximately 5%. Variations in the intensity of the diffuser spectra due to clouds at 9 – 10 a.m. can be also detected in the retrieved SIF signal (blue circle) (Figure 8).

b) Tree measurements

Figure 9: The red circle marks the viewing direction of the telescope unit.

The SIF signal of trees (blue, green, red) can be clearly distinguished from other objects such as walls or the sky (pink, black, turquois).

Figure 10: Diurnal SIF signal for 07/21/2015 color-coded with the different elevation angles.



c) Single leaf measurements

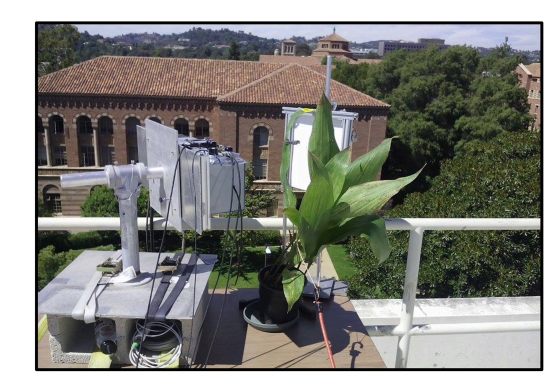


Figure 11: Single leaf of a cast iron plant (Aspidistra elatior) in front of the SIF telescope.

The SIF signal of a single leaf of a cast iron plant (*Aspidistra elatior*) (after 11 a.m.) can be clearly distinguished from a teflon plate (before 11 a.m.).

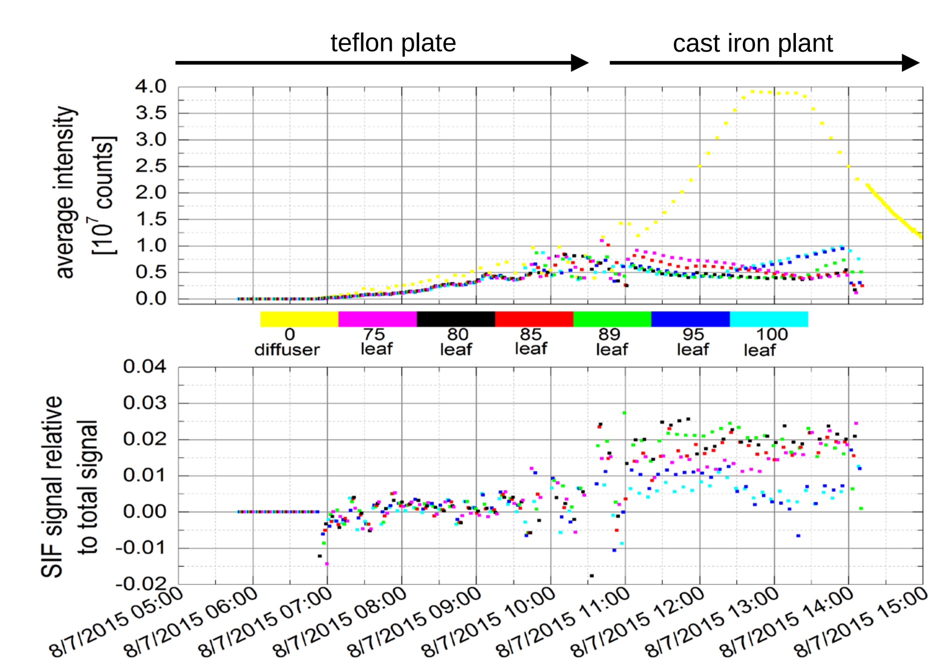


Figure 12: Diurnal average intensity (upper panel) and SIF signal (lower panel) for 08/07/2015 color-coded with the different elevation angles when looking onto a teflon plate and a leaf of a cast iron plant.

6. Summary

- We developed an automated remote sensing system for ground-based SIF measurements of plants.
- Theoretical studies show that the relative uncertainty of the SIF retrieval is approximately 5%.
- Initial test measurements on the rooftop of the UCLA Mathematical Sciences building show that we can clearly detect the SIF signal and distinguish vegetation (trees, leaves) from non-vegetation (walls, teflon plates).
- We are currently working on understanding the influence of clouds, the measurement geometry, and the movement of the leaves on the SIF signal.
- 5 instruments will be built and deployed at various locations to study the variations in photosynthetic activity of different plants in field experiment and long-term observation mode settings.

References

1. Frankenberg et al., 2012: Remote sensing of near-infrared chlorophyll fluorescence from space in scattering atmospheres: implications for its retrieval and interferences with atmospheric CO_2 retrievals, Atmos. Meas. Tech., 5, 2081-2094, doi: 10.5194/amt-5-2081-2012, 2012.
2. Frankenberg et al., 2014: Prospects for chlorophyll fluorescence remote sensing from the Orbiting Carbon Observatory-2, Remote Sensing of Environment, 147, 1-12, 0034-4257, http://dx.doi.org/10.1016/j.rse.2014.02.007, 2014.
3. Meroni et al.,2009: Remote sensing of solar-induced chlorophyll fluorescence: review of methods and applications, Remote Sens. Environ., 113, 2037–2051, doi:10.1016/j.rse.2009.05.003, 2009.
4. Krause and Weis, 1991: Chlorophyll fluorescence and photosynthesis-the basics, Annu. Rev. Plant. Phys. 42, pp. 313–349, 1991.
5. Porcar-Castell et al., 2014: Linking chlorophyll a fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges, Journal of experimental botany, 0022-095, doi:10.1093/jxb/eru191, 2014.
6. Frankenberg et al., 2013: Remote sensing of terrestrial chlorophyll fluorescence from space, SPIE Newsroom, doi: 10.1117/2.1201302.004725, 2013.
7. Platt and Stutz, 2008: Differential optical absorption spectroscopy, Springer Verlag, Heidelberg, 2008.
8. Guanter, L. et al., 2010: Developments for vegetation fluorescence retrieval from spaceborne high-resolution spectrometry in the O_2-A and O_2-B absorption bands, J. Geophys. Res., 115, D19303, doi:10.1029/2009JD013716, 2010.

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