Remote Sensing of Solar Induced Chlorophyll Fluorescence

The past, the present and the future

Christian Frankenberg$^{1,2}$
(1) California Institute of Technology, Pasadena, CA, United States
(2) Jet Propulsion Laboratory / Caltech, Pasadena, CA, United States
Absorption of sunlight drives it all.

Biggest 2 factors:
1) How much light is absorbed by the antenna system?
2) How efficiently is this light used for photosynthesis?

Chl + $h\nu$ → Chl$^*$

The light reactions

The light reactions

Unstable higher state, very fast transition to lower state

Chl $+ h\nu \rightarrow \text{Chl}^*$

Lowest excited state “somewhat” stable (lifetime of a few nanoseconds)

The light reactions

Lowest excited state “somewhat” stable (lifetime of a few nanoseconds)

Can do:
1. Re-emit a photon (fluorescence)
2. Fall back to ground level (release heat)
3. Transfer energy to another chlorophyll
4. Perform photochemistry, causing chemical reactions

\[
\text{Chl} + h\nu \rightarrow \text{Chl}^* 
\]
The light reactions

Lowest excited state
“somewhat” stable (lifetime of a few nanoseconds)

Can do:
1. Re-emit a photon (fluorescence)
2. Fall back to ground level (release heat)
3. Transfer energy to another chlorophyll
4. Perform photochemistry, causing chemical reactions

\[ \text{Chl} + h\nu \rightarrow \text{Chl}^* \]
Plants are not only light limited — what happens to excess light?
Plants are not only light limited — what happens to excess light?

Investment in Rubisco comes at a price, lots of N needed and maintenance respiration higher!
Light absorption can be dangerous!

Excitations to the PSII reaction center to a manageable level, depending on the light intensity and other conditions. The process appears to be an essential part of the regulation of antenna systems in most algae and plants.

Nonphotochemical quenching is the quenching of chlorophyll fluorescence (see Figure 7.5) by processes other than photochemistry. As a result of nonphotochemical quenching, a large fraction of the excitations in the antenna system caused by intense illumination are quenched by conversion into heat (Krause and Weis 1991). Nonphotochemical quenching is thought to be involved in protecting the photosynthetic machinery against overexcitation and subsequent damage.

The molecular mechanism of nonphotochemical quenching is not well understood, although it is clear that the pH of the thylakoid lumen and the state of aggregation of the antenna complexes are important factors. Three carotenoids, called xanthophylls, are involved in nonphotochemical quenching: violaxanthin, antheraxanthin, and zeaxanthin (Figure 7.36). In high light, violaxanthin is converted into zeaxanthin, via the intermediate antheraxanthin, by the enzyme violaxanthin de-epoxidase. When light intensity decreases, the process is reversed. Binding of protons and zeaxanthin to light-harvesting antenna proteins is thought to cause conformational changes that lead to quenching and heat dissipation (Demmig-Porter et al., 2000).

Protection against photodamage is a multilevel process. The first line of defense is suppression of damage by quenching of excess excitation as heat. If this defense is not sufficient and toxic photoproducts form, a variety of scavenging systems eliminate the reactive photoproducts. If this second line of defense also fails, the photoproducts can damage the D1 protein of photosystem II. This damage leads to photoinhibition. The D1 protein is then excised from the PSII reaction center and degraded. A newly synthesized D1 is reinserted into the PSII reaction center to form a functional unit. (After Asada 1999.)

Light absorption can be dangerous!

In high light, violaxanthin is converted into zeaxanthin, via the intermediate antheraxanthin, by the enzyme violaxanthin de-epoxidase. When light intensity decreases, the process is reversed. Binding of protons and zeaxanthin to light-harvesting antenna proteins is thought to cause conformational changes that lead to quenching and heat dissipation.
Light absorption can be dangerous!

- **Excitations to the PSII reaction center** to a manageable level, depending on the light intensity and other conditions. The process appears to be an essential part of the regulation of antenna systems in most algae and plants.

**Nonphotochemical quenching** is the quenching of chlorophyll fluorescence (see Figure 7.5) by processes other than photochemistry. As a result of nonphotochemical quenching, a large fraction of the excitations in the antenna system caused by intense illumination are quenched by conversion into heat (Krause and Weis 1991). Nonphotochemical quenching is thought to be involved in protecting the photosynthetic machinery against overexcitation and subsequent damage.

The molecular mechanism of nonphotochemical quenching is not well understood, although it is clear that the pH of the thylakoid lumen and the state of aggregation of the antenna complexes are important factors. Three carotenoids, called xanthophylls, are involved in nonphotochemical quenching: violaxanthin, antheraxanthin, and zeaxanthin (Figure 7.36).

In high light, violaxanthin is converted into zeaxanthin, via the intermediate antheraxanthin, by the enzyme violaxanthin de-epoxidase. When light intensity decreases, the process is reversed. Binding of protons and zeaxanthin to light-harvesting antenna proteins is thought to cause conformational changes that lead to quenching and heat dissipation (Demmig-Ploughman and Pfündel 1994).

**Overall picture of the regulation of photon capture and the protection and repair of photodamage.**

Protection against photodamage is a multilevel process. The first line of defense is suppression of damage by quenching of excess excitation as heat. If this defense is not sufficient and toxic photoproducts form, a variety of scavenging systems eliminate the reactive photoproducts. If this second line of defense also fails, the photoproducts can damage the D1 protein of photosystem II. This damage leads to photoinhibition. The D1 protein is then excised from the PSII reaction center and degraded. A newly synthesized D1 is reinserted into the PSII reaction center to form a functional unit. (After Asada 1999.)

**Chemical structure of violaxanthin, antheraxanthin, and zeaxanthin.** The highly quenched state of photosystem II is associated with zeaxanthin, the unquenched state with violaxanthin. Enzymes interconvert these two carotenoids, with antheraxanthin as the intermediate, in response to changing conditions, especially changes in light intensity. Zeaxanthin formation uses ascorbate as a cofactor, and violaxanthin formation requires NADPH. (After Pfündel and Bilger 1994.)

Fate of absorbed photons in antenna system

\[ \varphi_f = \frac{K_f}{K_f + K_d + K_n + K_p} \]

Fate of absorbed photons in antenna system

\[ \varphi_f = \frac{K_f}{K_f + K_d + K_n + K_p} \]

Solar photon

Fluorescence photon

Pure Chlorophyll Solution \(\rightarrow\) Kp and Kn=0, fluorescence yield around 1 higher fluorescence from Chl solution than leaf already found in 1874 (Mueller)

Alternative method: Avoid absorption in the first place
— Leaf orientation

Oxalis oregana

Time (min)

Leaf angle (degree)

1590 μmol quanta m$^{-2}$ s$^{-1}$

4 μmol quanta m$^{-2}$ s$^{-1}$

http://plantsinaction.science.uq.edu.au/
Alternative method: Avoid absorption in the first place
— Chloroplast movements

(A) Darkness  (B) Weak blue light  (C) Strong blue light

**FIGURE 9.5** Chloroplast distribution in photosynthesizing cells of the duckweed *Lemna*. These surface views show the same cells under three conditions: (A) darkness, (B) weak blue light, and (C) strong blue light. In A and B, chloroplasts are positioned near the upper surface of the cells, where they can absorb maximum amounts of light. When the cells were irradiated with strong blue light (C), the chloroplasts move to the side walls, where they shade each other, thus minimizing the absorption of excess light. (Micrographs courtesy of M. Tlalka and M. D. Fricker.)

Pulse Amplitude Modulated (PAM) fluorometry

\[ F_s \left( \frac{dSIF}{dAPAR} \right) \]

SIF

https://www.licor.com/env/help/6800/Content/theory.html
The leaf scale — Active Fluorometry

Fluorescence yield

\[ \Phi_f = \frac{K_f}{K_f + K_p + K_n} \]

Rates for:
- Fluorescence
- Photosynthesis
- Heat quenching (NPQ)

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)
The leaf scale — Active Fluorometry

- Fluorescence yield
  \[ \Phi_f = \frac{K_f}{K_f + K_p + K_n} \]

- Rates for:
  - Fluorescence
  - Photosynthesis
  - Heat quenching (NPQ)

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on ↑ and off ↓)
SP = Saturating Pulse (strong pulsed light at each ↑)
The leaf scale — Active Fluorometry

- Fluorescence yield
  \[ \Phi_f = \frac{K_f}{K_f + K_p + K_n} \]

- Rates for:
  - Fluorescence
  - Photosynthesis
  - Heat quenching (NPQ)

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)
The leaf scale — Active Fluorometry

**Fluorescence yield**

\[
\Phi_f = \frac{K_f}{K_f + K_p + K_n}
\]

- Rates for:
  - Fluorescence
  - Photosynthesis
  - Heat quenching (NPQ)

**Solar Induced Fluorescence**

**SIF from Space**

**NPQ**

\[
NPQ = \frac{F_{o m}}{F_{0 m}} - 1
\]

**Maximum PSII Yield**

\[
\text{maximum PSII yield} = \frac{F_m}{F_o}
\]

**Fluorescence Yields**

\[
F_{s} = K_f F_{m} + K_p F_{o} + K_n F_{t}
\]

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)
The leaf scale — Active Fluorometry

**Fluorescence yield**

\[ \Phi_f = \frac{K_f}{K_f + K_p + K_n} \]

- Rates for:
  - Fluorescence
  - Photosynthesis
  - Heat quenching (NPQ)

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)
**The leaf scale — Active Fluorometry**

- **Fluorescence yield**
  \[ \Phi_f = \frac{K_f}{K_f + K_p + K_n} \]

- Rates for:
  - Fluorescence
  - Photosynthesis
  - Heat quenching (NPQ)

---

**Graphical Representation**

- **Fluorescence yield**
  \[ F_s = \frac{F_{m^0}}{K_p=0, K_n=0} \]

- **Rates for**
  - Fluorescence yield
  - Photosynthesis
  - Heat quenching (NPQ)

- **From Maxwell & Johnson 2000**

- **AL** = Actinic Light (moderate light was turned on ↑ and off ↓)

- **SP** = Saturating Pulse (strong pulsed light at each ↑)

---

**Mathematical Expressions**

- **NPQ** = \( \frac{F_{0m}}{F_{0m}} \)
- **Maximum PSII yield** = \( \frac{F_{m^0}}{F_{0m}} \)
- **APAR** is the only thing we can measure from space.
THE POWER OF ACTIVE FLUOROMETRY

\[
\text{IPQ} = \frac{F_{0m}}{F_{0m}}
\]

\[
\text{PSII} = \frac{F_{0m}}{F_{0m}}
\]

Genty, Briantais, Baker (1988), >5000 citations

\[
\text{maximum PSII yield} = \frac{F_{m}}{F_{0m}}
\]

\[
\text{steady state fluorescence } F_t
\]

\[
\text{Ft} \text{ is the only thing we can measure from space}
\]

from Maxwell & Johnson 2000

AL=Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)
**THE POWER OF ACTIVE FLUOROMETRY**

- \( \text{NPQ} = \frac{(F_m^0 - F_m')}{F_m'} \)

\[
\begin{align*}
\text{PSII maximum yield} & = \frac{(F_m^0 - F_m)}{F_m} \\
\text{steady state fluorescence } F_t & \quad \text{Ft is the only thing we can measure from space}\n\end{align*}
\]

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on \( \uparrow \) and off \( \downarrow \))

SP = Saturating Pulse (strong pulsed light at each \( \uparrow \))
THE POWER OF ACTIVE FLUOROMETRY

- \( \text{NPQ} = \frac{(F_m^o - F'_m)}{F'_m} \)
- \( \Phi_{PSII} = \frac{(F'_m - F_t)}{F'_m} \)

Genty, Briantais, Baker (1988), >5000 citations

from Maxwell & Johnson 2000

AL=Actinic Light (moderate light was turned on \( \uparrow \) and off \( \downarrow \))

SP = Saturating Pulse (strong pulsed light at each \( \uparrow \))
THE POWER OF ACTIVE FLUOROMETRY

- \( \text{NPQ} = \frac{(F_m^o - F'_m)}{F'_m} \)
- \( \Phi_{PSII} = \frac{(F'_m - F_t)}{F'_m} \)

Genty, Briantais, Baker (1988), >5000 citations

- maximum PSII yield
  \( = \frac{(F_m - F_o)}{F_m} \)

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on \( \uparrow \) and off \( \downarrow \))

SP = Saturating Pulse (strong pulsed light at each \( \uparrow \))
THE POWER OF ACTIVE FLUOROMETRY

- NPQ = \( \left( \frac{F_m^0 - F_m'}{F_m'} \right) \)
- \( \Phi_{PSII} = \left( \frac{F_m' - F_t}{F_m'} \right) \)
  
  Genty, Briantais, Baker (1988), >5000 citations

- maximum PSII yield
  = \( \left( \frac{F_m - F_o}{F_m} \right) \)

- steady state fluorescence \( F_t \)

- \( F_t \) * APAR is the only thing we can measure from space

from Maxwell & Johnson 2000

AL = Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)
INTRODUCTION

CHLOROPHYLL FLUORESCENCE

SOLAR INDUCED FLUORESCENCE

How do F and P relate?

Fluorescence (ΦF) and photochemical (ΦP) yields (Equations 7 and 9, respectively) are affected by photochemical (PQ) and non-photochemical quenching (NPQ) (see Equation 10 and Fig. 9). In the field, the quantum yield of fluorescence is highly dynamic, both during the course of a day (Porcar-Castell et al., 2008b) and throughout seasons (Soukupová et al., 2008; Porcar-Castell, 2011), where ΦF decreases during stress episodes and increases upon recovery in a process that appears to be largely controlled by the presence of sustained NPQ forms (Ensminger et al., 2004; Porcar-Castell et al., 2008a; Porcar-Castell, 2011).

Therefore, ΦF is related to ΦP and hence to LUE. In conclusion, SIF contains information relating to LUE as well as APAR. Yet, disentangling these two contributions remains a challenge from a remotely sensed large-scale observation platform.

Over the course of a day, the relationship between ΦF and ΦP falls apart into two distinct phases: under low light (first morning hours and towards sunset) the changes in the quantum yield of photochemistry are controlled by PQ, with NPQ remaining approximately constant and low (Fig. 9). In contrast, under high light (noon hours) the changes in ΦP are dominated by NPQ, with PQ remaining rather constant.

Since decreasing PQ and increasing NPQ have opposite effects on ΦF (see Equation 7), this non-complementary behaviour generates a two-phased inverted 'V' relationship between ΦP and ΦF (Fig. 9), where ΦP and ΦF are inversely proportional under low light 'PQ-Phase', and proportional under high light 'NPQ-Phase'. The inverted 'V' relationship can be reproduced using current process-based understanding of the relationship between ChlF and photosynthesis (see Fig. in van der Tol et al., 2009).

Remotely sensed SIF will always be obtained under high-light conditions ('NPQ-Phase'); therefore, it could be expected that SIF and ΦP vary concomitantly in response to stress, with SIF ~ ΦFAPAR. Indeed, a good correlation between ΦF and photosynthesis has been observed in response to water stress episodes (Flexas et al., 2000) when measured under high light in the 'NPQ-Phase'. Similarly, both ΦF and ΦP tend to decrease simultaneously in response (ΦP) (ΦF).

Fig. 9. Relationships between the quantum yields of photochemistry (ΦP) and fluorescence (ΦF) in relation to photochemical (PQ) and non-photochemical quenching (NPQ) of excitation energy. Lines were obtained by assuming a maximum quantum yield of fluorescence at the Fm state of 10% [i.e. kF = 0.1(kF + kD)], and by varying PQ and NPQ to estimate ΦF = 0.1/(1+PQ+NPQ) and ΦP = PQ/(1+PQ+NPQ). It can be appreciated that under constant NPQ (dotted lines), fluorescence and photochemical yield are inversely proportional, whereas at constant PQ (solid lines), fluorescence and photochemical yield become proportional. Data were obtained during a summer day and using a Monitoring PAM fluorometer (Walz GmbH, Germany); data are from Porcar-Castell et al. (2008).

Black points correspond to data from midnight to noon, grey points from noon to midnight.

from Porcar-Castell et al (2014)
The leaf scale (why interested in SIF spectra?)
The leaf scale (why interested in SIF spectra?)

\[ \text{SIF} = \text{SIF(PSII)} + \text{SIF(PSI)} \]
The leaf scale (why interested in SIF spectra?)

\[
\text{SIF} = \text{SIF(PSII)} + \text{SIF(PSI)}
\]

**K_p** is variable
- back transfer of excitation at too high ETR

**K_p** constant
- steeper redox gradient, P700⁺ itself a quencher
The leaf scale (why interested in SIF spectra?)

\[ \text{SIF} = \text{SIF(PSII)} + \text{SIF(PSI)} \]

- **K_p** is variable
  - back transfer of excitation at too high ETR
  - steeper redox gradient, P700⁺ itself a quencher

- **K_n** is variable
  - Quenching in antenna system

- **K_p** constant
  - assumed constant
Combine PAM with SIF spectral shape measurements
A modified WALZ GFS-3000 system
Magney, Frankenberg et al, New Phytologist 2017
Remote Sensing of vegetation and SIF

- Chl a fluorescence (arbitrary units)
- Chl_{a,b} absorbance

Graph showing reflectance and Chl a fluorescence spectra.
KISS director has a relevant hobby
How to measure an additive signal?
How to measure an additive signal?
How to measure an additive signal?

\[ I_{\text{out}} = I_{\text{in}} + I_{\text{in}} \]

- **Introduction**
  - Vegetation Remote Sensing
  - Satellite retrievals from space

- **Absorption features in the sun's outer layers**
  - Within the Earth's atmosphere, the shape of isolatedFraunhofer lines is only affected in multiplicative ways by radiative transfer, the depth is conserved (exception: Rotational Raman Scattering, but mostly negligible for nadir).
How to measure an additive signal?

\[ I_{\text{out}} = I_{\text{in}} + I_{\text{change}} \]

- INTRODUCTION
- VEGETATION
- REMOTE SENSING
- SIF RETRIEVALS FROM SPACE
- SOLAR FRAUNHOFER LINES

Absorption features in the sun's outer layers

Within the Earth's atmosphere, the shape of isolated Fraunhofer lines is only affected in multiplicative ways by radiative transfer, the depth is conserved (exception: Rotational Raman Scattering, but mostly negligible for nadir).
Luminescence of the Moon and Solar Activity

Zdeněk Kopal

Department of Astronomy, University of Manchester, Manchester, England

Figure 9-2: The line-depth method of detecting luminescence calls for comparing profiles of absorption lines in the spectra A of the sun (left) and moon (right). An increase in the residual intensity in the case of the moon is a measure of the light ($i_p$) attributable to lunar luminescence—in this example 16.67 per cent of the total moonlight.
History of Fraunhofer line in-filling studies
Potter et al, 1984 —> unlikely to be a thermal effect (using multiple spectral ranges)

Lunar luminescence and the filling-in of Fraunhofer lines in moonlight

A. E. Potter, W. Mendell, T. Morgan

First published: 15 November 1984  Full publication history
DOI: 10.1029/JB089iS01p0C240  View/save citation
Cited by (CrossRef): 2 articles  Check for updates
Citation tools
Letters to Nature

Nature 193, 762 (24 February 1962) | doi:10.1038/193762a0

Anomalous Fraunhofer Line Profiles

J. F. GRAINGER & J. RING

1. Department of Astronomy, The University, Manchester.

DURING the spring of 1961 we made observations of the $H$ line of Ca(II) in the spectrum of moonlight, with the view of detecting any luminescent radiation which might have been present. The observations were made with the 50-in. reflector of the University of Padua’s Observatory at Asiago.
ROTATIONAL RAMAN SCATTERING IN
PLANETARY ATMOSPHERES*

R. T. BRINKMANN
Division of Geological Sciences, California Institute of Technology,
and Jet Propulsion Laboratory, Pasadena, California
Received March 9, 1968; revised May 24, 1968

ABSTRACT

When spectra of deep solar Fraunhofer lines recorded in sunlight scattered by the Earth’s atmosphere are compared with similar spectra of direct, unscattered sunlight, it is found that the scattered line profiles are systematically less deep (relative to the continuum) than the direct profiles by a few per cent. This has been taken to indicate the presence of an extra, inelastic component of the scattered radiation field. Its nature has remained unexplained. In this paper it is pointed out that rotational Raman scattering in the atmosphere can be expected to produce just such an extra component. Previous observational work is reviewed and interpreted in light of this explanation. The magnitude of the effect in the atmospheres of other planets is also briefly explored.
INELASTIC SCATTERING IN PLANETARY ATMOSPHERES.
I. THE RING EFFECT, WITHOUT AEROSOLS

GEORGE W. KATTAWAR, ANDREW T. YOUNG, AND TERRY J. HUMPHREYS
Texas A & M University
Received 1980 June 30; accepted 1980 August 11

ABSTRACT

We have investigated the contribution of inelastic molecular scattering (Rayleigh-Brillouin and rotational Raman scattering) to the filling-in of Fraunhofer lines in the light of the blue sky. Aerosol fluorescence is shown to be negligible, and aerosol scattering is ignored in this paper. We discuss the angular and polarization dependences of the filling-in detail for single scattering. An approximate treatment of multiple scattering, using a backward Monte Carlo technique, allows us to investigate the effects of the ground albedo. As the molecular scatterings alone produce more line-filling than is observed, it seems likely that aerosols dilute the effect by contributing unaltered sunlight to the observed spectra.

Subject headings: planets: atmospheres — polarization — radiative transfer
Need absorption features that are only un-changed in the atmosphere → Fraunhofer lines are ideal.
Incoming at the surface

Disk Integrated Solar Irradiance Spectrum at 0.05nm spectral resolution at surface level

- Fraunhofer lines
- H₂O absorptions
- O₂ absorptions
After reflection from canopy

Resulting reflectance spectrum

Fraunhofer lines
H$_2$O absorptions
O$_2$ absorptions
SIF spectrum $\times$ 50

Resulting reflected radiance

$L(\lambda) \text{ (W} / \text{m}^2/\mu\text{m/sr)}$
Ratio Spectrum (with/without SIF)

Ratio spectrum with and without SIF

- **Red line**: All absorptions
- **Blue line**: Only Fraunhofer lines
Ratio Spectrum (with/without SIF)

Ratio spectrum with and without SIF

- All absorptions
- Only Fraunhofer lines

SCIAMACHY (Ca II)

Hα
Earliest work with GOSAT
Hemispheric-scale CO$_2$ derivatives and SIF

CO$_2$ time derivative at Mauna Loa and SIF between 30N and 60N
The view from space: Now OCO-2

Sun et al, Solar-induced chlorophyll fluorescence from the Orbiting Carbon Observatory-2: Overview of the retrieval and biophysical performance
Primary Modes of GPP
Sun, Frankenberg et al, to be published end of Sept.
CFIS — Chlorophyll Fluorescence Imaging Spectrometer

Figure 2: Left: CFIS computer-aided design model, showing the mechanical and optical layout. Right: Picture of CFIS without housing can in the laboratory.
Airborne (CFIS)
Frankenberg et al, paper in prep

[Graph showing spectral reflectance and radiance data with annotations for Chlorophyll fluorescence, Solar induced fluorescence, O2 absorptions, H2O absorptions, and Fraunhofer lines.]

Reflectance
Solar induced fluorescence
O2 absorptions
H2O absorptions
Fraunhofer lines
Airborne (CFIS)
Frankenberg et al, paper in prep
OCO-2 underpasses — OCO2 SIF

Aug. 13
ND Orbit 5934

Aug. 16
ND Orbit 5978
White lines indicate edges and center of CFIS swath
OCO-2 SIF validation (via CFIS)

Aug. 16 OCO-2 overpass

Aug. 13 OCO-2 overpass

SIF (W/m²/sr/μm)

Latitude

Radiance (W/m²/sr/θ m)

OCO-2

CFIS
Ground-based measurements (enabled by KISS)
Ground-based measurements
PhotoSpec systems, enable by KISS
Ground-based measurements
PhotoSpec systems, enable by KISS
The future from space

- TROPOMI (will be launched soon, fingers crossed)
- FLEX (chosen by ESA as Earth Explorer 8)
- GeoCARB (Geostationary, SIF no primary focus though)
- Sentinel 3?