Retrieval of chlorophyll fluorescence from space

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• Motivation

• The fluorescence signal and how it is manifested in measurements

• Methods for retrieving fluorescence from
  - ground
  - space

• Initial results from the Japanese GOSAT satellite
Chlorophyll fluorescence always a by-product of photosynthesis

Incident light

reflectance

chlorophyll fluorescence

absorption

photosynthesis

heat

transmittance

- 400 - 700 nm
- 660 - 800 nm
- 400 - 700 nm
- 0.5 - 2%
- 0 - 82%
- 17.5 - 98%
The global carbon cycle (IPCC AR4)
Focus on Gross Primary Production (GPP)

Diagram showing the carbon cycle with various reservoirs and fluxes:
- Atmosphere: 597 + 165
- Vegetation, Soil & Detritus: 2300 + 101 - 140
- Fossil Fuels: 3700 - 244
- Marine Biota: 3
- Surface Ocean: 900 + 18
- Intermediate & Deep Ocean: 37,100 + 100
- Surface Sediment: 150

Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Key processes include:
- Weathering
- Respiration
- GPP
- Land sink
- Land Use Change

Numbers represent fluxes and reservoir sizes in GtC (Gigatons of Carbon) and GtC yr⁻¹ (Gigatons of Carbon per year).
Introduction

• Gross primary production (GPP) through photosynthesis by terrestrial ecosystems constitutes the largest global carbon sink.

• Two main spatially explicit approaches to quantify GPP globally:
  1) Meteorology-driven full land surface carbon cycle models (coupled or uncoupled);
  2) Remote sensing-driven and/or flux tower based semi-empirical models.

• Uncertainties in existing approaches:
  1) Model sensitivities, parameterization
  2) Indirectly inferred from “greenness”
On an annual basis, natural CO₂ fluxes are almost balanced.

OCO-2 will enable inversion of net fluxes (not disentangling uptake from respiration).

Target of fluorescence

120 Pg/yr

Figure from MPI-BGC Jena
Fig. 10. Fluorescence flux ($F_s$) versus PAR for three days: 214 no water stress, 243 maximal water stress effect, 248 after rainy days, and reversion of water stress.
(traditional) Optical Remote Sensing Parameters
(mainly based on absorption spectrum of chlorophyll)

From Luis Guanter
(traditional) Optical Remote Sensing parameters

http://bluemarble.ch/
(traditional) Optical Remote Sensing parameters
Satellite example: MODIS, the vegetation RS work-horse

Pros:
• High spatial resolution (sub-km)
• Full global mapping (no sampling)

Cons:
• Susceptible to atmospheric contamination
• Can saturate in dense forests
• Indicative of greenness, not activity (hence modeling for GPP needed)

From NTSG website (MODIS derived GPP)

y GPP and PsnNet for one MODIS 1-km pixel located in Amazon basin
(lat = −5.0, lon = −65.0) (Zhao et al. 2005)
Chlorophyll fluorescence

Normalized fluorescence emission spectrum
Pfendel, Photosynthesis Research, 1998

Reflectance and Fluorescence emission spectrum
Guanter et al, JGR, 2010
Basic problem for fluorescence retrievals:

- Fluorescence emission is "contaminated" with reflected solar light in the far red / near infrared.
- This reflected solar light dominates the signal (about 100 times stronger).
- Need "on/off" wavelengths where the atmosphere (or incoming light) is opaque.
In spectral regions with high atmospheric absorption (e.g. strong oxygen absorption bands), the fluorescence emission at canopy level can dominate the measured radiance (as opposed to transparent regions, where it barely adds to the signal).
On-ground retrieval methods
(review by Meroni et al, RSE 2009)

A) Solar Irradiance \downarrow

B) Target Radiance \uparrow

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

\[ F = \frac{L(\lambda_{\text{in}})}{L(\lambda_{\text{out}})} \]

For \( E(\lambda_{\text{in}}) \to 0 \)

Sensitivity of the method improves with degree of atmospheric saturation
\( O_2 \) bands ideal as almost saturated (depending on instrument spectral resolution and position)
Above the canopy, apparent reflectance (outgoing/incoming) in the oxygen bands is clearly increased and can be used to determine the $F_s$ contribution.
If the observer is in space (satellite), the emitted fluorescence spectrum is re-absorbed and atmospheric scattering contributes to the signal within the absorption bands.

Simulated radiances
Frankenberg, Butz, Toon (ancillary material), GRL, 2011
If the observer is in space (satellite), the emitted fluorescence spectrum is re-absorbed and atmospheric scattering contributes to the signal within the absorption bands.

Modeled total radiance and fluorescence emission in a scattering scene; note the different scale (factor 100)
Frankenberg et al, AMT, 2012
Chlorophyll fluorescence – complication from space
(O₂ A-band only for now)

Jacobians of the top-of-atmosphere radiance with respect to various atmospheric parameters (surface pressure, Albedo, aerosol optical depth, height of aerosol layer and Fluorescence signal.

Frankenberg, Toon, Butz, GRL, 2011

Solar irradiance

TOA radiance

Jacobians not linearly independent

Modeled radiance (with fluorescence) can be almost perfectly fitted without accounting for fluorescence
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Frankenberg, Toon, Butz, GRL, 2011
Chlorophyll fluorescence – complication from space

How to tackle the problem: 1) Use of reference surfaces

Use of low resolution O$_2$ A-band spectra (MERIS) and reference targets with no fluorescence:

**Idea:** Atmospheric conditions are similar for reference area and vegetated areas → provides knowledge on atmospheric condition to disentangle $F_s$ from scattering.

**Prerequisite:** Barren surface must exist + scattering spatially less variable than $F_s$ (will work for corn-field like areas but not extended homogenous areas like large forests.

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**Figure 1.** MERIS-derived NDVI and $F_s$ maps over the Barrax study site in 14 July 2004.

**Figure 10.** Input and retrieved $F_s$ maps in O$_2$-A with the FLD-S approach before and after the normalization by reference soil targets.

Guanter et al, GRL, 2007, JGR 2010
Chlorophyll fluorescence – complication from space
How to tackle the problem: 2) Use solar lines.

The solar spectrum is not a pure black-body spectrum but exhibits absorption lines from elements (e.g. Fe, Mg, Na) present in colder outer layers.
The Fraunhofer Line Discriminator MKII—An Airborne Instrument for Precise and Standardized Ecological Luminescence Measurement

JAMES A. PLASCYK AND FRED C. GABRIEL, MEMBER, IEEE

Abstract—The Fraunhofer line discriminator Mark II (FLD-II) is an airborne photometric instrument for the remote measurement, on a precise and quantitative scale, of solar-stimulated luminescence. The luminescence may originate in such diverse sources as oil spills and chemical pollutants, the chlorophyll of normal or stressed vegetation, and fluorescent tracer dyes used to study current flow and dispersion in large bodies of water. The instrument is the precise quantitative distinction between reflected sunlight and luminescence, which may be orders of magnitude weaker.

II. OPERATING PRINCIPLES
An elegant technique, first devised by lunar astrono-
• **Advantage:** In the absence of inelastic scattering (e.g. rotational Raman scattering causing the Ring-effect in the UV/Vis!), the fractional depth of solar absorption features is not changed within the atmosphere → no reabsorption in the Earth’s atmosphere and no interference with atmospheric scattering.

• **Challenge:** High spectral resolution needed to resolve Fraunhofer lines: Tradeoff between spectral resolution (FWHM, Full width at half maximum) and spatial resolution!

Chlorophyll fluorescence – complication from space
How to tackle the problem: 2) Use solar lines.
Chlorophyll fluorescence – complication from space
How to tackle the problem: 2) Use solar lines.

Use full spectral fitting routines to quantify the in-filling of Fraunhofer lines due to Fluorescence.

GOSAT (and OCO-2 in the future) are the first instruments to provide high resolution spectra in the O2 A-band (but not covering the full $F_s$ emission spectrum)

Fractional depth of solar lines (difference to continuum radiance within the line in log(radiance) space) only changed by $F_s$:

$$\tilde{f}(F_s^{\text{rel}}, a) = \log(<\tilde{I}_0 + F_s^{\text{rel}}>) + \sum_{i=0}^{n} a_i \cdot \lambda^i,$$

$$\arg \min ||S^{-1/2}_\varepsilon \left( \tilde{y} - \tilde{f}(F_s^{\text{rel}}, a) \right) ||_2,$$

No radiative transfer modeling necessary if Fraunhofer lines only are concerned!
Leverage from OCO-2 efforts: Implementing propagation of fluorescence into the orbit simulator, simulating complex realistic radiances in scattering atmospheres.
Chlorophyll fluorescence – complication from space
How to tackle the problem: 2) Use solar lines.

Simulate $F_s$ retrievals as done for GOSAT:
Retrieved vs. true (at TOA and surface) very consistent.

Fraction of surface fluorescence reaching top-of-atmosphere (TOA) as a function of optical depth → very insensitive to scattering, may eventually be one of the biggest advantages!

C. Frankenberg, C. O’Dell, L. Guanter, and J. McDuffie, AMT, 2012
Chlorophyll fluorescence – complication from space

How to tackle the problem: 3) Use entire emission spectrum (FLEX)

Reflectance and Fluorescence emission spectrum
Guanter et al, JGR, 2010

While $F_s$ retrievals using the $O_2$ A-band alone (without Fraunhofer lines) is ill-posed, the use of the full spectral range may alleviate the problem (e.g. fractional contribution of $F_s$ is much higher at shorter wavelengths.

**Biggest advantages:** Covering the red-edge will allow LAI and EVI retrievals in addition + $F_s$ ratios at different wavelengths are also powerful indicators for photosynthetic activity.

**Best of both worlds** (personal opinion): Have high spectral resolution to sample Fraunhofer lines AND extend the wavelength range to cover the short wavelength $F_s$ peak.
Application in the real world: Using GOSAT radiances.
Application in the real world: Using GOSAT radiances.

Do not forget: GOSAT is NOT a mapper as intended to measure long-lived trace gases, not surface properties!
Fluorescence from GOSAT
(retrieval paper and first real retrievals)

Disentangling chlorophyll fluorescence from atmospheric scattering effects in O$_2$ A-band spectra of reflected sun-light

C. Frankenberg, A. Butz, and G. C. Toon

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1. Introduction

1.1. Remote sensing of terrestrial vegetation is an important tool for monitoring its status and carbon flux estimation. Using space observations, vegetation biomass is estimated from chlorophyll content, which is linked to biomass, using canopy biophysics models that assimilate satellite observations. These models are used to estimate the chlorophyll content of vegetation, which is used to assess the status of vegetation and to estimate the carbon fluxes.

1.2. The chlorophyll fluorescence signal is a measure of the chlorophyll content of vegetation, which is used to estimate the carbon fluxes. The signal is measured using light detection and ranging (LiDAR) measurements, which are used to estimate the chlorophyll content of vegetation, which is used to assess the status of vegetation and to estimate the carbon fluxes.

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First observations of global and seasonal terrestrial chlorophyll fluorescence from space

J. Journaux, Y. Yoshida, A. P. Vasilkov, Y. Yoshida, L. A. Corp, and E. M. Middelton

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Published by Copernicus Publications on behalf of the European Geosciences Union.
Fluorescence from GOSAT (three different retrievals groups)

- Joiner et al, Biogesciences 2010, AMT 2012
  Use of measured solar spectra and/or measured spectra over vegetation free areas

- Frankenberg et al, GRL 2010, 2011
  Use of high resolution solar model and instrument model (ILS)

- Guanter et al, RSE 2012
  Physics based (high resolution modeling) + fast Singular Value Decomposition methods.

→ Despite differences in the techniques, methods agree well
Fluorescence from SCIAMACHY

Spectral resolution too low to sample fine Fraunhofer lines near 750nm but sufficient to use the wide Ca II line at 866.5 nm

Joiner et al
Biogesences 2010, AMT 2012
Facing reality:
Detection of a zero level offset in the GOSAT FTS

From now on, focus on JPL efforts (please note work by Joiner and Guanter though!).

• Initial GOSAT $F_s$ retrievals caused headache as high $F_s$ was retrieved over Antarctica
• Signal could be traced down to an FTS zero-level offset
• Empirical correction now in place (from all retrieval groups)
• → beware of zero level offset in FTS systems and spectral straylight in gratings spectrometers
Impact of the offset on the retrieval
Global fluorescence retrieval from GOSAT, annual average

C. Frankenberg, Fisher et al, GRL, 2011
GOSAT Fluorescence at 757nm
Gross Primary Production (GPP), MPI-BGC (Beer et al, Science)
Results: $F_s$ - GPP

Frankenberg, Fisher, et al.: GRL
Frankenberg, Fisher, et al.: GRL
Comparison with GPP, two year average

Top = $F_I$, bottom = GPP from MPI-BGC Jena

Two year average
July 2009

![Map of July 2009 fluorescence and GPP](image)

- Fluorescence: $F_r (W \, m^{-2} \, \mu m^{-1} \, sr^{-1})$
- GPP: GPP in (6.5 gC/m$^2$/d)

0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95
September 2009

![Map of global fluorescence and Gross Primary Production (GPP)](image)

- Fluorescence (F<sub>r</sub> in W m<sup>-2</sup> micron<sup>-1</sup> sr<sup>-1</sup>)
- GPP in (6.5 gC/m<sup>2</sup>/d)

0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95
October 2009

Fluorescence / (W m^{-2} micron^{-1} sr^{-1})

GPP in (6.5 gC/m2/d)

F_0 (W m^{-2} micron^{-1} sr^{-1}) ; GPP in (6.5 gC/m2/d)
December 2009

F / (W m$^{-2}$ micron$^{-1}$ sr$^{-1}$) ; GPP in (6.5 gC/m$^2$/d)

0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95
January 2010

F_r (W m^-2 micron^-1 sr^-1) ; GPP in (6.5 \text{ gC/m}^2/d)

0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95

Gross Primary Production / (gC/m^2/d)
June 2010

Fluorescence / (W m$^{-2}$ micron$^{-1}$ sr$^{-1}$) ; GPP in (6.5 gC/m$^2$/d)

0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95

Gross Primary Production / (gC/m$^2$/d)
October 2010

Fluorescence / (W m⁻² micron⁻¹ sr⁻¹)
Fₚ / (W m⁻² micron⁻¹ sr⁻¹) ; GPP in (6.5 gC/m²/d)
0.00 0.15 0.30 0.45 0.60 0.75 0.90 1.05 1.20 1.35 1.50 1.65 1.80 1.95

Gross Primary Production / (gC/m²/d)
November 2010

Fluorescence / (W m^-2 micron^-1 sr^-1)

Gross Primary Production / (gC/m^2/d)
• While GOSAT provides unique new data, the application of $F_s$ is still hampered by high single measurement noise and incomplete (and infrequent) sampling.

• OCO-2 will partially alleviate the first problem as it will provide 50 times more data, beating down standard errors. However, it will also NOT be a mapper, covering <2-3% of the Earth’s surface (both instruments are designed to measure trace gases, not surface properties)

• The Fraunhofer line retrieval method is very robust, embarrassingly simple and now proven. More dedicated missions (such as FLEX) using high spectral resolution covering both Fluorescence peaks would greatly improve both $F_s$ retrievals and allow for LAI/EVI retrievals at the same time.
Simple steps that could be done...

Enlarge the spectral range

Improve SNR and FWHM

Factor 2 difference in precision!
The retrieval of chlorophyll fluorescence from space is feasible, now proven with real data (and method validated on ground).

The Fraunhofer line retrieval method is simple, fast and robust. Most importantly, it is VERY insensitive to atmospheric scattering, potentially being able to sense $F_s$ through thin clouds.

The raw $F_s$ retrieval, without the application of a single ancillary dataset or model assumption, has more predictive skill in estimating GPP than any other current remote sensing measurement.

How much of this correlation is due to absorbed photosynthetically active radiation and how much due to photosynthetic efficiency is one major discussion point of the KISS workshop.

Chlorophyll fluorescence retrievals from GOSAT and OCO-2 in conjunction with their global atmospheric CO$_2$ measurements will provide an exceptional combination of a vegetation and atmospheric perspective on the global carbon budget, constraining our model predictions for future atmospheric CO$_2$ abundances.