Breakout session "Hyperspectral science and applications for shelf and open ocean processes"

Hyperspectral ocean color imagery and applications to studies of phytoplankton ecology

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Ryan et al. (2014) work with HICO in Monterey Bay
Global Hyperspectral Satellite data used by Phytooptics Group

SCIAMACHY* onboard ENVISAT

- relatively high spectral resolution (0.2 nm to 0.5 nm)
- 240 – 2380 nm (8 spectral channels)
- Pixel size: 30 km × 60 km at best
- Nadir/limb alternating measurements (6 days global coverage)
- March 2002 – April 2012

Outlook global coverage 1 day:

- OMI/AURA (2004-) & TROPOMI/Sentinel-5P (2016; 7x7km) - only until 520 nm

*Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY
The PhytoDOAS Method

- **Differential Optical Absorption Spectroscopy** applied to **Phytoplankton** and to oceanic inelastic processes: based on Beer-Lambert-Law, aims to fulfill following minimization

\[
I(\lambda) = I_0(\lambda) \cdot e^{-\tau(\lambda)} \Rightarrow \tau(\lambda) = \ln \left( \frac{I_0(\lambda)}{I(\lambda)} \right)
\]

\[
\tau(\lambda) = \sum_{k=1}^{K} S_k \sigma_k(\lambda) - \sum_{j=1}^{J} S_j a_j(\lambda) - S_{VRS} \nu(\lambda) - S_{lr} r_l(\lambda) - \sum_{i=0}^{I} x_i \lambda^i \Rightarrow \min.
\]

- Satellite earthshine and solar spectra from satellite
- Measured absorption spectra of all relevant absorbers
- Low frequency changes (Mie/Raleigh sc., …) approximated with low order polynomial

Differential Specific Absorption Spectra

![Phytoplankton](image)

Fit range PFT: 427-529 nm

![Fit spectra of differential VRS-WF](image)

**Inelastic scattering (VRS)**

Fit range VRS: 450-529 nm
PhytoDOAS from SCIAMACHY Data: Examples of PFT fit results

Absorption of phytoplankton groups by PhytoDOAS - comparisons to collocated in-situ data

only cyanobacteria

dominated (>80%) by diatoms

--- scaled in-situ spectrum
__ spectral fit from SCIAMACHY only cyanobacteria     dominated (>80%) by diatoms
--- in-situ reference spectrum
__   SCIAMACHY  Bracher et al. 2009

SCIAMACHY DOAS Fit 29. October 2005
Cyanobacteria absorption  Lat: 22.9 Lon: -22.1
Fit for Orbit 19158
Ground Pixel 9228

SCIAMACHY DOAS Fit 14. March 2004
Diatoms absorption  Lat:-46.0 Lon: 8.7
Fit for Orbit 10654
Ground Pixel 21071

--- in-situ reference spectrum
- SCIAMACHY

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PhytoDOAS Phytoplankton Groups from hyperspectral satellite data: Mean Chl-a March 2007

Longterm data set: SCIAMACHY (2002-2012)
Drawback: Spatial resolution ~60 km x 30 km (0.5°lat/lon - monthly resolution)
Application of PhytoDOAS times series data: Sadeghi et al. BG 2012, Ye et al. 2012

Diatoms
Dinoflagellates
Cyano-bacteria
Coccolithophores

chl-a conc. [mg/m³]

Bracher et al. BG 2009; Sadeghi et al. OS 2012

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Inelastic scattering (VRS) fitfactor definite relation to coccolithophore chl

Coccolithophores’ fitfactor only definite until 1 mg/m^3

Coccolithophores divided by VRS (proxy for observed light path) give definite relation up to 30 mg/m^3

Sensitivity study for PhytoDOAS

Coupled ocean-atmosphere radiative transfer model
SCIATRAN (Rozanov et al. 2014): simulates top of atmosphere spectra with definite chl-a conc. of coccolithophores

Spectra then used in PhytoDOAS retrieval
Light availability in ocean water utilizing Vibrational Raman Scattering (VRS) identified in hyperspectral data

Radiative transfer simulations to model filling in of Fraunhofer lines by inelastic scattering of light in water

Dependence of $E_0$ on VRS-fit factor with varying input of specific phytoplankton absorption and profile stratification

Then modelled filling-in spectra fitted in SCIAMACHY data via DOAS to obtain inelastic scattering in ocean waters (VRS)

Derived VRS fit-factor used to calculate

$\rightarrow$ light availability in water (i.e. scalar irradiance = $E_0$)

$\rightarrow$ PFT Chla (= PFT-fit factor / VRS-fit factor * X)

Excitation 390-444nm
Reemission 450-524nm

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Determination of the light availability in ocean water utilizing Vibrational Raman Scattering (VRS)

Dependence of $E_0$ to SZA

Light availability in ocean water for Oct 2008 derived from SCIAMACHY utilizing VRS-fit factor

Excitation at 390-444.5nm
Reemission at 450-524nm

Future: adapt to
- other wavelength regions
- similar sensors (GOME-2, TROPOMI)

Chl fluorescence from SCIAMACHY: sample fit

Account for:
- water vapor,
- inelastic scattering (rotational and vibrational Raman scattering),
- background radiance (atmospheric transmittance & surface reflectance).

Chl fluorescence
DOAS Fit window
681.8 nm – 685.5 nm
Fluorescence Line Height (2003-2011): hyper- (SCIAMACHY) vs. multispectral (MODIS)

PhytoDOAS retrieves filling-in of Fraunhofer Lines from backscattered (hyperspectral, 681-686 nm)


Multispectral (665, 677, 746 nm) algorithm by Behrenfeld et al. (2009)

http://oceancolor.gsfc.nasa.gov/cgi/l3
PhytoDOAS to retrieve red fluorescence peak applied globally to SCIAMACHY data (extension to terrestrial vegetation) (2003-2011)

Time Series of Coccolithophores in the North Atlantic (53°N-63°N/14°W-24°W; 2002-2010); Sadeghi et al. BG 2012

Objectives:
- test and improve PhytoDOAS
- develop independent method to study coccolithophores

GlobColour (MERIS-SeaWiFS-MODIS merged) tot chl-a

PIC from MODIS

PhytoDOAS coccolithophore chl-a
Wind (AMSR-E)

SST (AVHRR)

MLD (from FNMOC model output and SODA data assimilation)

www.orca.science.oregonstate.edu/1080.by.2160.mon.thly.hdf.mld.fnmoc.php

PIC (MODIS)

GlobColour tot chl-a

PhytoDOAS coccolithophores well related to: PIC, total chl-a, low wind, rising SST, low MLD
Key issues & benefits associated with hyperspectral data of SCIAMACHY using DOAS in marine science

+ Identification of high spectrally resolved optical imprints of water constituents using the full spectral information:
  - Quantitative identification of PFTs
  - Identification of inelastic scattering processes (requires <0.5 nm resolution) which enable determination of underwater light availability
  - Retrieval of marine and terrestrial Chl fluorescence (simultaneously)

+ Easy and efficient approach to account for atmospheric effects
+ Additional information and verification of empirical algorithms (band ratio) applied to multispectral ocean color imagery

- less spatial resolution and spatial coverage than multispectral ocean color sensors which limits also validation with in-situ data

Outlook:
Evaluation and improvement of parametrizations of biogeochemical (BGC) parameters in coupled bgc-ocean-modelling
Goal
Integrate HICO with other remote sensing and in situ data to study coastal phytoplankton ecology

Methods
HICO data atmospherically corrected; band-ratio and linear baseline (spectral shape) algorithms applied

Products

Ryan, Davis, Tufillaro, Kudela and Gao (2014) Remote Sensing
Key issues and benefits associated with hyperspectral data of HICO in marine science

+ Spectral resolution:
  1) Enables **applying any multispectral algorithm** for the benefits that the multispectral algorithm offers, as motivated by the optical properties of the water being studied and the research questions being asked.
  2) Detection of **dense, near-surface (dinoflagellate) blooms** by **resolving the near infrared reflectance peak** caused by them: high spectral resolution in red to NIR enables identifying **NIR peak intensity** somewhere near its center $\lambda$ (ARPH- adaptive reflectance peak height) - this spectral resolution enables a more consistent intensity quantification of peak

+ Spatial resolution:
  Detection of distinct patches of bloom types which can be small

- Underdevelopment: not enough ($\$) efforts into better atmospheric correction(!) by the community.
- Calibration also was an issue
- Low temporal resolution and spatial coverage: Balance of spatial and spectral resolution can be tuned to observing requirements.