Introduction into Ocean Colour Remote Sensing using MERIS data

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Changes, Scenarios and Operational Assessment of the Coastal Environment

- Emergency preparation
- Routine forecasts
- Monitoring technology
- Synoptic analysis
- Environmental modelling
- Scenarios
- Assessment of present state
- Assessment of possible futures
- Societal/economic needs
- Scientific knowledge
- Scientific challenges
Basic principles of Water Color RS

- bottom reflection
- scattering and absorption by water and its constituents
- reflection and refraction
- atmospheric scattering and absorption
- scattering and absorption by suspended particles (phytoplankton pigment, gelbstoff)
- reflection and refraction
- air molecules, aerosols, gases

sensor

sun
Absorption, scattering and beam attenuation

- Attenuation of a beam by absorption and scattering
- Consider a beam of photons which collide with particles

\[ c = a + b \ [m^{-1}] \]

The beam is attenuated by photons, which are absorbed and photons, which are scattered into another direction and, thus, do not reach the detector.
Spectral Colour and wavelength in Nanometer (nm)

1 nm = 1 billion of a Meter = or million part of a millimeters
Phytoplankton

Photos by Marion Rademaker
Pigment absorption spectra - summer period
SIRTRAM case 5

attenuation 1 µg/l pig, 10 mg/l spm, 0.1 m-1 gelb a(440), sun 45, view 20
Reflexion of water

\[ R = \frac{\sqrt{1 + 2bb/a} - 1}{\sqrt{1 + 2bb/a} + 1} \]

\[ k = \sqrt{a(a + 2bb)} \]

\[ R = \frac{k - a}{k + a} \]

Absorption \( a \):
\[ a = a_w + C_p a_p + C_s a_s + C_g + a_g \]

Backscattering \( bb \):
\[ bb = bb_w + C_p bb_p + C_s bb_s \]

- \( a_w \): absorption of water
- \( bb_w \): backscattering of water

\( C_p, C_s, C_g \): concentrations of pigment [\( \mu g/l \)], suspended matter [\( mg/l \)] and gelbstoff [\( a_{440}, m^{-1} \)]

- \( a_p, a_s, a_g \): specific absorption coefficients of pigment, suspended matter and gelbstoff

- \( bb_p, bb_s \): specific backscattering coefficients of pigment and suspended matter
Downwelling irradiance attenuation coefficient

\[
\lambda \text{ [nm]} \\
\begin{array}{ccccccc}
400 & 450 & 500 & 550 & 600 & 650 & 700 & 750 & 800 \\
0 & 0.5 & 1 & 1.5 & 2 & 2.5 & 3 & 3.5 & \\
\end{array}
\]

\[
k \text{ [m}^{-1}\text{]} \\
\begin{array}{ccccccc}
0.1 & 5 \text{ mg/l SPM, ag440 0.4 m}^{-1} \\
0.1 \text{ lg/l chlorophyll} \\
\end{array}
\]
Signal depth $z_{90}$

$$z_{90} = \frac{1}{k}$$

coastal:
- TSM = 5 mg/l
- Chlor. = 5 µg/l
- Gelb = $a_{380} = 1 \text{m}^{-1}$

open ocean:
- Chlor. = 1 µg/l
Case 1 Water
- Only 1 component modulates the radiance spectrum backscattered from the water: Phytoplankton Pigment + associated (correlated) substances
- Concentration range is 0.03 – 30 mg m-3
- Water in the near IR nearly black because of the high absorption of pure water and low concentration of particles (scattering)
- Atmospheric correction relatively simple
- MERIS product: algal_1

Case 2 Water
- Multiple independent components in water, which have an influence on the backscattered radiance spectrum
- Retrieval procedure has to deal with these multiple components, even if only one should be determined
- Optical properties are variable
- Often very high concentrations, where standard algorithms show saturation
- At high TSM concentrations problem with atmospheric correction
- MERIS products: algal_2, TSM, Gelbstoff
Wake up question 1

• How could a simple algorithm to determine the chlorophyll concentration look like?
Empirical model

\[ C = A \left[ \frac{R(445)}{R(550)} \right]^B \]
Comparison of the model for R445/R55

Morel & Antoine, MERIS ATBD
MERIS Global chlorophyll distribution 2003
MERIS RR Pacific Coast off Oregon
Chlorophyll distribution
Summary algal_1 pigment index algorithm

- Based on two colour ratios using a semianalytical model
- \( R(445)/R(555) \) for chlorophyll concentration range < 2 µg/l
- \( R(449)/R(555) \) for > 2 µg/L
- 3 orders of magnitude can be determined (0.03 – 30 µg/l)
- error < 30% on log scale
- Algal_1 index is determinded by all material in case I water, including various algal pigments, bacteria, small detrital particles etc., but it is related to chlorophyll a and expressed as the concentration of chlorophyll a and also validated against chl. A
- F/Q ratio has to be determined iteratively using tabulated values because it requires the knowledge of chl. a
ENVISAT Instrumente

[Diagram of ENVISAT satellite with labeled instruments: MIPAS, MERIS, GOMOS, RA-2, MIPAS Optics Module, SCIAMACHY Cooler, AATSR, MWR, DORIS, X-Band Antenna, LRR, Payload Module, Service Module, Solar Array, ASAR Antenna, Startracker, Nadir, Flight Direction]
**MERIS Medium Resolution Imaging Spectrometer**

- **FOV 68.5 deg, 1150 km**
- **IFOV 300 m, 1200 m**
- **revisit period 2-3 days**
- **5 cameras, each 14 deg FOV**
- **Spectral range: 390 nm to 1040 nm**
- **Spectral resolution: 1.8 nm**
- **Band transmission: 15 spectral bands, programmable in position and width**
- **Band-to-band registration: Less than 0.1 pixel**
- **Band-centre knowledge accuracy: Less than 1 nm**
- **Polarisation sensitivity: Less than 0.3%**
- **Radiometric accuracy: Less than 2% of detected signal, relative to sun**
- **Band-to-band accuracy: Less than 0.1%**
- **Dynamic range: Up to albedo 1.0**
- **radiometric resolution 12 bit**
## MERIS Spectral Band Setting

<table>
<thead>
<tr>
<th>No.</th>
<th>Band centre (nm)</th>
<th>Band width(nm)</th>
<th>Potential Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>412.5</td>
<td>10</td>
<td>Yellow substance and turbidity</td>
</tr>
<tr>
<td>2</td>
<td>442.5</td>
<td>10</td>
<td>Chlorophyll absorption (maximum)</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
<td>10</td>
<td>Chlorophyll and other pigment concentrations</td>
</tr>
<tr>
<td>4</td>
<td>510</td>
<td>10</td>
<td>Suspended sediment, red tides</td>
</tr>
<tr>
<td>5</td>
<td>560</td>
<td>10</td>
<td>Chlorophyll baseline (absorption minimum)</td>
</tr>
<tr>
<td>6</td>
<td>620</td>
<td>10</td>
<td>Suspended sediments, scattering, cyanobacteria</td>
</tr>
<tr>
<td>7</td>
<td>665</td>
<td>10</td>
<td>Chlorophyll absorption (maximum)</td>
</tr>
<tr>
<td>8</td>
<td>681.25</td>
<td>7.5</td>
<td>Chlorophyll fluorescence, red edge</td>
</tr>
<tr>
<td>9</td>
<td>708.75</td>
<td>10</td>
<td>Aerosol type, (Red/NIR boundary), atmos corr.</td>
</tr>
<tr>
<td>10</td>
<td>753.75</td>
<td>7.5</td>
<td>Oxygen absorption reference band, Vegetation</td>
</tr>
<tr>
<td>11</td>
<td>761.875</td>
<td>2.5</td>
<td>Oxygen absorption R-branch</td>
</tr>
<tr>
<td>12</td>
<td>778.75</td>
<td>15</td>
<td>Aerosols over ocean (thickn./type), Vegetation</td>
</tr>
<tr>
<td>13</td>
<td>865</td>
<td>20</td>
<td>Aerosols opt. thickn. -type, Vegetation</td>
</tr>
<tr>
<td>14</td>
<td>885</td>
<td>10</td>
<td>Water Vapour over land</td>
</tr>
<tr>
<td>15</td>
<td>900</td>
<td>10</td>
<td>Water Vapour, Vegetation</td>
</tr>
</tbody>
</table>
MERIS spectrometer
MERIS swath covered by 5 cameras
Das abbildende Spektrometer MERIS

Animation: ESA
Imaging Spectroscopy using MERIS

- ENVISAT
- MERIS

- clouds:
  - Albedo
  - optical thickness
  - top height

- Aerosols
- Water vapour

- Phytoplankton primary production
- Suspended matter
- Gelbstoff
- Vegetation / Land use

- Vegetation / Land use
Globale Wasserdampfverteilung 2003

ENVISAT - MERIS
Total column water vapor, clear sky - Global coverage - Annual average - 2003

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MERIS: Aufnahme der Helgoländer Bucht

MERIS FR
16.4.2003

Helgoland Bight

Section
160 km
Test area of Skagerrak seen by MERIS during a bloom of E. huxleyii June 2003
Mouths of the Ganga
India - Bangladesh
Nov. 2003

Calcutta
River discharge
Yangtze mouth (China)
March 2003
The Biosphere as seen by SeaWiFS

source: NASA GSFC and ORBIMAGE
Dissolved and suspended matter in coastal water

- water molecules
- hydrocarbons, amino acids
- clay-humic-metal complexes
- humic acids
- viruses
- terrigenous sm
- eroded mud and sand
- fly-ash
- desert-dust
- fecal pellets
- macroflocs
- bacterial colonies
- zooplankton
- phytoplankton
- dissolved 0.45 µm suspended
Suspended Matter and Phytoplankton in Coastal Water
Water leaving Radiance Reflectance Spectra of North Sea Water with first 10 MERIS spectral bands

![Graph showing water leaving radiance reflectance spectra for different water types: central North Sea, Red Tide North Sea, and North Sea coastal water. The graph plots wavelength in nm on the x-axis and RLw in sr⁻¹ on the y-axis.](image-url)
Case 2 water reflectance spectra North Sea
Multivariate Relationship

reflectance spectrum

sun zenith view zenith azimuth diff

inverse model

forward model

pure water phytoplankton suspended matter dissolved org. matter

sun zenith view zenith azimuth diff
Wake up question 2

- Which alternatives do we have to solve the case 2 water inverse problem?
Input layer: reflectances and angles

Hidden layer

Output layer: concentrations

\[ y_i = s(-d_i + \sum_{k=1}^{3} w_{ik} \cdot s(-c_k + \sum_{j=1}^{5} v_{jk} \cdot s(-b_j + \sum_{i=1}^{4} u_{ij} x_i))) \]
Case 2 Water Algorithm

Bio-optical measurements: 
\[ a(\lambda), b(\lambda), \text{Pig, TSM, C, Y} \]
\[ \text{Lu/Ed}(\lambda,z), \text{RLw} \]

Bio-optical Model: 
Incl. variability

Set up radiance transfer model: 
Monte Carlo, Hydrolight

Simulation of RLw(\lambda, \theta_v, \theta_s, \phi_v): 
> 20 000 Spectra

Training and Test of aNN

3 angles \(\text{RLw} \)

faNN, baNN

MERIS Processor

aNN

TSM, Pig, Gelb, Conf. Flag

MERIS Product
Radiative transfer simulations for NN training

- Direct radiance $F_o = 1.0$
- Fixed vertical profile of:
  - Ozone
  - Rayleigh
  - Aerosols
- Rough sea surface, fixed wind 7 m/s
- Cox-Munk isotropic slope distribution
- Homogenous water of infinite depth
- Water characterized by:
  - $a_w, a_c, a_g$
  - $b_w, b_s, b_c$
  - $P_w, P_s$
  - $a =$ absorption, $b =$ scattering, $P =$ phase function
  - $w =$ water, $c =$ chlorophyll,
  - $s =$ suspended matter, $g =$ gelbstoff

Detector:
- $E_d$
- $L_w(\theta, \phi)$

Concentration of:
- Total suspended matter mg/l
- Chlorophyll $\mu$g/l
- Gelbstoff $a_{440}$ m$^{-1}$
The MERIS case II water NN algorithm

- \( r, r' \) – log of reflectances
- \( c \) – log of concentrations
- \( g \) – geometry information
- \( q \) – quality indicator

C: 
\[
\begin{align*}
&\log(\text{b\_tot}) \\
&\log(\text{a\_ys+a\_btsm}) \\
&\log(\text{a\_pig}) \\
\end{align*}
\]

All at 443 nm

If \( RLw < 0.0009 \), \( RLw = 0.0009 \) \( (\rho \approx 0.003) \)
Scheme of a bio-optical model: optical components for MERIS

Water sample

In situ
AC-9
BB-4

particle
total absorption

Gelbstoff
yellow substance

Absorption of bleached fraction
= spm absorption

gelbstoff
absorption spectrum
spectral exponent

Absorption of bleached Fraction +
gelbstoff
= total gelbstoff

Absorption of Total - bleached fraction
= phytoplankton absorption

particle
scattering
backscattering

Optical properties at 442 nm

tsm

algal_2

a_ys
How to compute total scattering and absorption from case 2 products

- **Algal_2**
  - Conversion from \(a_{pig\_443}\) (NN output) to chlorophyll concentration
  - \(algal\_2 = 21 \times a_{pig\_443}^{1.04}\)
    - Inverse to compute absorption again:
    - \(a_{pig\_443} = \exp\left(\log\left(\frac{algal\_2}{21}\right)/1.04\right)\)

- **TSM**
  - Total_susp = \(1.73 \times b_{tot\_443}\)
    - Inverse to compute total scattering again:
    - \(b_{tot\_443} = \frac{total\_susp}{1.73}\)

- **Total absorption:**
  - \(a_{tot\_443} = a_{pig\_443} + yellow\_subs\)
Pigment absorption spectra H187, Norway different locations
COLORS Helgoland Gelbstoff absorption all stations

absorption \( a \) (m\(^{-1}\))

wavelength (nm)

-0.2
0
0.2
0.4
0.6
0.8
1
1.2
350
400
450
500
550
600
650
700
750

Pigment absorption – Chl. a, H187

Conversions:
Chl. a [mg m⁻³] = 21 * a_pig_442 ^1.04
Conversions:
TSM $\left[ \text{g m}^{-3} \right] = 1.72 \times b_{\text{tsm} \_442}$
Bio-optical model

- Based on: MAVT North Sea / German Bight (GKSS), Norwegian waters (NIVA, Uni Oslo, NERSC), Baltic Sea (IOW), recommendations by M. Babin

- Gelbstoff absorption exponent: 0.014 ± 0.002
- Bleached particle absorption exponent: 0.008 ± 0.005
- Particle scattering exponent: 0.4 ± 0.2
- White particles scattering exponent: 0.0
- Phytoplankton pigment absorption: > 221 spectra different areas and seasons

- Gelbstoff absorption ays(443): 0.005 – 5.0 m⁻¹
- Particle scattering bp(443): 0.005 – 30.0 m⁻¹
- White particle scattering: 0.005 – 30.0 m⁻¹
- Phytoplankton pigment abs. apig(443): 0.001 – 2.0 m⁻¹
- Minimum particle scattering bp(443): 0.25*a_pig(443)
- Bleached particle absorption abp(443): 0.1*bp(443)+ran_gauss*0.03*bp(443)
MERIS, TSM, 20030715
MERIS, Gelbstoff, 20030715
comparison transect Cuxhaven -> Helgoland
ca. 60 km from highly turbid waters to average North-Sea water
comparison concentrations Meris <-> in-situ along track Cuxhaven-Helgoland
comparison concentrations Meris <-> in-situ along track Cuxhaven-Helgoland
Chlorophyll Distribution Northsea March 2003 (MERIS)

L3-Product: Monthly Median MERIS-Algal2
March 2003, 37 scenes,
GKSS-ESA-Algorithm
Mean Chlorophyll
North Sea
March 2003

Project: REVAMP

The March 2003 Median Chlorophyll-a image shows that spring algae blooming has started in several areas along the West coasts of Belgium, Holland and Denmark plus along the South-East coast of the UK with concentrations above 10 mg/m³. Even in Skagerrak towards the Swedish and Norwegian coasts and in the central North Sea by the Dogger bank with concentration values up to 5 7 mg/m³ are seen, which is an increase compared to the normally lower values in these regions. Often the spring starts already in late February in Northern North Sea, Skagerrak and Kattegat.
March 2003 Maximum REVAMP Chlorophyll-a (mg m$^{-3}$)

The March 2003 Maximum Chlorophyll-a image by its nature displays more events and features from the individual scenes than the corresponding median image. The algae bloom areas show up stronger, and with higher concentration values. The March Bloom(s) for instance in Skagerrak has been confirmed by in-situ measurements (ferry-box) with diatoms with increasing concentrations towards the Norwegian coast in the middle of March. By the end of March concentrations in the order of 10-20 mg/m$^3$ were confirmed toward the coast on the Danish side.
The May 2003 Maximum Chlorophyll-a image shows a pronounced blooming area in the Central-Northern North Sea stretching all the way from the UK North-East coast to the Danish North-West coast in Skagerrak. The bloom extension is much influenced by the bathymetry and does not extend into the Norwegian Trench area. Here a different bloom is seen towards the Norwegian coast, which was confirmed in-situ to be of the species Psudou-Vittzhusa Pseudodiabolica.
The June 2003 Maximum Chlorophyll-a image shows mainly same features as the median image but with stronger concentration both in the NE North Sea, Skagerrak, along the Danish West Coast, in the German Bight and in the English Channel and Thames Estuary but also to some extent along the Dutch and Belgium coasts and by the Dogger Bank. Much of the blooming features at and around Horns Reef (55.5°N, 6°E) are due to suspended sediments so the true Chlorophyll-a concentrations in the region are in fact lower.
NN sensitivity test, all cases

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**Case 2 Water Chlorophyll Retrieval with NN**

The graph shows a scatter plot comparing model chlorophyll (µg/l) against nn-derived (µg/l) concentrations. The data points are close to the 45-degree line, indicating a good agreement between the two methods. The x-axis represents the model chlorophyll concentration, while the y-axis represents the nn-derived concentration.
NN sensitivity, typical North Sea water

Pigment in North Sea Water (gelb < 0.2 m-1, MSM < 5 mg/l)
Overall retrieval accuracy

- $a(gelb+part)$
- $conc_{bp}$: 0.05 - 0.5 - 5 - 45
- $conc_{pig}$: 0.005 - 0.03 - 0.15 - 1.0
- $conc_{gelb}$: 0.005 - 0.035 - 0.2 - 0.15

- $chl$ (green)
- $tsm$ (yellow)
Summary Case 2 water algorithm

- Based on inverse modelling: optimization, neural network
- Depending on bio-optical model 3 or more classes of substances can be derived
- Most robust is to derive first the inherent optical properties \((a, b, \beta)\)
- Beside concentrations also other properties can be determined, such as signal depth, penetration depth etc.
- Error depends on bio-optical model and possible masking by a dominant optical component, confidence range or error must be provided pixel by pixel
- Depending on the radiative transfer model, the bi-directional effects of radiances can be simulated and used in the inverse model
- Be aware of ambiguities
Comparison Case 1 / Case 2 Water Algorithm for Pigment

Adriatic Sea, May 3, 2002

Algal_1

Algal_2
Cascade 20020921

Algal_1

Algal_2
Algal 1 and 2 Mean

mg/m²

product id
Water leaving radiance reflectance spectra from MERIS
RLw for MERIS bands 1 (412 nm), 6 (560 nm), 10 (708 nm)

- a_gelb_440: 0.2, a_part_440: SPM/25, pig: 2 mg m\(^{-3}\)

- SPM [g m\(^{-3}\)]
- RLw [sr\(^{-1}\)]
Simulated relationship between TSM and MERIS TOA Red - NIR bands

![Graph showing the simulated relationship between TSM and MERIS TOA Red - NIR bands. The graph plots TSM (mg m\(^{-3}\)) against RLw (m\(^{-1}\)) with different lines representing different wavelengths: M5 560 nm, M6 620 nm, M9 708 nm, M10 753 nm, M12 778 nm, M13 865 nm. The wavelength values are indicated at the bottom of the graph.](image-url)
Difference TOA radiance reflectances

![Graph showing the difference in TOA radiance reflectances for various TSM concentrations.](image)

- M9-M6
- M10-M9
- M11-M10
- M12-M11

Result of NN test

NN test for 3 toa reflectance differences MERIS band 9,10,12,13

Neuroet
2 hidden
Log_tsm
Lin_outtransfer
Log-Sigmoid bias
LM training

Input:
RLtoa(10-9)
RLtoa(12-10)
RLtoa(13-12)
Out: log TSM

original TSM mg m⁻³

NNoutput TSM mg m⁻³
Thank You for Listening