NOWPAP – PICES
Joint Training course
on Remote Sensing Data Analysis
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Correction of the influence of the atmosphere in Ocean Colour RS

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„Atmospheric Correction“

• Goal: to determine the water leaving radiance or water leaving radiance reflectance from top of atmosphere (TOA) radiances or reflectances
• The following quantities have to be determined:
  – Path radiance of the atmosphere
  – Transmittance of solar flux through the atmosphere
  – Transmittance of the radiance at the bottom of atmosphere (BOA) to the satellite
  – Solar light which is reflected at the water surface
    • Direct: sun glint
    • After scattering in the atmosphere: reflected sky light
• Normalisation of the reflectance, i.e. recomputation of the bi-directional reflectance for a sun in zenith and nadir viewing direction
• Further problem is the adjacency effect: sun light, which is reflected by a bright target in the neighbourhood of the water surface and which is then scattered by the atmosphere into the sensor
• Correction of thin and sub-pixel clouds and cloud shadows not included here
Basic principles of Water Color RS

- bottom reflection
- scattering and absorption by water and its constituents
- reflection and refraction
- atmospheric scattering and absorption

sensor
sun
air molecules
aerosols
gases
suspended particles
phytoplankton pigment
gelbstoff

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Terms and Expressions

- Optical thickness of atmosphere: $\tau = -\log(T)$, $T$ = transmittance of beam TOA-BOA
- AOT aerosol optical thickness: thickness of only the aerosol component
- Angstrom coefficient (alpha): spectral shape of AOT $\alpha = -\log(\tau_1/\tau_2)/\log(\lambda_1/\lambda_2)$
- Path radiance: the radiance without the contribution from below the water surface
- Specular reflectance: air/sea interface fresnel reflection, depends on index of refraction
- TOA Top of atmosphere, BOA Bottom of Atmosphere
- Water leaving radiance (reflectance): radiance from below the water surface
- Remote sensing reflectance: water leaving radiance / irradiance above surface
- Atmospheric transmittance: transmittance of a beam
- Rayleigh scattering: scattering by air molecules (N2, O2)
- Cloud detection: identification of clouds, problem if optically thin or smaller than a pixel
Light paths to the sensor

the satellite observes both the ocean and the atmosphere
Optical Thickness, Transmittance, Angstrom

- Beam Transmittance $T = \frac{I_z}{I_0}$
- Extinction $\tau = -\log(T)$, $T = \exp(-\tau)$
- $T = \exp(-\frac{\tau}{\cos(\theta)})$
- Aerosol Optical Thickness $AOT = \tau_{ae}$

- Angstrom coefficient:
  - $\alpha = \frac{\log(\tau_{\lambda_1} / \tau_{\lambda_2})}{\log(\lambda_1 / \lambda_2)}$
Composition of Earth atmosphere:
- 78.09% nitrogen
- 20.95% oxygen,
- 0.247% water vapor (variable)
- 0.93% argon
- 0.038% carbon dioxide
- traces of hydrogen, helium, methane, ozone etc.

- Gases cause scattering and absorption
- Areas with no absorption are called windows

Aerosols:
- Salt crystals
- Dust from deserts
- Soot
- Vulcanic ash
Solar Spectrum 2

- idealer Schwarzer Körper (Temperatur 5900 K)
- extraterrestrische Sonnenstrahlung (Luftmasse AM0)
- terrestrische Sonnenstrahlung (Luftmasse AM1,5)
Atmospheric Transmission

Solar radiation at the top of the atmosphere and the actual radiation at sea level which has been reduced due to absorption by atmospheric gases. The dashed curve is a blackbody at 5900K for comparison with the solar curve outside the earth's atmosphere.
Solar Flux at TOA (Thullier)

Solar flux by Thullier

irradiance [W m\(^{-2}\) \(\mu\text{m}\)]

wavelength [nm]
Annual variation of the Aerosol optical depth 500nm

Helgoland Island - 2000-2003
Rame Head - 1997, 1998

Oostende - 2001-2003
Lille - 2000-2003
Azores 2000-2003

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Frequency of occurrences for Angstrom parameter $\alpha_{440\_870}$
Cosine effect

a

long distance

sun's rays

b

short distance

large area

Earth

equator

atmosphere
Snell's Law

\[
\frac{\sin \theta_a}{\sin \theta_w} = \frac{n_w}{n_a}
\]

\(n_w = 1.34\)

Fig. 2.11. Refraction and reflection of light at air–water boundary. (a) A light beam incident from above is refracted downwards within the water: a small part of the beam is reflected upwards at the surface. (b) A light beam incident from below at a nadir angle of 40° is refracted away from the vertical as it passes through into the air: a small part of the beam is reflected downwards again at the water–air boundary. (c) A light beam incident from below at a nadir angle greater than 49° undergoes complete internal reflection at the water–air boundary.
Specular reflectance

Fresnel’s Equation for unpolarized light

\[ r = \frac{1}{2} \left( \frac{\sin^2(\theta_a - \theta_w)}{\sin^2(\theta_a + \theta_w)} + \frac{\tan^2(\theta_a - \theta_w)}{\tan^2(\theta_a + \theta_w)} \right) \]

Fig. 2.10. Reflectance of water surface as a function of zenith angle of light (incident from above), at different wind speeds (data of Gordon, 1969; Austin, 1974a).
Remote Sensing Reflectance

For comparison with the satellite-sensed signal, it is needed to consider the above-surface remote-sensing reflectance which is the ratio of the upwelling radiance to the downwelling irradiance just above the sea surface

\[
R_{RS}(\lambda, \theta, \phi, 0^+) = \frac{L_u(\lambda, \theta, \phi, 0^+)}{E_d(\lambda, 0^+)}.
\]

The subsurface upwelling radiance \(L_u(0^-)\) passing through the sea surface decreases due to reflection and refraction; the above-surface downwelling irradiance passing through the sea surface decreases due to reflection but it is augmented due to internal reflection of the subsurface upward flux from the sea surface

\[
L_u(0^+) = (t_-/n^2)L_u(0^-); \quad E_d(0^-) = t_+ E_d(0^+)/(1-\gamma R)
\]

\[
R_{RS} = (t_- t_+/n^2) r_{RS} /(1-\gamma R); \quad R_{RS} = \zeta r_{RS} /(1-\Gamma r_{RS});
\]

\[
\zeta = t_- t_+/n^2 \quad ; \quad \Gamma = \gamma Q.
\]

For nadir viewing: \(\zeta \approx 0.518, \Gamma \approx 1.562\), (Lee et al. 1998).
Radiances at Top of Atmosphere (TOA)
The composition of the Radiance Spectrum at Top of Atmosphere

Contribution of $L_{\text{wat}}$, $L_{\text{aer}}$ and $L_{\text{ray}}$ to $L_{\text{toa}}$

Relative contribution to TOA radiance
- water leaving radiance: $L_{\text{wat}}$
- aerosol path radiance: $L_{\text{aer}}$
- Rayleigh path radiance: $L_{\text{ray}}$
Ocean color

the atmosphere is 80-90% of the total top-of-atmosphere signal in blue-green wavelengths (400-600 nm)

~1% error in instrument calibration or atmospheric model leads to
~10% error in $L_w(\lambda)$
# Effects of the atmosphere

<table>
<thead>
<tr>
<th>Rayleigh (80-85% of total signal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• small molecules compared to nm wavelength, scattering efficiency decreases with wavelength as $\lambda^{-4}$</td>
</tr>
<tr>
<td>• reason for blue skies and red sunsets</td>
</tr>
<tr>
<td>• can be accurately approximated for a given atmospheric pressure and geometry (using a radiative transfer code)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aerosols (0-10% of total signal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• particles comparable in size to the wavelength of light, scattering is a complex function of particle size</td>
</tr>
<tr>
<td>• whitens or yellows the sky</td>
</tr>
<tr>
<td>• significantly varies and cannot be easily approximated</td>
</tr>
</tbody>
</table>
Spectral Attenuation of Water Constituents

Diffuse attenuation $k$
for pure water, chlorophyll (30µg/l), sus. matter (50 mg/l), gelbstoff
Bands for atmospheric correction

Ltoa over water with high SPM and gelbstoff concentration

MERIS FR 20030416, x=589, y=194, Elbe/Oste
Atmospheric correction

\[ t_d(\lambda) L_w(\lambda) = \frac{L_t(\lambda)}{t_g(\lambda)} f_p(\lambda) - TL_g(\lambda) - tL_f(\lambda) - L_r(\lambda) - L_a(\lambda) \]

\[ nL_w(\lambda) = \frac{L_w(\lambda) f_b(\lambda)}{t_d(\lambda) \mu_0 f_0} \]

But, we need aerosol to get \( L_w(\lambda) \)

\( L_w(\lambda=\text{NIR}) \approx 0 \) and can be estimated (model extrapolation from VIS) in waters where \( Chl \) is the primary driver of \( L_w(\lambda) \)
Magnitudes of $L_w(\text{NIR})$:

- $L_w(\text{NIR}) = 0$ (clear water)
- $L_w(\text{NIR}) \neq 0$ (turbid or highly productive water)

The graph illustrates the spectral response of the Sargasso Sea and Mississippi River Delta, showing the difference in $R_\text{n}$ (sr$^{-1}$) across different wavelengths (nm) for clear vs. turbid waters.
Aerosol determination in visible wavelengths

Given retrieved aerosol reflectance at two $\lambda$, and a set of aerosol models $f_n(\theta, \theta_0, \phi)$.

$$\rho_a(748) \& \rho_a(869)$$

$$\rho_a(\text{NIR}) \Rightarrow \rho_{as}(\text{NIR})$$

$$\varepsilon(748, 869) = \frac{\rho_{as}(748)}{\rho_{as}(869)}$$

$$\varepsilon(\lambda, 869) = \frac{\rho_{as}(\lambda)}{\rho_{as}(869)}$$

$\varepsilon(748, 869)$

$\rho = \frac{\pi L}{F_0 \cdot \mu_0}$
Iterative correction for non-zero $L_w$(NIR)

1. assume $L_w$(NIR) = 0
2. compute $L_a$(NIR)
3. compute $L_a$(VIS) from $L_a$(NIR)
4. compute $L_w$(VIS)
5. estimate $L_w$(NIR) from $L_w$(VIS) + model
6. repeat until $L_w$(NIR) stops changing
   iteratively up to 10 times
Level-2 ocean color processing

(1) determine atmospheric and surface contributions to total radiance at TOA and subtract, iterating as needed.

(2) normalize to the condition of Sun directly overhead at 1 AU and a non-attenuating atmosphere (\(nL_w \text{ or } R_{rs} = nL_w/F_0\)).

(3) apply empirical or semi-analytical algorithms to relate the spectral distribution of \(nL_w\) or \(R_{rs}\) to geophysical quantities.

(4) assess quality (set flags) at each step
Atmospheric correction scheme

1. Correction for gaseous absorption and Rayleigh scattering
2. Spectral matching using a model for atmosphere and glint + ocean reflectance:
   \[ \rho_{TOA}(\lambda) = \frac{T(\lambda)c_D + c_1 \lambda^{-1} + c_2 \lambda^{-4} + t(\lambda)\rho_{W,mod}(\lambda,chl,b_{bs})}{\text{Atmosphere} + \text{Sun glint model}} \]

   - Simultaneous optimization of 5 parameters
   - Using the whole sensor spectrum (from 412 to 865 nm)
3. Iterative optimization using Nelder-Mead simplex method
Polymer model

Models

- We model the atmosphere + sun glint signal by a polynomial:

\[ c_0 + c_1 \lambda^{-1} + c_2 \lambda^{-4} \]

  - sun glint, clouds, foam, aerosols (fine mode)
  - couplings (coarse mode)

- Water reflectance \( \rho_w(\lambda) \): based on Morel and Maritorena (2001). Parameters used:
  - Chlorophyll concentration [chl]
  - Suspended matter backscattering coefficient \( Bb_s \)

- 5 parameters are finally retrieved

Courtesy of F. Steinmetz, Hygeos
Polymer results

Example of sun glint correction
Comparison of 2 scenes taken one day apart

With sun glint

RGB composite

May 14, 2007

$\rho(490)$

Without sun glint

RGB composite

May 15, 2007

Workshop on atmospheric correction over turbid waters, Wimereux, 13-14 June 2012

Courtesy of F. Steinmetz, Hygeos
Polymer: increase of global coverage

Global coverage increase (Level 3)

MERIS [chl] MEGS 7.4
(masks HIGH_GLINT, ABSOA_DUST, PCD_1.13)

MODIS [chl]
(3 daily level 3 from OC Web)

3 days composite
June 3-5, 2003

Coverage increase with respect to standard product:
about a factor 2

Courtesy of F. Steinmetz, Hygeos
Case 2 water reflectance spectra (simulations)

Case 1
- High absorption
- Low scattering

Clear case 2

High absorption
Low scattering

High absorption
High scattering

R. Doerffer
Strange Spectra producing negative reflectances

![Graph showing reflectance vs wavelength](image-url)
Main Problems

• Atmospheric correction often not sufficient for all 9 bands

• Partly bands 1-2 negative, or bands 7,8,9 noisy (in case 1 water)
Design of a Model Atmosphere

Model Atmosphere

direct calc.

Ozone variable

Rayleigh variable

stratosphere

Cirrus

MC calculation

troposphere with fixed continental aerosol

planetary boundary layer variable aerosol maritime, urban

water with scattering particles

TOA

\( L_{\text{toa}} \)

\( E_{o_{\text{toa}}} \)

TOSA

\( L_{\text{tosa}} \)

\( E_{o_{\text{tosa}}} \)

BOA

\( L_{\text{boa}} \)

\( E_{d_{\text{boa}}} \)
Sun glint problem: Hawai 20030705
Cross section Hawai scene

radiance_9 [mW/(m²*sr*nm)]

longitude (deg)
No glint and high glint TOA reflectance spectra

MERIS spectra for no sun glint with RL_toa band 865 < 0.004

MERIS spectra for sun glint with RL_toa band 865 > 0.06
Simulated Rayleigh path radiance reflectance and sun glint radiance reflectance

![Graph showing simulated Rayleigh path radiance and sun glint radiance reflectance. The graph plots wavelength against radiance reflectance and includes curves for the Rayleigh path and sun glint, with specifications for the angle of sun zenith and wind speed.]
NN for atmospheric correction - 3rd version in C2R and Glint processor

RLtosa
12 bands
sun zenith
view zenith
azimuth diff
[Opt. Wind]

Input

Output

RLw(θ, φ) = Lw(θ, φ) / Ed

Tau_aerosol 412, 550, 778, 865
Sun_glint ratio
a_tot, b_tot
MERIS band 1-9
Trans tosa-surface
Path radiance reflectance
RLw
errcode
Radiance reflectance: TOA, path, RLw

![Graph showing radiance reflectance: TOA, path, RLw](image)
C2R Chlorophyll (MERIS FR)

100 km

Shetland
MERIS full resolution: Baltic and North Sea, 20080606

Spatial resolution: 300 m
Swath: 1200 km, 4800 pixel

Baltic Sea
North Sea
Water leaving radiance reflectance
Path radiance reflectance incl. Sun glint band 5 (560 nm)
Water leaving radiance reflectance band 5 (560 nm)
Water leaving radiance reflectance RGB

Ca. 100 km
MERIS 20070505: TOA reflectances RGB
reflectance RLpath MERIS band 5 (560 nm)
reflectance RLW MERIS band 5 (560 nm)
Chlorophyll
MERIS FR USA East Coast 12.6.2008, Signal depth z90
Summary and Conclusions

- Atmospheric correction is essential for most ocean colour applications
- Small errors in AC may cause large errors in the retrieval of water optical properties
- For case 1 water: standard technique using information from NIR spectral bands is successful
- For turbid water technique must include contribution by scattering of water constituents in NIR spectral range
- For highly absorbing water AC must include all spectral bands: forward model and optimization or inverse modeling using neural network
- Correction of sun glint requires also all spectral bands, 2 methods:
  - Neural network
  - Forward model like polymer
- The adjacency effect can be corrected also for standard methods (less necessary for NN and polymer)
- Open issues:
  - Cloud contamination (thin clouds, sub-pixel clouds)
  - Correction of cloud shadows