„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
Basic principles of Water Color RS

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

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 $\tau = -\log(T)$, $T = \exp(-\tau)$
- $T = \exp(-\tau / \cos(\theta))$
- Aerosol Optical Thickness $AOT = \tau_{ae}$

- Angstrom coefficient:
  - $\alpha = \log(\tau_{\lambda_1} / \tau_{\lambda_2}) / \log(\lambda_1 / \lambda_2)$

Solar Spectrum 1

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

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.

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)

Downwelling irradiance
Aerosol Optical Properties

Aeronet sites considered

1. Helgoland Island
2. Hamburg
3. Oostende
4. Lille
5. Rame Head
6. Azore Islands

North Sea
Atlantic Ocean
Annual variation of the Aerosol optical depth 500nm

Frequency of occurrences for Angstrom parameter $\alpha_{440,870}$
Cosine effect

Transmission air-water

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

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

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

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

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

\[
 L_u(0^-) = (t - t_+ / n^2) L_u(0^+) ; \quad E_d(0^-) = t_+ E_d(0^+)/ (1 - \gamma R) \times
 R_{RS} = (t - t_+ / n^2) r_{RS} / (1 - \gamma R) ; \quad R_{RS} = \xi r_{RS} / (1 - \Gamma r_{RS}) ;
\]

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

For nadir viewing: \( \xi = 0.518, \Gamma = 1.562 \), (Lee et al. 1998).
Radiances at Top of Atmosphere (TOA)

The composition of the Radiance Spectrum at Top of Atmosphere
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

- Gaseous absorption (ozone, water vapor, oxygen)
- Rayleigh scattering by air molecules
- Mie scattering and absorption by aerosols (haze, dust, pollution)
- Polarization (MODIS response varies with polarization of signal)

**Rayleigh (80-85% of total signal)**
- Small molecules compared to nm wavelength, scattering efficiency decreases with wavelength as $\lambda^{-4}$
- Reason for blue skies and red sunsets
- Can be accurately approximated for a given atmospheric pressure and geometry (using a radiative transfer code)

**Aerosols (0-10% of total signal)**
- Particles comparable in size to the wavelength of light, scattering is a complex function of particle size
- Whitens or yellows the sky
- Significantly varies and cannot be easily approximated
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

\[ t_d(\lambda) \ L_w(\lambda) = L_d(\lambda) / t_g(\lambda) / t_p(\lambda) - TL_g(\lambda) - TL_f(\lambda) - L_r(\lambda) - L_a(\lambda) \]

\[ \mu_0 f_0 \]

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

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

Magnitudes of \( L_w(\text{NIR}) \)

\( L_w(\text{NIR}) \neq 0 \) (turbid or highly productive water)  
\( L_w(\text{NIR}) = 0 \) (clear water)
Aerosol determiniation in visible wavelengths

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

$$\rho_a(748) \text{ & } \rho_a(869)$$

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

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

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

Iterative correction for non-zero $L_w(\text{NIR})$

(1) assume $L_w(\text{NIR}) = 0$
(2) compute $L_a(\text{NIR})$
(3) compute $L_a(\text{VIS})$ from $L_a(\text{NIR})$
(4) compute $L_w(\text{VIS})$
(5) estimate $L_w(\text{NIR})$ from $L_w(\text{VIS}) + \text{model}$
(6) repeat until $L_w(\text{NIR})$ stops changing

iterating 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 (nLw or Rrs = nLw/F_0).

(3) apply empirical or semi-analytical algorithms to relate the spectral distribution of nLw or Rrs to geophysical quantities.

(4) assess quality (set flags) at each step
Strange Spectra producing negative reflectances

Main Problems

- Atmospheric correction often not sufficient for all 9 bands
- Partly bands 1-2 negativ, or bands 7,8,9 noisy (in case 1 water)
Design of a Model Atmosphere

Model Atmosphere

- Ozone variable
- Rayleigh variable
- stratosphere
  - Cirrus
- troposphere with fixed continental aerosol
- planetary boundary layer variable aerosol maritime, urban
- water with scattering particles

MC calculation

direct calc.

TOA

E_{toa} E_{tosa} E_{boa}

L_{toa} L_{tosa} L_{boa}

Attenuation coefficients of boundary layer aerosols

Attenuations coefficients of maritime and urban aerosols, normalized at 550 nm. The maritime aerosol has an angstrom coefficient of – 0.065, the urban aerosol of - 2.15
Variables of the atmosphere

<table>
<thead>
<tr>
<th>Aerosol</th>
<th>Layer [km]</th>
<th>Optical thickness at 550 nm</th>
<th>Max mean extinction at 550 nm [km⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>maritime (99 % rel. hum.)</td>
<td>0 - 3 km</td>
<td>0 - 0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>urban (45% rel. hum.)</td>
<td>0 - 3 km</td>
<td>0 - 0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>continental</td>
<td>2-12</td>
<td>0 – 0.6</td>
<td>0.165</td>
</tr>
<tr>
<td>cirrus</td>
<td>8-11</td>
<td>0 - 0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>stratosphere</td>
<td>12-50</td>
<td>0 - 0.003</td>
<td>0.0000625</td>
</tr>
<tr>
<td>max. optical thickness</td>
<td></td>
<td></td>
<td>0.6</td>
</tr>
</tbody>
</table>

Max optical thickness at 550 nm: 0.6
Wind speed 0 – 8 m/s

Aerosol Optical Properties used for NN Training data set
Sun glint problem: Hawai 20030705

Cross section Hawai scene
No glint and high glint TOA reflectance spectra

Simulated Rayleigh path radiance reflectance and sun glint radiance reflectance
NN for atmospheric correction - 3rd version in C2R and Glint processor

Input
- RLtosa
- 12 bands
- Sun zenith
- View zenith
- Azimuth diff
- [Opt. Wind]

Neural Network

Output
- Tau_aerosol 412, 550, 778, 865
- Sun_glint ratio
- a_tot, b_tot
- Trans_tosa-surface
- Path radiance reflectance
- RLw
- errcode

\[ RLw(0, \phi) = Lw(0, \phi) / Ed \]

Training of a neural network for atmospheric correction

1. Atmosphere-optical model
2. MC code
3. NNforward water (based on Hydrolight simulations)
4. Optional Polarisation correction
5. RPath_noglint
6. RPath_glint
7. Ed_boa
8. Tau_aerosol
9. RLw
10. Transmittance \( L_{up} \)
11. RLtosa
13. Training & Test data set
**MERIS 20070429**

![Standard AC Algal_2](image1)

![C2R full spek AC Algal_2](image2)

**Radiance reflectance: TOA, path, RLw**

![Graph showing radiance reflectance](image3)
TOA Radiance reflectance RLw RGB

Shetland

Path radiance at 550 nm
C2R Chlorophyll (MERIS FR)

100 km

MERIS full resolution: Baltic and North Sea, 20080606

Spatial resolution: 300 m
Swath: 1200 km, 4800 pixel
Water leaving radiance reflectance

Path radiance reflectance incl. Sun glint band 5 (560 nm)
Water leaving radiance reflectance band 5 (560 nm)

MERIS FR, Area of Gotland, TOA RLw RGB

Stockholm

Gotland

Estonia

Lettland

Baltic Sea

sunglint

Ca. 100 km
Water leaving radiance reflectance RGB

Gotland

Black Sea MERIS RR May 12 2007

Sun glint

Full swath
RR 1200 m
RL_toa
Total Suspended Matter

Chlorophyll distribution
Water leaving radiance reflectance band 5

MERIS 20070505: TOA reflectances RGB
reflectance RLpath MERIS band 5 (560 nm)

reflectance RLw MERIS band 5 (560 nm)