Overview of Atmospheric Correction
(For Global Ocean Color Data Processing)

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Brief History

Color photographs of the oceans were obtained from spacecraft (Apollo, etc., 1960’s).

Clarke et al. (1970) showed the systematic measurements of radiance spectra of sea (ocean color) from aircraft, demonstrated the possibility of detecting the chlorophyll concentration within the ocean upper layers. They also showed atmospheric effects on the measured signals.

Tyler & Smith (1970) performed field measurements of upward & downward irradiance spectra in different water bodies. Thereafter, there were many similar in situ water optical measurements.

Interpretation of in situ reflectance measurements was given in the frame of radiative transfer by Gordon et al. (1975) and also in terms of optically-significant water substances by Morel and Prieur (1977) and Smith and Baker (1978).

Gordon (1978; 1980) developed a single-scattering atmospheric correction algorithm for processing the NASA CZCS ocean color data, demonstrating the feasibility of satellite ocean color remote sensing.

Advanced atmospheric correction algorithm, e.g., Gordon and Wang (1994)-type algorithm has been developed for various more sophisticated ocean color satellite sensors, e.g., OCTS, SeaWiFS, GLI, MODIS, MERIS, VIIRS, OLCI, etc., following the successful CZCS proof of concept mission.

Other approaches, including the SWIR, spectral matching (e.g., POLYMER), Neural Network, etc.

In recent years, atmospheric correction effort has been on dealing with more complex water properties in coastal and inland waters, as well as strongly-absorbing aerosols.
Algorithms for Various Ocean Color Sensors
(Routine Global Ocean Color Data Processing)

Standard Algorithms:
- **Gordon and Wang** (1994) for SeaWiFS, MODIS, and now VIIRS ocean color products.
- **Fukushima** et al. (1998) for OCTS and GLI ocean color products.
- **Antoine and Morel** (1999) for MERIS and now OLCI ocean color products.
- **Deschamps** et al. (1999) for POLDER ocean color products.

Other approaches:
- Various approaches for dealing with NIR ocean contributions.
- **Steinmetz** et al. (2011) POLYMER for the CCI project.
- Neural Network approach for MERIS and OLCI coastal regions (R. Doerffer), Spectral Match.


Menghua Wang, NOAA/NESDIS/STAR
Satellite Sensor Measured TOA Reflectance Spectra

(a) M80 model, $\tau_a(865) = 0.1$

$\theta_0 = 60^\circ$, $\theta = 45^\circ$, $\Delta\phi = 90^\circ$

$\rho_t(\lambda)$

TOA Reflectance $\rho_t(\lambda)$

Wavelength (nm)
The TOA Ocean Contributions

M80 model, $\tau_a(865) = 0.1$

$\theta_0 = 60^\circ$, $\theta = 45^\circ$, $\Delta \phi = 90^\circ$

Case 1, $C = 0.1 \text{ mg/m}^3$

Case-2, Sediment Dominated

Case-2, Yellow Substance
Atmospheric Correction

**Standard atmospheric correction algorithm** (Gordon and Wang 1994)

\[
L_t(\lambda) = L_r(\lambda) + L_A(\lambda) + t(\lambda)L_{wc}(\lambda) + T(\lambda)L_g(\lambda) + t(\lambda)t_0(\lambda)\cos\theta_0 \ nL_w(\lambda)
\]

\[
\rho_{WN}(\lambda) = \pi nL_w(\lambda)/F_0(\lambda) \quad \text{and} \quad R_{rs}(\lambda) = nL_w(\lambda)/F_0(\lambda)
\]

- \(nL_w\) is the desired quantity in ocean color remote sensing.
- \(TL_g\) is the sun glint contribution—avoided/masked/corrected.
- \(TL_{wc}\) is the whitecap radiance—computed from wind speed.
- \(L_r\) is the scattering from molecules—computed using the Rayleigh lookup tables (vector RTE, wind speed, atmospheric pressure dependents).
- \(L_A = L_a + L_{ra}\) is the aerosol and Rayleigh-aerosol contributions — estimated using aerosol models.

For Case-1 waters at the open ocean, \(nL_w\) is usually **negligible** at the NIR 750 & 865 nm, i.e., \(L_A\) can be estimated using these two NIR bands, and extrapolated into visible using aerosol models.

However, the black pixel assumption is usually incorrect at the NIR bands for coastal and inland waters.
Spectral Matching Algorithm

**POLYMER** (Steinmetz et al., 2011)--- Polynomial based algorithm applied to MERIS, which has been used for the CCI global ocean color data processing for MERIS, SeaWiFS, and MODIS:

\[
L_t(\lambda) = L_r(\lambda) + L_A(\lambda) + t(\lambda)L_{wc}(\lambda) + T(\lambda)L_g(\lambda) + t(\lambda)t_0(\lambda)\cos\theta_0 nL_w(\lambda)
\]

- **\(nL_w\) spectra are modeled using bio-optical model.**
- The rest of radiance contributions are modeled assuming a polynomial as a function of the wavelength, i.e.,
  \[a_0 + a_1 \lambda^{-1} + a_2 \lambda^{-4}\]
- **\(L_t\) spectra are then estimated and compared with the sensor-measured values----** \(nL_w\) spectra with the best fit to the sensor-measured TOA radiance can be derived.

**Important Notes:**

- **Require good in-water model** (results are from in-water model).
- **Aerosol models are not important**, or aerosol spectral reflectance follows: \(c_0 + c_1 \lambda^{-1}\) (simple non-absorbing, power law aerosol size distribution).
SeaWiFS, MODIS, MERIS, VIIRS Experiences Show:

High quality ocean color products for the global open oceans (Case-1 waters).

Significant efforts are needed for improvements of ocean color products in the coastal & inland regions:

- Turbid Waters  
  (violation of the NIR black ocean assumption)
- Strongly-Absorbing Aerosols  
  (violation of non- or weakly absorbing aerosols)
Algorithm Developments for Productive/Turbid Waters

• Arnone et al. (1998) and Siegel et al. (2000) to account for the NIR ocean contributions for SeaWiFS and MODIS NIR bands.
• Hu et al. (1999) proposed an adjacent pixel method.
• Gordon et al. (1997) and Chomko et al. (2003) the spectral optimization algorithm.
• Ruddick et al. (2000) for regional Case-2 algorithm using the spatial homogeneity of the aerosol in a given area.
• Lavender et al. (2004) regional bio-optical model (suspended sediments) for SeaWiFS application.
• Wang and Shi (2005) derived NIR ocean contributions using the MODIS shortwave infrared (SWIR) bands.
• Doerffler et al. and others developed Artificial Neural Network for coastal Case-2 waters (implemented for MERIS data processing).
• Wang (2007) and Wang & Shi (2007) proposed the SWIR and NIR-SWIR atmospheric correction for the coastal waters.
• Bailey et al. (2010) developed an improved NIR model for the NASA standard ocean color data processing (SeaDAS).
• Wang et al. (2012) developed an NIR model for western Pacific regions (highly turbid) using the data from the SWIR algorithm for GOCI sensor.
• Jiang and Wang (2014) developed BMW algorithm--combined Bailey, Ruddick, and Wang algorithms for VIIRS global ocean color data processing.
The NIR Ocean Contribution Modeling (I)

Various investigators all sought to remove the NIR $nL_w(\lambda)$ contributions from the TOA NIR radiances, so that a “black pixel” could be provided to the Gordon and Wang (1994) type atmospheric correction:

- **Siegel** et al. (2000) used chlorophyll estimate to determine the NIR $nL_w(\lambda)$.
- **Lavender** et al. (2005) used a sediment estimate to determine the NIR $nL_w(\lambda)$.
- **Ruddick** et al. (2000) fixed the aerosol and backscatter type and then solved for both the NIR $nL_w(\lambda)$ and NIR aerosol reflectance simultaneously.
- **Arnone** et al. (1998) and **Stumpf** et al. (2003) used a bio-optical model for absorption coefficient at the red band and then used that with the red $nL_w(\lambda)$ to find the NIR $nL_w(\lambda)$.
- **Bailey** et al. (2010) developed an improved NIR model for the NASA standard ocean color data processing (SeaDAS).
- **Wang** et al. (2012) developed an NIR model for western Pacific regions (highly turbid) using the data from the SWIR algorithm for GOCI sensor.
- **Jiang and Wang** (2014) developed BMW algorithm--combined Bailey, Ruddick, and Wang algorithms for VIIRS global ocean color data processing.
Spectral Optimization Algorithm (II)

- The **Spectral Optimization Algorithm (SOA)** (Chomko and Gordon, 1998) derives the properties of the ocean and atmosphere simultaneously using sensor-measured TOA radiance from the blue to NIR (entire radiance spectra from visible to NIR). However, the algorithm has no attempt to use realistic aerosol models.
  - Use a simple power-law size distribution aerosol model
  - Use the Garver-Siegel-Maritorena (GSM) ocean bio-optical model
  - Some studies with SeaWiFS data show improved results over the coastal productive waters (Kuchinke et al., 2009).

- The SOA approach with simultaneously ocean and atmosphere properties retrieval (one-step) requires **robust ocean bio-optical model** (e.g., over complex turbid waters).
Neural Network Approach (III)

NN for atmospheric correction – 3rd version in C2R and Glint processor

Input

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

Output

- 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

RLw(θ,ϕ) = Lw (θ,ϕ) / Ed

From R. Doerffer
The shortwave infrared (SWIR) algorithm can be operated the same way as the NIR approach for turbid coastal/inland waters with the black pixel assumption. Require high SWIR SNR performance (MODIS and VIIRS SWIR bands do not meet the requirement).

Black ocean at the SWIR bands: Absorption at the SWIR bands is at least an order larger than that at the NIR 865 nm!
Simply Cases with Strongly-absorbing aerosols:
Which upward radiance is largest and smallest?
# Characteristics of the Aerosol Models

<table>
<thead>
<tr>
<th>Aerosol Model</th>
<th>Single Scattering Albedo $\omega_a(865)$</th>
<th>Asymmetry Parameter $g$</th>
<th>Ångström Exponent $\alpha(510, 865)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic†</td>
<td>1.0</td>
<td>0.724-0.840</td>
<td>-0.087~ -0.016</td>
</tr>
<tr>
<td>Maritime†</td>
<td>0.982-0.999</td>
<td>0.690-0.824</td>
<td>0.09-0.50</td>
</tr>
<tr>
<td>Coastal‡‡</td>
<td>0.976-0.998</td>
<td>0.682-0.814</td>
<td>0.23-0.76</td>
</tr>
<tr>
<td>Tropospheric†</td>
<td>0.930-0.993</td>
<td>0.603-0.769</td>
<td>1.19-1.53</td>
</tr>
<tr>
<td>Urban†</td>
<td>0.603-0.942</td>
<td>0.634-0.778</td>
<td>0.85-1.14</td>
</tr>
<tr>
<td>Dust‡‡‡</td>
<td>0.836-0.994</td>
<td>0.662-0.763</td>
<td>0.29-0.36</td>
</tr>
</tbody>
</table>

† Shettle and Fenn (1979) aerosol models. ‡‡Gordon and Wang (1994)
Strongly-absorbing aerosols: Urban Aerosols

Absorbing Aerosol (Vertical Effects)

Reflectance Ratio $[\rho_t - \rho_r](\lambda, 865)$

Wavelength (nm)

NIR reflectances are not enough to retrieve absorbing aerosol properties

Menghua Wang, IOCCG Lecture Series 2014--Atmospheric Correction
Effects of Dust Aerosol Vertical Distribution

AERONET Dust Model, Black Ocean

$\tau_a(869) = 0.6$, $\theta_o = 60^\circ$, $\theta = 45^\circ$, $\Delta \phi = 90^\circ$
CASE ONE: Dust In Japan/East Sea on 5/26/2007

MODIS Granule (2007146)

MODIS True Color Image and CALIPSO Track
Dealing with Strongly Absorbing Aerosols

For dealing with the strongly absorbing aerosols, it is necessary to first **detect the presence** of the strongly absorbing aerosols (e.g., using measurements in the **UV** bands where the TOA signal is sensitive to the aerosol absorption), and to derive the **aerosol vertical profile** (e.g., from Lidar measurements) with sufficient accuracy for atmospheric correction.

We also need realistic absorbing aerosol models (e.g., dust model).
For highly turbid coastal and inland waters, we need the **SWIR** bands with high SNR performance (over ocean, low signal), i.e., at ~100-200.

For strongly absorbing aerosols (usually over coastal and inland regions):

- We would like to have UV bands for **absorbing aerosol detection**, and
- It is required to have **aerosol vertical profile information** (e.g., accuracy to ~100-500 m) for carrying out atmospheric correction.
- We also need **realistic absorbing aerosol models**, e.g., dust model, for generating proper aerosol lookup tables.