Introduction to atmospheric correction over land (Optical Domain)

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Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
MODIS Land Products

**Energy Balance Product Suite**
- Surface Reflectance
- Land Surface Temperature, Emmisivity
- BRDF/Albedo
- Snow/Sea-ice Cover

**Vegetation Parameters Suite**
- Vegetation Indices
- LAI/FPAR
- GPP/NPP

**Land Cover/Land Use Suite**
- Land Cover/Vegetation Dynamics
- Vegetation Continuous Fields
- Fire and Burned Area

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practices
MODIS Land Data Production Processing Chart

Atmospheric Correction Product (MOD09) crucial input to the MODIS land products

Level 1 Geo., L1B, Cld. Mask, Atmos. Prof.

Level 2 Snow, Sea Ice, Fire

Level 2 Land Surf. Refl.

Level 2/3 Daily Land Surf. Temp./Emiss.

Polar Level 2G/3 Daily Snow, Sea Ice

Level 2G/3 Daily Geoang, Pointers, Agg./Text., Land Surf. Refl., Fire, Snow


Level 3 daily, 8-day GPP

Level 3 yearly NPP

Level 3 16-day VI, BRDF, CC

Level 3 32-day Land Cov. DB, VCF

Level 3 96-day Land Cover/Dynamics

Ancillary Data (GMAO, NMC)

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Land Climate Data Record

Needs to address calibration, atmospheric/BRDF correction issues

**CALIBRATION**

Degradation in channel 1 (from Ocean observations)

Channel1/Channel2 ratio (from Clouds observations)

**ATMOSPHERIC CORRECTION**

**BRDF CORRECTION**

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The need for Surface Reflectance
BOREAS ETM+ scene
Scene: p033r021
Date: 09/17/2001

Top-of-atmosphere TOA
Surface Reflectance

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Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practices
Atmospheric Correction of Earth Observation Data for Environmental MODIS Granule over Southern Africa (Sept 13, 2001, 8:45 to 8:50 GMT)

Red, Green, Blue MODIS top of atmosphere reflectance

No atmospheric correction

Surface Reflectance: Atmospheric effect has a strong impact on remotely sensed data
MODIS Granule over Southern Africa (Sept 13, 2001, 8:45 to 8:50 GMT)

Red, Green, Blue MODIS surface reflectance

With atmospheric correction
Goals/requirements for atmospheric correction

- Ensuring compatibility of missions in support of their combined use for science and application (example Climate Data Record)
- A prerequisite is the careful absolute calibration that could be insured by cross-comparison over specific sites (e.g. desert)
- We need consistency between the different AC approaches and traceability but it does not mean the same approach is required – (i.e. in most cases it is not practical)
- Have a consistent methodology to evaluate surface reflectance products:
  - AERONET sites
  - Ground measurements
- In order to meaningfully compare different reflectance product we need to:
  - Understand their spatial characteristics
  - Account for directional effects
  - Understand the spectral differences
- One can never over-emphasize the need for efficient cloud/cloud shadow screening
Surface Reflectance (MOD09)

The **Collection 5 atmospheric correction algorithm** is used to produce MOD09 (the surface spectral reflectance for seven MODIS bands as it would have been measured at ground level if there were no atmospheric scattering and absorption).

**Goal:** to remove the influence of
- atmospheric gases
  - NIR differential absorption for water vapor
  - EPTOMS for ozone
- aerosols
  - own aerosol inversion

**Home page:** [http://modis-sr.ltdri.org](http://modis-sr.ltdri.org)

**Movie credit:** Blue Marble Project (by R. Stöckli)
[www.nasa.gov/vision/earth/features/blue_marble.html](http://www.nasa.gov/vision/earth/features/blue_marble.html)

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Basis of the AC algorithm

The Collection 5 AC algorithm relies on

- the use of very accurate (better than 1%) vector radiative transfer modeling of the coupled atmosphere-surface system
- the inversion of key atmospheric parameters (aerosol, water vapor)
Vector RT modeling

The Collection 5 atmospheric correction algorithm look-up tables are created on the basis of RT simulations performed by the 6SV (Second Simulation of a Satellite Signal in the Solar Spectrum, Vector) code, which enables accounting for radiation polarization.

May 2005: the release of a β-version of the vector 6S (6SV1.0B) extensive validation and testing.

May 2007: the release of version 1.1 of the vector 6S (6SV1.1)
6SV Features

**Spectrum:** 350 to 3750 nm

**Molecular atmosphere:** 7 code-embedded + 6 user-defined models

**Aerosol atmosphere:** 6 code-embedded + 4 user-defined (based on components and distributions) + AERONET

**Ground surface:** homogeneous and non-homogeneous with/without directional effect (10 BRDF + 1 user-defined)

**Instruments:** AATSR, ALI, ASTER, AVHRR, ETM, GLI, GOES, HRV, HYPBLUE, MAS, MERIS, METEO, MSS, TM, MODIS, POLDER, SeaWiFS, VIIRS, and VGT
6SV Validation Effort

The complete 6SV validation effort is summarized in two manuscripts:


Effects of Polarization

Example: Effects of polarization for the mixed (aerosol (from AERONET) + molecular) atmosphere bounded by a dark surface.

The maximum relative error is more than 7%.
6S v 1.1 is a basic RT code used for calculation of look-up tables in the MODIS atmospheric correction algorithm. It enables accurate simulations of satellite and plane observations, accounting for elevated targets, modeling of realistic molecular, aerosol, or mixed atmospheres, use of Lambertian and anisotropic ground surfaces, and calculation of gaseous absorption. The β-version of the vector 6S has been extensively validated since the time of its release in May 2005, two years later it was transformed into version 1.1. In addition to the code, we also provide a special 6S interface which can help an inexperienced user learn how to use the code and build necessary input files.

If you want to subscribe to the 6S user list to get information on 6S updates or have any questions regarding the code, please send an e-mail to 6S@ltdri.org.
6SV Interface

We provide a special Web interface which can help an inexperienced user learn how to use 6SV and build necessary input files.

Make your own atmospheric correction

The 6s code predicts the satellite signal from 0.25 to 4.0 microns assuming cloudless atmosphere. The main atm account. Non-uniform surfaces may be considered, as well as bidirectional reflectances as boundary conditions.

The following input parameters are needed:

1. Geometrical conditions
2. Atmospheric Model
3. Target & Sensor Altitude
4. Spectral Conditions
5. Ground Reflectance
6. Signal
7. Results

At each step, you can either select some proposed standard conditions (for example, spectral bands of satellite.

This interface also lets us track the number and location of 6SV users based on their IP addresses.
6SV Users (over the World)

Total: 898 users

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Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practices
6SV Users (Distribution per Country)

6SV e-mail distribution list: 142 users
Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Code Comparison Project (1)

All information on this project can be found at http://rtcodes.ltdri.org

Welcome!

This is an official code comparison site of the **MODIS atmospheric correction group** at the University of Maryland. Our group is responsible for the development, further improvement,
Code Comparison Project (2)

Goals:
- to illustrate the differences between individual simulations of the codes
- to determine how the revealed differences influence on the accuracy of atmospheric correction and aerosol retrieval algorithms

Example: Results of the comparison for a molecular atmosphere with $\tau = 0.25$. 

![Graph showing comparison results](image-url)
Input Data for Atmospheric Correction

- Key atmospheric parameters
  - surface pressure
  - ozone concentration
  - column water
  - aerosol optical thickness (new)

Vector 6S → LUTs → AC algorithm

coarse resolution meteorological data
MODIS calibrated data

### Error Budget (collection 4)

**Goal:** to estimate the accuracy of the atmospheric correction under several scenarios

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical conditions</td>
<td>10 different cases</td>
</tr>
<tr>
<td>Aerosol optical thickness</td>
<td>0.05 (clear), 0.30 (average), 0.50 (high)</td>
</tr>
<tr>
<td>Aerosol model</td>
<td>Urban clear, Urban polluted, Smoke low absorption, Smoke high absorption (from AERONET)</td>
</tr>
<tr>
<td>Water vapor content (g/cm²)</td>
<td>1.0, 3.0, 5.0 (uncertainties ± 0.2)</td>
</tr>
<tr>
<td>Ozone content (cm · atm)</td>
<td>0.25, 0.3, 0.35 (uncertainties ± 0.02)</td>
</tr>
<tr>
<td>Pressure (mb)</td>
<td>1013, 930, 845 (uncertainties ± 10)</td>
</tr>
<tr>
<td>Surface</td>
<td>forest, savanna, semi-arid</td>
</tr>
</tbody>
</table>
Calibration Uncertainties

We simulated an error of ±2% in the absolute calibration across all 7 MODIS bands.

Results: The overall error stays under 2% in relative for all $t_{aer}$ considered.

(In all study cases, the results are presented in the form of tables and graphs.)

Table (example): Error on the surface reflectance (x 10,000) due to uncertainties in the absolute calibration for the Savanna site.
Uncertainties on Pressure and Ozone

The pressure error has impact on

- molecular scattering (specific band)
- the concentration of trace gases (specific band)
- $\tau_{aer}$ (all bands)

The ozone error has impact on

- the band at 550 nm (mostly)
- the band at 470 nm → the retrieval of $\tau_{aer}$ → all bands
Uncertainties on Water Vapor

Retrieval of the column water vapor content:

- if possible, from MODIS bands 18 (931-941 nm) and 19 (915 – 965 nm) by using
  the differential absorption technique. The accuracy is better than 0.2 g/cm².

- if not, from meteorological data from NCEP GDAS

Table (example): Error on the surface reflectance (x 10,000) due to uncertainties in the water vapor content for the Semi-arid site:

<table>
<thead>
<tr>
<th>Central Wavelength (nm)</th>
<th>470</th>
<th>550</th>
<th>645</th>
<th>870</th>
<th>1,240</th>
<th>1,650</th>
<th>2,130</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Reflectance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>×10,000</td>
<td>700</td>
<td>1,246</td>
<td>1,400</td>
<td>2,324</td>
<td>2,929</td>
<td>3,085</td>
<td>2,800</td>
</tr>
<tr>
<td>Maximum Error</td>
<td>Clear</td>
<td>0004d</td>
<td>0024j</td>
<td>0011i</td>
<td>0030i</td>
<td>0024i</td>
<td>0018i</td>
</tr>
<tr>
<td>×10,000</td>
<td>High</td>
<td>0004d</td>
<td>0024j</td>
<td>0011i</td>
<td>0030i</td>
<td>0024i</td>
<td>0018i</td>
</tr>
<tr>
<td>Minimum Error</td>
<td>Clear</td>
<td>0001a</td>
<td>0005a</td>
<td>0008c</td>
<td>0005c</td>
<td>0000c</td>
<td>0000a</td>
</tr>
<tr>
<td>×10,000</td>
<td>High</td>
<td>0001a</td>
<td>0003a</td>
<td>0004c</td>
<td>0003c</td>
<td>0000c</td>
<td>0000a</td>
</tr>
<tr>
<td>Average Error</td>
<td>Clear</td>
<td>3</td>
<td>7</td>
<td>11</td>
<td>9</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>×10,000</td>
<td>High</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Impact of water vapor uncertainties (+/-0.2g/cm²)
Retrieval of Aerosol Optical Thickness

**Original approach:** “dark and dense vegetation (DDV) technique”, a linear relationship between $\rho_{VIS}$ and $\rho_{NIR}$, limitation to the scope of dark targets

**Current approach:** a more robust “dark target inversion scheme”

- a non-linear relationship derived using a set of 40 AERONET sites representative of different land covers
- can be applied to brighter targets

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises 20
Uncertainties on the Aerosol Model

In the AC algorithm, an aerosol model is prescribed depending on the geographic location. We studied an error generated by the use of an improper model.

*Prescribed:* urban clean  
*Additional:* urban polluted, smoke low absorption, smoke high absorption

The choice of the aerosol model is critical for the theoretical accuracy of the current product (in particular, for the accuracy of optical thickness retrievals).
Pioneer aerosol inversion algorithms for AVHRR, Landsat and MODIS (*Kaufman et al.*)

(the shortest λ is used to estimate the aerosol properties)

**Refined aerosol inversion algorithm**

- use of all available MODIS bands (land + ocean e.g. 412nm as in *Deep Blue*)
- improved LUTs
- improved aerosol models based on the AERONET climatology
- a more robust “dark target inversion scheme” using Red to predict the blue reflectance values (in tune with *Levy et al.*)
- inversion of the aerosol model (rudimentary)
Example 1: **Alta_Floresta 2003197 14:30 (SCF)**

<table>
<thead>
<tr>
<th>Aeronet</th>
<th></th>
<th>MOD09</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AOT</td>
<td>delta AOT</td>
<td>WV</td>
<td>delta WV</td>
</tr>
<tr>
<td>0.29856</td>
<td>0.00153</td>
<td>2.91618</td>
<td>0.01956</td>
</tr>
</tbody>
</table>

**RGB (670 nm, 550 nm, 470 nm)**
Top-of-atmosphere reflectance

**RGB (670 nm, 550 nm, 470 nm)**
Surface reflectance
Example 1: Alta_Floresta 2003197 14:30 (SCF)

<table>
<thead>
<tr>
<th>Aeronet</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AOT</td>
<td>0.29856</td>
<td>delta AOT</td>
<td>0.00153</td>
<td>WV</td>
</tr>
</tbody>
</table>

Red (670nm)
Top-of-atmosphere reflectance

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practices
Example 2: **Alta_Floresta 2003256 14:10** (SCF)

### Aerōnet

<table>
<thead>
<tr>
<th>AOT</th>
<th>delta AOT</th>
<th>WV</th>
<th>delta WV</th>
<th>DTaot</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.86180</td>
<td>0.01204</td>
<td>5.94636</td>
<td>0.00395</td>
<td>14</td>
</tr>
</tbody>
</table>

### MOD09

<table>
<thead>
<tr>
<th>avg AOT</th>
<th>std AOT</th>
<th>avg WV</th>
<th>std WV</th>
<th>nb obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.95974</td>
<td>0.26412</td>
<td>3.67405</td>
<td>0.06463</td>
<td>0</td>
</tr>
</tbody>
</table>

**AOT = 0.896** (7km x 7km)

Model residual:
- **Smoke LABS:** 0.003082
- **Smoke HABS:** 0.004978
- **Urban POLU:** 0.04601
- **Urban CLEAN:** 0.006710

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**RGB (670 nm, 550 nm, 470 nm)**
- Top-of-atmosphere reflectance

**RGB (670 nm, 550 nm, 470 nm)**
- Surface reflectance
Example 3: **Mongu 2003257 08:20 (SCF)**

### AERONET

<table>
<thead>
<tr>
<th>AOT</th>
<th>delta AOT</th>
<th>WV</th>
<th>delta WV</th>
<th>DTaot</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98179</td>
<td>0.01919</td>
<td>2.18265</td>
<td>0.00130</td>
<td>14</td>
</tr>
</tbody>
</table>

### MOD09

<table>
<thead>
<tr>
<th>avg AOT</th>
<th>std AOT</th>
<th>avg WV</th>
<th>std WV</th>
<th>nb obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98953</td>
<td>0.04857</td>
<td>1.87310</td>
<td>0.04040</td>
<td>0</td>
</tr>
</tbody>
</table>

**AOT = 0.927** (7km x 7km)

Model residual:
- Smoke LABS: 0.005666
- **Smoke HABS: 0.004334**
- Urban POLU: 0.004360
- Urban CLEAN: 0.005234

RGB (670 nm, 550 nm, 470 nm)

Top-of-atmosphere reflectance

RGB (670 nm, 550 nm, 470 nm)

Surface reflectance
Overall Theoretical Accuracy

Overall theoretical accuracy of the atmospheric correction method considering the error source on calibration, ancillary data, and aerosol inversion for $3 \tau_{aer} = \{0.05 \text{ (clear)}, 0.3 \text{ (avg.)}, 0.5 \text{ (hazy)}\}$:

<table>
<thead>
<tr>
<th>Reflectance/VI</th>
<th>Forest</th>
<th>Savanna</th>
<th>Semi-arid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>value</td>
<td>Aerosol Optical Depth</td>
<td>value</td>
</tr>
<tr>
<td></td>
<td>clear</td>
<td>avg</td>
<td>hazy</td>
</tr>
<tr>
<td>$\rho_3$ (470 nm)</td>
<td>0.012</td>
<td>0.0052</td>
<td>0.0051</td>
</tr>
<tr>
<td>$\rho_4$ (550 nm)</td>
<td>0.0375</td>
<td>0.0049</td>
<td>0.0055</td>
</tr>
<tr>
<td>$\rho_1$ (645 nm)</td>
<td>0.024</td>
<td>0.0052</td>
<td>0.0059</td>
</tr>
<tr>
<td>$\rho_2$ (870 nm)</td>
<td>0.2931</td>
<td>0.004</td>
<td>0.0152</td>
</tr>
<tr>
<td>$\rho_5$ (1240 nm)</td>
<td>0.3083</td>
<td>0.0038</td>
<td>0.011</td>
</tr>
<tr>
<td>$\rho_6$ (1650 nm)</td>
<td>0.1591</td>
<td>0.0029</td>
<td>0.0052</td>
</tr>
<tr>
<td>$\rho_7$ (2130 nm)</td>
<td>0.048</td>
<td>0.0041</td>
<td>0.0028</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.849</td>
<td>0.03</td>
<td>0.034</td>
</tr>
<tr>
<td>EVI</td>
<td>0.399</td>
<td>0.005</td>
<td>0.006</td>
</tr>
</tbody>
</table>

The selected sites are Savanna (Skukuza), Forest (Belterra), and Semi-arid (Sevilleta). The uncertainties are considered independent and summed in quadratic.

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory
Performance of the MODIS C5 algorithms

To evaluate the performance of the MODIS Collection 5 algorithms, we analyzed 1 year of Terra data (2003) over 127 AERONET sites (4988 cases in total).

Methodology:

Subsets of Level 1B data processed using the standard surface reflectance algorithm

Comparison

Reference data set

Atmospherically corrected TOA reflectances derived from Level 1B subsets

Vector 6S

AERONET measurements

\( T_{aer}, H_2O, \text{particle distribution} \)

If the difference is within \( \pm (0.005 + 0.05p) \), the observation is “good”.

http://mod09val.ltdri.org/cgi-bin/mod09_c005_public_allsites_onecollection.cgi

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises 28
Validation of MOD09 (1)

Comparison between the MODIS band 1 surface reflectance and the reference data set.

The circle color indicates the % of comparisons within the theoretical MODIS 1-sigma error bar:
- **green**: > 80%
- **yellow**: 65% < 80%
- **magenta**: 55% < 65%
- **red**: < 55%

The circle radius is proportional to the number of observations.

Clicking on a particular site will provide more detailed results for this site.
Validation of MOD09 (2)

Example: Summary of the results for the Alta Foresta site.

**Each bar:** date & time when coincident MODIS and AERONET observations are available

**The size of a bar:** the % of “good” surface reflectance observations

**Scatter plot:** the retrieved surface reflectances vs. the reference data set along with the linear fit results
Validation of MOD09 (3)

In addition to the plots, the Web site displays a table summarizing the AERONET measurement and geometrical conditions, and shows browse images of the site.

Similar results are available for all MODIS surface reflectance products (bands 1-7).

**Percentage of good:**

<table>
<thead>
<tr>
<th>Band</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86.62%</td>
</tr>
<tr>
<td>2</td>
<td>94.13%</td>
</tr>
<tr>
<td>3</td>
<td>51.30%</td>
</tr>
<tr>
<td>4</td>
<td>75.18%</td>
</tr>
<tr>
<td>5</td>
<td>96.36%</td>
</tr>
<tr>
<td>6</td>
<td>97.69%</td>
</tr>
<tr>
<td>7</td>
<td>98.64%</td>
</tr>
</tbody>
</table>

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises 31
Validation of MOD13 (NDVI)

Comparison of MODIS NDVI and the reference data set for all available AERONET data for 2003. Globally, **97.11%** of the comparison fall within the theoretical MODIS 1-sigma error bar ($\pm(0.02 + 0.02\text{VI})$).

- green > 80%, 65% < yellow < 80%, 55% < magenta < 65%, red < 55%
Validation of MOD09 (EVI)

Comparison of MODIS EVI and the reference data set for all available AERONET data for 2003. Globally, 93.64% of the comparison fall within the theoretical MODIS 1-sigma error bar (±(0.02 + 0.02VI)).

green > 80%, 65% < yellow < 80%, 55% < magenta < 65%, red < 55%
Generalization of the approach for downstream product (e.g., Albedo)

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises


Comparison over Lamont, OK (period 273-288): Albedo 0.161
Collection 5

Collection 5:

Terra Aqua

Surface Reflectance Daily L2G Global 250 m MOD09GQ MYD09GQ

Surface Reflectance Daily L2G Global 500 m and 1 km MOD09GA MYD09GA

Surface Reflectance 8-Day L3 Global 250 m MOD09Q1 MYD09Q1

Surface Reflectance 8-Day L3 Global 500 m MOD09A1 MYD09A1

Surface Reflectance Quality Daily L2G Global 1km MOD09GST MYD09GST

Surface Reflectance Daily L3 Global 0.05Deg CMG MOD09CMG MYD09CMG

Description: [http://modis-sr.ltdri.org](http://modis-sr.ltdri.org)

Availability: February 2000 through December 2000, Terra only

* CMG – Climate Modeling Grid

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises 35
Approach for the surface reflectance product

- Atmospheric correction consistent with the MODIS, AVHRR and NPP-VIIRS approach, ensuring consistent reflectance data across resolutions based on rigorous radiative transfer
  - http://6s.ltdri.org
  - http://rtcodes.ltdri.org/

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Validation of the 6S code

The new version of 6S

Vector mode (with polarization)

- Molecular atmosphere
  - Coulson’s tabulated values
- Aerosol atmosphere
  - Monte Carlo
- Molecular + aerosol atmosphere
  - Water-leaving reflectances

Scalar mode (no polarization)

- Molecular atmosphere
- Aerosol atmosphere
  - MODTRAN
  - DISORT
  - SHARM
The corrected MODIS AQUA water-leaving reflectances using AERONET and 6SV vs. the MOBY-measured water-leaving reflectances for $\lambda = \{412; 443; 490; 530; 550\} \text{ nm}$. The MOBY data were collected off the coast of Lanai Island (Hawaii) during the year 2003 (From Kotchenova et al., 2006).

The corrected IKONOS reflectance’s using AERONET and 6SV (including adjacency effect correction) vs. the reference tarp reflectance’s. The data were acquired over Stennis Space flight Center on February, 15, 2002.
Using AERONET sun photometer measurements, the atmospheric correction was performed over site where simultaneous measurements of the surface reflectance over selected sites (Bare soil, Harvested corn, Yellow grass) using a ASD spectrometer were performed.

Despite strong heterogeneity of the sites showed by the measured standard deviation the agreement between the LANDSAT surface reflectance and the surface measurements is very good especially in the visible where the aerosol effect is the strongest.
6S Radiative transfer code validation (Landsat)

Harvested corn

Bare soil

Yellow grass

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
6SV Radiative transfer code validation (Landsat)

- Using the Harvested corn site (bright surrounded by dark forest) we were able to show that the adjacency effect correction tested theoretically was improved the agreement between measurement and Landsat surface reflectance.

Reflectance’s observed over a horizontal transect on the checkerboard. The red bars are the “true” surface reflectance, the blue bars correspond to the top of the atmosphere signal including adjacency effect. The green bars correspond to the corrected data using the infinite target assumption. The open square correspond to the data corrected for the adjacency effect using the operational method developed.
Theoretical uncertainties for the surface reflectance MODIS product

- Validation and uncertainties estimates. Theoretical error budget, comprehensive evaluation.

<table>
<thead>
<tr>
<th></th>
<th>FOREST</th>
<th>SAVANNA</th>
<th>SEMI-ARID</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Belterra</td>
<td>Skukuza</td>
<td>Sevilleta</td>
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<tr>
<td></td>
<td>Clear</td>
<td>Average</td>
<td>Hazy</td>
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<td>$\lambda_{\text{nm}}$</td>
<td>$\rho \times 10000$</td>
<td>$\Delta \rho \times 10000$</td>
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<td>NDVI x1000</td>
<td>$\Delta$NDVI x1000</td>
<td>NDVI x1000</td>
<td>$\Delta$NDVI x1000</td>
</tr>
<tr>
<td>849</td>
<td>30</td>
<td>34</td>
<td>40</td>
</tr>
</tbody>
</table>

Error in ~0.5% in reflectance unit

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Verification over AERONET sites

Subsets of Level 1B data processed using the standard surface reflectance algorithm

Comparison

Reference data set

Atmospherically corrected TOA reflectances derived from Level 1B subsets

Vector 6S

AERONET measurements

\( \tau_{\text{aer}}, \text{H}_2\text{O}, \text{particle distribution} \)

Level 1.5 filtered for abnormal imaginary part of refractive index (Climatology based on level 2.0 data)

If the difference is within \( \pm(0.005+0.05\rho) \), the observation is “good”.

http://mod09val.ltdri.org/cgi-bin/mod09_c005_public_allsites_onecollection.cgi

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Comprehensive analysis of performance using the AERONET network 2000-2007 Results (25542 cases)

Version 2 AERONET (i.e. with Background correction and spheroid)

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Toward a quantitative assessment of performances (APU)

1.3 Millions 1 km pixels were analyzed for each band.

Red = Accuracy (mean bias)
Green = Precision (repeatability)
Blue = Uncertainty (quadratic sum of A and P)

On average well below magenta theoretical error bar
MODIS used as a reference for past and future land data record (example NDVI)

Evaluation over AERONET (2003)
0.007 <Precision < 0.017

Independent evaluation of the precision
Over 2000-2004 CMG daily time series

FOREST
Precision=0.016

SAVANNA
Precision=0.01

CROPS
Precision=0.013
BRDF/Atmosphere coupling correction


Time series of surface reflectance derived from Terra/MODIS reflectances at Keoma (Zambia) for different level of processing.

Cumulative histogram of the apparent noise of the reflectance (Black) and corrected reflectance (blue average model, green red and magenta classical and 2009 approach) time series in MODIS Channel 2 (from 2012 paper). Derived from 100 sites over one year.

Impact of the coupling atmosphere BRDF on the retrieval of the broad band albedo (a) RMS (b) bias.

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Error due to atmospheric effect in MODIS band 1, 2 and 4, (bottom) residual error for the same bands due to the Lambertian assumption in the MODIS surface reflectance collection 5 algorithm [Franch et al., 2013]. It should be noted than in the visible the residual error is about 20 times lower than the original perturbation. This work confirmed the magnitude of this effect (5%-10%) as previously derived results using a variety of sources of surface BRDF and radiative transfer approach [Lee and Kaufman, 1986] [Hu et al., 1999; Lyapustin, 1999] as the recent work of [Wang et al., 2010] seemed to indicate much higher effect (15%-40%).
Internal cloud mask improvement

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practices
Internal cloud mask improvement

Collection 5 internal Cloud mask flag (yellow) let a substantial amount of cloud go through (leakage)

Collection 6

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Monitoring of product quality (exclusion conditions cloud mask)

Aqua true color surface reflectance image for March, 2, 2007. The CALIOP track is shown in red, only matchups over Land are selected.

<table>
<thead>
<tr>
<th></th>
<th>MOD35 Global</th>
<th>MOD35 60S-60N</th>
<th>ICM Global</th>
<th>ICM 60S-60N</th>
<th>ICM Global Case1</th>
<th>ICM Global Case2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage</td>
<td>6.1%</td>
<td>5.6%</td>
<td>5.8%</td>
<td>4.0%</td>
<td>2.6%</td>
<td>2.1%</td>
</tr>
<tr>
<td>False Det.</td>
<td>6.1%</td>
<td>6.4%</td>
<td>6.5%</td>
<td>6.7%</td>
<td>6.5%</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

Analysis of the performance of MOD35 and ICM under various scenarios. Global (Global), excluding latitude higher than 60N or lower than 60S (60S-60N), excluding cloud incorrectly detected as snow (ICM Global Case1) using the ICM snow quality flag, and finally further excluding ICM cloud adjacent quality flag (ICM Global Case2).
Validation of cloud/cloud shadow mask on TM data

- Evaluated for 157 Landsat scenes covering a variety of conditions
- Cloud mask comparison
  - ACCA cloud mask
  - SRBM (Surface reflectance Based Mask): Internal cloud mask based on SR product
  - VCM : Truth Validation Cloud Mask (operator made)
- Metrics for cloud detection versus VCM
  - Rate of omission of cloud %: Leakage
  - Rate of commission of cloud %: False detection
- As far as leakage the internal cloud mask, SRBM, is superior to ACCA/ In term of commission ACCA has better performance than SRBM
- LEDAPS SRB shadow algorithm needs improvements
LEAKAGE RATE comparison

Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Atmospheric Correction of Earth Observation Data for Environmental Monitoring: Theory and Best Practises
Improving the aerosol retrieval

(a) Revised the aerosol model using the latest result of the AERONET database, in particular the accounting for particles non-sphericity and the version 2, level 2 particles properties inversions. A new model for dust is under development.

(b) Started improving the ratio used in the visible and swir used in the inversion. Currently a default value is used globally, that value is adequate for vegetated area but not on sparsely vegetated or desert area. We used the MISR data and the CMG product to produce a spatially explicit CMG climatology of these ratios and will use those in the aerosol inversion.
The performance of the reflectance product for band 4 (550nm) for the fixed ratio (left side) versus spatially variable (right side), although modest the improvement in the performance of the product is clearly visible especially in the lower range of reflectance’s that correspond to vegetation/forest.
Evidence of different polarization sensitivity sensitivities of the two mirror sides of MODIS Terra, (left side, courtesy of MODIS Calibration Science Team) the oscillations of the mirror side ratio over Libya/N. Atlantic Ocean and Australia that are offset by ~6 months in phase. This is well explained by the expected degree of polarization (right side, simulated using 6S [Kotchenova and Vermote, 2007; Kotchenova et al., 2006]) that shows the same phase offset between the Atlantic/Libya (blue) and Australia latitudes (red).
Using Landsat 30m data we simulate the reflectance observed in the MODIS 1km footprint over 45 days. If MODIS was a perfect 1km footprint always assigned to the same location, the data will show a constant reflectance, however here due to pixel size growth with view zenith angle and other gridding artifacts, we see a substantial variation of the reflectance (+/-0.015) (The site is in BONDVILLE, IL)