Remote Sensing for aerosol research

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International workshop on Air Quality in Asia, Hanoi, Vietnam, June 24-26 2014
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 Land Surf. Refl.

Level 2 Snow,
Sea Ice, Fire

Level 2G/3 Daily
Snow, Sea Ice

Polar
Level 2G/3 Daily
Snow, Sea Ice

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

Ancillary Data
(GMAO, NMC)

Level 3 8-day
Land Surf. Refl.,
Fire (+daily),
Land Surf. Temp./Emiss.
Snow, Sea Ice,
LAI/FPAR

Level 3 16-day
VI, BRDF, CC

Level 3 32-day
Land Cov. DB,
VCF

Level 3 96-day
Land Cover/Dynamics

Level 3 daily,
8-day GPP

Level 3 yearly
NPP

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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
MODIS Granule over Southern Africa (Sept 13, 2001, 8:45 to 8:50 GMT)

Red, Green, Blue MODIS top of atmosphere reflectance

No aerosol correction

Surface Reflectance: aerosol 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 aerosol 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)

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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 model:** 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
The complete 6SV validation effort is summarized in three 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%.

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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.

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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, and distribution of the MODIS atmospheric correction algorithms.

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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 $\tau = 0.25$. 

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Input Data for Atmospheric Correction

Key atmospheric parameters → Vector 6S → LUTs → AC algorithm

- surface pressure
- ozone concentration
- column water
- aerosol optical thickness

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>

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Retrieval of Aerosol Optical Thickness

**Original approach:** “dark and dense vegetation (DDV) technique”

- A linear relationship between $\rho_{\text{VIS}}$ and $\rho_{\text{SWIR}}$ 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
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).
Collection 5 Aerosol Inversion Algorithm

Pioneer aerosol inversion algorithms for AVHRR, Landsat and MODIS (Kaufman et al.)

(the shortest $\lambda$ 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)

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Example 1: **Alta_Floresta 2003197 14:30 (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>0.29856</td>
<td>0.00153</td>
<td>2.91618</td>
<td>0.01956</td>
<td>15</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>0.22569</td>
<td>0.02469</td>
<td>3.08241</td>
<td>0.06199</td>
<td>46</td>
</tr>
</tbody>
</table>

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

**RGB (670 nm, 550 nm, 470 nm)**  
*Surface reflectance*

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Example 1: **Alta_Floresta 2003197 14:30 (SCF)**

<table>
<thead>
<tr>
<th>AERONET</th>
<th>AOT</th>
<th>delta AOT</th>
<th>WV</th>
<th>delta WV</th>
<th>DTaot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.29856</td>
<td>0.00153</td>
<td>2.91618</td>
<td>0.01956</td>
<td>15</td>
</tr>
</tbody>
</table>

Red (670nm)
Top-of-atmosphere reflectance

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Example 2: **Alta_Floresta 2003256 14:10 (SCF)**

### Aerosol \ MOD09

<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>

<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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Example 3: Mongu 2003257 08:20 (SCF)

<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></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

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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

Reference data set

Atmospherically corrected TOA reflectances derived from Level 1B subsets

AERONET measurements ($\tau_{aer}, H_2O, \text{particle distribution}$)

Vector 6S

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 Practices
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.

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

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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>MOD35</th>
<th>MOD35</th>
<th>ICM</th>
<th>ICM</th>
<th>ICM</th>
<th>ICM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>60S-60N</td>
<td>Global</td>
<td>60S-60N</td>
<td>Global Case1</td>
<td>Global Case2</td>
</tr>
<tr>
<td>Leakage</td>
<td>6.1%</td>
<td>5.6%</td>
<td>5.8%</td>
<td>4.0%</td>
<td>2.6%</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>
</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).

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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.
Improving the aerosol retrieval: impact on surface reflectance product

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.

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Collection 6 improvements on the aerosol products (preliminary)

Abracos Hill (Aqua 2003)

\[ y = 1.0973x - 0.0242 \]
\[ R^2 = 0.9462 \]

Solar Village (Aqua 2003)

\[ y = 0.6115x + 0.0427 \]
\[ R^2 = 0.6927 \]

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Collection 6 improvements on the aerosol products (preliminary)

Avignon (Aqua 2003)

y = 0.7596x + 0.0026
R² = 0.7439

Bac Ciang (Aqua 2003)

y = 0.7569x - 0.0265
R² = 0.6564

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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%).
Merging dataset to improve aerosol characterization (absorption)

RGB image of the area near Mongu AERONET site (15.25 degree South, 23.15 degree East), for the clear day (July, 17, 2004) and for the hazy (August, 2, 2004). The data have been corrected for the molecular scattering effect. The location of the test site used in the analysis (3km x 3km) is indicated by a red cross.
Merging dataset to improve aerosol characterization (absorption)

RGB image of the area near the Alta Floresta AERONET site (9.92 degree South, 56.02 degree West), for the clear day (August, 2, 2002), and for the hazy day (August, 18, 2002). The data have been corrected for the molecular scattering effect. The location of the test site used in the analysis (3km x 3km) is indicated by a red cross.

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Merging dataset to improve aerosol characterization (absorption)

<table>
<thead>
<tr>
<th>Case</th>
<th>Aerosol Optical depth at 550nm AERONET (MODIS for the clear day)</th>
<th>Angstrom Parameter AERONET</th>
<th>Ozone Content [cm.atm] NCEP</th>
<th>Water Content [g/cm³] MODIS</th>
<th>Solar Zenith angle</th>
<th>View Zenith Angle MODIS</th>
<th>Relative Azimuth MODIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mongu 7/17/2004 08h50GMT</td>
<td>0.155 (0.21)</td>
<td>1.85</td>
<td>0.273</td>
<td>1.11</td>
<td>43.86</td>
<td>13.40</td>
<td>116.9</td>
</tr>
<tr>
<td>Mongu 8/2/2004 08h50GMT</td>
<td>0.428</td>
<td>1.85</td>
<td>0.278</td>
<td>1.42</td>
<td>41.11</td>
<td>13.40</td>
<td>118.11</td>
</tr>
<tr>
<td>Alta Floresta 7/22/2004 14h05GMT</td>
<td>0.116 (0.09)</td>
<td>1.7</td>
<td>0.2675</td>
<td>3.48</td>
<td>39.34</td>
<td>1.73</td>
<td>49.93</td>
</tr>
<tr>
<td>Alta Floresta 8/23/2004 14h05GMT</td>
<td>0.972</td>
<td>2.05</td>
<td>0.2675</td>
<td>4.13</td>
<td>32.56</td>
<td>1.73</td>
<td>40.95</td>
</tr>
</tbody>
</table>
Merging dataset to improve aerosol characterization (absorption)

Surface properties (BRDF) are derived from MISR on the clear day and used during the Hazy days to invert the aerosol absorption

**Mongu**

**Alta Floresta**

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Merging dataset to improve aerosol characterization (absorption)

\[
\text{Residual} = \frac{\sum_{i=1}^{9} |\rho_{\text{red}}^{\text{cor}} - \rho_{\text{red}}^{\text{pred}}|}{9} + \frac{\sum_{i=1}^{9} |\rho_{\text{NIR}}^{\text{cor}} - \rho_{\text{NIR}}^{\text{pred}}|}{9}
\]

Where \(\rho_{\text{band}}^{\text{cor}}\) is the corrected reflectance in red or NIR for camera i, and \(\rho_{\text{band}}^{\text{pred}}\) is the predicted reflectance in red or NIR for camera i.
Conclusions

• Must revisit aerosol model and maybe be more flexible in inversion (no fixed model, angstrom exp?, follow the two modes ocean approach?)
• Take advantage of sensor fusion
• New sensors with high spatial, spectral and radiometric resolution are or will be available (Landsat8, Sentinel 2) with improved cirrus detection capability should be very useful for air quality studies
• Need to adapt the aerosol inversion to the given problem at hand (like for atmospheric correction) to retrieve the most pertinent parameters to air quality
• Error budget, continuous ground observations and validation protocols are keys.

Cám ón