Challenges with atmospheric corrections over Land

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WGCV activity planning meeting, 24-25 Feb. 2015, Radebeul
A Land Climate Data Record

Multi instrument/Multi sensor Science Quality Data Records used to quantify trends and changes

Emphasis on data consistency – characterization rather than degrading/smoothing the data

MODIS (M0(Y)D09 CMG) 2000-present
VIIRS 2011 – 2025
SPOT VEGETATION 1999-2000
Sentinel 3 2014

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Land Climate Data Record (Approach)

Needs to address geolocation, calibration, atmospheric/BRDF correction issues.

- **CALIBRATION**
  - Degradation in channel 1 (from Ocean observations)
  - Channel 1/Channel 2 ratio (from Clouds observations)

- **ATMOSPHERIC CORRECTION**

- **BRDF CORRECTION**
  - [Map of NDVI at California Redwood Site, 1981-1999]
  - [Map of Noise reduction (%)]

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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
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).

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)

Home page: [http://modis-sr.ltdri.org](http://modis-sr.ltdri.org)
The complete 6SV validation effort is summarized in three manuscripts:

Code Comparison Project

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,
## Error Budget

**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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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 aerosol cases 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.

<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 × 10,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>636</td>
<td>800</td>
<td>2,226</td>
<td>2,880</td>
<td>2,483</td>
<td>1,600</td>
</tr>
<tr>
<td>Maximum Error × 10,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>0013j</td>
<td>0013b</td>
<td>0024i</td>
<td>0065i</td>
<td>0080i</td>
<td>0080i</td>
<td>0080i</td>
</tr>
<tr>
<td>Avg.</td>
<td>0015i</td>
<td>0015i</td>
<td>0030i</td>
<td>0074i</td>
<td>0079i</td>
<td>0070i</td>
<td>0054i</td>
</tr>
<tr>
<td>High</td>
<td>0013d</td>
<td>0011a</td>
<td>0049i</td>
<td>0101i</td>
<td>0098i</td>
<td>0088i</td>
<td>0071i</td>
</tr>
<tr>
<td>Minimum Error × 10,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>0008a</td>
<td>0009j</td>
<td>0016c</td>
<td>0045c</td>
<td>0056f</td>
<td>0048f</td>
<td>0031f</td>
</tr>
<tr>
<td>Avg.</td>
<td>0006c</td>
<td>0004j</td>
<td>0016c</td>
<td>0046c</td>
<td>0058e</td>
<td>0049e</td>
<td>0032c</td>
</tr>
<tr>
<td>High</td>
<td>0001e</td>
<td>0005j</td>
<td>0018c</td>
<td>0048c</td>
<td>0058e</td>
<td>0050c</td>
<td>0032c</td>
</tr>
<tr>
<td>Average Error × 10,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>9</td>
<td>11</td>
<td>17</td>
<td>49</td>
<td>61</td>
<td>56</td>
<td>45</td>
</tr>
<tr>
<td>Avg.</td>
<td>8</td>
<td>11</td>
<td>19</td>
<td>53</td>
<td>63</td>
<td>54</td>
<td>37</td>
</tr>
<tr>
<td>High</td>
<td>6</td>
<td>9</td>
<td>24</td>
<td>63</td>
<td>68</td>
<td>59</td>
<td>42</td>
</tr>
</tbody>
</table>
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>Value</th>
<th>Aerosol Optical Depth</th>
<th>Value</th>
<th>Aerosol Optical Depth</th>
<th>Value</th>
<th>Aerosol Optical Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>clear</td>
<td>avg</td>
<td>hazy</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>
<td>0.0052</td>
<td>0.04</td>
<td>0.0052</td>
</tr>
<tr>
<td>$\rho_4$ (550 nm)</td>
<td>0.0375</td>
<td>0.0049</td>
<td>0.0055</td>
<td>0.0064</td>
<td>0.0636</td>
<td>0.0052</td>
</tr>
<tr>
<td>$\rho_1$ (645 nm)</td>
<td>0.024</td>
<td>0.0052</td>
<td>0.0059</td>
<td>0.0065</td>
<td>0.08</td>
<td>0.0053</td>
</tr>
<tr>
<td>$\rho_2$ (870 nm)</td>
<td>0.2931</td>
<td>0.004</td>
<td>0.0152</td>
<td>0.0246</td>
<td>0.2226</td>
<td>0.0035</td>
</tr>
<tr>
<td>$\rho_5$ (1240 nm)</td>
<td>0.3083</td>
<td>0.0038</td>
<td>0.011</td>
<td>0.0179</td>
<td>0.288</td>
<td>0.0038</td>
</tr>
<tr>
<td>$\rho_6$ (1650 nm)</td>
<td>0.1591</td>
<td>0.0029</td>
<td>0.0052</td>
<td>0.0084</td>
<td>0.2483</td>
<td>0.0035</td>
</tr>
<tr>
<td>$\rho_7$ (2130 nm)</td>
<td>0.048</td>
<td>0.0041</td>
<td>0.0028</td>
<td>0.0042</td>
<td>0.16</td>
<td>0.004</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.849</td>
<td>0.03</td>
<td>0.034</td>
<td>0.04</td>
<td>0.471</td>
<td>0.022</td>
</tr>
<tr>
<td>EVI</td>
<td>0.399</td>
<td>0.005</td>
<td>0.006</td>
<td>0.007</td>
<td>0.203</td>
<td>0.003</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.
Methodology for evaluating the performance of MOD09

To first evaluate the performance of the MODIS Collection 5 SR 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 ($\tau_{aer}$, H$_2$O, particle distribution, refractive indices, sphericity)

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](http://mod09val.ltdri.org/cgi-bin/mod09_c005_public_allsites_onecollection.cgi)

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Validation of MOD09

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%, 65% < yellow <80%, 55% < magenta < 65%, red <55%.

The circle radius is proportional to the number of observations.

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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 (quadatric sum of A and P)

On average well below magenta theoretical error bar

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Improving the aerosol retrieval (by using a ratio map instead of fixed ratio) in collection 6 well reflected in APU metrics.

**COLLECTION 5:** accuracy or mean bias (red line), Precision or repeatability (green line) and Uncertainty or quadratic sum of Accuracy and Precision (blue line) of the surface reflectance in band 1 in the Red (top left), band 2 in the Near Infrared (top right also shown is the uncertainty specification (the line in magenta), that was derived from the theoretical error budget. Data collected from Terra over 200 AERONET sites from 2000 to 2009.

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Improving the aerosol retrieval in collection 6 reflected in APU metrics

**COLLECTION 6**: accuracy or mean bias (red line), Precision or repeatability (green line) and Uncertainty or quadratic sum of Accuracy and Precision (blue line) of the surface reflectance in band 1 in the Red (top left), band 2 in the Near Infrared (top right) also shown is the uncertainty specification (the line in magenta), that was derived from the theoretical error budget. Data collected from Terra over 200 AERONET sites from 2003.
MODIS product and validation methodology used to evaluate other surface reflectance product: example LANDSAT TM/ETM+

**WELD (D. Roy) 120 acquisitions over 23 AERONET sites (CONUS)**


**GFCC: Comparison with MODIS SR products**

- **GLS 2000 demonstration**
  

- **GLS 2005 (TM and ETM+)**
  

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WELD/LEDAPS/LDCM results (Red-band3)

LEDAPS

WELD uses MODIS aerosol

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Continuous analysis of time series allow an independent assessment of precision

Evaluation over AERONET (2003)
0.007 < Precision < 0.017

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

Precision=0.016

Precision=0.013

Precision=0.01

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Quantification of time series noise

• For each triplet of observations, one can estimate middle one from the earlier and later:

\[ \rho_i^* = \frac{(t_i - t_{i-1})\rho_{i+1} + (t_{i+1} - t_i)\rho_{i-1}}{t_{i+1} - t_{i-1}} \]

One can then compute a “noise” from the quadratic sum of the difference between the measurement and their interpolated counterpart:

\[ \sigma^2(\rho) = \frac{\sum_{i=2}^{N-1} \frac{1}{t_{i+1} - t_{i-1}} (\rho_i^* - \rho_i)^2}{\sum_{i=2}^{N-1} \frac{1}{t_{i+1} - t_{i-1}}} \]

We use this definition in the following to quantify the time series quality
Evaluation of VJB BRDF correction at CMG spatial resolution (0.05 deg) over AERONET sites (Bréon and Vermote, 2012)

Examples over 3 sites
Black: Original
Red: VJB
Blue: MCD43A2
Green: average

Results over 115 sites

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Evaluation of BRDF correction at native spatial resolution (500m) over Australia

- MODIS data are distributed as “tiles” (10° of lat.)
- To limit data volume, we focus on a single tile
- Select a tile over Eastern Australia for (i) variety of surface cover, (ii) number of clear observations, (iii) low aerosol load

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Impact of spatial scale

- The noise of the corrected time series is much larger than that we obtained earlier using CMG (Climate Modeling Grid: 5 km) lower resolution data.

- We show here a comparison of the noise obtained at the full resolution against that obtained when aggregating 5x5 pixels.
There is a very strong correlation between the spatial heterogeneity (quantified here as the 3x3 standard deviation) and the noise on the corrected time series.

Clearly, the spatial heterogeneity affects the quality of the time series and there is an easy explanation for that (gridding and FOV)
Impact of spatial scale

- The “noise” of the time series decreases when the spatial aggregation increases. There seems to be an optimal scale at 2 km (4x4 pixels)
Use of BRDF correction for product cross-comparison

Comparison of aggregated FORMOSAT-2 reflectance and MODIS reflectance. No BRDF correction. Density function from light grey (minimum) to black (maximum); white = no data.

Comparison of aggregated FORMOSAT-2 reflectance and BRDF corrected MODIS reflectance. Corrections were performed with Vermote al. (2009) method using for each day of acquisition, the angular configuration of FORMOSAT-2 data.
Continuous monitoring and assessment of instrument performance is also important.

CALIBRATION

Comparison of a preliminary Collection 6 MODIS Terra surface reflectance true color composite (RGB, band 1,4,3) using Level 1B Collection 5 input (left) or 6 (right). The artifacts due to the suboptimal calibration of Collection 5 are clearly visible (the reddish abnormal color over vegetated surfaces) and result from non-uniform mirror degradation that could not be tracked properly by the use of the on-board calibration system and periodic lunar looks. The approach taken for Terra calibration in Collection 6 is different than Collection 5 (use of ground desert targets in addition to lunar and on-board calibration) and provides much better results as evidenced by the Surface Reflectance product.
Continuous monitoring and assessment of instrument performance is also important
POLARIZATION EFFECT (BAND8)
Continuous monitoring and assessment of instrument performance is also important

POLARIZATION EFFECT (Aerosol optical thickness)
Monitoring of product quality (exclusion conditions cloud mask using CALIOP)

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).
Protocol for the use of AERONET data

To correctly take into account the aerosols, we use the **aerosol microphysical properties** provided by the AERONET network including size-distribution ($\%C_f$, $\%C_c$, $C_f$, $C_c$, $r_f$, $r_c$, $\sigma_r$, $\sigma_c$), complex refractive indices and sphericity.

Over the 670 available AERONET sites, we selected **230 sites** with sufficient data.

To be useful for validation, the aerosol model should be readily available anytime, which is not usually the case.

Following *Dubovik et al.*, 2002, JAS,*² we used regressions for each microphysical parameters using as parameter either $\tau_{550}$ (aot) or $\tau_{440}$ and $\alpha$ (*Angström* coeff.)

We tested 3 types of regression:

1. regression with $\tau_{550}$: models use $C_f$ and $C_c$ **ACTUAL**
2. regression with $\tau_{440}$ and $\alpha$: models use $C_f$ and $C_c$
3. regression with $\tau_{440}$ and $\alpha$: models use $\%C_f$ and $\%C_c$
Result on Land Surface Reflectances Retrieval

We generated TOA synthetic data using aerosol models from AERONET (20 different models for each site) and determined APU on the surface reflectance retrieval. The global uncertainties are reported in table below for 40 AERONET sites for MODIS band 1 (red) and 3 (blue) for 4 surface reflectances.

<table>
<thead>
<tr>
<th></th>
<th>$p_{surf} = 0.05$</th>
<th>$p_{surf} = 0.10$</th>
<th>$p_{surf} = 0.20$</th>
<th>$p_{surf} = 0.40$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression 1</td>
<td>0.0050 – 0.0060</td>
<td>0.0054 – 0.0067</td>
<td>0.0069 – 0.0091</td>
<td>0.0111 – 0.0153</td>
</tr>
<tr>
<td>Regression 2</td>
<td>0.0039 – 0.0056</td>
<td>0.0043 – 0.0064</td>
<td>0.0056 – 0.0087</td>
<td>0.0094 – 0.0144</td>
</tr>
<tr>
<td>Regression 3</td>
<td>0.0039 – 0.0056</td>
<td>0.0043 – 0.0064</td>
<td>0.0056 – 0.0087</td>
<td>0.0093 – 0.0143</td>
</tr>
</tbody>
</table>

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Impact on validation

Example of APU for MODIS band 1 (red) for the whole 2003 year data set

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Improvements are still needed

(1) The new protocols 2 and 3, using $\tau_{440}$ and $\alpha$, gives globally uncertainties lower than 20% in band 1 (red) and 5-10% in band 3 (blue) compared to the protocol 1 which is actually used.

(2) This study shows that we get marginal improvement using explicit aerosol models for atmospheric corrections close to the performance of the operational MODIS Surface Reflectance product. Further improvements will require a new validation approach… in progress…
Conclusions

• Surface reflectance (SR) algorithm is mature and pathway toward validation and automated QA is clearly identified.
• Algorithm is generic and tied to documented validated radiative transfer code so the accuracy is traceable enabling error budget.
• The use of BRDF correction enables easy cross-comparison of different sensors (MODIS, VIIRS, AVHRR, LDCM, Landsat, Sentinel 2, Sentinel 3…)
• Cloud and cloud shadow mask validation protocol needs to be fully developed.