Satellite remote sensing of Aerosols

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Land Climate Data Record

Needs to address calibration, atmospheric/BRDF correction issues

CALIBRATION

Degradation in channel 1 (from Ocean observations)

ATMOSPHERIC CORRECTION

BRDF CORRECTION

Channel1/Channel2 ratio (from Clouds observations)

International Workshop on Land Use/Cover Changes and Air Pollution in Asia August 4-7th, 2015, Bogor, Indonesia
EVIDENCE OF ATMOSPHERIC EFFECTS (SCATTERING)

Landsat 8/OLI RGB composite (Red Band04, Green Band03, Blue Band02), over Missoula, MT, acquired on June 30, 2013. The Left side corresponds to the reflectance at the top of the atmosphere, the right side to the surface reflectance. The “color stretch” used for both side is the same.
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
A robust accurate validated RT code is needed

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

Map of the ratio between MODIS Terra band 3 (0.47µm) and band 1 (0.67µm). This is the average ratio observed over a period of 10 years using coincident MODIS/MISR observations and the optical thickness from MISR to perform atmospheric correction.
Ratio Map Retrieval Flowchart

1. Terra TOA Band_3,8,9,10
2. Terra TOA Band_1,2,7
3. MISR AOT
4. Atmospheric correction
5. Terra SR Band_3,8,9,10
6. Terra SR Band_1
7. Terra SR Band_2,7
8. Ratio Band_3,8,9,10/Band_1
9. Ratio = a*NDWI + b
10. a, b Map (CMG) band_3,8,9,10
ATMOSPHERIC CORRECTION FLOWCHART

Aerosol retrieval

- AOT inversion based on OLI Band_4/Band_1 ratio or Band_4/Band_2 ratio
- Ratios Map (30 m)
- OLI TOA Band_1
- OLI TOA Band_2
- OLI TOA Band_4

Atmospheric correction

- OLI Atmospheric correction
- OLI TOA 7 Bands
- OLI SR 7 Bands
- AOT Map

Ancillary (Ozone, Water Vapor, DEM)
Use of the residual from AOT retrieval for cloud identification

\[ \text{Residual} = \sqrt{\frac{(\rho_1^s - r_{1,4} \rho_4^s)^2 + (\rho_2^s - r_{2,4} \rho_4^s)^2}{2}} \]

Residual is computed from Band 1,2 (blue) and 4 (red) after atmospheric correction using the ratio's \((r_{1,4} \text{ and } r_{2,4})\) derived from MODIS/MISR.

RGB detail of the Missoula scene (left), (center) color scaled residual: the Magenta pixels correspond to higher residual later flagged as cloud, the red were not flagged as cloud but discarded (in that case water and cloud shadow), the purple are clouds flagged early in the processing by the cirrus band (note the threshold on the cirrus band has been set very conservatively \(\sim 0.02\) reflectance unit). (right) Cirrus band 09.
MODIS Aerosol Inversion

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

<table>
<thead>
<tr>
<th>Aeronet</th>
<th></th>
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<tbody>
<tr>
<td>AOT</td>
<td>0.29856</td>
<td>0.00153</td>
<td>2.91618</td>
<td>0.01956</td>
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<td>delta AOT</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>WV</td>
<td>15</td>
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Red (670nm) Top-of-atmosphere reflectance

Aerosol Optical Depth

0.2
0.4
0.5
MODIS Aerosol Inversion

Alta_Floresta 2003256 14:10 (SCF)

AERONET

<table>
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<th>delta AOT</th>
<th>WV</th>
<th>delta WV</th>
<th>DTaot</th>
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<td>0.86180</td>
<td>0.01204</td>
<td>5.94636</td>
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MOD09

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

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

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

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MODIS Aerosol Inversion

Mongu 2003257 08:20 (SCF)

<table>
<thead>
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<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>
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</table>

<table>
<thead>
<tr>
<th>AVG AOT</th>
<th>STD AOT</th>
<th>AVG WV</th>
<th>STD WV</th>
<th>NB OBS</th>
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<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
OLI surface reflectance validation: AERONET, MODIS, Flux towers

Map of the AERONET sites (yellow squares) used for the validation and the OLI scenes (red square) used for the OLI-MODIS inter-comparison

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Methodology for evaluating the performance of surface reflectance product over AERONET (generic)

- Subsets of Level 1B data processed using the standard surface reflectance algorithm
  \[ \text{comparison} \]

- Reference data set

- Atmospherically corrected TOA reflectances derived from Level 1B subsets

- Vector 6S

- AERONET measurements
  \[ \tau_{aer}, \text{H}_2\text{O}, \text{particle distribution} \]
  \[ \text{Refractive indices, sphericity} \]

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Validation Metrics

- **Accuracy** (A) = the bias
  \[ A = \frac{1}{N} \times \sum_{i=1}^{N} \varepsilon_i \]

- **Precision** (P) = the repeatability
  \[ P = \left( \frac{1}{N-1} \times \sum_{i=1}^{N} (\varepsilon_i - A)^2 \right)^{1/2} \]

- **Uncertainty** (U) = the actual statistical deviation
  \[ U = \left( \frac{1}{N} \times \sum_{i=1}^{N} \varepsilon_i^2 \right)^{1/2} \]

- **Specification** (S) = Uncertainty requirement
  \[ U^2 = \frac{\sum_{i=1}^{N} (\mu_i^e - \mu_i^a - A + A)^2}{N} = \frac{N-1}{N} p^2 + A^2 \]

From Vermote and Kotchenova, 2008

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LANDSAT8 SR APU FOR BANDS 1,2,3,4

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LANDSAT8 APU FOR BANDS 5,6,7 and NDVI
LANDSAT 8 / MODIS CROSS-COMPARISON

Cross-comparison between Aqua MODIS BRDF and spectrally adjusted SR CMG product and OLI SR aggregated over the CMG. The six subplots correspond to six OLI spectral bands used for the cross-comparison. Plots are represented through density function from light gray (minimum) to black (maximum); white means no data. Red lines correspond to the linear fits. $r^2$. Relatives A, P and U are reported under bracket. N is the number of points.

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LANDSAT 8 ALBEDO ANALYSIS

Validation of Landsat (5/7) Albedo derived by Shuai et al. (2011) and Franch et al. (2014). Note that Franch used AERONET data to improve the surface reflectance of the LEDAPS reflectance product used as input. (From Franch et al. 2014.)

Same as left side but for Landsat8 Albedo, no AERONET data were used to improve the surface reflectance product.
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.
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/cm^2] 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>
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<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>
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<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.
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 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.