Aerosol Research Algorithm for TEMPO and TEMPO+GOES

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TEMPO Science Team Meeting
Washington D. C.
Algorithm development strategy

- **Forward thinking**: the GOES+TEMPO synergy algorithm is for aerosol science 5-8 years from now.
- **Holistic thinking**: aerosol will affect O3 and other gas retrieval in UV + Vis gas retrieval algorithm; likewise, gas affects aerosol retrieval.
- **Think about users**:  
  - Satellite data are valuable but cannot provide all information users need.
  - Getting the data is not a key question; the key is the uncertainty associated with each retrieval and how does that help what users already have, in places where obs. data is not available.
  - A big community to use these data will modelers and data assimilation folks.
- **Think about validation**: link retrieval to what can be measured.
- **Think about STM**: climate or air pollution?
- **Start with theory, then real data**

*slide from 2014 GEO-CAPE meeting*
The retrieval framework has been tested with AERONET multiple spectral and polarization data.
Progress for TEMPO Retrieval Algorithm

• What we have been developed so far:
  – A inversion/optimization framework that is consistent with what TEMPO’s gas retrieval framework
  – Seek to provide uncertainty for each individual retrievals.
  – State-of-the-art treatment of gas absorption
  – Tested with AERONET sky radiance so far; Put physically-based constraints to ensure retrieval smoothness and reduce unphysical outliers.
  – Tested with synthetic data and GEO-TASO data

• Decision has not been made; some can not be answered without further studies:
  – Treatment of surface (there were multi-ways to do it, discuss later)
  – The role of priori knowledge for the retrieval: e.g., aerosol climatology from models, ground-based network, and existing satellite products.
  – What to retrieve and what not? Trying to pushing the limits, while still maintaining good accuracy. Fine-mode AOD, surface reflectance?
GOES+TEMPO

GEO-CAPE and GOES-R/S synergy

Joint retrieval from observations collected from dual viewing angles and multiple scattering angles to characterize particle shape and derive aerosol plume speed and stereo height

TEMPO/GEO-TASO

JQSRT, 2014

A numerical testbed for remote sensing of aerosols, and its demonstration for evaluating retrieval synergy from a geostationary satellite constellation of GEO-CAPE and GOES-R

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JQSRT, 2016

An algorithm for hyperspectral remote sensing of aerosols: 1. Development of theoretical framework

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GOES-R to be launched in 2016?

ABI: Advanced Baseline Imager

<table>
<thead>
<tr>
<th>Future GOES imager (ABI) band</th>
<th>Wavelength range (µm)</th>
<th>Central wavelength (µm)</th>
<th>Nominal subsatellite IGFOV (km)</th>
<th>Sample use</th>
<th>Heritage instrument(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45–0.49</td>
<td>0.47</td>
<td>1</td>
<td>Daytime aerosol over land, coastal water mapping</td>
<td>MODIS</td>
</tr>
<tr>
<td>2</td>
<td>0.59–0.69</td>
<td>0.64</td>
<td>0.5</td>
<td>Daytime clouds fog, insolation, winds</td>
<td>Current GOES imager/sounder</td>
</tr>
<tr>
<td>3</td>
<td>0.846–0.885</td>
<td>0.865</td>
<td>1</td>
<td>Daytime vegetation/burn scar and aerosol over water, winds</td>
<td>VIIRS, spectrally modified AVHRR</td>
</tr>
<tr>
<td>4</td>
<td>1.371–1.386</td>
<td>1.378</td>
<td>2</td>
<td>Daytime cirrus cloud</td>
<td>VIIRS, MODIS</td>
</tr>
<tr>
<td>5</td>
<td>1.58–1.64</td>
<td>1.61</td>
<td>1</td>
<td>Daytime cloud-top phase and particle size, snow</td>
<td>VIIRS, spectrally modified AVHRR</td>
</tr>
<tr>
<td>6</td>
<td>2.225–2.275</td>
<td>2.25</td>
<td>2</td>
<td>Daytime land/cloud properties, particle size, vegetation, snow</td>
<td>VIIRS, similar to MODIS</td>
</tr>
<tr>
<td>7</td>
<td>3.80–4.00</td>
<td>3.90</td>
<td>2</td>
<td>Surface and cloud, fog at night, fire, winds</td>
<td>Current GOES imager</td>
</tr>
</tbody>
</table>

from Schmit et al., 2005.
Joint retrieval reduces AOD and fine-mode AOD uncertainties respectively from 30% to 10% and from 40% to 20%.

The improvement of AOD is especially evident for cases when either TEMPO or GOES-R (but not both) are located close to the direction of the Sun (solar azimuth).
Brief History of Geo. Weather Satellite

1st geo., launched in 02/14/1963, a communication sat., NASA

GOES-A/1
1st geo for environment
GOES-1, launched 10/16/1975, NASA

Syncom I
1st geo., launched in 02/14/1963, a communication sat., NASA

Himawari-8
Latest geo weather, JAXA
Launched 10/7/2014

Spin Scan Radiometer (VISSR)
0.55-0.75 μm, 1 km
10.5-12.6 μm, 9 km

Advanced Himawari Imager (AHI)
16 bands
3 vis., 1 km & .5 km
4 NIR, 2 km
9 TIR, 2 km.
10 minutes/full disk
Brief History of Geo. Aerosol/Air Pollution Satellite

Imager → Spectrometer

Launch 2018?

GOES-2

MSG, 8/28/2002
12 channels
2 visible

Fraser, Kaufman, Mahoney, 1984, AE

Lee et al., 2010.
RSE
6 visible
2 NIR

Schmit et al., 2005
Laohoz et al., 2012
Fishman et al., 2012
Policy-relevant science and environmental services enabled by common observations

• Improved emissions, at common confidence levels, over industrialized Northern Hemisphere
• Improved air quality forecasts and assimilation systems
• Improved assessment, e.g., observations to support the United Nations Convention on Long Range Transboundary Air Pollution
Most aerosol algorithms use data from radiometers

Table 1
List of current satellite sensors with measurement specifications relevant for operational retrieval of aerosol properties.

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Full names</th>
<th>Wavelengths (nm)</th>
<th>Measurements characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>MERIS</td>
<td>Medium Resolution Imaging Spectrometer</td>
<td>15(^{a}) bands in 390 nm to 1040 nm including one O(_2) A band</td>
<td>Radiance at single view angle</td>
</tr>
<tr>
<td>MISR</td>
<td>Multi-angle Imaging SpectroRadiometer</td>
<td>446, 558, 672, and 867 for both land and ocean algorithm</td>
<td>Radiance at view angles ± 26.1(^{b}), ± 45.6°, ± 60.0°, and ± 70.5°, and 0°</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
<td>470, 678, 2130 for land 550, 678, 870, 1240, 1640, and 2130 for ocean</td>
<td>Radiance at single view angle(^{c})</td>
</tr>
<tr>
<td>OMI</td>
<td>Ozone Monitoring Instrument</td>
<td>354, 388 for Aerosol index 19 channels(^{d}) in 332–500 for multi-channel algorithm</td>
<td>Radiance at single view angle</td>
</tr>
<tr>
<td>POLDER</td>
<td>POLarization and Directionality of the Earth’s Reflectances</td>
<td>670, 865</td>
<td>Radiance and polarization at 14–16 viewing angles(^{e})</td>
</tr>
<tr>
<td>VIIRS</td>
<td>Visible Infrared Imaging Radiometer Suite</td>
<td>410, 440, 488, 672, 2250 nm for land 672, 746, 865, 1610, 1240, 2250 nm for ocean</td>
<td>Radiance at single view angle(^{f})</td>
</tr>
<tr>
<td>CALIOP</td>
<td>Cloud-Aerosol Lidar with Orthogonal Polarization</td>
<td>532, 1064</td>
<td>Layer backscattering radiance and depolarization ratio(^{g})</td>
</tr>
</tbody>
</table>

\(^{a}\) 412, 442, 490, 510, 560, 620, 665, 681, 705, 753, 760, 775, 865, 890, 900 nm.
\(^{b}\) Positive and negative signs respectively denote the view angles in the forward and backward plane of the local vertical (e.g., nadir).
\(^{c}\) Radiances are measured at 36 channels from 405 nm to 14395 nm.
\(^{d}\) 332, 340, 343, 354, 367, 377, 388, 340, 406, 416, 426, 437, 442, 452, 463, 477, 484, 495, and 500 nm.
\(^{e}\) The exact number of view angles depends on the geographical location. Radiances and linear polarization at 490 nm, 670 nm and radiance-only at 440 nm, 565 nm, and 1020 nm.
\(^{f}\) 22 channels with centers from 412 nm to 1201 nm.
\(^{g}\) Depolarization ratio is only measured at 532 nm.

Wang et al., 2014, JQSRT
Past work done using spectral fitting, primarily in the infrared spectrum

A unified approach to infrared aerosol remote sensing and type specification

ACP, 2013

(sulfate acid, ammonium sulfate, dust, smoke, volcanic ashes)

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³UPMC Univ. Paris 6; Université Versailles St.-Quentin, CNRS/INSU, LATMOS-IPSL, Paris, France
Hyperspectral remote sensing of aerosols in the shortwave spectrum?

Need to characterize the surface spectra.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>450</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>0.02</td>
</tr>
<tr>
<td>550</td>
<td>0.04</td>
</tr>
<tr>
<td>600</td>
<td>0.06</td>
</tr>
<tr>
<td>650</td>
<td>0.08</td>
</tr>
<tr>
<td>700</td>
<td>0.10</td>
</tr>
</tbody>
</table>

- AOD = 1
- \( R_{\text{TOA}} \) of GeoTASO
- \( R_{\text{TOA}} \) (AOD = 0 & \( R_{\text{surf}} \) = 0)
- \( R_{\text{TOA}} \) (\( R_{\text{surf}} \) = 0)
- \( R_{\text{surf}} \) of plant

Molecule contribution

Aerosol contribution

Coupled contribution
Spectral characteristics of different surface types

a) Green vegetation

b) Bare soil

c) Rangeland

d) Concrete

e) Mixed case

Reflectance vs. Wavelength (nm)
PCA analysis of surface reflectance
Self-consistent Check

assuming aerosol properties are well known (such as in field campaigns to derive surface reflectance); 1% measurement error.

- Only 6 weight factors of PCA are retrieved to reconstruct surface reflectance.
- Error in reconstruction in terms of rms is < 0.003.

Hou et al., 2016, JQSRT
A numerical test: can we retrieve PCs from hyperspectral reflectance measured at TOA?

**Input**
- Aerosol parameters
- Observation geometry
- Other setting

**UNL-VRTM**
- TOA reflectance
- Add Gaussian noise

**Surface reflectance**
- Spectral dataset in atmospheric window channel

**PCA**
- Principal components
- Weighting coefficients

**Correction**
- Rayleigh scattering
- Gas absorption

**Error analysis**
- Principal components
- Surface reflectance
The challenge: strong coupling between surface & atmosphere

AOD = 0.2
TOA spectra, at atmospheric window channels, resonates the characteristics of surface reflectance, regardless of AOD.
Evaluation of PC and W derived from TOA spectra (after correction of Rayleigh scattering)
Errors in reconstructed surface spectra from different methods

(a) 400-700 nm

- Reconstructed by PCs of $\rho^\text{TOA}$
- Reconstructed by PCs of $\rho^\text{corrected}$
- Reconstructed by PCs of $\rho^s$

(b) 400-2400 nm

(c) Relative error of $\rho^s$ (%)

Surface type: Vegetation, Soil, Rangeland, Concrete, Mixed

(d) Surface type: Vegetation, Soil, Rangeland, Concrete, Mixed
Total DFS Analysis (TEMPO spectral range)
assuming surface spectra is known with uncertainties

AOD = 0.2
Fine-dominated

Well-mixed
Coarse-dominated

AOD = 0.8

Number of wavelength sort by SFS (400-700nm)
Total DFS Analysis (400-2400 nm)

assuming surface spectra is known with uncertainties

AOD = 0.2

Fine-dominated

AOD = 0.8

Well-mixed

Coarse-dominated

Number of wavelength sort by SFS (400-2400nm)
DFS for aerosol parameters as a function of AOD

- Fine-dominated
- Well-mixed
- Coarse-dominated

**Graphs:**
- Total DFS of aerosol retrieval (with W)
- Aerosol optical depth
DFS for retrieving W

400-700 nm

Total DFS of weighting coefficient retrieval vs. Aerosol optical depth

400 - 2400 nm

Total DFS of weighting coefficient retrieval vs. Aerosol optical depth
DFS for aerosol retrieval parameters

AOD = 0.2

Fine-dominated

Well-mixed

Coarse-dominated

DFS of each retrieval parameter

V$_{\text{total}}$, FMF$_{V}$, r$_{\text{eff}}$

AOD = 0.8

V$_{\text{total}}$, FMF$_{V}$, r$_{\text{eff}}$

Retrieval parameters (400-700nm)
DFS for retrieving $W$ for PCs

AOD = 0.2

AOD = 0.8

DFS of each retrieval parameter

Retrieval parameters (400-700nm)
If we reconstruct the surface spectra using TOA spectra in low-AOD conditions

DFS for aerosol size parameters

AOD = 0.2

(a) Fine-dominated

(b) Well-mixed

(c) Coarse-dominated

AOD = 0.8

(j)

(k)

(l)
DFS for aerosol refractive index

AOD = 0.2

AOD = 0.8

Retrieval parameters (400-700nm)
Segment of picture at each band

Real Data Analysis

The aircraft GEO-TASO data in Houston, Sep. 13, 2013
AOD retrieved from GEO-TASO
AOD validation

![AOD validation graph](image-url)
Polarimetric remote sensing in oxygen A and B bands: sensitivity study and information content analysis for vertical profile of aerosols

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\textsuperscript{a}now at: Earth Resources Technological Inc., Laurel, MD 20707, USA
Summary

• TEMPO has strong synergy with GOES-R

• TEMPO’s unique offer
  – Hourly, high spatial resolution (4km), measurements of UV for aerosol retrieval - 1\textsuperscript{st} time of its kind
  – Hourly Vis spectra contains more information for characterizing aerosols, especially fine-mode particles ($r_{\text{eff}}$ and real-part of refractive index)
  – In line with trop. O3 retrievals that will have a surface spectra database, it likely we will had at least two pieces of information for aerosols in addition to AOD.

• Making good progress with GEO-TASO data

• No heritage algorithm, so it takes time to develop...
**400 – 2400 nm**

**d** Fine-dominated

**e** Well-mixed

**f** Coarse-dominated

DFS of each retrieval parameter (with W)

Retrieval parameters (400-2400nm)
Error in reconstructed surface reflectance

(a) 400-700 nm

10^3 * (Absolute error) of $\rho^S$

- Reconstructed by PCs of $\rho^{TOA}$_{corrected}
- Reconstructed by PCs of $\rho^{TOA}$
- Reconstructed by PCs of $\rho^S$

(c) Relative error of $\rho^S$ (%)

- Vegetation
- Soil
- Rangeland
- Concrete
- Mixed

Surface type
Thank you.
## ABI Capability

<table>
<thead>
<tr>
<th>ABI</th>
<th>Current GOES Imager</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral Coverage</strong></td>
<td></td>
</tr>
<tr>
<td>16 bands</td>
<td>5 bands</td>
</tr>
<tr>
<td><strong>Spatial Resolution</strong></td>
<td></td>
</tr>
<tr>
<td>0.64 μm Visible</td>
<td>0.5 km</td>
</tr>
<tr>
<td>Other visible/near-IR</td>
<td>1.0 km</td>
</tr>
<tr>
<td>Bands (&gt;2 μm)</td>
<td>2 km</td>
</tr>
<tr>
<td><strong>Spatial Coverage</strong></td>
<td></td>
</tr>
<tr>
<td>Full Disk</td>
<td>4 per hour</td>
</tr>
<tr>
<td>CONUS</td>
<td>12 per hour</td>
</tr>
<tr>
<td>Mesoscale</td>
<td>Every 30 sec</td>
</tr>
</tbody>
</table>

Visible (reflective bands)

| On-orbit calibration | Yes | No |

http://www.goes-r.gov/