Development and Validation of High Resolution Simplified MODIS Aerosol Retrieval Algorithm (SARA)

Dr. Muhammad BILAL
Prof. Janet E. NICHOL

Department of Land Surveying and Geo-Informatics
The Hong Kong Polytechnic University
Hong Kong

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Atmospheric aerosols are suspended particles in the atmosphere that vary in their size distribution, shape, total column content, and composition (Kaufman et al., 1997a).

Atmospheric aerosols emitted from natural and anthropogenic sources (Dubvoik et al., 2002; Wallace and Hobbs, 2006) have gained attention worldwide, as they are responsible for uncertainty in the climate system (Kaufman et al., 2002; Sun and Ariya, 2006), poor air quality, degradation of visibility, and impact on human health (Pope et al., 2002; Gent et al., 2009).

Ground-based monitoring station, such as AErosol RObotic NETwork (AERONET, Holben et al., 1998 & 2001), has been established worldwide for regular measurements of aerosol optical properties, such as aerosol optical depth (AOD).
Literature Review

- AERONET provides high spectral and temporal information of AOD but only at a point-location.

- Therefore, a fine spatial coverage along with spectral and temporal information is required for full understanding of aerosol loadings at local to global scales.

- Satellite remote sensing is an unique and effective technique for retrieving much denser spatial distribution of AOD over the globe.
AOD products over land can be obtained by sensors such as:

- the Total Ozone Mapping Spectrometer (TOMS, Torres et al., 2002),
- the Sea-viewing Wide Field-of-view Sensor (SEAWIFS, Sayer et al., 2012),
- the Ozone Monitoring Instrument (OMI, Torres et al., 2007),
- the Polarization and Directionality of the Earth’s Reflectances (POLDER, Herman et al., 1997),
- the Along Track Scanning Radiometer (ATSR-2, North, 2002),
- the Geostationary Operational Environmental Satellite (GOES, Prados et al., 2007),
- the Advanced Very High Resolution Radiometer (AVHRR, Hauser et al., 2005; Riffler et al., 2010),
- the MEdium Resolution Imaging Spectroradiometer (MERIS, Vidot et al., 2008),
- the Multiangle Imaging SpectroRadiometer (MISR, Kahn et al., 2005, 2010), and
- the MODerate Resolution Imaging Spectroradiometer (MODIS, Hsu et al., 2004; Hsu et al., 2006; Levy et al., 2007a, 2010; Remer et al., 2005, 2008)
MODIS Traditional AOD Algorithms

Dark-Target (DT) & Deep Blue (DB)

- Dark-target (DT) pixels are selected based on SWIR (221nm) having surface reflectance between 0.01 and 0.25.
- Surface estimation based on the ratio of visible and shortwave infrared as a function of a vegetation index and scattering angle.

- The MODIS Deep Blue (DB) algorithm was developed to retrieve AOD at 10 km resolution over bright desert surfaces as well as utilizing deep blue wavelengths, where the land surface reflectance is lower than for longer wavelengths (Hsu et al., 2006, 2004).
- Surface reflectance is estimated using Minimum Reflectance Technique (MRT).
Research Objectives

- Develop a **better and simpler** AOD retrieval algorithm for MODIS images at 500 m resolution **without** constructing a look-up-table (LUT)

- Compare the retrieval quality of SARA algorithm with the MODIS Collection 5 & 6 Dark-target (DT) and Deep Blue (DB) aerosol products (MOD04)
Study Area
## Datasets

<table>
<thead>
<tr>
<th>Instrument/Product</th>
<th>Parameter</th>
<th>Resolution</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>AERONET</td>
<td>AOD</td>
<td>----</td>
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</tr>
<tr>
<td>MOD/MYD02HKM</td>
<td>Radiance</td>
<td>500 m</td>
<td>500 m</td>
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<tr>
<td>MOD/MYD03</td>
<td>Elevation</td>
<td>1 km</td>
<td>500 m</td>
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<tr>
<td></td>
<td>Zenith Angles</td>
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<td></td>
<td>Azimuth Angles</td>
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<tr>
<td>MOD09</td>
<td>Surface Reflectance</td>
<td>500 m</td>
<td>500 m</td>
</tr>
<tr>
<td>MOD/MYD04 C5/C6</td>
<td>Cloud Mask&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10 km</td>
<td>10 km</td>
</tr>
<tr>
<td></td>
<td>DT&lt;sup&gt;b&lt;/sup&gt;, DB&lt;sup&gt;c&lt;/sup&gt;, and Combined DT/DB&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MYD04_3K C6</td>
<td>DT&lt;sup&gt;b&lt;/sup&gt; AOD</td>
<td>3 km</td>
<td>3 km</td>
</tr>
</tbody>
</table>

- <sup>a</sup> Aerosol_Cldmask_Land_Ocean
- <sup>b</sup> Optical_Depth_Land_And_Ocean
- <sup>c</sup> Deep_Blue_Aerosol_Optical_Depth_550_Land_Best_Estimated
- <sup>d</sup> AOD_550_Dark_Target_Deeep_Blue_Combined

(Bilal et al., 2013, 2014)
Research Methodology
Simplified Aerosol Retrieval Algorithm (SARA)

- The SRA Algorithm at 500 m resolution is based on
  - real viewing geometry and encompassing
  - a wider range of aerosol types and conditions \((SSA = 0.30-1.00)\) that
  - does not use the common technique of constructing a Look-up-table (LUT).

- The SARA algorithm retrieves AOD based on three assumptions:
  - (i) the surface is Lambertian,
  - (ii) single scattering approximation, and
  - (iii) the single scattering albedo and asymmetry factor do not vary spatially over the region on day of retrieval.

(Bilal et al., 2013, 2014)
Simplified Aerosol Retrieval Algorithm (SARA)  

\[
\tau_{a,\lambda} = \frac{4\mu_s\mu_v}{\omega_o P_{\alpha}(\theta_s, \theta_v, \phi)} \left[ \rho_{TOA}(\lambda, \theta_s, \theta_v, \phi) - \rho_{Ray}(\lambda, \theta_s, \theta_v, \phi) - \frac{e^{-(\tau_R + \tau_{a,\lambda})/\mu_s} e^{-(\tau_R + \tau_{a,\lambda})/\mu_v} \rho_s(\lambda, \theta_s, \theta_v, \phi)}{1 - \rho_s(\lambda, \theta_s, \theta_v, \phi)(0.92\tau_R + (1-g)\tau_{a,\lambda}) \exp\left[-(\tau_R + \tau_{a,\lambda})\right]} \right]
\]

\[
\rho_{TOA}(\lambda, \theta_s, \theta_v, \phi) = \text{top of atmosphere reflectance (TOA)}
\]

\[
\rho_{Ray}(\lambda, \theta_s, \theta_v, \phi) = \text{Rayleigh path reflectance}
\]

\[
\rho_s(\lambda, \theta_s, \theta_v, \phi) = \text{surface reflectance}
\]

\[
P_{\alpha}(\theta_s, \theta_v, \phi) = \text{aerosol phase function}
\]

\[
\mu_s = \text{cosine of solar zenith angle}
\]

\[
\mu_v = \text{cosine of sensor zenith angle}
\]

\[
\omega_o = \text{single scattering albedo (SSA)}
\]

\[
g = \text{asymmetry parameter}
\]

\[
\tau_R = \text{Rayleigh optical depth}
\]

\[
\tau_{a,\lambda} = \text{aerosol optical depth (AOD)}
\]

AOD (L.H.S) = AOD (R.H.S) = ?

SSA = ?

ASY = ?

AOD (R.H.S) = AERONET AOD

Various combinations of SSA (0.30–1.0) and ASY (0.0–1.0) are used to retrieve AOD (L.H.S) over AERONET site.

AOD (L.H.S) = AERONET AOD

(Bilal et al., 2013, RSE)
Expected Error (EE)

Expected error (EE) is used here for the confidence envelopes of MODIS aerosol retrieval algorithm over land to evaluate the quality of SARA and C005 AOD and is defined as follows (Remer et al., 2008; Levy et al., 2010):

\[ EE = \pm (0.05 + 0.15 AOD_{\text{sunphotometer}}) \]

Good matches (quality) of satellite (SARA and C005) AOD are reported when satellite AOD falls within the following envelope (Levy et al., 2010):

\[ AOD_{\text{sunphotometer}} - |EE| \leq AOD_{\text{satellite}} \leq AOD_{\text{sunphotometer}} + |EE| \]

(Bilal et al., 2013, RSE)
Statistical Analysis

- Fraction of Expected Error (FOE)

- The fraction of expected error (FOE) is the ratio of satellite – Sun photometer AOD to the absolute value of EE and can be computed as (Mi et al., 2007):

\[
FOE = \frac{(AOD_{satellite} - AOD_{sunphotometer})}{|EE|}
\]

- Where |FOE| < 1, indicates a good (quality) match (Levy et al., 2010). Values of FOE < 0 and FOE > 0 represent underestimation and overestimation of the satellite retrievals, respectively.
Results

Validation of SARA AOD over Hong Kong

A Simplified high resolution MODIS Aerosol Retrieval Algorithm (SARA) for use over mixed surfaces

Muhammad Bilal a, Janet E. Nichol a,*, Max P. Bleiweiss b, David Dubois c

a Department of Land Surveying & Geo-Informatics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
b Center for Applied Remote Sensing in Agriculture, Meteorology, and Environment, Department of Entomology, Plant Pathology, and Weed Science, New Mexico State University, Las Cruces, NM, USA
c Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM, USA
Validation of SARA AOD with AERONET AOD

SARA AOD
100% of good accuracy

C5 AOD
81% of good accuracy

(Bilal et al., 2013, RSE)
Validation of SARA AOD with Sky-radiometer and Microtops II Sun photometer AOD

(Bilal et al., 2013, RSE)
Validation of SARA AOD with Sky-radiometer and Microtops II Sun photometer AOD

SARA AOD: CityU ~ 80% of good quality – HKIA ~ 78% of good quality

C005 AOD: CityU ~ 67% of good quality – HKIA ~ 12% of good quality

(Bilal et al., 2013)
Spatial pattern of SARA (a), and C005 (b) AOD for a high aerosol loading event (30th January 2007) over the Pearl River Delta (PRD) region and Hong Kong. Also shown, in panel (c), is the SARA AOD under-laid with road data over Kowloon and Hong Kong Island.

(Bilal et al., 2013, RSE)
Validation and accuracy assessment of a Simplified Aerosol Retrieval Algorithm (SARA) over Beijing under low and high aerosol loadings and dust storms

Muhammad Bilal, Janet E. Nichol, Pak W. Chan

\(^a\) Department of Land Surveying & Geo-Informatics, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

\(^b\) Hong Kong Observatory, Kowloon, Hong Kong
Validation of SARA AOD and C5 DT AOD at Beijing_RADI and Beijing_CAMS AERONET sites

\[ Y = 0.91X + 0.03, \quad R = 0.983, \quad N = 220 \]
\[ \text{RMSE} = 0.103, \quad \text{RMB} = 0.97 \]
\[ \text{Data Quality} = 92\% \]

\[ Y = 0.97X + 0.02, \quad R = 0.993, \quad N = 93 \]
\[ \text{RMSE} = 0.070, \quad \text{RMB} = 1.00 \]
\[ \text{Data Quality} = 95\% \]

\[ Y = 1.22X + 0.02, \quad R = 0.967, \quad N = 46 \]
\[ \text{RMSE} = 0.115, \quad \text{RMB} = 1.12 \]
\[ \text{Data Quality} = 52\% \]

\[ Y = 1.44X - 0.05, \quad R = 0.726, \quad N = 15 \]
\[ \text{RMSE} = 0.342, \quad \text{RMB} = 1.33 \]
\[ \text{Data Quality} = 20\% \]

(Bilal et al., 2014, RSE)
Validation of SARA AOD at 1 km to 10 km resolutions at Beijing_RADI and Beijing_CAMS sites (Bilal et al., 2014)
Severe Dust Storm over Beijing (17th April 2006)

**Date:** 17th April 2006

**Origin:** Gobi Desert

(Logan et al., 2010; Lue et al., 2010)

**Affected regions:**

Beijing (Papaynannis et al., 2007), XiangHe (Logan et al., 393 2010), Xinglong (Zu et al., 2014) and the Bohai Sea areas.

**Amount of Dust:** 330 thousand tons of dust in Beijing (Yang et al., 2008)

**Particle Size:** 2 to 50 μm (Lue et al., 2010).

**AOD levels:** AOD > 3.5

**Angstrom Exponent:** below 0.1 (Logan et al., 2010; Papaynannis et al., 2007; Zu et al., 2014).

**Data Source:** National Disaster Reduction Center of China
Severe Dust Storm over Beijing (17th April 2006)

(Bilal et al., 2014, RSE)
Validation of SARA and AQUA MODIS Collection 6

(Bilal et al., submitted, GRL)
High Aerosols Loading (5th October 2013)

(Bilal et al., submitted, GRL)
SARA PM$_{2.5}$ model ($\text{PM}_{2.5} = 110.5 \times \text{AOD} + 12.56$)

**Development:** 4 urban and suburban air quality stations (2007-08)

**Validation:**
4 urban and suburban air quality stations (2009) & 1 rural air quality station (2007-09)
Spatial distribution of SARA-retrieved PM$_{2.5}$ over (a) Pearl River Delta (PRD) region and (b) Hong Kong during a high pollution episode (4$^{th}$ December 2007)
SARA AOD retrieval at 2 m resolution for Shadow areas of Hong Kong using World View II

RGB Composite

Shadow Areas
SARA AOD retrieval at 2 m resolution for Shadow areas of Hong Kong using World View II
Conclusions
Conclusions

- The correlation coefficient of the SARA method is higher \((R = 0.97)\) than the previously developed MODIS aerosol retrieval algorithms based on a LUT at
  - 10 km \((R = 0.88, \text{Levy et al., 2007b})\),
  - 1 km \((R = 0.91, \text{Li et al., 2005})\) and
  - 500 m spatial resolutions \((R = 0.88, \text{Wong et al., 2011}; R = 0.83, \text{Wang et al., 2012})\).

- The SARA retrieved AOD is able to represent the true picture of aerosol loadings over the complex and hilly terrain of Hong Kong as well as Beijing.
Conclusions

- The SARA AOD because of its higher spatial resolution can identify detailed pollution sources, whereas the C5/C6 DT and DB retrievals at 3 km and 10 km resolutions are unable to depict pollution sources including fine particulates and dust storms.

- The implementation of this new methodology requires at least two ground-based Sun photometers, one for the development of the SARA method and the second for its validation, and this is the LIMITATION of this methodology.
Thank You!

Questions?