Retrieval of Atmospheric Aerosol Properties for geostationary and JAXA polar-orbital Satellite Imaging Sensors

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Motivation

Our final goal
• produce synergistic global aerosol data set
  – using JAXA Polar-orbiting and geostationary satellites
  – Provided in near real time

This study
• A common aerosol retrieval algorithm is developed
  – for various satellite imaging sensors
  – over both land and ocean

Current and Upcoming Aerosol Monitoring Satellite

Target sensors

Geostationary: Himawari-8/AHI, GOES-R, Meteosat
Polar-orbiting: Aqua, Terra/MODIS, GCOM-C/SGLI, GOSAT2/CAI2, EarthCARE/MSI
## Sensor Characteristics

### Himwari-8/AHI characteristics

<table>
<thead>
<tr>
<th>CH</th>
<th>λ (nm)</th>
<th>IFOV (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>471</td>
<td>1000</td>
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<tr>
<td>2</td>
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</table>

16 bands in Visible-Infrared

10 minutes interval

### GCOM-C/SGLI characteristics

<table>
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<th>λ (nm)</th>
<th>IFOV (m)</th>
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<td>VN2</td>
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<td>VN4</td>
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<td>VN5</td>
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<td>VN6</td>
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<td>VN7</td>
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<td>VN9</td>
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<td>VN10</td>
<td>868.5</td>
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<td>VN11</td>
<td>868.5</td>
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</tr>
<tr>
<td>POL1</td>
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<td>POL2</td>
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<td>SW4</td>
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<tr>
<td>TIR2</td>
<td>12000</td>
<td>250</td>
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</table>

19 bands in Visible-Infrared

High spatial resolutions

High temporal resolutions
L2 Algorithm (aerosol retrieval)

- Based on the method developed by Higurashi and Nakajima (1998) and Fukuda et al. (2013)
- 3 ideas for common retrieval

- Aerosol models
  - Automatically select the optimum channels by considering uncertainty in TOA reflectance resulted from the surface reflectance uncertainty
  - Apply to various sensors without recalculation
  - Set common candidate models over land and ocean

- Observed TOA reflectance $\rho_{i}^{\text{obs}}$
  - Simulated TOA reflectance $\rho_{i}^{\text{sim}}$
  - Sensor response function
  - LUTs for sensor

- LUTs for every 1nm (300 ~ 2500nm)
- Gas abs. correction
- Cloud mask

- Satellite sensor (AHI, MSI, SGLI, CAI)

- $AOT$, fine ratio, refractive index (img)
- Ångström exponent $\alpha$
- Single-scattering albedo $\omega$

Yoshida et al., 2018
Aerosol model

external mixture (mixing ratio $\eta$)

- Coarse particle
  - absorption
  - spherical: exterior mixture
  - non-absorption
  - marine

- Fine particle
  - absorption
  - spherical: soot
  - Non-spherical: sulfate
  - Non-spherical: refractive index ($m_i$)

*each aerosol model is based on Omar et al., 2005 and Sayer et al., 2012.

Estimated parameter

- Aerosol optical thickness
- Fine ratio ($\eta$)
- Single scattering albedo
  - coarse: external volume mixing ratio ($\eta_{dust}$)
  - fine: imaginary part of the refractive index ($m_i$)
Quality control (cloud screening) of AOT using difference in spatiotemporal variability between aerosol and cloud. Minimize the missing data by using past and surrounding data. 

Kikuchi et al., 2018
Retrieval Results (Himawar-8/AHI)

16 JST 27 Apr. 2018 : continental air pollutant transported to Kyusyu

- The high and nearly continuous AOT over land and ocean are estimated
- High AOT caused by local noise or insufficient cloud screening was eliminated and interpolated smoothly in L3
Retrieval Results (Himawar-8/AHI)

• The high and nearly continuous AOT over land and ocean are estimated

• High AOT caused by local noise or insufficient cloud screening was eliminated and interpolated smoothly in L3

• Aerosol transport are captured using frequent observation from AHI

2018-04-27 08:00 JST

Jeju Island (altitude: 1950m) (blocks the aerosol)
29 Jan. 2019 Thailand (school closed due to air pollution at Bangkok)

- The high AOT and AE (i.e. fine particles) are estimated corresponding to local air pollution report
- Estimated AOT and AE are consistent with SGLI polarization observation
Validation (AHI vs AERONET)

Frequency distributions: 1 year, all AERONET site

- L2 Ver.020 2017/5 – 2018/4
- AOT: H8/AHI L2 vs AERONET

AHI L2 AOT vs AERONET AOT

- BIAS = 0.011
- RMSE = 0.368
- r = 0.665
- Y = 0.057 + X * 0.883
- NUM = 212384

Time variation

Baeksa in Korea

- AERONET
- AHI (L2, L3)

L2: snapshot retrievals every 10 min
L3: cloud screening data using 1 hour data

• AHI AOT successfully represent the time variation of AERONET

• AHI AOT is generally consistent with AERONET
Validation (SGLI) : preliminary

AOT over Ocean (Monthly) vs. MODIS (DT method)

AOT over Land (Monthly) vs. MODIS (DT method)

AOT over Land (instantaneous)
SGLI 0.1 deg. Grid average vs. In-situ (SKYNET, AERONET)

RMSE

<table>
<thead>
<tr>
<th>Estimated errors</th>
<th>Release threshold</th>
<th>Standard accuracy</th>
<th>Target accuracy</th>
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</thead>
<tbody>
<tr>
<td>0.09 (ocean-other sat., monthly ave.)</td>
<td>0.10 (monthly ave.)</td>
<td>0.10 (scene)</td>
<td>0.05 (scene)</td>
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<tr>
<td>0.15 (land-other sat., monthly ave.)</td>
<td>0.15 (monthly ave.)</td>
<td>0.15 (scene)</td>
<td>0.10 (scene)</td>
</tr>
</tbody>
</table>

Release threshold is achieved
Data distribution

- Himawari-8/AHI: JAXA Himawari Monitor
- GCOM-C/SGLI: G-Portal

User Registration →

2016/04/25


Yellow dust

https://gportal.jaxa.jp/

- distribute original (Level 1) and geophysical (Level 2) products
- Data can be achieved with simple user registration
JMA-JAXA Collaboration Framework

- JAXA provided JMA the Himawari aerosol algorithm (L2, L3)
- JMA implemented the algorithm to its operational system and started its experimental operation since December 2018
Next step: Utilization of aerosol transport model

A priori

Satellite observation → retrieval

Aerosol parameters

Data assimilation → Analysis → Forecast

Observed RGB

AOT (satellite)

Yoshida et al., 2018

Yumimoto et al., 2018

Retrieval @JAXA

Data assimilation and forecast @MRI

aerosol data assimilation system collaborated with MRI and Kyusyu-Univ.
Preliminary Results

Retrieval (current)  New Results  A priori (model forecast)

AOT

Fine ratio

Absorption ratio

02UTC, 19 May 2016: Aerosol originated from wildfires

- Absorption ratio seems to be improved
- Less noisy AOT and fine ratio
- AOT seems to well capture observed aerosol front
- Should be validated in future
Summary

• We developed a **common algorithm** to retrieve aerosol properties for various satellite sensors over land and ocean.
  – common aerosol models
  – common lookup tables
  – automatic selection of the optimum channels

• This method was applied to the **Advanced Himawari Imager (AHI) /Himawari-8** and **SGLI/GCOM-C**.

• The retrieved AOT are generally **consistent with MODIS and AERONET** product.

• The retrieved product is distributed at **JAXA Himawari Monitor and G-portal**.

• **The utilization of aerosol properties forecasted by a global aerosol transport model** as a priori seems to improve the retrieval, but should be validated in future.
Thank you
BackUp
• we derived the aerosol parameters \( (\tau, \eta_f, \text{ and } m_i) \) using an optimal estimation method (Rodgers 2000).

• The state vector of a set of aerosol parameters \( \mathbf{x} = \{\tau, \eta_f, m_i\} \) was derived by minimizing the object function \( J \) (Eq. 6). It uses the measurement vector of a gas-corrected observed reflectance set \( \mathbf{R} = \{\rho_i^{\text{obs}}, i = 1, \ldots, N \} \) and simulated TOA reflectance \( \mathbf{F}(\mathbf{x}) = \{\rho_i^{\text{sim}}, i = 1, \ldots, N\} \), where \( N \) is the channel number.

\[
J = [\mathbf{R} - \mathbf{F}(\mathbf{x})]^T \mathbf{S}_e^{-1} [\mathbf{R} - \mathbf{F}(\mathbf{x})] + [\mathbf{x} - \mathbf{x}_a]^T \mathbf{S}_a^{-1} [\mathbf{x} - \mathbf{x}_a]
\]

Eq. 6,

\[
\mathbf{x}_a = \{\tau_a, \eta_{f_a}, m_{i_a}\} : \text{the vector of a prior estimate of } \mathbf{x}
\]

\( \mathbf{S}_e \) and \( \mathbf{S}_a \): the covariance matrices of \( \mathbf{R} \) and \( \mathbf{x}_a \)

\[
\mathbf{S}_e = \begin{bmatrix}
\sigma_1^2 & 0 \\
\vdots & \ddots \\
0 & \sigma_N^2
\end{bmatrix}
\]

Eq. 7

• the uncertainty in TOA reflectance \( \sigma_i^2 = \sigma_s^2 + \sigma_n^2 \),

\( \sigma_s \) : the uncertainty in the TOA reflectance that results from \( \Delta \rho_i^s \).

\( \sigma_n \) : sensor noise (calculated from the signal-to-noise ratio)

• We assume \( \Delta \rho_i^s \) to be some percentage of the surface reflectance \( \rho_i^s \) at each channel. The percentage is calculated at each pixel from the standard deviation of surface reflectance for 1 month at a channel whose \( \rho_i^{\text{sim}} \) is most sensitive to \( \rho_i^s \) (i.e., \( \rho_i^{\text{sim}} / \rho_i^s \) is the largest), when \( \rho_i^s \) at 470 nm is lower than \( \rho_i^s \) at 640 nm (i.e., the reflectance should be minimally influenced by heavy aerosol loading).

• the uncertainties of the three aerosol parameters \( (\tau, \eta_f, \text{ and } m_i) \) \( \mathbf{S}_{\hat{x}} \) were calculated using the law of error propagation, as follows:

\[
\mathbf{S}_{\hat{x}} = (\mathbf{A}^T \mathbf{S}_e^{-1} \mathbf{A})^{-1}
\]

Eq. 10

\( \mathbf{A} \): the Jacobian matrix
Surface reflectance

- adopt the **second lowest reflectance** \( (\rho^S_i) \) at 470 nm within one month
- In the case of \( \rho^S_i@470nm > \rho^S_i@640nm \)
  - influenced by residual aerosol contamination
  - **adopt the modified Kaufman method** (Fukuda et al. 2013)

\[
\rho^S_i = \sum_{k=0}^{4} a_k \text{NDVI}^k,
\]

\[
\text{NDVI} = \frac{R_{\text{band}4} - R_{\text{band}3}}{R_{\text{band}4} + R_{\text{band}3}}
\]

- The **standard deviation of surface reflectance in one month** is used for the reference of the \( \rho^S_i \) **estimation error** for the AOT retrieval

**Probability density distribution**
- all AHI area
- 1 year data in 2016
- \( \rho^S_i@470nm < \rho^S_i@640nm \)
  (less influenced by heavy aerosol loading)

Fitting by mode values

\text{band3(0.64\mu m )}
L3 algorithm

Described aerosol temporal/spatial variance in RMSD from the target

$$\sigma_{\Delta L, \Delta t} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \{AOT(x', y', t') - AOT(x_0, y_0, t_0)\}^2}$$

AOT where $\Delta L, \Delta t$ away from the target  AOT at the target

Derived 2 types of AOT

1. AOTmerge

   Estimated the target AOT by the optimum interpolation using the surrounding and the past one hour data, including the target AOT

   **AOTmerge is an AOT dataset with minimum missing retrieval**

   $$AOT_{merge}(x_0, y_0, t_0) = \sum_{i=0}^{n} w_i AOT(x_i, y_i, t_i)$$

   $w_i = \frac{1}{\sigma_{merge}(x_i, y_i, t_i)^2}$

   surrounding and past AOT
   weighted according to AOT difference induced from the distance and time difference

2. AOTPure

   Estimated the target AOT by the optimum interpolation using the surrounding and the past one hour data, excluding the target AOT

   \(\rightarrow\) selected to be AOTPure if it was within the 99% of confidence interval*1

   *1 defined to be within 2.58σ assuming the error was in normal distribution

   **AOTPure is a highly accurate AOT dataset with minimum cloud contamination**

   $$AOTPure(x_0, y_0, t_0) = \begin{cases} AOT(x_0, y_0, t_0) & \text{if } AOT_{est}(x_0, y_0, t_0) - 2.58\sigma_{pure}(x_0, y_0, t_0) \leq AOT(x_0, y_0, t_0) \leq AOT_{est}(x_0, y_0, t_0) + 2.58\sigma_{pure}(x_0, y_0, t_0) \\ N/A & \text{else} \end{cases}$$

   observed AOT

June 2016

Ocean

Sea: 2016/06: AOT Confidence = very good or good

AOT: AHI (L2 Ver.010c5) vs MODIS (Aqua/Terra)

- BIAS = 0.035
- RMSD = 0.057
- $R = 0.891$
- $Y = X \times 1.017 + 0.033$
- NUM = 957661

Land

Land: 2016/06: AOT Confidence = very good or good

AOT: AHI (L2 Ver.010c5) vs MODIS (Aqua/Terra)

- BIAS = -0.002
- RMSD = 0.132
- $R = 0.893$
- $Y = X \times 0.837 + 0.038$
- NUM = 112259
02 UTC, 19 May 2016
Aerosol originated from wildfires at a proximity to Lake Baikal in Russia

- The high AOT and AE (fine particles) are estimated over land and ocean, corresponding to aerosol transport from the continent
- nearly continuous AOT over land and ocean
図4 2018年4月27日の済州島におけるライダの観測結果。横軸は時刻（日本時刻）、縦軸が高度（メートル）。赤い色ほど濃い大気浮遊物質が観測されている*4。