

Algorithm Theoretical Basis Document:  
**Aerosol Retrieval by Polarization with GCOM-C/SGLI**

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2018

## Preface

GCOM-C/SGLI has multiple channels (19), including the near-UV (0.380  $\mu\text{m}$ ) and violet (0.412  $\mu\text{m}$ ) wavelengths, and polarization channels in the red (0.670  $\mu\text{m}$ ) and near-IR (0.865  $\mu\text{m}$ ) wavelengths. This feature of SGLI is useful for the remote sensing of aerosols. It has been demonstrated, from measurements by the Polarization and Directionality of the Earth's Reflectances (POLDER)-1, -2 and -3, that polarization information is very effective for aerosol retrieval (Mukai and Sano, 2000; Deuzé et al., 2001), and also, from the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus-7 satellite, that UV wavelengths are effective for aerosol remote sensing, especially for the sensing of absorbing aerosols (Torres et al., 1998). The present system utilizes not only polarization information, but also near-UV data, in order to reproduce aerosol properties from SGLI measurements.

## Method

### 1. Overview

Figure 1 presents the block flow of the proposed aerosol retrieval method from SGLI data.

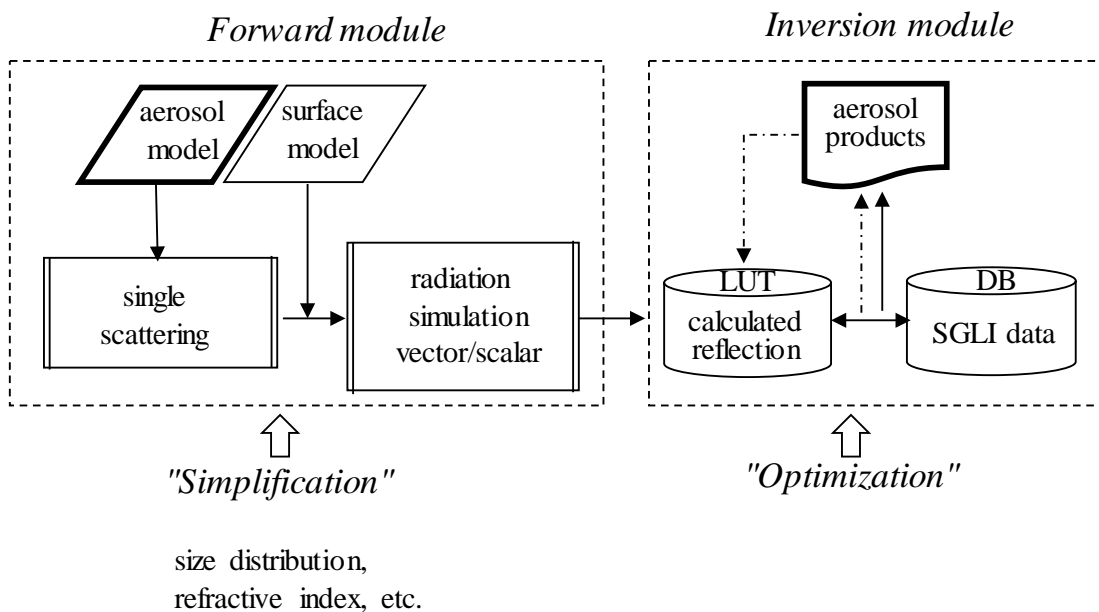


Fig. 1 Basic framework for aerosol retrieval.

The system is roughly divided into two modules: the forward module and the inversion module. The former completes numerical simulations for the Earth atmosphere-surface system, and the latter contains the optimization process for the calculated values and satellite observed data.

Advanced aerosol models, such as Fig. 1, play an important role in the efficiency of aerosol retrieval because radiation simulations require long computing times in the various aerosol models at each pixel of the satellite data.

## 2. Aerosol model

The characteristics of aerosols can be represented using several parameters. The most basic parameter is the spectral aerosol optical thickness,  $AOT(\lambda)$ , at wavelength  $\lambda$ . The Ångström exponent (AE) is derived from the spectral  $AOT(\lambda)$  and is closely related to the aerosol size. Several other aerosol parameters, such as the size distribution and refractive index, are also derived from the  $AOT(\lambda)$  and radiance.

First, the size of the aerosols is discussed. The size distributions, derived from the accumulated NASA/AERONET data, had two modes (fine and coarse) in a bimodal log-normal distribution of particle volume, with six parameters (volume concentration, mode radius, and the standard deviation of the fine and coarse mode particles). Too many parameters are excessive for the retrieval of the optimized size of aerosols at a global scale. Therefore, a simplification was made for the aerosol size distribution function (Mukai et al., 2015). As a result, the size distribution function of particle volume ( $V$ ) for continental aerosols can be approximately expressed in a simpler form, defined by a unique variable of the fine particle fraction ( $f$ ) of the volume concentration:

$$\frac{dV}{d \ln r} \sim \frac{f}{\sqrt{2\pi} \ln 1.533} \exp\left[-\frac{(\ln r - \ln 0.144)^2}{2 \ln^2 1.533}\right] + \frac{(1-f)}{\sqrt{2\pi} \ln 2.104} \exp\left[-\frac{(\ln r - \ln 3.607)^2}{2 \ln^2 2.104}\right]. \quad (1)$$

The next aerosol characteristic of interest is the refractive index. It is reasonable to consider that a mixture of various aerosol types exists in nature. Although particle mixing is an issue to be considered, as well as understood, a simple homogeneous internal two-component mixing model was adopted here, using the Maxwell Garnett mixing (MGM) rule (Bohren and Wickramasinghe, 1977). The MGM rule provides a complex refractive index, calculated as follows:

$$\varepsilon = \varepsilon_m \frac{(\varepsilon_j + 2\varepsilon_m) + 2g(\varepsilon_j - \varepsilon_m)}{(\varepsilon_j + 2\varepsilon_m) - g(\varepsilon_j - \varepsilon_m)}, \quad (2)$$

where  $\varepsilon$  denotes the dielectric constant; the subscripts  $m$  and  $j$  represent the matrix and inclusion, respectively;  $g$  is the volume fraction of the inclusions. The present aerosol retrieval is made using visible and near-IR band data because the refractive index can be assumed to be independent of the wavelength in these spectral regions. It was determined that the matrix and inclusions were  $1.410-0.004i$  and  $1.520-0.035i$ , respectively, for applications using the visible and near-IR bands data. This indicated that the matrix and inclusions are weakly and strongly absorbing particles, respectively. Moreover, spectral absorption was considered (i.e., the imaginary part of the refractive index) at near-UV wavelengths. In short, aerosol models are more simply represented by two parameters ( $f$ ,  $g$ ) (Mukai et al., 2016); the size of the aerosols is represented by an approximate bimodal log-normal distribution defined by the fine particle fraction ( $f$ ), as given by Eq. (1), and the refractive index is induced from the internal mixing of aerosol types with the volume fraction of the inclusions ( $g$ ) by Eq. (2).

### 3. Surface model

The polarized reflectance by the Earth surface was interpreted by POLDER's empirical model (Nadal and Bréon, 1999). In practice, according to a simple equation proposed by Deuze et al. (2001), the surface polarization signal was combined with the upward radiance at TOA (top of atmosphere) simulated in the complex system of atmosphere and black & Lambert (no polarization) bottom surface.

### 4. Radiation simulation

Radiation simulation denotes multiple light scattering calculations in the Earth atmosphere model, which are hereinafter referred to as radiative transfer. Radiative transfer takes Rayleigh scattering by molecules and Mie scattering by aerosols in the atmosphere, as well as reflection by the Earth's surface, into account. The space-borne sensors measure upwelling radiance at the top of atmosphere, and it is known that incident solar light multiply interacts with atmospheric particles.

Function  $\mathbf{I}(\tau, \Omega)$  is defined to be the specific intensity vector at the optical depth  $\tau$  in the direction of  $\Omega$ , given by  $\Omega = (\mu, \varphi)$  and  $d\Omega = d\mu d\varphi$ , where  $\mu$  is the cosine of the zenith angle  $\theta$  between the outward normal of the plane parallel medium and the direction of the

light (i.e.  $\mu = \cos \theta$ ), and  $\varphi$  is the azimuth angle of the light measured from a fixed direction. Also,  $\tilde{P}(\Omega, \Omega')$  is the matrix of  $\mu, \mu', \varphi,$  and  $\varphi'$ ; similarly defined quantities on incident and scattered ray (denoted by ' after the variable). Hereafter,  $(\mu, \varphi)$  is abbreviated to  $\Omega$ . The standard problem in the functions for a given medium with constant or vertically-resolved single scattering albedo  $\varpi$ . The basic physical concept is simple. The intensity  $\mathbf{I}(\tau, \Omega)$  is reduced by  $e^{-d\tau}$  after traversing over an optical thickness  $d\tau$  at wavelength  $\lambda$ . The equation of radiative transfer describes this circumstance (Chandrasekhar 1960):

$$\mu \frac{d\mathbf{I}(\tau, \Omega)}{d\tau} = \mathbf{I}(\tau, \Omega) - \frac{\varpi}{4\pi} \int \tilde{P}(\Omega, \Omega') \cdot \mathbf{I}(\tau, \Omega') d\Omega', \quad (3)$$

where  $\varpi$  and  $\tilde{P}$  represent the albedo and phase matrix for single scattering, respectively. The integration is carried out over all solid angle. The vector  $\mathbf{I}$  is defined to be the four-dimensional representation of the polarized radiation field,

$$\mathbf{I} = (I_l, I_r, U, V) \text{ or } (I, Q, U, V), \quad (4)$$

These four quantities represent the Stokes parameters, and the  $4 \times 4$  matrix  $\tilde{P}$  represents the phase relation in light scattering. The boundary conditions for the standard problem are (i) at the top of the medium,  $\tau = 0$ , there is no radiation falling, except in direction  $-\mu_0$ . (ii) at the bottom of the medium,  $\tau = \tau_0$ , for a finite medium, radiation reflects according to the surface reflection law, as mentioned in the previous section.

A more direct approach to solving the problem is by formulating a set of functional equations for the reflection and transmission functions. The principle of invariance, stated originally by Ambartsumian (1958) and examined extensively by Chandrasekhar (1960), is an elegant way to approach the problem. Suppose there is an incident radiation of flux  $\mathbf{F}$  in direction  $(\mu_0, \varphi_0)$  falling on the top of the atmosphere, and the flux is supposed to be polarized as

$$\mathbf{F} = (F_l, F_r, F_U, F_V). \quad (5)$$

Let the diffusely reflected radiation intensity vector be  $\mathbf{I}(\Omega)$ . The diffusely reflected intensity denotes the emergent intensity from TOA ( $\tau = 0$ ) and is derived using the reflection matrix  $\tilde{R}$  so that

$$\mathbf{I}(\Omega) = \frac{1}{4\pi} \int_{-} \tilde{R}(\Omega, \Omega') \cdot \mathbf{F}(\Omega') \mu' d\Omega' \quad (6)$$

where the integration covers the inward hemisphere and the reflection matrix is expressed by the Stokes parameters:

$$\tilde{R} = \begin{pmatrix} R_{II} & R_{Ir} & R_{IU} & R_{IV} \\ R_{rI} & R_{rr} & R_{rU} & R_{rV} \\ R_{UI} & R_{Ur} & R_{UU} & R_{UV} \\ R_{VI} & R_{Vr} & R_{VU} & R_{VV} \end{pmatrix}. \quad (7)$$

In a similar way, the diffusely transmitted intensity at the bottom of atmosphere ( $\tau = \tau_0$ ) is defined by the transmission matrix  $\tilde{T}$ . As usual, the solar incident flux is assumed to be non-polarized, namely  $\mathbf{F} = (0.5, 0.5, 0, 0)$ , and hence computational efforts are rather reduced. The calculation algorithm was the same as previous studies (Mukai et al. 1996, Sano, 2004).

### Output and Outlook

This work proposed algorithms for aerosol retrieval from SGLI. The output of SGLI is AOT, AE and SSA (single scattering albedo) in terms of polarization data at 0.670  $\mu\text{m}$  and 0.865  $\mu\text{m}$ , and radiance at 0.38  $\mu\text{m}$ . The SGLI has multiple channels (19) including not only polarization channels in the red and near-IR wavelengths, but also in near-UV (0.380  $\mu\text{m}$ ) channel. The near-UV data should be utilized more, for example in the detection of absorbing aerosols. The combined use of multi-band data and polarization information is expected to facilitate subsequent aerosol/cloud characterization.

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