Sensitivity of Scattering and Absorbing Aerosol to Top of Atmosphere Polarization Pattern

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Abstract. In this letter we simulated the top of atmosphere (TOA) polarization patterns with scattering and absorbing aerosol situations through a successive orders of scattering (SOS) radiative transfer model. In the analysis of single scattering properties of aerosol particles, absorbing aerosol has an obvious different pattern from those non-absorbing aerosols. The TOA Degree of Linear Polarization (DoLP) decreases significantly when scattering aerosol optic depth (AOD) increases. While for absorbing aerosol case, the TOA DoLP keep stable or even increases when aerosol absorbing AOD increases, which suggest a way to retrieve absorbing property of aerosol.

1. Introduction
In the past decades, great progress has been made in the understanding of aerosol properties and its climate effects with satellite remote sensing [1, 2]. To get more accurate aerosol climatology, several algorithms have been developed with the help of satellite-based remote sensing data[3]. Despite these efforts, it is increasingly urgent that additional information is needed for aerosol retrieval considering the limits of common intensity only methods[4-6]. Polarization could provide additional information about the scattering of aerosol and is considered to be a relatively new and effective way to retrieve physical properties of aerosol [7, 8]. Retrieving aerosol properties with polarization information utilizes the TOA polarization reflection made by the earth-atmosphere system[9, 10] which is strongly affected not only by surface property but also aerosol physical properties[11, 12].

To effectively utilize polarimetric reflective signals, a lot of polarized remote sensing sensors have been developed, such as Polarization and Directionality of the Earth’s Reflectances (POLDER) [13, 14], Directional Polarimetric Camera (DPC) [15], Research Scanning Polarimeter (RSP) [16], Ground-based Multi-angle Spectral Polarimetric Imager (Ground MSPI) [17]. However, compared with massive remote sensing sensors utilizing light intensity[18-21], the number of polarimetric remote sensing sensors is still few.

With these polarimetric remote sensing sensors, a lot of remote sensing applications have been done[22, 23], such as aerosol retrieval. And simultaneous retrievals of aerosol optical depth and microphysical properties are limited[24-26]. In this study, we simulated the TOA DoLP distribution pattern of different scattering and absorbing AODs at 860 nm with SOS radiative transfer model.
Second Simulation of the Satellite Signal in the Solar Spectrum (6S)[27-29]. The results reveals that as the AOD of scattering aerosol increases, the TOA DoLP has a decreasing trend, which is contrary to the absorbing aerosol situation. The sensitivity results suggest that TOA DoLP distribution pattern is strongly sensitive to the content of absorbing aerosol and could be used to retrieve absorbing aerosol properties.

2. Single Scattering Properties of Absorbing Aerosol

The signals remote sensing sensors receive at top of atmosphere is light scattered by both the earth surface and atmosphere. Light scattered by atmosphere is affected by both atmosphere molecules and aerosols through multi-scattering. However, for multi-scattering calculation, it is impossible to get an analytical solution considering the complexity of atmosphere processes. Therefore, a series of radiative transfer models are developed to better approach TOA reflection through numerical methods such as 6S[15], RT3[16], MODTRAN[17]. Multi-scattering is composed of numerous single scattering processes which describe aerosol and molecule particles’ effect on incident light. To get rational multi-scattering calculation results, it is essential to model the single scattering effects of both aerosols and molecules.

For molecules, the scattering could be calculated through Rayleigh theory with high accuracy at non-absorbing bands. While for aerosols, Rayleigh theory is not proper to describe the scattering of aerosols considering the size distributions and shape of aerosols. For spherical aerosol particles, MIE theory is used to simulate the scattering. If the aerosol particles are considered to be non-spherical, other even more complicated methods are needed such as T- Matrix[18], which is time consuming. There are two major parts of single scattering property of aerosol particles, the first one is scattering phase matrix which describes how aerosols change the propagation of incident light; the other one is single scattering albedo describing the absorbing property of aerosol.

To describe the effects of aerosol on light propagation, we adopt the Stokes Parameters as:

\[
\begin{bmatrix}
I_s & Q_s & U_s & V_s
\end{bmatrix}
= \begin{bmatrix}
P_{11}(\Theta) & P_{12}(\Theta) & 0 & 0 \\
P_{12}(\Theta) & P_{22}(\Theta) & 0 & 0 \\
0 & 0 & P_{33}(\Theta) & P_{34}(\Theta) \\
0 & 0 & P_{-34}(\Theta) & P_{44}(\Theta)
\end{bmatrix}
\begin{bmatrix}
I_0 \\
Q_0 \\
U_0 \\
V_0
\end{bmatrix}
\]

where \(\Theta\) is the scattering angle, \(I, Q, U\) and \(V\) are the components of the Stokes vector represents the polarization state of a light beam (Subscript \(s\) means scattering light and \(0\) means incident light). The \(4 \times 4\) matrix in the Eq. (1) is the scattering phase matrix and \(P_{11}(\Theta)\) is the intensity phase function and the rest are polarization phase function. For non-spherical, randomly oriented particles, for example spheroidal, the six independent elements in the phase matrix should be modeled through T-Matrix or geometry optic method. In this case, we assumed that the aerosol particles are spherical. In this situation, \(P_{11} = P_{22}, P_{33} = P_{44}\). As the \(V\) component describes the circular polarization information that could be neglected in atmosphere remote sensing, the phase matrix could be simplified to be a \(3 \times 3\) matrix containing 3 independent parameters which reduces the number of independent elements in the phase matrix.

For absorbing medium, the electromagnetic wave could be described as:

\[
\vec{E}(x, t) = A_0 e^{i\frac{\omega}{c} \bar{n} x - \omega t}
\]

where \(\bar{E}(x, t)\) is the electromagnetic wave after transfer distance of \(x\) at time \(t\). \(A_0\) is amplitude of original wave, \(\omega\) is circular frequency of the wave, \(c\) is speed of light. \(\bar{n}\) is the complex refractive index of the medium. \(\bar{n}\) could be rewritten as:

\[
\bar{n} = n + \frac{ca}{2\omega} i
\]

where \(\alpha\) is the absorbing coefficient of the medium, suggesting the aerosol’s absorbing properties is directly proportional to the imagine part of the complex refractive index of the aerosol.

In this study, we assumes the size distribution of aerosol particles is log-normal distribution with a median radius of 0.4µm, a standard deviation of 0.6. Five levels (0: non-absorbing; 0.001: nearly non-
absorbing; 0.01: little absorbing; 0.1: medium absorbing; 0.5: strong absorbing) of imagine part of complex refractive index are selected to model the phase matrix of aerosol particles through MIE code calculations shown as Figure.1. The results shown that, polarization phase function is more sensitive to the absorbing aerosols, especially for those strong absorbing aerosols.

![Figure 1. Single Scattering Properties of Aerosol particles with Different Absorbing Properties](image)

### 3. TOA DoLP Patterns of Scattering and Absorbing Aerosol Atmospheres

Instead of working with intensity units directly, measurements of TOA signal are usually describes as reflectance format, where the TOA reflectance could be written as:

\[
R_I = \frac{\pi I}{\mu_0 F_0} \quad (4)
\]

\[
R_Q = \frac{\pi Q}{\mu_0 F_0} \quad (5)
\]

\[
R_U = \frac{\pi U}{\mu_0 F_0} \quad (6)
\]

where \( R_I, R_Q \) and \( R_U \) are reflectance, \( Q \) reflectance and \( U \) reflectance respectively. \( \mu_0 \) is the cosine of the solar zenith angle, \( F_0 \) is the radiation flux at TOA. \( I, Q \) and \( U \) are the intensity, \( Q \) intensity and \( U \) intensity reflected. The DoLP at the TOA level, it could be given by:

\[
DoLP = \frac{R_Q^2 + R_U^2}{R_I} \quad (7)
\]

6SV is the vector version of 6S radiative model and capable of accounting for radiation polarization. TOA DoLP pattern describes the distribution of polarization signal the sensor receives and is essential to the aerosol properties retrieval. TOA DoLP is not only decided by AOD but also the scattering properties of aerosol. In this sensitivity research, an absorbing aerosol model “soot” and a scattering aerosol model “water-soluble” are adopted here to analyze the dependence of TOA DoLP pattern on the absorbing aerosol properties. The two aerosol models adopted here both have a lognormal distribution with the size distribution parameters shown as Table. 1. Taking 860 nm band as an example, 6 different AOD level (0, 0.01, 0.05, 0.1, 0.5 and 1.0). The surface is assumed to be an open ocean and the water-leaving radiance of the ocean water could be neglected. The polarization of the ocean surface is described by rough ocean surface suggested by [19]. The TOA DoLP patterns of scattering and absorbing aerosol atmosphere is shown as Figure.2 and Figure.3.

| rg  | \( \sigma \) | \( n_r \) | \( n_l \) |
|-----|-------------|---------|---------|
| Soot | 0.0118 | 2.0 | 1.69 | 0.440 |
| water-soluble | 0.005 | 2.99 | 1.53 | 0.008 |

Surface reflection is another factor that influences the accuracy of simulations. In this study, we assumed the ocean underlying surface which could be described as three independent components:

\[
\rho_{os} = \rho_{wc} + (1 - W) \rho_{gl} + (1 - \rho_{wc}) \times \rho_{sw} \quad (8)
\]
Where $\rho_{os}$ is the reflectance of ocean surface, $\rho_{wc}$ is the reflectance due to whitecaps of ocean, $\rho_{gl}$ is the specular reflectance of ocean surface, $\rho_{sw}$ is the volume scattering of ocean body. $W$ is the relatively area covered with whitecaps and could be determined by wind speed and wind directions.

Figure 2 show the sky DoLP in principle plane (Figure 2a) and perpendicular principle plane (Figure 2b) under different scattering AOD situations. The principle plane contains solar incident direction and specular direction. The negative zenith angles suggest observing near sun position, while positive zenith angles denote near specular direction. It could be found that when viewing angles get near to sun positions, DoLP is the lowest (near 10%). While observing near specular directions, DoLP could get as high as 80%. When scattering AOD increase, DoLP near sun directions varies little. While at the specular directions, when scattering AOD increase, DoLP decrease greatly. When scattering AOD increases to 1.0, sky DoLP is very low, suggesting the scattering AOD will decrease sky polarization pattern.

Figure 3 show the sky DoLP in principle plane (Figure 3a) and perpendicular principle plane (Figure 3b) under different absorbing AOD situations. Similar to scattering aerosol conditions, when observing directions get near to sun positions, DoLP is the lowest. When observing at specular directions, the DoLP is the largest. However, when absorbing AOD increases, TOA DoLP does not decrease. Instead, when absorbing aerosol increase, the specular directions and other large zenith angle directions have little increase of DoLP(90%). In the perpendicular principle directions, the differences between different ADO situations are not as large as scattering AOD. Therefore, different from scattering AOD, the increase of absorbing AOD will increase the polarized signals obtained by sensors.

Figure 2. TOA DoLP Pattern of Scattering Aerosol Atmosphere with Different AODs.

Figure 3. TOA DoLP Pattern of Absorbing Aerosol Atmosphere with Different AODs.

4. Conclusions
In conclusion, we analyzed the single scattering properties of aerosol particles with different absorbing properties, finding out that absorbing aerosol particles have extraordinary different polarization scattering features from non-absorbing aerosol particles. Through employing two aerosol model
commonly used in aerosol retrieval, we simulated the TOA DoLP patterns of both scattering and absorbing aerosol atmosphere with different AODs. The results shown that the presence of scattering aerosol will decrease the DoLP at the TOA level and tends to uniform the DoLP of all directions. While the presence of absorbing aerosol will not decrease but even slightly increase the DoLP at the TOA level.

Previous studies mainly pay less attentions in the microphysical properties of aerosols in aerosol retrievals. While our studies suggested that different aerosols have different angular patterns in polarization signals, suggesting that it is easy to distinguish them. This indicates that it is feasible to retrieve the aerosol properties through multi-angular and polarization signals together with intensity signals.

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