The effects of non-sphericity on geostationary satellite retrievals of dust aerosols

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Received 23 September 2003; revised 27 October 2003; accepted 20 November 2003; published 30 December 2003.

[1] Using data collected during the Puerto Rico Dust Experiment (PRIDE), we examine the effect of non-spherical phase functions on dust aerosol retrievals from geostationary satellites. We utilize a statistical model based on Scanning Electron Micrograph (SEM) analysis of individual dust particles. Using T-matrix calculations and assuming that dust particles are randomly-orientated oblate spheroids we compute the dust phase function and scattering properties. Although the non-spherical function developed in this study compares well with the synthetic non-spherical phase functions [*Liu et al.*, 2003], new retrievals using the non-spherical phase function only show slight improvement at scattering angles (Θ) from $110° \sim 150°$, and become worse for Θ between $150° \sim 170°$. However the retrievals are greatly improved at all angles when retrieval algorithms account for the combined effect of *both* spherical and non-spherical phase functions. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 8040 Structural Geology: Remote sensing. **Citation:** Wang, J., X. Liu, S. A. Christopher, J. S. Reid, E. Reid, and H. Maring, The effects of non-sphericity on geostationary satellite retrievals of dust aerosols, *Geophys. Res. Lett.*, *30*(24), 2293, doi:10.1029/2003GL018697, 2003.

1. Introduction

[2] Satellite measurements play an important role in the estimation of aerosol radiative forcing and validation of aerosol transport models [*Kaufman et al.*, 2002]. The accuracy of satellite aerosol retrievals is affected by many factors including the proper characterization of aerosol phase functions [*Mishchenko et al.*, 1997]. Although most aerosol species in the atmosphere appear reasonably spherical (e.g., smoke or sulfate), and their phase functions can be calculated from Lorenz-Mie theory, non-spherical dust particles pose greater challenges. For the same effective diameter, non-spherical and spherical particles have very different phase functions, especially at scattering angles (Θ) from 90° to 180° [*Mishchenko et al.*, 2003]. With the exception of the Multi-angle Spectroradiometer (MISR) aerosol retrieval algorithms where dust particles are assumed to be randomly-oriented spheroids [*Kahn et al.*, 1997], most satellite methods use spherical phase functions, that could result in errors during the retrieval of dust aerosol optical thickness (AOT, τ) [e.g., *Mishchenko et al.*, 2003; *Wang et al.*, 2003].

[3] Several methods have been proposed to obtain the dust non-spherical phase functions, including laboratory measurements, numerical modeling [see *Mishchenko et al.*, 2000 and the references therein], and recent retrieval techniques where the non-spherical phase function is inferred by finding the best match between calculated and measured sky radiances from the Aerosol Robotic Network (AERONET) observations [*Dubovik et al.*, 2002]. Several studies have showed that a general agreement between modeled and measured phase functions might be reached in some but not in all cases even when the complex refractive index, size distribution and the particle shape are properly defined [e.g., *West et al.*, 1997; *Volten et al.*, 2001]. However, the samples collected in these laboratory studies were mainly from the surface of deserts and may not represent real aerosols in the atmosphere thousands of kilometers downwind of source regions. Due to lack of *in situ* measurements, the data necessary for the modeling of aerosol scattering properties are rarely available concurrently in the same spatial and temporal domain and therefore climatological aerosol properties are commonly used to investigate the effect of non-sphericity on dust aerosol retrievals [*Mishchenko et al.*, 2003; *Zhao et al.*, 2003].

[4] During PRIDE, the dust size distribution, extinction and scattering coefficients as well as dust morphology (through SEM analysis) were concurrently obtained [*Reid et al.*, 2003a], thereby providing an opportunity to derive the dust optical properties and to quantitatively examine the effect of non-sphericity on satellite retrievals. Using Mie calculations, dust AOT in PRIDE was retrieved from Geostationary Observational Environmental Satellite (GOES8) imagers [*Wang et al.*, 2003] and the Moderate Resolution Imaging Spectroradiometer (MODIS) [*Levy et al.*, 2003], both of which attributed the effects of non-sphericity as one of the major uncertainties in the satellite retrieval algorithms. When compared to polar-orbiters like MODIS and MISR, one advantage of geostationary satellites is their high temporal resolution, through which observations over a wide range of scattering angles become available even for the same dust layer on the same day. The intent of this study is to use collocated *in situ* data to explore if consideration of non-spherical

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0094-8276/03/2003GL018697$05.00

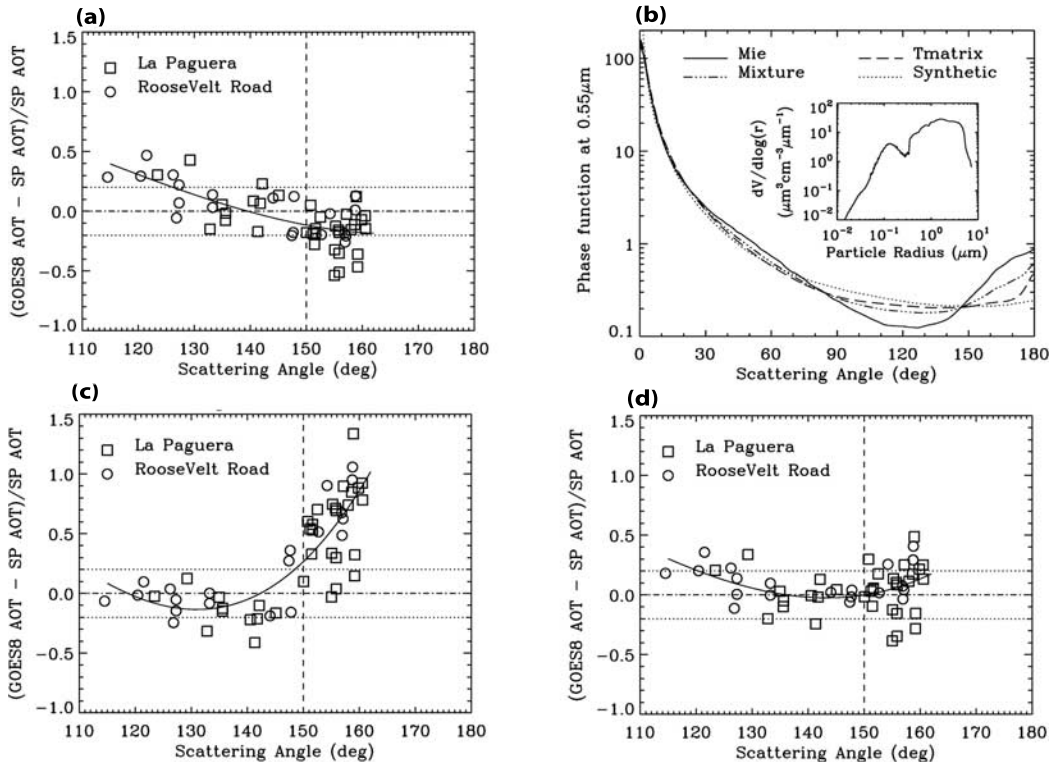

Figure 1. Retrieval errors as a function of scattering angles for using (a) spherical phase functions [*Wang et al.*, 2003], (c) non-spherical phase function, and (d) a composite phase function for the mixture of spherical and non-spherical particles. Figure 1b shows the comparison of these three phase functions. The synthetic phase function by *Liu et al* [2003] is also shown in Figure 1b for reference purposes. The inset in Figure 1b shows the average of measured aerosol volume size distribution in dusty conditions (AOT > 0.2). The dotted lines in (a), (c) and (d) show the possibly maximum relative errors (±20%) from the uncertainties other than phase function. The different symbols in (a), (c) (d) denote two AERONET sites at Roosevelt Road (18.20°N, 65.60°W) and La Paguera (17.97°N, 67.05°W).

effects will improve the satellite retrievals in a data-rich environment.

2. Data and Models

[5] The data used in this study include size distribution data obtained from two aerosol sizers, scattering/absorption volume coefficients inferred from nephelometers, and images of dust morphologies (e.g., shape and size of each particle) through SEM analysis. These datasets have been carefully calibrated and corrected for possible instrument non-idealities [*Reid et al.*, 2003a]. Using measured size distributions, dust optical properties were calculated through Lorenz-Mie theory and were then used in a Discrete Ordinate radiative transfer model for the GOES8 AOT retrievals [*Wang et al.*, 2003]. Although the GOES8 retrieved AOT (τ_{GOES8}) agreed well with sunphotometer AOT (τ_{SP}, linear correlation coefficient R = 0.85), the relative errors, defined as $(\tau_{GOES8} - \tau_{SP})/\tau_{SP}$, showed a clear pattern as a function of Θ for dust aerosol conditions (total of 53 points with $\tau_{SP} > 0.2$ are used and shown in Figure 1a with *mean* τ_{SP} of 0.33) [*Wang et al.*, 2003]. Between 90° ∼ 150°, the τ_{GOES8} is larger than τ_{SP} and between 150° ∼ 180° the τ_{GOES8} is less than the τ_{SP} [*Wang et al.*, 2003]. Such error patterns have also been shown in theoretical studies, and have been attributed to the effect of non-spherical phase functions [*Mishchenko et al.*, 1997].

[6] To evaluate the non-spherical effect on GOES8 retrievals and to maintain consistency, we utilize the same GOES8 datasets, retrieval techniques and comparison procedures as reported in *Wang et al.* [2003], except that the aerosol optical properties are calculated for non-spherical particles by using the T-matrix algorithm [*Mishchenko et al.*, 1997]. We utilized the statistical model derived from SEM data [*Reid et al.*, 2003] to characterize aerosol shape parameters, while maintaining the same aerosol size distribution and refractive indices as reported in *Wang et al.* [2003]. Finally, the synthetic phase function reported by *Liu et al.* [2003] was used as a reference to compare with our SEM-derived non-spherical phase function. This study is unique because it uses both *in situ* and satellite measurements from the same spatio-temporal domain to examine the effects of non-sphericity on dust AOT retrievals.

3. Methodology and Results

[7] The satellite aerosol retrieval process usually consists of at least two steps. The first step is to model the aerosol optical properties and the second step is to use these properties in a radiative transfer model to create LUTs where the top of atmosphere (TOA) reflectance is calculated as a function of Sun-satellite geometries, surface reflectance ρ_{sfc} and AOT (τ). For a cloud-free pixel, the AOT is retrieved by searching the LUT to find the best match

between satellite and calculated reflectance values [*Wang et al.*, 2003].

3.1. Modeling Dust Optical Properties

[8] The statistical model based on the SEM analysis of 60,500 particles is used to characterize aerosol shape (cf. Figure 9a of [*Reid et al.*, 2003]). The statistical model uses a total of 6 size intervals (ranging from about 0.1 μm to more than 10 μm) and 15 aspect ratios (from 1.2 to 10) to describe the size and shape of dust particles. For each size interval, the percentage of particles with different aspect ratios is given. To apply this morphology into T-matrix calculations, we assume that dust particles are oblate spheroids. The size distribution of particles measured from the Aerodynamic Particle Sizer (APS) and the Scanning Mobility Particle Sizer covers the size ranging from 0.01 ∼ 15 μm in diameter (Figure 1b, inset) [*Maring et al.*, 2003], and represents one of the most reliable size distribution datasets in PRIDE [*Reid et al.*, 2003b]. Using T-matrix, the scattering/absorption cross sections ($\sigma^{sca}/\sigma^{abs}$) and phase functions $P(\Theta)$ of the particles for each aspect ratio and each size bin were first calculated, and then integrated over the daily measured size distributions to calculate the daily bulk aerosol properties [*Mishchenko et al.*, 1997].

[9] The derived optical properties (e.g., σ_{sca}, σ_{abs}, single scattering albedo ω, and phase function $P(\Theta)$) from T-matrix calculations on different days are then compared with Mie calculations. The results are consistent with previous studies [e.g., *Mishchenko et al.*, 1997], indicating minor differences (<3%) for σ_{sca}, σ_{abs} and ω between T-Matrix and Mie calculated values but large differences for phase function (Figure 1b) at $90° < \Theta < 150°$ (non-spherical ≫ spherical) and $150° < \Theta < 180°$ (spherical ≫ non-spherical). Also shown in Figure 1b is an independent synthetic phase function derived from both observations [*Volten*, 2001] and model calculations [*Liu et al.*, 2003; *Mishchenko et al.*, 2003]. Due to the limitations of measurement techniques, the phase function cannot be fully measured at the forward and back scattering angles. In Figure 1b, the values of the synthetic phase function between 5° ∼ 173° are laboratory-measured averaged phase function for polydisperse, randomly-oriented mineral dust aerosols [*Volten et al.*, 2001], while values at other scattering angles are inferred from T-matrix calculations by forcing the normalization of measured phase function [*Liu et al.*, 2003]. It is interesting to find that our model-calculated phase function (using SEM data during PRIDE) is in general agreement with the phase functions reported by *Liu et al.* [2003].

3.2. Analysis of Phase Function Effect on the Retrievals

[10] Using calculated non-spherical phase function and optical properties the LUT is reconstructed and then used in the retrieval of dust AOTs. The relative errors of new retrievals as a function of Θ are presented in Figure 1c. Figure 1b indicates that using spherical phase function will result in τ_{GOES8} values systematically overestimating τ_{SP} for $110° < \Theta < 150°$ and underestimating τ_{SP} values for $150° < \Theta < 170°$ that is also consistent with previous studies [e.g., *Mishchenko et al.*, 1997]. To quantify the effect of the phase function on the systematic retrieval errors in these two angle ranges, the *mean* relative errors ($\bar{\varepsilon}$, where $\varepsilon = (\tau_{GOES8} - \tau_{SP})/\tau_{SP}$; absolute errors $\overline{|\varepsilon|}$, where $|\varepsilon| = |\tau_{GOES8} - \tau_{SP}|/\tau_{SP}$; and their ratio $\gamma = \bar{\varepsilon}/\overline{|\varepsilon|}$) in these two scattering ranges are listed in Table 1. Also listed in Table 1 are the $\bar{\varepsilon}$ and $\overline{|\varepsilon|}$ for all angles. The ratio γ provides a simple and efficient way to evaluate the change of systematic errors in different Θ ranges. Usually, the smaller the $|\gamma|$ values, the smaller are the systematic errors. When $\gamma = 0$, the errors are totally random; $\gamma = 1$ implies that the AOTs are systematically overestimated, and $\gamma = -1$ indicates AOTs are systematically underestimated.

Table 1. Mean of Relative Retrieval Errors ($\bar{\varepsilon}$), Absolute Retrieval Errors ($\overline{|\varepsilon|}$), and their Ratio (γ) at Different Scattering Angle Ranges for Different Phase Functions.

	Scattering angles							
	110° ∼ 150°			150° ∼ 165°			All angle	
	$\bar{\varepsilon}$	$\overline{\lvert\varepsilon\rvert}$	γ	$\bar{\varepsilon}$	$\overline{\lvert\varepsilon\rvert}$	γ	$\bar{\varepsilon}$	$\overline{\lvert\varepsilon\rvert}$
Spherical	11%	17%	0.65	−17%	19%	−0.89	−6%	18%
Non-Spherical	−7%	14%	−0.50	62%	63%	0.98	31%	41%
Composite	4%	11%	0.37	6%	17%	0.35	5%	14%

($\bar{\varepsilon}$ and ($\overline{|\varepsilon|}$) are in percentage ratios).

[11] Compared to Figure 1a (for spherical phase function), Figure 1c shows that the consideration of non-spherical effect slightly improves the retrievals for $110° < \Theta < 150°$ (both $\overline{|\varepsilon|}$ and $|\gamma|$ decrease), but make it worse for $150° < \Theta < 170°$ (both $\overline{|\varepsilon|}$ and $|\gamma|$ increase). The distinct negative systematic errors at $150° < \Theta < 170°$ in Figure 1a become more distinct positive systematic errors in Figure 1c (γ changes from −0.89 to 0.98 as shown in Table 1). Overall, using non-spherical phase functions produced larger retrieval errors (see last column in Table 1).

[12] Several studies have also showed that the difference between spherical and non-spherical phase functions for $110° < \Theta < 170°$ depends upon particle irregularity [*Yang et al.*, 2000; *Kalashnikova and Sokolik*, 2002]. In our calculations thus far, we have assumed that all aerosols are non-spherical and did not consider any spherical particles such as wet sea salt and accumulation mode of sulfate particles that were actually included in the size distribution measurements [*Maring et al.*, 2003] and contribute to the column AOTs in the real atmosphere. To examine the combined effect of spherical and non-spherical particles, the ratio of number concentration between spherical and non-spherical particles must be known *a priori* that is difficult to obtain. Satellite retrievals have noted that spherical phase function is suitable for background (dust-free) aerosol retrievals over oceans [*Levy et al.*, 2003]. Therefore, the AERONET AOT in dust-free and dusty conditions provides a useful reference to estimate the optical contributions from spherical and non-spherical particles. The AOT is about 0.1 in dust-free conditions and increases to about 0.3 in dusty conditions. The ω, σ^{sca} and σ^{abs} have little difference between spherical and non-spherical particles. Therefore, we generate the new non-spherical phase function by compositing the spherical and non-spherical phase functions in a ratio of 1:2 (i.e., $P(\Theta)_{composite} = 1/3\ P(\Theta)_{spherical} + 2/3 \times P(\Theta)_{non\text{-}spherical}$). Compared to retrievals using only spherical (Figure 1a) or non-spherical phase functions (Figure 1b), Figure 1d shows that the composite phase function produces much less systematic errors ($|\gamma|$ decreases about 50% compared to Figure 1a for $110° < \Theta < 150°$ and $150° < \Theta < 170°$) and overall improvement for all angles (Table 1, $\overline{|\varepsilon|}$ decreases

from 18% in Figure 1a to 14% in Figure 1d, and no distinct error pattern as a function of Θ).

[13] We recognize that beside phase function, several other factors could also affect the retrieval accuracy [*Wang et al.*, 2003]. For instance, the TOA reflectance errors (due to sensor calibration) and surface reflectance uncertainties could have the same sign and magnitude thus reducing the retrieval errors or act in opposite direction thereby magnifying the errors. Usually, for a specific pixel, it is hard to separate the retrieval errors due to sensor calibrations and the errors due to surface reflectance uncertainties. However, sensitivity studies [*Wang et al.*, 2003] showed that on the average, those uncertainties are about 10 $\sim$ 15% with possible maximum of up to 20% (i.e., $|\Delta\tau| < 0.07$ for mean τ_{SP} of 0.33). This is smaller in magnitude when compared to the effect of using appropriate phase functions for dust aerosol retrievals. Since the real atmosphere has both spherical and non-spherical particles, using composite phase functions is more reasonable, and produces the best retrievals with the least systematic errors (as a function of Θ) as shown in this study. Since dust aerosols are larger when compared to sulfate and smoke aerosols, the ratio of the effective radius between fine and coarse mode [*Kaufman et al.*, 2002] or the Ångström exponent can provide some information on the relative abundance of spherical and non-spherical particles. However, it is difficult to distinguish spherical and non-spherical particles with similar sizes such as dust (non-spherical) and wet (spherical) sea salt particle over most of the globe [*Mishchenko et al.*, 2003]. From this perspective, this study underscores the difficulties in using a simple and reliable method to perform necessary corrections for the retrievals of the non-spherical particles in current satellite retrieval algorithms.

4. Summary

[14] Using SEM analysis and T-matrix calculations, the non-spherical phase function is calculated and its effect on dust aerosol retrievals from geostationary satellite data is examined. Major conclusions include:

[15] • The calculated non-spherical phase function is in general agreement with synthetic phase function derived from independent measurements [*Liu et al.*, 2003].

[16] • Applying purely non-spherical phase functions into the satellite retrieval algorithms only shows slightly improvement at certain scattering angles. However, using composite phase function by considering both spherical and non-spherical particles greatly improves the retrievals. The implication of this study to both satellite aerosols retrievals and phase function retrievals from ground-based sky radiance measurements [e.g., *Dubovik et al.*, 2002] needs to be further explored. Further studies using Meteosat Second Generation (MSG) satellite and calculation of the phase function of sharp-edge particles are ongoing.

[17] • Satellite retrievals are a practically complicated process. We agree with previous theoretical studies that non-spherical phase function has an important effect on dust aerosol retrievals. But we also show that applying non-spherical phase function into the satellite retrieval algorithms is a difficult task because current multi-channel retrievals cannot determine the percentage ratios between spherical and non-spherical particles.

[18] • Further efforts are needed to combine the use of multi-angle (e.g., MISR), multi-channel (e.g., MODIS) polarization data sets (e.g., POLDER) to retrieve the morphologies of particles [*Kahn et al.*, 1997] and to apply them in satellite retrievals.

[19] **Acknowledgments.** This research is supported by NASA's Radiation Sciences, Interdisciplinary Sciences and ACMAP programs. We thank Dr. Mishchenko for providing the synthetic phase functions and the T-matrix code.

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