Abstract

Multi-angle, multi-spectral remote sensing observations, such as those anticipated from the Earth Observing System (EOS) Multi-angle Imaging SpectroRadiometer (MISR), can distinguish spherical from non-spherical particles over calm ocean for mineral dust like particles with the range of sizes and column amounts expected under natural conditions. The ability to make such distinctions is critical if remote sensing of atmospheric aerosol properties is to provide significant new contributions to our understanding of the global scale, clear sky solar radiation balance. According to theoretical simulations, the measurements can retrieve column optical depth for non-spherical particles to an accuracy of at least 0.05 or 10%, whichever is larger. In addition, three to four distinct size groups between 0.1 and 2.0 microns effective radius can be identified at most latitudes.

1. Introduction

In a recent paper, Mishchenko et al. [1995] studied the implications of assuming spherical particles in the retrieval of aerosol properties from remote sensing data, when non-spherical particles are present in the atmosphere. They demonstrate that for observations of dust-like aerosols over ocean, if a retrieval of total column optical depth is performed based on an assumption of spherical particles when in fact the particles are non-spherical, the results can be seriously in error. For the cases studied, the systematic error in total column optical depth is very sensitive to the geometry of the observation, and can be arbitrarily large, when simulated monospectral satellite measurements at a single emission angle are used in the retrieval, even assuming noiseless data.

The systematic errors demonstrated by Mishchenko et al. [1995] are unacceptable large for climate change studies. The magnitude of direct radiative effects from atmospheric aerosols is as yet uncertain, but it may be comparable to the size of the anticipated incremental greenhouse warming due to a doubling of atmospheric CO2 [Andreae, 1994; Penner et al., 1994; Kick and Bruegge, 1995; Charlson et al., 1992; Hansen and Lebedeff, 1990]. Dust-like particles, which are likely to be non-spherical, make important contributions to the optical depth over large regions of the planet [Tegen and Fung, 1994].

Currently, satellite-based remote sensing instruments provide the best hope of obtaining the spatial and temporal coverage required for global monitoring of atmospheric aerosols. Although the only global-scale satellite-based retrieval of total column aerosol optical depth now in routine operation relies on a single channel of AVHRR data [Kaw et al., 1989; Hansen and Stowe, 1994], new satellite remote sensing instruments with multi-angle and multi-spectral capabilities are being built. We present in this paper a theoretical study of the ability of multi-angle and multi-spectral remote sensing techniques to distinguish between spherical and non-spherical particles. This study is part of our program to characterize the performance of the Multi-angle Imaging SpectroRadiometer (MISR) instrument, which is scheduled for launch into polar orbit on the EOS AM-1 platform in June, 1998 [Diner et al., 1991].

The MISR instrument will measure the upwelling visible radiance from Earth in 4 spectral bands centered at 443, 550, 670, and 865 nm, at each of 9 emission angles spread out in the forward and aft directions along the flight path at 270.5°, 360°, 45°, 90°, and nadir. The spatial sampling rate is 775 meters in the cross-track direction at all angles. Over a period of 7 minutes, a 360 km wide swath of Earth comes into the view of the cameras at each of the 9 emission angles, providing a wide range of scattering angle coverage for each surface location. The data will be used to characterize aerosol optical depth, aerosol type, surface albedo and bi-directional reflectance, and cloud properties. Global coverage will be acquired about once in 9 days at the equator, the nominal mission lifetime is 6 years.
2. Modeling the Observations

For this study, we use simple scattering phase functions and albedos for spherical and nonspherical particles similar to those generated by Mishchenko et al. [1995]. The nonspherical particles are modeled as a mixture of polydisperse prolate and oblate spheroids with a uniform distribution of aspect ratios ranging between 1.2 and 2.4. Both spherical and nonspherical particle sizes are given by power-law distributions, with \( n(r) \) = \( C r^{-1} \) for \( r < r_1 \), \( n(r) = C (r/r_1)^{k} \) for \( r_1 \leq r \leq r_2 \), and \( n(r) = 0 \) for \( r > r_2 \). Here \( r \) is the particle radius for spherical particles and the radius of a sphere with equal surface area for nonspherical particles. \( C \) is a normalization constant for the distribution. \( r_1 \) and \( r_2 \) are parameters, selected so that the cross section mean weighted radius of the distribution as a whole is \( r_{\text{eff}} \), and the variance of the distribution is \( \sigma^2 \) [Mishchenko and Travis, 1994]. For all cases, \( r_{\text{eff}} \) is 0.7 and the particle index of refraction is 1.53 - 0.008i, independent of wavelength. The wavelength dependence of single scattering properties scales as \( x \), where \( x = 2 \pi r / \lambda \), and \( \lambda \) is the wavelength [Hansen and Travis, 1978]. Unless specified otherwise, optical properties presented in this paper are for MISR Band 3 (670 nm); in the underlying calculations, optical properties are properly scaled to account for wavelength dependence in each of the MISR bands used.

Figure 1 compares the single scattering phase functions for distributions of spherical and nonspherical particles of several effective sizes. For the smallest particles, \( r_{\text{eff}} = 0.05 \mu m \), which is typical of "nucleation mode" aerosols in the atmosphere, but smaller than common atmospheric mineral dust aerosol distributions. The single scattering phase functions for spherical and nonspherical particles at these sizes are indistinguishable. Distributions with effective radii in the 0.5- to 10 \( \mu m \) range are typical of suspended atmospheric mineral dust aerosols [e.g., Tegen and Fung, 1994]. For these larger aerosols, the nonspherical particles put a smaller fraction of the total scattering into the back-scattering direction at scattering angles greater than about 150°, and a larger fraction into the scattering angles between about 100° and 150°, compared to spherical particles with equivalent surface area. The characteristics shown in Figure 1 have been reproduced for other types of randomly-oriented aggregates of non-spherical particles [e.g., Takano and Liou, 1989].

The optical properties given by Mishchenko et al. [1995] allow us to treat particles with sizes up to about 2 \( \mu m \), which is adequate to cover the transition in simple scattering characteristics between small (Rayleigh) and large (geometric optics) regimes. Qualitatively, the results for the largest particles we can treat also apply to particles with effective radii between 2 and 10 \( \mu m \). Quantitative treatment of the sensitivity of multiangle remote sensing to the larger particles requires additional calculations that are currently underway.

The scattering angle coverage for each of the 9 MISR cameras, as a function of latitude and location in the scan line, is shown in Figure 2 for March 21, for the nominal EOS AM1 platform orbit. In midlatitudes, scattering angles around 150° are covered by the 9 cameras, whereas at high latitudes the range is approximately 40° to 150°, and at low latitudes, 100° to 150°. With changing seasons, the pattern of coverage remains nearly the same, but shifts toward the summer pole.

The MISR Team has developed a radiative transfer code, based on the adding-doubling method [Hansen and Travis, 1974], to simulate top-of-atmosphere reflectances as would be observed by the MISR instrument, for arbitrary choice of aerosol type and amount, and variable surface reflectance properties [Diner et al., 1994]. For the present study we have simulated MISR measurements over a Fresnel-reflecting calm ocean surface, in a cloud-free, Rayleigh scattering atmosphere with a surface pressure of 1.013 bar and a standard midlatitude temperature profile. A layer containing either nonspherical or spherical particles is placed between the gas component and the surface. (Sensitivity studies show that for the range of aerosol optical depth treated here, the results would be unaffected if the aerosols were modeled as mixed with the gas in the lowest part.
3. Sensitivity of Multi-angle Multi-spectral Radiance to Panel Position

The radiance data, `\( \mathbf{R} \)`, has three key information about the ability to distinguish among modes is presented. The three key information about the ability to distinguish among modes is presented. The first is the difference in the radiance between the measured and calculated values, which can be used to derive an image of the measurement. The second is the difference in the radiance between the measured and calculated values, which can be used to derive an image of the measurement. The third is the difference in the radiance between the measured and calculated values, which can be used to derive an image of the measurement.

\[
\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 \\ \mathbf{R}_2 \\ \mathbf{R}_3 \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} \mathbf{C}_1 \\ \mathbf{C}_2 \\ \mathbf{C}_3 \end{bmatrix}
\]

\[
\delta \mathbf{R} = \mathbf{R} - \mathbf{C}
\]

Since the \( \delta \mathbf{R} \) is proportional to the number of channels used, where less than or more than.

The WISE camera, when

\[
\mathbf{I} = \begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \mathbf{I}_3 \end{bmatrix}, \quad \mathbf{O} = \begin{bmatrix} \mathbf{O}_1 \\ \mathbf{O}_2 \\ \mathbf{O}_3 \end{bmatrix}
\]

\[
\delta \mathbf{I} = \mathbf{I} - \mathbf{O}
\]

\[
\mathbf{K} = \begin{bmatrix} \mathbf{K}_1 \\ \mathbf{K}_2 \\ \mathbf{K}_3 \end{bmatrix}
\]

\[
\delta \mathbf{K} = \mathbf{K} - \mathbf{I}
\]

\[
\mathbf{S} = \begin{bmatrix} \mathbf{S}_1 \\ \mathbf{S}_2 \\ \mathbf{S}_3 \end{bmatrix}
\]

\[
\delta \mathbf{S} = \mathbf{S} - \mathbf{K}
\]

\[
\mathbf{E} = \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \mathbf{E}_3 \end{bmatrix}
\]

\[
\delta \mathbf{E} = \mathbf{E} - \mathbf{S}
\]

where \( \mathbf{R} \) is the radiance data, \( \mathbf{I} \) is the intensity data, and \( \mathbf{O} \) is the output data.

\[
\mathbf{R} = \begin{bmatrix} \mathbf{R}_1 \\ \mathbf{R}_2 \\ \mathbf{R}_3 \end{bmatrix}, \quad \mathbf{I} = \begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \mathbf{I}_3 \end{bmatrix}, \quad \mathbf{O} = \begin{bmatrix} \mathbf{O}_1 \\ \mathbf{O}_2 \\ \mathbf{O}_3 \end{bmatrix}
\]

\[
\delta \mathbf{R} = \mathbf{R} - \mathbf{O}
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\[
\mathbf{K} = \begin{bmatrix} \mathbf{K}_1 \\ \mathbf{K}_2 \\ \mathbf{K}_3 \end{bmatrix}, \quad \mathbf{S} = \begin{bmatrix} \mathbf{S}_1 \\ \mathbf{S}_2 \\ \mathbf{S}_3 \end{bmatrix}, \quad \mathbf{E} = \begin{bmatrix} \mathbf{E}_1 \\ \mathbf{E}_2 \\ \mathbf{E}_3 \end{bmatrix}
\]

\[
\delta \mathbf{K} = \mathbf{K} - \mathbf{S}
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\[
\delta \mathbf{S} = \mathbf{S} - \mathbf{E}
\]

\[
\delta \mathbf{E} = \mathbf{E} - \mathbf{K}
\]

where \( \mathbf{R} \) is the radiance data, \( \mathbf{I} \) is the intensity data, and \( \mathbf{O} \) is the output data.
In Table 3 we examine the effect of MISER-2 on noise made in the presence of non-irradiated particles. For the purpose of this study, both the noise and non-irradiated particles are considered to be present in the system. The results show that the noise is significantly reduced when non-irradiated particles are included in the model. This suggests that the inclusion of non-irradiated particles in the model is necessary for accurate predictions of the system's behavior.
The detection of the presence of MS: several methods for a range of particle compositions are used. Compton effect, Rutherford scattering, and electron capture occur under these conditions. The effect is observed in a single detector with a high energy threshold, where the photons of the MS are used for discrimination. "Best-fit" models predict the presence of MS, while the method of backscattering can be used for confirmation.

According to the theoretical simulations, MS-KK measurements can replace other optical depth measurements.

\[ \frac{(\gamma')^{\text{obs}}}{(\gamma')^{\text{true}}} \cdot \mathbf{I} \cdot \mathbf{L} \]

4. Conditions

observed as better as well as lowered thresholds.

2.0% of the optical depth (of less for lower thresholds) are used to determine the presence of MS. The threshold for the threshold sensitivity is set to produce a false alarm rate of 1%. The threshold sensitivity is determined by the receiver operating characteristic (ROC) curve, where the threshold sensitivity is set to achieve the maximum ROC curve.

\[ \text{false positive rate} = \frac{\text{false positive rate}}{100} \]

which means the threshold sensitivity is set to achieve the maximum ROC curve.

According to the theoretical simulations, MS-KK measurements can replace other optical depth measurements.
hydration state, mixing of particle types, effects of thin cirrus, fogs, stratospheric aerosols, and underlying surface type.

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References


**Figure Captions**

**Figure 1.** Single scattering phase functions for several pairs of spherical and non-spherical particles with the same values of $r_{eff}$. For all cases, $\alpha_{eff} = 0.2$, and $\lambda$ is 670 nm. (A) $r_{eff} = 0.05$ \(\mu\)m (Note that the non-spherical case is hidden by the spherical case for this size particle); $r_{eff} = 0.1$ \(\mu\)m, and $r_{eff} = 0.1 \mu$m. (B) $r_{eff} = 0.5$ \(\mu\)m, (B) $r_{eff} = 1.0 \mu$m; and $r_{eff} = 2.0 \mu$m.

**Figure 2.** Range of scattering angles to be sampled by the MISR cameras, as functions of latitude and location in the instrument scanline, for March 21 and the nominal EOS-AM Platform orbit. Sampling extends to 82° latitude, and in some seasons folds over toward 60° in the opposing hemisphere. The pattern remains nearly the same, but shifts poleward, as the solstice seasons approach.

**Figure 3.** Tests of the ability to distinguish spherical from non-spherical aerosols. (A) For each panel, simulated MISR reflectances were produced for an atmosphere containing non-spherical particles with the specified $r_{a, atm}$ and $r_{a, atm}$. $r_{a, atm}$ increases to the right from panel to panel, whereas $r_{eff, atm}$ increases from panel to panel toward the top of the figure. $\chi^2_{geom}$ was then calculated using the two longest wavelength MISR channels in all 9 cameras, for comparison models that assume distributions of spherical particles with effective radii $r_{comp}$ and column aerosol optical depth $\tau_{comp}$. All simulations presented are for mid-latitude geometry over a Fresnel-reflecting, calm ocean surface, and include a standard Rayleigh scattering contribution. Colors indicating the value of $\chi^2_{geom}$ are plotted in each panel, with $r_{comp}$ increasing toward the top of each plot and $\tau_{comp}$ increasing to the right. (B) Same as Figure 3A, except that the atmosphere is assumed to contain spherical particles, and comparison models assume non-spherical particles.

**Figure 4.** Tests of the ability to constrain non-spherical aerosols. (A) $\chi^2_{geom}$ for the same parameter space as in Figure 3, except that the measured and comparison models both assume non-spherical particles. (B) $\chi^2_{abs}$ for the same parameter space as in Figure 4A.
Non-Spherical Atmosphere, Spherical Comparison (Fresnel Surface)

\( \mu = 0.60 \)  \( \Delta \phi_{\text{Nadir}} = 0.26 \)

\( \tau_{\text{atm}} = 2.0 \quad \tau_{o, \text{atm}} = 0.05 \)

\( \tau_{\text{atm}} = 1.0 \quad \tau_{o, \text{atm}} = 0.05 \)

\( \tau_{\text{atm}} = 0.5 \quad \tau_{o, \text{atm}} = 0.05 \)

\( \tau_{\text{atm}} = 0.1 \quad \tau_{o, \text{atm}} = 0.05 \)

\( \chi^2_{\text{geom}} \)
Spherical Atmosphere, Non-Spherical Comparison (Fresnel Surface)

\[ \mu_0 = 0.60 \quad \Delta \phi_{\text{hcdir}} = 26.0 \]
Non-Spherical Atmosphere, Non-Spherical Comparison (Fresnel Surface)

\( \mu_0 = 0.60 \)  \( \Delta \phi_{\text{Nadir}} = 26.0 \)

\( r_{\text{atm}} = 2.0 \)  \( \tau_{\text{atm}} = 0.05 \)

\( r_c = 2.0 \)  \( \tau_{\text{atm}} = 0.20 \)

\( r_{\text{atm}} = 2.0 \)  \( \tau_{\text{atm}} = 0.80 \)

\( r_{\text{atm}} = 1.0 \)  \( \tau_{\text{atm}} = 0.05 \)

\( r_{\text{atm}} = 1.0 \)  \( \tau_{\text{atm}} = 0.20 \)

\( r_{\text{atm}} = 1.0 \)  \( \tau_{\text{atm}} = 0.80 \)

\( r_{\text{atm}} = 0.5 \)  \( \tau_{\text{atm}} = 0.05 \)

\( r_{\text{atm}} = 0.5 \)  \( \tau_{\text{atm}} = 0.20 \)

\( r_{\text{atm}} = 0.5 \)  \( \tau_{\text{atm}} = 0.80 \)

\( r_{\text{atm}} = 0.1 \)  \( \tau_{\text{atm}} = 0.05 \)

\( r_{\text{atm}} = 0.1 \)  \( \tau_{\text{atm}} = 0.20 \)

\( r_{\text{atm}} = 0.1 \)  \( \tau_{\text{atm}} = 0.80 \)

\( \chi^2_{\text{abs}} \)

FIGURE 4B