Multiangle Remote Sensing of Aerosols Over Ocean

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ABSTRACT

Multiangle, multispectral remote sensing observations, such as those anticipated from the Earth Observing System (EOS) Multiangle Imaging SpectroRadiometer (MISR), can significantly improve our ability to constrain aerosol properties from space. According to theoretical simulations, we can retrieve column optical depth from measurements over calm ocean, for particles with typical size distributions and compositions, to an accuracy of at least 0.05 or 10%, whichever is larger, even if the particle properties are poorly known. The measurements also allow us to distinguish spherical from nonspherical particles, and to identify three to four distinct size groups between 0.1 and 2.0 microns effective radius at most latitudes, based on the theoretical study.

INTRODUCTION

Recent advances in modeling the Earth's climate have brought us to a point where the contributions made by aerosols to the global radiation budget have an impact on the results (e.g., *Andreae*, *1995; Charlson et al.*, 1992; *Hansen et al.*, 1997; *Penner et al.*, 1994). Aerosols are thought to contribute significantly to direct radiative forcing in the atmosphere, and indirectly, through their influence as nucleation sites for cloud particles. Knowledge of both aerosol optical depth and the microphysical properties of the particles are needed to adequately model aerosol effects.

Currently, we must rely on satellite remote sensing to provide the spatial and temporal coverage required for global monitoring of atmospheric aerosols. However, the retrieval of aerosol properties by remote sensing is a notoriously under-determined problem. And the only demonstrated global-scale, satellite-based retrieval of aerosols derives aerosol optical depth from single-angle, monospectral data, using assumed values for all the aerosol microphysical properties *(Rao et al.*, 1989; *Stowe et d.*, 1997).

Multiangle, multispectral remote sensing observations, such as those anticipated from the Earth Observing System (EOS) Multiangle Imaging SpectroRadiometer (MISR), provide a type of information about the characteristics of aerosols never before obtained from satellites (*Diner et al.*, 1991). We plan to retrieve aerosol optical depth and aerosol "type, " which represents a combination of index of refraction, size distribution, and shape constraints, globally, at 17.6 km spatial resolution. The instrument is scheduled for launch into a 10:30 AM, sun-synchronous polar orbit in June, 1998.

MISR will measure the upwelling visible radiance from Earth in 4 spectral bands centered at 446, 558, 672, and 866 nm, at each of 9 emission angles spread out in the forward and aft directions along the flight path at ±70.5°, ±60.0°, ±45.6°, ±26.1°, and nadir. The spatial sampling rate is 275 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 hi-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.

Our aerosol retrieval approach involves separating the data into cases where the surface is dark water, dense dark vegetation (DDV), heterogeneous land, or "other" (*Diner et* al., 1994). Aerosol retrievals will be performed on data in the first 3 categories. For dark water retrievals, wc use the red and near-infrared bands only, where the surface is darkest, and we model surface glitter and whitecap effects as a function of estimated surface wind speed, using standard models.

This paper summarizes our current understanding of the MISR sensitivity to natural ranges of optical depth, particle size distribution (as represented by the effective radius in a log-normal distribution function), and particle shape. We focus on situations under which the MISR sensitivity to particle properties is likely to be greatest: over calm ocean. These results provide a theoretical upper bound on the sensitivity of actual MISR retrievals. For this study, we consider atmospheres containing "pure" particle types -- aerosol populations with uniform composition, and with aerosol sizes characterized by unimodal, log-normal distribution functions. Subsequent work will explore sensitivity to particle composition, and to mixes of particle types.

OUR APPROACH TO THE AEROSOL PROPERTIES SENSITIVITY STUDY

We rely on simulations of top-of-atmosphere radiation to explore the sensitivity of multiangle observations to aerosol properties prior to launch of the MISR instrument, The MISR Team has developed a radiative transfer code, based on the adding-doubling method [*Hansen and Travis,* 1974], to simulate reflectance 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]. (We define reflectance as the radiance multiplied by π, and divided by the exe-atmospheric solar irradiance at normal incidence.) For the present study we 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. (In the actual MISR retrievals over ocean, we include sun glint and whitecap models that depend on near-surface wind speed.) The results reported here emphasize mid-latitude geometry. With the nominal orbit, the MISR instrument samples a broad range of scattering angles, between about 60" and 160", in mid and high latitudes. Due to the sun-spacecraft geometry, the range of scattering angles at low latitudes is diminished to about 100° to 160°. This reduces the sensitivity of the retrieval to particle properties.

A layer containing particles with selected optical depth, spectral single scattering albedo, extinction coefficient, and single scattering phase function is placed between the gas component and the surface. Extinction and scattering properties for log-normal distributions of spherical particles are derived at selected values of particle effective radius, real index of refraction, and imaginary index of refraction, using a standard Mie scattering code. The width parameter in the log-normal function is set to 2.5, representing fairly broad, natural distributions of particles. Non-spherical particles are modeled using the T-matrix method, with properties typical of Sahara dust (*Mishchenko et al., 1997).*

Our overall approach is to designate one set of simulated atmospheric reflectance as the "measurements," with fixed aerosol optical depth (τ_a), particle radius (r_a), real index of refraction (n_{ra}), and imaginary index of refraction (n_{ia}). We then test whether they can be distinguished, within instrument uncertainty, from a series of "comparison" model reflectance. For the comparison models, we systematically vary aerosol optical depth (τ_c), effective radius (r_c), real index of refraction (n_{rc}), and imaginary index of refraction (n_{ic}). The goal is to determine the ranges of comparison model parameters that give an acceptable match with the measurements.

Testing the Agreement Between Comparison Models and the "Measurements"

Over ocean, the MISR retrieval makes use of up to 18 measurements: 9 angles at each of the 2 longest MISR wavelengths (Bands 3 and 4, centered at 672 and 866 nm, respectively), where the water surface is darkest. We define 4 test variables to decide whether a comparison model is consistent with the measurements. Each is based on the χ^2 statistical formalism [e.g., *Bevington*, 1969].

One test variable that weights the contributions from each observed reflectance according to the slant path through the atmosphere of the observation:

$$\chi^2_{\text{abs}} = \frac{1}{N\langle w_k\rangle}\sum_{l=3}^{4}\sum_{k=1}^{9}\frac{w_k\left[\rho_{meas}(l,k) - \rho_{comp}(l,k)\right]^2}{\sigma^2_{abs}(l,k)} \tag{1}$$

where ρ_{meas} is the simulated "measured" reflectance, ρ_{comp} is the simulated reflectance for the comparison model, 1 and k are the indices for wavelength band and camera, N is the number of measurements included in the calculation, w_k are weights, chosen to be the inverse of the cosine of the emission angle appropriate to each camera k, $\langle w_k \rangle$ is the average of weights for all the measurements included in the calculation. σ_{abs} has units of reflectance and is the absolute calibration uncertainty in the reflectance for MISR band *1* and camera k.. For the MISR instrument, σ_{abs} nominally falls between 0.03 for a target with reflectance of 100%, and 0.06 for a reflectance of 5%, in all channels [Diner-et al., 1994]. For these simulations, we model σ_{abs} as varying linearly with reflectance.

χ^2_{abs} alone reduces 18 measurements to a single statistic. χ^2_{abs} emphasizes the absolute reflectance, which depends heavily on aerosol optical depth. However, there is more information in the measurements that may improve the retrieval discrimination ability.

A second χ^2 test variable emphasizes the geometric properties of the scattering, which depend heavily on particle size and shape, and takes advantage of the small camera-to-camera relative uncertainty as compared to the absolute uncertainty. Here each spectral measurement is divided by the corresponding spectral measurement in the nadir camera:

$$\chi^2_{\text{geom}} = \frac{1}{N\langle w_k\rangle}\sum_{l=3}^{4}\sum_{\substack{k=1\\ k\neq nadir}}^{9}\frac{w_k\left[\dfrac{\rho_{meas}(l,k)}{\rho_{meas}(l,nadir)} - \dfrac{\rho_{comp}(l,k)}{\rho_{comp}(l,nadir)}\right]^2}{\sigma^2_{geom}(l,k)} \tag{2a}$$

where σ_{geom} (a dimensionless quantity) is the uncertainty in the measured channel-to-channel reflectance ratio, derived from the expansion of errors for a ratio of measurements (e.g., *Bevington, 1969):*

$$\sigma^2_{geom}(l,k) = \frac{\sigma^2_{rel}(l,k)}{\rho^2_{meas}(l,nadir)}\left[1 + \frac{\rho_{meas}(l,k)}{\rho^2_{meas}(l,nadir)}\right] \tag{2b}$$

$\sigma_{rel}(l,k)$ has units of reflectance and is the camera-to-camera relative calibration uncertain y in the reflectance between band l, camera k., and band 1, nadir. σ_{rel} is nominally one third the corresponding value of σ_{abs} for the MISR instrument [*Diner et al.*, 1994]. Note that σ_{rel} includes the effects of systematic calibration errors for ratios of reflectance between channels. Random error due to instrument noise is negligible, based on the high signal-to-noise ratio demonstrated during MISR camera testing.

A third test variable χ^2_{spec}, is defined similarly to χ^2_{geom}, except the band 3 data is used rather than the nadir camera data in the denominator of the reflectance ratio, and the σ value is altered accordingly. The final test variable χ^2_{maxdev}, is simply the largest term in the sum on the right side of equation (1).

Since each χ^2 variable is normalized to the number of channels used, a value less than or about unity implies that the comparison model is indistinguishable from the measurements. Values larger than about 5 imply that the comparison model is not consistent with the observations.

RESULTS

We performed the analysis using interactive, computer-bawd tools that allow us to plot χ^2 values, encoded in color, for any 3 independent variables. We can slice through this volume and display the color-bar values of any of the test variables, or for the maximum of the **4 test** variables, in a 2-dimensional image. For each point in these images, we can call up the values of all the independent and test variables, as well as graphs of the calculated reflectance values for the associated atmosphere and comparison model.

Given the limitations of the current format, we must simply quote the results of this work. Two-dimensional color displays showing key parts of the parameter space appear in other publications (*Kahn et al., 1997a;* b). We begin by fixing the aerosol optical depth, aerosol effective radius, and indices of refraction for the "atmosphere." We then vary the comparison model aerosol values over natural ranges given in Table 1. We calculate the values of the four test variables for each case; if any of the four is larger than a threshold value, which we nominally set to 2, we conclude that the comparison model does not match the atmosphere. The smaller the range of acceptable comparison models, the more powerful the data are in constraining aerosol properties.

Regardless of atmospheric particle size or composition, the range of optical depth for acceptable comparison models is always small, and is centered around the correct value. Of the test variables, χ^2_{abs} provides the strongest constraint in most cases, since it measures the absolute brightness. The calm ocean surface is black at the wavelengths used for the retrieval, and particles brighten the scene. The absolute precision of optical depth retrieval at 0.55 microns wavelength is about 0.05 for atmospheric optical depths of a few tenths or less, increasing to no more than 10% as the atmospheric optical depth reaches 1.0. The decrease in absolute sensitivity with optical depth is due to the assumed value of the σ_{abs}, which nominally increases with absolute brightness. (The actual size of this effect will be reassessed once in-flight calibration information is available.)

High sensitivity to optical depth is achieved because the geometric path through the atmosphere varies systematically, in a known way, among the 9 cameras; weighting by the path length improves the result. This conclusion relies on the aerosol properties being horizontally uniform over the retrieval sampling region, which at the surface is 17.6 km, increasing to several hundred km higher in the atmosphere, where aerosols are likely to be uniformly distributed over greater distances.

We investigated the ability of multiangle data to distinguish spherical from nonspherical particles using accumulation mode mineral dust particles, with n_r = 1.53 and n_i = 0.008 (*Mishchenko et al.*, 1997). Of the common aerosol types, the only large, nonspherical particles expected would have mineral dust composition. We took an atmosphere containing nonspherical particles, and asked whether we could find an acceptable comparison model containing any sized particles with spherical shape. We were unable to do so, except for an atmosphere containing the tiniest nonspherical particles, with effective radii around 0.05 microns (*Kahn et al.*, 1997a).

In this case χ^2_{geom} usually provides the strongest constraint. Particle sphericity has a big impact on the shape of the particle single scattering phase function, in the range of scattering angles between 90° and 140°. This range is well-sampled by MISR. For very small particles, however, the single scattering phase function is almost flat, independent of shape, so neither the retrieval, nor the atmospheric radiative properties of interest to modelers, depend on particle shape in this case.

For all the above studies, we noted that over the aerosol parameter space, acceptable comparison models clump into three to four distinct size groups. The clumping increases with increasing atmospheric aerosol optical depth, as might be expected since the aerosol signal stands higher over the background Rayleigh scattering as the aerosol optical depth increases. Figure 1 is a bar chart that illustrates the sensitivity to effective radius, for a case where the atmospheric particles have n_r = 1.47 and n_i = 0.0. Along the vertical direction, the ranges of particle radius values (r_c) for all comparison models in the parameter space that give acceptable matches to an atmosphere with fixed particle properties are shown with bars. Bars are produced for 8 choices of atmospheric particle radius (r_a) between 0.1 and 2. For each r_a, bars are produced for 4 choices of atmospheric optical depth τ_a, from 0.05 to 1.0. The influence of atmospheric optical depth on the range of acceptable r_c is easy to see.

Also, for τ_a larger than 0.1, the constraint on r_c is much tighter for atmospheric particles smaller than 0.8 microns than for larger ones. This transition is traced to the way the single scattering phase function varies with effective radius. For the smaller sizes, the phase functions are changing between fairly flat curves, characteristic of Rayleigh scattering particles, and large particles with well-developed forward peaks, rainbow features, and backscattering. For r_a between 0.1 and 0.8, the phase functions are changing between the two regimes, and small changes in particle effective radius produce relatively large changes in phase function. For particles with r_a 0.8 or greater, the phase functions changes much less with increasing particle radius. More subtle features in this chart are caused by details in the way the phase functions change with particle size or real index of refraction, coupled with the assumed variation in instrument sensitivity with absolute brightness.

CONCLUSIONS

According to theoretical simulations, MISR data will allow us to retrieve column aerosol optical depth over calm ocean surfaces to an accuracy of at least 0.05 or 10%, whichever is larger, for natural ranges of aerosol type and amount. In addition, three to four distinct size groups between 0.1 and 2.0 microns effective radius can be identified at mid and high latitudes, when the aerosol optical depth is about 0.1 or greater. We can also distinguish spherical from non-spherical particles, according to these studies.

The theoretical sensitivity of MISR to particle composition, represented by the real and imaginary parts of the index of refraction, and the impact of measurement noise on the retrieval sensitivity, are currently under investigation. Pre-launch work will include a study of sensitivity to mixes of particles. But as useful as these results may be in preparing for the analysis and interpretation of measurements, we will not really know the power of the multiangle technique until MISR begins making observations of Earth.

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Table 1. The Parameter Space of Aerosol Properties Used in this Study

	Minimum Value	Maximum Value	# Steps
Aerosol optical depth at 0.55 microns	0.05	1.00	20
Effective Radius	0.05	2.00	40
Real Index of Refraction	1.33	1.55	12
Imaginary Index of Refraction	0.0	0.50	20

Figure Caption

Figure 1. Bar chart showing the ranges of particle radius values (rc) for comparison models that give acceptable matches to an atmosphere with particles having real index of refraction nr_a = 1.47, and imaginary index of refraction nr_i = 0.0. Bars are drawn for 8 values of atmospheric particle radius (ra), spread along the horizontal axis, for four cases of atmospheric aerosol optical depth (taua).

How well can we constrain r?
nra = 1.47 nia = 0, chisq_max between 0.0 and 2.0