Satellite based retrieval of aerosol optical thickness: The effect of sun and satellite geometry

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[1] The DOE research satellite instrument, the Multispectral Thermal Imager (MTI), has several spectral bands in the visible and near infrared part of the spectrum that can be used for AOD (Aerosol Optical Depth) retrieval. Small pixel size (5 m × 5 m in the visible and 20 m × 20 m in the infrared) eliminates most sub-pixel size cloud problems. We analyze 18 pairs of images, taken close to nadir and back along the track at a viewing angle around 60°, and compare results of a single view AOD retrieval algorithm with the AERONET measurements. We find that the single view AOD retrieval algorithm is more accurate at smaller scattering angles (at off-nadir view). The root mean square (RMS) error of the MTI AOD single view retrieval in this region is around 0.03 compared to 0.11 for larger scattering angles at near-nadir view. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1640 Global Change: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Chylek, P., B. Henderson, and M. Mishchenko, Satellite based retrieval of aerosol optical thickness: The effect of sun and satellite geometry, *Geophys. Res. Lett.*, *30*(11), 1553, doi:10.1029/2003GL016917, 2003.

1. Introduction

[2] Aerosols in the atmosphere play a central role in the earth's energy balance by scattering and absorbing solar and terrestrial radiation [*Chylek and Coakley*, 1974; *Charlson et al.*, 1992; *Kiehl and Briegleb*, 1993; *Chylek and Wong*, 1995; *Russell et al.*, 1999; *Sateesh and V. Ramanathan*, 2000], and by modifying optical properties [*Twomey*, 1991] and lifetime of clouds [*Ramanathan et al.*, 2001, *Rotstayn and Lohmann*, 2002]. Biomass and fossil fuel burning produce regional haze layers that have become regular features over several continents and adjacent seas. The increase in aerosol concentration has exerted a cooling effect on climate and moderated the expected warming effects of green house gases [*Hansen*, 2002]. Due to a high spatial and temporal variability of aerosol loading, and due to complicated and not fully understood link between aerosols and cloud properties, the total aerosol forcing of the climate system remains uncertain. In addition to global climate, aerosols affect the climate of specific regions and their water cycle. In this respect, South East Asia with its large "brown haze" is of special interest [*Ramanathan et al.*, 2001] due to a possible impact on the Indian monsoon cycle.

[3] Remote sensing is the only means capable of providing global observational aerosol data that are needed for assessing direct and indirect aerosol effects. Data from current satellite multi-spectral instruments (at visible and near infrared wavelengths) can be used to estimate AOD. The NASA MODerate resolution Imaging Spectroradiometer (MODIS) demonstrated a high accuracy in aerosol optical depth retrieval. *Tanre et al.* [1999] found the error $\pm(0.01 + 0.05\tau)$ of the retrieved AOD over the ocean (τ is the aerosol optical depth). *Kaufman et al.* [1997a, 1997b] estimated MODIS accuracy for the retrieval of aerosol optical depth over land to be $\pm(0.05 + 0.2\tau)$. *Veefkind et al.* [1999] used the forward look of the along track scanning radiometer 2 (ATSR-2) to demonstrate that the AOD over the ocean can be retrieved using the ATSR-2 with an accuracy of 0.03. The advanced very high resolution radiometer (AVHRR) data (for the same scene) provided the AOD over the ocean with a considerably larger error of 0.05 to 0.15 in AOD. Similarly *Coakley et al.* [2002] retrieved the AOD over the ocean using the AVHRR data with the accuracy of 0.07 to 0.10.

[4] Using a dual or a multiple-angle view of the same scene (at nearly the same time) should improve significantly the accuracy of the satellite AOD retrieval [*Flowerdew and Haigh*, 1996]. The ATSR-2 can measure the reflected solar radiances at nadir and at approximately 55° along track. *Veefkind et al.* [1999] found the accuracy of the AOD retrieval using the ATSR-2 dual view to be in "good agreement" with the ground truth in three out of four cases (in the fourth case the error was about 100% for an AOD case close to 0.1). *Robles-Gonzalez et al.* [2000] compared the ATSR-2 dual algorithm retrieval averaged on a 10 km × 10 km grid with ground based sun photometer measurements and found an agreement within 0.05. *North* [2002] estimated the accuracy of the AOD deduced form the ATSR-2 dual angle imagery to be 0.02 or 20% of the AOD, whichever is larger. Further improvements can be expected from the multi-angle imaging spectroradiometer (MISR) that uses four spectral bands and nine different viewing angles [*Martonchik et al.*, 2002] and from polarization measurements [*Chowdhary et al.*, 2001].

[5] In the reported research, the single view aerosol optical depth retrieval code developed by *Kaufman et al.*

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[1997a, 1997b] has been applied to the DOE Multispectral Thermal Imager (MTI) observed radiances to determine the effect of viewing geometry on the accuracy of the AOD estimate. The purpose is to find out which satellite view (close to nadir or around 60° back along the track) provides a more accurate estimate of AOD.

2. The Multispectral Thermal Imager

[6] The DOE research satellite instrument [*Weber et al.*, 1999], the MTI, has ten spectral bands that can be potentially useful for aerosol optical depth retrieval (three spectral bands in the visible part of the solar spectrum centered on 485, 560 and 650 nm, and seven near infrared bands at 810, 875, 940, 1150, 1375, 1645 and 2225 nm). The MTI pixel size is 5 m × 5 m in the visible and 20 m × 20 m in the infrared region; its swath width is around 12 km. The satellite is in a circular sun synchronous orbit at about 570 km. Although the MTI operates routinely as a single view instrument, it has a dual view capability. The reflected solar radiances can be measured close to nadir and then back along the track at a viewing angle around 60°. Both images are generally taken within two minutes from each other. The change of the solar zenith angle is usually within 1 degree between the first and the second image. The MTI's small pixel size eliminates most errors in retrieval due to unresolved sub-pixel size cloudiness. In addition to clear sky images, partially cloudy scenes are used for retrieval as long as clouds or cloud shadows do not affect a considerable fraction of an image.

3. Aerosol Retrieval Code

[7] A code developed by *Kaufman et al.* [1997a, 1997b] has been modified and used for the MTI single view retrieval. Only the major steps are summarized here.

[8] The top of the atmosphere outgoing radiances are composed of two major components. One is the solar radiation reflected by the surface and the other is the radiation reflected by atmospheric gases and aerosols. For retrieval of aerosols it is advantageous to minimize the ground reflected radiation. Thus the first step of the retrieval is to find dark pixels with low reflectance. Within the given image the algorithm selects pixels with high values of the normalized vegetation index and with low reflectivity in the 2225 nm (MTI "O" band) channel. This step also minimizes the effect of variation of ground albedo. Next, using the satellite level observed radiances, we estimate the surface reflectance in the MTI O band, where the aerosol effect is considerably smaller than at visible wavelengths (due to an approximate inverse wavelength dependence of the aerosol scattering cross section). Then, using the correlation between the vegetation ground reflectance at the infrared (2225 nm) and visible wavelengths, the ground reflectance at visible wavelengths is estimated. The used empirical relation between ground reflectance in near infrared and at visible wavelengths was found to be valid at the nadir as well as off nadir view. Finally from the measured radiances and the estimated ground reflectance at visible wavelengths, the aerosol optical thickness at 550 nm is deduced using the 6s radiative transfer code for a given set of environmental variables and sun and satellite geometry. Since the intensity computed with the exact theory including polarization usually differs only by a few % from the intensity computed in the scalar approximation [*Hansen*, 1971; *Mishchenko et al.*, 1994; *Mishchenko and Travis*, 1997], the polarization effects are neglected in our calculations. We are using one of the standard 6s aerosol types [*Vermote et al.*, 1997], referred to as "Continental," which is a mixture of the three basic aerosol components: 70% dust-like, 29% water-soluble and 1% soot.

4. Satellite and Ground Truth Data

[9] To evaluate the accuracy of aerosol optical depth retrieval, we need to compare the satellite derived optical thickness with other aerosol measurements. Due to large spatial and temporal aerosol variations and due to a small pixel size of the MTI we need to compare the satellite aerosol optical thickness estimates with independent aerosol data of known quality that are taken at the same location within a short time of the satellite image. To satisfy these requirements, we have chosen the AERONET [*Holben et al.*, 1998] aerosol optical thickness measurements at the Stennis and the ARM Oklahoma sites. The AERONET level 2 and 1.5 data have an accuracy of about 10%. Within the time span from June 2000 to July 2002 we have available 36 MTI images (18 pairs) of the Stennis and Oklahoma ARM sites under clear sky or partially cloudy (up to 15% cloudiness) sky conditions. Images with time differences of more than two hours were not considered suitable for the validation (most of the images are taken within 20 minutes from the available AERONET AOD measurements). The 36 images consist of 18 pairs of MTI first (satellite zenith angle < 20 degrees) and second looks (satellite zenith angle between 50 and 70 degrees). Each image, nadir and off-nadir, was treated independently when selecting pixels for computing aerosol optical thickness.

5. Results and Conclusion

[10] The errors of the MTI retrieved aerosol optical thickness at 550 nm, with respect to the AERONET ground measurement, are shown in Figure 1. The solar zenith angle varies between 12 and 54°. What is surprising is that the accuracy of the retrieval with the satellite viewing angle around 60° is considerably higher than the accuracy of the close to nadir view. The scatter-gram of the MTI retrieval using the MTI "first look" (close to nadir view) suggests that the RMS error of retrieval is around 0.11 or 65% of an average AOD (Figure 2), while the retrieval using the "second look" (satellite zenith angle around 60° back along the track) of the same scene shows the RMS error of 0.03 or 20% of an average AOD (Figure 3). The differences in accuracy cannot be caused by the differences in cloudiness or other atmospheric variables since the images (18 pairs) are taken within two minutes of each other.

[11] The physics of the scattering problem is contained in the aerosol phase function as a function of the scattering angle [*Mishchenko et al.*, 2002]. The scattering angle is determined by the solar and satellite zenith angles, and the difference in their azimuth angles. In Figure 4 the errors in the MTI AOD retrieval are shown as a function of the scattering angle. The accuracy of the MTI AOD depth

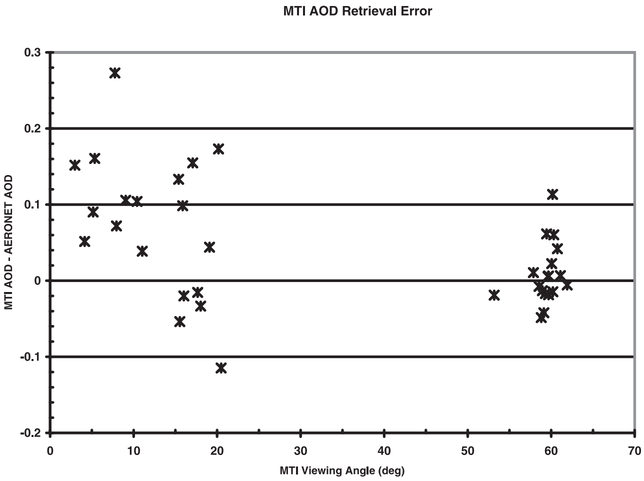

Figure 1. Errors in the MTI aerosol optical depth retrieval (the difference between the MTI retrieved and the AERONET optical depth) as a function of the satellite zenith angle. 18 pairs of images taken within two minutes from each other are used. The zenith angles of the close to nadir view (the MTI first look) are within 0 to 20° range. The second look (back along the track) corresponds to satellite zenith angles near 60°.

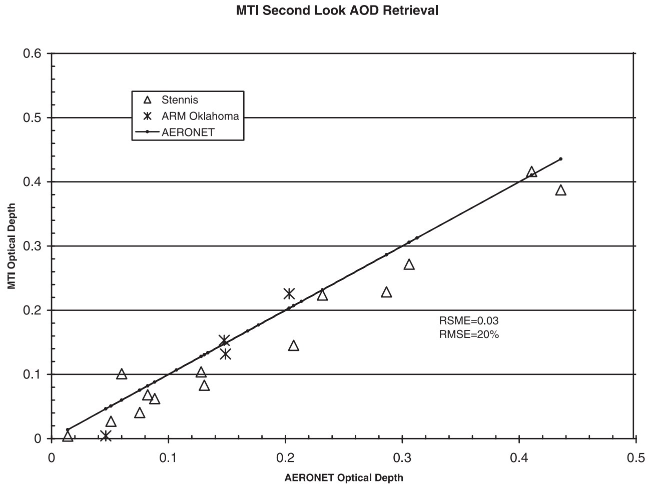

Figure 3. The accuracy of the AOD single view retrieval using the off-nadir view (MTI second look with the satellite zenith angle around 60°), of the same scenes as in Figure 2, is 0.03 or 20% of the average AOD.

retrieval using the scattering angles between 60 and 100° is around 0.03, quite comparable to the accuracy of the two-angle view algorithm results [*Veefkind et al.*, 1998; *North et al.*, 1999; *Robles-Gonzalez et al.*, 2000; *North*, 2002]. The accuracy of the retrieval at scattering angles between 100 and 180° is about 0.11 in AOD.

[12] We conclude that the DOE MTI is capable of retrieving the aerosol optical depth with an accuracy (RMS error) of around 0.03 in aerosol optical depth, when a satellite viewing angle is selected in such a way that the aerosol scattering angle is in the range between 60 and 100°. We conjecture that other single viewing satellite instruments may be able to increase the accuracy of the AOD retrieval if the sun-satellite geometry is chosen in such a way that the aerosol scattering angle is between 60 and 100°. This suggests the satellite viewing angles away from the common near-nadir look.

[13] There are several reasons why scattering angle between 60° and 100° may provide more accurate AOD retrieval than the usual close to nadir look (at scattering angles close to the backward direction). The aerosols scattering path is generally longer at the smaller scattering angles and thus we have a higher aerosol signal to the surface reflection ratio. The higher aerosol signal provides a higher signal-to-noise ratio and diminishes a relative effect of various instrumental errors like stray light, dark current and digitization step. The uncertainties in aerosol parameters, especially in the real and the imaginary parts of refractive indices and the shapes of aerosol particles - have larger effect on the scattering phase function close to the backward direction than at the medium scattering angles between 60 and 100° degrees.

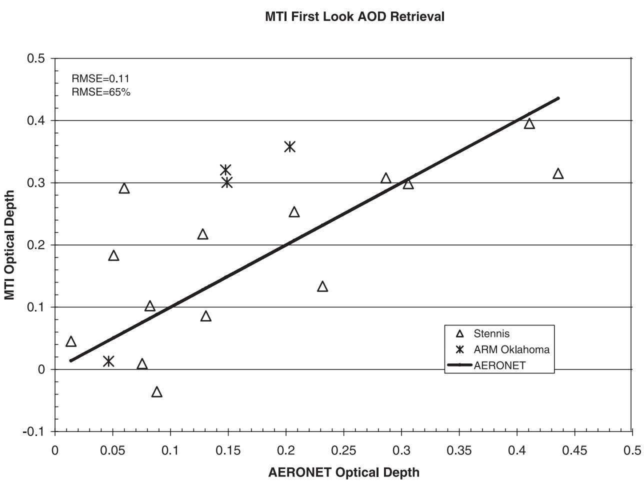

Figure 2. The accuracy (the RMS error) of the AOD single view retrieval using near nadir view (MTI first look) is 0.11 or 65% of the average AOD.

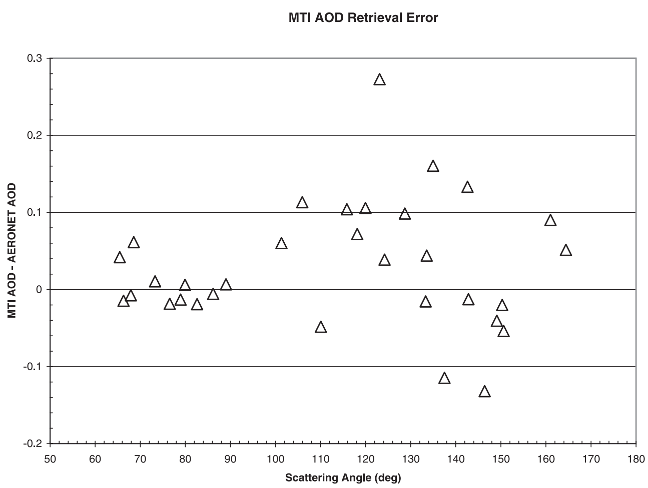

Figure 4. Errors in the MTI AOD single-view retrieval as a function of the scattering angle.

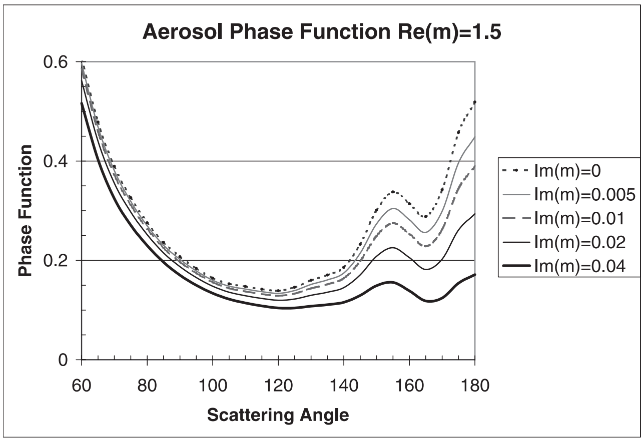

Figure 5. The effect of the imaginary part of refractive index on the aerosol phase function is much stronger near the backscattering angles than at the medium scattering angles between 60 and 90°.

[14] The effect of the imaginary part of refractive index on aerosol phase function is shown in Figure 5. Changes of imaginary part of refractive index between 0 and 0.04 lead to the changes in the phase function of about 15% close to the scattering angle of 60°, while producing the changes up to 80% close to the backward direction. Similarly the change of real part of refractive index and in the shape of aerosol particles have much larger effect close to the backward direction [*Mishchenko and Travis*, 1997; *Mishchenko et al.*, 2002].

[15] There is no doubt that a new line of satellite multiangle viewing instruments, like MISR or ATSR-2 will lead to a considerable improvement in all areas of remote sensing including the retrieval of the AOD. However, our suggestion of properly selected viewing geometry may improve the accuracy of the AOD retrieval of the current single view operational instruments. Reliable measurements of the AOD are needed to improve the assessment of aerosol effect on regional and global climate.

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