

Estimating Aerosol Absorption, Optical Depth, and Vertical Extent Using Satellite Measurements in the UV/Blue Spectral Domain

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Introduction

Until recently, the retrieval of aerosol absorption properties from space seemed so prone to error as to be almost worthless. The principal difficulty being that if the aerosol optical depth is relatively low, then the signal measured at the satellite is proportional to $\omega\tau P(\theta)$, where ω is the single-scattering albedo, τ is the optical depth and θ is the scattering angle. It is, therefore, impossible to separate variations in optical depth from variations in single-scattering albedo. However, the development of a method for the detection of absorbing aerosols using the ultraviolet (UV) measurements made by the Total Ozone Mapping Experiment Spectrometer (TOMS) instrument (Herman et al. 1997) has provided new hope for the reliable estimate of aerosol single-scattering albedo from space, at least in the blue/UV spectral domain.

Measurement Approach

The method uses wavelengths for which there is significant Rayleigh scattering. If aerosols are mixed to any significant height in the atmosphere, radiation will interact with both the aerosols and the Rayleigh scattering molecules. If measurements are made at two wavelengths with significantly different molecular scattering optical depths, the multiple scattering at the two wavelengths will differ in a way that can be used to differentiate between aerosol single-scattering albedo and optical depth. In the following figures, it is assumed that absorption occurs in small, strongly absorbing (e.g., soot) particles for which the scattering cross section is much smaller than the absorption cross section. These are mixed externally with non-absorbing (e.g., sulfate) particles with an effective radius of 0.4 μm and a refractive index of $1.45+0.0i$. The only effect of the soot on the scattering properties of the aerosol mixture is to reduce the single-scattering albedo. The underlying surface properties are chosen to be representative of a vegetated surface (Bréon et al. 1995, Kaufman et al. 1997). The differentiation of aerosol single-scattering

albedo and optical depth can be seen in Figure 1, where the variation of the reflectance ratio between 340 nm and 380 nm and the reflectance at 380 nm is shown as a function of optical depth and single-scattering albedo. The

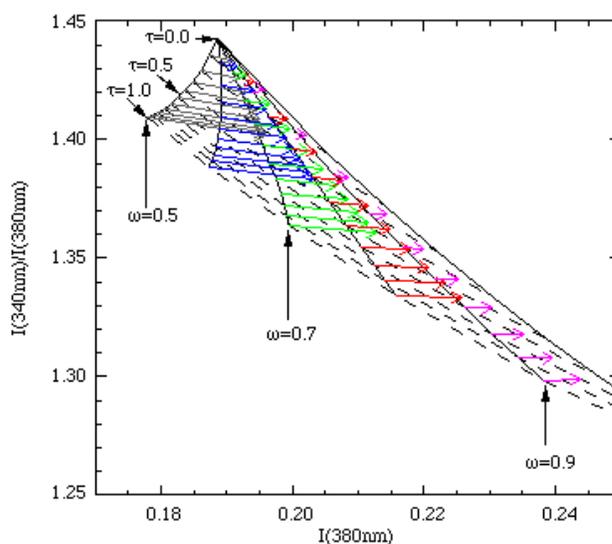


Figure 1. The radiance ratios (340 nm/380 nm) and radiances (380 nm) shown in this figure are calculated assuming that the aerosols are mixed with 300 mbars of molecular scattering and the remaining molecular scattering is above the aerosol layer. The solid lines are each drawn for a fixed single-scattering albedo and varying optical depth. The dashed lines are each drawn for a fixed optical depth and varying single-scattering albedo. The optical depths and single-scattering albedos for each line are indicated on the figure. The lines with arrows indicate the shift in calculated radiances when the aerosols are mixed with 100 mbars of molecular scattering and the remaining molecular scattering is above the aerosol layer. (For a color version of this figure, please see http://www.arm.gov/docs/documents/technical/conf_9803/cairns-98.pdf.)

reflectances shown here are for a solar zenith angle of 60 and a viewing zenith angle of 0. The solid lines are each drawn for a fixed single-scattering albedo and varying optical depth. The dashed lines are each drawn for a fixed optical depth and varying single-scattering albedo. This demonstrates how the TOMS channels at 340 nm and 380 nm can be used to detect absorbing aerosols and estimate their optical depth and single-scattering albedo, because a particular pair of radiance values at 340 nm and 380 nm uniquely defines the optical depth and single-scattering albedo. There are a number of practical difficulties with the use of this method. One problem is that because the footprint of UV instruments such as TOMS and Global Ozone Monitoring Experiment (GOME) is quite large, their field of view is frequently contaminated with cloud. The other principal difficulty is that the optical depth and single-scattering albedo that are retrieved depend on the assumed height to which the aerosol is mixed with the molecular atmosphere. Indeed, if the aerosol is confined to a very low mixed layer, the method is scarcely sensitive to aerosols at all.

The lines shown in Figure 1 are based on calculations for an aerosol layer mixed with 300 mbars of Rayleigh scattering molecules, with the remaining Rayleigh scattering molecules above this mixed layer. Each intersection of a solid line with a dashed line in that figure represents the reflectances that would be observed for a particular optical depth and single-scattering albedo of the aerosol. The lines with arrows show how these intersection points shift if the aerosol is actually mixed with 100 mbars of molecules with the remaining Rayleigh optical depth above this mixed layer. This demonstrates that if the retrieval algorithm assumes that the aerosols are mixed with 300 mbars of Rayleigh scattering molecules when the aerosols are actually mixed with 100 mbars of Rayleigh scattering molecules, there will be a pathological underestimation of the aerosol optical depth and single-scattering albedo. That is, the lower the aerosol mixed layer depth the less sensitive this retrieval method is to absorbing aerosols. Thus, the use of ground-based measurements of the vertical extent of aerosol layers from both micropulse lidar (MPL) and Raman lidar (RL) at the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) site in the Southern Great Plains (SGP) can provide extremely useful information for constraining this type of retrieval.

The method just introduced, aside from requiring significant Rayleigh optical depths, also needs a low surface reflectance. This is the case for most surface types in the UV and is also true for vegetated surfaces and many soil surfaces in the violet/blue spectral region, where

forthcoming satellite sensors [multiangle imaging spectroradiometer (MISR) and moderate-resolution imaging spectroradiometer (MODIS)] will make measurements. In the left-hand panel of Figure 2, we show that the reflectances at 410 nm and 470 nm provide qualitatively similar information about aerosol optical depth and single-scattering albedo as the UV reflectances used by TOMS. It should be noted that accuracy of calibration is an issue when applying this method, because even if the relative wavelength to wavelength calibration is very good (so the reflectance ratio is known very accurately), the retrieved properties are very sensitive to the absolute calibration of the measurement at 470 nm. The effect of uncertainties in vertical mixing of aerosols on the retrieved aerosol properties is similar to that shown in Figure 1. It is also worth noting in view of recent results (Gordon et al. 1997) that using scalar radiative transfer calculations as the basis for retrieval methods in this spectral region leads to highly misleading results, as has been noted by Herman et al. (1997).

Just as the reflectances at 410 nm and 470 nm are affected in a characteristic way by absorbing aerosols, so are the polarized reflectances. The right-hand panel of Figure 2 is similar to the left-hand panel except that the abscissa and ordinates are the polarized reflectances at 410 nm and 470 nm in the plane of scattering. Thus, measuring polarized reflectances can provide a complementary method for retrieving aerosol optical depth and single-scattering

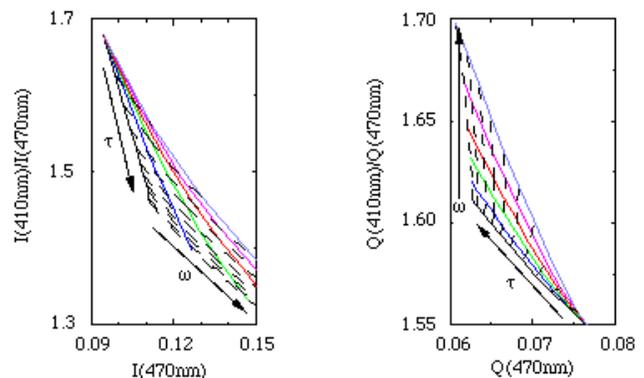


Figure 2. Similar to Figure 1 except that a) the left-hand panel is based on calculations for reflected radiances at 410 nm and 470 nm and b) the right-hand panel is based on calculations for reflected polarized radiances in the plane of scattering at 410 nm and 470 nm. (For a color version of this figure, please see http://www.arm.gov/docs/documents/technical/conf_9803/cairns-98.pdf.)

albedo over surfaces that may be bright, but that are weakly polarizing, such as snow-covered surfaces or sandy desert surfaces.

Multangle Measurements

So far we have only examined the retrieval of optical depth and aerosol single-scattering albedo using single viewing angle measurements at two wavelengths. However, both satellite and aircraft sensors that make multiangle measurements and polarized multiangle measurements have been or will be available [Polarization and Directionality of the Earth's Reflectances (POLDER), MISR]. Therefore, we show in Figure 3 what sort of results can be obtained for the retrieval of aerosol optical depth and single-scattering albedo for a viewing geometry typical of MISR viz., cosine

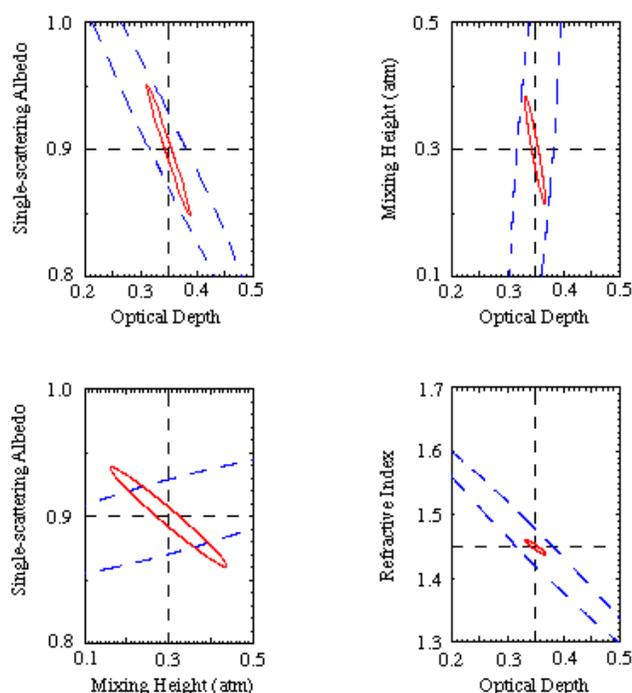


Figure 3. The areas enclosed by contours indicate the range of optical depths, single-scattering albedos, mixing heights and refractive indices that are consistent with a standard model. The standard model is indicated by the intersection of dashed lines. The domain of consistency is based on values of 2% relative root mean square (rms) error for the expected absolute calibration of intensity (dashed blue contour) and 0.2% for the absolute calibration of the degree of linear polarization (solid red contour). (For a color version of this figure, please see http://www.arm.gov/docs/documents/technical/conf_9803/airns-98.pdf.)

of the solar zenith angle of 0.8, cosine of satellite viewing zenith angle of 1.0, 0.8, 0.6, 0.4, and 0.2 with a relative solar azimuth angle of 60 (and -120). The wavelength of 470 nm is used because it will be available on the aircraft-based Research Scanning Polarimeter (RSP) that we hope to use at the ARM SGP site during the coming year. The qualitative behavior at a wavelength of 443 nm, which is used by MISR and POLDER, would be the same.

Figure 3 shows contours of the range of optical depths, single-scattering albedos, mixing heights, and refractive indices that are consistent with a standard model. The standard model is indicated by the intersection of dashed lines. The area enclosed by the blue (dashed) contour shows the range of parameters for which the multiangle intensities have a relative difference with the multiangle intensities of the standard model of less than 2%. The value of 2% chosen as the cutoff for the contour is representative of the best expected absolute calibration of a multi-element charge-coupled device (CCD) detector such as MISR or POLDER. The area enclosed by the blue (dashed) contour, therefore, shows the range of aerosol models that are consistent with the measured radiances (standard model), given the expected accuracy of the measurements. The area enclosed by the red (solid) contour shows the range of parameters for which the multiangle degree of linear polarization calculations have an rms difference with the multiangle degree of linear polarization of the standard model of less than 0.2%. The 0.2% value is chosen as the cutoff for the polarization contour because it is representative of the expected absolute polarimetric calibration of a polarimeter with onboard calibration of polarization and simultaneous measurement of the first three components of the Stokes vector (which ensures that scene polarization is negligible). The area enclosed by the red (solid) contour, therefore, shows the range of aerosol models that are consistent with the measured polarization (standard model), given the expected accuracy of the measurements.

In Figure 3, the upper-left, upper-right, and lower-left panels are a plan, elevation, and side view of the domain of possible retrievals of single-scattering albedo, optical depth, and mixing height of an aerosol layer, when all of these parameters are retrieved simultaneously. It can be seen that with this level of calibration accuracy, it is not feasible using multiangle intensity measurements to retrieve the aerosol (standard) model with any degree of certainty. If multiangle intensity measurements at 410 nm and 670 nm are included, the verisimilitude of the retrieval is improved, but the domain of retrievals is still larger than that for a single wavelength multiangle polarization measurement. In contrast, the standard aerosol model can be retrieved using multiangle polarization measurements, although it is

apparent from examining the lower left-hand panel of Figure 3 that if the mixing height is known from MPL or RL measurements, the retrieval of optical depth and single-scattering albedo is substantially improved. The lower right-hand panel indicates the sort of errors that are caused by a lack of knowledge of refractive index if only multiangle intensity measurements are used. Any error made in assigning the aerosol refractive index can obviously compound those errors made in retrieving optical depth, single-scattering albedo, and mixing height; whereas the refractive index does not need to be assigned when using multiangle polarization measurements and can in fact be retrieved very accurately.

Conclusions

It is possible to retrieve both optical depth and aerosol single-scattering albedo from multi-spectral intensity and/or polarization measurements in the blue/violet. These retrievals are sensitive to the accuracy of instrumental calibration and to the assumed vertical extent of the aerosol layer. Using multiangle polarization measurements, it is possible to estimate the height to which aerosols are mixed, as well as to retrieve the optical depth and single-scattering albedo. However, the retrieval of single-scattering albedo and optical depth from multiangle polarization measurements can be substantially improved if the mixing height of the aerosols is obtained from other (e.g., MPL or RL) measurements. The use of multiangle intensity and/or polarization measurements at a single wavelength cannot

constrain single-scattering albedo retrievals to better than ± 0.05 at low ($t < 1.0$) optical depths, although the simultaneously retrieved optical depth is still quite accurate (± 0.025). These results suggest that a combination of lidar to monitor aerosol vertical distribution, and multispectral, multiangle polarimetry would provide the best measurements for the remote sensing of aerosol microphysical properties.

References

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