

# Estimation of Aerosol Single-Scattering Albedo Over ZSS from MFRSR Data

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## Introduction

Single-scattering albedo  $\omega$  is one of the main parameters determining the climatic effect of the atmospheric aerosol. Two main approaches to  $\omega$  retrieval in the atmospheric column from ground-based measurements are known. The first is independent determination of the extinction optical thickness  $\tau_{\text{ext}}$  from transmission measurements and scattering optical thickness  $\tau_{\text{sc}}$  from the measurements of phase functions (Wang and Gordon 1993; Devaux et al. 1998). Another method, based on radiation flux measurements, was proposed in a paper by Herman et al. (1975). Its main thrust consists of using the ratio of the diffuse horizontal to direct normal flux with both fluxes measured by the same detector. This eliminates the need of the absolute calibration of the radiometer. But, on the other hand, this ratio depends upon unknown *a priori* optical properties of aerosol, surface reflectivity, and gaseous absorption. This paper concerns the possibility of application of the direct-diffuse method to the processing of the Multi-filter Rotating Shadowband Radiometer (MFRSR) data. The MFRSR instrument is deployed at the Zvenigorod Scientific Station (ZSS) of the IAP RAS, 40 km to the west of Moscow.

## Factors Affecting the Diffuse-Direct Ratio

The diffuse-direct method is based on the relation between the ratio of the hemispheric diffuse to the directly transmitted solar radiation flux in clear-sky conditions and aerosol absorption. The problem is complicated by the dependence of this ratio on many other parameters, such as aerosol and molecular optical thickness, aerosol phase function, aerosol stratification, ground albedo, sun position, and gaseous absorption. Aerosol optical thickness is derived from MFRSR diffuse and total horizontal irradiances. Sun elevation can be easily calculated. To estimate the influence of the phase function, vertical distribution, and ozone absorption we made a set of numerical experiments using Modtran 3 radiative code and the Monte Carlo method. Calculations showed, as was expected, that diffuse-direct ratio for the real atmosphere is nearly the same as for the atmosphere with weighted mean cosine of the phase function  $g = g_a \tau_{\text{as}} / (\tau_{\text{as}} + \tau_{\text{ms}})$ , weighted single-scattering albedo  $\omega = 1 - (1 - \omega_a) \tau_a / (\tau_a + \tau_m)$ , where  $g_a$  - mean cosine of the aerosol phase function,  $\tau_a, \tau_m$  - aerosol and molecular optical thickness,  $\tau_{\text{as}}, \tau_{\text{ms}}$  - optical thicknesses due to the scattering,  $\omega_a$  - aerosol single-scattering albedo. Because the main part of the aerosol is situated in the lower troposphere, stratospheric ozone and nitrogen dioxide identically change both diffuse and direct irradiances, so the diffuse-direct ratio remains the same. Variations of the vertical distribution also have no significant effect on this ratio. Thus, the diffuse-direct ratio can be

regarded as a function of the following variables - weighted mean single-scattering albedo  $\omega$ ,  $\tau = \tau_a + \tau_m$ ,  $g$ , air mass  $m$  (or solar zenith angle  $\theta$ ), and surface albedo  $A$ .

## Empirical Expression for Diffuse-Direct Ratio

To find analytical parameterization for the ratio of diffuse to the direct normal irradiance we computed this ratio for a set of parameters covering most of the possible atmospheric situations. Optical thickness  $\tau$  was varied from 0.02 to 0.8, mean cosine  $g$  - from 0 to 0.7, surface albedo  $A$  - from 0 to 0.7, single-scattering albedo  $\omega$  from 1 to 0.8. Calculations were performed by Monte Carlo method for four values of the solar zenith angle  $\theta = 45^\circ, 60^\circ, 70^\circ$ , and  $80^\circ$ . Because Henyey-Greenstein phase functions (Henyey and Greenstein 1941) depend only on one explicit parameter—mean cosine—calculations were made with these phase functions.

Constructing the empirical analytical expression describing the direct-diffuse ratio  $R$ , we started from the formula proposed in Smerkalov 1997:

$$R = \frac{\Gamma}{\Gamma + 4} \{[\exp(\tau m) + 1](1 + A\tau) - 2\}, \quad (1)$$

where  $\Gamma$  is the ratio of scattering into forward to backward hemisphere.

This parameterization is rather simple, but its accuracy is insufficient to quantitative estimations of  $R$ . Our analysis showed that more precise expression can be written in the following form:

$$R = \frac{c_1(\theta)}{1 - gc_2(\theta)} \omega \exp \left[ \frac{\tau}{k(A)} \left\{ [\exp(\tau mc_3(\theta)) + 1] (1 + Af_2(g) \tau^{f_1(g)}) - 2 \right\} m^{-1} \right], \quad (2)$$

where

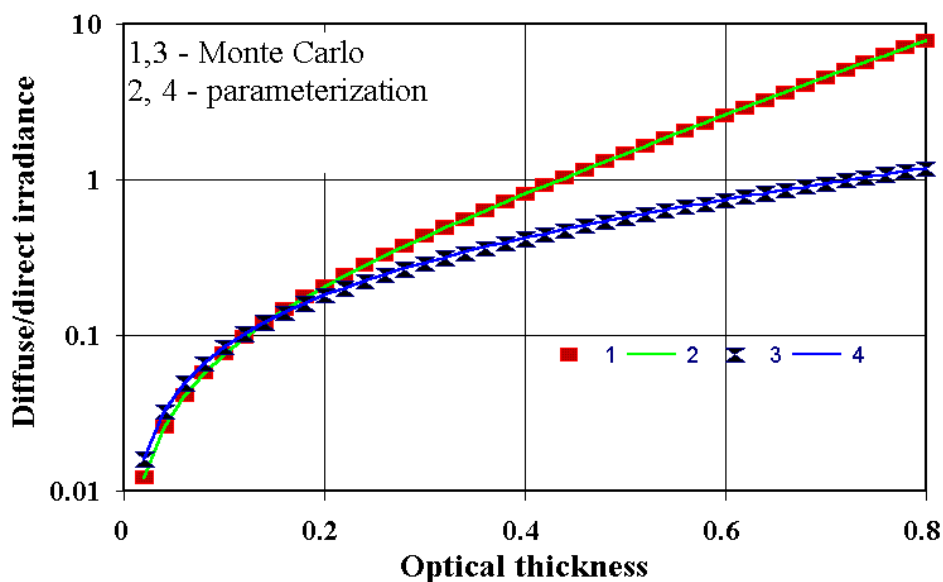
$$f_1(g) = 0.915 + 0.14g \quad (3)$$

$$f_2(g) = 0.59 - 0.55g. \quad (4)$$

The value of  $k(A)$  is about 0.6, slightly diminishing when  $A$  increases. Parameters  $c_1, c_2, c_3$  are given in Table 1 for different solar zenith angles.

$\theta$	$45^\circ$	$60^\circ$	$70^\circ$	$80^\circ$
$c_1(\theta)$	0.69	0.62	0.57	0.53
$c_2(\theta)$	0.57	0.53	0.46	0.335
$c_3(\theta)$	0.79	0.84	0.885	0.925

The mean uncertainty of the formula (2) is within 1% in case of conservative scattering. For  $\omega$  less than 1, the error for big values of optical thickness can reach several percentage points. The approximation (2) is compared with Monte Carlo simulations in Figure 1 for situations with and without aerosol absorption. Excluding  $\omega$ , two parameters are under determination in equation (2)—mean cosine of the phase function and surface reflectivity. If there is no independent information about surface albedo, it can be estimated in case of very small aerosol loading in the atmosphere, when uncertainties in aerosol absorption and mean cosine are negligible due to predominant input of molecular scattering into formation of the diffuse irradiance. Mean cosine of the aerosol-phase function can be estimated from spectral extinction measurements, as will be shown in the next chapter.



**Figure 1.** Empirical parameterization of the diffuse-direct ratio for  $\theta = 80^\circ$ ,  $A = 0.3$ ,  $g = 0.3$ ,  $\omega = 1$  (2) and  $\theta = 60^\circ$ ,  $A = 0.5$ ,  $g = 0.6$ ,  $\omega = 0.9$  (4). 1, 3 - Monte Carlo simulations.

## Estimation of the Mean Cosine of the Phase Function from Transmission Measurements

Spectral behavior of the aerosol optical thickness follows in general Angstrom's power law

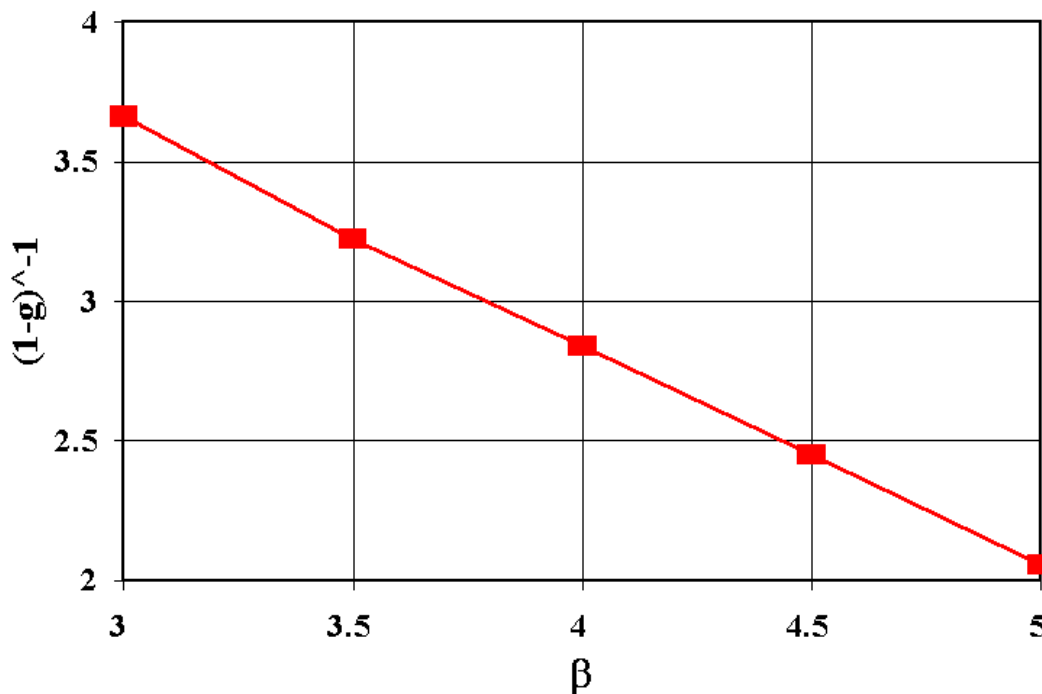
$$\tau_a \propto \lambda^{-\alpha} \quad (5)$$

The same spectral dependence of the optical thickness is inherent to power law aerosol size distribution

$$a(r) \propto r^{-\beta} \quad (6)$$

with  $\beta = \alpha - 3$ . It must be noted that although relation (5) follows from (6), similar spectral dependence in the limited wavelength range can display aerosol distributions with different shapes. However, one may expect that mean cosines of phase functions in visible spectral region for aerosols with identical spectral extinction dependences in this region do not differ dramatically.

A close correlation exists between mean cosine of phase function and parameter of the power law size distribution. It is shown in Figure 2 and can be expressed in the range  $\beta = 3 - 5$  for index of refraction  $n = 1.48$  and wavelength 613 nm as



**Figure 2.** Relation between mean cosine of phase function and parameter of the power law aerosol size distribution for  $n = 1.48$ .

For other indices of refraction (7) may be modified by multiplying the right part to the coefficient  $[0.48/(n-1)]^{0.3}$ . Formally, a mean cosine of the phase function for power distribution must be constant for different wavelengths. In reality, due to the finite particle size range, it slightly changes with wavelength within 0.01 - 0.02 in the MFRSR spectral region. These variations do not exceed the accuracy of the determination of  $g$  and can be neglected. In case of spectral behavior of extinction distinct from (5), the mean cosine can be estimated solving the inverse problem for the MFRSR aerosol optical thickness data.

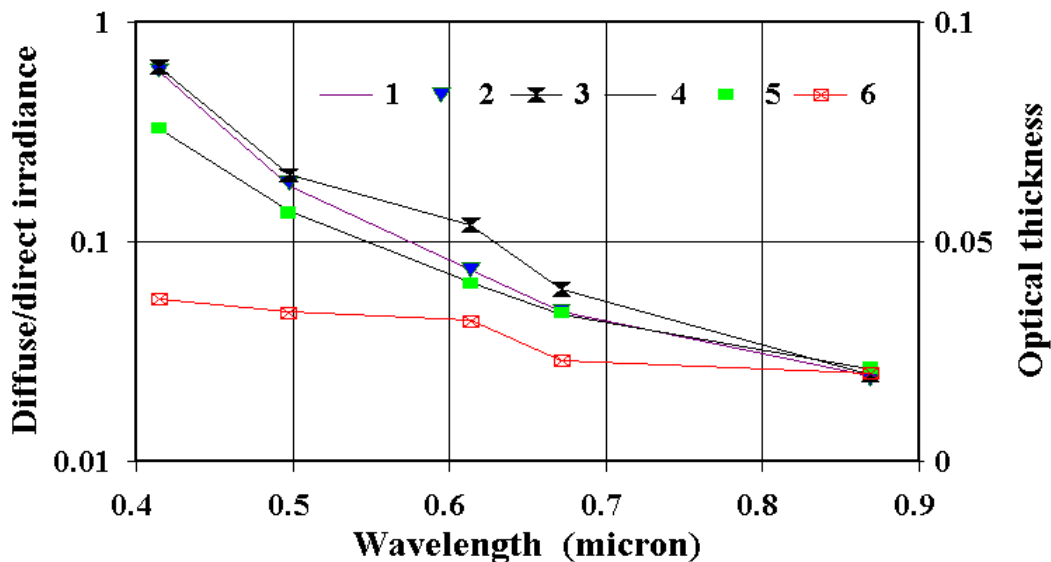
## Comparison of the Calculated and Measured with MFRSR Diffuse-Direct Ratio

We began comparisons of the observed and calculated ratios from situations with low aerosol concentration. One of them was registered on January 7, 2002, another on March 16, 2002. In both cases, aerosol optical thickness near 500 nm was about 0.03. It was found that coincidence between measurements and calculations can be achieved in the first case assuming surface albedo  $A = 0.3$  is small for the fresh snow and low sun elevation ( $10^\circ$ ). In the second case, measurements and calculations matched only for zero albedo. Analysis of other situations showed that in most cases, independent from the aerosol optical thickness, the measured ratios are about 10% less than calculated for realistic ground

reflectivity. This discrepancy can't be explained by aerosol absorption, since it takes place even in situations where aerosol optical thickness is at 414 nm, 10 times less than molecular. This possibly

$$g = \frac{5.04 - 0.8\beta}{6.04 - 0.8\beta} \quad (7)$$

may be caused by non-lambertian response of the MFRSR to the diffuse flux and partial covering of the horizon by forest surrounding ZSS. This problem needs further investigation to determine why the surface albedo is so small in the spring in the region of ZSS or whether uncertainties are caused by underestimation of the diffuse irradiance. In the present work we formally multiplied diffuse irradiance by 1.1. With such correction of the diffuse irradiance, rather good agreement is achieved between measured and calculated R. The results of comparison for 07.01 and 16.03 are presented in Figure 3. Surface albedos are equal to 0.7 in the first case and 0.2 in the second (no snow cover occurred until this day in the Moscow region). The 07.01 calculations were also made without correction to ozone absorption. It follows from Figure 3 that diffuse-direct ratio can be used for estimations of gaseous absorption, too. In most analyzed situations no significant aerosol absorption was displayed. One exception is the air mass, which came to the ZSS region on March 18. It was characterized by high aerosol loading ( $\tau_a$  at 500 nm exceeded 0.3) and small particles (Angstrom exponent about 2). Retrieval of the single-scattering albedo was performed with surface albedo as it was estimated two days before. Spectral dependences of the aerosol optical thickness, aerosol absorption, and single-scattering albedo obtained after processing of the measurement data are presented in Figure 4. It must be noted that alternative assumption about the surface albedo does not noticeably change the results of the  $\omega$  (in this case no correction of diffuse irradiance is needed).



**Figure 3.** Diffuse-direct ratios measured by MFRS in clear conditions on January 7 ( $2, \theta = 80^\circ$ ) and March 16 ( $5, \theta = 70^\circ$ ); 1, 3, 4 - calculations for  $A = 0.7$  (1,3) and  $A = 0.2$  (4). Curve 3 is calculated for optical thickness without subtracting the ozone absorption. Curve 6 - aerosol optical thickness on January 7, 2002. Measured ratios are multiplied to 1.1.

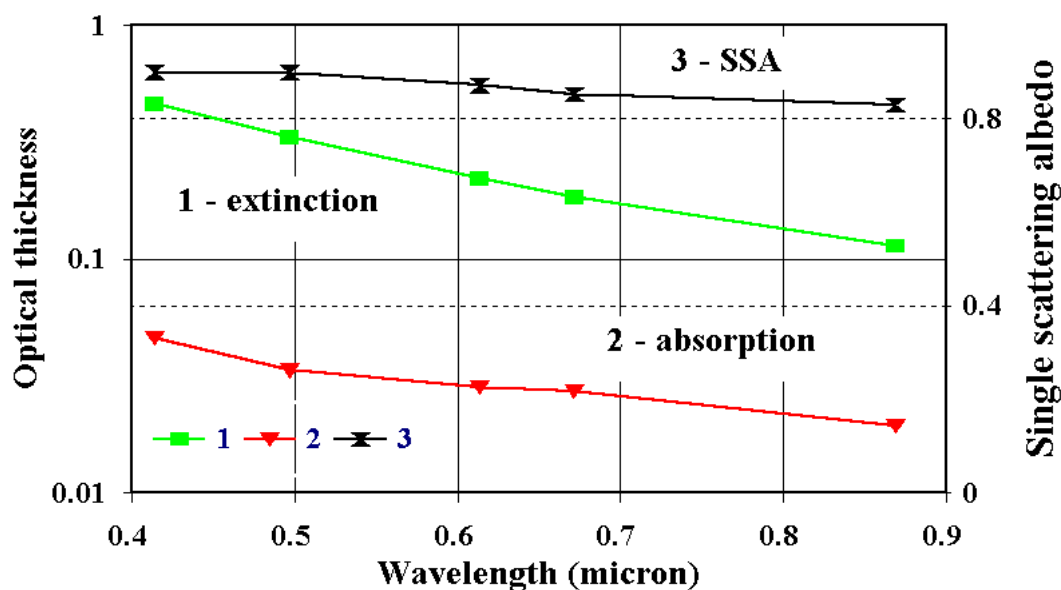


Figure 4. Retrieval of the columnar aerosol single-scattering albedo.

## Summary

An empirical analytic parameterization is proposed for the ratio of diffuse horizontal to direct normal irradiance. The *a priori* unknown variables in this formula—mean cosine of the aerosol phase function and surface reflectivity—can be estimated using MFRSR data, first from spectral dependence of the optical thickness, and second from diffuse-direct ratios in situations having small aerosol concentrations in the atmospheric column. Calculated and observed ratios are in a good agreement after 10% correction of the diffuse flux. In situations with high aerosol loading the estimations of the aerosol absorption gave the value of the single-scattering albedo at about 0.85.

## Acknowledgment

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