Parameterization of the ratio of diffuse to direct solar irradiances and its application to estimates of single scattering albedo with MFRSR type instruments

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An analytical parameterization of the ratio of diffuse to direct solar irradiances is proposed. The possibility to correct the data of measurements of diffuse radiation by radiometers of the MFRSR type is analyzed. Results of calculations with parameterization proposed are compared with the data of field observations.

Introduction

The atmospheric aerosol single scattering albedo Λ_a is an important characteristic, affecting not only the magnitude, but also the sign of the aerosol radiative forcing.[1] Different techniques, among them indirect, are used to determine Λ_a in the atmospheric column from the measurements of the spectral extinction and daytime sky brightness in the clear-sky conditions, including solution of the inverse problem and following recalculation of the scattering and extinction for the retrieved size distributions and real and imaginary parts of the refractive index.[2]

Semi-empirical methods for estimation of the aerosol scattering optical thickness immediately from the observed angular dependence of the sky brightness in the solar almucantar are justified in Refs. 3–5. The iteration approach to retrieving the phase function from measurements of the sky brightness in the solar almucantar and in the solar principal plane with following calculation of the single scattering albedo on the base of the information on the aerosol optical thickness was suggested in Refs. 6 and 7. To use both direct and indirect methods for retrieving Λ_a, sky brightness measurements in absolute units ($W/(m^2 \cdot sr)$ or simply sr^{-1}) is necessary. Moreover, approaches[3–5] are based on the model simulations for a few size distributions; and the solving of the inverse problem is connected with difficulties caused by the specificity of the ill-posed problems.

To determine the imaginary part of the aerosol refractive index and the surface albedo A_s, it was proposed[8,9] to use the dependence of the ratio G of the measured diffuse to direct transmitted solar fluxes on the zenith angle θ. An important advantage of this approach, called the Diffuse/Direct (or D/D) method is that in case of measurements of both irradiances by the same detector, the calibration of the device is not necessary. However, the problem of estimation of the absorption index from the data on the flux ratio is so underdetermined, that studies in this direction were not continued. To reveal the aerosol climatic effects, not optical constants of the aerosol matter are required, but the single scattering albedo, immediately affecting the diffuse radiative flux. Therefore, the D/D method is more promising for estimating Λ_a.

The measured ratio is a function of many parameters. Therefore, the fitting of the analytical parameterization of G is undoubtedly helpful in practical implementation of the D/D method. Moreover, the use of such parameterization simplifies the analysis of the influence of different factors on the G value and on the retrieved values of the single scattering albedo.

In this paper, an analytical approximation of the ratio of diffuse to direct solar flux (normal to the receiving area) is suggested, which is valid in the wide range of variations of the input parameters. Since the presently known wide-angle detectors have the angular response different from the Lambertian one, the correct accounting for the non-ideal cosine characteristics of the detector is needed.

The analysis of the possibility to correct the results of the diffuse radiation measurements is carried out here for the Multi-Filter Rotating Shadowband Radiometer (MFR-7), as an example. As the illustration, the ratio G, obtained from the data of field measurements, numerical computations, and the values of the single scattering albedo, retrieved by the D/D method, were compared with those obtained from simultaneous measurements of the sky brightness and the transparency of the atmosphere with the solar photometer CIMEL CE-318, included into the worldwide aerosol monitoring network AERONET (AErosol RObotic NETwork).[10]

Assumptions in D/D ratio calculations

The ratio of the diffuse to direct solar fluxes depends on aerosol and molecular optical thicknesses

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τ_a and τ_R, coefficients of the aerosol and gaseous absorption, surface albedo A_s and aerosol phase function (its asymmetry factor g_a). Let us introduce a model with weighted optical characteristics:

$$\tau = \tau_a + \tau_R; \tag{1}$$

$$g = \Lambda_a g_a \tau_a (\Lambda_a \tau_a + \tau_R)^{-1}; \tag{2}$$

$$\Lambda = (\Lambda_a \tau_a + \tau_R)\tau^{-1}, \tag{3}$$

where index "a" means aerosol, and "R" denotes the molecular (Rayleigh) scattering.

Measurements of the diffuse radiance are carried out with the MFR-7 radiometers in five spectral bands: 415, 500, 615, 673, and 870 nm (spectral channel at a wavelength of 940 nm is used for determination of the water vapor content in the atmospheric column). In addition to aerosol absorption and scattering, the solar radiance fluxes can be also affected by O_3 and NO_2 absorption. At background conditions O_3 and NO_2 are mainly located in the stratosphere, where during last decade after cleaning the atmosphere from the after-effects of the Pinatubo volcano eruption, aerosol content is significantly less, than in the troposphere.

In this connection, in the first approximation, the processes of the Rayleigh and aerosol scattering and gaseous absorption at the wavelengths, where the O_3 and NO_2 absorption is noticeable, can be regarded as spaced in height, and the ratio G should be the same as in the absence of these gases at the optical thickness equal to the measured one with the subtracted portion caused by the O_3 and NO_2 absorption.

The data, pointing out to the significant influence of the weekly absorbing aerosol stratification (in the absence of gaseous absorption) and a particular angular dependence of the angular scattering coefficients (at a constant mean cosine) on the magnitude of the diffuse fluxes, are unknown to authors. Therefore, the model of plane-parallel, vertically homogeneous atmosphere without accounting for the molecular absorption was used in the calculations, and the Henyey–Greenstein phase functions[11]:

$$p(\psi) = (1 - g^2)(1 + g^2 - 2g\cos\psi)^{-3/2}, \tag{4}$$

where ψ is a scattering angle, explicitly depending on g, were selected as the model ones. Computations of the radiance fluxes as functions of τ, g, Λ, solar zenith angle θ, and surface albedo A_s were conducted by the Monte Carlo technique (direct modeling[12]); therewith, the values of the solar zenith angles θ in numerical simulations did not exceed 80°.

Fitting of the approximating relations

The problem of parameterization of the diffuse radiation (both monochromatic and integral over solar spectrum) has a long-term history. Summary of the principal formulas, suggested to the end of the last century is given in the monograph by V.A. Smerkalov,[13] where the author proposed more precise, than known to date, relation:

$$G = \frac{\Gamma}{\Gamma + 4}\left\{\left[\exp(\tau_s m) + 1\right](1 + A_s\tau_s) - 2\right\} m^{-1}, \tag{5}$$

where τ_s is the scattering optical thickness; m is the air mass in direction to the Sun ($m = \sec(\theta)$ for the plane-parallel atmosphere); Γ is the characteristic of the phase function asymmetry, equal to the ratio of the radiance scattered into the forward and the backward hemispheres:

$$\Gamma = \int_0^{\pi/2} p(\psi)\sin\psi\, d\psi \Bigg/ \int_{\pi/2}^{\pi} p(\psi)\sin\psi\, d\psi. \tag{6}$$

Comparison of Eq. (5) with results of Monte Carlo simulations has shown that its accuracy is insufficient for estimations of the aerosol absorption. Therefore, remaining the structure of Eq. (5) unchanged, we propose[14] a more precise formula:

$$G = \frac{c_1(\theta)}{1 - gc_2(\theta)}\Lambda\exp\left[(\Lambda - 1)\frac{\tau}{0.7}\right]\times$$
$$\times\left\{\left[\exp\left(\tau m c_3(\theta)\right) + 1\right]\left(1 + A_s f_2(g)\tau^{f_1(g)}\right) - 2\right\} m^{-1}. \tag{7}$$

Empirical functions $f_1(g)$ and $f_2(g)$, as well as values of c_1, c_2, and c_3 for four values of solar zenith angles: 45, 60, 70, and 80° are given in Ref. 14. The approximation (7) was used for estimation of the single scattering albedo of smoke aerosol during forest and peat-bog fires in Moscow Region in summer and fall of 2002 [Refs. 15 and 16]. However, formula for G in form (7), as it will be shown below, is not true for large values of the surface albedo. Moreover, it is desirable to have an approximating relation not only for several fixed solar zenith angles, but for their wide enough range. In the new version of parameterization of the ratio of diffuse to direct solar fluxes, proposed in the present paper, the rigorous relation[9] was taken as the base:

$$G = \frac{G_0 + A_s S(\tau, g, \Lambda) m^{-1}}{1 - A_s S(\tau, g, \Lambda)}, \tag{8}$$

where G_0 is the value of G at $A_s = 0$, and $S(\tau, g, \Lambda)$ has the sense of the integral reflection function. It follows from Eq. (8) that impossibility to use the approximation (7) at high values of the surface albedo is conditioned by its linearity relative to A_s as distinct from the more complicated dependence, determined by the last relationship.

The following parameterization is proposed based on the analysis of a large array of computational data [$\tau = 0.05$–1.0 (step 0.05); $\Lambda = 0.8$–1 (0.05); $g = 0.2$–0.6 (0.2); $\theta = 45$–$80°$ (5°); $A_s = 0$–0.6 (0.2)]:

$$G_0 = \frac{c_1(\theta)g^{1,5} + c_2(\theta)}{1 + 0.533g}\Lambda\exp\left[(\Lambda - 1)\tau(0.05 + 1.35\theta)\right]\times$$
$$\times\left[\exp\left(-\tau c_3(\theta)\cos\theta\right) - 1\right]\cos\theta;$$
$$c_1(\theta) = -0.4073\theta^2 + 0.5728\theta - 0.1559,$$
$$c_2(\theta) = 0.909 - 0.28\theta, \tag{9}$$

$$c_3(\theta) = 0.612 + 0.223\theta,$$

where the solar zenith angle is measured in radians.

Parameterization of $S(\tau, g, \Lambda)$ was fitted in the following form:

$$\begin{gathered} S = F_1(\Lambda,\tau)F_2(g)\left[1 - \exp\left(-F_3(g)\tau\right)\right]; \\ F_1(\Lambda,\tau) = \Lambda\exp\left[1.54(\Lambda - 1)\tau\right], \\ F_2(g) = 0.57 - 0.314g, \\ F_3(g) = 1.787 - 0.276(1 - g)^{-1}. \end{gathered} \tag{10}$$

Probability distribution of the parameterization errors corresponding to the scheme (8)–(10) is presented in Fig. 1.

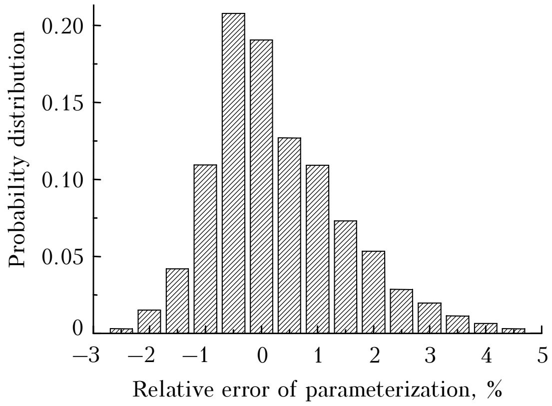


Fig. 1. Distribution of the parameterization errors of the ratio G of diffuse to direct flux.

More than 90% of nodes of the aforementioned grid of parameters fall into the range of errors not exceeding 2%. The maximal uncertainties are observed for small optical thicknesses and a solar zenith angle of 45°, and minimal ones – for a large optical thickness and zenith angle of 80°, which is maximal among the considered ones. Due to the monotonous dependence of G on the single scattering albedo, the value of Λ can be easily found by numerical methods at known A_s and g , and Λ_a can be retrieved from its value using Eq. (3). In case of the absence of satellite or direct measurements, observations in situations with minimal aerosol loading of the atmosphere can be used for A_s estimation. In such conditions, especially in the blue and green spectral regions, mean weighted asymmetry factor should be close to zero, and mean weighted single scattering albedo – to unity. Therefore, the errors in setting g_a and Λ_a will have an insignificant effect on the value of G, that must allow one to estimate A_s at a known value of τ.

On a possibility of correction of the angular characteristics of the MFRSR type radiometers

Multi-Filter Rotated Shadowband Radiometers MFRSR are widely used for determination of the aerosol optical thickness. The instrument measures spectral fluxes of global and diffuse radiation. The direct radiation, inferred from their difference is used for the retrieval of the atmospheric optical thickness. When measuring, the instrument is strongly oriented to the cardinal points.

Normalized response of each instrument is measured in two directions: north–south and east–west with the artificial light source under laboratory conditions. This allows one to introduce corrections for the non-ideality of the cosine characteristics of the radiometer, when calculating the direct radiation, because the Sun position in the sky dome is known in any moment, and the correcting coefficient $R(\theta, \varphi)$ can be calculated as the mean with weights of the angular distances to the reference planes. However, the question about the possibility of correcting the measured diffuse fluxes is more complicated, since the angular distribution of the incoming radiation intensity is *a priori* unknown, and requires an individual analysis.

The problem of errors, arising from the difference of the angular characteristic of the hemispherical detectors from the Lambertian one, became especially actual since the discrepancies between measured and calculated shortwave radiative fluxes in the clear sky conditions have been revealed (see Ref. 17, e.g.).

Analysis of errors, arising from the non-ideality of the angular characteristic and the neglecting of the polarization sensitivity of the receiver, was conducted[18] for several types of radiometers, including MFRSR. The error magnitudes in Ref. 18 were obtained with the use of the simplest models of sky brightness, including isotropic one. They were −1.5 – 1% when neglecting the polarization effect and −4 – −5% when neglecting the real cosine characteristics.

Contrary to Ref. 18, we have undertaken an attempt to study the errors, caused by the non-ideality of the cosine characteristics for realistic aerosol models, and to analyze their dependence on aerosol optical properties and solar zenith angle.

To estimate the measurement errors for diffuse radiation, the results of sky brightness $I^{\downarrow}(\xi, \varphi)$ computations by the local estimate method in approximation of the plane-parallel aerosol-molecular atmosphere and underlying surface, reflecting by the Lambert law[12] was used. The sensitivity of the detector to the state of the polarization of the incident radiation was not taken into account at this stage. The sky brightness was calculated for 84 azimuth angles φ with a step of 1° for zenith angle ξ. As aerosol microstructure models, two different types of particle size distribution, typical for the continental aerosol: power law Ar^{-b}, $b = 3$, 4, 5; and lognormal (median of the particle radius was 0.05 μm, the variance of the logarithm of radius was 0.5) were chosen. Mean cosine of the phase function varied in the range 0.53–0.75.

In order to simulate the MFRSR response, the sky brightness for each azimuth and zenith angle was multiplied by the factor $R_L(\xi, \varphi)$, which value was taken from the table attached to the instrument documentation

(MFR head S/N 425), and was integrated over the hemisphere. The ratio of the integrals

$$R = \int_0^{2\pi}\int_0^{\pi/2} I^{\downarrow}(\xi,\varphi) R_L(\xi,\varphi)\cos\xi \, d\xi d\varphi \Bigg/ \int_0^{2\pi}\int_0^{\pi/2} I^{\downarrow}(\xi,\varphi)\cos\xi \, d\xi d\varphi \qquad (11)$$

was regarded as the correction factor for the diffuse irradiance. The examples of R computations are illustrated in Figs. 2 and 3.

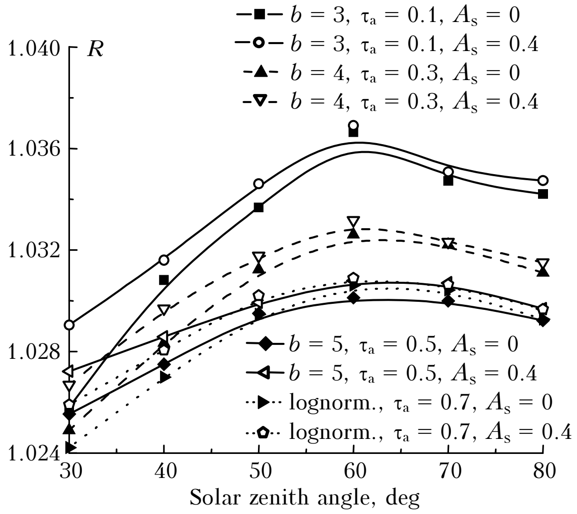


Fig. 2. Dependence of the correction coefficient on the zenith angle of the Sun for the wavelength $\lambda = 496$ nm.

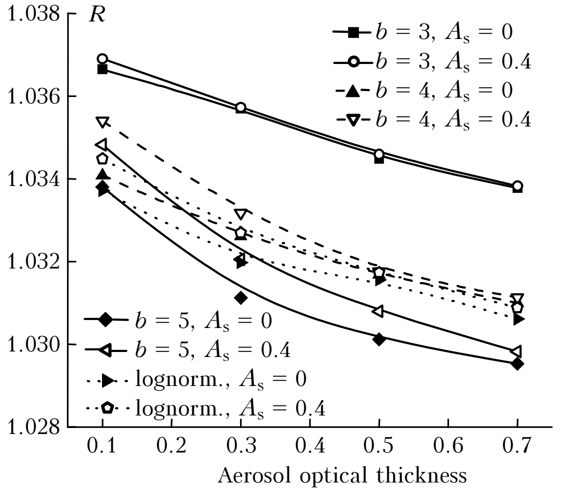


Fig. 3. Dependence of the correction coefficient on the optical thickness for a solar zenith angle of 60° and the wavelength $\lambda = 496$ nm.

It follows from the results of calculations that fluxes "measured" by MFRSR are by 2–4% less than "real" ones (fluxes were calculated without and with accounting for correcting factors $R_L(\xi, \varphi)$, respectively). The ratio R of "actual" to "measured" flux depended rather weakly on azimuth and zenith angles of the Sun, the asymmetry factor of the phase function, the wavelength, the surface albedo and the aerosol optical thickness. A tendency of diminishing R with growth of the aerosol optical thickness was observed. Maximum of R as a function of the solar zenith angle is reached approximately in the region 60–70°. Analysis of the calculations showed that the measurement data could be improved, when using correcting coefficients corresponding to a particular instrument (to an error not exceeding ≈ 1%).

Comparison with the data of observations

Measurements of the atmosphere transparency and sky brightness with use of the CIMEL CE-318 photometer, included into world-wide AERONET network, were carried out at Zvenigorod Scientific Station of IAP RAS since fall of 2006. AERONET photometers were regularly calibrated at NASA Goddard Space Flight Center. In spring the CIMEL photometer operated in parallel with MFR-7 radiometer. Three spectral bands (~ 500, 670, 870 nm) of CIMEL CE-318 and MFR-7 are close to each other, therefore, in comparison of calculations by Eqs. (8)–(10) with data of observations, optical thickness, measured by CIMAL at these three wavelength, were used and the ratio of fluxes independent of the calibration was taken from MFR-7 data.

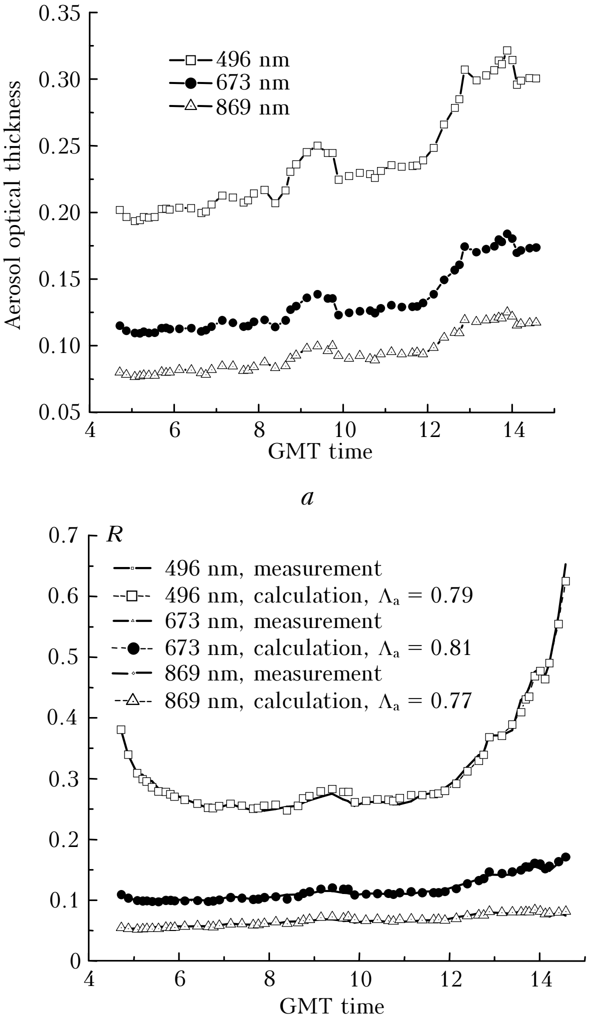
Comparison of calculation results with the data of observations is shown in Fig. 4.

The surface albedo was assumed to be equal to 0.1 at wavelengths of 496 and 673 nm, and 0.25 at a wavelength of 869 nm (there was no snow cover in Moscow Region in this period). The mean cosine of phase function was assumed to be the same as for the power law particle size distribution with the corresponding Angström exponent equal to that measured by CE-318. As it follows from Fig. 4, in spite of the imperfect synchronism of the measurements (MFR-7 measured every 2 min and CIMEL every 15 min), calculations by Eqs. (8)–(10) adequately describe the temporal behavior of G at all three wavelengths. Note that significant diurnal variations of the optical thickness were registered at the measurement period. The values of single scattering albedo retrieved with the help of the D/D-method (0.80; 0.86; 0.80 on March 28, 2007 and 0.79; 0.81; 0.77 on March 29, 2007) do not contradict the results of the inverse problem solution for these days presented at AERONET site[10] (0.80; 0.82; 0.80 и 0.80; 0.78; 0.775, respectively.).

Conclusions

The suggested parameterization of D/D-ratio can be useful for modeling of the diffuse irradiance and estimations of the aerosol absorption. Taking into account that errors of the modern photometers, when measuring the optical thickness, are about 0.01, sufficiently large aerosol turbidity of the atmosphere

($\tau_a > 0.1$) is needed to obtain satisfactory results (similar restrictions are imposed by other remote methods).



a

b

Fig. 4. Time behavior of optical thicknesses (*a*); measured and calculated ratios of diffuse to direct solar fluxes (*b*). Zvenigorod, 03.29.07.

To increase the accuracy of the *D/D* estimates, reliable data on the mean cosine of the phase function of aerosol scattering and the albedo of the underlying surface are needed. Note that at invariable aerosol properties and underlying surface during the day, g_a and A_s can be found via the dependence of G on the solar zenith angle. The possibility of such an estimate, as well as another approaches to the mean cosine determination from observations of the atmosphere transparency and sky brightness are the subject of the further consideration.

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