Integral method for determination of the optical depth due to light scattering from data on the sky brightness

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Based on analysis of data obtained from solution of the radiative transfer equation through the atmosphere by the Monte Carlo method, we have developed an integral method for determination of the atmospheric optical depth due to aerosol scattering from data on sky brightness along the solar almucantar. The approximation formulas obtained apply to two visible wavelengths that are being used in the NASA sun photometers. The utility of the method and its accuracy are addressed.

One of the important problems in atmospheric physics nowadays is a wide-scale investigation of aerosol absorptivity. Determination of the vertical optical depth τ of the cloudless atmosphere is usually based on the well-known law of light extinction (Bouguer law):

$$F = F_0 = \exp(-\tau m), \quad (1)$$

where F_0 and F are the spectral fluxes of direct solar radiation at the atmospheric top and at the surface level; m is the atmospheric mass along the direction toward the sun. The optical depth τ includes the components due to scattering τ_s and absorption τ_{abs}, which, in their turn, can be divided into the molecular and aerosol components:

$$\tau = \tau_s + \tau_{abs} = \tau_{ms} + \tau_{as} + \tau_{m,abs} + \tau_{a,abs}. \quad (2)$$

Here τ_{ms} and τ_{as} are the optical depths due to molecular and aerosol scattering; $\tau_{m,abs}$ and $\tau_{a,abs}$ are respectively the molecular and aerosol absorption depths.

The molecular component τ_{ms} can be calculated in a standard way. The $\tau_{m,abs}$ component can be separated based on the approach proposed in Refs. 1 to 3. In the wavelength region $400 \le \lambda \le 700$ nm that is considered here, the main absorbing gas is atmospheric ozone having a wide continuous Chappuis absorption band.

To determine the aerosol optical depth (AOD) due to absorption, we have to know the AOD due to scattering. It can be found by various methods from observations of angular and spectral characteristics of the radiation field from the earth's surface. Most of the current techniques for reconstructing the aerosol scattering depth assume measurements of brightness of the clear cloudless atmosphere along the solar almucantar. (Note that for the first time the idea of determination of the scattering depth $\tau_s = \tau_{ms} + \tau_{as}$ from measurements of brightness along the solar almucantar was put forward by E.V. Pyaskovskaya-Fesenkova[4]; a brief bibliography of current approaches to solution of this problem can be found in Ref. 5.)

Introduce designations of the basic scattering characteristics (see, e.g., Ref. 6), which will be used throughout this paper. The absolute radiance indicatrix at solar almucantar $f(\varphi)$ (φ is the scattering angle) is related to the sky brightness $B(\varphi)$ by the following equation:

$$B(\varphi) = E_0 \exp(-\tau m)\, m f(\varphi),$$

E_0 is the extraterrestrial solar constant. The absolute radiance indicatrix $f(\varphi)$ includes the following components:

$$f(\varphi) = f_{as}(\varphi) + f_{ms}(\varphi) + f_2(\varphi) + f_{sur}(\varphi), \quad (3)$$

where $f_{as}(\varphi)$ and $f_{ms}(\varphi)$ are the coefficients of directional aerosol and molecular single scattering; $f_2(\varphi)$ and $f_{sur}(\varphi)$ are the terms describing the multiple scattering effects and the influence of the surface.

Observations of the radiance indicatrix are used to determine the function

$$\tau_{obs} = 2\pi \int_0^{\pi} f(\varphi) \sin\varphi \, d\varphi, \quad (4)$$

which is called the brightness optical depth of the atmosphere. Based on Eq. (3), τ_{obs} is traditionally represented as

$$\tau_{obs} = \tau_s + \tau_2 + \tau_{sur}, \quad (5)$$

where

$$\tau_s = 2\pi \int_0^{\pi} [f_{as}(\varphi) + f_{ms}(\varphi)] \sin\varphi \, d\varphi,$$

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$$\tau_2 = 2\pi \int_0^\pi f_2(\varphi)\sin\varphi\, d\varphi, \quad \tau_{sur} = 2\pi \int_0^\pi f_{sur}(\varphi)\sin\varphi\, d\varphi.$$

One of the simple techniques of τ_{as} reconstruction from measurements at solar almucantar was suggested in Ref. 5. This difference technique was based on the idea of the possibility of determining τ_{as} through τ^*, which is determined by the equation

$$\tau^* = 2\pi \int_0^{\pi/2} f(\varphi)\sin\varphi d\varphi - 2\pi \int_{\pi/2}^{\pi} f(\varphi)\sin\varphi d\varphi. \quad (6)$$

The symmetry of the function $f_{ms}(\varphi)$ about the point $\varphi = \pi/2$ and the assumption that $\int_0^{\pi/2} f_{sur}(\varphi)\, d\varphi \approx \approx \int_{\pi/2}^{\pi} f_{sur}(\varphi)\, d\varphi$ mean that τ^* is determined by the aerosol component of the atmosphere and the multiple scattering effects and is insensitive to the influence of the surface. These circumstances allowed the relation between the difference τ^* and the optical depth due to aerosol scattering to be approximated by simple equations.

In this paper, to determine the scattering optical depth $\tau_s = \tau_{ms} + \tau_{as}$, it is proposed to replace the difference of the forth and back integrals [Eq. (6)] by their sum, which is nothing else than the brightness optical depth of the atmosphere τ_{obs} [Eq. (4)]. According to Eq. (5), the value of τ_{obs} depends on scattering optical depth τ_s and the value of $\tau_{2,sur} = \tau_2 + \tau_{sur}$ caused by multiple scattering and reflection of light from the surface with the albedo A_s. By analogy with the difference method, we can assume that there is some functional relation between τ_s and τ_{obs}. The aim of this paper is to derive simple approximation formulas for determination of scattering optical depth τ_s (and, consequently, τ_{as}) from experimentally measurable τ_{obs}.

The possibility of deriving such formulas is apparently connected with the accuracy of $\tau_{2,sur}$ estimation. Various approaches that were used earlier for this purpose showed[6] that $\tau_{2,sur}$ could only be considered accurately if based on the data of solution of the radiative transfer equation for the atmosphere. Such numerical data may be obtained, for example, using Monte Carlo algorithms.[7,8] The accuracy in calculating $f(\varphi)$ using modern computer technologies is rather high: relative errors $\delta f(\varphi)$ for all reasonable aerosol scattering phase functions, scattering optical depth $\tau_s \lesssim 1$, and secant of the solar zenith angle $\sec Z_☉ \le 5$ do not exceed a few tenths of percent.

The absolute radiance indicatrix $f(\varphi)$ was calculated, as in Ref. 5, by the method of conjugate wanderings (with the allowance made for the axial symmetry of the Earth–atmosphere–sun system) within the framework of the plane-parallel vertically homogeneous molecular-aerosol atmosphere. The aerosol model of the atmosphere included three groups of particles with the lognormal size distributions: Aitken nuclei, submicron and coarse fractions.[9] The forward peak of the aerosol scattering phase function

$$\Gamma_a = \int_0^{\pi/2} f_{as}(\varphi)\, d\varphi \Bigg/ \int_{\pi/2}^{\pi} f_{as}(\varphi)\, d\varphi$$

was specified by variations of the number of particles in the modes. Finally, we have selected the aerosol scattering phase functions with the following values of Γ_a: $\lambda = 439$ nm – $\Gamma_a = 7.03$, 8.6, and 10.2; $\lambda = 675$ nm – $\Gamma_a = 7.03$, 9.7, and 11.6. (Recall that the wavelengths correspond to the spectral ranges of the NASA sun photometers in the visible spectral region.[10]) The molecular scattering optical depths τ_{ms} were taken equal to 0.2379 for $\lambda = 439$ nm and 0.0427 for $\lambda = 675$ nm; the aerosol extinction optical depths τ_a varied in the range $0.1 \le \tau_a \le 0.9$ with the step of 0.2 (these boundaries encompass most of the experimental AOD values measured in an industrial city[11]). The single scattering albedo ω_a was taken equal to $\omega_a \in \{0.7, 0.8, 0.9, 1.0\}$ and covered the majority of cases of the presence of both natural and urban aerosol particles in the atmosphere. The solar zenith angle varied within $60 \le Z_☉ \le 80°$ ($2 \le \sec Z_☉ \le 5$); the equality $\sec Z_☉ = m$ was assumed to be valid in this range of the $Z_☉$ angle. The spectral albedo of the surface A_s was taken equal to, respectively, 0.06 ($\lambda = 439$ nm) and 0.15 ($\lambda = 675$ nm), which is equivalent to summer conditions for most types of the surface cover. Light absorption by air molecules in the spectral range under consideration was assumed negligibly small.

The sky radiance indicatrix $f(\varphi)$ was calculated for the angles $[0, \varphi_{max}]$, where $\varphi_{max} = 2Z_☉$. Interpolation of $f(\varphi)\sin\varphi$ in the range $[\varphi_{max}, 180°]$ that was needed for the following calculation of τ_{obs} was performed with the use of third-power polynomials. Because the function to be interpolated is smooth, the extra error introduced by the interpolation did not exceed 2–3% (Ref. 12).

Before passing on to determining the functional dependence between τ_{obs} and τ_s, let us estimate the contribution of $\tau_{2,sur} = \tau_2 + \tau_{sur}$ to τ_{obs}, where the term $\tau_2 = \tau_{2,sur}(A_s = 0)$ is referred to as the optical depth due to multiple scattering. As AOD increases, the fraction of multiply scattered radiation to brightness $B(\varphi)$ increases, and the relative contribution of the component τ_2 to τ_{obs} increases too. As follows from the calculated results shown in Fig. 1, the fraction of τ_2 varies from ≈ 45% at $\tau_a = 0.1$ to ≈ 85% at $\tau_a = 0.7$. At the same time, the relative contribution of τ_{sur} to τ_{obs} decreases: if at $\tau_a = 0.1$ and A_s varying within $0 \le A_s \le 0.8$ the increment of τ_{sur} was ≈ 12%, then at $\tau_a = 0.7$ the relative fraction of τ_{sur} did not exceed

≈ 5%. In this connection, we can expect that the procedure of τ_s restoration from the data on τ_{obs} will be most efficient at relatively small values of the albedo A_s. Therefore, the array of observations, which can be analyzed by the "integral" technique, should correspond to the summer conditions.

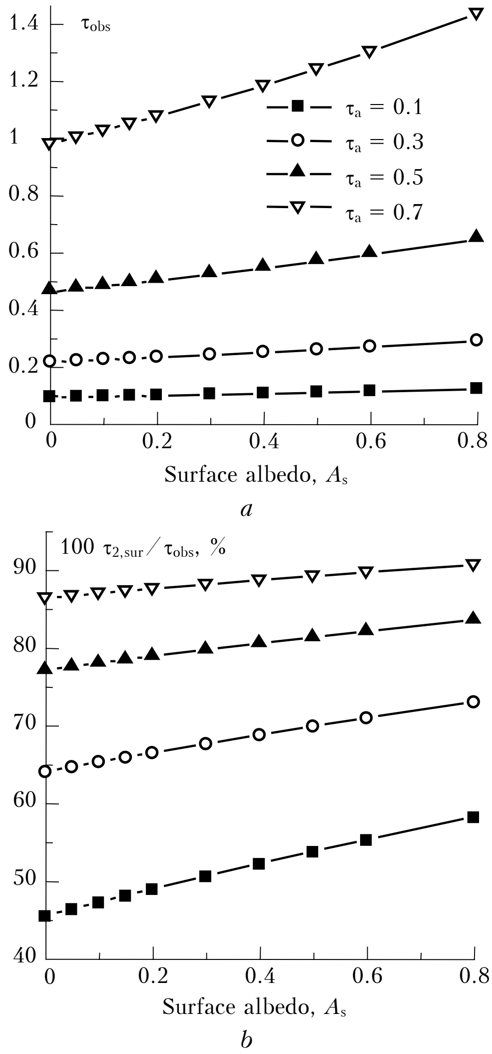

Fig. 1. The effect of surface albedo A_s on the brightness atmospheric depth τ_{obs} (*a*) and the relative contribution of $\tau_{2,sur}/\tau_{obs}$, % (*b*). Wavelength $\lambda = 439$ nm, $\Gamma_a = 8.77$, $m = 5$.

Already the first careful calculations of τ_{obs} have shown[13] that it is generally a function of the scattering optical depth τ_s and weakly depends on the light absorption by aerosol under condition that $0.7 \le \omega_a \le 1$ and the scattering depth $\tau_s \lesssim 0.95$ for $\lambda = 439$ nm and $\tau_s \lesssim 0.65$ for $\lambda = 675$ nm. More detailed idea of this can be obtained from the results depicted in Fig. 2: when drawing each of the curves of τ_{obs} as a function of τ_s, we used calculated $f(\varphi)$ for all the four values $\omega_a \in \{0.7; 0.8; 0.9; 1.0\}$. It is worthy to note that the curves corresponding to different wavelengths $\lambda = 439$ and 675 nm are close at a relatively high sun elevation above the horizon: $m \le 3$. Since the forward peak of the scattering phase function in the molecular-aerosol atmosphere

$$\Gamma_1 = \frac{\int_0^{\pi/2} [f_{as}(\varphi) + f_{ms}(\varphi)] \sin\varphi \, d\varphi}{\int_{\pi/2}^{\pi} [f_{as}(\varphi) + f_{ms}(\varphi)] \sin\varphi \, d\varphi}$$

is significantly different because of the contribution of molecular scattering in different spectral ranges, it can be concluded that at $m \le 3$ it only slightly influences the value of τ_{obs}. It should be noted that the influence of the shape of the scattering phase function on τ_{obs} can manifest itself only through the multiply scattered radiation: it becomes more marked as m increases.

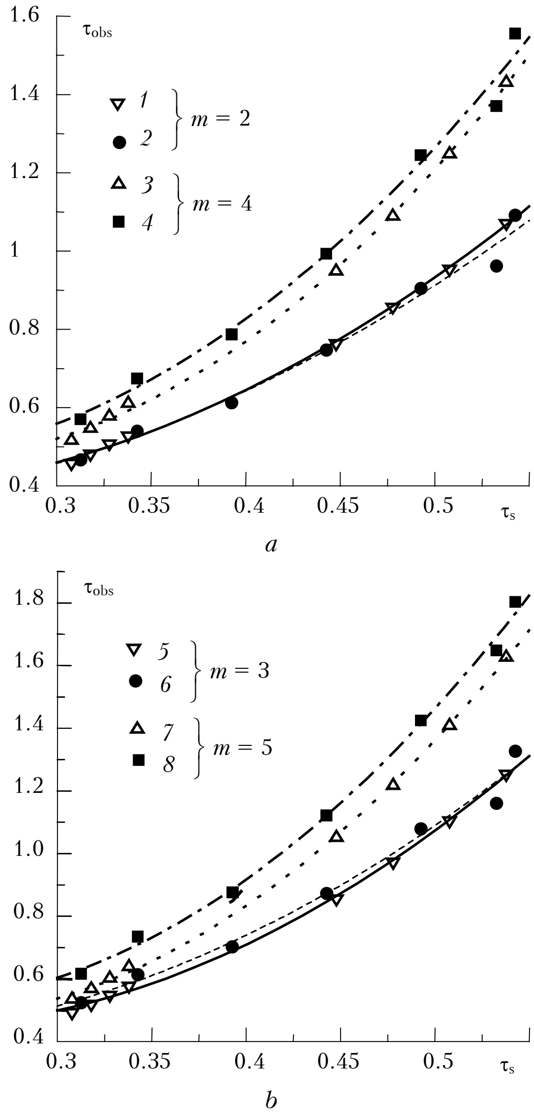

Fig. 2. Dependence of τ_{obs} on τ_s at different values of m and wavelength: $\lambda = 439$ nm (*1*, *3*, *5*, *7*) and 675 nm (*2*, *4*, *6*, *8*) at $0.3 \le \tau_s \le 0.55$.

Figure 3 depicts calculated τ_{obs} as a function of τ_s at four values of m nearby $\lambda = 675$ nm. At low atmospheric turbidity ($\tau_s \le 0.15$) the discrepancy between the curves does not exceed 10%, as was mentioned earlier by E.V. Pyaskovskaya-Fesenkova based on the data of observations.[4] With the following increase of τ_s, differentiation of the curves with respect to m becomes clearer due to the increasing contribution of multiple scattering to the sky brightness.[9]

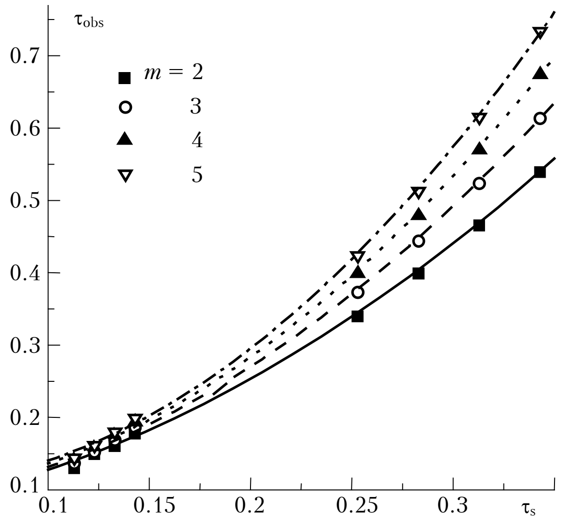

Fig. 3. Dependence of τ_{obs} on τ_s at $0.1 \le \tau_s \le 0.35$ for $\lambda = 675$ nm ($\Gamma_a = 7.03$).

By analogy with the difference technique, from the solution of the radiative transfer equation for the aerosol models of the atmosphere mentioned above we derived the approximation formulas relating τ_{obs} and τ_s, in which τ_{obs} is considered as the initial one, since it just serves the basis for determination of the scattering optical depth. For every spectral region, the values of τ_s are represented as

$$\tau_s = K_2\tau_{obs}^2 + K_1\tau_{obs} + K_0. \qquad (7)$$

The following analysis has shown that to avoid the loss of accuracy in determination of τ_s, the coefficients K_i, i=0,1,2, should be calculated for two ranges of τ_s: $0.31 \le \tau_s \le 0.54$–0.59 and $0.54 \le \tau_s \le 0.92$–0.94 for $\lambda = 439$ nm and $0.11 \le \tau_s \le 0.36$–0.39 and $0.34 \le \tau_s \le 0.64$–0.67 for $\lambda = 675$ nm. These changes of τ_s, in fact, cover the absolute majority of variations of the scattering optical depth of both natural and anthropogenic aerosol.

The coefficients in Eq. (7) depend on the atmospheric mass m (Fig. 3), and they can be approximated by the second-power polynomials with the acceptable accuracy:

$$K_i = P_{i,2}m^2 + P_{i,1}m + P_{i,0},\ i = 0, 1, 2. \qquad (8)$$

The values of the coefficients K_i, $i = 0, 1, 2$, at different τ_s and the above values of Γ_a are given in Tables 1 and 2.

Using one of the aerosol models of the atmosphere ($\Gamma_a = 7.03$) as an example, Fig. 4 depicts the variability ranges of the brightness atmospheric optical depth τ_{obs} corresponding to the ranges of τ_s variations. If the values of τ_{obs} fall in the region of overlap of the ranges $\tau_{obs}^{(1)} \le \tau_{obs} \le \tau_{obs}^{(2)}$, then both sets of the coefficients K_i, $i = 0, 1, 2$, can be used in calculation of the scattering optical depth. Note that the region of overlap $(\tau_{obs}^{(1)}, \tau_{obs}^{(2)})$ in every spectral range depends on the value of the forward peak of the aerosol scattering phase function considered.

Table 1. Coefficients K_i, $i = 0, 1, 2$, for calculation of τ_s nearby $\lambda = 439$ nm

Ranges of τ_s	$\Gamma_a = 7.03$	$\Gamma_a = 8.6$	$\Gamma_a = 10.2$
$0.31<\tau_s<0.59$	$K_2=0.0082m^2-0.023m-0.196$	$K_2=-0.0096m^2+0.123m-0.476$	$K_2=-0.0004m^2+0.055m-0.358$
	$K_1=-0.019m^2+0.05m+0.667$	$K_1=0.015m^2-0.23m+1.194$	$K_1=-0.0041m^2-0.09m+0.954$
	$K_0=0.012m^2-0.062m+0.104$	$K_0=-0.00195m^2+0.051m-0.099$	$K_0=0.0082m^2-0.021m+0.014$
$0.54<\tau_s<0.94$	$K_2=-0.00163m^2+0.027m-0.101$	$K_2=-0.0078m^2+0.074m-0.181$	$K_2=-0.0046m^2+0.0485m-0.133$
	$K_1=0.0025m^2-0.112m+0.635$	$K_1=0.027m^2-0.3m+0.95$	$K_1=0.015m^2-0.202m+0.765$
	$K_0=0.0057m^2+0.028m+0.07$	$K_0=-0.0083m^2+0.131m-0.091$	$K_0=-0.00038m^2+0.071m+0.014$

Table 2. Coefficients K_i, $i = 0, 1, 2$, for calculation of τ_s nearby $\lambda = 675$ nm

Ranges of τ_s	$\Gamma_a = 7.03$	$\Gamma_a = 9.7$	$\Gamma_a = 11.55$
$0.11<\tau_s<0.39$	$K_2=0.018m^2-0.09m-0.332$	$K_2=-0.0087m^2+0.122m-0.73$	$K_2=0.0011m^2+0.053m-0.593$
	$K_1=-0.011m^2+0.018m+0.859$	$K_1=0.014m^2-0.18m+1.229$	$K_1=0.0045m^2-0.115m+1.102$
	$K_0=0.0028m^2-0.015m+0.024$	$K_0=-0.00127m^2+0.017m-0.032$	$K_0=0.0022m^2-0.0081m+0.012$
$0.34<\tau_s<0.67$	$K_2=-0.00119m^2+0.035m-0.182$	$K_2=-0.0069m^2+0.078m-0.262$	$K_2=-0.0058m^2+0.07m-0.239$
	$K_1=0.0051m^2-0.13m+0.815$	$K_1=0.016m^2-0.218m+0.974$	$K_1=0.014m^2-0.206m+0.927$
	$K_0=0.001m^2+0.023m+0.016$	$K_0=-0.001m^2+0.036m-0.0052$	$K_0=0.001m^2+0.025m+0.021$

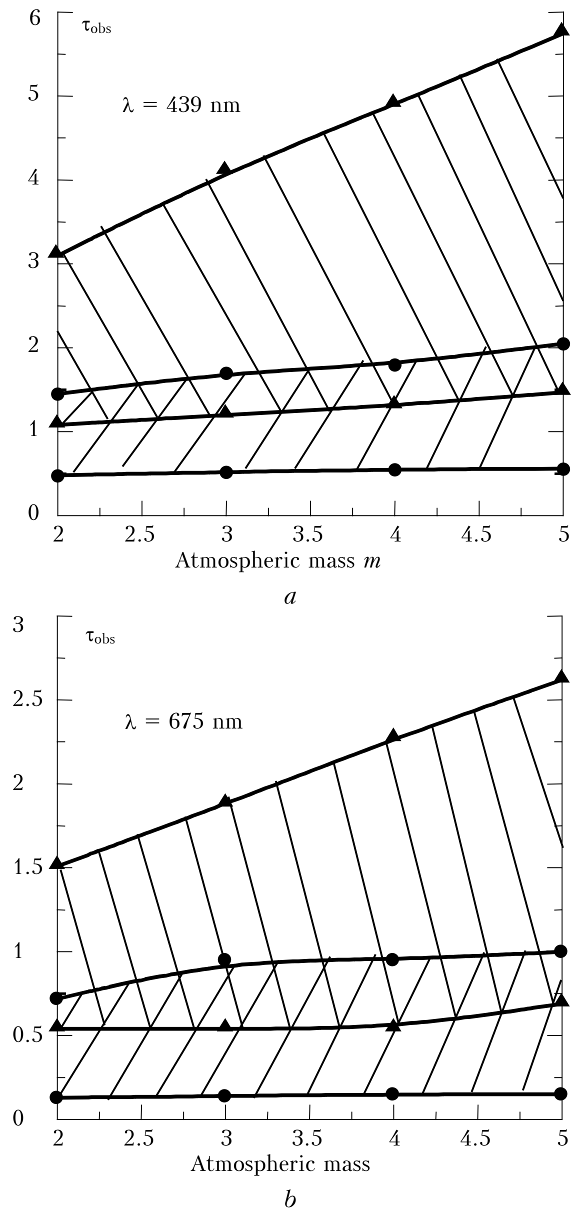

Fig. 4. Regions of variation of τ_{obs} that determine regions of variation of τ_s in calculations by Eq. (7): $0.31 \le \tau_s \le 0.54$–0.59 ($\lambda = 439$ nm) and $0.11 \le \tau_s \le 0.36$–0.39 ($\lambda = 675$ nm) (circles); $0.54 \le \tau_s \le 0.92$–0.94 ($\lambda = 439$ nm) and $0.34 \le \tau_s \le 0.64$–0.67 ($\lambda = 675$ nm) (triangles); $\Gamma_a = 7.03$.

Thus, we have obtained the approximation formulas based on the theory of radiative transfer and allowing reconstruction of the scattering optical depth τ_s from observations τ_{obs} with the atmospheric mass varying within $2 \le m \le 5$. The accuracy of these formulas can be judged from the data of Table 3, which presents the relative deviations of calculated τ_s from the values initially used in the calculations. It can be seen that the maximum deviations are observed at large values of the optical depth and atmospheric mass $m = 4$–5. The systematic deviations characteristic of some rows (e.g., for $\lambda = 439$ nm, $\tau_s \ge 0.5079$, $\Gamma_a = 10.2$, and $m = 5$) is the consequence of twice representation of τ_s by polynomials. In the overlapping regions $0.54 \le \tau_s \le 0.59$ for $\lambda = 439$ nm and $0.34 \le \tau_s \le 0.39$ for $\lambda = 675$ nm, as was mentioned above, the formulas for any of the two regions can be used equivalently. The value of scattering AOD τ_{as} can be found by subtracting the molecular component τ_{ms} from the determined value of τ_s.

Let us now solve the problem of selection of Γ_a at the practical use of the method proposed for determination of τ_{as}. In spite of significant differences in the coefficients $P_{i,j}$, i, j = 0, 1, 2, depending on Γ_a (see Tables 1 and 2), the equations presented for every spectral range give close results on τ_{as} independent of the aerosol model. This can be illustrated as follows. Let us select a wavelength, for example, $\lambda = 439$ nm. The approximation formulas derived for the first ($\Gamma_a = 7.03$) and third ($\Gamma_a = 10.2$) aerosol models are used, in turn, for calculation of τ_s all over the array of calculated τ_{obs} (Γ_a = 7.03, 8.6, and 10.2). Then find $\tau_{as} = \tau_s - \tau_{ms}$ and compare with the scattering aerosol depths initially used in the calculations. Then repeat this procedure for the red spectral region, using the corresponding parameters. The histograms of deviations (in %) for both spectral regions are compared in Fig. 5. It is clearly seen that they are a little bit shifted with respect to each other. The mean deviation with allowance for the sign is ≈ –0.5% for the first histogram (formulas for $\Gamma_a = 7.03$) and ≈ 1.6% for the second one (formulas for $\Gamma_a = 10.2$ and 11.55 for $\lambda = 439$ nm and $\lambda = 675$ nm, respectively), which falls within the usual measurement error corridor of τ. The maximum discrepancies achieving 15–18% arise at small ($\tau_a < 0.1$) and large ($\tau_a > 0.4$–0.5) aerosol optical depths. When using the second model for analysis of the whole array of data, the root-mean-square deviation is 4%. It should be noted here that the absolute error $\Delta\tau_a$ in determination of τ_a by the Bouguer method is usually 0.01–0.02. At $\tau_a = 0.1$ this is equivalent to the relative error of 10–20%, and $\tau_a > 0.4$–0.5 are rather rare under real conditions.

Thus, based on solution of the radiative transfer equation, we have derived simple approximation formulas that allow the scattering optical depth to be reconstructed from the data on τ_{obs}. The integral technique of τ_{as} determination should be used in the summer period, when the surface albedo is low and its variations only weakly influence τ_{obs}. Otherwise, when $A_s > 0.2$, the albedo should be measured and the corresponding corrections should be introduced to the formulas proposed for determination of τ_{as}. An obvious advantage of the approach proposed is low sensitivity of τ_{as} to the asymmetry factor of the scattering phase function. In the further studies, we plan to compare the scattering AOD reconstructed using the difference and integral techniques both in the computer experiment and based on field measurements.

Table 3. Accuracy of reconstruction of the scattering optical depth τ_s by Eqs. (7) and (8). The errors calculated by formulas for the overlap regions are given in separate columns

τ_s		0.3079	0.3179	0.3279	0.3379	0.4479	0.4779	**0.5079**	**0.5379**	**0.5079**	**0.5379**	0.5879	0.6379	0.6879	0.7379	0.7279	0.7979	0.8679	0.9379
Γ_a	m	$\delta\tau_s$ (λ = 439 nm), %																	
7	2	−0.8	−2	−2.5	−2.7	0.6	0.3	**0.2**	**0.7**	**−1**	**−1.5**	3.5	1.8	−0.5	−2.5	4.5	2	0.5	0.5
8.6	2	1.6	0.8	−0.6	−0.5	0.6	−0.2	**−0.1**	**0**	**−1.7**	**−3.1**	2.2	0.4	−1.6	−5.3	2.6	0.5	−0.6	0.4
10.2	2	−1.4	−2	−2.6	−3.5	0.5	−0.1	**−0.3**	**0.1**	**−1.7**	**−2.8**	2.3	0.7	−1.2	−3.3	3.1	1.2	−0.1	0.2
7	3	2.9	2	0.9	0.1	1.2	1.1	**0.3**	**0.5**	**−2.1**	**−3**	2.1	0.7	−1.5	−3.4	2	0.1	−1.2	0
8.6	3	1	0.4	−0.4	−1	1.3	0.6	**0.3**	**0.9**	**−1.5**	**−1.9**	2.8	1.5	−0.3	−2.5	2.9	0.8	−0.7	−0.1
10.2	3	1.9	1.1	0.4	−0.6	1.3	0.5	**0.2**	**0.9**	**−2.3**	**−3**	1.5	0	−2.1	−4.5	1.5	−0.8	−2.3	−1.4
7	4	3.9	3.2	2.5	1.7	2.9	2	**1.8**	**2.3**	**−2.3**	**−2.2**	1.4	0.8	−0.7	−2.5	0.6	−1.2	−2.3	−0.6
8.6	4	1.9	1.4	1	0.4	2.5	1.8	**1.6**	**2.2**	**−0.6**	**0**	3.7	3.1	1.3	−1.4	2.5	−0.8	−4.6	−7.9
10.2	4	3	2.4	1.7	1	2.1	1.3	**1.1**	**2**	**−2.9**	**−2.8**	1	0	−2	−4.7	−0.8	−3.8	−6.6	−7.2
7	5	3.2	3	2.7	2.4	3.4	2.7	**2.5**	**2.9**	**−3.4**	**−2**	0.8	1.2	0.5	−1.2	−1.6	−4	−6.7	−8.1
8.6	5	1.8	1.7	1.5	1.3	2.9	2.5	**2.6**	**3.6**	**−2.1**	**−0.7**	2.5	3.1	2.6	1.3	1.3	−0.3	−1.4	0.4
10.2	5	0.8	0.7	0.5	0.3	1.8	1.1	**0.9**	**1.6**	**−5.3**	**−4.1**	−1.2	−1.2	−2.4	−4.6	−3.5	−6.1	−8.4	−7.9
		Root-mean-square deviation																	
		1.6	1.7	1.7	1.7	1	1	1	1.1	1.2	1.1	1.3	1.2	1.5	1.9	2.3	2.4	3	3.8

τ_s		0.1127	0.1227	0.1327	0.1427	0.2527	0.2827	**0.3127**	**0.3427**	**0.3127**	**0.3427**	0.3927	0.4427	0.4927	0.5427	0.5327	0.6027	0.6727
Γ_a	m	$\delta\tau_s$ (λ = 675 nm), %																
7	2	−1.1	−1.3	−1.8	−2.3	1	0.4	**0.2**	**0.3**	**−0.7**	**−1.8**	3.1	1.3	−1	−3.3	3.1	1.1	−0.2
9.7	2	1.8	−2.3	−0.8	−3.2	0.2	−0.7	**−1**	**−0.7**	**−1**	**−2.2**	2.6	0.8	−1.4	−3.5	2.5	0.9	0.4
11.6	2	−3.9	−4.2	−4.7	−5.2	−1.9	−2.2	**−2.2**	**−1.8**	**−2.3**	**−3**	1.7	0.5	−1.3	−3.3	2.2	0.8	0.4
7	3	1.9	1.1	0.2	−0.8	1	0.2	**0**	**0.6**	**−1.9**	**−2.7**	2.3	0.5	−1.9	−4.4	1.6	−0.4	−0.8
9.7	3	1	0.1	−0.5	−1.7	0.7	−0.1	**−0.2**	**0.4**	**−0.3**	**−1**	4	2.5	0.4	−1.8	3.8	2.2	2.4
11.6	3	1.2	0.7	−0.1	−0.9	0.8	−0.2	**−0.6**	**−0.1**	**−1**	**−1.6**	3.4	1.8	−0.3	−2.6	3.4	1.8	2.2
7	4	2.7	2	1.4	0.5	1.7	0.9	**0.9**	**2**	**−2.1**	**−2.3**	2.5	1	−1.2	−3.6	1.3	−0.6	−0.4
9.7	4	0.6	0.2	−0.1	−0.6	1.8	1.1	**1**	**1.8**	**1.1**	**1.1**	5.9	4.9	3	1.1	5.6	4.2	5
11.6	4	2.3	2	1.4	0.6	1.6	0.5	**0.1**	**0.9**	**−0.4**	**−0.3**	5.1	3.9	1.9	−0.3	4.7	3.2	4.4
7	5	0.9	0.9	0.6	0.1	2.1	1.2	**0.9**	**1.8**	**−2.8**	**−2.2**	2.4	1.3	−0.9	−3.8	−0.9	−3.7	−4.5
9.7	5	0.2	−0.2	−0.2	−0.5	1.6	0.7	**0.5**	**1.6**	**0.7**	**1.6**	6.4	6	4.9	3.6	5.7	5.5	8.8
11.6	5	−1.5	−1.3	−1.4	−1.8	0	−1.2	**−1.7**	**−0.7**	**−1.8**	**−0.8**	4.7	4.3	2.8	1.1	4.4	3.7	6.9
		Root-mean-square deviation																
		1.9	1.8	1.6	1.7	1.1	1	1	1.2	1.2	1.5	1.5	1.9	2.2	2.5	1.9	2.5	3.7

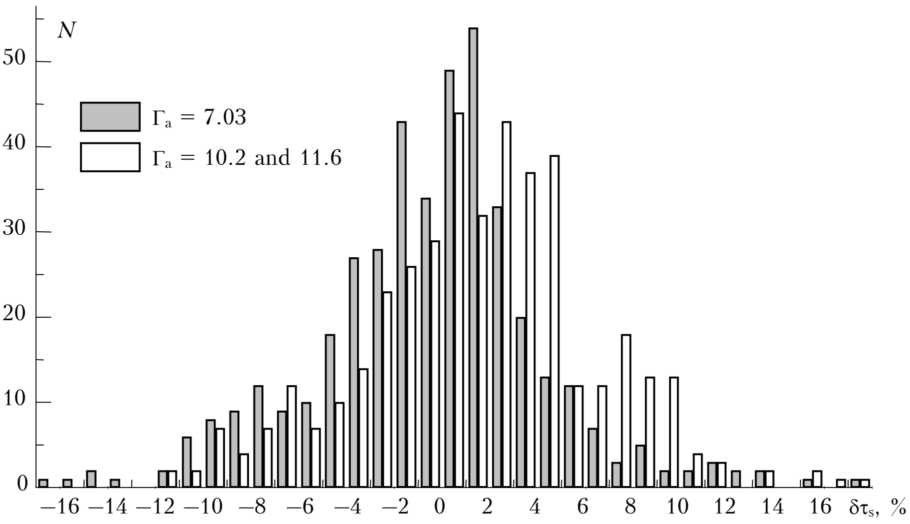

Fig. 5. Distribution of relative deviations of the reconstructed values of aerosol scattering optical depth τ_{as} from those used in calculations.

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