The Effect of Gas Absorption on the Scattered Radiation in the Solar Almucantar: Results of Numerical Simulation

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Introduction

The methods for reconstruction of the aerosol optical characteristics (e.g., aerosol size distribution, and single-scattering albedo) from diffuse and direct radiation measured in the solar almucantar has been widely used during the last decade. The photometers with filters in the "atmospheric transparency windows" in the wavelength range 0.4 to 1 μm were applied for measurements. Usually it was assumed that one could neglect the molecular absorption of the measured diffuse radiation. Further development of the method can be related to taking into account gas absorption in the procedures for calculation of the diffuse radiation. It allows to extend the method to the more longwave spectral range and to increase the accuracy of reconstruction of the aerosol characteristics.

Approach

To take into account molecular absorption in the vertically inhomogeneous aerosol-gas atmosphere, the method of k-distribution is used, since this method allows approximation of the broadband transmission function of atmospheric gases in the wavelength interval $\Delta\lambda = (\lambda_1, \lambda_2)$ by a short exponential series. The spectrally integral sky brightness can also be represented as a series (Firsov et al. 2002):

$$B^{AG} = \sum_{i=1}^{N} C_i B_i^{AG} \tag{1}$$

where B_i^{AG} is the monochromatic brightness for radiation at the i-th wavelength, C_i are the coefficients of the Gauss quadrature formulas. The effective absorption coefficients $k_i(h)$ at the height h that are used for calculation of B_i^{AG} are determined through the function g(k, h):

$$g(k) = \frac{1}{\nu_2 - \nu_1}\int_{\nu_1}^{\nu_2} W(\nu)d\nu\,, \quad W(\nu) = \begin{cases} 1, & K(\nu) < k \\ 0, & K(\nu) > k \end{cases} \tag{2}$$

Here, $F(\lambda)$ is the photometer's instrumental function normalized to unity, $S(\lambda)$ is the spectral solar constant, α (λ, h) is the molecular absorption coefficient. The function g(k, h) is inverse to k(g, h), and the effective coefficient $k_i(h) \equiv k(g_i, h)$, (g_i is the cumulative wavelength [Firsov et al. 2002]). Thus, $k_i(h)$ accounts for spectral features of the spectral instrumental function and the solar constant.

To calculate brightness fields of the incoming monochromatic solar radiation, we use the method of adjoint walks developed for the spherical model of the atmosphere with allowance for symmetry of the system earth–atmosphere–sun (Marchuk et al. 1976). The angular distribution of the radiation coming to the point A is represented in the local rectangular coordinate system, in which the direction of the incident solar radiation is described by the vector $\vec{\omega}_0 = (\xi_0, \varphi_0)$ and the viewing direction is described by the vector $\vec{\omega} = (\xi, \varphi)$. The vertically inhomogeneous model of the aerosol-gas atmosphere is specified as a set of homogeneous layers, each characterized by the aerosol extinction and scattering coefficients, molecular scattering coefficient, and the effective absorption coefficient, as well as the aerosol and Rayleigh scattering phase functions. The incident radiation is reflected from the surface according to the Lambert law with the albedo A_S.

The calculations presented in this paper were made for four atmospheric windows: (a) spectral ranges of 0.50 and 0.87 μm that are traditionally used in measurements; (b) spectral ranges of 1.245 and 2.137 μm that are promising for new investigations. The calculations of the effective absorption coefficients involved the data from the HITRAN-2000 spectroscopic database (ftp://cfa-ftp.harvard.edu/pub/HITRAN). The vertical profiles of temperature, air pressure, and concentrations of atmospheric gases (e.g., H_2O, CO_2, O_3, and CH_4) were specified in accordance with the Air Force Geophysics Laboratory (AFGL) meteorological model for the mid-latitude summer (Anderson et al. 1986). Optical characteristics of aerosol were chosen according to the World Climate Research Programme (WCP 1986) recommendations for continental conditions; in the height range of 0 to 12 km we used the exponential profile of the aerosol extinction coefficient. The main calculations were performed for two types of aerosol turbidity (Table 1, column 2), $A_S = 0.2$ and the solar zenith angles $\xi_0 = 60°$and 80°. The relative error in calculation of monochromatic brightness did not exceed 0.5%; the number of terms in the series in Eq. (1) was N = 10.

Results

To estimate the effect of absorption by atmospheric gases, we have performed comparative calculations of the azimuth distributions of sky brightness in the solar almucantar for the models of the aerosol-gas $B^{AG}(\varphi)$ and aerosol $B^{A}(\varphi)$ atmosphere. The calculated results have shown that the neglect of molecular absorption in the atmospheric windows leads to the decrease in both direct and diffuse radiation. The value of extinction of the direct radiation for the selected spectral ranges at the zenith angle of 60° was 2% to 7% (Figure 1). The discrepancies in calculation of the diffuse radiation due to the neglect of absorption were estimated as absolute $\Delta = (B^{AG} - B^{A})$ and relative $\delta = (100\% \times \Delta/B^{AG})$ errors for the azimuth angles φ or the corresponding scattering angles θ. The estimates in consideration of the single (s) and multiple (m) scattering components of brightness were estimated in the similar way. The angular dependence of the calculation errors for some conditions are illustrated in Figures 2 to 4, while the data on Δ and δ for the angles φ =0 and 90° are generalized in Table 1.

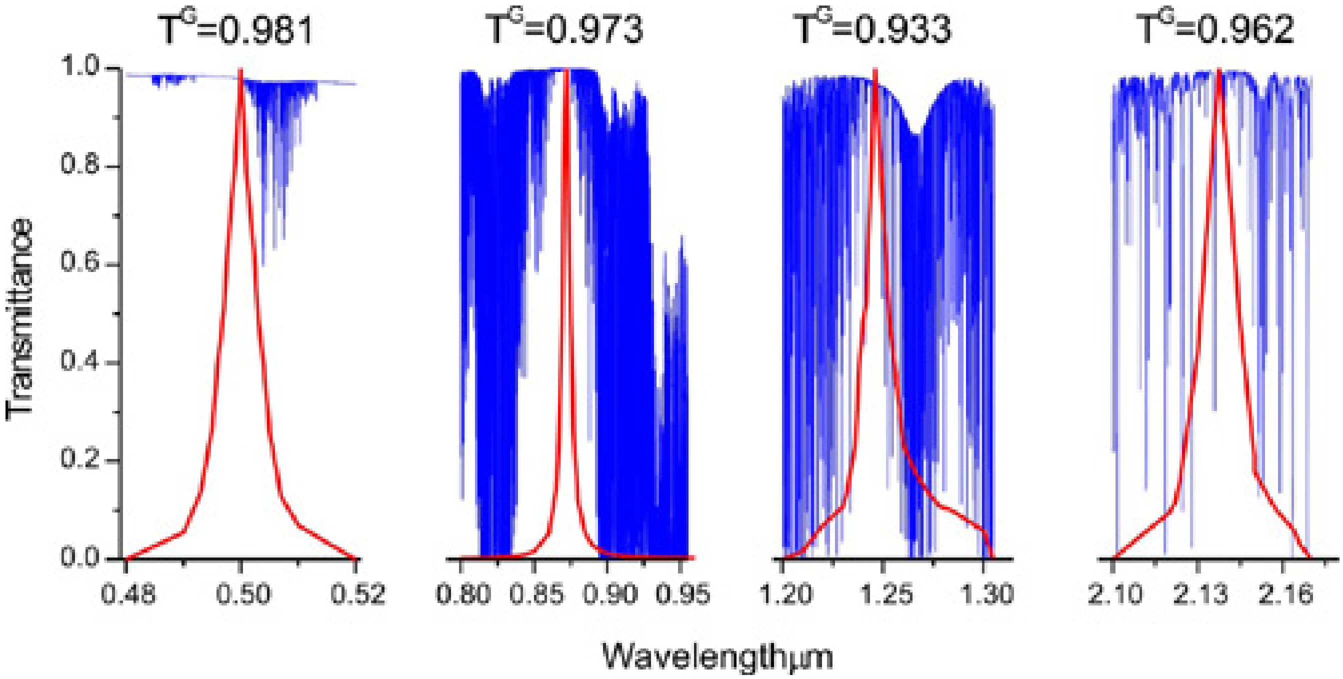

Figure 1. Spectra of the atmospheric and filters transmittance and the broadband transmission functions of atmospheric gases -T^G for different spectral channels (zenith angles ξ_0 =60°).

Table 1. Absolute Δ [W/m^2·sr] and relative δ discrepancies in calculation of the diffuse radiation due to the neglect of molecular absorption.

λ, μm	AOD	ξ_0 =60°				ξ_0 =80°			
		φ =0°		φ =90°		φ =0°		φ =90°	
		$-\Delta\cdot 10^{-2}$	$-\delta$,%	$-\Delta\cdot 10^{-5}$	$-\delta$,%	$-\Delta\cdot 10^{-2}$	$-\delta$,%	$-\Delta\cdot 10^{-5}$	$-\delta$,%
0.50	0.06	2.48	1.9	8.7	2.3	8.5	5.1	25.5	5.6
	0.4	8.5	1.9	13.8	2.2	8.4	5.1	17.9	5.3
0.87	0.03	2.67	2.7	3.2	3.1	9.5	4.2	8.7	4.4
	0.2	12.9	2.8	11.5	3.1	24.5	4.2	18.5	4.3
1.24	0.03	5.3	7.1	4.8	8.6	30.0	17.9	18.4	19.8
	0.1	15.4	7.1	13.1	8.5	67.5	17.8	42.9	20.1
2.14	0.03	1.4	3.9	0.9	4.9	8.1	9.2	3.4	10.6
	0.1	4.2	3.9	2.8	4.8	18.3	9.2	9.6	10.6

Consider first the effect of different factors on the sky brightness without dividing it into the single and multiple scattering components. In the traditional spectral ranges (0.5 and 0.87μm), the relative errors are 2% to 5%, and in the longwave range (1.24 and 2.14 μm) they increase up to 4% to 20%. The angular behavior of the absolute error $\Delta(\theta)$ agrees well with the dependence of sky brightness $B^{AG}(\theta)$ with the maximum values in the range of forward scattering angles (Figure 2), while the relative error δ decreases a little with the increasing scattering angle (Figures 3 and 4). The effect of molecular

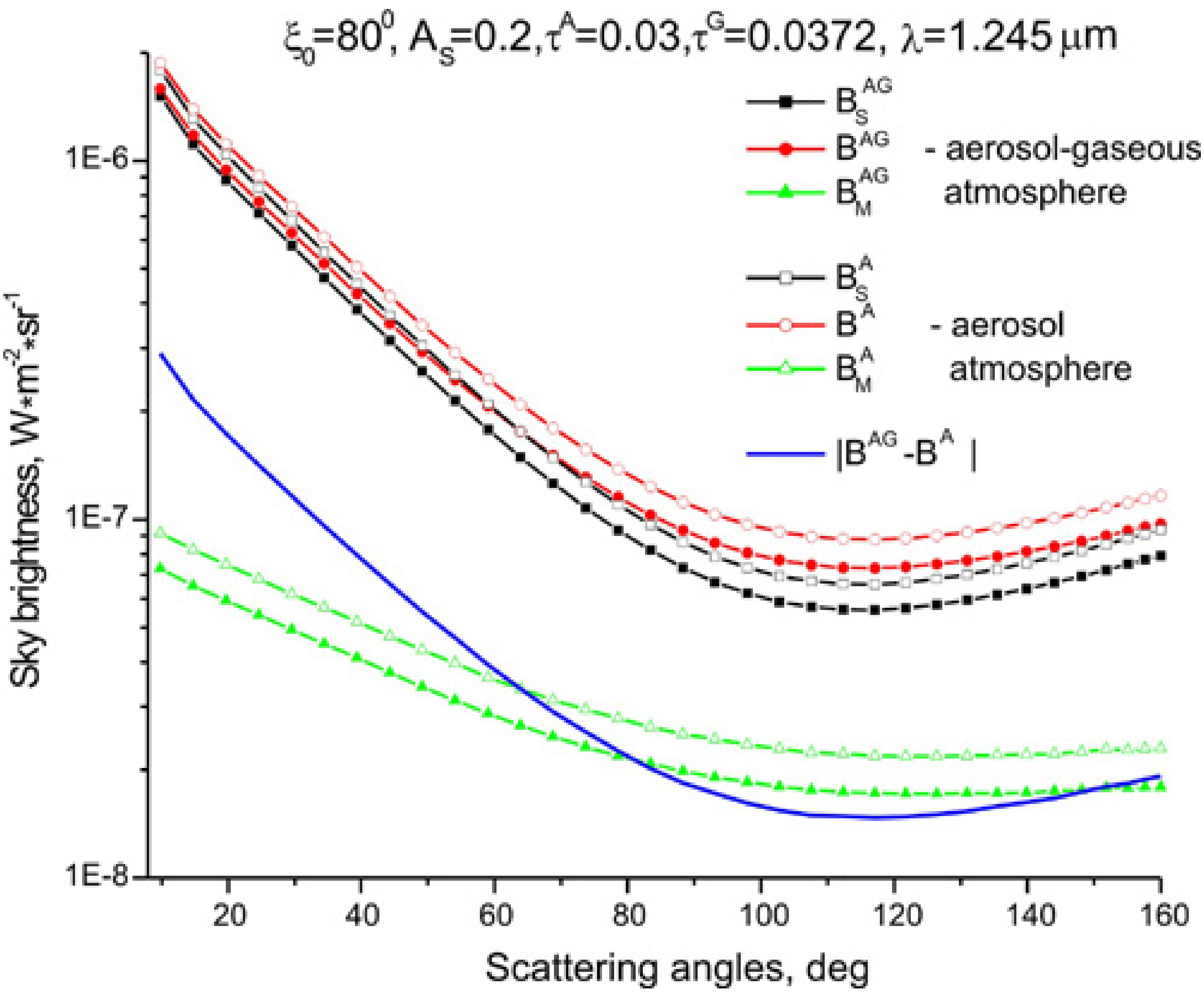

Figure 2. The angular dependence of the sky brightness - B^{AG}, B^{A} and absolute discrepancies in calculation of the radiation (1.245 μm channel).

absorption on the diffuse radiation increases with the increasing zenith observation angles so that as ξ varies from 60° to 80°, the value of δ doubles, on the average. The relative error δ in the whole range of the scattering angles is almost independent of variation of the aerosol turbidity of the atmosphere and the surface albedo.

Analysis of individual components of brightness showed that relatively large discrepancies caused by the neglect of absorption arose for the multiple scattered component of radiation δ_m. This component depends on the scattering angle, and this dependence becomes stronger as the contribution of molecular absorption increases (the maximum value of δ_m in the 1.24 μm channel). The relative errors in calculation of the single-scattered radiation δ_s almost do not depend on AOD and the scattering angle.

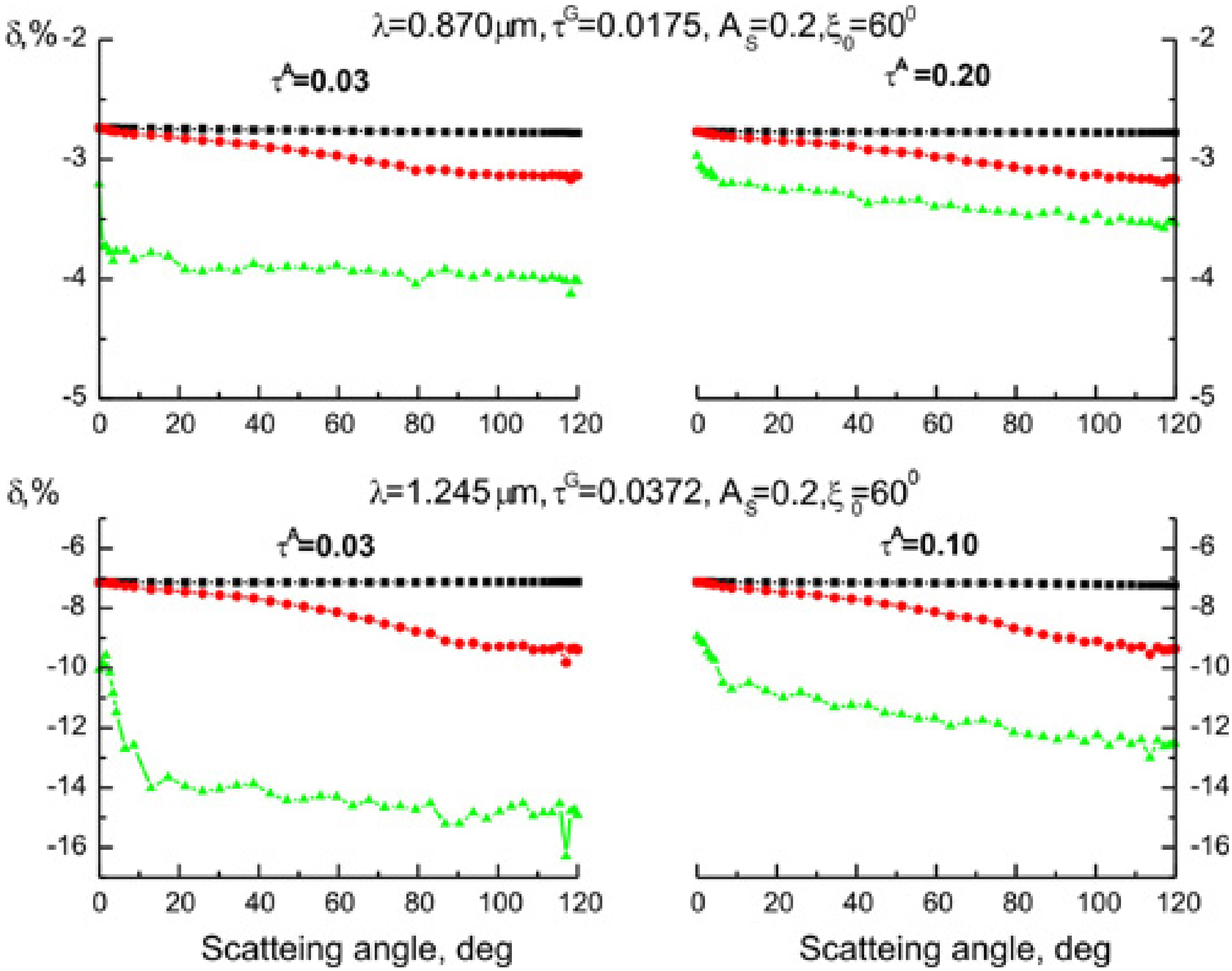

Figure 3. Relative discrepancies in calculation of the diffuse radiation due to the neglect of molecular absorption (0.87 and 1.245 μm channels).

As a consequence, the error for the sum radiation δ varies from δ_s to δ_m (Figures 3 and 4). The results of model calculations have shown that the effect of molecular absorption on the diffuse radiation manifests itself, to a sufficient degree, through the multiple scattered component and the value of δ_m increases with the increase of the zenith observation angle and the scattering angle.

Thus, the neglect of molecular absorption in the IR region can lead to marked errors in calculation of the diffuse radiation and, as a consequence, to distortion of the results of reconstruction of the aerosol characteristics from the sky brightness in the solar almucantar. It is difficult to give the general estimate to the effect of absorption on solution of the inverse problem, ignoring peculiarities of the procedures used for separation of the aerosol scattering component from the measured sky brightness.

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