Solar diffuse radiation variations upon variations of aerosol parameters in Earth's limb sounding (numerical simulation and preliminary analysis of measurement information content)

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Received October 13, 2004

The author's algorithm and computer code for simulating solar diffuse radiation in the Earth's atmosphere is described, which includes calculations of derivatives with respect to atmospheric and surface parameters. The code is used for analysis of variations of outgoing radiation intensity depending on atmospheric parameter variations as the first step in investigation of the information content of space measurements of Earth's limb brightness aiming at retrieval of atmospheric aerosol parameters. Some calculated results, their analysis, and basic conclusions are presented.

Introduction

One of the known schemes of satellite sensing of atmosphere is the limb vision along tangent paths,[1] i.e., any above-surface paths crossing the atmosphere. Limb sensing makes it possible to study gas and aerosol composition of the stratosphere through measuring its spectral transparency (for example, with SAM-2,[2] SAGE I, II, III,[3] "Ozone-Mir"[4] instrumentation) or the intensity of the diffuse solar radiation field (SAGE III, SOLSE, LORA, OSIRIS, SCIAMACHY[5–9] instrumentation). In the latter case, there are essential advantages connecting with the possibility of realization of much greater measurements above the whole illuminated side of the planet. However, interpretation of such measurements is very difficult, because diffuse radiation depends on many atmospheric and surface parameters.

Measurements of the diffuse solar radiation spectra of the planet limb in visible and near IR ranges contain information about parameters of gas and aerosol state of the atmosphere.[5–8,10,11] Most attention was paid by researchers to analysis of possibilities and examples of determination of characteristics of the atmospheric gas composition, first of all, ozone. It is also interesting to consider a possibility of retrieving atmospheric aerosol parameters from such measurements.

This paper is devoted to one of the initial stages of solving this problem – numerical analysis of influence of variations of different aerosol parameters on the measured intensity of the diffuse solar radiation in the scheme of the limb sensing. Results would allow one to draw preliminary conclusions on the possibility of retrieving the parameters from measurements. First of all, the stratospheric aerosol is of interest, whose effect is maximal, although the diffuse radiation field depends on the parameters throughout the atmospheric column.

Model of radiative transfer in spherical atmosphere

The model of spherically symmetric atmosphere is considered, in which all parameters depend only on the height, but not on geographical coordinates. This approximation is standard for the noted class of remote sensing problems, although note that the radiative transfer model itself can be easily written for inhomogeneous atmosphere and such 3D models are realized recently in calculations.[9,12,13] The atmospheric refraction is neglected.[1]

Following Ref. 4, as the origin point of the coordinate l on the radiation propagation path, its nearest point to the Earth's center is taken. Then for three other coordinates of the transfer model in the spherically symmetrical atmosphere[1,14]: the height $z(l)$, cosine of the radiation zenith angle $\eta(l)$, and cosine of the solar zenith angle $\eta_0(l)$, the following relations can be written

$$z(l) = r(l) - R, \quad \eta(l) = -l/r(l),$$

$$\eta_0(l) = \{(R + z_b)\eta_{0,b} - [(R + z_b)\eta_b + l]\chi_0\}/r(l);$$

$$r(l) = \sqrt{l^2 + (R + z_b)^2(1 - \eta_b^2)},$$

$$\chi_0 = \eta_{0,b}\eta_b + \sqrt{(1 - \eta_{0,b}^2)(1 - \eta_b^2)}\cos(\varphi_b - \varphi_{0,b}), \qquad (1)$$

where R is the Earth's radius, z_b, η_b, $\eta_{0,b}$ are the aforementioned coordinates at some fixed point of the path, which further will be called the vision point (with $l_b = -(R + z_b)\eta_b$); φ_b and $\varphi_{0,b}$ are the radiation and solar azimuths at the vision point, usually,[1,14] $\varphi_{0,b} = 0$, when reading the azimuths φ_b from the Sun. If at $l = 0$ the magnitude $h = z(0)$, called the sight height of the path, exceeds zero, then the path, when

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viewing from the space, is designated tangent; it stretches in the atmosphere from the top boundary z_∞ through h to z_∞ .

Consider the single scattering approximation for monochromatic radiation. Because of the small optical thickness of the background stratosphere, the mean contribution of scattering of higher orders at limb sensing does not exceed several percent,[9,15] although it can dramatically increase and reach tens of percent at decrease of the wavelength and sight height.[9] To avoid this effect, we ignore too small sight heights and consider only visible wavelength range. Thus, the use of the single scattering approximation for estimation of relative variations is justified, because taking into account multiple scattering only slightly changes their values (no more than 1.5 times), and this does not affect the principal conclusions of the study drawn below. However, the use of the single scattering approximation in this work does not mean that the authors recommend it for solving inverse problems and interpretation of limb measurements. A particular analysis of relations between the measurement accuracy and the used physical-mathematical models is necessary for solving such problems.

On physical grounds, the formula for single-scattered radiation intensity can be written by analogy with the formula for plane atmosphere[1]:

$$I(z_{\rm b},\eta_{0,\rm b},\eta_{\rm b},\varphi_{\rm b}) = \frac{F_0}{4\pi}\int\limits_{l_1}^{l_2}\sigma(z(l))x(z(l),\chi_0)P(l)P_0(l)\mathrm{d}l,$$

$$P(l) = \exp\left(-\left|\int\limits_{l}^{-(R+z_{\rm b})\eta_{\rm b}}\alpha(z(l'))\mathrm{d}l'\right|\right),$$

$$P_0(l) = \exp\left(-\left|\int\limits_{-\eta_0(l)r(l)}^{-\mathrm{sign}(\eta_0(l))\sqrt{(R+z_\infty)^2-r^2(l)(1-\eta_0^2(l))}} \alpha\left(\sqrt{(l')^2 + r^2(l)\left(1-\eta_0^2(l)\right)} - R\right)\mathrm{d}l'\right|\right). \quad (2)$$

where F_0 is the extraatmospheric spectral flux of solar radiation, α is the extinction coefficient, σ is the scattering coefficient, x is the scattering phase function, sign(y) is the function of the sign (sign(y) = 1 at $y > 0$, sign(y) = −1 at $y < 0$). The limits of integration l_1 and l_2 in Eq. (2) are determined by the geometry of vision and the illuminated part of the vision path, the boundaries of which are found from the square equation $r^2(l)(1-\eta_0^2(l)) = (R+z_0)^2$, where z_0 is the height of the underlying surface. Parameters $P(l)$ and $P_0(l)$ are functions of the atmospheric transmission along the paths "scattering point – vision point" and "scattering point – Sun", respectively. The integrals entering them are the optical lengths of these paths. In the framework of partially linear approximation of the vertical profile of the total extinction coefficient $\alpha(z)$, they can be calculated analytically taking into account Eq. (1).

Computer code SCATRD

Codes usable in realization of the models of radiative transfer in the atmosphere can be conditionally divided into two types: for processing the data from particular instruments and for scientific investigation of remote sensing problems, development of new techniques and procedures for measuring, and interpreting the results. In research problems, the main criterion in the choice of some code is not its speed of operation, but its flexibility and universality, i.e., ability to simulate radiation field measurements in different wavelength ranges, accounting for or ignoring different factors, in particular, the atmospheric sphericity. Another essential requirement to a research model is a necessity to analytically calculate derivatives of simulated values with respect to any parameters of the atmosphere and underlying surface. The case in point is just derivatives, but not weight functions often used instead of them,[1,13,16] which are derivatives only of the atmospheric parameters determining absorption,[1] but, for example, not of the parameters of the aerosol scattering phase function.

Since the available modern codes,[13,16] in opinion of the authors, do not completely satisfy the noted requirements, the aforementioned model has been realized in the original authorized code SCATRD (scattering radiation with derivatives).

The code SCATRD is developed as universal for any possible geometry of vision (satellite including limb, airborne, ground-based) both in spherical and plane atmosphere

The code is based on the principle of mathematical simulation of actual objects, which presumes that all input data of the code are considered as description of corresponding models (of the atmosphere, measuring instrument, etc.). This affords, in principal, flexible use of the above models of different types. Practically all parameters controlling calculations (for example, determining the accuracy) are put into a special file out of the code text, that allows their free change without the code text retranslation. In such a way, there appears a possibility to easily study the dependence of the simulated parameters on the aforementioned "inner" parameters of the calculating algorithm.

The code SCATRD is now under development. To the moment of writing this paper, it allows one to simulate measurements of the atmospheric transmission function and the intensity of singly scattered solar radiation in the spherical atmosphere, as well as to calculate their derivatives with respect to all atmospheric and surface parameters. The contribution into the total radiation intensity of interaction with the surface is added to the calculation ignoring the surface. Polarization and refraction are not taken into account. Molecular and aerosol scattering are considered in the model of the atmosphere, hence, derivatives are calculated with respect to the profiles of the total aerosol scattering and absorption coefficients, as well as parameters of the aerosol scattering phase function. The isotropic model[1] (the reflection component is taken into account without scattering in the atmosphere) and ideal mirror model[1] (the reflection components are taken into account after scattering, scattering after reflection, and scattering between two reflections) are taken as the models of the surface.

As an important example of the use of the code SCATRD, we present the estimate of the error of the ignoring of the atmospheric sphericity. This error is maximal at viewing from space (Fig. 1).

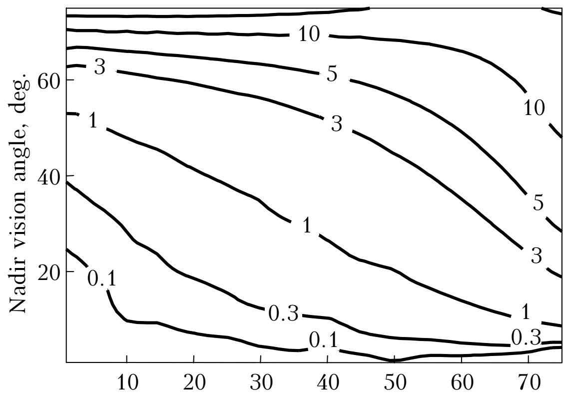

Fig. 1. The error of approximation of the plane atmosphere, %. Background aerosol model.[17] The viewing azimuth is 180°; surface albedo is 0.9; the wavelength is 0.55 μm.

As is seen in Fig. 1, at strong requirements to the calculation accuracy, the accounting for the sphericity is necessary already at quite small viewing and solar zenith angles. Note that calculations for plane and spherical geometry have been realized in the code SCATRD independently, so the coincidence of their results can be considered as the code test.

Model of the atmosphere and its parameters

We considered the Lowtran 7 model[17] commonly used for testing codes and analyzing variations of the diffuse radiation intensity[9,12,13] as the aerosol model of the atmosphere. Coefficients of the aerosol scattering and absorption were set[17] as tables of different heights. They were considered as variable parameters of the aerosol model (besides, vertical profiles of air temperature and pressure were set for calculation of molecular scattering).

The problem of parameterization of the aerosol scattering phase function presents a considerable challenge. It is impossible to use the tabulated values for each point and vary them for each height. Therefore, it is necessary to use approximations of the scattering phase function by some functions with a small number of parameters. In our case, we used the classic Henyey–Greenstein function,[1,18] the only parameter of which is the mean cosine of the scattering phase function. It is known that this function quite roughly approximates actual scattering phase functions. Really, according to our estimates through approximation of the scattering phase functions, calculated by Mie theory, the error of the Henyey–Greenstein function is about 30%. However, as in the case of the single scattering approximation discussed above, this error is justified in the framework of this work, because it does not affect the principal conclusions. Again, the use of the Henyey–Greenstein function does not mean any our recommendations on its application to the problems of data processing. Note that passing to more complicated analytical approximations does not significantly amend the accuracy. For example, for two-parameter modification of the Henyey–Greenstein function (the sum of the scattering phase functions elongated forward and back) the error is about 20%.

In the framework of the aerosol model,[17] the background model of the stratosphere and several different models of the troposphere and near-ground layer were considered. The choice of the background model is dictated by the particular situation observed in the stratosphere during the last 10 years. Besides, to study the information capacity of measurements of the aerosol parameters, the background model is limiting. In general, the information capacity of post-volcanic models is higher, because, evidently, the more is the aerosol concentration, the more information is in the measurements. This conclusion also holds for background models different from the one described in Ref. 17. Since it is impossible without measurements to answer the question, what model is the best, the authors restricted their attention only to this model.

Only an ideal mirror surface can affect the intensity of radiation in the limb geometry in the considered approximation, therefore, this model of reflection was used with selection of the effective parameter (refractive index of the surface substance) corresponding to the given albedo.

Derivatives of intensity with respect to aerosol parameters of the atmosphere at sensing along tangent paths

Variation derivatives of the diffuse solar radiation intensity with respect to the aerosol scattering coefficient and the mean cosine of the aerosol scattering phase function calculated by SCATRD are shown in Fig. 2.

It follows from Fig. 2 that to reach the intensity variation of 1%, the variation of the coefficient of about 10% and the mean cosine of the scattering phase function about 0.05 are sufficient, that is less then *a priori* uncertainty of these parameters (about 30% and 0.1, respectively). This means that measurements with such accuracy are quite sensitive to variations of the aerosol parameters and, hence, are informative for their retrieval. Note that commonly the problem of retrieving parameters of the aerosol scattering phase function is not posed in the modern algorithms for processing the limb sensing data (it is fixed), although, as was shown above, the sensitivity of measurements to its variations is very high [that is clear from formula (2)]. Therefore, when developing new algorithms and modifying the available ones, retrieving the scattering phase function parameters, in our opinion, is necessary and allows an increase of accuracy of the atmospheric sensing.

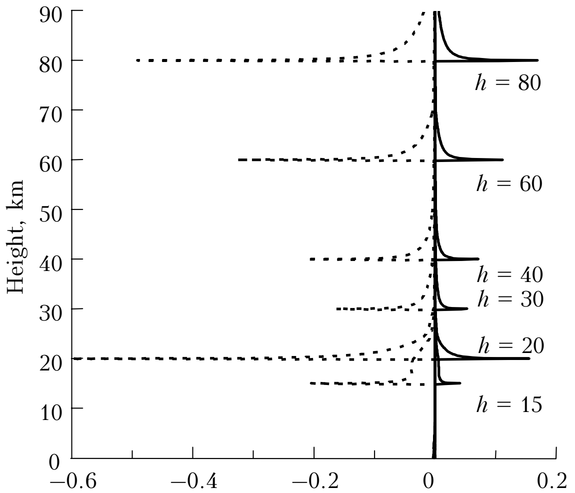

Fig. 2. Relative (%) variation derivatives of the diffuse solar radiation intensity with respect to the aerosol scattering coefficient (per percent of its variation per km) (solid lines) and mean cosine of the aerosol scattering phase function (per 0.01 of its variation per km) (dotted lines) as functions of the sight height h. Wavelength λ is 0.55 μm. Background aerosol model is taken from Ref. 17. Solar zenith angle is 75°. Viewing azimuth is 45°. Surface albedo is 0.9.

A feature of the considered derivatives is their strong dependence on the viewing azimuth. The same derivatives but at the viewing azimuth of 160° are exemplified in Fig. 3. Their decrease by almost one order of magnitude is well seen, hence, this direction is essentially less informative than 45°.

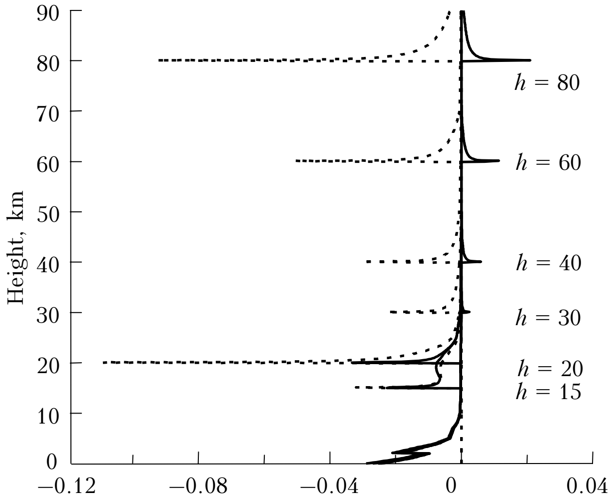

Fig. 3. The same as in Fig. 2 for viewing azimuth of 160°.

The noted peculiarity is related to decrease of contribution of variation of the product of total scattering coefficient by the total scattering phase function $\sigma x(\chi_0)$ into the intensity variations (2). Hence, we can draw a preliminary conclusion that the range of small scattering angles, corresponding to the aerosol scattering phase function maximum (and, consequently, its most contribution into the total scattering phase function), as well as, perhaps, the range of the maximum variations of the scattering phase function, are the most informative for retrieving the aerosol scattering parameters. It should be emphasized that relative variations of the intensity in a complicated manner depend on many parameters: relation between molecular and aerosol scattering, mean cosine, and the form of the used approximation of the aerosol scattering phase function. Therefore, such investigation of the greatest information capacity range is reasonable at posing a particular task of the experimental data processing.

Note also that, as opposite to Fig. 2, variation derivatives with respect to the aerosol scattering coefficient shown in Fig. 3 change a sign: they become negative starting from the sight height of 20 km. It can be explained by the following effect. The aerosol scattering coefficient increases the intensity in Eq. (2) due to the term $\sigma x(\chi_0)$ and decreases it due to functions $P(l)$ and $P_0(l)$, where it is a component of the extinction coefficient α. At the heights, where optical lengths of radiation propagation paths are quite long, the latter process (decrease) begins to prevail over the first one (increase), and the variation derivative of the intensity with respect to the aerosol scattering coefficient becomes negative.

With accounting for reflection from the ground surface, the noted effect leads to appearance of negative variation derivatives well seen in Fig. 3 (the negative part also exists in Fig. 2 but is not seen on its scale). This is caused by the contribution of the radiation extinction on the path "top of the atmosphere – reflecting surface – scattering point" into variation of its intensity.

If the reflection is neglected, derivatives higher than the sight height change sign insignificantly, but lower this height all of them are equal to zero. So the surface effect can change the sign of the total variations of intensity at variations of the entire profile of the aerosol scattering coefficient: it is positive at neglecting the surface effect and negative otherwise. This is the case under conditions of Fig. 3 at sight heights of 30–80 km.

Even maximal derivatives of the intensity with respect to the total aerosol absorption coefficient for the background model[17] are of the order of 10^{-4}. It means that to reach intensity variations of 1%, the aerosol absorption coefficient should change by approximately 100 times (and the total aerosol scattering coefficient, – see above – by 10%). Therefore, against the background of such scattering effect, we can deal only with retrieval of the order of the magnitude of the aerosol absorption coefficient.

Note the following important technical detail. For sufficiently accurate approximation of variation derivatives in Figs. 2 and 3, the height step in the model of the atmosphere was taken 0.1 km. The use of such model, containing 901 height levels as input to SCATRD, required no modifications of the already generated code. This is the advantage of the code SCATRD over the codes traditionally used in the atmospheric optics, for example, MODTRAN[17] with its strongly restricted number of levels in the height grid (34 levels).

Analysis of radiation intensity variations

The use of derivatives allows one to analyze in detail the effect of atmospheric parameter variations on the intensity of the diffuse solar radiation, however, the latter depends in the used model on ten parameters: wavelength, solar zenith angle, sight height and viewing azimuth, profiles of air temperature and pressure, aerosol scattering and absorption coefficients, mean cosine of the aerosol scattering phase function, and the surface albedo. Taking this into account, a simple technique was used for initial analysis of the noted multi-dimension dependence, i.e., direct calculation of intensity variations at variations of particular atmospheric and surface parameters. One of the examples of such calculations is shown in Fig. 4.

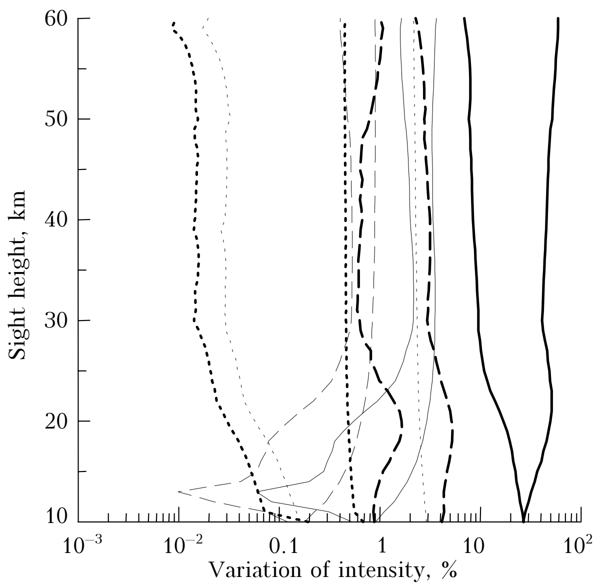

Fig. 4. Relative signless variations of intensity. Wavelength is 0.55 μm. Solar zenith angle is 75°. Surface albedo is 0.9. Background aerosol model.[17] Bold lines refer to aerosol variations: solid – +100% of the scattering coefficient, dashed – +0.1 of the mean cosine of the scattering phase function, dotted – +100% of the absorption coefficient. Thin lines refer to other parameters: solid – +10°K of temperature, dashed – +1% of pressure, dotted – +0.1 of albedo. For variations of the scattering coefficient and the mean cosine, the right curves refer to viewing azimuth of 0°, left ones to that of 180°, for variations of other parameters to the contrary: right ones to viewing azimuth of 180°, left ones to that of 0°.

As was mentioned above, the dependence of intensity variations on the viewing azimuth is the most significant. In its turn, it is caused by the dependence of the total scattering phase function on the scattering angle. Variations of almost all parameters at different azimuths change approximately by an order of magnitude (see Fig. 4). Variations with respect to the total aerosol scattering coefficient and mean cosine of the aerosol scattering phase function are maximal at azimuth of 0°, and to the contrary, variations with respect to the total aerosol absorption coefficient, temperature, and air pressure are minimal at this azimuth. This is confirmed by the conclusion drawn above about the information capacity for determination of the aerosol parameters just of small scattering angles, because as azimuth (and the scattering angle) increase, variations with respect to all considered parameters approach closely. As the azimuth dependence actually is the dependence on the scattering angle, it is well pronounced at large solar zenith angles; at small ones the scattering angle changes insignificantly, and the dependence on the viewing azimuth is weakly pronounced.

Some dependence on the surface albedo is also observed, it manifests itself quite complicatedly at different azimuth angles and different types of variations. For variations with respect to the total aerosol scattering coefficient, air temperature and pressure, strong reflection from the surface can lead to change of sign; this effect was discussed above. In its turn, this phenomenon also depends on the viewing azimuth. The effect of the surface at azimuth of 0° is usually insignificant. At azimuth angles of 90° and 180°, the dependence of variations on the reflecting surface is pronounced much stronger.

From the practical point of view, it is interesting to compare variations with respect to aerosol parameters with variations with respect to the factors "interfering" their determination: temperature and pressure of air (determining the molecular scattering) and the surface albedo. Strong spectral dependence is observed here stipulated by the dependence on the wavelength of the molecular scattering coefficient.[1]

Variations at a wavelength of 0.38 μm with respect to temperature and pressure (see below) exceed the variations with respect to the total aerosol scattering coefficient and the mean cosine of the scattering phase function (except of azimuth of 0°), at λ = 0.55 μm they become approximately equal (again, except for azimuth of 0°), and at λ = 1.5 μm they are almost two orders of magnitude less. Hence, variations with respect to aerosol parameters increase with increase of wavelength and decrease of the molecular scattering – variations with respect to the total aerosol scattering coefficient at a wavelength of 1.5 μm are close to 100% per 100%, and even variations with respect to the total aerosol absorption coefficient exceed 1% per 100%.

Note that intensity variations were calculated by variation of air temperature of 10°, that approximately corresponds to *a priori* mean climatic value. When using more precise data (radiosounding, meteorological forecast), the variations will be approximately 1–2° and, hence, the variation of intensity will decrease approximately 10 times, and even at $\lambda = 0.38$ μm it will be essentially less than variations with respect to aerosol scattering parameters.

Variation of intensity with respect to the surface albedo was calculated at maximal reflection. Hence, this is its extreme estimate. The noted variation also strongly depends on the wavelength, which is explained by increase of contribution of the reflected radiation to the intensity and by decrease of scattering. The variation with respect to albedo at $\lambda = 0.55$ μm is approximately 1% per 10% and strongly depends on the viewing azimuth (maximum for 180°), and at $\lambda = 1.5$ μm this variations is already close to 10% per 10%, and its strong azimuth dependence disappears.

Some increase of variations with respect to albedo is observed as solar zenith angle increases. This can be explained by increase of the portion of radiation incident on the surface and, hence, reflected radiation. Variations with respect to albedo at zenith angle of 10° are 4–7% opposite a maximum of 2% at an angle of 75°.

On the whole, the analysis confirms the conclusion drawn above about a good sensitivity of measurements to variations of the aerosol scattering coefficient and the mean cosine of the aerosol scattering phase function.

Note that the analysis was carried out without taking into account the molecular absorption (to do this, the wavelengths were chosen, where it is small). Obviously, its contribution will slightly decrease all considered variations.

Conclusions

The following conclusions about the possibility of retrieving aerosol parameters from measurements of the diffuse solar radiation intensity can be drawn on the basis of the conducted analysis.

1. The information capacity of measurements is sufficient for statement of the problem of retrieval of the total aerosol scattering coefficient and the mean cosine of the scattering phase function. As for the aerosol absorption coefficient, one can deal only with retrieval of the order of its magnitude (for the background aerosol stratosphere).

2. A strong dependence of variation derivatives with respect to the aerosol scattering coefficient and the mean cosine of the aerosol scattering phase function on the viewing azimuth is observed. Hence, it is possible to state the problem of selection of a scheme of vision optimal for determination of aerosol parameters.

3. Strongly reflecting surface can lead to appearance of an essential range of negative values of the variation derivatives with respect to the aerosol scattering coefficient, which, in its turn, can cause a change of sign of the total variation of intensity at variations of the profile of this coefficient. Therefore, in the model of radiative transfer, the surface reflection must be taken into account. *A priori* data on the surface albedo are also necessary.

4. Model uncertainties of practically all parameters of the atmosphere and the surface are essential at high-precise measurements (of order of fractions of percent), including profiles of pressure and temperature, as well as the surface albedo. Hence, it is desirable to use additional *a priori* data.

Acknowledgments

Authors would like to thank Yu.M. Timofeev for statement of the problem and active discussion of the obtained results.

This work was supported in part by Russian Foundation for Basic Research (grant No. 03–05–64626) and the grant "Universities of Russia" No. 01.01.044.

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