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A DIFFERENTIAL METHOD OF DETERMINING THE PRINCIPAL OPTICAL PARAMETERS OF AN ATMOSPHERIC AEROSOL IN THE ULTRAVIOLET BAND

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Based on the well-known three-wave method of measuring small gaseous components of the atmosphere and the Angström formula, a differential method of determining the optical density of the aerosol constituent of the atmosphere in the ultraviolet band is suggested.

Introduction. The aerosol represents the most important constituent of the atmosphere and determines the energy balance of the entire Earth. Its principal parameters are the optical density as well as some others associated with it, to which the Angström index can be related [1]. The optical density of aerosol can be determined by both "direct" and "inverse" methods. The principal "direct" method is that of Lengly [2]. The crux of the method is taking the logarithm of the fundamental equation of the optical radiation extinction in the atmosphere (the Bouguer–Beer law) and imparting a linear form to the graph of this equation at the slope in the UV band equal to the linear sum of individual optical densities:

$$\tau_\Sigma = \tau_{\mathrm{aer}\lambda} + \tau_{\mathrm{oz}} + \tau_{\mathrm{R}} \,. \tag{1}$$

The values of τ_{oz} and τ_{R} found or known for the wavelengths given are used for calculations. Thus, the complexity of direct measurements of the optical density of an aerosol in the UV band leads to the necessity of carrying out indirect determination and corresponding calculations outside this band.

As noted above, the principal optical parameters of aerosol can also be found by an "inverse" method based on the mathematical apparatus of integral equations, in particular, of the Fredholm equations of the first and second kind. Here, researchers face the chief challenge of incorrectly posed problems of mathematical physics where arbitrary small errors in the values measured may lead to arbitrary great errors in the functions sought.

However, the aim of the present work is to determine not the function $\tau(\lambda)$, but rather a separate discrete value τ at selected wavelengths with the aid of "direct" measurements, using the Bouguer–Beer equation. In this connection, the problems of stability and "regularization," inherent in "inverse" problems, are not considered in the present article.

We note that the problem of taking into account the influence of the aerosol is also present in ozonometry, but not of measuring the optical density of aerosol but rather of eliminating its effect. The widely known Dobson ozonometric method presupposes, in some particular cases, the elimination of the aerosol error by performing measurements at two pairs of wavelengths [2]. However, the method does not permit one to carry out aerosol measurements eliminating the effect of the atmospheric ozone and therefore cannot be recognized as a universal and exact one to be used for investigating the optical parameters of individual components of the atmosphere in the UV band. Such universality, in our opinion, is characteristic of the method of three-wave measurements examined in most detail in [3]; below, we present a variant of the application of this method to determining the principal optical parameters of the aerosol.

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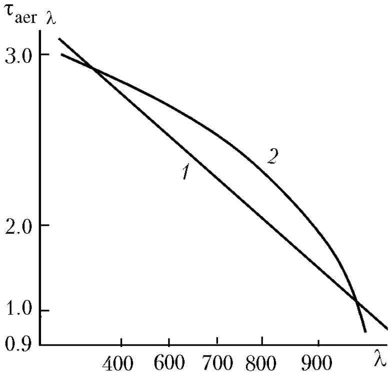

Fig. 1. Curves of the dependence ln $\tau_{\text{aer}\lambda} = f(\ln \lambda)$: 1) linear approximation; 2) nonlinear dependence [7].

First of all, we set forth the crux of the proposed differential method of finding the optical density of aerosol. As is known [1], $\tau_{\text{aer}\lambda}$ is defined by the Angström empirical formula

$$\tau_{\text{aer}\lambda} = C_1 \lambda^{-\alpha} . \tag{2}$$

Taking the derivative of (2) with respect to λ, we obtain

$$\frac{d\tau_{\text{aer}\lambda}}{d\lambda} = - \alpha C_1 \lambda^{-(\alpha+1)} , \tag{3}$$

which lies at the basis of the proposed differential method.

As concerns the applicability of Eq. (2), the following arguments are appropriate. Having taken logarithms of both sides of Eq. (2), we have

$$\alpha = - \frac{d \ln \tau_{\text{aer}\lambda}}{d \ln \lambda} , \tag{4}$$

i.e., α is defined as the derivative $\tau_{\text{aer}\lambda}$ of the wavelength in a logarithmic scale. In [4, 5] it is shown that $\alpha > 2.0$ for fresh aerosol particles of smoke, whereas for large disperse desert dust aerosol particles the value of α approaches zero.

In [6] the value of α calculated within the range 380–862 nm was analyzed, and the relationship between it and the effective radius r of the quantitative distribution of the sizes of aerosol particles was revealed. The Angström index α is related to the parameter ν of the Junge distribution law [7] as

$$\alpha = \nu - 2 , \tag{5}$$

where $\frac{dN}{d \ln r} = Cr^{-\nu}$ is a mathematical expression of the Junge distribution law. However, in an actual case, the aerosol obeys the size distribution law different from expression (5) and as a result of such deviation from the Junge law an expression in the form of the second-order polynomial to describe the interrelationship between $\tau_{\text{aer}\lambda}$ and α is suggested:

$$\ln \tau_{\text{aer}\lambda} = \alpha_0 + \alpha_1 \ln \lambda + \alpha_2 (\ln \lambda)^2 . \tag{6}$$

Equation (6) has found experimental confirmation. Figure 1 presents an experimental nonlinear curve corresponding to Eq. (6) and a theoretical linear approximation for the range 340–1020 nm [7]. In this case, the quantity α calculated over the spectral lengths had the following values: α(340–380 nm) = 0.46; α(380–440 nm) = 1.03; α(440–500 nm) = 1.28; α(500–675 nm) = 1.76; and α(675–870 nm) = 2.31.

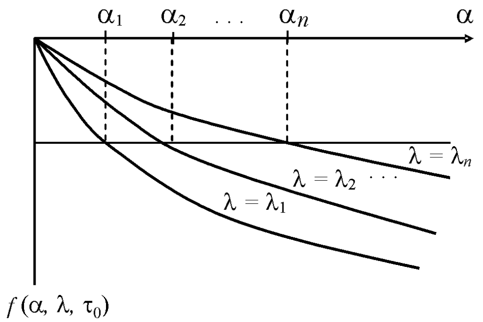

Fig. 2. Graphical illustration of the solution of Eq. (7).

The foregoing refinement of the relationship between such parameters as α, $\tau_{\text{aer}\lambda}$, and λ are very important for investigation of $\tau_{\text{aer}\lambda}$ in a wide range of wavelengths, for example, at λ = 340–1000 nm.

The aim of the present work is to determine $\tau_{\text{aer}\lambda}$ in the UV band, which justifies the further use of expressions (2) and (3) for solving the problem set.

Expression (3) represents a transcendental equation for α whose solution can be performed graphically. Here, it should be kept in mind that the right-hand side of Eq. (3) for the UV band is a monotonic function of α. The essence of such a solution consists of the construction of a family of curves of the function

$$\frac{\Delta\tau_{\text{aer}\lambda}}{\Delta\lambda} = f(\alpha, \lambda, C_1) \tag{7}$$

at the given discrete values of λ for the specified continuous interval $\alpha = \alpha_{\max} - \alpha_{\min}$. The intersection of the curves of the indicated family with the horizontal line $y = \Delta\tau_{\text{aer}\lambda}/\Delta\lambda$ yields the unknown values of $\alpha_1, \alpha_2, ..., \alpha_n$.

Conventionally the process of the solution of Eq. (7) is shown in Fig. 2. It is evident that its solution presupposes the presence of the estimate of the differential parameters $\Delta\tau_{\text{aer}\lambda}/\Delta\lambda$. To calculate the latter, the above-mentioned three-wave method is used, according to which measurements are made at three wavelengths λ_1, λ_2, and λ_3, where $\lambda_1 < \lambda_2 < \lambda_3$, as a result of which we obtain $I_1(\lambda_1)$, $I_2(\lambda_2)$, and $I_3(\lambda_3)$ corresponding to the solar radiation intensities at the level of the ground at these wavelengths [3]. Thereafter, a relative value of z is calculated:

$$z = \frac{\sqrt[k]{I_1(\lambda_1)\, I_3(\lambda_3)}}{I_2(\lambda_2)}, \tag{8}$$

where $k = 2 \pm \Delta'$.

We will avail ourselves of Bouguer's formula, which in application to the output signals of the optical channels of meter I has the following form [1]:

$$I = \Delta\lambda\omega S_0 \cdot 10^{-[\gamma_{\text{oz}}\mu X + \tau_{\text{R}} m + \tau_{\text{aer}\lambda} m_1]}, \tag{9}$$

where $\Delta\lambda$ is the spectral width of the optical channel of the meter. With account for Eqs. (8) and (9), with the parameters of the optical channels being identical, we have

$$z = \frac{\sqrt[k]{S_{01}S_{03}}}{S_{02}} \cdot 10 - \left[\mu X\left(\frac{\gamma_{0\lambda_1} + \gamma_{0\lambda_3}}{k} - \gamma_{0\lambda_2}\right) + m\left(\frac{\tau_{\text{R}\lambda_1} + \tau_{\text{R}\lambda_3}}{k} - \tau_{\text{R}\lambda_2}\right) + m_1\left(\frac{\tau_{\text{aer}\lambda_1} + \tau_{\text{aer}\lambda_3}}{k} - \tau_{\text{aer}\lambda_2}\right)\right]. \tag{10}$$

It is well known that among all above-considered components which influence the overall extinction of an optical ray in the atmosphere, the aerosol has the greatest variability. To clearly isolate the aerosol part in Eq. (10) maximally, the value of the parameter k should be selected in such a way that the following equality should be satisfied:

$$\mu X\left(\frac{\gamma_{0\lambda_1}+\gamma_{0\lambda_3}}{k}-\gamma_{0\lambda_2}\right)+m\left(\frac{\tau_{R\lambda_1}+\tau_{R\lambda_3}}{k}-\tau_{R\lambda_2}\right)=0\,. \tag{11}$$

To control the attainment of condition (11) one has to calculate the autocorrelation function of the parameter z. It is evident that with condition (11) being met, the ratio of the high-frequency part of the autocorrelation function of the parameter z to its low frequency part must have a maximum value.

In this case, expression (10) takes the form

$$z=\frac{\sqrt[k]{S_{01}S_{03}}}{S_{02}}\cdot 10^{-m_1}\left(\frac{\tau_{\mathrm{aer}\lambda_1}+\tau_{\mathrm{aer}\lambda_3}}{k}-\tau_{\mathrm{aer}\lambda_2}\right). \tag{12}$$

Next, assuming the function $\tau_{\mathrm{aer}}(\lambda)$ to be linear in a narrow range λ_1–λ_3, we have

$$z=\frac{\sqrt[k]{S_{01}S_{03}}}{S_{02}}\cdot 10^{-m_1}\,(\overset{*}{\tau}_{\mathrm{aer}\lambda_1\lambda_3}+\tau_{\mathrm{aer}\lambda_2})\,, \tag{13}$$

$$\overset{*}{\tau}_{\mathrm{aer}\lambda_1\lambda_3}=\frac{\tau_{\mathrm{aer}\lambda_1}+\tau_{\mathrm{aer}\lambda_3}}{k}\,. \tag{14}$$

Equation (13) yields

$$\overset{*}{\tau}_{\mathrm{aer}\lambda_1\lambda_3}-\tau_{\mathrm{aer}\lambda_1\lambda_2}=\ln\frac{\sqrt[m_1+k]{S_{01}S_{03}}}{\sqrt[m_1]{zS_{02}}}\,. \tag{15}$$

From Eq. (15) it follows that

$$\frac{\Delta\tau_{\mathrm{aer}\lambda}}{\Delta\lambda}=\frac{1}{\Delta\lambda}\ln\frac{\sqrt[m_1+k]{S_{01}S_{03}}}{\sqrt[m_1]{zS_{02}}}\,. \tag{16}$$

Thus, the considered three-wave method of measuring allows one to estimate the value of $\Delta\tau_{\mathrm{aer}\lambda}/\Delta\lambda$, which is required to calculate the parameters α with the aid of expression (4).

Conclusions. The proposed differential method of calculating the optical parameters of the atmospheric aerosol can be formulated as follows:

1) three-wave measurements are made in the regime in which the high-frequency component of the autocorrelation function of the parameter z takes a maximum value;

2) based on the results of measurement according to Item 1 the quantity $\Delta\tau_{\mathrm{aer}\lambda}/\Delta\lambda$ is calculated;

3) a graphical solution of Eq. (7) is made (see Fig. 2).

We also note that the proposed differential method, unlike the Langley method, is based on the results of measurements in the UV band, which is responsible for the validity of the results obtained by this method.

NOTATION

$C_1 = \tau_{\mathrm{aer}\lambda}(\lambda = 1\ \mu\mathrm{m}) = \mathrm{const}$; C, the Junge parameter; I, the output signal of the optical channels of the meter, mA; m, optical mass of the Rayleigh atmosphere; m_1, optical mass of the atmospheric aerosol; N, total number of aerosol particles in a vertical column at atmosphere of section 1 cm^2 the radius of which is smaller than r; r, radius of aerosol particles, μm; S_0, solar radiation flux on the outer boundary of the atmosphere, W·cm^{-2}·μm^{-1}; X, overall content of ozone in the atmosphere, matm·cm; α, Angström factor; α_0, zero component of the Angström factor in series expansion; γ_{oz}, coefficient of attenuation of ozone, matm·cm^{-1}; Δ', regulated value; λ, wavelength, μm; μ, optical mass of ozone; ν, Junge index; τ, optical density; ω, spectral sensitivity of the meter, mA·W^{-1}·cm^2. Subscripts: aer, aerosol; oz, ozone; R, Rayleigh.

REFERENCES

1. G. P. Gushchin (Ed.), *Total Content of Atmospheric Ozone and Spectral Transparency of Atmosphere* [in Russian], Gidrometeoizdat, Leningrad (1980).
2. *Multi-Filter Rotating Shadow Band Radiometer*, http://www.ess.uci.edu/~ cmclinden/link/rsr.html.
3. Kh. G. Asadov and A. A. Isaev, General theory of three-wave ozonometric measurements, *Izmer. Tekh.*, No. 8, 66–68 (2005).
4. Y. J. Kaufman, A. Setzer, D. Ward, D. Tanre, B. N. Holben, P. Menzel, M. C. Pereira, and R. Rasmussen, Biomass burning airborne and spaceborne experiment in the Amazonas (BASE-A), *J. Geophys. Res.*, **97**, 14581–14599 (1992).
5. B. N. Holben, T. F. Eck, and R. S. Fraser, Temporal and spatial variability of aerosol optical depth in the Sahel region in relation to vegetation remote sensing, *Int. J. Remote Sensing*, **12**, 1147–1163 (1991).
6. N. O'Neill and A. Royer, Extraction of bimodal aerosol-size distribution radii from spectral and angular slope (Angstrom) coefficients, *Appl. Opt.*, **32**, 1642—1645 (1993).
7. T. F. Eck, B. N. Holben, J. S. Reid, O. Dubovik, A. Smirnov, N. T. O'Neill, I. Slutsker, and S. Kinne, Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols, *J. Geophys. Res.*, **104**, No. D24, 31333–31349 (1999).