MULTIWAVE METHOD FOR INTERPRETATION OF THE DATA ON THE SPECTRAL SKY BRIGHTNESS IN THE ZENITH

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A new multiwave technique for the ozone total content and aerosol optical thickness determination from the spectra of radiation scattered in the zenith has been described. The efficiency of the proposed technique has been confirmed by results of experimental data processing and by numerical simulation.

In Ref. 1 two techniques (two-wave differential and four-wave) for the ozone and nitrogen dioxide total content (TC) determination were considered and approved with the use of the data on the spectral sky brightness in the zenith measured in the UV range. The techniques were based on the model of single scattering of radiation in the atmosphere. Because the spectra of signals were almost continuous (the wavelength step was 0.1 nm), statistical processing of signals was possible for both techniques so the reliability of the obtained data on gas concentration was increased. Without going into advantages and disadvantages of these techniques, it should be emphasized that they can be used only for estimation of gas concentration. In the present paper, we propose a multiwave technique of data processing that allows one to determine not only the gas concentration but the aerosol optical thickness as well.

Multiwave techniques have been developed and used for passive sounding with the direct solar radiation for a long time.[2–7] However, we are not aware of papers describing this technique as applied to sounding with the use of the scattered radiation.

Similarly to Ref. 1, the basis for this technique is a solution of the transfer equation in the approximation of single scattering in a cloudless atmosphere. In this case, for a ground-based device with the optical axis pointed at the zenith assuming that the solar zenith angle θ is not too large (less than 75°), measurable signals $J(\lambda)$ are connected with the atmospheric parameters by the following expressions:

$$J(\lambda) = S_0(\lambda)\, C(\lambda) \int\limits_0^H d(\lambda, \theta, z) \times$$

$$\times \exp\left[-\int\limits_0^z \alpha_\Sigma(\lambda, z')\, dz' - \frac{1}{\mu}\int\limits_z^H \alpha_\Sigma(\lambda, z')\, dz' \right] dz\,, \qquad (1)$$

$$\alpha_\Sigma(\lambda, z) = k_g(\lambda, z)\, \rho_g(z) + \alpha_{am}(\lambda, z),$$
$$\alpha_{am}(\lambda, z) = \alpha_a(\lambda, z) + \alpha_m(\lambda, z),$$
$$d(\lambda, \theta, z) = \alpha'_a(\lambda, z)\, g_a(\theta) + \alpha_m(\lambda, z)\, g_m(\theta),\ \mu = \cos\theta,$$

where $S_0(\lambda)$ is the solar constant, $C(\lambda)$ is the instrumental constant expressed as a product $C(\lambda) = C_0 \times C_\lambda$ of the constant and wavelength-dependent factors, $d(\lambda, \theta, z)$ is the total coefficient of aerosol and molecular scattering at an angle θ at an altitude z, $k_g(\lambda, z)$ and $\rho_g(z)$ are the altitude profiles of the extinction coefficient and density of the examined gas, respectively, H is the height of the upper boundary of the atmospheric model, $\alpha'_a(\lambda, z)$ and $\alpha_m(\lambda, z)$ are the profiles of the aerosol and molecular light scattering coefficients, $g_a(\theta)$ and $g_m(\theta)$ are the scattering phase functions corresponding to these profiles, $\alpha_a(\lambda, z)$ is the coefficient of aerosol extinction (in the 300–400 nm spectral range the aerosol absorption is negligible comparing with scattering, so $\alpha_a \approx \alpha'_a$). It also should be noted that in Eq. (1) the absorption by interfering gases is neglected.

Multiplying the integrand of Eq. (1) by the factor

$$\exp\left[\frac{1}{\mu}\int\limits_0^z \alpha_\Sigma(\lambda, z')\, dz' - \frac{1}{\mu}\int\limits_0^z \alpha_\Sigma(\lambda, z')\, dz' \right],$$

grouping the terms, and taking the constant factor $\exp\left[-\frac{1}{\mu}\int\limits_0^H \alpha_\Sigma(\lambda, z')\, dz' \right]$ out of the integral, we obtain the expression

$$J(\lambda) = S_0(\lambda)\, C(\lambda) \exp\left[-\frac{1}{\mu}\int\limits_0^H \alpha_\Sigma(\lambda, z)\, dz \right] \times$$

$$\times \int\limits_0^H d(\lambda, \theta, z) \exp\left\{ \left(\frac{1}{\mu} - 1\right) \int\limits_0^z \alpha_\Sigma(\lambda, z')\, dz' \right\} dz \qquad (2)$$

analogous to the formula derived in Ref. 1.

Then, taking the factor with a given upper integral limit $z_{eff} < H$ (according to the mean value theorem)

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$$\exp\left[\left(\frac{1}{\mu}-1\right)\int\limits_0^{z_{\mathrm{eff}}}\alpha_g(\lambda, z')\,\mathrm{d}z'\right]$$

out of the second integral of Eq. (2), neglecting the altitude dependence of the extinction coefficient of the examined gas ($k_g(\lambda, z) = k_\lambda$), and taking the logarithm, we obtain the following expression:

$$\ln I_\lambda = k_\lambda \{[(1/\mu) - 1]\, X_{\mathrm{eff}} - (1/\mu)\, X\} + \ln C_0 +$$
$$+ \ln\left\{\int\limits_0^H d\,\exp\left[\left(\frac{1}{\mu}-1\right)\int\limits_0^z \alpha_{\mathrm{am}}\,\mathrm{d}z'\right]\mathrm{d}z\right\} - \frac{1}{\mu}\tau_{\mathrm{am}}(\lambda), \quad (3)$$

$$\tau_{\mathrm{am}}(\lambda) = \tau_{\mathrm{a}}(\lambda) + \tau_{\mathrm{m}}(\lambda), \quad \tau_{\mathrm{a}}(\lambda) = \int\limits_0^H \alpha_{\mathrm{a}}(\lambda, z)\,\mathrm{d}z;$$

$$\tau_{\mathrm{m}}(\lambda) = \int\limits_0^H \alpha_{\mathrm{m}}(\lambda, z)\,\mathrm{d}z,$$

$$I_\lambda = J(\lambda)/[C_\lambda\, S_0(\lambda)],$$

where τ_{a} and τ_{m} are the vertical optical thicknesses of the aerosol extinction and molecular scattering, respectively; $X = \int\limits_0^H \rho(z)\,\mathrm{d}z$ is the total content of the examined gas in the vertical atmospheric column; $X_{\mathrm{eff}} = \int\limits_0^{z_{\mathrm{eff}}} \rho(z)\,\mathrm{d}z$ is its effective total content. Strictly speaking, X_{eff} depends on λ due to the dependence of z_{eff} on λ. Using the approximation $d(\lambda, \theta, z) = \alpha_{\mathrm{m}}(\lambda, z)\, g(\theta)$, where $g(\theta)$ is the average scattering phase function for the layer $0-H$, we reduce the third term of Eq. (3) to the form

$$\ln\left\{g(\theta)\int\limits_0^H \frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{\mu}{1-\mu}\exp\left[\left(\frac{1}{\mu}-1\right)\int\limits_0^z \alpha_{\mathrm{am}}(\lambda, z')\,\mathrm{d}z'\right]\right)\mathrm{d}z\right\} =$$
$$= \ln\left\{g(\theta)\,\frac{\mu}{1-\mu}\left(\exp\left[\left(\frac{1}{\mu}-1\right)\tau_{\mathrm{am}}(\lambda)\right]-1\right)\right\}.$$

Grouping this term with the second and fourth terms we obtain the resultant expression

$$\ln I_\lambda = k_\lambda\left[\left(\frac{1}{\mu}-1\right)X_{\mathrm{eff}} - \frac{1}{\mu}X\right] +$$
$$+ \ln\left\{C_0\, g(\theta)\,\frac{\mu}{1-\mu}\,(\mathrm{e}^{-\tau_{\mathrm{am}}} - \mathrm{e}^{-\tau_{\mathrm{am}}/\mu})\right\}. \quad (4)$$

The assumption that $g(\theta)$ is independent of λ is acceptable only if the wavelength range chosen for data processing is narrow enough. For the employed spectral range (near 300 nm) it corresponds to several tens of nanometers. We consider the function C_λ (see Eq. (3)) to be known (as a rule, the instrumental constant is determined to within the constant factor C_0). We also assume that the solar constant $S_0(\lambda)$ is known. As an initial approximation in calculations, we set

$$X_{\mathrm{eff}} = \left\langle \ln\left(\frac{I\,C_\lambda}{I\,C\,S_\lambda}\right)\Big/\left(\frac{1}{\mu}-\mu\right)k_\lambda\right\rangle_\lambda, \quad (5)$$

where

$$IC_\lambda = \int\limits_0^H d\,\exp\left[\left(\frac{1}{\mu}-1\right)\int\limits_0^z \alpha_\Sigma\,\mathrm{d}z'\right]\mathrm{d}z,$$

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Here, $\langle\ \rangle_\lambda$ denotes averaging over all wavelengths.

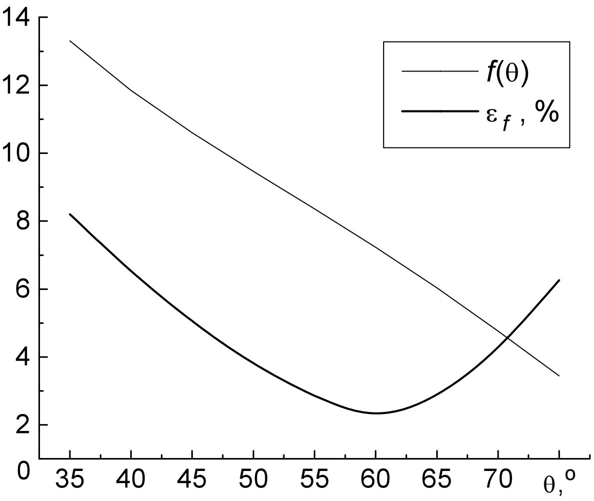

FIG. 1. Functions $f(\theta)$ and ε_f (%) at $X = 330$ Dobson units (D.u.) *for the summer atmospheric model at mid-latitudes*[10] *and the aerosol model borrowed from Ref. 9.*

Numerical analysis has demonstrated that the ratio X/X_{eff} is a quasi-linear function of θ and depends weakly on X and τ_{a}. The dependence $X/X_{\mathrm{eff}} = f(\theta)$ is shown in Fig. 1 at $X = 330$ Dobson units (D.u.) for the summer atmospheric model at mid-latitudes[10] and the aerosol model described in Ref. 9. The parameter X_{eff} was calculated using Eq. (5). It is seen that $f(\theta)$ decreases linearly as θ increases. In the same figure the dashed line shows the deviation (ε_f, %) of $f(\theta)$ from the initial straight line when the parameter X changes by 25% and the optical thickness of aerosol changes by 50% (the influence of τ_{m} variations can be disregarded). To the left of the minimum, the deviation is primarily determined by the aerosol component, to the right of it – by variation of X. It is seen that at $\theta = 40-75°$ the deviation is no greater than 6%. So we can use the obtained dependence

$$X/X_{\rm eff} \equiv f(\theta) = \frac{X}{\left\langle \ln\left(\frac{I\,C_\lambda}{I\,C\,S_\lambda}\right) \Big/ \left(\frac{1}{\mu} - \mu\right) k_\lambda \right\rangle_\lambda}, \qquad (6)$$

assuming that it is independent of X and τ_a if the parameters X and τ_a exceed their initial values by no more than 25 and 50%, respectively. When deviation is greater, the function $f(\theta)$ should be recalculated using the current values of X and τ_a. After that, the process of reconstruction should be repeated.

Introducing the approximation for the aerosol optical thickness in the form

$$\tau_a(\lambda) = \tilde{\tau}_a(\lambda_0/\lambda)^q \qquad (7)$$

(where $\tilde{\tau}_a$ is the aerosol optical thickness at the wavelength λ_0 and q is the parameter) and substituting Eqs. (6) and (7) into Eq. (4) we obtain a system of linear equations

$$y_i = p_1 R_i + p_2 + b_i(p_3, p_4), \quad i = 1, \dots, N \quad (8)$$

for four unknown parameters

$$p_1 = X,\ p_2 = \ln\{C_0\, g(\theta)\, [\mu/(1-\mu)]\},$$

$$p_3 = \tilde{\tau}_a, \quad p_4 = q,$$

where

$$b_i(p_3, p_4) = \ln\left\{\exp\left[-\left(p_3\left(\frac{\lambda_1}{\lambda_i}\right)^{p_4} + \tau_m(\lambda_i)\right)\right] - \right.$$

$$\left. - \exp\left[-\frac{1}{\mu}\left(p_3\left(\frac{\lambda_1}{\lambda_i}\right)^{p_4} + \tau_m(\lambda_i)\right)\right]\right\},$$

$$y_i = \ln\{J(\lambda_i)/[C_{\lambda_i}\, S_0(\lambda_i)]\},$$

$$R_i = k_{\lambda_i}\{[1 - \mu - f(\theta)]/[\mu\, f(\theta)]\}.$$

Here, N is the number of wavelengths. If N is greater than four, the least-squares method can be applied to solve Eq. (8), i.e., the solution can be found from the condition of minimum for the functional

$$F = \sum_i [y_i - p_1 R_i - p_2 - b_i(p_3, p_4)]^2.$$

The proposed method of experimental data processing allows one to determine not only the total content of the gas but the aerosol optical thickness as well.

The model inverse problem was solved for the following initial parameters. The solar constant was borrowed from Ref. 8. The aerosol optical thickness was calculated for the model described in Ref. 9 and the Rayleigh optical thickness – for the summer atmospheric model at mid-latitudes.[10] The initial value of the generalized light scattering phase function $g(\mu)$ was defined numerically from the equation

$$\int_0^H d(\theta, \lambda, z) \exp\left[\left(\frac{1}{\mu} - 1\right)\int_0^z \alpha_{\rm am}(\lambda, z')\, dz'\right] dz =$$

$$= g(\theta)\,\frac{\mu}{1-\mu}\left\{\exp\left[\left(\frac{1}{\mu} - 1\right)\tau_{\rm am}(\lambda)\right] - 1\right\}$$

for the model borrowed from Ref. 9.

The instrumental constant C_0, entering into the parameter p_2, was assumed equal to unity in the model experiment. In processing of the experimental data, the initial value of the parameter, p_2^0, was defined from Eq. (8) by averaging over all wavelengths

$$p_2^0 = \langle y_i - p_1^0 R_i - b_i(p_3^0, p_4^0)\rangle_i,$$

where p_j^0 (j = 1, 3, 4) are the initial values of the other parameters determined for corresponding models.

To simulate the measurement noise, the values of calculated signals were distorted with the use of a random number generator. The variance of this "noiseB was 2%. The results of inverse problem solution for ozone are presented in Table I. The totality of 200 wavelengths from the 302–322 nm spectral range was included in data processing with the 0.1-nm step. In the first column the initial values of the parameters p_j^0 are presented that differ from their exact values by 10–30%; in the second column the reconstructed mean values $\bar{p}_j$ are given. In parentheses the standard deviations (in per cent) $\sigma_{p_j}/\bar{p}$ of the parameters found by a solution of the inverse problem for 100 realizations are given. Here, σ_{p_j} is the variance of the jth parameter. The exact values of the parameters are given in the third column. The values of the parameter $p_3(\tau_a)$ correspond to the wavelength λ_0 = 302 nm. Simulation was performed for the solar zenith angle θ = 55°.

TABLE I. Results of the numerical experiment on determination of p_i for 2% noise level.

j	p_j^0	$\bar{p}_j$ ($\sigma_{p_j}/\bar{p}_j$, %)	p_j (exact)
1	360.0 D.u.	330.2 D.u. (0.8)	329.1 D.u.
2	– 2.52	– 2.33 (2.2)	–2.30
3	0.520	0.385 (15.8)	0.402
4	0.85	0.78 (28.0)	0.77

It is seen that the total content of ozone p_1 is most robust. For this parameter the variance and bias of its reconstructed mean value are minimum. Reconstruction of the parameter p_2, being a function of the instrumental constant and the average scattering phase function, as well as the aerosol optical thickness p_3, is less robust. The spectral index of the aerosol extinction p_4 is least robust.

The results of processing of the actual sky brightness measured in the spectral range 302–322 nm over Tomsk on September 7, 1995 are presented in Table II. The good coincidence of the obtained total ozone content is seen with the results of measurements with the M-124 device presented in the last column. Unfortunately, we had no way of checking for the correctness of reconstruction of the other parameters.

TABLE II. Results of determination of the parameters in processing of the actual signals measured on September 7, 1995.

j	p_j^0	Reconstructed	Exact
1	329.0 D.u.	302.5 D.u.	307.0 D.u. (M–124)
2	2.0	1.94	–
3	0.40	0.37	–
4	0.77	0.62	–

In conclusion, it should be noted that though the proposed technique was based on the model of single scattering, reliable results may be expected for the turbid atmosphere and the atmosphere with a small cloud amount when the influence of multiple scattering becomes more significant. The last statement is based on the fact that the spectral dependence of multiply scattered radiation correlates with such dependence for singly scattered radiation. This allows one to represent a significant portion of multiply scattered radiation (see Eq. (1)) as a constant factor C_M, i.e., to rewrite Eq. (1) in the form

$$J(\lambda) \sim S_0(\lambda)\, C(\lambda)\, C_M .$$

Here, C_M enters into the parameter p_2 along with C_0 and $g(\theta)$. From this fact it follows that the influence of multiple scattering is partially allowed for in the proposed technique.

Thus, the performed numerical simulation and preliminary results of actual signal processing confirm the efficiency of the proposed multiwave technique for determining the total ozone content and the aerosol optical thickness from the spectra of radiation scattered in the zenith. The accuracy of this technique should be studied in more detail. In the estimation of different components of the atmosphere by the above-described technique, of some interest is the choice of the optimal spectral ranges and solar zenith angles.

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