METHOD FOR INVESTIGATING THE STRUCTURE OF THE STRATOSPHERIC AEROSOL LAYER BASED ON LASER ECHO DEPOLARIZATION MEASUREMENTS

A.P. Chaikovskii

Institute of Physics
of the Academy of Sciences of the Bellorussian SSR, Minsk
Received June 29, 1990

A method for calibrating and processing laser sounding data in measurements of the degree of depolarization of the radiation scattered by stratospheric aerosol is described.

Measurement of the polarizationcharacteristics of a lidar pulse in stratospheric sounding gives additional information about the structure of the particles in the stratospheric aerosol layer (SAL).[1] It is sufficient to record the degree of depolarization of the lidar signal Q, when sounding the SAL with linearly polarized radiation, in order to identify the layers containing nonspherical particles, originating in emissions of volcanic ash, supercooling of the stratosphere, and formation of crystalline clouds.[2,3] However, when aerosol scattering is weaker than molecular scattering and the depolarized component of the lidar signal is weak, as is characteristic for the background state of the SAL, information about the aerosol can be obtained only by using measuring methods and a data processing algorithm that correspond to these conditions. This paper is devoted to analysis of this question.

When the SAL is sounded the measured characteristics are the components of the intensity of the lidar signal I_1 and I_2 recorded with the analyzer oriented parallel and perpendicular, respectively, to the polarization plane of the sounding pulse. These components are used to calculate the degree of depolarization $Q = \frac{I_2}{I_1} = \frac{\beta_2}{\beta_1}$, where β_1 and β_2 are the backscattering factors corresponding to the two components of the light flux.[2] The parameter Q is related with the elements of the backscattering matrix of am elementary volume S_{ij}:

$$Q = \frac{S_{11} - S_{22}}{S_{11} + 2S_{12} + S_{22}} . \tag{1}$$

The method for estimating the parameter $Q(h)$ (Ref. 2) is based on the normalization of this function to the value at the point h_0, i.e., to the layer with the minimum aerosol content, located at am altitude of about 35 km or in the region of the tropopause ($Q(h_0) \approx 0.05$). Then

$$Q(h) = \frac{N_2(h)}{N_1(h)} \cdot \frac{N_1(h_0)}{N_2(h_0)} \cdot Q(h_0), \tag{2}$$

where $N_1(h_0)$ and $N_2(h)$ are the number of recorded photons from the layer at altitude h in a given interval Δh in the first and second, respectively, charnels of the recording system.

However when low stratospheric aerosol concentrations are studied it is best to use the parameter $Q_a(h) = \frac{\beta_{a,2}}{\beta_{a,1}}$ — the degree of depolarization accompanying scattering by the aerosol component of the atmosphere — rather than the parameter $Q(h)$. Aside from the quantities Q amd Q_a, characterizing the depolarization of the lidar signal, the ratio of the backscattering $R = \frac{\beta_a + \beta_m}{\beta_m}$, where β_a and β_m are the aerosol and molecular backscattering coefficients, characterizing the contribution of the aerosol to the backscattering, can be reconstructed from measurements of $N_1(h)$ and $N_2(h)$. The parameters R_1 and R_2 for two components of the reflected signal can be studied analogously. Of all the quantities Q, Q_a, R, R_1, and R_2 only two are independent. From here, we obtain the relations

$$Q = \gamma \cdot \frac{R_2}{R_1} . \tag{3}$$

$$R = \frac{R_1 + \gamma R_2}{\gamma + 1} = \frac{R_1(Q + 1)}{\gamma + 1} . \tag{4}$$

$$Q_a = \gamma \cdot \frac{R_2 - 1}{R_1 - 1} = \frac{R_1 Q - \gamma}{R_1 - 1} , \tag{5}$$

where $\gamma = \frac{\beta_{2,m}}{\beta_{1,m}} = 0.017$ (Ref. 4).

As follows from Eq. (5) and the expression (9) presented below, for errors in the measurements of the parameter Q_a with a relative error in prescribing $Q(h_0)$ of the order of 0.3 … 0.4 (Ref. 2) and under conditions $R \sim 1$ and $Q \sim \gamma$, which is characteristic for the background state of the SAL, the lidar measurements give no information about the parameter $Q_a(h)$. To eliminate this factor, we developed a method for performing measurements in which only the parameter $R_1(h)$ is calibrated with respect to the layer in the region of h_0. Calibration of the lidar for reconstruction of $Q(h)$ is performed based on measurements of the number of photons $N_1^0(\Delta H)$ and $N_2^0(\Delta H)$ from the layer ΔH, performed with the polarization plane of the radiation at the output of the source oriented at an angle of 45° to the direction of orientation of the analyzers in the detector. In this case

$$Q(h) = \frac{N_2(h)}{N_1(h)} \cdot \frac{N_1^0(\Delta H)}{N_2^0(\Delta H)} . \tag{6}$$

To achieve sufficient accuracy $\Delta H \sim 5$ km the relative calibration error in this case can be reduced to approximately 0.02. The calibration can also be performed by illuminating the input mirror with depolarized radiation. In this case, however, a nonuniformity can appear in the light field formed.

The profile $R_1(h)$ is calculated based on the algorithm developed in Ref. 5 for estimating the parameter $R(h)$, the difference being that the quantity $R_1(h_0)$, related with the quantity $R(h_0)$ employed in Ref. 5 by the relation

$$\frac{R_1(h_0) - 1}{R(h_0) - 1} = \frac{1 + \gamma}{1 + Q_a(h_0)} , \tag{7}$$

is used as the minimum value at the point h_0. The structure of Eq. (7) is such that the error in estimating $R_1(h_0)$ is virtually independent of the error in giving $Q_a(h_0)$.

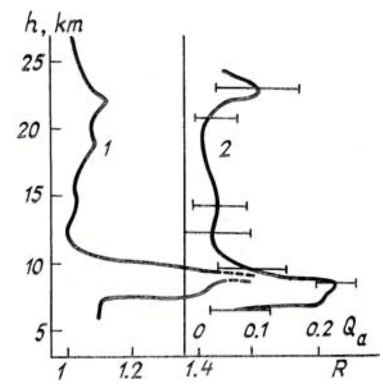

FIG. 1. Profiles of the parameters R and Q_a: 1) R(h) and 2) $Q_a(h)$.

The profiles $R(h)$ and $Q_a(h)$ are determined from the formulas (4) and (5). In a real experiment, small deviations in the orientation of the polarization plane oft the source radiation relative to the analyzers in the detection channel as well as the partial depolarization in the source and detector channels strongly affect measurements of the profile $Q_a(h)$. This factor can be taken into account by transferring in Eqs. (4) and (5) from Q to $Q - Q_0$, where Q_0 is the value measured beforehand for a given apparatus. Figure 1 shows profiles of the parameters $R(h)$ and $Q_a(h)$, measured using the apparatus described in Ref. 6. The high values of R and Q_a below the tropopause $h_0 = 10$ km probably characterize a layer of cirrus clouds.

The relative errors ε in the estimates of the parameters $R(h)$ and $Q_a(h)$ are determined by the expressions

$$\varepsilon^2(R) \approx \varepsilon^2(R_1) + \varepsilon_1^2. \tag{8}$$

$$\varepsilon^2(Q_a) = \frac{R_1^2}{\gamma^2} \cdot \frac{Q^2\varepsilon_2^2 + Q_0^2\varepsilon_3^2}{(R_1/\gamma(Q - Q_0) - 1)^2} + \varepsilon_1^2 \frac{R_1^2}{(R_1 - 1)^2} \times$$
$$\times \frac{\left[\dfrac{R_1(Q - Q_0)}{\gamma} - 1\right]}{(R_1/\gamma(Q - Q_0) - 1)^2} + \varepsilon_0^2 \cdot \frac{1}{(R_1 - 1)^2} \times$$
$$\times \frac{R_1^2 \left[\dfrac{Q - Q_0}{\gamma} - 1\right]}{\left[\dfrac{R_1(Q - Q_0)}{\gamma} - 1\right]^2} , \tag{9}$$

where

$\varepsilon_0^2 = \varepsilon^2(R_1(h_0)) + \varepsilon^2(\beta_m(h_0)) + \varepsilon^2(\beta_m(h)) - 2C(h_0, h) \times$

$\times \varepsilon(\beta_m(h_0)) \cdot \varepsilon(\beta_m(h)) + \varepsilon^2(N_1(h_0)) + \varepsilon^2(T^2 \cdot (h - h_0));$

$\varepsilon_1^2 = \varepsilon^2(N_1(h)),\ \varepsilon_2^2 = \varepsilon^2(N_2(h)) + \varepsilon^2(N_1^0) + \varepsilon^2(N_2^0);$

and, $\varepsilon_3^2 = \varepsilon^2(Q_0)$, $T(h - h_0)$ is the attenuation of radiation in the layer $h - h_0$: $C(h, h_0)$ is the correlation coefficient of the molecular backscattering coefficient at the points (h, h_0). The quantities $\varepsilon(R_1)$, ε_0, ... , appearing in Eqs. (8) and (9), can be estimated by a method analogous to that described in Ref. 5. In the experiment, the results of which are presented in Fig. 1, $\varepsilon(R) \sim 0.05$ and $\varepsilon(Q_a(h))$ ranges from 0.15 to 1. The horizontal segments show the standard deviation of the estimates of $Q_a(h)$ in Fig. 1. The increase in the relative error $\varepsilon(Q_a(h))$ for small values of R and Q is characteristic.

REFERENCES

1. V.E. Zuev, B.V. Kaul', V.N. Kozlov, and I.V. Samokhvalov, in: *Abstracts of Reports at the Sixth All Union Symposium on Laser and Acoustic Sounding of the Atmosphere*, Institute of Atmospheric Optics, Siberian Branch of the Academy of Sciences of the USSR, Tomsk (1980), Part 1, pp. 11–14.
2. Y. Iwasaka, Geomag. Geoelectr. **38**, 729 (1986).
3. G.S. Kent, L.R. Poole, and M.P. McCormick, J. Atm. Sci. **43**, No. 20, 2149 (1986).
4. V.E. Zuev and G.M. Krekov, *Optical Models of the Atmosphere* (Gidrometeoizdat, Leningrad, 1986), 256 pp.
5. P.B. Russel, J.Y. Surssier and M.P. McCormick, Appl. Opt. **18**, No. 22, 3783 (1979).
6. A.N. Borodavko, N.P. Vorobei, V.N. Gubskii, et al., Opt. Atm. **1**, No. 3, 109–115 (1988).