EFFICIENCY OF RAMAN LIDAR SOUNDING OF TEMPERATURE PROFILES AND SCATTERING RATIO WITH ADAPTIVE SMOOTHING OF SIGNALS

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This paper considers the capabilities of the least–square method for adaptive spatial smoothing of lidar return signals recorded in the photon counting mode. An example is given of application of the adaptive smoothing procedure for reconstruction of the vertical profiles of temperature and scattering ratio.

Routine measurements of the vertical profiles of temperature and scattering ratio up to the tropopause height are carried out at the High–Altitude Sounding Station of the Institute of Atmospheric Optics. The higher accuracy of measuring the indicated profiles under conditions of limited power potential of a lidar can be reached by means of careful selection of a processing algorithm. Algorithms for optimal estimation of the parameters were analyzed in Ref. 1 for the case of aerosol sounding with the optimal Marcovian filtration.

In this paper, we discuss the capabilities of the least–square method for adaptive spatial smoothing of lidar return signals recorded in the photon counting mode.

When using a Raman lidar, lidar returns in the photon counting mode have the following form:

$$N(\lambda_0, H) = C\Phi(H)(\beta^{a}_{\pi}(H) + \beta^{m}_{\pi}(H))T^{2}(\lambda_0, H)H^{-2} + N_{n},$$
$$N(\lambda, H) = C\Phi(H)\beta^{R}_{\pi}(H)T(\lambda_0, H)T(\lambda, H)H^{-2} + N_{n}, \quad (1)$$

where $N(\lambda_0, H)$ and $N(\lambda, H)$ are the lidar return signals recorded in the channels of elastic and nonelastic scattering, C is the instrumental constant including the number of emitted photons, $\Phi(H)$ is the geometric factor, $\beta^{a}_{\pi}(H)$ and $\beta^{m}_{\pi}(H)$ are the volume aerosol and molecular backscattering coefficients, $\beta^{R}_{\pi}(H)$ is the volume backscattering coefficient for the rotational spontaneous Raman scattering with the rotational quantum number J, $T(\lambda, H)$ is the volume transmittance, H is the height, and N_{n} is the background signal.

Determination of the vertical profiles of temperature and scattering ratio from measured lidar returns was described in details in Refs. 2 and 3. To do this, the ratio of lidar returns in the channels of elastic and nonelastic scattering of a Raman lidar is used. To obtain the vertical profile of the temperature, the ratio of signals in two selected sections of purely rotational Raman spectrum is used. Then from the dependence

$$R(H) = \exp(\alpha/T(H) + \beta), \quad (2)$$

where $R = \{N_1(\lambda_1, H) - N_{n1}\}/\{N_2(\lambda_2, H) - N_{n2}\}$ is the ratio of two signals measured in two selected sections of the rotational spectrum, α and β are the constants, and $T(H)$ is the temperature. One can obtain the expression for temperature:

$$T = \alpha/\{\ln R - \beta\}. \quad (3)$$

To simplify the expression, we designate R and T instead of $R(H)$ and $T(H)$. As a rule, the centers of the sections of the rotational Raman spectrum are selected for the respective rotational quantum numbers J being equal to 6 and 14.

To obtain the scattering ratio profile, the ratio of the aerosol signal to the sum of Raman signals from the sections sensitive to temperature is used; the temperature dependence is then mutually compensated.[4]

Disregarding the problems of calibration for the scattering ratio and the accuracy in determining the constants α and β, we write the estimate of the absolute error in determining the ratio of two signals in the form:

$$\delta R = \sqrt{\left(\frac{\partial R}{\partial N_1}\right)^2 \delta^2 N_1 + \left(\frac{\partial R}{\partial N_{n1}}\right)^2 \delta^2 N_{n1} + \left(\frac{\partial R}{\partial N_2}\right)^2 \delta^2 N_2 + \left(\frac{\partial R}{\partial N_{n2}}\right)^2 \delta^2 N_{n2}}. \quad (4)$$

Assuming the Poisson statistics of signal recorded in the photon counting mode, we have

$$N = \delta^2 N,$$

$$N_{n} = \delta^2 N_{n}.$$

Designating the noise contribution to a valid signal as

$$\varepsilon = N_{n}/N_{s},$$

where $N_{s} = N - N_{n}$ is the valid signal, we derive from Eq. (4)

$$\delta R / R = \sqrt{(1 + 2\,e_1)/N_{s1} + (1 + 2\,e_2)/N_{s2}}. \quad (5)$$

Separation of a recorded lidar return into noise and valid signals became possible after selection of the noise by strobing during the signal accumulation. The time delay of the noise strobe in the signal was selected so that the noise exceeded the valid signal by several orders of magnitude.

Taking into account Eq. (3), the estimate of the absolute error in measuring the temperature is

$$\delta T = T^2/\alpha\, \delta R/R.$$

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The characteristic profile of the estimates of relative and absolute errors for the majority of measured profiles is shown in Fig. 1 for the temperature and scattering ratio obtained on December 21, 1991. It is seen that the variation of the estimate profiles reaches one order of magnitude with minimum at a height of 2 km, what is connected with the effect of geometric factor at low heights and quadratic decrease of lidar return signal as the height increases. The large value of the estimate of the relative error in determining the scattering ratio at a height of 22 km is connected with the fact that the value of the signal ratio contains the aerosol signal obtained after its suppression in the first monochromator by four orders of magnitude. To find the functional relationship between the experimental values, let us apply the classical least–square method, i.e., let us find such functional relationship that

$$\sum_i (Y_i - Y'_i)^2$$

be minimum. The only argument in favor of the least–square method, is its simplicity. In our opinion, this circumstance is sufficiently weighty argument, especially at the first stage of experiment. The traditional application of the least–square method is the smoothing of experimental data by the window whose width is selected depending on the degree of selected polynomial and on a scatter of experimental data. For example, if the window width is equal to the polynomial degree plus one, we will obtain the exact solution, i.e., the polynomial will pass through the experimental points. If the window passes consequently through all experimental points, we will obtain the smoothed functional relationship taking into account a scatter of the measured data. However, when the error estimate varies along the measured lidar return signal profile, as is seen in Fig. 1, the choice of the smoothing criterion or the window width is difficult. The idea of the method we propose is to make the number of smoothing points or the window width depending on the error estimate value in each step of smoothing.

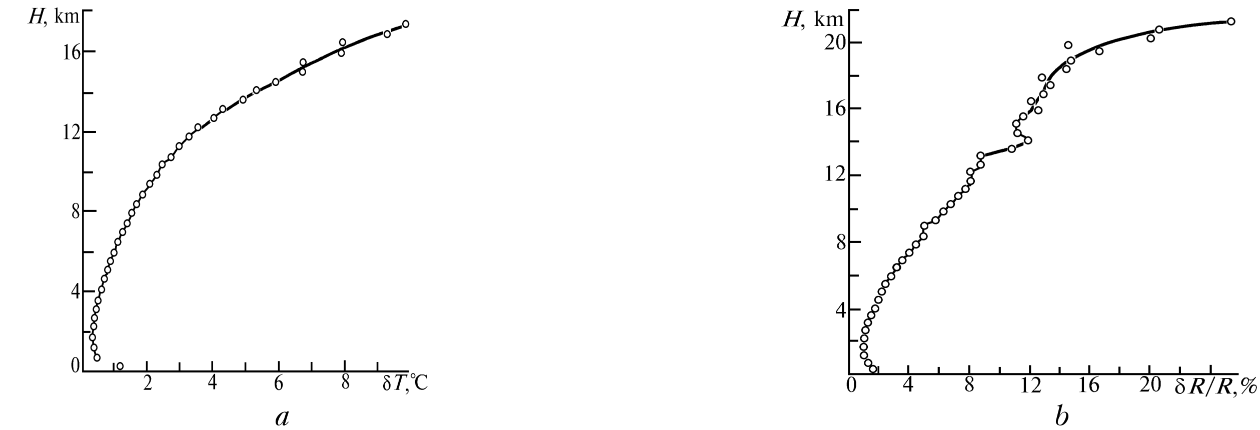

FIG. 1. Vertical profiles of the estimate of the statistical error in determining the temperature (a) and scattering ratio (b).

The vertical profiles of temperature and scattering ratio obtained by the proposed technique are shown in Fig. 2. The polynomial of the fourth degree was used for smoothing of the obtained profiles by the least–square method. The smoothing criterion was selected so that the smoothing window width varied by three times (from 5 to 15) as the error estimate changes by one order of magnitude. The window width in each smoothing step was averaged over five previous points and was calculated for the temperature from the relationship

$$n = \sum_{i=1}^{5} \delta T_i ,$$

and for the scattering ratio

$$n = 50 \sum_{i=1}^{5} \frac{\delta R_i}{R_i} .$$

As an example of application of the proposed method, the formation shown in Fig. 2*b* was identified between 12–14 km. In case of identification of this stratus formation by the traditional method, the corresponding values above 13.5 km would be smoothed insufficiently, i.e., nonexistent layer structure would be revealed.

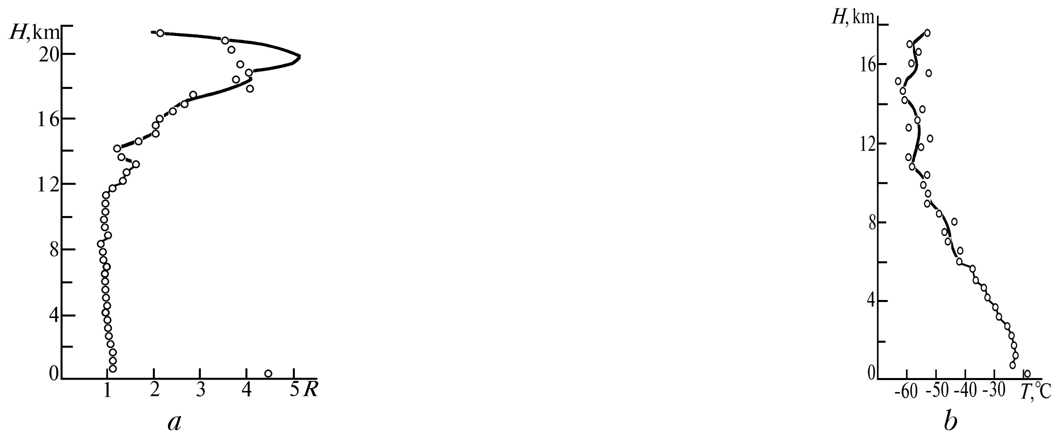

FIG. 2. Vertical profiles of temperature (a) and scattering ratio (b).

Thus, we can conclude that in addition to existing methods for selecting a valid signal against the noise background, the adaptive smoothing of profiles is sufficiently reliable method that increases the efficiency of the sounding of the atmospheric parameters.

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