THE PROCEDURE FOR PROCESSING THE LIDAR RETURNS FROM THE STRATOSPHERE

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An efficient algorithm for reconstructing the vertical profile of the aerosol attenuation coefficient in the atmosphere from one-frequency laser sounding data is proposed. The computational algorithm and the results of control calculations are presented and compared with well-known model profiles of the aerosol attenuation.

The results of laser sounding of the altitude profiles of the atmospheric aerosol are, as a rule, represented in the form of profiles of the ratio of the total volume backseattering coefficient to the molecular backscattering coefficient

$$R(h) = [\beta_{\pi a}(h)+\beta_{\pi m}(h)]/\beta_{\pi m}(h), \tag{1}$$

where it is assumed that the molecular profile $\beta_{\pi m}(h)$ is either known from models or has been calculated from meteorological measurements in terms of the pressure and temperature.[1,2] Since absolute calibration of a lidar is difficult to perform the calibration is done based on the signal from a layer located at an altitude h^* where the ratio $R(h^*)$ is known (usually at altitudes above 20 km where aerosol is least likely to occur and $R(h^*) \simeq 1$). Writing the lidar equation[1]

$$S(h) = P(h)h^2 = A[\beta_{\pi a}(h)+\beta_{\pi m}(h)]T_0^2(0,h)T_m^2(0,h) \tag{2}$$

for $h = h^*$ and dividing Eq. (2) by the equation so obtained gives

$$\varphi(h) \equiv \frac{S(h)}{S(h^*)}\frac{T_m^2(h_0,h^*)}{T_m^2(h_0,h^*)}\;\frac{\beta_{\pi m}(h^*)}{\beta_{\pi m}(h)}R(h^*) = R(h)\frac{T_a^2(h_0,h)}{T_a^2(h_0,h^*)}, \tag{3}$$

where $S(h)$ is the so-called Iidar S function; $P(h)$ is the signal received from an altitude h (corrected for the geometric function of the lidar); A is the instrumental constant; $T(h_0, h) = \exp\left\{-\int\limits_{h_0}^{h}\beta_s(h')dh'\right\}$ is the transmission of the layer $[h_0, h]$; h is the starting point of the sounding path; $\beta_s(h)$ is the volume scattering coefficient (neglecting atmospheric absorption). Thus the right side of Eq. (3) contains all unknown optical parameters of the atmospheric aerosol, while the experimental data are represented by the function $\varphi(h)$.

The simplest method of interpreting lidar signals consists of neglecting the aerosol transmission $T_a(h_0, h)$ (as a result of which (3) gives $R(h) = \varphi(h)$) or giving a model profile $T_a(h_0, h)$. As shown in Ref. 4, however, variations of the turbidity of the stratosphere can strongly affect the interpretation of the lidar signals, as a result of which the profile of the aerosol transmission must be determined in-line. The most useful values from the viewpoint of practical realization, are those obtained from the lidar data themselves; this is made possible by introducing the a priori relation $\beta_{\pi a}(h)/\beta_{sa}(h) = g_a(h)$ established based on model calculations using the fact that for the molecular component $g_m = 3/8\pi$ sr^{-1}.

Reference 4 gives a quite detailed presentation of methods for solving the lidar equation. Given the relation $g_a(h) = \beta_{\pi a}(h)/\beta_{sa}(h)$, the lidar equation reduces to a first – order linear differential equation for $T_a^2(h^*, h) = T_a^2(h_0, h) / T_a^2(h_0, h^*)$, which follows from (3) substituting (1),

$$T_a^2(h^*,h) - \frac{g_a(h)}{2\pi\beta_{\pi m}(h)}\frac{dT_a^2(h^*,h)}{dh} = \varphi(h), \tag{4}$$

whose solution has the form

$$T_a^2(h^*,h) = f^{-1}(h)\left[1-2\int\limits_{h^*}^{h}\varphi(h')f(h')\times \beta_{sm}(h')\frac{g_m}{g_a(h')}dh'\right], \tag{5}$$

where

$$f(h) = \exp\left\{-2\int\limits_{h^*}^{h}\frac{g_m}{g_a(h')}\beta_{sm}(h')dh'\right\}.$$

TABLE 1.

Format of the results of laser sounding of the stratosphere (example of data for July 16, 1987).

h, km	β_{sm}, km^{-1}	g_a sr^{-1}	β_{sa}, km^{-1}	$\tau(h)$
10	4.4880E-03	5.2945E-02	2.3534E-04	7.5884E-03
11	3.9676E-03	5.1736E-02	6.9292E-04	7.0455E-03
12	3.4859E-03	5.0748E-02	7.2319E-04	6.2599E-03
13	3.0292E-03	3.9025E-02	4.9580E-04	5.6569E-03
14	2.6136E-03	3.8850E-02	1.9329E-04	5.3559E-03
15	2.2302E-03	3.6777E-02	2.6876E-04	5.1259E-03
16	1.9137E-03	3.4363E-02	3.5940E-04	4.8194E-03
17	1.6389E-03	3.3656E-02	3.4656E-04	4.4622E-03
18	1.3933E-03	3.2872E-02	4.5683E-04	4.0427E-03
19	1.1874E-03	3.1681E-02	6.1732E-04	3.4932E-03
20	1.0088E-03	2.8315E-02	6.6995E-04	2.8449E-03
21	8.5892E-04	2.7308E-02	6.2501E-04	2.1989E-03
22	7.3309E-04	2.6575E-02	4.8913E-04	1.6707E-03
23	6.2577E-04	2.5557E-02	3,8597E-04	1.2297E-03
24	5.3307E-04	2.4522E-02	2.8406E-04	8.8489E-04
25	4.5636E-04	2.3498E-02	2.2034E-04	6.0560E-04
26	3.9058E-04	2.2691E-02	1.2885E-04	4.4798E-04
27	3.3476E-04	2.1890E-02	7.9880E-05	3.3316E-04
28	2.8617E-04	2.1022E-02	4.4988E-05	2.7710E-04
29	2.4582E-04	2.0222E-02	4.2376E-05	2.3726E-04
30	2.1014E-04	1.9476E-02	3.2331E-05	1.9768E-04
31	1.8033E-04	1.9426E-02	4.6873E-05	1.6163E-04
32	1.5510E-04	1.9426E-02	3.4526E-05	1.2305E-04

We note that this solution is valid for any choice of the calibration altitude $h^* \in [h_0, h_N]$ and if $h < h^*$, expression (5) is greater than unity (the upper limit of integration becomes less than the bottom limit), so that for $h < h^*$ $T_a^2(h^*, h)$ must be interpreted as the formal definition of this quantity given by the identity on the left side of (5).

It is also not difficult to write down from (1) and (3) the solution for $R(h)$ and $\beta_{sa}(h)$

$$R(h) = \varphi(h)/T_a^2(h^*, h), \tag{6}$$

$$\beta_{sa}(h') = \beta_{sm}\frac{g_m}{g_a(h)}\left[R(h)-1\right]. \tag{7}$$

For purposes of programming it is more convenient to rewrite the expression (5) in the form

$$T_a^2(h^*, h) = [1-2J_1(h)+2J_1(h^*)]f^{-1}(h), \tag{8}$$

$$f(h) = \exp\{2J_2(h)-2J_2(h^*)\}, \tag{9}$$

where

$$J_1(h) = \int_{h_0}^{h} \varphi(h')f(h')\beta_{sm}(h')\frac{g_m}{g_0(h')}dh';$$

$$J_2(h) = \int_{h_0}^{h} \frac{g_m}{g_a(h')}\beta_{sm}(h')dh'.$$

Programs for processing lidar signals automatically choose the calibration altitude h^* from the minimum of $R(h)$. According to (3) $R(h)$ reaches a minimum value for $h = h_{\min}$ that minimizes the ratio $\varphi(h) / T_a^2(h^*, h)$. For weak atmospheric turbidity $h_{\min} = \arg\min\varphi(h)$. To eliminate any effect of possible variations in the transmission on the determination of the calibration altitude the program searches for $h_{\min}$ by minimizing $\varphi(h) / T_a^2(h^*, h)$, the starting approximation $h_{\min}$ is fixed a priori and refined by subsequent iteration, for which h^* is set equal to $h_{\min}$ in (5).

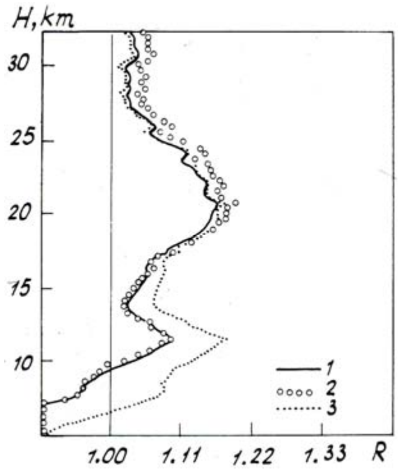

FIG. 1. The results of the iInterpretation of lidar returns from the stratosphere: 1) based on the proposed iteration scheme (5) and (6); 2) using a model profile $T_a(h_0, h)$; 3) neglecting the transmission $T_a(h_0, h)$.

Figure 1 shows an example of the quantitative interpretation of the lidar return from the stratosphere at the wavelength $\lambda = 0.53$ μm using a priori model lidar ratios of the aerosol component of an "average cyclical" atmosphere[1]. It is obvious that such information greatly improves the accuracy of the reconstruction of the altitude profile of the scattering ratio $R(h)$. In addition, it becomes possible to determine approximately, at the level of accuracy of the model $g_a(h)$, the vertical profile of the main radiation characteristic of an aerosol atmosphere, i.e., the attenuation coefficient $\beta_t(h)$. The behavior of this coefficient for the indicated realization $R(h)$ is shown in Table 1 in terms of the dimensionless optical thickness of the segments $\tau(h_1) = \int_{h_1}^{\infty} \beta_t(h)dh$.

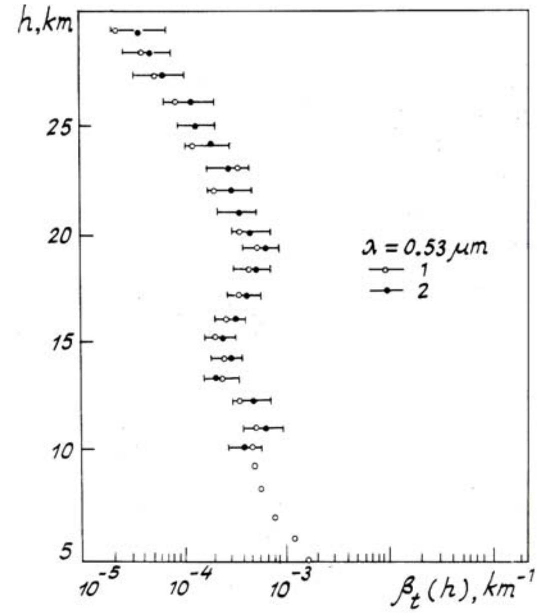

FIG. 2. Comparison of the model profiles $\beta_2(h)$: 1) from Ref. 7 and 2) the average experimental values.

As shown in Ref. 5, the proposed procedure can be applied efficiently in the case of exoatmospheric sounding.

The method described above is now employed for processing systematic lidar measurements, performed at the High-Altitude Sounding Station of the Institute of Atmospheric Optics[6]. The results of sounding are processed and documented with the help of the IRZAR-50M universal computer complex.

Systematic statistical analysis of the accumulated results makes it possible to correct the continental model of the aerosol atmosphere forpurposes of establishing regional features peculiar to Western Siberia and the characteristics of the seasonal trend. Figure 2 gives an example of a quantitative comparison of the vertical profile of the aerosol attenuation coefficient averaged over the winter of 1988 with the average cyclical approximate model[7] reflecting the residual effect of periodic volcanic eruptions.

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