STUDY OF THE ACCURACY CHARACTERISTICS OF RECONSTRUCTION OF TEMPERATURE PROFILES FROM LIDAR SIGNALS OF MOLECULAR SCATTERING

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The accuracy characteristics of the temperature reconstructing from realistic lidar signals of molecular light scattering are analyzed. The temperature was sounded by means of two Rayleigh lidars: the first with a mirror 2.2 m *in diameter at* λ = 532 nm *operating in the upper stratosphere and mesosphere* (30–75 km) *and the second with a mirror* 1 m *in diameter at* λ =353 nm *operating in the lower and middle stratosphere* (13–35 km). *Total, random, and systematic errors of temperature calculation and their dependence on the altitude were estimated as well as deviations of the temperature profiles depending on the error values. The lidars are shown to ensure satisfactory accuracy of the temperature measurement within the altitude range from* 13 *to* 30 km *and from* 30 *to* 60 km, *respectively. The rms error at maximum altitudes in both cases does not exceed* 10 K. *To decrease the error, it will suffice to increase the pulse accumulation time. A more drastic alternative is the increase of the lidar energy potential. Due to the use of a shorter wavelength of UV range* (353 nm) *and taking into account the pulse attenuation caused by the molecular light scattering, the altitude range from* 13 *to* 35 km *has been mastered by us for temperature measuring by the Rayleigh method.*

The first lidar measurements harnessing the effect of molecular light scattering were applied to study the structure of the atmosphere (measurement of the density of the atmosphere[1,2]). Further this method was applied to measure the temperature.[3]

First measurements of temperature profiles in the upper stratosphere and mesosphere (30 to 75 km) were carried out at the Siberian Lidar Station (Tomsk, 56.5°N, 85.1°E) in 1994 by the lidar[4] with a receiving mirror 2.2 m in diameter and a Nd:YAG laser with a wavelength of 532 nm. In 1995, these works were supplemented by sounding of the temperature in the lower and middle stratosphere in the altitude range from 13 to 35 km by the lidar with a receiving mirror 1 m in diameter and an excimer XeCl laser with an output wavelength of 353 nm after its stimulated Raman scattering conversion in hydrogen.[5] We note that it is the wavelength of 353 nm which made it possible to master the low altitude range, where, as is known, molecular scattering at short wavelengths is prevalent over aerosol one.

An important problem in reconstructing the temperature profiles from lidar return signals of Rayleigh scattering is to ensure the necessary accuracy. The accuracy of reconstruction of the temperature profile depends on the signal itself, the altitude range of signal processing, and *a priori* data. In this paper, we analyze the error in reconstructing the temperature profile and its deviation by the formula derived by us in Ref. 5

$$T(H) = \frac{P^2(H)}{N(H)\,H^2} \times \left[\frac{N(H_m)\,H_m^2}{P^2(H_m)}\,T(H_m) + \frac{1}{R}\int\limits_{H_m}^{H} \frac{N(h)\,h^2\,g(h)}{P^2(h)}\,\mathrm{d}h \right], \qquad (1)$$

where H and H_m are the current and maximum altitude, respectively from which reasonably reliable lidar return signal is received; $N(H)$ is the lidar return signal; $P(H)$ is the transparency of the molecular atmosphere from the level of the lidar position up to the altitude H; R is the specific gas constant, and g is the gravitational acceleration.

We note that to take into account the signal attenuation, especially noticeable when operating in the lower layers of the stratosphere, we have introduced the transmission function $P(H)$. It was supposed for our analysis that the random noise of lidar return signals obeyed the Poisson distribution.

According to Eq. (1), the expression for estimating the rms error in calculating the temperature has the form

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$$\partial T_i = \sqrt{A_i^2\left(\frac{\partial A_i}{A_i}\right)^2 + B_i^2\left(\frac{\partial B_i}{B_i}\right)^2}\,, \tag{2}$$

where A_i and B_i are the first and second terms of Eq. (1) written taking into account the discrete signal reception mode in strobes,

$$\left(\frac{\partial A_i}{A_i}\right)^2 = \left(\frac{\partial N_i}{N_i}\right)^2 + \left(\frac{\partial N_m}{N_m}\right)^2 + \left(\frac{\partial T_m}{T_m}\right)^2 = \frac{N_i + F}{N_i^2} + \frac{N_m + F}{N_m^2} + \left(\frac{\partial T_m}{T_m}\right)^2, \tag{3}$$

$$\left(\frac{\partial B_i}{B_i}\right)^2 = \frac{N_i + F}{N_i^2} + \frac{\sum\limits_{i+1}^{m-1}\left[(N_j + F)^{3/2}\, H_j^2/N_j\right]^2}{\left[\sum\limits_{i+1}^{m-1} N_j\, H_j^2\right]^2}\,. \tag{4}$$

Here, F is the total noise caused by the background and dark current. The error in assigning the temperature at the maximum altitude was defined as $\partial T_m/T_m = 0.1$.

Figure 1 shows the accuracy characteristics of reconstructing the temperature from realistic signals recorded at a wavelength of 532 nm for the example of the data obtained on May 11, 1995 (accumulation time was 60 min).

The lidar (*1*) and model (*2*) profiles of temperature and the corresponding rms errors in calculating the temperature are shown in Fig. 1*a*. Deviations of the temperature profile due to the error in assigning the temperature at the maximum altitude are shown in Fig. 1*b*. A maximum altitude of 70 km was taken here, and three profiles were calculated for assigned values of the model temperature $T_0(H)$ (curve *2*), $1.1T_0(H)$ (curve *1*) and $0.9T_0(H)$ (curve *3*). Contribution of the random (signal noise) and systematic (improper assignment of the temperature at the maximum altitude) errors is shown in Fig. 1*c*. The square roots of the random (*1*) and systematic (*2*) variances are also shown here. It is seen that the

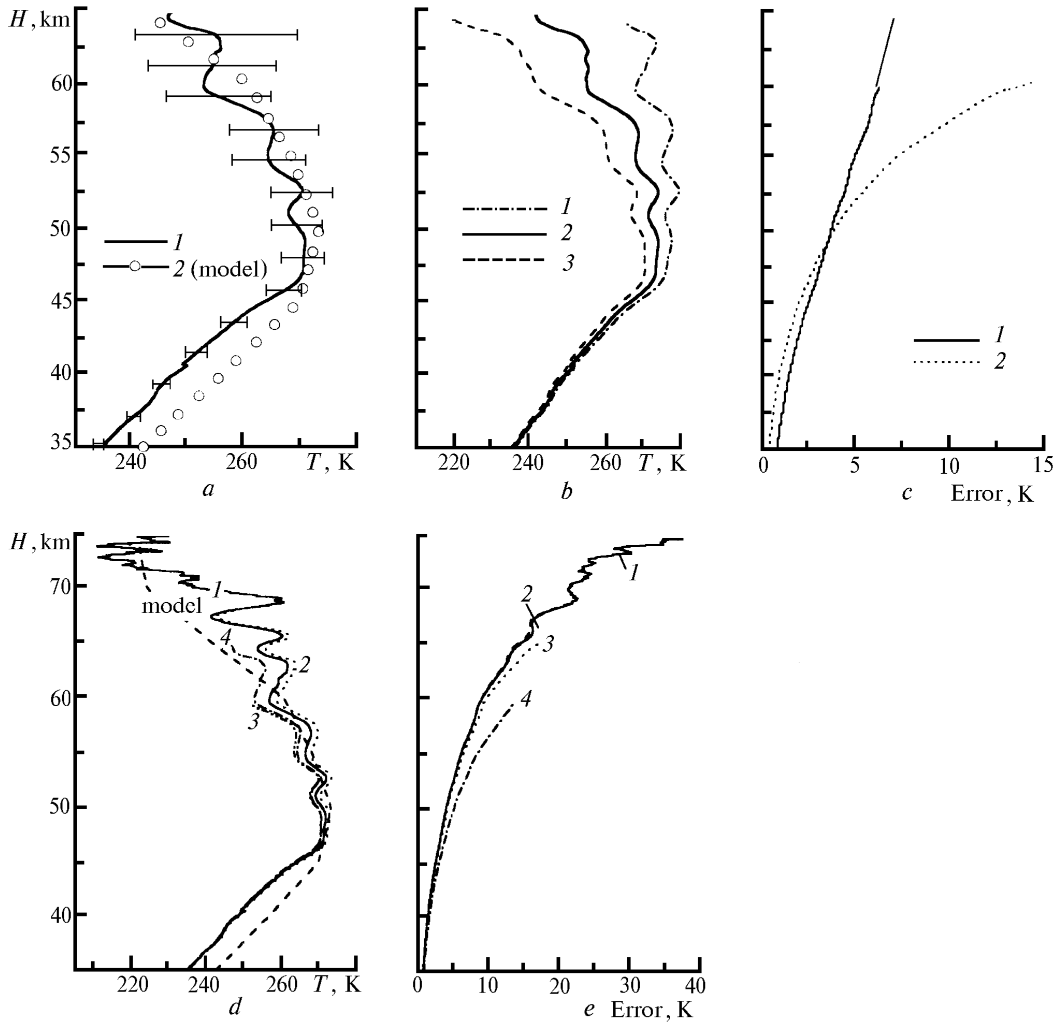

FIG. 1. Results of an analysis of errors in reconstructing the temperature profiles from lidar return signals at a wavelength of 532 nm.

principal contribution to the total error in the altitude range from 50 to 60 km is made by the systematic error, below the contribution of the random error becomes slightly more noticeable. The dependence of reconstruction of the temperature profile on the assigned maximum altitude of signal reception is shown in Fig. 1*d*. Here, maximum altitudes of 80, 75, and 70 km were chosen, for which the temperature profiles up to 75(*1*), 70(*2*) and 65(*3*) km were obtained. It is seen that the error caused by the choice of the maximum altitude for calculations is within 8 K at an altitude of 65 km and decreases very fast as the altitude increases. Figure 1*e* shows the error profiles for the cases of signal processing from maximum altitudes of 80(*1*), 75(*2*), 70(*3*) and 65(*4*) km. It is seen that some increase of the error occurs with the decrease of the maximum altitude of processing, which can be explained by the loss of the valid signal. The error is 10 K at an altitude of 60 km and does not exceed 1 K at an altitude of 35 km.

Figure 2 shows the results of analysis of the errors in reconstructing the temperature profile from the lidar signals obtained at a wavelength of 353 nm on May 24, 1996 (accumulation time was 40 min). Figure 2 is drawn by the scheme analogous to Fig. 1. The temperature profile calculated in the altitude range from 13 to 35 km and the corresponding rms error are shown in Fig. 2*a*. The latter varies as follows: ±1 K at an altitude of 15 km; ±2 K at an altitude of 20 km; ±4 K at an altitude of 25 km; and, ±8 K at an altitude of 30 km.

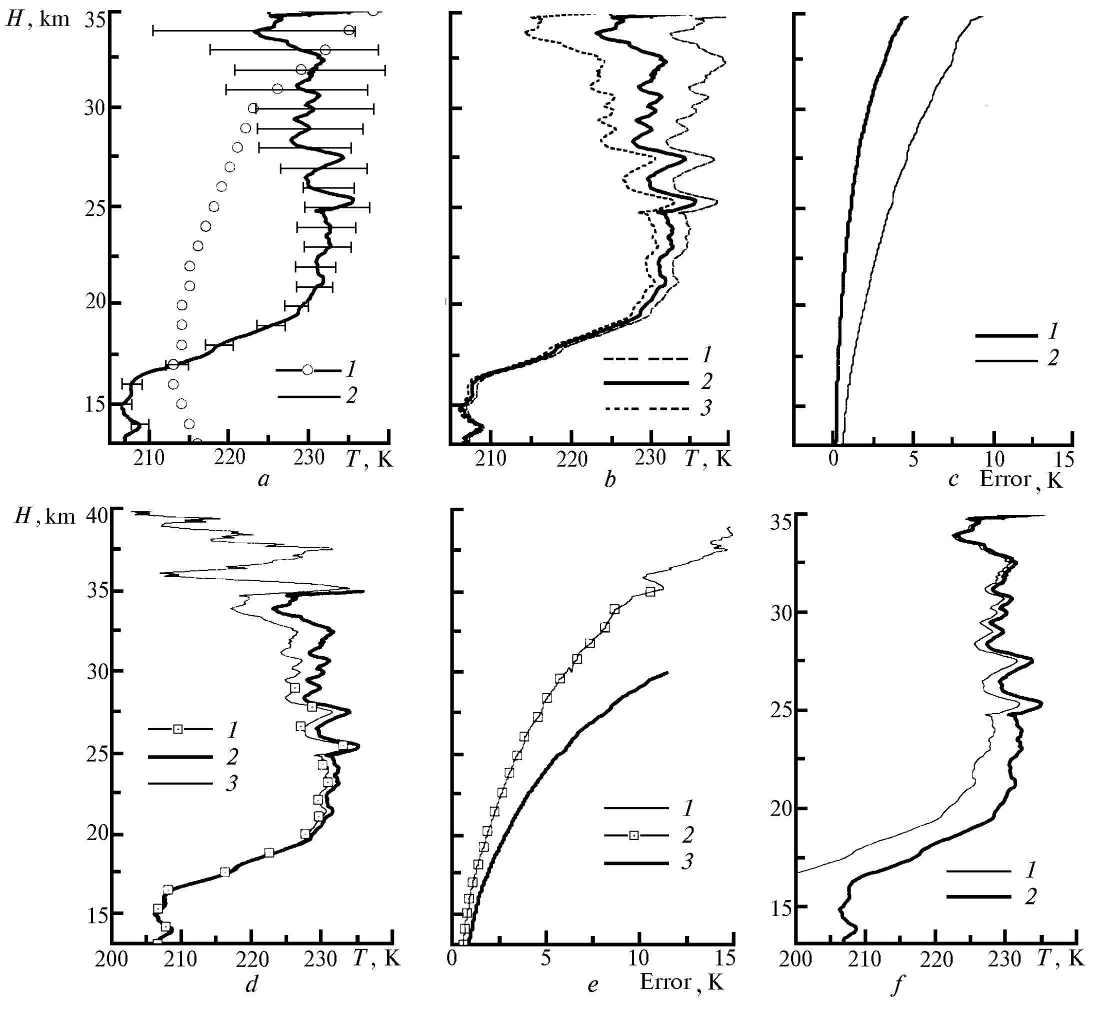

FIG. 2. Results of an analysis of the error in reconstructing the temperature profiles from the lidar return signals at a wavelength of 353 nm.

Deviation of the temperature profile due to arbitrary assignment of the temperature in the point H_m is shown in Fig. 2*b*. Here, the central profile corresponds to $T = T_m$, the left is for $T = 0.9T_m$, and the right is for $T = 1.1T_m$. The contribution of the aforementioned error is most noticeable in the upper layer from 30 to 35 km, it is ±5 K at an altitude of 30 km. So it is recommended to present the temperature profile beginning with the altitude ~5 km below the maximum altitude, from which the calculation starts. The contribution of the systematic (curve *2*) and random (curve *1*) errors to the total error is illustrated by Fig. 2*c*. Here, the prevalence of the systematic error over the random one is observed in the entire altitude range. The values of systematic and random errors at an altitude of 30 km are ±5 K and ±2 K, respectively. The fast decrease of the errors is revealed with the decrease in the altitude practically down to zero at an altitude of 13 km. The effect of the choice of the maximum altitude, from which the calculation of temperature starts, on the deviation of the reconstructed profile is shown in Fig. 2*d*. The maximum altitudes are 45, 40, and 35 km. The corresponding profiles are shown in the figure from altitudes of 40 (curve *3*), 35 (curve *2*) and 30 (curve *1*) km.

As follows from Fig. 2, deviation of the profiles is insignificant and becomes noticeable above 30 km (≤3 K). Analogous results, but for the error profiles, are illustrated by Fig. 2*e*. As in the case of the signals at a wavelength of 532 nm (Fig. 1*c*), deviations of the error profiles for calculation from an altitude of 35 km (curve *3*) toward greater values can be explained by the loss of the useful data (neglect of the signal in the altitude range from 35 to 45 km). The temperature profiles calculated taking into account the molecular scattering (curve *2*) and without it (curve *1*) are shown in Fig. 2*f*. It is seen that the correction for the molecular light scattering is necessary starting from the altitudes below 30 km. The deviation is 7 K at an altitude of 20 km, and increases fast as the altitude decreases.

Thus, the analysis of the accuracy characteristics of reconstructing the temperature from realistic lidar signals shows the sufficient accuracy of lidar temperature measurements at a wavelength of 532 nm in the altitude range from 30 to 60 km and at a wavelength of 353 nm in the altitude range from 13 to 30 km. To obtain better accuracy or to increase the maximum sounding range, it is sufficient to increase the lidar signal accumulation time. A more radical alternative is the increase of the energy potential of the lidar.

In what follows the use of a shorter wavelength in the UV spectral range (353 nm) with the correction for the signal attenuation due to the molecular scattering has made it possible to master the altitude range from 13 to 35 km.

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REFERENCES

1. P.D. McCormic, E.C. Silverberg, S.K. Poultney, et al., Nature, No. 215, 1262–1263 (1967).
2. M.C.W. Sandford, J. Atmos. Terr. Phys., No. 29, 1657–1662 (1967).
3. A. Hauchocorne and M.-L. Chanin, Geophys. Res. Lett. **7**, No. 8, 565–568 (1980).
4. S.L. Bondarenko, V.D. Burlakov, M.V. Grishaev, et al., Atmos. Oceanic Opt. **7**, Nos. 11–12, 899–900 (1994).
5. V.V. Zuev, V.N. Marichev, S.L. Bondarenko, et al., Atmos. Oceanic Opt. **9**, No. 10, 879–884 (1996).