Results of temperature measurements in the upper troposphere and the middle atmosphere by means of a lidar using the channels of Rayleigh and Raman scattering

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ABSTRACT

The lidar complex used combined optical sensing method for the lower and middle atmosphere. The method is based on the reception signal Rayleigh (elastic molecular scattering of light at a wavelength of 532 nm) and Raman (radiation first vibrational-rotational transition of molecules of nitrogen cents a wavelength of 607nm when excited by laser radiation in the latter wavelength of 532nm) light scattering. Using Raman channel possible to eliminate the distorting effect of the aerosol on the heights of its location (up to 25km) for the temperature measurement accuracy.

With the simultaneous measurement of signals in the two receiving channels received extended temperature profiles in heights from 7 to 60 km, covering the upper troposphere and middle atmosphere. A good agreement with satellite data and upper-air measurements, as well as model representations.

INTRODUCTION

The lidar equation determining the value of the received Raman signal in the single-scattering approximation has the form

$$N(H) = CF(H)P^2(H)\beta_R H^{-2} + N_{BG}, \tag{1}$$

where H is the altitude (distance, in general case), N(H) is the return signal from the altitude H, $\beta_R(H)$ is the Raman backscattering coefficient, C is the instrumentation constant of the lidar, including the area of the receiving telescope, transmission of the receiving-transmitting path, laser pulse energy, quantum efficiency of the photodetector; F(H) is the lidar geometric factor taking into account overlap of the beam and the field of view of the antenna; P(H) is the transparency of the atmospheric layer from the lidar up to the current altitude H at the wavelength of sounding; N_{BG} is the total background and dark noise. The data on the spatial distribution of temperature in the Raman method is contained in the backscattering coefficient $\beta_R = \sigma_R \cdot n$ both in the scattering cross-section σ_R and the density of molecules of the gas to be sounded n. This peculiarity determined two ways for realization of the Raman lidar method: using the rotational and vibrational-rotational Raman spectra.

The first method was proposed by Cooney [2] and was further developed in [3, 7, 8]. The method is based on the dependence of the individual line intensity on temperature at Boltzmann distribution of the rotational spectrum. the ratio of two parts of the rotational Raman spectra including several lines of nitrogen or oxygen are used for determination of temperature.

The second method was found by Strauch et al [4] and realized for the first time by Melfi [5]. The essence of the technique lies in correlation of the signal from the vibrational-rotational spectrum of the nitrogen or oxygen molecules with the air density and therefore, with temperature through the ideal gas state equation. Subsequently, the method was applied in domestic lidars destined to measuring the temperature and water vapor content of the atmosphere. The description of them can be found in [6, 9, 10].

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21st International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics,
edited by G. G. Matvienko, O. A. Romanovskii, Proc. of SPIE Vol. 9680, 96806R
© 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2205766

If compare two methods, it is necessary to note that the first method wins from the energetic point of view, because the Raman signals of the rotational spectrum are two orders of magnitude greater than the signals of the vibrational-rotational spectrum. This circumstance makes the use of rotational spectra more preferable for lidar sounding of temperature. However, realization of the method using the Raman rotational spectra is technically difficult, because it is necessary to separate the signals of Raman scattering from the elastic Rayleigh scattering and aerosol scattering in a narrow spectral range of about 5 nm. Therefore, the strict requirements appear to suppression of the elastic scattering, which is three orders of magnitude greater than the Raman scattering.

The channel for Raman signals was created in [5] in UV lidar used for sounding of ozone and temperature in the stratosphere. Excitation of the 1-st vibrational-rotational transition of the N_2 molecules (384 nm) was carried out for the first time by radiation at the wavelength of 353 nm obtained, in turn, at stimulated Raman scattering (SRS) transformation of radiation of the excimer XeCl laser with the wavelength of 308 nm in a chamber with hydrogen.

The temperature profiles were retrieved from Raman scattering signals using the concentration of nitrogen molecules, i.e. the atmospheric density. A formula was derived for calculation of the temperature T from the Raman signals, analogously to that for calculation of temperature from Rayleigh signals [1, 5]:

$$T(H) = \frac{P_1(H)P_2(H)}{N(H)H^2}\left[\frac{N(H_m)}{P_1(H_m)P_2(H_m)}T(H_m) + \frac{1}{R^*}\int_{H_m}^{H}\frac{N(h)h^2 g(h)dh}{P_1(h)P_2(h)}\right] \qquad (2)$$

Here $P_1(H)$, $P_2(H)$ is the transparency of the atmosphere from the level of the lidar arrangement up to the altitude H at the wavelengths of 532 and 607 nm, R* is the universal gas constant, g(h) is the gravity acceleration, H_m is the maximum altitude, from which the reliable signals are recorded, suitable for processing (so called altitude of calibration, at which the boundary conditions for temperature $T(H_m)$ are set).

RESULTS OF LIDAR MEASUREMENTS OF TEMPERATURE

Measurements of temperature were carried out using the modernized lidar complex with the diameter of the main receiving mirror 1m, the description of which at the previous stage of modernization is presented in [11]. The laser transmitter in the lidar was replaced with the more powerful Nd:YAG laser (LS-2137-UV3, LOTIS TII Co.) with the pulse energy of 400 mJ (previous one had 200 mJ), and the pulse repetition rate of 10 hz at the wavelength of 532 nm. The photosensor module with the built-in cooling unit H7422P-40 designed at the same corporation with the sensitivity more than one order og magnitude greater than the previous one was installed instead of the previous photodetector (R7207-01, Hamamatsu Co.). These measures allowed to prodive for stable receving the Raman signals from the altitudes up to 30 km. The lidar signals were received in the photopulse counting mode with spatial resolution of 192 m and acquisition of 12×10^4 laser pulses (time of acquisition was about two hours). The interference light filter with the transmission band half-width of 10 nm was used for spectral selection of the received signal.

The selected results of lidar measurements of the vertical distribution of temperature inm May 2014 are shown in Fig. 1.

Here the profiles above the level of 28 km (the point of "stitching" the profiles or, in other words, the altitude of calibration H_m) are calculated from the signals of the Rayleigh scattering of light, and the profiles below 28 km are calculated from the signals of Raman scattering. The value of temperature $T(H_m)$ for Raman signals was determined from the temperature profiles calculated from the Rayleigh signals, and the value $T(H_m)$ for the last at the upper boundary of H_m = 60 km was set by the model value of CIRA-86.

The quite long profiles of temperature were experimentally obtained in the altitude range from 7 up to 60 km covering the upper troposphere, stratosphere and the lower mesosphere. As is seen in Fig. 1, good agreement of the vertical structure of temperature is observed in the entire altitude range between the lidar and satellite measurements, as well as with the CIRA-86 model. Horizontal parentheses in the plot of May 6 show the rms error in lidar measurement of temperature. When calculating temperature from the Rayleigh signals, it is ±7% at the altitude of 57 km and decreases with altitude to the value of ±1% at the altitude of about 40 km. When measuring temperature from the Raman signals, the rms error changes from 7% at the altitude of 23 km to ±1.3% at the altitude of 12 km.

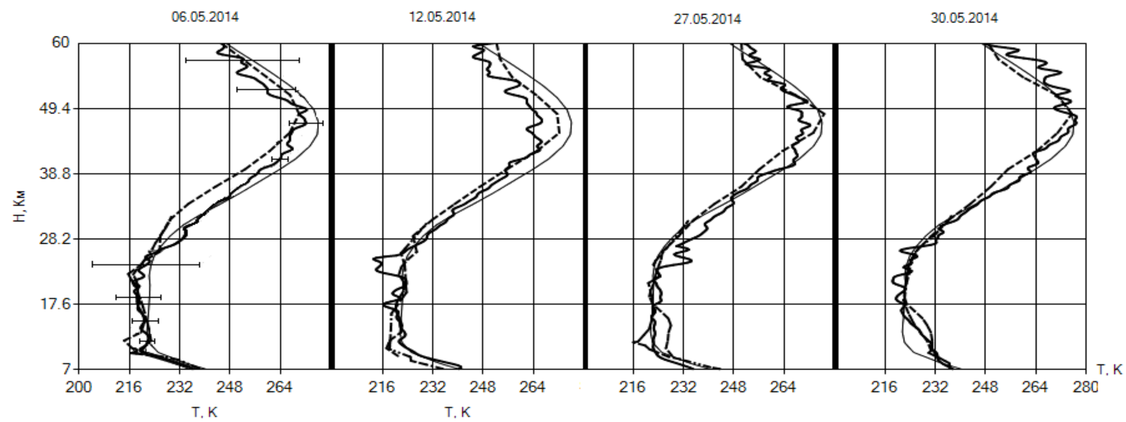

Figure 1. Lidar profiles of temperature (bold solid line) in comparison with the temperature profiles obtained by the “Aura” satellite (dotted line) and balloons (dashed lines in the lower part of the plot) as well as the model CIRA-86 (thin solid line)

Comparing of lidar and radiosonde temperature profiles is shown in Figure 2 (a, left side).
The ratio of aerosol scattering R (H) shows a vertical stratification of aerosol (b, right side of fig.2)

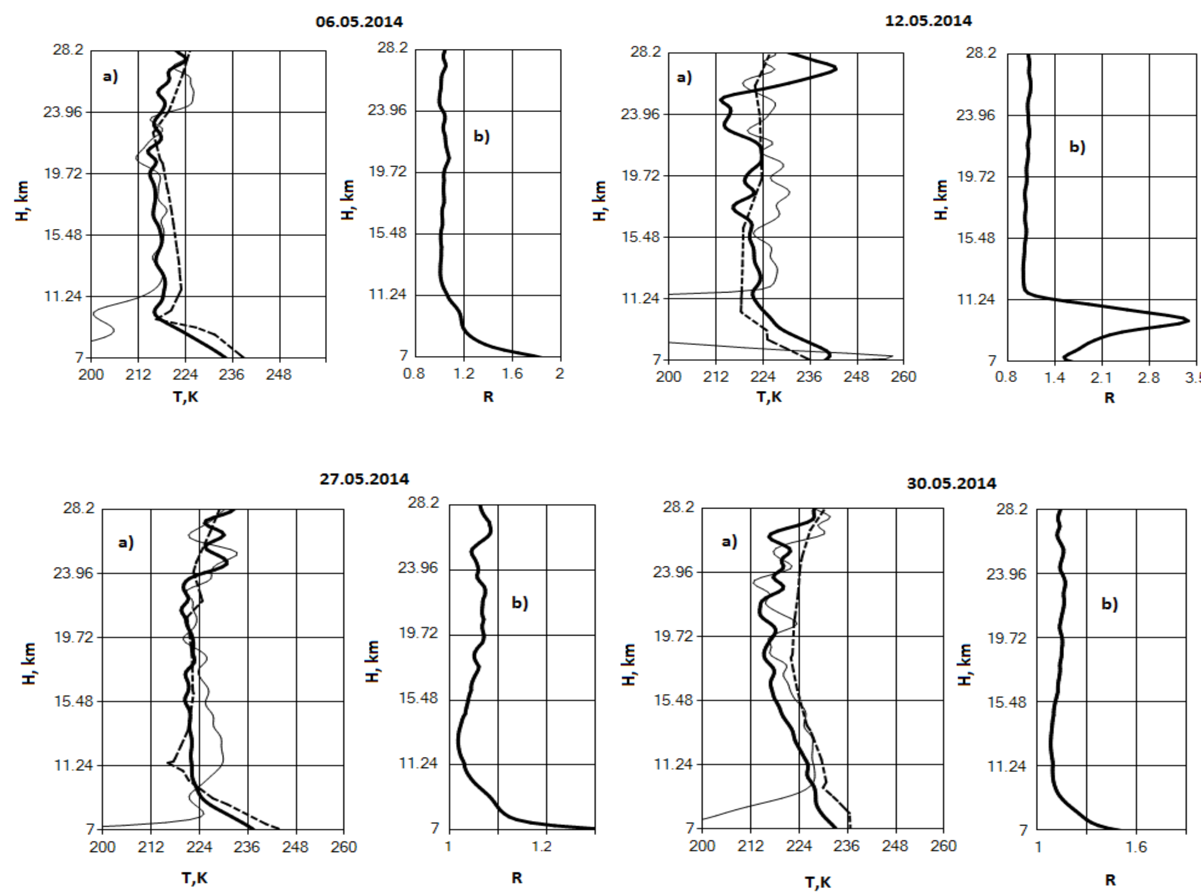

Figure 2. Comparing lidar temperature profiles obtained in Raman channel, the channel of Rayleigh scattering of light (thin curves) with sounding balloons (dashed curve).

This article uses the results obtained during of the project 8.1.12.2015, within the Program "Scientific Foundation. D. I. Mendeleev Tomsk State University" in 2015.
The work was supported in part by Russian Foundation for Basic Research (grant No. 13-05-01036a), grant of the President of RF No. NS4714.2014.5, and grant of Russian Scientific Foundation No. 14-27-00022.

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