

**LASER TECHNOLOGIES FOR ATMOSPHERIC SENSING AT
THE SIBERIAN LIDAR STATION**

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Abstract

The Siberian Lidar Station (SLS) measurement complex of V.E. Zuev Institute of Atmospheric Optics, Russian Academy of Sciences, is described. The SLS multichannel stationary lidar complex is developed on the basis of different-type laser sources, generating in the wavelength range 266-1064 nm, and receiving telescopes on the basis of 2.2, 0.5, and 0.3-m diameter mirrors. The lidar station, located in Tomsk, is the only place in the Asian part of the territory of Russia, where remote optical sensing methods are used to perform a regular monitoring of such atmospheric parameters and constituents as aerosol, temperature, clouds, ozone, and gas components of ozone cycles. Results of long-term regular measurements are presented.

Key words: aerosol, ozone, remote sensing, lidar

1. INTRODUCTION

Aerosol and ozone are among most important constituents of the atmosphere, determining to a considerable degree the radiation-temperature regime and chemical balance of the atmosphere. The radiation-temperature effects, caused by the stratospheric aerosol (scattering of shortwave solar radiation – albedo cooling effect and absorption of longwave thermal radiation of Earth – greenhouse effect), depend to a large degree on the sizes of the aerosol particles. The particle surface area is a key parameter, determining the efficiency of the heterogeneous chemical reactions on the surface of the sulfur acid stratospheric aerosol. These and other microstructure characteristics can be determined from data of the multi-frequency sensing of stratospheric aerosol (SA). For these purposes we developed the [Siberian Lidar Station](#).

2. THE SIBERIAN LIDAR STATION

A multifrequency and multichannel system of lidar and spectrophotometric facilities for atmospheric sensing at the [Siberian Lidar Station](#) (SLS) (Zuev V.V., 2001, Burlakov V.D. et al., 2004), employing laser sources with Stimulated Raman Scattering (SRS) gas cells and nonlinear frequency converters operating in the spectral region of 266-1064 nm and receiving telescopes using mirrors 2.2, 0.5, and 0.3 m in diameter, allows different laser sensing methods to be applied to measure the stratospheric aerosol layer (since 1986), the ozone concentration (since 1989), and temperature (since 1995) in different altitude ranges from the troposphere to the mesosphere. Lidar measurements of geometrical and optical characteristics of clouds, including sensing of high clouds (cirrus clouds) through low cloudiness are carried out at a wavelength of 1064 nm at night and in the daytime. Passive spectrophotometric methods are used to measure total column ozone, total content and vertical distribution of nitrogen dioxide, which is one of the major components of the nitrogen cycle of ozone depletion.

In 1995 the Russian Ministry of Science issued the directive that the SLS was included in the List of Unique Research and Experimental Systems of National Significance (its registration number is 01-64).

This paper presents the possibilities of the Siberian Lidar Station for remote sensing of stratospheric aerosol and ozone.

Table 1 summarizes the main technical characteristics of laser sources and receiving elements of the lidar complex.

Table 1. Technical characteristics of lidar complex

Lidar parameters	Measured characteristics								
	Aerosol					Temperature	Ozone		
Transmitter									
Sensing wavelength λ , nm	511	532	355	683	1064	532		308 353	299 341
Pulse energy (at λ), mJ	1	100	40	60	200	150		100 50	20
Repetition rate (at λ), Hz	2500	15	15	15	15	20		50-200	15
Divergence, mrad	~0.1					0.1		0.1-0.3	0.1-0.3
Receiver									
Sensing method	Elastic backscattering on aerosols and molecules					Molecular scattering	SRS from N ₂	Differential absorption and scattering	
Wavelength, nm	511	532	355	683	1064	532	607	308 353	299 341
Diameter of mirror, m	2.2	0.3	0.3	0.3	2.2	2.2	2.2 0.3	0.5	0.5
Focal distance, m	10	1	1	1	10	10	10 1	1.5	1.5

3. THREE-FREQUENCY LIDAR FOR SENSING OF OPTICAL AND MICROPHYSICAL CHARACTERISTICS OF STRATOSPHERIC AEROSOL

Regular sensing of the optical aerosol characteristics is carried out by the lidar, using three sensing wavelengths 355, 532, and 683 nm, where 355 and 532 nm are respectively the third and second harmonics of the main frequency of Nd:YAG laser radiation, 683 nm is the first Stokes component of conversion of radiation at the wavelength of 532 nm on the basis of the effect of stimulated Raman scattering in high-pressure hydrogen-filled cell.

To study the ozone dynamics in the tropopause region and, in particular, to investigate the processes of stratosphere - troposphere exchange, we developed a lidar for measurements of ozone distribution

in the upper troposphere – lower stratosphere. The sensing is performed using the method of differential absorption and scattering at the pair of wavelengths 299/341 nm, respectively, which are the first and second Stokes components of stimulated Raman shifting of the Nd:YAG fourth harmonic (266 nm) in hydrogen. Using lidar with the receiving mirror 0.5 m in diameter, we performed the ozone sensing in altitude range of 5-18 km.

The block-diagram of lidar for three-frequency sensing of stratospheric aerosol is presented in Figure 1.

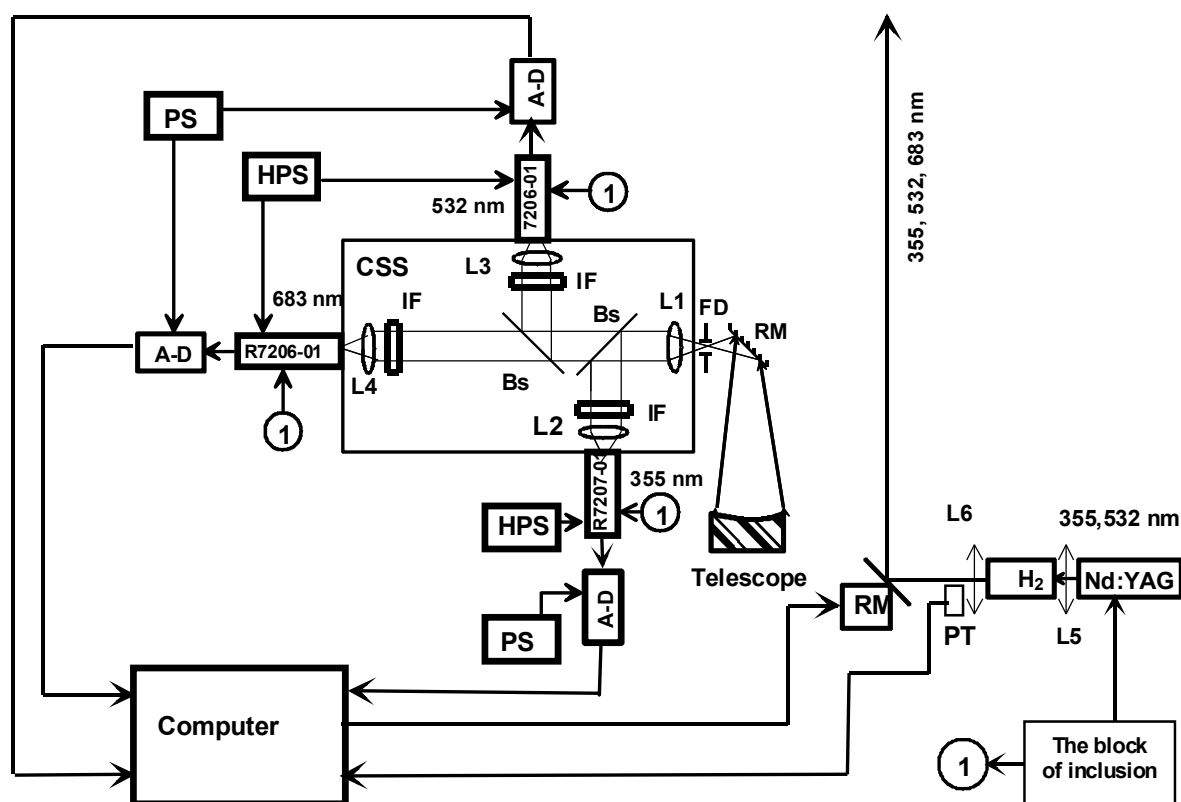


Fig. 1. Block-diagram of aerosol lidar. FD are field diaphragms ; CSS are cells for spectral selection with PMT; Nd:YAG is the laser; H₂ is the Raman cell with hydrogen; AD are the amplifiers-discriminators; HPS is high-power supply; PS is power supply; RM is the reflection mirror; L are lenses; Bs are the beam splitters; IF are interference filters; PT is the phototransistor

We use the Nd:YAG laser, model LS-2132T-LBO, LOTIS TII firm, Minsk. The technical characteristics of the lidar transmitter: pulse energy of radiation is 70 mJ at wavelength of 532 nm, 25 mJ at 355 nm, and 25 mJ at 683 nm; the pulse repetition rate is 20 Hz; the beam divergence is ~ 0.8 mrad; hydrogen pressure in SRS cell is 12 atm and higher. Using the mirror RM, installed on the automated adjustment unit, created on the basis of computer-driven stepper motors, the radiation is directed to the atmosphere. The receiving telescope is developed according to Newtonian scheme, on the basis of the main mirror with diameter of 0.3 m and focal distance of 1 m. The optical lidar signal arrives at 3-wavelength cuvette of spectral selection (CSS) with Hamamatsu photomultipliers (PMTs). Lidar signals are recorded in the photocurrent pulse counting mode. To cut off the powerful

return from near sensing zone, a device of electronic control of PMT amplification coefficient is used, allowing us to switch on the PMT into working regime starting from a certain sensing height.

We determined the regimes of SRS conversion, ensuring optimal relationship of energy parameters at the three wavelengths. Figure 2 shows the dependence of the relative intensities at 355, 532, and 683 nm on the hydrogen pressure in SRS cell. From Figure 2 it is seen that, to obtain an optimal relationship of the energy characteristics at the three wavelengths, the working hydrogen pressure in SRS cell should be 12 atm and higher. The Raman cell is fabricated from (stainless steel) tube with inner diameter of 3 cm and length of 1 m. The pumping power density, required to obtain the effect of SRS conversion, is ensured by the lens L5 with the focal distance of 1 m, which is installed before the SRS cell and focuses the radiation to the cell center. After the cell, the collimating lens L6 is installed confocal with the focusing lens.

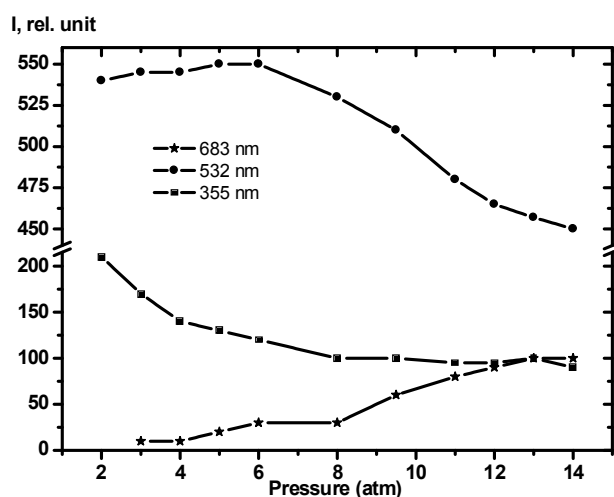


Fig. 2. Dependence of the relative intensities of radiation at the wavelengths of 355, 532, and 683 nm on the hydrogen pressure.

Figure 3.a presents an example of three-frequency sensing in the form of the measured profiles of the scattering ratio $R(H)$ (ratio of the sum of aerosol and molecular backscattering coefficients to the latter). The $R(H)$ profiles finely reflect the altitudinal SA stratification. The presented profiles were measured on October 10, 2008, when in the stratosphere over Tomsk we still recorded the traces of volcanic aerosol after a series of volcanic eruptions on Aleutian Islands: Okmok (53.4°N, 168.1°W) and Kasatochi (52.2°N, 175.5°W), which occurred in July – August 2008. On the $R(H)$ profiles, a well-defined aerosol layer at height of about 16 km is seen.

Method of inversion of the spectral dependences of aerosol backscattering coefficients, measured at the sensing wavelengths of 355, 532, and 683 nm, was used to determine different microphysical parameters of SA (size distribution of particle geometric cross section, number concentration, mean radius, particle surface area, etc.). Figure 3.b shows the altitude distribution of the total specific particle volume V , and Figure 3.c presents the total geometric cross section S , retrieved from the data of sensing on October 10, 2008.

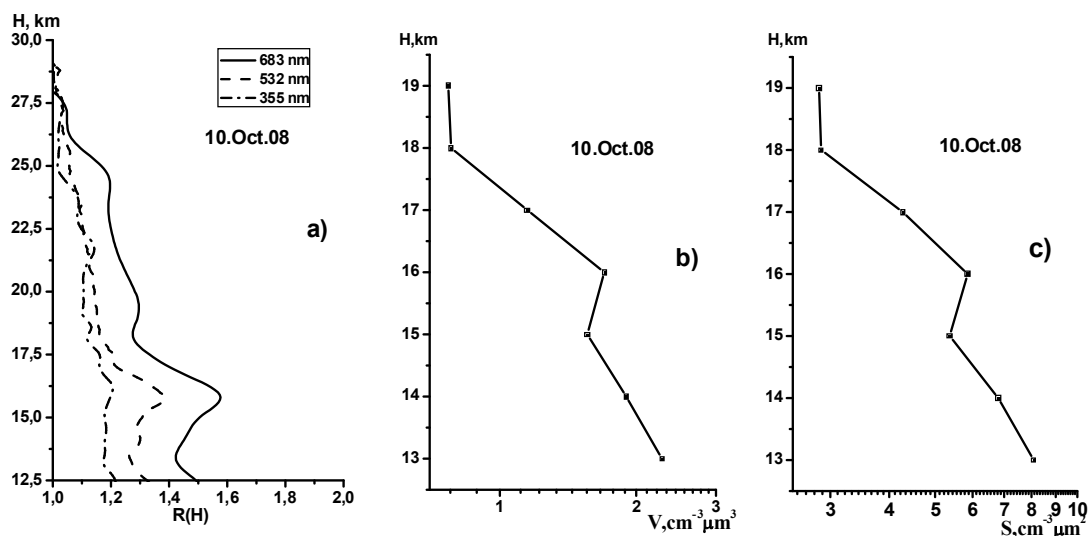


Fig. 3. (a) Vertical profiles of the scattering ratio at 355, 532, and 683 nm, (b) retrieved total volume, and (c) total particle cross section.

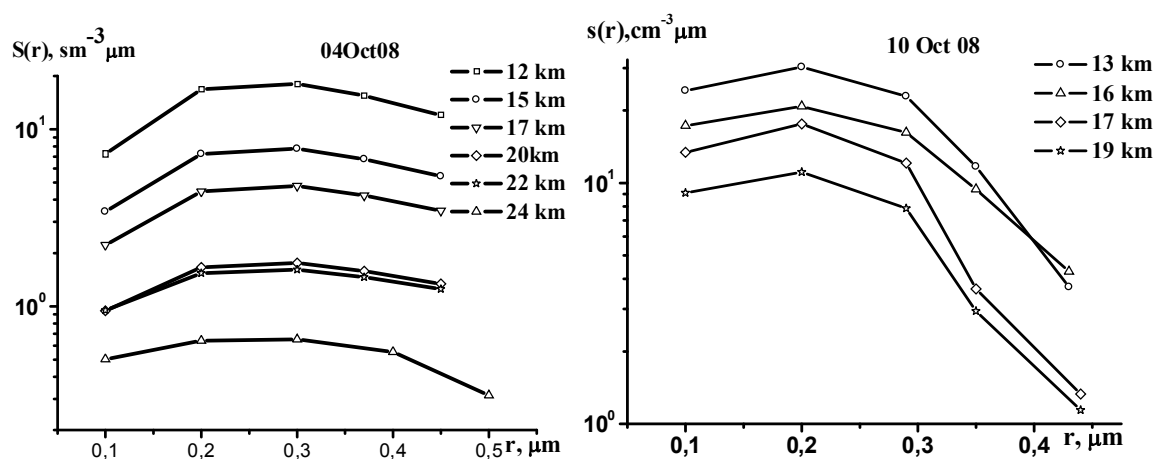


Fig. 4. Size distribution of particle cross sections, retrieved at different heights in the lower stratosphere.

From the figures we see the increases of V and S values at heights of about 16 km, where the volcanic aerosol layer was located.

Figure 4 shows the distribution of particle geometrical cross section over the sizes r (r is the particle radius) at different altitudes for the background conditions of the state of the stratospheric aerosol layer on February 4, 2008 and under conditions of volcanic perturbation of the stratosphere on October 10, 2008. We see that $S(r)$ values increase at all considered heights under conditions of the volcanic perturbation of the stratosphere in comparison with the background conditions of February 2008.

4. DIFFERENTIAL ABSORPTION LIDAR FOR OZONE SENSING IN THE UPPER TROPOSPHERE – LOWER STRATOSPHERE

Tropospheric measurements of ozone usually use excimer KrF laser (248 nm) or fourth harmonic of Nd:YAG laser (266 nm) in combination with the technique of SRS conversion in H₂, D₂, CO₂, and other gases (Galani E. et al., 2003, Bucurev V.S. et al., 1996). H₂ and D₂ are most wide spread species. In different altitude of the troposphere and lower stratosphere, different wavelength combinations are used. For instance, the wavelength pairs 289/316 and 287/299 nm allow for the determination of ozone profile up to the height of about 10 km (Galani E. et al, 2003); the pair 292/319 nm is usable up to heights of 12-14 km (Bucurev V.S., 1996); and the pairs 277/313 and 292/313 nm are usable up to heights of 8-12 and 15 km respectively (H. Eisele et al., 1999).

We made preliminary numerical estimates (Zuev V.V. et al., 2008) of the possibilities of sensing the vertical ozone distribution (VOD) in the upper troposphere – lower stratosphere at the wavelength pair 299/341 nm. The wavelength $\lambda_{on}=299$ nm falls within the region of ozone absorption band with the absorption cross section $\sigma_{299}=4.4 \cdot 10^{-19}$ cm², which is a factor of three larger than the absorption cross section at the wavelength of 308 nm, $\sigma_{308}=1.4 \cdot 10^{-19}$ cm². The maximum sensing height is determined primarily by the range of signal recording at λ_{on} , which is always less than the range of signal recording at λ_{off} , because of strong absorption by ozone. In this regard, $\lambda_{on}=299$ nm is more preferable than 277 or 292 nm. The 299- and 341-nm wavelengths are realized in one sensing beam (in one SRS cell), in contrast, e.g., to the 292/313-nm pair. Moreover, the system on the basis of the SRS cell with hydrogen is cheaper than that using deuterium.

Figure 5 presents the block-diagram of the lidar. As the source of the laser radiation, we use the fourth harmonic (266 nm) of the main frequency of radiation of the Nd:YAG laser, model LS-2134UT, LOTIS TII firm, Minsk, with its subsequent conversion in hydrogen into first (299 nm) and second (341 nm) Stokes components.

The receiving telescope is developed according to Newtonian scheme on the basis of the main mirror with the diameter of 0.5 m and with the focal distance of 1.5 m. The recording channel of lidar uses the HAMAMATSU photomultipliers (R7207-01) and amplifiers-discriminators (C3866). Recording of lidar signals is performed in the photocurrent pulse counting mode. To maintain the linear regimes of PMT operation, we used the mechanical obturator, which cuts off the powerful optical signal from near sensing zone. The SRS cell is fabricated from (stainless steel) tube with the inner diameter of 3 cm and length of 1 m. The entry and exit windows are fabricated from quartz KU. The energy of the pumping pulse at the wavelength of 266 nm is 60 mJ. The pumping power density, required to obtain the effect of SRS conversion, is ensured by the lens L1 with the focal distance of 1 m, which is installed before the SRS cell and focuses the radiation to the cell center. After the cell, the collimating lens L2 is installed, confocal with the focusing lens. The sensing radiation is output with the exit rotated mirror RM, installed at the automated adjustment unit, developed on the basis of computer-driven stepper motors.

We determined the efficiency of SRS conversion as a function of hydrogen pressure in the cell. The hydrogen pressure in the cell was changed from 1 to 9 atm. The dependence of the relative intensities at the wavelengths of 266, 299, and 341 nm on the hydrogen pressure, obtained at the SRS cell output, is presented in Figure 6. At the hydrogen pressure of 2 atm, the intensities of the 299 and 341-nm lines become equal, providing the possibility of ozone sensing with equal energy characteristics of radiation at these wavelengths. However, to increase the maximum sensing height, it is more efficient to use the pressure of 1 atm, because in this case the energy characteristics are redistributed in favor of the 299-nm line, which is stronger absorbed by ozone than the 341-nm line.

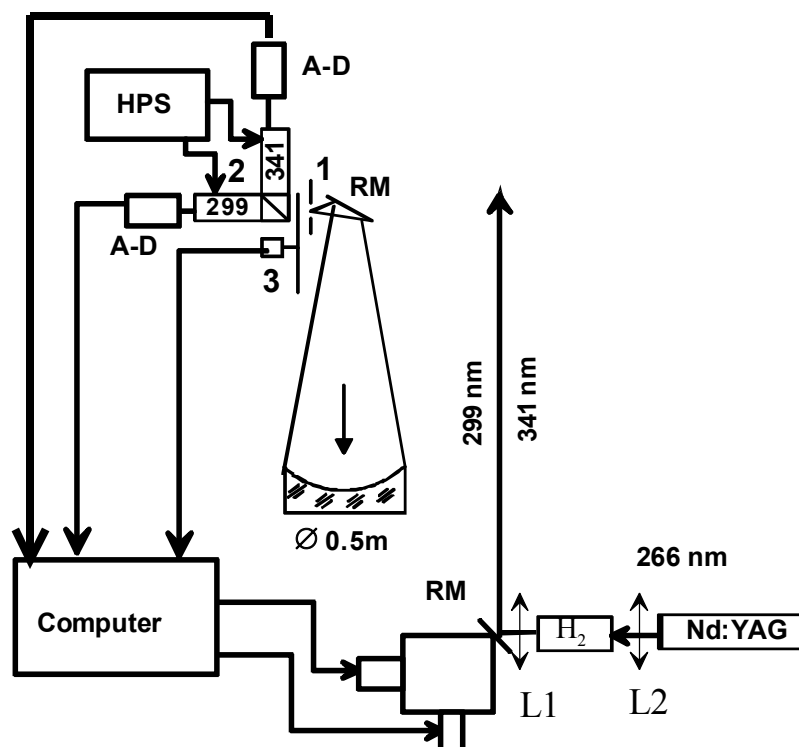


Fig. 5. Block-diagram of ozone lidar. 1 are the field diaphragms; 2 are the cells for the spectral selection with PMT; 3 is the chopper; Nd:YAG is the laser; H₂ is Raman cell with hydrogen; AD are amplifiers-discriminators; HPS is the high-power supply; RM is the reflection mirror; L1 and L2 are lenses.

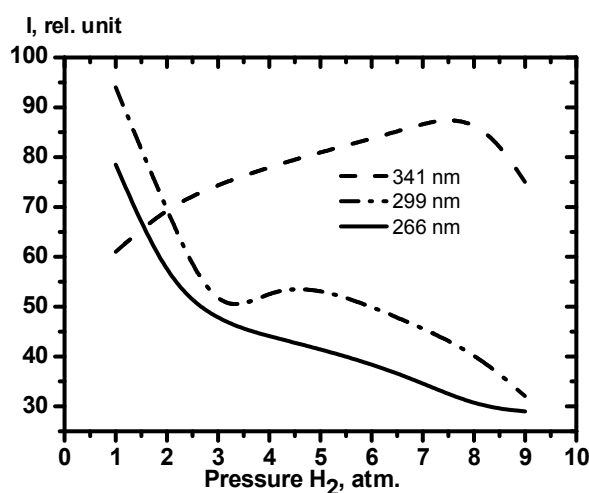


Fig. 6. Dependences of the relative intensity of radiation at 266, 299, and 341 nm on hydrogen pressure

Figures 7.a and 7.b present the shape of the lidar signals and the retrieved profile of ozone concentration respectively. The signals were recorded in the photocurrent pulse counting mode using 25 000 shots (the accumulation time was ~ 30 min). The achieved maximum height of signal recording at the wavelength of 299 nm was 17 km.

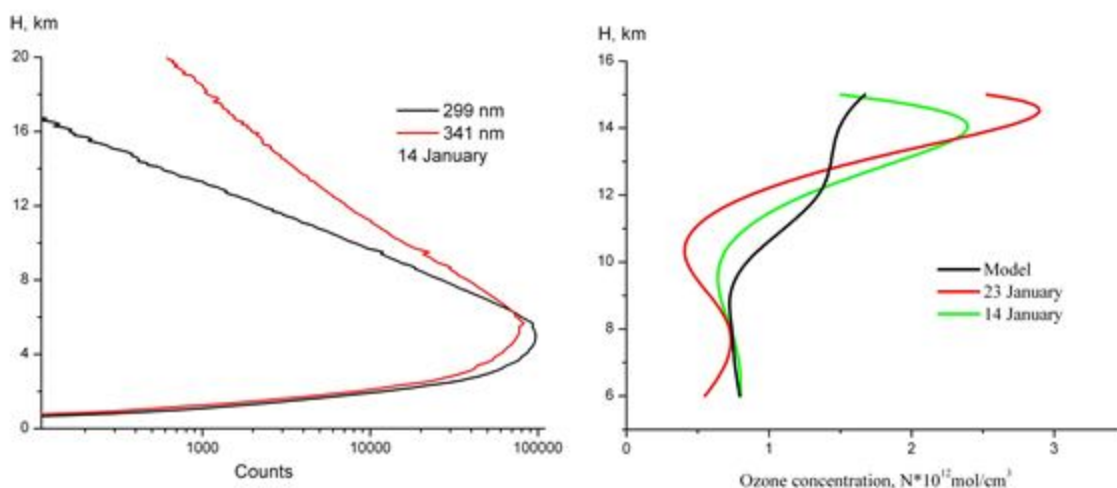


Fig. 7. a) - shape of the lidar signals; b) - retrieved profile of ozone concentration

Increase of the accumulation time of the lidar signals will make it possible to increase the maximum sensing height. The proposed method makes it possible to retrieve the ozone concentration profiles in the altitude range 6-15 km (Figure 7.b). The retrieved profiles were compared with midlatitude model of Krueger (Krueger A.J. et al., 1976). It should be noted that the measured profiles qualitatively coincide with the model profile up to height 12 km. On separate observation days, the retrieved profiles diverge from the model one, which is natural for ozone layer dynamics.

5. CONCLUSION

In contrast to most schemes of the multi-frequency sensing, using a few laser sources, the sensing wavelengths of 355, 532, and 683 nm are realized in one coaxial beam from one laser source, which makes the lidar system much cheaper and simplifies its operation in the regime of regular measurements.

The results of the lidar measurements at the wavelengths of 299 and 341 nm agree with the model estimates. At present, works are under way to optimize the optical and photoelectronic elements of the recording system of lidar signals with the purpose of increasing the maximum sensing height and improving the measurement accuracy. In conclusion, we can also note that, for ozone sensing in the altitude region of 5-20 km, the lidar on the basis of Nd:YAG laser is more preferable than lidar on the basis of excimer KrF laser, which is more costly, more difficult to use, and requires exceptionally pure gases for the working mixture, frequent purification or replacement of the resonator optics.

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REFERENCES

1. Buceev V.S., Vartapetov S.K., Veselovskii I.A. et al (1996) Combined lidar system for stratospheric and tropospheric ozone measurements, Appl. Phys., B 62, pp. 97-101.
2. Burlakov V.D., Dolgii S.I., and Nevzorov A.V. (2004) Modification of the measuring complex at the Siberian Lidar Station, Atmos. Oceanic Opt., 17, pp.756-762.
3. Galani E., Balis D., Zanis P., Zerefos C., Papayannis A., Wemli H., and Gerasopoulos E.. (2003) Observations of stratosphere-to-troposphere transport events over the eastern Mediterranean using a ground-based lidar system, J. Geophys. Res., 108 (D12), pp. STA12/1-STA12/10.
4. H. Eisele, H.E. Scheel, R. Sladkovic, and T. Trickl J. (1999) High resolution lidar measurements of stratosphere – troposphere, Atmos. Sci., 56, pp. 319–330.
5. Krueger A.J., Minzner R.A. (1976) A mid-latitude ozone model for the 1976 U.S. standard atmosphere, J. Geophys. Res., 81 (D 24), pp. 4477-4481.
6. Zuev V.V. et al. (2001) The Siberian Lidar Station
<http://iclas.hamptonu.edu/Pages/directory/zuev1.html>
7. Zuev V.V., Burlakov V.D., Dolgii S.I., Nevzorov A.V. (2008) Differential absorption lidar for ozone sensing in the upper troposphere – lower stratosphere, Atmos. Oceanic Opt., 21, pp. 765-768.