Development of Tomsk State University lidar as a unique complex for atmospheric monitoring

I.V. Samokhvalov, S.M. Bobrovnikov, P.P. Geiko, A.V. El'nikov, and B.V. Kaul

[1] *Tomsk State University*
[2] *Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk*
[3] *Institute of Monitoring of Climatic and Ecological System, Siberian Branch of the Russian Academy of Sciences, Tomsk*

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We present the conception on the development of the high-altitude Tomsk State University lidar as a unique complex for atmospheric monitoring to be the basis for educational and research center. The efforts are mainly concentrated on the lidar upgrade aimed at improving its performance characteristics and extending the scope of studies that can be accomplished using it.

Introduction

At present, the high-altitude polarization lidar of Tomsk State University that has been designed jointly with the Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, proved to be a unique experimental complex for laser monitoring of the atmosphere. Unique studies of atmospheric aerosol are being carried out using this complex by measuring the profiles of all elements of the back-scattering phase matrix of atmospheric aerosol including the cloud aerosol. The lidar has been included into the "List of unique research facilities of the national significance"[1]; an information on this lidar can be found in the international catalog published in the USA.[2] Thereby, it is included into the worldwide network of stations for laser sounding of the atmosphere. The lidar being the basic element for atmospheric researches, has many other potentialities.

The lidar, if equipped with the modern optical-electronic systems including the laser transmitter with increased power, optical polarization elements, spectral isolation devices with narrower passbands, CCD-matrix-based system for recording lidar returns, and a spectrum analyzer would acquire better spatial and temporal resolution. All this will provide higher level of the crystal cloud research[3,4] and will transform it into a multi-purpose aerosol-gas lidar.

Laser sounding is a remote, contactless and operational method. Functional relations between the atmospheric and lidar parameters are determined by the lidar equation that has been discussed in detail in a series of monographs.[5,6] The key device determining the potentialities of laser (lidar) sounding is the source of coherent optical radiation (laser).

Laser radiation source

At present, the polarization lidar of Tomsk State University is equipped with an ILTI-405 laser. Its parameters are presented in Table 1 in comparison with parameters of lasers from Quantel and LOTIS companies that have been purchased under the modernization program. As follows from the table, energy of new lasers at $\lambda = 532$ nm, which is widely used in practice of lidar sounding, exceeds the available laser energy, in the first case, by 19 times, and in the second, by 10 times. Therefore, the time required for recording lidar return $N(H)$ in the photon counting mode accurate to a given random error will be 19 times shorter with Quantel laser and 5 times shorter with the LOTIS laser, as compared with that in the case with ILTI-405 laser operated at its "cruising" pulse repetition frequency about 20 Hz. In addition, higher energy of radiation delivered in a shorter pulse (pulse duration for the lasers purchased is 8 and 6–7 ns, while the available laser delivers pulses of 14 ns duration) provides for improvement of the signal-to-noise ratio in the return signals recorded and thus to increase the altitude of sounding. Besides, no field experiments in the atmosphere could be realized at the harmonics frequencies because of the initially low energy of the ILTI-405 laser.

Table 1. Laser radiator parameters

Laser	Quantel YG981E-20	LOTIS LS-2137U	ILTI-405
Wavelength, nm	Energy, mJ		
1064	1600	700	–
532	780	400	40
355	420	160	–
266	120	120	–
Pulse repetition frequency, Hz	20	10	12.5–25.0
Beam divergence, mrad	<0.5	0.8	3.5
Pulse duration (1064 nm), ns	8	6–7	14

Energy parameters of the laser pulses presented in Table 1, correspond to the cases when lasers are operated at one frequency. Nevertheless, both lasers to be put into operation are equipped with the built-

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in generators of the harmonics of the fundamental laser frequency (λ = 1064 nm). Consequently, one can obtain simultaneously, at the laser output, radiation at four wavelengths: 1064, 532, 355, and 266 nm. The frequency conversion efficiency makes tens of percent and the pulse energy of the harmonic is lower than values presented in Table 1, but even so it is quite sufficient for solving many problems in laser sounding.

Scope of the tasks for laser sounding provided by the lidar upgrade

The entire spectrum of potentially feasible measurements and studies of atmospheric parameters and components using the laser radiation at the wavelengths available is presented as a block diagram in Fig. 1.

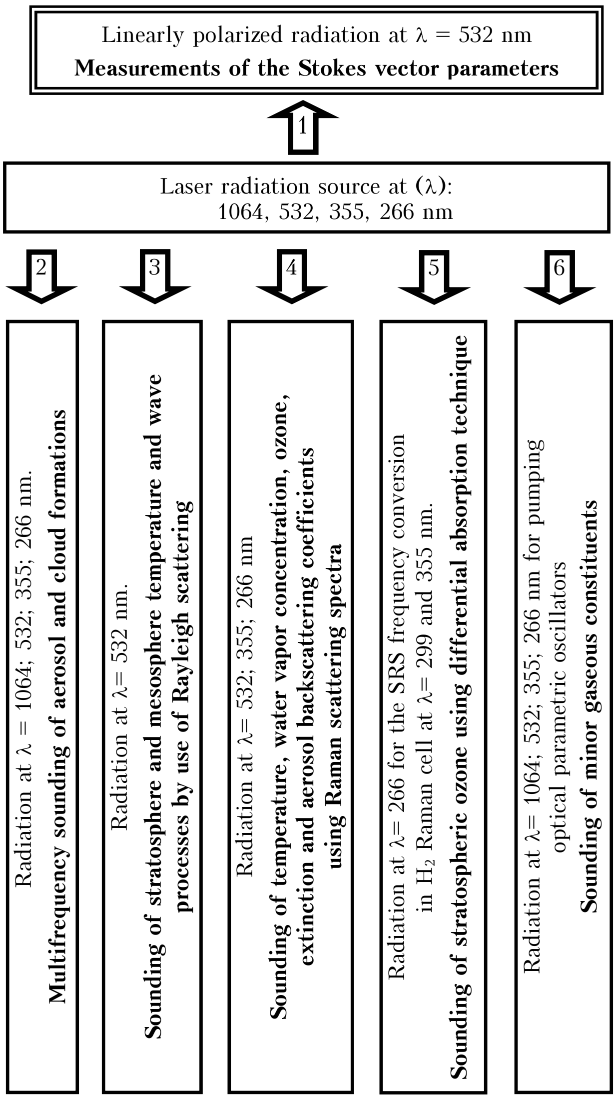

Fig. 1. Block diagram of a complex for aerosol-gas measurements planned to be conducted using the lidar of Tomsk State University.

It is worthy to note that at least one of the authors of this paper took part in solution of the problems presented in the block-diagram demonstrating the potential technological and methodical capabilities of laser sounding. In the upper part of the block-diagram (research field 1), the lidar studies of the Stokes vector parameters are presented. These studies have already proved to be efficient in nighttime measurements. Increase of the energy potential of laser radiation source will improve the accuracy of similar measurements, will reduce measurement time, and will make the measurements feasible under conditions of daylight, provided better spectral isolation of the return signals (at present, the interference filter half-width is about 2.5 nm). The lower part of the block diagram presents the promising tasks that can be achieved owing to the multi-frequency laser transmitter that has good energy resource and enabling one to obtain the necessary radiation frequencies for solving some particular problems.

Techniques that provide achieving the task

Solutions of the ill-posed inverse problems of atmospheric optics using lidar data, including the multi-frequency aerosol sounding (research area 2) are described in detail in Ref. 7. However, due to the lack of the high-power laser transmitters, there are only few publications on realization of this theory in application to field experiments.[8,9]

Remote measurements of temperature using lidar technique based on Rayleigh scattering in the stratosphere, mesosphere, as well as the study of the internal gravity waves (research area 3) has been recognized in the lidar community for a long time (see, for example, Refs. 10 and 11). Similar but single measurements, reflecting the specifics above the Western Siberia region have also been carried out in Tomsk.[12]

Basic properties of the Raman scattering effect in application to multicomponent analysis (research area 4) have been described in detail in Ref. 5 and have been further developed in Refs. 13–15. Most popular, during recent 20 years, technique for measuring stratospheric ozone by the differential absorption method (research area 5) uses radiation of XeCl excimer lasers at λ = 308 nm (fundamental wavelength, which is absorbed by ozone), and frequency conversion of its portion in an SRS-cell filled with H_2 into radiation at 353 nm wavelength (reference wavelength), which is not absorbed by ozone. The data on ozone concentration are retrieved from analysis of the radiation extinction at the given wavelengths.[16,17] Using λ = 299 nm as a fundamental wavelength, which is the derivative from λ = 266 nm (see the block-diagram) and where the ozone absorption is four times higher than at λ=308 nm, allows one to increase contrast of the differential absorption effect.

Table 2. Parameters of commercial OPOs, emitting in the UV, visible, and near IR

Model	Company, country	Tuning range, nm	Energy, mJ	Repetition frequency, Hz	Pulse duration, ns	Method of pumping	Line width	Divergence, mrad	Note
MOPO-HF	Spectra-Physics, USA	440... 1800	75	10	4...6	Nd:YAG	0.075 cm^{-1}	–	OPO with auto-tracking
Scan Linc-S	Lambda Physics Inc., USA	420...2500	150	1000	7	Nd:YAG with diode pumping	1	–	OPO
Panther	Continuum, USA	410...2500	100	10	7	Nd:YAG	0.06 nm	–	OPO
Mirage 3000	Continuum, USA	1500...4000	10	10	0,5	Nd:YAG	0.007 nm	–	OPO
BBO-3BII	U-Oplaz Technologies Inc., USA	200...4000	100	1...100	1...10	Nd:YAG	–	–	Single-frequency OPO
OPO-C	Polytec PI Inc., USA	205...4000	Up to 150	50	6...12	Nd:YAG	0.05 nm	–	OPO
Vega 200	Thomson CSF Laser, France	225... 4000	50	10	10	Nd:YAG	<0.2 cm^{-1}	–	OPO
Sunlite EX	Continuum, USA	205...5000	50	10	7	Nd:YAG	0.002 nm	–	OPO
1100	Aculight Corp., USA	1390...4700	10^{-2}	20000	10	Diode	10MHz	–	OPO
LT-2215	Lotis-TII, Belorussia	410–2300 (205–2300)	Up to 40	20	5–6	Nd:YAG	< 0.15 nm	4–8	OPO

Intense development of the differential absorption method aimed at measuring wider list of minor atmospheric gases is related to the research area 6, where the optical parametric oscillators are used (OPO).[18–20] Table 2 presents the parameters of some commercially available narrow-band OPOs smoothly tunable in a wide frequency range that enable creation of lidars gas-analyzers. The main feature of the OPOs is the possibility of smoothly tuning spectrally narrow laser radiation frequency within a wide spectral region in the IR, which is much promising for daylight measurements (see Table 2). For example, the OPO pumped by the third harmonics of the Nd:YAG laser covers the ranges from 416 to 487 and from 1306 to 2411 nm at the efficiency of 35%. The lidar considered is equipped with an LT-2215 OPO from LOTIS Company (the bottom line in Table 2).

The design solutions on constructing a combined laser transmitter capable of delivering radiation in the spectral regions required, as well as adaptation of all the above-mentioned techniques to meet the performance characteristics of the transmitter–receiver of the polarization lidar make up another one task of its modernization and development.

Upgrade of the receiving and recording blocks of the lidar

Upgrade of the receiving and recording blocks of the lidar, first, is connected with the replacement for newer ones of the main part of spectral selection elements (rotating mirrors, interference filters). It is planned to include a monochromator into the set of optical devices of the lidar receiving optics that would provide the isolation of the spectral ranges, formed by radiation of the optical parametric oscillators.

Modern photomultiplier tubes from Hamamatsu will be used as the detectors of radiation backscattered by atmospheric components in the UV and visible regions. Detection of the returns in the IR range will be provided with use of avalanche photodiodes.

Geophysical problems to be solved

The upgrade of high-altitude lidar and integration of laser sounding technologies to study the atmospheric properties and components, developed by the lidar community worldwide, would enable us to start solving the following geophysical problems. First of all, simultaneous measurements of the height profiles of the elements of back-scattering phase matrix and temperature in the upper troposphere will give an opportunity for correctly studying the formation of spatially oriented crystal particles in the upper level clouds, thereby, solving the problem of radiation transfer through crystal clouds. The main task of the polarization lidar that has been formulated is the study of optical characteristics of the crystal clouds, compiling the corresponding database that would enable constructing an empirical statistical model of cirrus clouds will be further developed.

The experience in experimental and theoretical studies of scientists in the above-mentioned problem, gained earlier, allows to plan the future steps toward realization of the model of orientation state for crystal clouds. The main point of the studies planned is making the probability estimations of the orientation parameters using only few input parameters (cloud height, vertical profiles of temperature and wind velocity). All the input parameters are standard and readily available meteorological information. They are transformed into the energy dissipation rate that causes efficiency of the orientation particle mechanisms. Orientation parameters will be determined by means of polarization lidar measurements using the techniques that have been developed earlier. The probability estimations of the orientation state will be obtained from correlations between the input and orientation parameters.

Meridional and zonal transfer of air masses including the mechanism of exchange between the atmospheric disturbances in the polar latitudes with the air at midlatitudes is directly related with the complex analysis of meteorological situation and of the lidar sounding data in these regions on the parameters that are the tracers (aerosol, ozone, etc.) of the processes under study. The basis for obtaining the laser sounding data (on the parameters being the tracers) in polar regions has already been done by lidars put into operation in Yakutsk and Petropavlovsk-Kamchatski.

A special attention will be given to the problem of tropospheric–stratospheric exchange. Information on a wide list of atmospheric components and parameters, which are typical only for the troposphere or only for the stratosphere, will allow identifying the given processes based on their joint behavior in space and time to investigate their characteristics.

Conclusion

Thus, equipping the high-altitude polarization lidar, whose peculiarity is the three telescopic systems with the mirror diameters of 0.5 m, with the modern laser transmitters and spectral selection blocks will open not only the qualitatively new level of polarization studies of the atmospheric aerosol formations, but also will extend the number of the atmospheric parameters observed. This, in its turn, will form the basis for studies of the atmospheric processes.

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