SPATIOTEMPORAL PICTURE OF THE ATMOSPHERIC POLLUTION WITH AEROSOLS OVER VOLGA RIVER

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In this paper we present some results of lidar sounding of the atmosphere over Volga river en route from Moscow to Nizhny Novgorod obtained during a complex ecological expedition on board a ship "Il'ya Repin" at the period from 28.06.1993 till 07.07.1993. The investigation has been carried out using a compact aerosol lidar with an eye–safe laser radiation. A comparison of lidar return signals obtained under similar conditions enabled us to reveal regions of especially clear (aerosol free) atmosphere and regions with aerosol pollution. The atmosphere over certain sections of the route (for example, near small towns Ples and Khvoinyi Bor) is considered as the reference or background atmosphere for assessing the degree of aerosol pollution of the atmosphere over industrial centers.

INTRODUCTION

The air quality in the atmosphere over big cities and the problem on diagnostics of the level of its pollution has recently become an important problem among other problems of environmental monitoring in many countries. In Germany, for example, more than a half of citizens interrogated in 1990 mentioned this problem as the main among other eight problems.[1] In this connection the development of methods and especially of compact systems for remote control of the atmosphere is an urgent problem.

The possibility of applying lidars to control the aerosol pollution of the atmosphere has been considered in a number of monographs.[2,3] In Ref. 4 the examples of using a lidar, installed in an automobile van, for mapping the fields and for determining the intensity of emissions from stacks of local pollution sources of air basins in Kemerovo and Pavlodar are given.

This paper presents some results on atmospheric sounding along Volga river, conducted with a compact lidar[5–7] and on spatiotemporal variations of the aerosol pollution on the whole route of the ship "Il'ya Repin". Detailed profiles on a short sections of the route within the cities and industrial centers are also given. In some cases the essential changes in the backscattered coefficients were found, which can easily be associated with the pollution sources located on the bank of the river. Of the particular importance are simultaneous records of the lidar returns from smoke plumes near the stack mouth of the boiler of the elevator in the city Rybinsk and of its lower layer containing the most heavy fraction of the emission at the distance of 330 m from the lidar.

A comparison of the backscattered coefficient obtained under similar conditions of field experiment allows us to reveal zones with maximum and minimum aerosol pollution of the atmosphere. The sections of the route with clear atmosphere (the town Ples, the borough Khvoinyi Bor) are considered as the reference or background ones to evaluate the level of the aerosol pollution over industrial centers, such as Rybinsk, Tver, Yaroslavl, and Nizhny Novgorod.

In this connection we discuss here some prospects of using a compact lidar that emits very low energy sounding pulses (below the spectral energy density of solar radiation) for environmental monitoring.

SPATIOTEMPORAL VARIATIONS OF THE AEROSOL POLLUTION OF THE ATMOSPHERE ALONG VOLGA RIVER

Measurement technique. The experimental model of the lidar based on a semiconductor laser and a quantum counter in the receiving channel was used in this study. Its technical characteristics were described in Ref. 7. The basic components of the experimental setup were the optical unit with the transceiving objectives, the electronic control unit, and the system of processing and displaying the information based on a microcomputer. The lidar model was developed at the Space Research Institute of the Russian Academy of Sciences under support of the Research Industrial Enterprise "Al'kor". It was based on the lidar––altimeter designed for investigations of the Mars atmosphere during the Mars–94/96 mission. The optical unit was fixed on a tripod with a ball hinge that enables one to choose practically any sounding direction. For the operative aiming at an object under study we used a telescopic sight mounted in parallel to the optical axis of the lidar receiving channel. The direction of sounding was chosen so that it provided maximum reduction of the effect of the aerosol plume occurring as a result of action of the life providing systems placed in the bow and stern parts of the ship on the recorded signal. The height above the water level at which the lidar was placed can be changed from 2 to 13 m depending on the number of the deck it is mounted at. To compare the routine results more correctly, the direction of sounding was chosen to be parallel to the water surface.

Depending on the background intensity and the object under study 32 000–1 024 000 laser pulses were used in one measurement cycle, that corresponds to the measurement time from 13 s to 6 min at the pulse repetition frequency of 2.5 kHz. During this time interval the ship moved by a distance up to 3 000 m. Therefore the lidar return could be averaged over space and time simultaneously.

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The typical shape of a lidar return from the smoke plume near the stock mouth of a boiler of the elevator in Rybinsk is presented in Fig. 1 without a correction for squared range. The first peak bears information about the level of the aerosol pollution of the atmosphere immediately adjacent to the lidar, and the second one relates to the density and scattering properties of the plume or any other object. The resulting profile of the variation of the level of the aerosol pollution of the atmosphere along the whole route of the ship was determined from the amplitude values of the first peak in the backscattered signal after processing histograms. In doing so, the value of the backscattering coefficient (BSC) was determined in accordance with the lidar calibration carried out earlier[7] against the number of counts in the fifth channel of the histogram $\beta = KN_5/N$, where N_5 is the number of the signal photocounts in the 5th channel of the retrieved histogram compiled from N laser shots and $K = 1.2\cdot 10^{-3}$ m$^{-1}\cdot$sr^{-1} is the calibration constant.

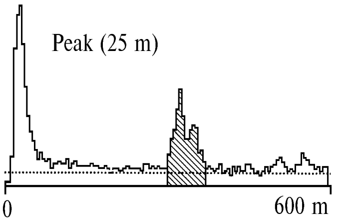

Fig. 1.

The BSC profile along the sounding path was calculated using both the data from a single histogram, and from series of measurements with the strobe moved along the sounding path at a large distance.

The error in the BSC value was determined by the spread of the calibration coefficient K (~ 15%) and by the variance of the number of the signal photocounts in the 5th channel of the histogram. It is worth emphasizing that the calibration coefficient in the 5th channel presented here is obtained under assumption of the atmospheric homogeneity. To determine the degree of a medium nonstationarity when estimating the backscattering coefficient, the cycle of measurements was carried out for each section of the ship's route. After that the random average values and variances of the number of signal photocounts were calculated. As a rule, the relative rms deviation over a series of measurements did not exceed 15%, that was taken as an actual value of the degree of the atmospheric nonstationarity during the measurement time.

Experiment. In Figure 2 the large–scale spatiotemporal variations of the backscattering coefficient, obtained in the process of sounding the atmosphere above the water surface and in the low layer of the atmosphere en route Moscow–Nizhny Novgorod (see Fig. 2*a*) and Nizhny Novgorod–Moscow (see Fig. 2*b*) onboard the ship "Il'ya Repin" from 29.06.93 to 07.07.93 are presented.

Note, that strong fluctuations of the return signal can be caused by intense emissions from the engine stacks of the ships plying in the vicinity of "Il'ya Repin" ship. During the expedition an increase of a lidar signal after the ship "Il'ya Repin" passed by a passenger–carrying freighter from the windward side was firmly established.

Large spread of the values of the backscattering coefficient during the mooring in Nizhny Novgorod (Fig. 2*a*) within the range 4–20$\cdot 10^{-6}$ m$^{-1}\cdot$sr^{-1} is explained in our opinion, because the ship was in the zone of the plume of the aerosol emissions of industrial and other objects of the city in the case when the wind blew from the city along the Oka to the Volga.

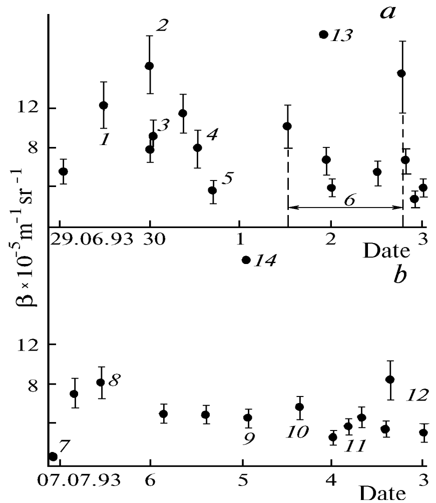

FIG. 2. Variations of measured values of the BSC en route Moscow–Nizhny Novgorod–Moscow in the direct (a) and back (b) routes: 1 – Kalyazin; 2, 3, and 9 – Rybinsk lock; 4 and 10 – Yaroslavl; 5 and 11 – Ples; 6 – Nizhny Novgorod; 7 – Khvoinyi Bor; 8 – Tver; 12 – Kineshma; 13– smoke plume of ship; and, 14 – oil filling moorage (Rybinsk).

Since all measurements during the expedition were performed under comparable weather conditions within a relatively short time interval, it is believed that the high level of the backscattered signal corresponds to the high aerosol concentration in the atmosphere.[3] In our case this assumption is well supported by the coincidence of the level of the backscattered signal of $3.5\cdot 10^{-6}$ m$^{-1}\cdot$sr^{-1} in the atmosphere over town Ples when the ship was en forward (30.06.93) and back (03.07.93) route. The coincidence of the results and small value of the BSC are indicative of a high transmission stability of the atmospheric parameters,[2,3] that is most likely conditioned by the absence of industrial objects and other sources of the local atmospheric pollution in Ples. This fact, from the standpoint of the results obtained, allows us to consider the value of the BSC in Ples as a reference one to be used for a comparative analysis of the level of the atmospheric aerosol pollution in other cities.

Thus, it can be seen from Figs. 2*a* and *b*, that the atmosphere over all industrial centers along the route of the ship was characterized by a high aerosol content as compared with that above Ples. The peak value of the aerosol pollution was recorded in the evening on 02.07.93 in the region of the passenger port during the mooring in Nizhny Novgorod and on the traverse of the filling port in Rybinsk (see Figs. 3*a* and *b*).

The measurements of the small–scale variations of the BSC within the urban zones of Nizhny Novgorod and Rybinsk (see Figs. 3*a* and *b*) show the correlation of the return signal from the atmosphere with the location of industrial objects on the windward side bank. Such a correlation also occurred at moving away from Nizhny Novgorod (see light circles with a cross in Fig. 3*a*). In many cases individual bursts of the backscattered signal relative to its average value were not accompanied by simultaneous observation of the visual inhomogeneities in the atmosphere. Thus, the increase of a backscattered signal by more than five times relative to the background one near the oil filling moorage at the entry to Rybinsk (see Fig. 3*b*) was accompanied by the smell of hydrocarbons in the absence of any visible changes of optical characteristics of the atmosphere along the sounding path. Fluctuations of the backscattered signal in coming up to Nizhny Novgorod (see Fig. 2*a*) were not accompanied either by any visual signs of the plumes from the bank through the Volga which would be intersected by the sounding path.

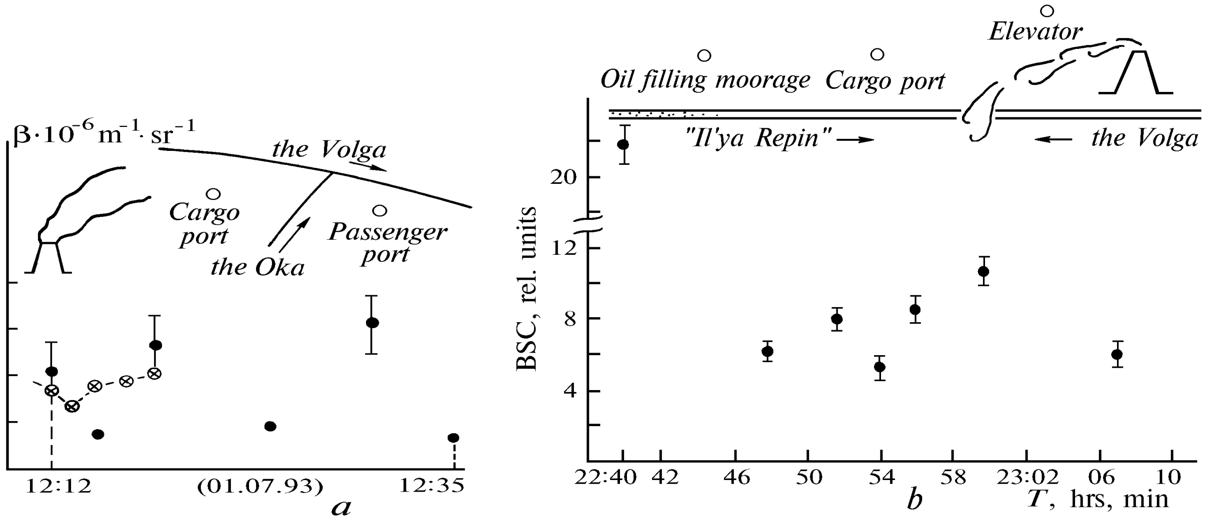

Fig. 3. Values of the BSC at some sectors of the Volga fairway; (a) – when going in (•) and out (⊗) the port of Nizhny Novgorod and (b) – when crossing Rybinsk.

It should be noted also that the correlation between backscattered signal and variations of meteorological conditions exists. Thus, near Kalyazin, on 29.06.93, a weak rain occurred between two measurements made in a 20–minute interval. After processing the results of sounding the decrease of the backscattered signal by a factor of nine was discovered, that clearly illustrates and supports the earlier observed[5,6] effect of washing out of aerosol particles from the atmosphere by rain.[3] Maybe, such small rains en back route just washed out the aerosol pollution from the atmosphere reducing thus the backscattered signal on the whole (see Fig. 2*b*).

Thus, the results presented in the paper show the possibility of recording the relative level of the aerosol pollution of the atmosphere over industrial centers with the use of portable backscattering lidar with the eye–safe level of radiation.

SOUNDING OF THE ATMOSPHERIC EMISSIONS FROM LOCAL SOURCES

The presence of the continuously operating power diesel machine of the ship 'Il'ya Repin" emitting exhaust gases enables us to make the test of sensitivity and the lidar ability of detecting invisible atmospheric inhomogeneities above the stack mouth of a ship at any time during the expedition. At the mooring we succeeded in making similar observations by sounding the emissions above the stacks of other ships. In doing so, we recorded the changes of the lidar signal depending on the engine power and the rate of the engine revolutions.

A profile of the backscattered signal from the stack emission of the ship "Il'ya Repin" is depicted in Fig. 4*a*. To increase the statistical significance of the measurements 256 000 laser shots were used in this case. Two maxima are distinctly seen on the histogram of distribution of count number *vs* distance. The first is conditioned by light scattering in the homogeneous atmosphere near the lidar, the second one is caused by the scattering in the plume above the ship stack mouth. In Fig. 4*b* the profile of the backscattering coefficient in this plume is presented, calculated with the help of data, which have been obtained, taking the lidar calibration into account.[7] A small value of the BSC in the plume, comparable with the general level of the atmospheric pollution in Zaporozhie,[3] corresponds to the extinction coefficient less then 0.5 km^{-1} (Ref. 3). It follows from this fact that this plume absorbs the lidar radiation weakly and therefore it can be more easily detected not because of the blackening of the atmosphere, but because of the optical inhomogeneities of the hot gases above the stack, the temperature gradient from which contributes, probably, into the backscattered signal. It follows from the half–width of the BSC peak in Fig. 4*a*, which does not exceed essentially the 100 ns width of the laser pulse, that the thickness of the plume along the sounding path is much less than 15 m.

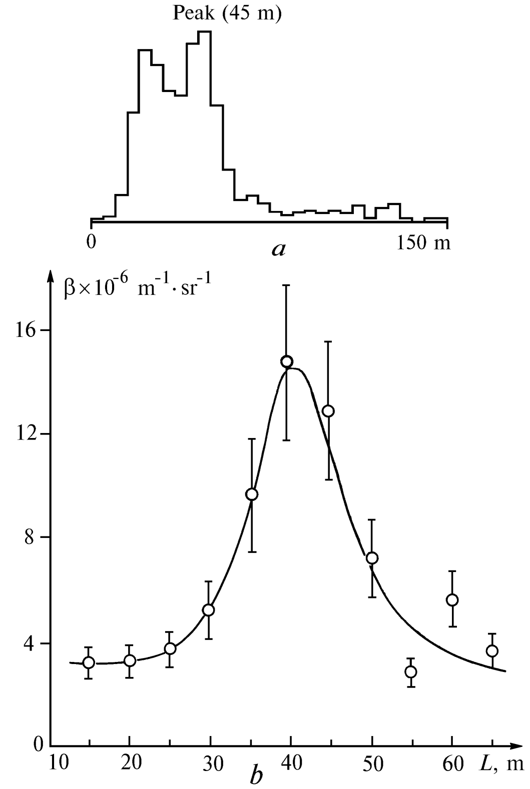

FIG. 4.. Results of sounding the emission above a stack mouth of the power engine of the ship "Il'ya Repin": a – typical shape of the signal histogram of photocounts and b – profile of the BSC along the sounding path.

One more example of sounding the emission from a stack at a longer distance from the lidar is shown in Fig. 1. The presence of two maxima in the backscattered signal (see Fig. 1) received from the plume near the stack mouth during 26 s measurement time may be conditioned both by a nonstationarity of the smoke plume and by a layered plume structure. To calculate the physical values in such cases, the *a priory* information is needed about the object sounded.[3] In the case of its absence, only the estimate of the low limit of the backscattering coefficient and the value of the mass concentration of aerosol emission from the elevator stack with relations from Ref. 3 is possible. Thus, in the case discussed above the mass concentration of aerosol emission is not less than 69 mg/m^3 (Ref. 3) without taking into account light absorption along the sounding path, which can be estimated using the value of the first peak in Fig. 1. It is evident, that such a capability of a lidar is of special importance when sounding remote objects through turbid and absorbing atmosphere.

Note, that we succeeded in recording simultaneously the transverse dimension of the region of falling down of the most heavy fraction of the plume crossed by the ship at entry to Rybinsk. The dimension of this region, as estimated from changes of the amplitude of the first signal in the series of measurements during 10 min is not less than 3 km. Thus, the given stack as a local source pollutes not only the atmosphere, but also the soil, the water in the river, and the living quarters within the radius of 300 m and more, if the wind direction is changed.

CONCLUSION

The results of the remote sounding of the atmosphere presented in the paper demonstrate the potentialities of applying a compact backscattering lidar to detection and analysis of the aerosol pollution of the atmosphere at distances of some hundred meters.

The lowest possible level of the sounding radiation makes it advantageous for monitoring the habitat which is most sensitive to the impact of laser radiation. Therefore, it seems to be prospective to use a compact lidar described in the paper for atmospheric sounding in inhabited areas without a risk to damage to the environment. The results obtained open new opportunities for developing a new class of lidars with the eye–safe level of radiation and with necessary metrological certification.[3]

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