GROUND–BASED AND AIRBORNE LASER SOUNDING OF PLUMES FROM A POWER STATION

I.E. Penner and V.S. Shamanaev

Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences
Received November 1, 1993

In this paper we present some results of airborne lidar sounding of a plume from the Gusinoozersk State Regional Power Station. Then this lidar was removed from the aircraft and used for ground–based sounding. It was shown in these experiments that under stable weather conditions the plume is, at least, ten kilometers long. A power of lidar return signals from dry smoke aerosol near the stack mouth, as well as fluctuation and polarization characteristics of these signals are strongly affected by the performance of boilers at the power station. This circumstance allows us to use these characteristics of lidar returns for routine ecological monitoring.

The capabilities of laser sounding of industrial aerosol emissions can be extended by means of application of both airborne and ground–based lidars.

In this case one can perform the real–time "police" observations of the pollution sources, longer–term averaged observations of ecological nature, and purely scientific atmospheric physics investigations. The OPTIK–É aircraft–laboratory[1] provides a good basis for such investigations. One copy of the MAKREL'–2 lidar[2] has been placed onboard the aircraft. It is used for airborne laser sounding of the atmosphere. The second copy of lidar of the same kind or lighter–weight, for example, the M2M lidar[3] has been placed in cargo compartment of the aircraft. During the experiment, it is carried by air to any required station of ground–based measurements in a few hours.

We accepted such an experimental arrangement in sounding of aerosol emissions from the Gusinoozersk State Regional Power Station (Buryat). Ground–based measurements were performed few days later than airborne measurements.

A recording system based on the Elektronika–60 computer and a 7–bit analog–digital converter with a data sampling interval of 10 ns was employed in both lidars.

When sounding the atmosphere in the nadir direction, the scattering coefficients were reconstructed by the Klett method,[4] in which an *a priori* known value of the scattering coefficient is assumed at the far end of the path

$$\sigma(H) = \frac{\exp\left[F(H)\,H^{2} - F(H_m)\,H_m^{2}\right]}{\dfrac{1}{\sigma_m} + 2\displaystyle\int\limits_{H}^{H_m} \exp\left[F(x)\,x^{2} - F(H_m)\,H_m^{2}\right] dx}, \qquad (1)$$

where H is the current distance from the lidar, F is the power of the received signal, H_m is the distance from the reference point at the far end of the path, where the value of the scattering coefficient σ_m is *a priori* known. The value of σ_m was determined here from ground–based measurements of the meteorological visibility range S_m near the State Regional Power Station by the well–known formula $\sigma_m = 3.9/S_m$.

When processing the data of sounding of the weakly turbid atmosphere in upward direction, the iteration algorithm[5] was implemented. The first iteration was a well–known formula that is well applicable in the considered case of small sounding distance

$$\sigma(H) = \left(F(H)\,H^{2}/F(H_0)\,H_0^{2}\right)\sigma(H_0)\,, \qquad (2)$$

where $\sigma(H_0)$ is the reference value of the scattering coefficient but, unlike the previous case, at the beginning of the sounding path. It was also estimated from the horizontal meteorological visibility range in the atmosphere above the ground.

The Gusinoozersk State Regional Power Station is situated in isolation, to the south–east of Baikal Lake, and has two smoke stacks. The first stack built earlier is 180 m high. It is loaded by boilers with high degree of service wear and outdated purifying system. This stack emits most aerosol particles into the atmosphere. The second stack is 300 m high and has highly efficient purifying system. Local coal is the principal type of fuel. Fuel oil burners are used for the stabilization of the combustion regime in contingencies. Moistening is used for purification of aerosol and gaseous emissions.

During ground–based experiment, the operating conditions of the State Regional Power Station varied within wide limits due to reasons independent of its staff. The portion of fuel oil in the fuel balance varied strongly. Moistening was controlled down to its switching off.

During airborne sounding the wether conditions were stable, and the operating conditions of the Power Station were standard. The aircraft was handled visually along the plume axis at an altitude of 800 m above the State Regional Power Station.

The two–dimensional profile of the scattering coefficient in the plume is shown in Fig. 1. It is constructed from 160 laser shots in 50 s. Sounding was started at a distance of 280 m from the first stack mouth. It is seen that after the passage of approximately 1 km, smoke wisp rose to 500–600 m and spread further with the wind. After the passage of 6 km the aircraft was far from the plume due to mountainous local topography. But the smoke plume was still observed both visually and from lidar readings.

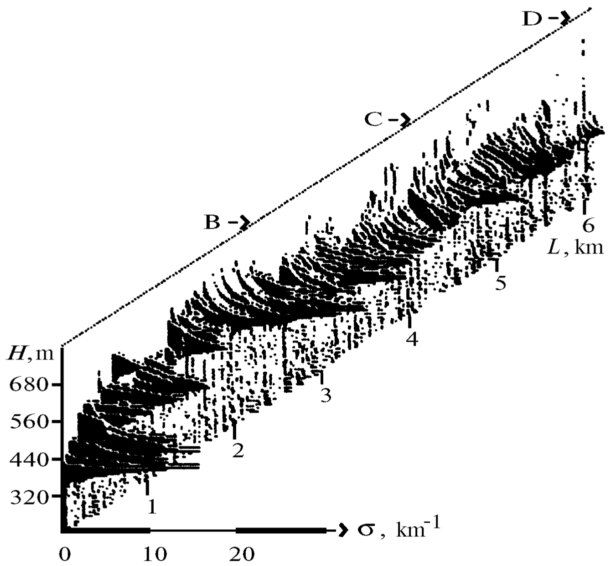

FIG. 1. Spatial profile of the scattering coefficient σ *along the axis of smoke plume from the State Regional Power Station. Here H is the barometre altitude above the ground, and L is the distance from the smoke source along the plume. The flight height is* 800 m.

The lidar profiles corresponding to the points B and C of the plume, are shown in Fig. 2. The cross section D corresponds to the "clear" atmosphere outside of the plume. It shows that the atmosphere was not stratified in vertical direction, judging from the scattering coefficient. It is not known wether or not a temperature inversion existed. At the same time, the fact that the altitude of the plume axis practically remained unchanged makes us to speculate the presence of a barrier layer.

It is seen from the figures that the plume existed as an integral formation at a distance of approximately 6 km. Optical thickness of the plume τ_p was integrated over the region in which the scattering coefficient was greater than in the ambient atmosphere. It was $\tau_p = 0.4\pm0.25$ along the examined line. Vertical geometrical thickness of the plume was 100±80 m. We note that the spatial distribution of τ_p along the plume exhibited oscillations ("puffs of smoke"). We have succeeded in identifying the fastly varying component with a period of 290±110 m and the slowly varying component with a period of about 2.5 km, for local maxima of τ_p at this section of the flight route 6 km long. On the whole, the vertical optical thickness of the plume decreases at a rate of about 0.04 km^{-1} along the plume. If we take the double excess of the optical density over that of the ambient atmosphere as a criterion for identification of a plume, the extrapolation beyond the investigated 6–km section of the route will give the total length of the plume 11–13 km. (It is interesting that wispy character of the smoke aerosols was observed, according to our airborne data, at a distance of approximately 30 km from the smoke source.[6]) Such a pattern of aerosol spreading suggests that the track from sedimentating particles has a shape of sufficiently narrow band.

An analysis of the airborne lidar data allowed us to estimate the large–scale parameters of the plume, while sounding of its initial part for a long time made it possible to judge the operational conditions of boilers. (Smoke wisp was recorded by TV camera.)

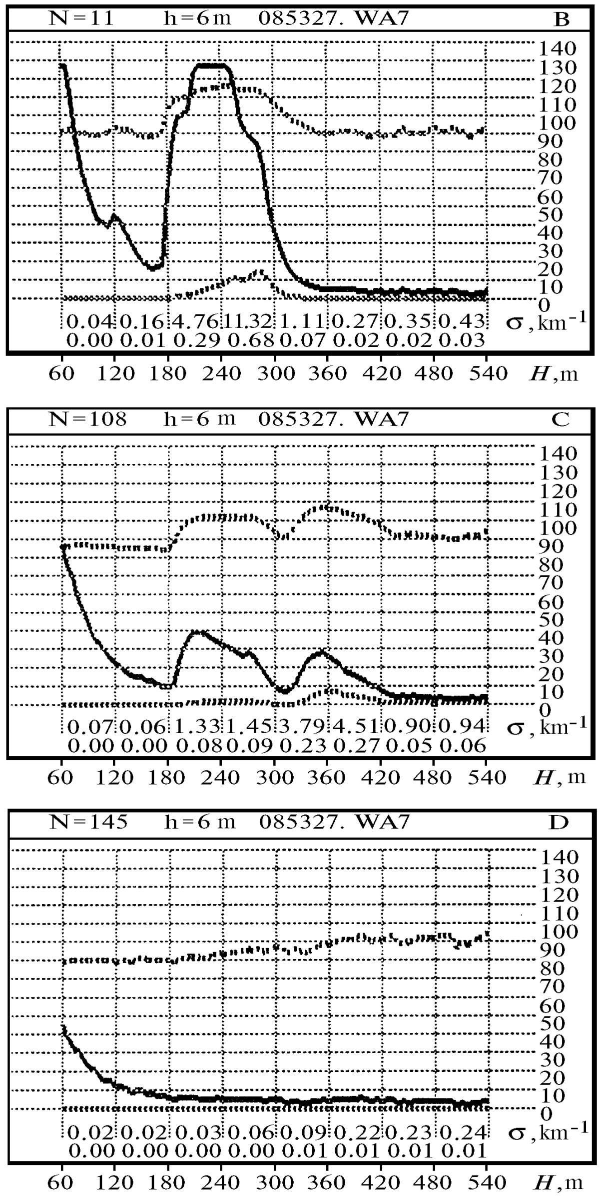

FIG. 2. Local cross–section through the plume for the points B and C marked by arrows in Fig. 1. The point D is outside the plume and is used for comparison. Solid curve is for the signal F(H); the scale in units of the analog–digital converter code is shown to its right. The lower dashed curve is for the profile σ(*H*)*, its absolute values averaged over* 60 m *intervals along the beam are shown at the bottom. The upper dashed curve is for the profile F*(*H*) *H* ^{2} *in relative units.*

We note one peculiarity of sounding of smokes near the stack mouth. This is the high optical density of the emissions from the first stack. In this case the contribution of multiple scattering is so great that it becomes impossible to retrieve the profile of the scattering coefficient in smoke. So we decided to analyze only the amplitude of the lidar return signal from smoke in relative units of the analog–digital converter code at depths of 6 and 24 m from its physical boundary. The depolarization ratio of the return signal was also measured at the same points as a ratio of its cross–polarized component to polarized one.

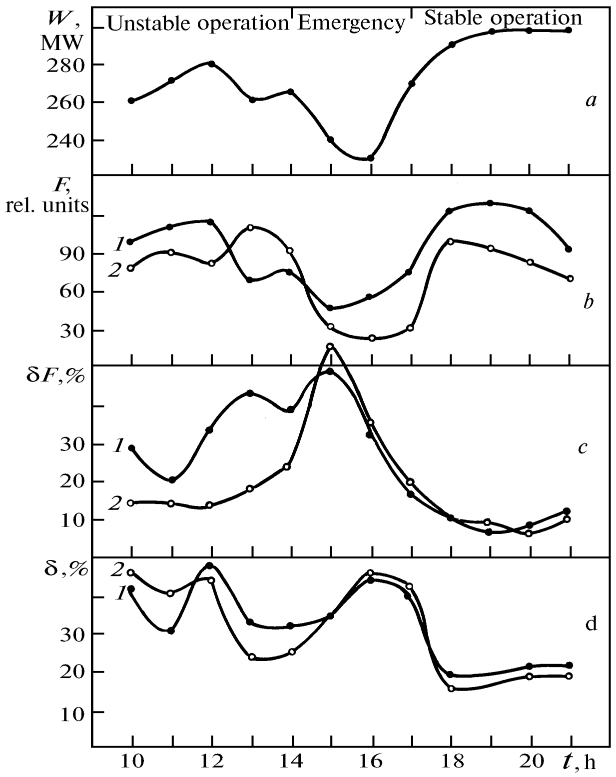

FIG. 3. Correlation between the parameters of the lidar signal and the operating conditions of the first part of the State Regional Power Station: a) output power of the electric generators W, in MW*; b) power of the lidar return signal F in the code units of analog–digital converter; c) standard deviation δF of the lidar signal power; d) depolarization ratio of laser signal. Curves 1 and 2 are for measurements at depths of* 6 *and* 24 m *from the physical boundary of the plume and t is local time, in hours.*

Figure 3 shows the result of monitoring of the smoke from this "bad" stack for 12 h. The data at each measurement point were derived from a 180–shot average. The total electric power produced by generators as well as brief description of operation of the whole power block are shown in Fig. 3 *a*. It is seen from Fig. 3 *b* that the power of the return signal from the smoke satisfactorily correlates with the electric power produced by the State Regional Power Station. The correlation coefficient is equal to 0.78 on the outside of the smoke and 0.51 on the inside. The nature of this correlation is obvious: the electric power produced by the Station is proportional to the amount of burnt fuel, i.e., the mass concentration of the emitted aerosol and its scattering coefficient. Different values of the correlation coefficients are most likely dependent on a combination of reasons, namely, variable ratio of coal and fuel oil in the fuel, different degree of moistening of the smoke gases, and finally, contribution of multiple light scattering.

Nevertheless, it is seen that even from so simple lidar measurements one can remotely monitor principal changes in the operating conditions of the Power Station by deviation of the signal power from its average (rated) values. Moreover, the signal parameters shown in Figs. 3 *c* and *d* testify the feasibility of monitoring of the boiler performance. Indeed, the low fluctuations in the return signal power at both depths with a standard deviation of about 10% correspond to stable operating conditions of boilers from 18 h, LT. Fluctuations in the return signal from smoke in the central part of wisp exceed 50% over the period of maximum instability in boiler operation (between 14 and 17 h, LT). There is reason to think that turbulent processes in the emitted aerosol–gas mixture are influenced by the regimes of combustion of the coal dust and fuel oil in the boiler fuel sprays. The constructed histograms of the relative frequency of occurrence of the specific values of the reflected power show that they obey the normal law though with different variance, as seen from the curves.

Another useful signal characteristic is the depolarization ratio δ that saturates at a level of 20% after 18 h, LT. In the preceding period the parameter δ reaches 30–50%, varies with time, and did not correlate with the macroparameters of the boilers. The error in measuring the parameter δ did not exceed 10–15%. Qualitative aspect of this phenomenon can be explained easy: variations in the regimes of combustion result in variable size and shape of smoke particles. In its turn, the depolarization ratio of the scattered radiation depends on them, though in a complicated way.

The empirical approach is suitable for ecological monitoring, namely, after measuring the parameter δ in the period of stable operation of the State Regional Power Station, we may judge further performance of the boilers by its deviations.

Sounding of the smoke from the "good" stack of the second modern part of the State Regional Power Station by means of the same lidar was carried out for comparison. The slant distance to the point of beam entering the smoke column was 630 m, that is, 30 m above the stack mouth 300 m in height. The stability of the situation for this stack is illustrated by Fig. 4 where the data obtained in few hours are shown. Since the smoke was light (practically it was invisible), we have succeeded in retrieving the profile of the scattering coefficient in the smoke for the slant section of the column. Optical thicknesses in these cases were 0.08 and 0.06.

The behavior of the profiles of depolarization ratio was typical of the particles of irregular shape and small concentration. The value of δ was constant along the plume cross section and high, its absolute value was 40–45% with calculational error 10–15%.

It is important to note the interesting physical point. Higher value of depolarization ratio is characteristic of the purified smoke particles in comparison with the particles from the first stack, subject to obviously unsatisfactory filtration, i.e., having much greater size.

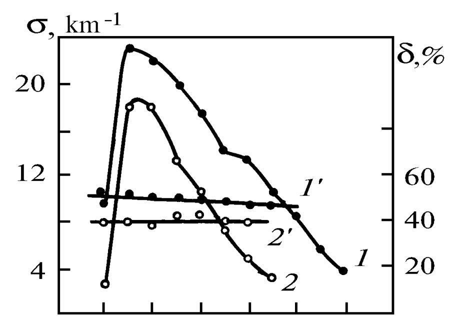

FIG. 4. Slant sectional view of the smoke plume above the stack of the second part of the State Regional Power Station. Curves 1 and 2 are for the profiles of the scattering coefficient σ measured in few hours; curves 1' and 2' are for the corresponding profiles of the depolarization ratio.

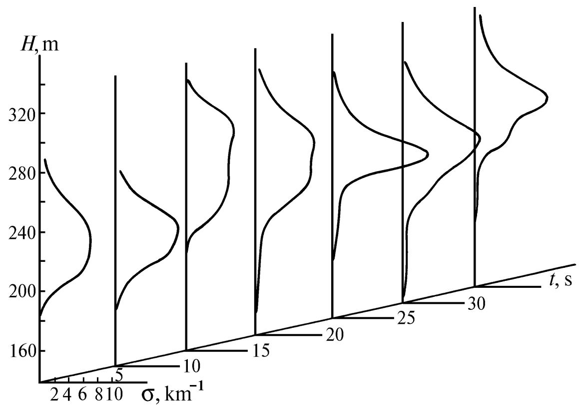

FIG. 5. Cross section through a wisp of smoke plume at a distance of 230 m *from the stack. Here H is the altitude above the ground and t is the current time from the start of sounding.*

Measurements were also carried out when the lidar sounded the atmosphere vertically upward at a distance of 230 m from the first stack and 575 m from the second stack. Both stacks were in range of vision of the lidar, but undoubtedly, the first stack provided most emissions. The return signals were processed by formula (2). Stable wind favoured that sufficiently diffuse plume passed just above the measurement point. A family of the obtained vertical profiles of the scattering coefficient is shown in Fig. 5. Every profile was derived from a five–shot average. Here t is the current time. Over a 30 s period of measurements the maximum of the scattering coefficient in the plume was 8.8 ± 2.3 km^{-1} and its vertical thickness was 63±11 m. The lower boundary was at an altitude of 200±15 m.

We note that the layer with the clearest air in which $\sigma = 0.2$ km^{-1} was observed at an altitude of 120 m. The near–ground value of the scattering coefficient along the plume track in horizontal direction was $\sigma = 0.4$ km^{-1} while in perpendicular direction in "undisturbed" atmosphere it was $\sigma = 0.2$ km^{-1}. This is indicative of sedimentation, but its peculiarities themselves pose a number of questions. One of them is the aforementioned minimum of the scattering coefficient, since there must be no minimum under conditions of continuous sedimentation. The second question is the altitude behavior of depolarization ratio that increases from the near–ground value $\sigma = 0.12\pm0.05$ up to $\sigma = 0.45\pm0.08$ at an altitude of 80 m with 4.25 km^{-1} gradient. Then it sharply decreases and is equal to 0.05 in the plume depth. This value is less than in the ambient atmosphere and is indicative of moistening of the smoke particles. The lower 200 m layer of the atmosphere is of special interest. Here stratification of the scattering coefficient is determined by the dynamic microstructure of aerosols in a complex way (unfortunately, the microstructure was not measured) as well as by depolarizability of aerosols.

Thus consideration of the aforementioned data allows us the following conclusions:

The use of a lidar carried by air is quite reasonable, useful, and feasible for simultaneous airborne and ground–based measurements of aerosol pollution.

One can judge the performance of the boilers from the data on the power, fluctuations, and polarization ratio of the lidar signals from the smokes obtained near the mouth of a stack of the State Regional Power Station.

Smoke plume may spread as an integral formation at distances no less than 10 km under conditions of stable wind regime.

REFERENCES

1. V.E. Zuev, B.D. Belan, D.M. Kabanov, et al., Atmos. Oceanic Opt. **5**, No. 10, 658–663 (1992).

2. A.I. Abramochkin, V.V. Zanin, I.Ė. Penner, et al., Opt. Atmos. **1**, No. 2, 92–96 (1988).

3. A.I. Abramochkin, I.Ė. Penner, and V.S. Shamanaev, Atm. Opt. **4**, No. 3, 264–265 (1991).

4. J.D. Klett, Appl. Opt. **24**, No. 11, 1638–1643 (1985).

5. V.V. Veretennikov, I.Ė. Naats, I.V. Samokhvalov, and V.S. Shamanaev, in: *Laser Sounding of the Atmosphere* (Nauka, Moscow, 1976), pp. 98–103.

6. B.D. Belan, V.V. Burkov, M.V. Panchenko, et al., Atmos. Oceanic. Opt. **5**, No. 2, 121–125 (1992).