OPTOACOUSTIC SOUNDING OF THE NUMBER DENSITY OF COARSE ATMOSPHERIC AEROSOL PARTICLES

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Received July 15, 1996

Results of optoacoustic sounding of the number density of micron-sized atmospheric aerosol particles are presented. Their comparison with the microphysical model of the aerosol atmosphere for Western Siberia demonstrates satisfactory agreement. The calculated relative error in measuring the number density of aerosol particles by the proposed method varies from 1.1 *to* 23.1%.

Experiments systematized in Ref. 1 demonstrated that the aerosol particles with radii larger than the critical one, a_{cr}, initiate local spherical plasma formations upon exposure to high-power laser radiation when the energy density of acting radiation Q was greater than 6 J/cm^2, where

$$a_{cr} \simeq (\hat{A}/I)^{1/k}, \qquad (1)$$

$\hat{A} = 2.9{\cdot}10^9$ W/(cm·μm$^{1.5}$), and k = 1–2. This means that in the investigated wavelength range 1–10 μm, the critical radius is inversely proportional to the intensity I of acting laser radiation and depends slightly on materials and shapes of aerosol particles. Each localized plasma inhomogeneity radiates a single spherical acoustic pulse, whose shape reproduces an N-wave and the total acoustic signal of a long laser spark represents the linear superposition of pulses from separate plasma formations[2] (PFs).

Therefore, the number of pulses in the acoustic signal radiated by the laser spark bears information on the number density of aerosol particles with radii larger than the critical value. The method of optoacoustic sounding of the number density of coarse atmospheric aerosol particles[3] is based on this effect.

The block diagram of an optoacoustic laser radar harnessing this method is shown in Fig. 1. Radiation of the high-power CO_2 laser *1* was focused into the atmosphere at distances 50–500 m using the Cassegrain telescope *2–5*. The focal distance was varied by the displacement of the hyperbolic mirror *4* along the optical axis. The acting laser radiation energy density in the laser beam caustic varied from 6 to 20 J/cm^2 resulting in the origin of local spherical plasma formations near the laser beam caustic initiated by the aerosol particles of micron size. The acoustic pulse of the laser spark was received by the omnidirectional microphone *6* and the acoustic pressure was recorded by the precision impulse sound level meter *7* in the frequency range 20 Hz – 20 kHz. The signal from the amplifying output of the sound level meter was applied to the ACP–10 analog-to-digital converter (ADC) *10* and digitized with a sampling frequency of 100 kHz.

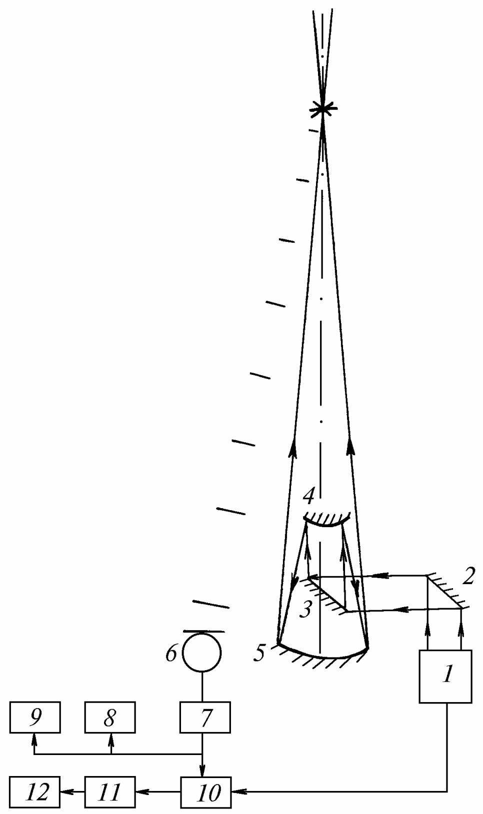


FIG. 1. Block diagram of the optoacoustic laser radar: 1) high-power pulsed CO_2 laser (λ = 10.6 μm, τ_l = 0.3 μs, *and* E_{max} = 300 J); *2–5) focusing system of the Cassegrain telescope type with the large parabolic mirror 5* 50 cm *in diameter and the small hyperbolic mirror 4* 12 cm *in diameter; 6) half-inch MK–221 omnidirectional microphone with the MV–201 preamplifier; 7) PSI 00017 precision impulse sound level meter; 8) S8–17 storage oscilloscope; 9) Olimp tape-recorder; 10) ACP–10 analog-to-digital converter; 11) K–16 CRATE controller; 12) Elektronika MS–0215 microcomputer with DZM–180 digital printer and XY plotter.*

0235-6880/97/01 65-06 $02.00

The ADC was triggered by the laser *1* which provided a synchronizing pulse for the ADC external trigger input. The reference trigger pulse was generated by the G5–54 generator. After filling of the on-line 64 kbyte memory built into the ADC, further ADC acting was blocked to preserve the information. This block of data was then transmitted into the microcomputer *12* through the K–16 CRATE controller *11* which linked the CAMAC bus with the microcomputer. The data were processed in the microcomputer by special algorithms. This data processing cycle was performed after each single laser shot. After data transmission, the ADC was ready to record a new block of data. Simultaneously, the signal from the sound level meter was fed into the oscilloscope *8* for visual monitoring and recorded by the tape-recorder *9*.

For narrow laser beams with diameters smaller than the average distance between the aerosol particles initiating plasma formations, the number density of coarse aerosol particles, numerically equal to that of plasma formations, was calculated from the formula

$$N = (N_l)^3 = (K/L_{sp})^3, \quad (2)$$

where N_l is the number of plasma formations per unit of length, L_{sp} is the laser spark length, and K is the number of PFs calculated using microcomputer data processing as the number of positive pulses with the amplitudes above the threshold level $U_{th} = 2U_N$. Here, U_N is the rms noise level measured without laser radiation.

For wide laser beams, the breakdown region can be approximated by a cylinder and

$$N = \frac{K}{p\, L_{sp}\, a_c^2}, \quad (3)$$

where a_c is the beam radius in the caustic. The laser spark length was calculated based on the geometry of the experiment.

For the optoacoustic laser radar shown in Fig. 1, the acoustic signal was received at the angle $\theta = 180°$ to the laser beam propagation direction and

$$L_{sp} = c\, \tau_{sp} = c\, (t_2 - t_1). \quad (4)$$

Here, c is the sound speed in air, τ_{sp} is the total duration of the acoustic signal from the laser spark equal to the time difference between the moments of arrival of acoustic pulses radiated by the farthest and nearest PFs, and $t = 0$ is the instant of laser radiation emission.

At $\theta = 90°$, when the microphone is placed under the laser beam caustic,

$$L_{sp} = 2\sqrt{c\, t_{sp}\, (2R + c\, t_{sp})}, \quad (5)$$

where $R = ct_1$ is the distance from the laser beam axis to the microphone.

The measurements were performed in the territory of the Institute of Atmospheric Optics of the SB RAS in the evenings and at nights. The measurement path between two buildings of the Institute was 5–7 m above the ground. The receiving microphone was placed under the beam caustic at different distances from the beam axis varying from several centimeters to several tens of centimeters. Figure 2 shows panoramic photographs of laser sparks made by focusing of a wide (Figs. 2*a* and *b*) or narrow (Fig. 2*c*) laser beam at a distance of 120 m. The number of PFs calculated from the photograph was 67 for the second realization and 14 for the third realization and coincided with the number of acoustic pulses calculated from the time history of acoustic signals shown in Fig. 3 for the second and third realizations.

It is seen that for the second realization t_1 = 1.2 ms, t_2 = 39.4 ms, τ_{sp} = 38.2 ms, and from Eq. (5) we derive L_{sp} = 26.1 m. Taking into account that $S = \pi a_c^2$ = 10 cm^2, from Eq. (3) we obtain N = 2567.1 m^{-3}. For the third realization, t_1 = 0.12 ms, τ_{sp} = 3.56 ms, and from Eq. (4) L_{sp} = 1.18 m. Then from Eq. (2) we obtain N = 1669.9 m^{-3}.

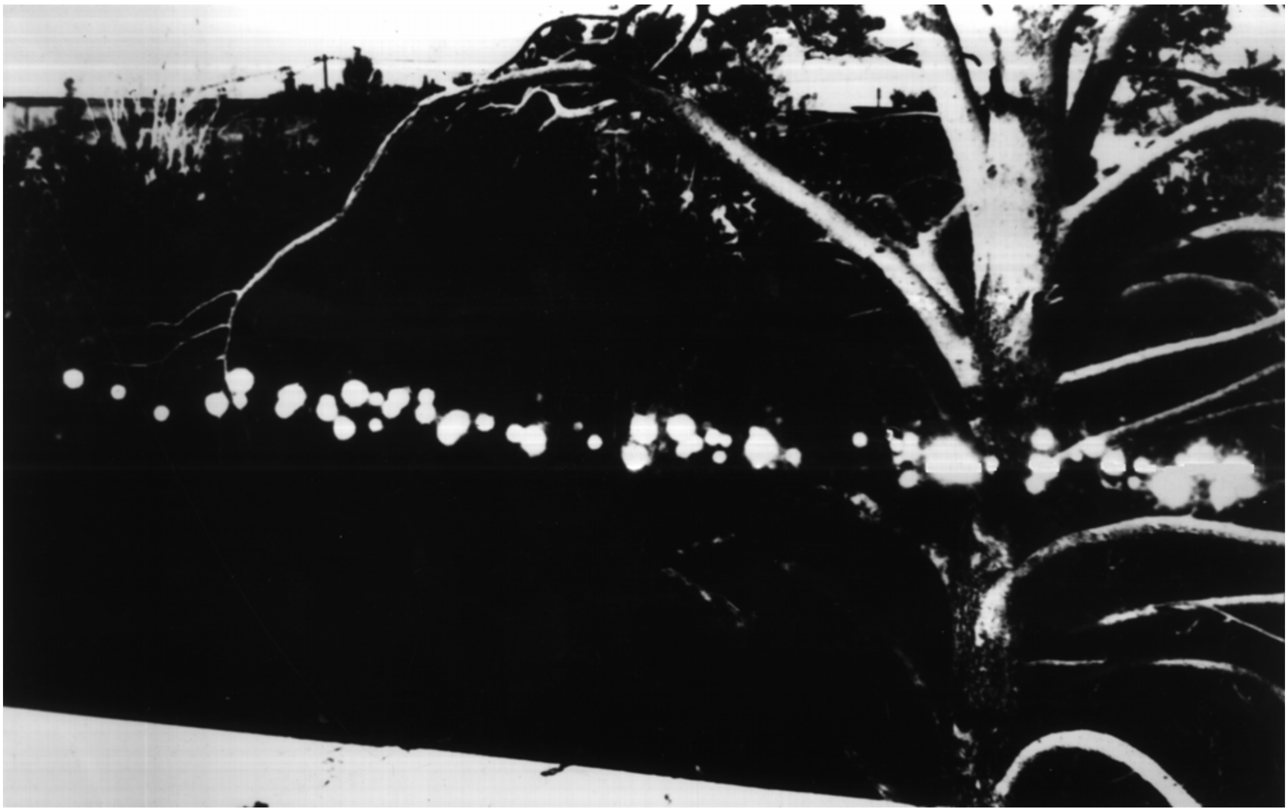
The second measurement run was carried out at the experimental atmospheric-optical station of the Institute of Atmospheric Optics of the SB RAS. The measurement path was 2–2.5 m above the homogeneous underlying surface. The high-power CO_2-laser radiation (λ = 10.6 μm, τ_l = 1 μs, E_{max} = 2 kJ) was focused into the atmosphere at a distance of 500 m. The receiving microphone was placed under the beam caustic at a distance of 0.5 m from the beam axis. Results of measurements are given in Table I.

TABLE I. Results of optoacoustic measurements of the number density of coarse atmospheric aerosol particles vs. the energy density of the acting laser radiation.

Q, J/cm^2	5.8	6.7	7.9	18.8
N, m^{-3}	474	3483	4251.5	4895

The increase of N with the energy density of the acting radiation is explained by the decrease of the critical radius of aerosol particles initiating plasma formations. Thus, according to Ref. 4, $2a_{cr}$ is larger than 10 μm for Q = 5.8 J/cm^2 and $2a_{cr}$ ~ 7.5 μm for Q = 18.8 J/cm^2. These data agree well with the microphysical model of the aerosol atmosphere for Western Siberia (see Ref. 5), for which the mean number density of aerosol particles with radii from 7 to 10 μm in the surface atmospheric layer is N_{mod} = 6000 m^{-3}. The relative deviation of our data $\delta N = [(N - N_{mod})/N_{mod}]\cdot 100\%$ is 18.4%.

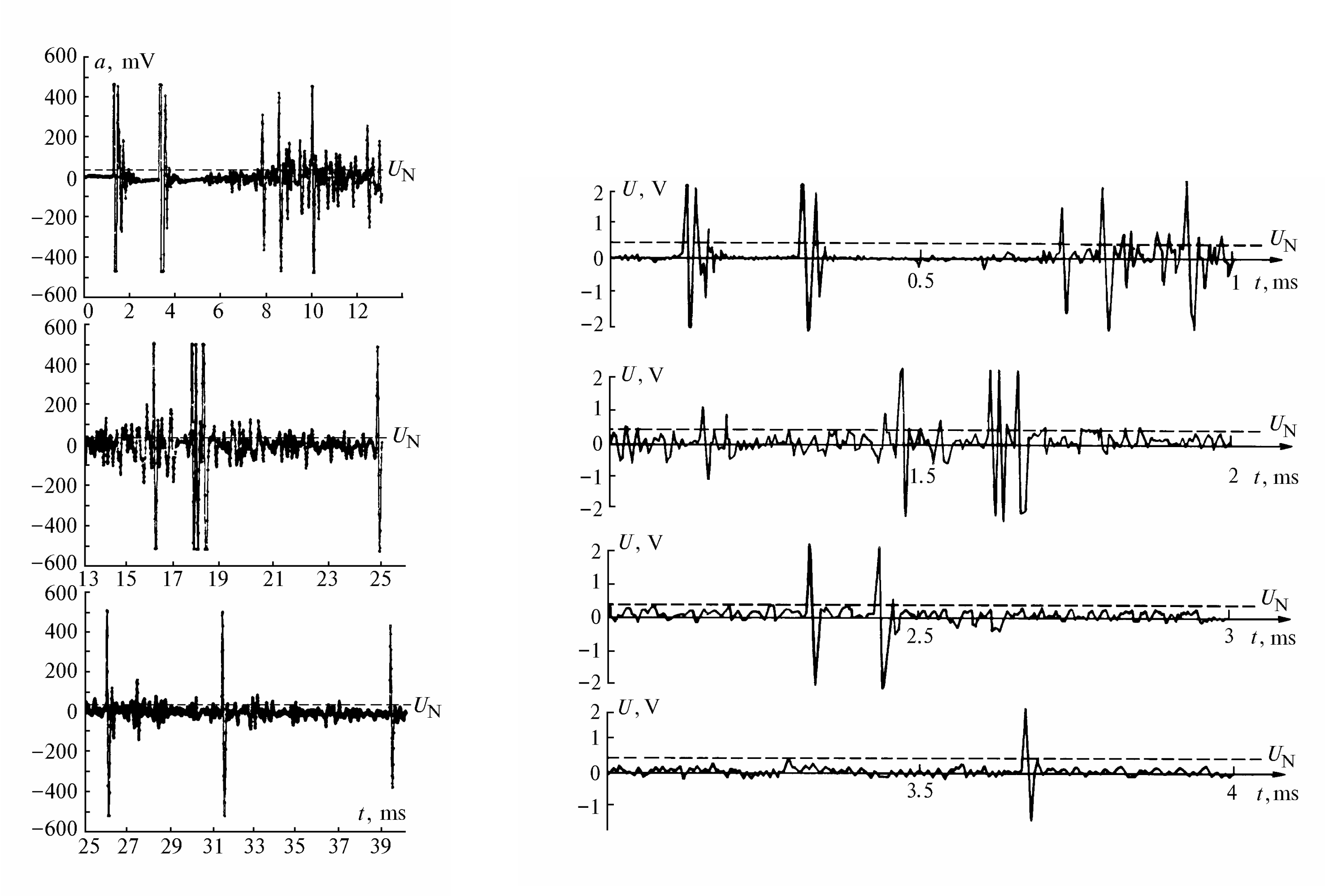
a



b

c

FIG. 2. Panoramic photographs of laser sparks made by focusing of laser radiation at the distance $F = 120$ m *into the atmosphere. The focal spot area was* $S = 10$ *(a, b) and* 3 cm^2 *(c). The laser energy density in the laser beam caustic was* $Q = 18$ *(a),* 8 *(b), and* 6 J/cm^2 *(c). The objective field-of-view angle of the Zenit camera was* 34.5°.



a *b*

FIG. 3. Time history of acoustic signals radiated by laser sparks shown in Figs. 2b and c. The ordinate is the electrical analog, in volts, of the acoustic pressure. The receiving microphone was placed at distances R = 0.004 (b) and 0.4 m (a) from the beam axis under the beam caustic. The time history shown in Fig. 4b is drawn by the XY plotter. The time history shown in Fig. 2a is computer graphics of digitized signal. The receiving microphone was placed in a special tent to reduce the noise level when recording the signal shown in Fig. 3a. For the conditions of our measurements, this noise was due to the wind.

The absolute error in measuring the number density of micron-sized aerosol particles by the proposed method can be estimated as

$$\Delta N = \sqrt{\left(\frac{\partial N}{\partial K}\Delta K\right)^2 + \left(\frac{\partial N}{\partial c}\Delta c\right)^2 + \left(\frac{\partial N}{\partial t_{sp}}\Delta t_{sp}\right)^2}, \quad (6)$$

where ΔK, Δc, and $\Delta\tau_{sp}$ are the absolute errors in measuring the number of acoustic pulses, sound speed, and duration of the acoustic signal from the spark.

From Eqs. (2) and (4), we obtain

$$\frac{\partial N}{\partial K}\Delta K = 3\left(\frac{K}{c\, t_{sp}}\right)^2 \frac{\Delta K}{c\, t_{sp}}, \quad \frac{\partial N}{\partial c}\Delta c = 3\left(\frac{K}{c\, t_{sp}}\right)^2 \frac{K\,\Delta c}{c^2\,\tau_{sp}},$$

$$\frac{\partial N}{\partial \tau_{sp}}\Delta\tau_{sp} = 3\left(\frac{K}{c\,\tau_{sp}}\right)^2 \frac{K\,\Delta\tau_{sp}}{c\,\tau_{sp}^2} \quad (7)$$

and the relative error in measuring the number density is

$$\delta N = \sqrt{\left(\frac{\Delta N}{N}\right)^2} = 3\sqrt{\delta^2 K + \delta^2 c + \delta^2 \tau_{sp}}, \quad (8)$$

where $\delta K = \Delta K/K$, $\delta c = \Delta c/c$, and $\delta\tau_{sp} = \Delta\tau_{sp}/\tau_{sp}$ are the relative errors in measuring the number of acoustic pulses, sound speed, and duration of the acoustic signal from the spark.

Let us analyze each term in Eq. (8). Let us assume that random distances between the aerosol particles initiating PFs obey the Poisson distribution. Then for the dimensionless parameters $L_0 = L/r$ and $n_0 = n/r$, where L is the average distance between PFs, r is the mean PF radius, and n is the distance between PFs in the specific realization of random process, we obtain

$$P(n_0) = \frac{L_0^{n_0}}{n_0!}\, e^{-L_0}. \quad (9)$$

Two PFs will be indistinguishable when $n_0 = 1$. In accordance with the microphysical model[5] of the aerosol atmosphere for Western Siberia, the average number density of micron-sized aerosol particles in the surface layer is $N_{av} = 1.069$ cm^{-3}. This yields $L = 0.97$ cm.

From the data of Ref. 6, $r = 0.1$–0.25 cm, from which it follows that $L_0 = 3.9$–9.7. By substituting these values in Eq. (9), we obtain

$$P(1) = \delta K = 0.0006 - 0.079. \quad (10)$$

The sound speed depends on the atmospheric air temperature as

$$c = 20.05\sqrt{T}, \quad (11)$$

where T is in K. Therefore it follows that

$$\Delta c = \frac{\partial c}{\partial T}\Delta T = \frac{20.05\,\Delta T}{2\sqrt{T}}, \quad (12)$$

where ΔT is the absolute error in measuring the temperature and

$$\delta c = \frac{1}{2}\delta T. \quad (13)$$

Assuming that $\Delta T = 1$ K, we obtain

$$\delta c = 0.0037. \quad (14)$$

Given that the data sampling frequency is 100 kHz, $\Delta\tau_{sp} = 10^{-5}$ s and for $\tau_{sp} = 4$–40 ms we obtain

$$\delta\tau_{sp} = 0.00025 - 0.0025. \quad (15)$$

By substituting the relative measurement errors from Eqs. (10), (14), and (15) into Eq. (8), we obtain

$$\delta N = 0.0112 - 0.2313, \quad (16)$$

that is, the total relative error in measuring the number density by the proposed method varies from 1.1 to 23.1%.

In conclusion, it should be noted that the proposed method for measuring the number density of micron-sized atmospheric aerosol particles can be used any time of the day. The maximum sounding range is 500 m and is limited by the maximum distance of making the laser spark. The estimates show that the acoustic signal from the laser spark can be recorded reliably even when the receiving microphone is at distances larger than 1 km under conditions of light wind. For strong wind, microphones should be placed in a special metal net cover or in a special tent to protect from wind.

Additional advantage of this method is the possibility of its simultaneous operation with the spectrochemical lidar[2] capable to detect the chemical composition of aerosol particles from the optical emission spectrum of the laser spark and to obtain qualitatively new information on the atmosphere with the minimum extra expense.

ACKNOWLEDGMENT

The author would like to acknowledge A.P. Godlevskii and Yu.D. Kopytin for experiments on making laser sparks and V.P. Muravskii for participation in the experiments.

REFERENCES

1. Yu.D. Kopytin, E.T. Protasevich, L.K. Chistyakova, and V.I. Shishkovskii, *Air Medium upon Exposure to the Laser and HF Radiation* (Nauka, Novosibirsk, 1992), 189 pp.
2. L.G. Shamanaeva, "*Development and investigation of potentialities of the remote methods for sounding of the atmospheric parameters based on the use of the optical and acoustic radiation*," Candidate's Dissertation in Physical and Mathematical Sciences, Tomsk State University, Tomsk (1983), 129 pp.
3. L.G. Shamanaeva, in: *Study of the Atmospheric Boundary Layer above* Land *and Ocean by the Acoustic Methods* (USSR Academy of Sciences Press, Moscow, 1990), Vol. 2, pp. 20–25.

4. Yu.V. Akhtyrchenko, N.N. Bochkarev, Yu.P. Vysotskii, et al., in: *Abstracts of Reports at the 8th All-Union Symposium on Laser and Acoustic Sensing of the Atmosphere*, Tomsk (1984), Vol. 2, pp. 114–118.
5. B.D. Belan, A.I. Grishin, G.G. Matvienko, and I.V. Samokhvalov, *Spatial Variability of theAtmospheric Aerosol Characteristics* (Nauka, Moscow, 1989), pp. 126–127.
6. Yu.D. Kopytin, Yu.M. Sorokin, A.M. Skripkin, et al., *Optical Breakdown in Aerosols* (Nauka, Novosibirsk, 1990), 69 pp.