ABOUT TWO SCALES OF SPATIAL CORRELATION OF LASER BEAM INTENSITY FLUCTUATIONS IN DISPERSED MEDIA

A.G. Borovoy, N.I. Vagin, N.A. Vostretsov, and A.F. Zhukov

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received August 1, 1997

Experimental data on laser beam propagation in a coarsely dispersed aerosol are analyzed. It is shown that there are optical thicknesses for which two scales of intensity fluctuations are observed. The first scale is the diffraction correlation radius, which decreases monotonically with the increase of the optical thickness. The second scale is the quasi-isotropic radius, which is much smaller than the diffraction one.

In case of laser beam propagation through a coarsely dispersed aerosol, significant multiple scattering is observed already for short paths. Experiments have shown that the intensity fluctuations of laser beams propagating in the coarsely dispersed aerosol have some specific features in comparation with the intensity fluctuations of laser beams propagating in randomly inhomogeneous media. So, for example, a new regime of fluctuation damping during laser beam propagation in snowfalls was established by Borovoi et al.[1] The model of light fluctuations in precipitation, based on the separation of the multiply scattered field into two components, namely, the component multiply diffracted by surfaces of particles and the reflected component, was proposed there.

In the interpretation of the intensity fluctuations it was found that every component has different correlation radii, i.e., there are two scales of spatial correlation of the intensity functions in coarsely dispersed media. The results of investigations of relative contributions of these fields to the intensity fluctuations are given in the present paper. With this aim, the following experiment was pursued. A model medium was sensed by a Gaussian beam of an LG–79 laser. A suspension of polystyrene particles in water was chosen as a medium. The length of a cell was 20 cm. Water in the cell was continuously mixed. Particle sizes varied from 100 μm to 1.2 mm.

We were interested in the spatial correlation function for the intensity of radiation coming from the cell. However, direct measurements of the correlation function face with two problems: high spatial resolution is required (the correlation radius of quasi-isotropic radiation intensity can be of the order of the wavelength), and separation of one function into two components. Therefore, we used the following experimental method. The observation plane was at a certain distance z from the cell, and the measurements were performed not only within the laser beam, but also when the observation points were displaced from the beam axis, i.e., when we dealt only with the quasi-isotropic radiation. The diffraction of random waves was observed. In this case, the transverse coherence function is inambiguously related with the coherence function of radiation in the plane $z = 0$ of interest for us[2]

$$\Gamma(\mathbf{r}, \mathbf{R}, z) = \left(\frac{k}{2\pi z}\right)^2 \int_{-\infty}^{+\infty} \Gamma_0(\mathbf{r}', \mathbf{R}') \times$$

$$\times \exp\left(-\frac{ik}{z} (\mathbf{r} - \mathbf{r}') (\mathbf{R} - \mathbf{R}')\right) \mathrm{d}\mathbf{r}' \, \mathrm{d}\mathbf{R}', \qquad (1)$$

$$\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1, \quad \mathbf{R} = (\mathbf{r}_1 + \mathbf{r}_2)/2 .$$

With the increase of z the coherence radius increases not only for the diffracted radiation, but also for the quasi-isotropic one. Thus, the following measurement procedure was chosen. A linear array of photodiodes was placed inside the beam at different distancies from the cell (65, 90, 115, and 146 cm). It allowed us to record the radiation intensity in 100 points (with a step of 50 μm) on the segment 5 mm in length perpendicular to the path. An individual measurement included recording of the profile of a Gaussian beam that had passed through the cell filled by water without particles. Then the particle suspension was prepared by continuous water mixing, and 200 realizations of random distribution of the radiation intensity in these points were recorded in the computer memory. In addition, the linear array of photodiodes was displaced in the transverse direction at a distance of 3 mm and the second data array was recorded. Preparing suspensions of different densities we obtained different optical thicknesses $1.7 < \tau < 10.8$ (the radiation was focused with an additional lense to measure it). In addition, the parameters of the Gaussian beam were specially determined. Here, the complex amplitude

0235-6880/98/04 269-03 $02.00

$$A = \exp\left(-\frac{r^2}{a_0^2} - \frac{ik}{2\,R_\mathrm{f}}\,r^2\right) \tag{2}$$

in the plane $z = 0$ had the following parameters:

$R_\mathrm{f} = 1570$ mm, $a_0 = 0.314$ mm.

Statistical data processing was used to estimate two spatial functions, namely, the average intensity profile of the transmitted radiation $I(R)$ and the correlation function for the intensity of quasi-isotropic radiation $K(r)$ (with transverse displacement of the linear array of photodiodes). An example of $I(R)$ for optical thickness $\tau = 7.6$ and $z = 115$ cm is shown in Fig. 1. The measurements of $K(r)$ with the linear array of photodiodes placed at the distance $z = 146$ cm from the cell are shown in Fig. 2 for two optical thicknesses $\tau = 2.2$ and 8.2.

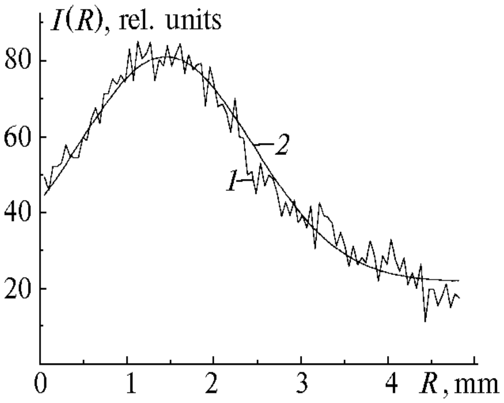

FIG. 1. Profile of the average radiation intensity with $z = 115$ cm *and* $\tau = 7.6$: *experiment (1), calculations by Eq. (7) with* $h = 0.36$, $R_a = 1.43$ mm *(2).*

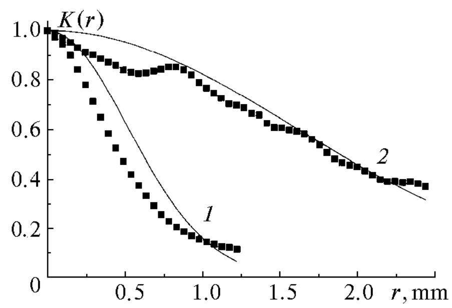

FIG. 2. Correlation functions for the intensity at $z = 146$ cm: $\tau = 2.2$ *(1) and* 8.2 *(2); squares are for the experiment.*

Let us analyze the dependences between the obtained functions and the optical thickness. First let us consider broadening of the Gaussian beam with the increase of τ and z. With this aim, let us use Eq. (1) and determine the coherence function in the plane $z = 0$. First we restrict ourselves by the coherence function of the diffracted radiation, because we consider $I(R)$ for angles characteristic of diffraction of the most unperturbed beam. Second, though it is possible to determine this coherence function as a function of particle sizes more adequately, we restrict ourselves by a simpler model function, namely, Gaussian one. It is clear that the first assumption imposes limitations on τ from above and the second assumption – from below. Thus, we take

$$\Gamma_0(\mathbf{r}', \mathbf{R}') = \exp\left(-\frac{2\mathbf{R}'^2}{a_0^2} - \frac{\mathbf{r}'^2}{r_\mathrm{ef}^2} - \frac{ik}{R_\mathrm{f}}\,\mathbf{R}'\,\mathbf{r}'\right), \tag{3}$$

where

$$\frac{1}{r_\mathrm{ef}^2} = \frac{1}{\rho^2} + \frac{1}{2a_0^2}, \tag{4}$$

ρ is the coherence radius of the diffracted beam in the plane $z = 0$. Then in accordance with Ref. 2, the average intensity at the distance z is

$$I(R, z) = \frac{1}{u^2}\exp\left(-\frac{2R^2}{a^2(z)}\right), \tag{5}$$

where

$$a(z) = a_0\,u, \quad u^2 = \left(\frac{z}{R_\mathrm{f}} + 1\right)^2 + \left(\frac{2\sqrt{2}\,z}{ka_0r_\mathrm{ef}}\right)^2. \tag{6}$$

Experimental profiles $I(R)$, as can be seen from Fig. 1, differ from that described by Eq. (5), namely, they can be represented as

$$I(R) = I_0\,[h + \exp(-R^2/R_g^2)]. \tag{7}$$

Here, h has a simple sense: it is the ratio of the ray intensity in the forward direction for quasi-isotropic radiation to the corresponding intensity of the diffracted beam. Thus, considering that the second term in Eq. (7) describes function (5), one can set the experimental beam width R_g equal to the diffracted one: $R_g = a(z)/\sqrt{2}$ and using Eqs. (4) and (6) calculate ρ.

Such calculations were done for the entire set of our data. The dependences of the coherence radius on the optical thickness are shown in Fig. 3 and of the parameter h – in Fig. 4. From Fig. 3 it can be seen that ρ decreases monotonically with the increase of τ. The smoothed solid curve shows the dependence

$$\rho = b/\tau, \tag{8}$$

where $b = 1.21$ mm.

From Fig. 4 one can see that the contribution of the quasi-isotropic radiation first increases and near $\tau = 10.0$ the rate of increase slows down. The joint effect of two factors, namely, the decrease of the coherence radius of the diffracted beam and the increase of the quasi-isotropic contribution, whose coherence radius is much smaller than the diffraction one, leads to damping of fluctuations. We emphasize that the optical thickness at which this occurs is $\tau = 4.0$ and probably depends insignificantly on the scatterer sizes, for example, in Ref. 1 $\tau = 5.0$ for the snowfalls.

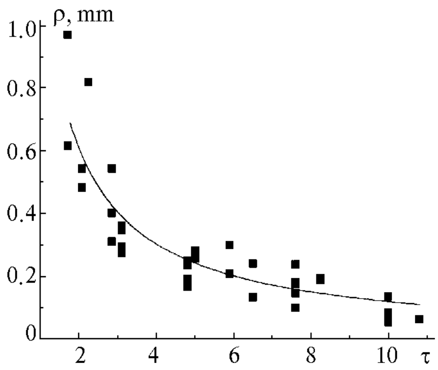

FIG. 3. Dependence between the coherence radius of the diffracted beam and the optical thickness (squares are for the experiment).

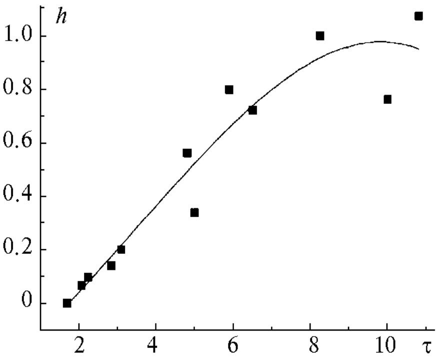

FIG. 4. Dependence between the ratio h and the optical thickness τ (squares are for the experiment).

Now we consider the correlation functions $K(r)$ measured in the scattered radiation. The correlation radius is defined as a parameter of Gaussian curve R_k (shown by the solid curve in Fig. 3)

$$K(r) = \exp\,(-r^2/R_k^2)\ . \tag{9}$$

The experimental data shown in Fig. 5 indicate the significant increase of the correlation radius with the increase of the optical thickness.

The data shown in Figs. 2 and 5 can be interpreted in the following way. The speckle structure observed experimentally is caused only by the refracted field. Together with that, regions of the scattering medium, which have sizes of the order of the coherence radius in the diffracted field act as efficient incoherent sources. By the van Zittert–Zernike theorem, such sources form the speckle pattern with the angular correlation radius $\theta \sim \lambda/\rho$.

In Fig. 5 the solid curve was calculated for this model with the coherence radius given by Eq. (8). Because the experimental and calculated data agree fairly well in Fig. 5, then, on one side, this supports the above-given interpretation of the speckle structure and on the other side, this gives a new method for measuring the coherence radius in the multiply diffracted field. Such method is efficient for large optical thicknesses of the medium, when the previous method based on broadening of the beam (see Fig. 1) becomes inefficient.

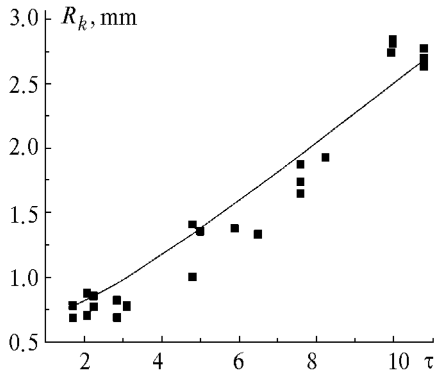

FIG. 5. Dependence between the correlation radius of the scattered beam and the optical thickness for z = 146 cm (squares are for the experiment).

As a whole, the following conclusions can be drawn based on the results of our experiment. There is the range of optical thicknesses, for which the intensity fluctuations of laser beams propagating in the coarsely dispersed aerosol have two spatial scales. The diffraction correlation radius, that decreases monotonically with the increase of τ, and the quasi-isotropic correlation radius, which is much smaller then the diffraction one, correspond to this range. Moreover, the quasi-isotropic field can be neglected for the transmitted radiation when $\tau < 3.0$, but its contribution to the fluctuations becomes noticeable already at $\tau = 4.0$. As to the question to which optical thicknesses there is a great difference between this two scales, the sizes of scatterers, the beam parameters, and the path length as well should be taken in to account.

ACKNOWLEDGMENT

This work was supported in part by the Russian Foundation for Basic Researches (Grant No. 96–02–16388a).

REFERENCES

1. A.G. Borovoi, N.A. Vostretsov, A.F. Zhukov, A.B. Kargin, and S.M. Prigarin, Atmos. Oceanic. Opt. **10**, No. 3, 141–145 (1997).
2. S.A. Akhmanov, Yu.E. D'yakov, and A.S. Chirkin, eds., *Introduction into Statistical Radio Physics and Optics* (Nauka, Moscow, 1981), 639 pp.
3. A.G. Borovoi, Izv. Vyssh. Uchebn Zaved., Ser. Radiofiz. **25**, No. 4, 301–400 (1982).