STUDY OF THE INFLUENCE OF BACKSCATTERING EFFECT IN A TURBULENT MEDIUM ON THE LASER BEAM IMAGE

V.A. Banakh, V.M. Sazanovich, R.S. Tsvik, and B.-N. Chen

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received August 15, 1996

The influence of the counter waves correlation on a quality of a point object image viewed through a random medium is studied experimentally. It is shown that in the case when illuminating and reflected waves pass through the same inhomogeneities of the medium the mean intensity distribution of the point object image has two characteristic scales. The larger scale is determined by the wave sphericity and blurring when passing through the turbulent layer. The smaller scale which is within the distribution center takes into account the correlation between counter waves so it is close to the diffraction beam size.

The use of lasers to illuminate objects has arisen some problems in viewing objects through randomly inhomogeneous media, which are connected with the object imaging using coherent optical irradiation. One of the problems arises in a situation when the radiation reflected from an object correlates with the incident radiation because both waves pass through the same inhomogeneities of the medium in the forward and backward direction. As shown in Refs. 1–3 theoretically, under certain conditions the correlation between the counter waves improves the quality of images. In this paper we present some results of the study of the influence of the correlation between illuminating and return waves on the image of a point object viewed through a randomly inhomogeneous medium.

Consider a point object illuminated with a coherent light of the wavelength λ from a source located at a distance L. The optical source emits a collimated beam with the Gaussian intensity distribution of the effective radius a. The object is observed with a telescope having the focal length F_t and effective radius of the receiving aperture a_t through the turbulent atmosphere with the Kolmogorov spectrum of the refractive index fluctuations under the conditions of strong intensity fluctuations when the parameter $\beta_0^2 = 1.23\, C_n^2 k^{7/6} L^{11/6}$, characterizing the conditions of propagation through the atmosphere, exceeds unit ($\beta_0^2 \gg 1$, C_n^2 is the structure constant of the refractive index, $k = 2\pi/\lambda$ is the radiation wave number). If the source and the telescope are located in the same plane and their optical axes coincide the light propagates from the source to the object and back along the correlated paths. The influence of correlation between counter waves on the image quality was considered in Ref. 3, where the expressions for the spatial spectrum of the mean intensity of radiation behind the lens were derived, which show that under the conditions of strong intensity fluctuations the spatial spectrum of a point object image can be considered as a sum of two terms. The first term corresponds to the case of propagation along the path of the length $2L$ ignoring the correlation. The second term allows for the correlation between counter waves and contains information on high frequency part of the spatial spectrum, which is filtered out by an inhomogeneous medium in the absence of the correlation between counter waves. The account of the second term must lead to improvement in the quality of an image in the focal plane.

Using the Fourier transform of the spatial spectrum[3] we obtain the mean intensity distribution in the telescope focal plane which has the following form for the collimated beam:

$$I(\rho,\, F_\mathrm{t}) = \frac{A_1}{A_1 + A_2} \exp\left(-\frac{\rho^2}{a_0^2}\right) + \frac{A_2}{A_1 + A_2} \exp\left(-\frac{\rho^2}{a_d^2}\right), \tag{1}$$

$$a_0^2 = a_{d0}^2 (1 + \Omega_\mathrm{t}^2 + 2p\Delta), \tag{2}$$

$$a_d^2 = a_{d0}^2 \left(1 + p\Delta + \frac{(1+p)\Omega_\mathrm{t}^2}{1 + p(1+\Delta)} - (1+p)p^2\Delta \frac{\left[1 + \dfrac{\Omega\Omega_\mathrm{t}}{1 + p(1+\Delta)}\right]^2}{\left[\Omega^2 + (1+p)^2 + \dfrac{\Omega\,\Omega_\mathrm{t}\, p^2}{1 + p(1+\Delta)}\right]} \right), \tag{3}$$

where A_1 and A_2 are the amplitudes, a_0 and a_d are the effective radii of the intensity distributions; $p = 0.8\ \Omega_{\rm t}(\beta_0^2)^{6/5}$; $\Omega_{\rm t} = ka_{\rm t}^2/L$, $\Omega = ka^2/L$, and $\Delta = \Omega_{\rm t}/\Omega$ are the Fresnel numbers of the telescope and transmitting apertures and their ratio, respectively; $a_{d0} = F_{\rm t}/ka_{\rm t}$ is the radius of the diffraction image for the plane wave; ρ is the two-dimensional vector in the plane perpendicular to the propagation direction.

Analysis of this relationship shows that if the source and the telescope are located independently then only the first term remains in the expression (1). This term describes the intensity distribution in the object image in the case of uncorrelated paths when the viewed object is illuminated from side (at an angle). Characteristic dimension of this distribution coincides with the size of the object image blurred by the medium turbulence along the path of doubled length. The contribution of the correlation between counter waves is described by the second term whose characteristic dimension is close to the object image size. The contributions from the first and second terms are comparable when the size of the apertures of a coherent source and the telescope are the same ($\Omega_{\rm t} = \Omega$).

Experimental study of the influence of correlation between counter waves on the image of an illuminated object was carried out in laboratory conditions with the use of a setup modeling the conditions of a developed convective turbulence.[5] As a source of illumination a frequency stabilized LGN-302 He–Ne laser was used. Using an optical system we formed a quasiplane wave. A flat mirror with a diaphragm of 0.8 mm diameter set before it was used as an object. The distance to this object (7 m) is a sum of three paths of the beam through the turbulent layer all being independent paths. The light beam reflected from the object propagated backward along the same path. To analyze the effect of the counter wave correlation on the object image the telescope was located in the source plane exactly and their axes coincided. To observe the object image using an uncorrelated path of the double length we changed the location of light reflecting elements of the setup.

The strength of turbulence along the path was determined from the measurements of fluctuations of the angles of plane wave arrival. For this purpose an additional path was arranged with a separate source and optics forming a quasiplane wave with the Fresnel number $\Omega = 35$. The strength of turbulence along the propagation path could be changed by varying temperature of the heated surface or the height of propagation path over the heated surface. For changing the turbulent conditions of propagation in the experiment the height of measurement path was changed. The laser beams propagated along the main and additional paths propagated at the same height. The strength of turbulence and the image size were measured simultaneously. The structure constant of the refractive index C_n^2 as a function of height h over the heated surface is shown in Fig. 1

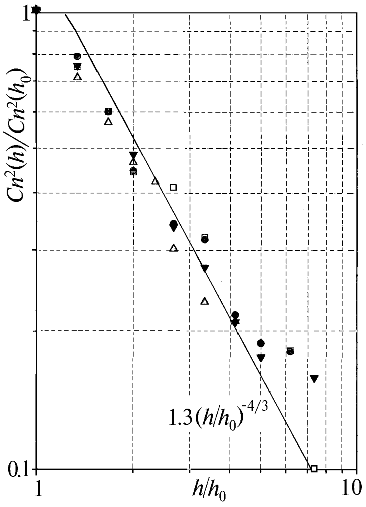


FIG. 1. The profile of the air refractive index structure constant C_n^2 above the heated surface. Solid line is the power-low dependence $C_n^2 \sim (h/h_0)^{-4/3}$, where $h_0 = 6$ cm.

The object image was caught with a videocamera at the focal plane of the telescope lens ($F_{\rm t} = 160$ cm) and recorded with a computer in the accumulation mode during 4 min. that corresponds to 72 frames. A number of points in the image was 256×256, the spatial resolution of the system "videocamera-computer" was 33 μm. To obtain the parameters of intensity distribution over the beam image the horizontal and vertical cross sections were chosen. These sections were obtained by averaging over 2–3 lines (X-axis) and columns (Y-axis) passing through the maximum of the intensity distribution. Then the amplitude of the intensity distribution in every section was normalized by the maximum value, ($A_1 - A_2$), and for every measured distribution the parameters (A, x_0, a) were selected by the fit method for one exponent ($A\exp\{-((x - x_0)/a)^2\}$) or a sum of two exponents ($A_1\exp\{-((x - x_{01})/a_0)^2\} + A_2\exp\{-((x - x_{02})/a_2)^2\}$) which describe the given intensity distribution most accurately. Such a technique of processing allows the amplitude ratios and effective radii of every scale of image to be determined without measuring the absolute value of the intensity.

To test the measurement technique and data processing the measurements with a collimated beam ($\Omega = 22$) and infinite reflector were carried out along an uncorrelated path at different propagation heights above the heated surface. In Fig. 2 the measured radii of a laser source image along the X and Y-axes are shown as functions of the parameter D_s, characterizing the strength of optical turbulence similarly to the parameter β_0^2. The solid curve in Fig. 2 is calculated by the formula $0.012(2.96 + 1.41 D_s^{6/5})^{1/2}$ obtained in accordance with the known theory of imaging in a turbulent medium[4] for the beam parameters and receiving aperture used in the experiment.

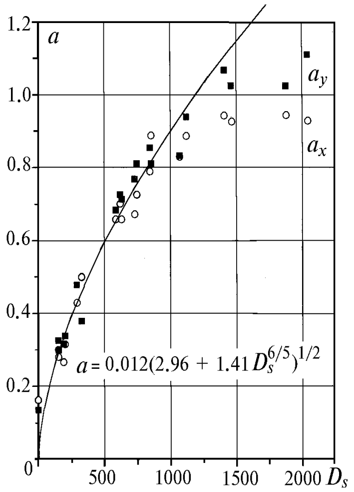


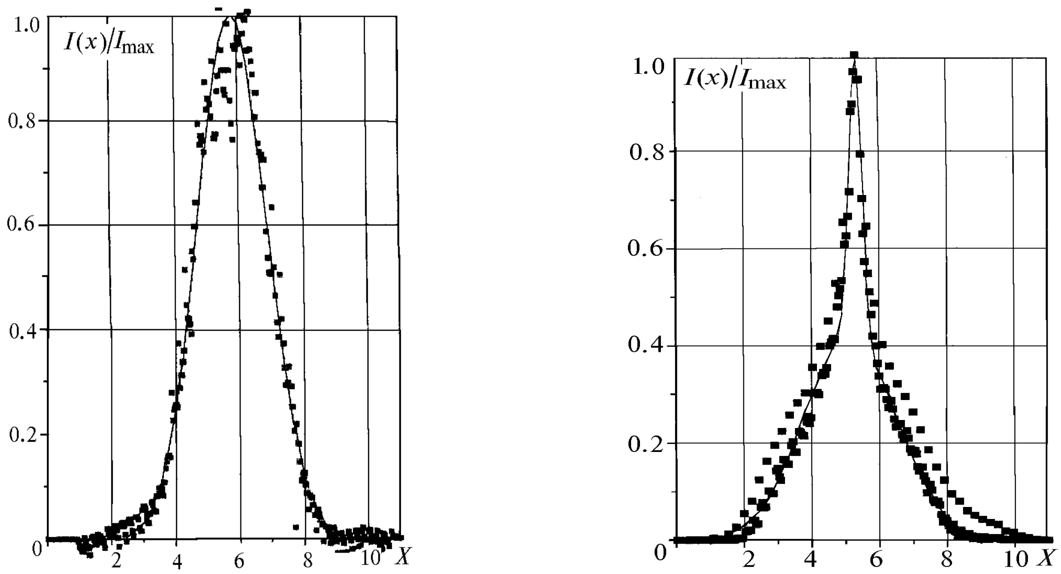
FIG. 2. Image size of a laser source as a function of the parameter D_s for the case of an uncorrelated path and reflection from an infinite reflector.

The intensity distribution over a point object image was measured as a function of the diffraction size of the receiving telescope lens Ω_t at different values of the parameter β_0^2 (under the conditions of strong optical turbulence). It was found that for $\beta_0^2 \gg 1$ the intensity distribution has two distinct scales if the illuminating and return beams pass through the same inhomogeneous medium (correlated path). For $\beta_0^2 < 0.5$ both scales become equal in size and indistinguishable.

In Fig. 3 the examples of the image intensity distribution in the focal plane of the receiving telescope for the case of uncorrelated path (Fig. 3*a*) and the correlated one (Fig. 3*b*) are presented for the same measurement parameters. The intensity values are normalized to the maximum one $I_{\max}$. It is seen that the intensity distribution in the case of uncorrelated path is described quite well by a single exponent with the effective radius $a = 1.52$ mm. In the case of correlated path the intensity distribution has two scales. The larger scale of 1.93 mm is determined by an ordinary turbulent blurring of the image and it is close to the width of the intensity distribution for the case of uncorrelated path. The width of the narrow peak in Fig. 3*b* is about 0.27 mm and the diffraction size of the image $1.22\lambda F/2a = 0.25$ mm.

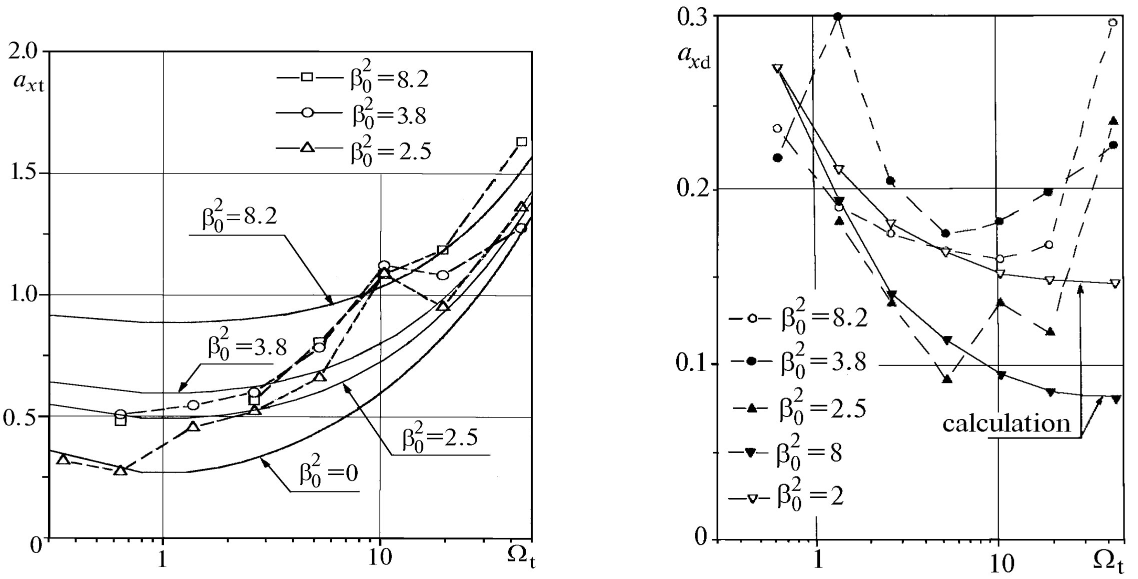
Figure 4 shows the dimensions of the turbulent pedestal (Fig. 4*a*) and narrow diffraction peak (Fig. 4*b*) obtained as a result of processing of the image intensity distributions according to the described technique as a function of the parameter Ω_t under different turbulent conditions β_0^2. The solid curves in Fig. 4*a* are calculated using the first term of the formula (1) and describe the turbulent blurring of the image distribution in the focal plane of objective with the allowance for sphericity of the reflected waves. Dashed curves show the experimental data. Solid curves in Fig. 4*b* show the results of calculation in accordance with the second term of Eq. (1) and dashed curves correspond to the experimental dimensions of the smaller scale (narrow peak of the intensity distribution). The minimum size of this scale is obviously observed at $\Omega_t \approx 3$–10 that does not coincide with the theoretically predicted situation on the necessity of making equal apertures in order to improve the image quality.

Thus, the obtained experimental results show that under conditions of strong intensity fluctuations when the object is illuminated and viewed from the same point the object image quality can be improved when using the transmitting and receiving apertures of equal size.



a *b*

FIG. 3. The X-axis intensity distributions in the object image in the case of uncorrelated path (a) and for the case of correlation between the illuminating and return waves (b).



a *b*

FIG. 4. The turbulent (a) and diffraction (b) radii of the intensity distribution in the focal plane for the case of a point reflector and a correlated path.

REFERENCES

1. V.A. Banakh and B.-N. Chen, in: *Atmospheric Propagation and Remote Sensing III*, Walter A. Flood and Walter B. Miller, eds., Proc. SPIE **2222**, 1994.
2. V.A. Banakh and B.-N. Chen, in: *Atmospheric Propagation and Remote Sensing IV*, Ch. Dainty, ed., Proc. SPIE **2471**, 1995.
3. V.A. Banakh and B.-N. Chen, Atmos. Oceanic Opt. **7**, Nos. 11–12, 827–830 (1994).
4. V.E. Zuev, V.A. Banakh, and V.V. Pokasov, *Optics of Turbulent Atmosphere* (Gidrometeoizdat, Leningrad, 1988), 272 pp.
5. V.A. Banakh, V.M. Sazanovich, and R.S. Tsvik, Atmos. Oceanic Opt **7**, Nos. 11–12, 831–833, (1994).