INFLUENCE OF THE TURBULENCE LEVEL OF A MEDIUM ON THE INTENSITY DISTRIBUTION OVER OPTICAL IMAGE AT LASER RANGING

V.A. Banakh, V.M. Sazanovich, and R.Sh. Tsvyk

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received July 9,1998

The effect of long-range correlation of the wave field reflected from a plane mirror on the intensity distribution over focal plane of a lens is studied experimentally. We have revealed from our study that under conditions of "saturatedB intensity fluctuations of a wave incident on the reflector part of the reflected field is highly coherent thus resulting in a narrow peak in the intensity distribution behind the lens that appears on the background of a blurred turbulent spot with the intensity of the peak being equal to that of a turbulent spot. As a result, the intensity on the lens' optical axis is doubled. We have managed to determine the radius, amplitude, and the fraction of the total intensity made up by the narrow peak as functions of the turbulence level along the propagation path.

The space-time inhomogeneity of a random medium results in blurring images of the objects viewed. In this case the data on fine details of an object are lost and errors in determination of its coordinate increase. From Refs. 1–6 it follows that quality of imaging objects viewed using single-ended optical arrangement can be improved using the backscattering effect or, more exactly, the effect of long-range correlation of direct and reflected waves leading to conservation of high coherence in a portion of the reflected wave. This effect has been observed experimentally in Refs. 3 and 4 under laboratory conditions where it was shown that separate out the coherent component of light reflected from an object in a turbulent medium using the polarization properties of light. In this case the visibility of the interference pattern is essentially improved.

The fraction of coherent waves in the reflected light produces a narrow peak in the intensity distribution over the focal plane of a lens occurring against the background of a spot blurred by a turbulent medium. The experimental studies, Ref. 6, with a point reflector, provided that the reflector size is much less than the Fresnel zone, exhibited the dependence of the narrow peak parameters on the level of turbulence along the path and on the size of receiving aperture. We describe in this paper some results of the experimental study on how the level of turbulence in a medium influences the formation of an extended object's image, if the incident and reflected waves propagate through the same (correlated) inhomogeneities of the medium.

The experimental studies have been carried out under laboratory conditions using the setup that models a convective randomly inhomogeneous medium above a heated surface. Turbulent parameters of the model medium are given in Ref. 6. The object is a plane mirror illuminated by coherent radiation with $\lambda = 0.63$ μm from a He–Ne frequency stabilized laser. Using optics we formed a quasi-plane wave with the Gaussian intensity distribution and effective radius $a = 0.7$ cm. In this case the Fresnel parameter of the emitter $\Omega = ka^2/L = 70$, where $k = 2\pi/\lambda$; the path of 7 m length, L, was formed by triple passage of the beam through a turbulent layer along independent paths. The diaphragms placed before a mirror make it possible to vary the reflector size from a point size ($\Omega = 0.3$ is characteristic of a spherical reflected wave) to the infinite size (a beam was intercepted and reflected fully without any limitation). Light beam reflected from the mirror was transmitted along the same path in the backward direction. The receiving telescope with a focal length $F_t = 160$ cm was located in the source plane. The axes of the telescope and the source coincided. The input aperture of the telescope did not limit the size of the incident beam.

The investigations were carried out under conditions of strong intensity fluctuations when the parameter $\beta_0^2 = 1.23\, C_n^2\, k^{7/6}\, L^{11/6}$ (C_n^2 is the structure characteristic of the refractive index of the medium) describing the conditions of propagation through the atmosphere exceeds unity. As shown in Refs. 1 and 2, under conditions of "saturatedB intensity fluctuations the coherence function of a plane wave transmitted through the turbulent layer to a reflector (at $\Omega_r >> 1$) and back can be divided into the sum of two components

0235-6880/98/10 910-04 $02.00

$$c_2^R(x_0, \bar{\rho}) = c_{2o}^{(1)} + c_{2o}^{(2)} = A\left\{\exp\left(-\frac{8}{3}D_s\,\rho_f^{5/3}\right) + \left[1 + \frac{16}{3}\left(\frac{4}{3}D_s\right)^{12/5}\right]^{-1} \times \exp\left[-\frac{2((4/3)\,D_s)^{6/5}\,\rho_f^2}{1 + (16/3)((4/3)\,D_s)^{12/5}}\right]\right\},$$

where D_s is the structure function of the spherical wave phase and $\rho_f = |\rho|\sqrt{kL}$; the former expression coincides with the coherence function of direct wave transmitted through a turbulent medium along the path $2L$ taking into account the field variation on the reflector due to diffraction, while the latter one is determined by the far-field correlations of the reflected wave. These functions differ in magnitude and scale of the components. Thus, when reflecting from the mirror the component $c_{2o}^{(2)} \sim D_s^{-12/5}$ being asymptotically small as compared to $c_{2o}^{(1)}$. However, the scale of this function decay is much larger than that of $c_{2o}^{(1)}$ and is determined by the diffraction size of the coherence radius either of a plane or a spherical wave depending on the reflector size and it increases with growing turbulence.

Thus, the wave field at the input aperture of the telescope produced by this component has a "wide zoneB of high coherence but low intensity, and in the lens focal plane a narrow peak appears in the intensity distribution against the background of a spot blurred by the turbulence. At high intensity of turbulence the intensity at the distribution center is twice as large as that occurring at the wave propagation along uncorrelated path of a doubled length.

Based on these assumptions, we have considered in the experiment the intensity distributions of waves, reflected from an object, in the focal plane of the receiving objective. The distributions were recorded with a videocamera and a computer in the mode of data accumulation during 8 minutes that corresponded to grabbing of 145 frames. The spatial resolution provided by the videocamera and recording system used was 33 μm. To determine the parameters of intensity distribution in the horizontal and vertical cross sections, we selected three columns and three lines across the intensity distribution maximum to perform the averaging of data over these cells. Then in every cross section the amplitude of intensity distribution was normalized to maximum and the method of fitting was used for selecting the parameters A, a, x_0 of one exponent or the sum of two exponents describing this distribution most exactly. This method of processing makes it possible to determine the amplitude ratios and effective distribution scales without measuring the absolute intensity values.

Figure 1 shows the examples of the intensity distributions obtained in a lens focal plane in the horizontal (x) and vertical (y) cross sections for a wave reflected from a plane mirror having the size of one Fresnel zone ($\Omega_r = 6.3$) at different levels of turbulence in the medium. The values of β_0^2 correspond to the path length L up to the reflector. The point numbers in the image (the distance between the points is 33 μm) are plotted along the horizontal axis. The figures show the parameters of fitted Gaussian curves.

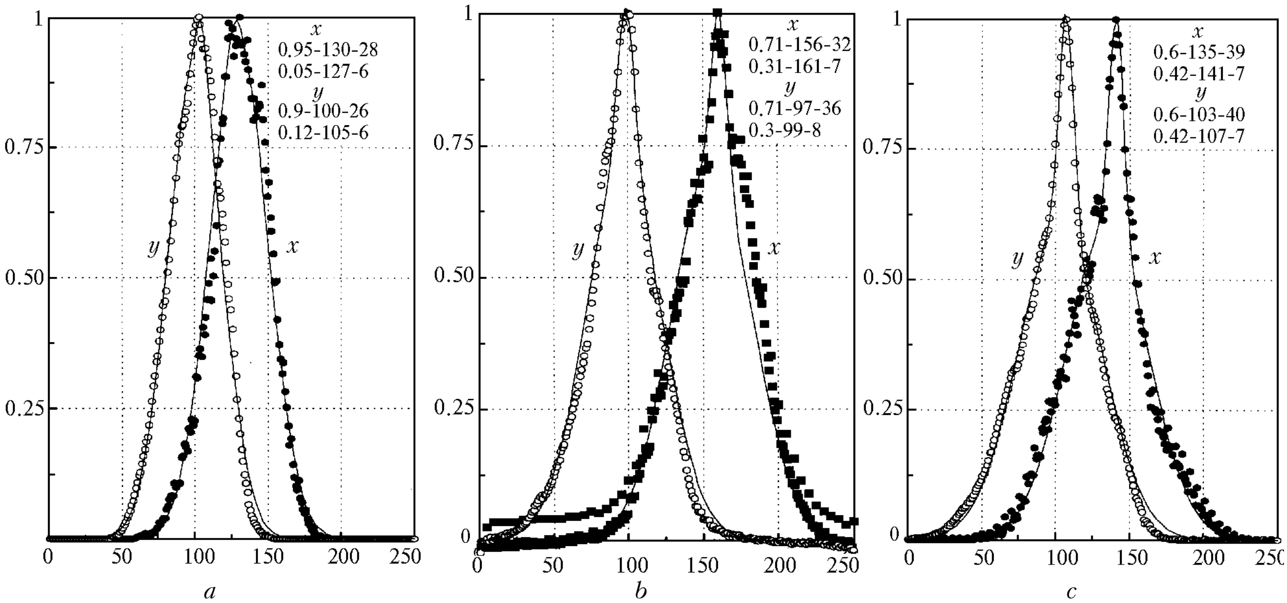

FIG. 1. Intensity distribution for the case of a reflector having the size of one Fresnel zone: $\beta_0^2 = 2.3$ *(a),* 3.8 *(b), and* 9.8 *(c).*

Figure 2 presents the assessed contribution to the intensity distribution amplitude coming from the turbulent (A_t) and coherent (A_c) components for an infinite reflector. According to the processing technique used, the summed amplitude equals $A = A_t + A_c = 1$. The contribution of the coherent component grows with the increase of turbulence level along the path, so that at $\beta_0^2 \sim 1$ the distribution is described by one exponent and only at $\beta_0^2 > 1.5$ a marked effect of the coherent component is observed. Against the background of the turbulent spot a narrow central part of higher intensity is observed. The relative contribution of coherent component to the total intensity at the center of the spot is compared with the contribution of the turbulent component only at $\beta_0^2 \sim 10$; this is the level of medium turbulence at which the intensity fluctuations of the plane and spherical waves saturate, Ref. 1. The analytical relationships for A_t and A_c presented in Fig. 2 were obtained by the method of least squares based on measured values.

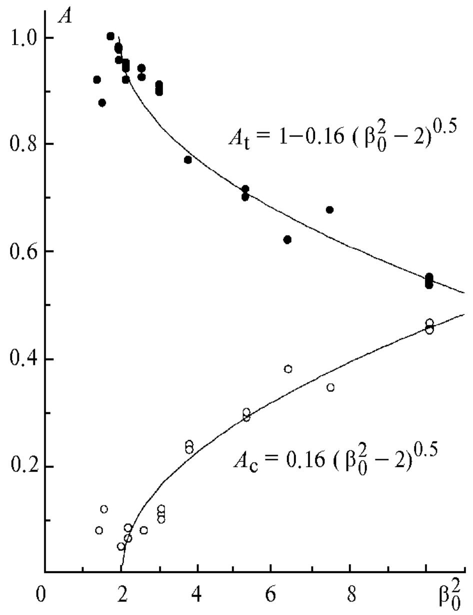

FIG. 2. The amplitudes of the turbulent A_t and coherent A_c components as functions of the turbulence level in the medium at the reflector size $\Omega_r > 100$.

The measurement carried out using the reflectors of different size at $\beta_0^2 \sim 10$ showed that the amplitudes of the components A_t and A_c only slightly depend on the reflector size being almost equal in magnitude (Fig. 3).

Figure 4 shows the dependence of the effective radii (scales) of the turbulent spot and narrow peak of the intensity distribution in the lens focal plane for the infinite (a_{tp}, a_{cp}) and point (a_{ts}, a_{cs}) reflectors when varying β_0^2.

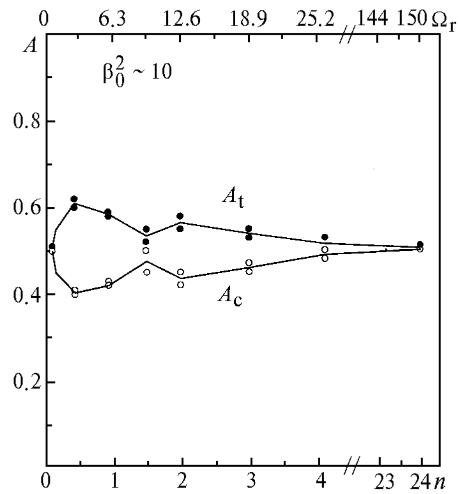

FIG. 3. The amplitudes of the turbulent A_t and coherent A_c components as functions of the reflector size in units of the Fresnel zone size ($n = \Omega_r / 2\pi$) and Ω_r.

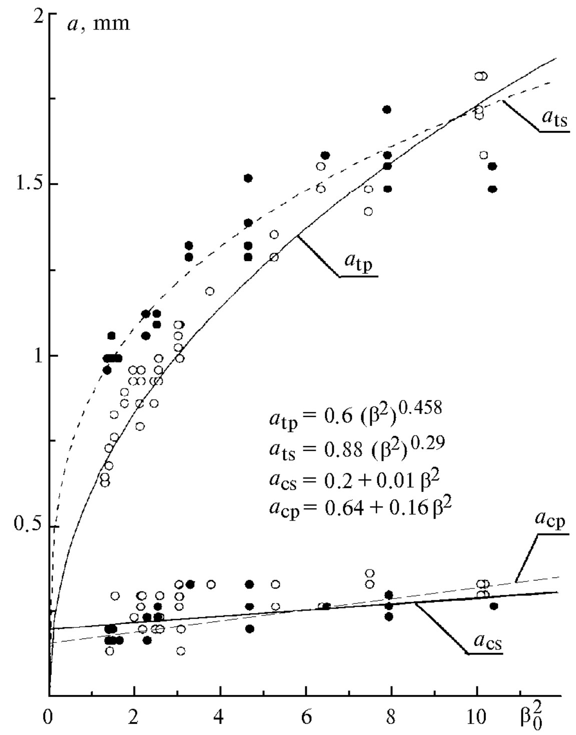

FIG. 4. The scales of intensity distribution in the lens focal plane as functions of the turbulence level in the medium.

The mirror limited by an aperture of 1-mm diameter was used as a point reflector. The Fresnel parameter of the reflector $\Omega_r = 0.3$. The analytical expressions shown in the figure are the approximations of the experimental data. The estimates of the size of the laser beam image with a plane wave front, transmitted through the turbulent medium along the path of length $2L$ to the reflector and back, give the relationship proportional to $(\beta_0^2)^{0.6}$, Ref. 1. The experimental sizes of the spot a_{tp} and a_{ts} at small values of β_0^2 are 25–30% less than the calculated ones and become closely related at the $\beta_0^2 \sim 10$. Large values of the spot size for the point reflector, as compared with the infinite one, can be explained by the fact that the measurements with the point reflector were made not in the plane of minimal image size, but in the focal plane of the receiving lens. The decrease of the turbulent spot size at large values of the β_0^2 can be explained by two reasons, namely, the energy transfer to the narrow peak as well as the effect of the outer scale on the structure phase function, since $\beta_0^2 = 10$ was obtained at rather small height above the heated surface.

It is clear from Fig. 4 that the values of the coherent scale radius a_{cp}, a_{cs} do not actually depend on the level of the medium turbulence although the calculated, for the path length $2L$, values of the radius of the field coherence of plane wave decrease from 3.5×10^{-1} mm to 1×10^{-1} mm with the increase of β_0^2 from 1.5 to 10.

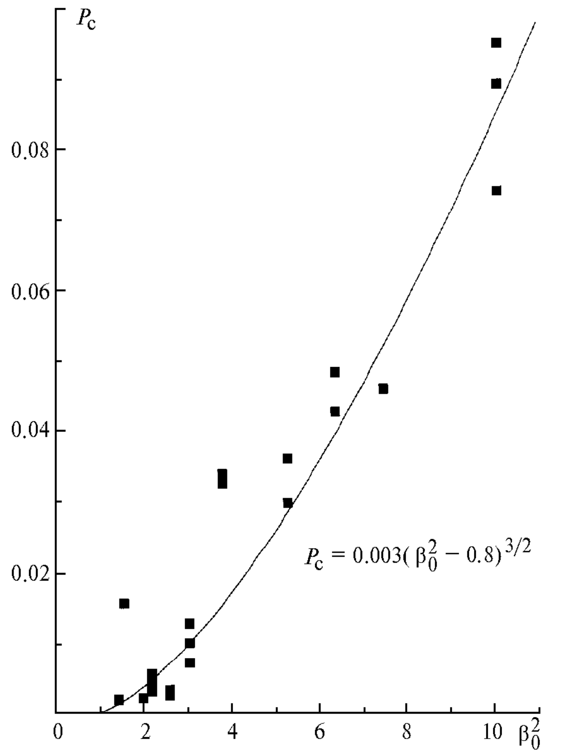

FIG. 5. The energy fraction of the coherent component of the beam in its total energy in the focal plane of a lens

The wide spread of a_{cp} and a_{cs} values at small values of β_0^2 is due to the experimental errors. The mean values of the coherent scale radius for the infinite and point reflectors are approximately the same and at $\beta_0^2 \sim 10$ equal 0.25 mm. This corresponds to the size of the coherence zone in the plane of input aperture of the receiving lens $\rho = F/ka_c \approx 0.7$ mm.

Hence the size of high coherence zone is several times larger than the coherence radius of a plane wave, but by an order of magnitude less than the initial size of the transmitted beam.

Figure 5 presents the assessed fraction of the coherent component's energy in the total wave energy for the infinite reflector $P_c = \overline{A_{cp}\, a_{cp}^2} / (\overline{A_{tp}\, a_{tp}^2} + \overline{A_{cp}\, a_{cp}^2})$ at different values of β_0^2. It is clear that fraction of the coherent component, in our experiments, did not exceed 8–10% of the total energy. So we assume that with the further increase of β_0^2 the saturation of P_c takes place since the value of intensity of a narrow beam on the axis reaches its maximum at $\beta_0^2 \sim 10$.

Thus, the above investigations have shown that under conditions of “saturatedB fluctuations of the wave intensity, when reflecting from a plane mirror, the intensity on the beam axis in the lens focal plane at back propagation is twice as large as the intensity on the axis at direct propagation along the path of double length due to the effect of far correlations that results in improvement of resolution of an optical system operating using single-ended optical arrangement.

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