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Fluctuations of laser beams over urban near-the-ground path

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***Abstract*. A comparative analysis of the fluctuation structure of laser radiation over urban near-the-ground paths is performed for different turbulent states. The data obtained in experiments allow changes in the statistical characteristics of laser beams, which are induced by aperture effects, to be compared to those caused by changes in the turbulent state of the propagation medium. The influence of intermittency of small-scale turbulence on the radiation characteristics is considered. It is found that the intermittency has a weak effect on the rms shift of the beams' 'centers of gravity' but affects substantially the spatial and temporal intensity fluctuations.**

Keywords: *laser beams, turbulence, near-the-ground atmosphere, radiation fluctuations.*

1. Introduction

The problem of wave beam propagation in the near-the-ground atmosphere is closely related to studies in the laser physics and technology. No progress in developing navigation, metrological, and radar devices and data communication systems can be achieved without solving this problem [1 – 4]. Studying specific features of the radiation propagation in a turbulent atmosphere has become especially urgent recently due to extensively developing commercial works for creating city optical communication systems using open propagation channels [5].

Open channels are characterised by various types of instabilities that appreciably affect the behaviour of a laser beam. Such instabilities often manifest themselves in the form of small-scale turbulence (SST) intermittency [6]. SST intermittency, which is usually observed under conditions of substantial vertical temperature gradients, leads to a more complicated spatiotemporal structure of radiation, thereby causing sporadic beam stochastisation, and thus negatively affects the amount and quality of information transmitted.

The existing difficulties in optimising the characteristics of optical devices that use surface channels in large cities are explained by the lack of experimental and theoretical information on the laser-beam fluctuations. The aim of this work was to perform a comparative analysis of the fluctuation structure of radiation over the urban near-the-ground path in various turbulent states. It continues a series of studies [6 – 9] performed in the recent years at the Department of Physics of Moscow State University. Unlike previous results, the data of this study allow one to compare the changes in the statistical characteristics of radiation caused by both the aperture effects and changes in the turbulence states in the propagation channel.

2. Experimental setup. Results of measurements

A horizontal path typical for communication systems under conditions of a large city was used in the experiments. It was arranged in Moscow (buildings of Moscow State University at the Vorob'evy hills were used) and operated in a ranging mode; its one-way length was 280 m. A 0.63 μm He – Ne laser served as the light source. Transmitting and receiving devices were positioned at a height of 25 m. Radiation could propagate along the path in the form of one or two variable-diameter beams spaced by a small distance. The experiments were performed under various meteorological conditions, and the images of the beams transmitted along the path were video recorded. The recording duration was usually as long as 5 – 8 min. The sections corresponding to appreciable changes in the meteorological conditions (violent windblasts, sporadic sun shielding by clouds under variable clouding, etc.) were then removed from the recorded image. During the subsequent computer processing of images, the statistical characteristics were calculated by averaging the parameters over the remaining sections of the video record. As a rule, these sections of the actual process included from several hundred to several thousand video frames.

2.1 Characteristics of the beams under conditions of steady-state turbulence

The first stage of our study was devoted to fluctuations in the parameters of laser beams of different diameters under virtually stationary turbulence conditions (no turbulence intermittency is present). Figure 1 shows consecutive video images of the collimated laser output beams with diameters D varied from 3 to 10 cm, which are characteristic of such conditions. They were recorded in winter at a wind velocity of 1.8 m s^{-1} and $T = -0.6\,^{\circ}\mathrm{C}$ between 5 : 00 p. m. and 6 : 00 p. m.

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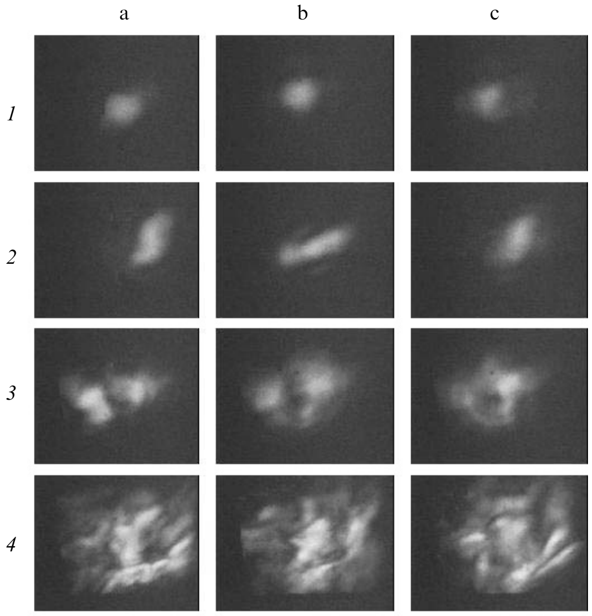

Figure 1. Consecutive images (a – c) of laser beams with diameters of (*1*) 3, (*2*) 3.5, (*3*) 7, and (*4*) 10 cm at the output of an atmospheric path.

Figure 1 clearly shows that, as the output-beam diameter increases, the structure of the radiation transmitted along the path becomes more complex due to an increased number of transverse structural fragments of various shapes and intensities. Estimates of the beam-intensity fluctuations have shown that, as the beam diameter increases, the changes in the intensity-correlation radii for beams of different diameters are small with allowance for measurement errors. For example, for $D = 7$ and 10 cm, the correlation radii in the horizontal plane are $r_c = 3.1 \pm 0.7$ and $r_c = 4.0 \pm 0.4$ cm, respectively.

Perturbations in the structures of the beams appearing with increasing their apertures affect considerably the profile of the probability-density distribution of intensity fluctuations. Figure 2 presents histograms of the spatial intensity fluctuations for beams with diameters of 3, 7, and 10 cm. It is clearly seen that, as the diameter increases, the distribution peak shifts from the central region to the left, thereby testifying to a trend for a transition to a log-normal intensity-fluctuation distribution law [9].

In experiments with beams of different diameters, the rms deviations of the beams' 'centers of gravity' (CG) σ were calculated. Figure 3 shows the results characterising these deviations in the horizontal and vertical directions obtained during the same measurement session. Although the difference in the behaviour of deviations in different planes is small, in the horizontal plane a certain trend to a decrease in the σ values is observed with increasing the beam aperture. This trend is less pronounced for fluctuations in the vertical plane.

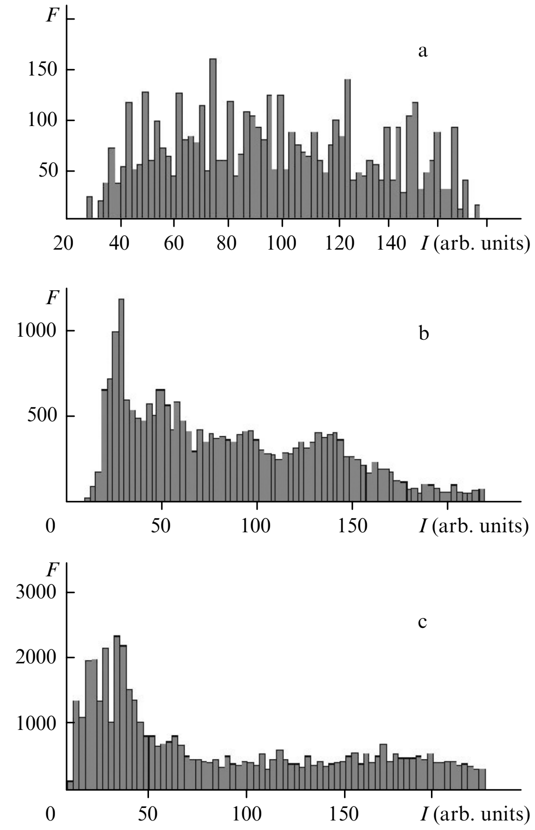

Figure 2. Histograms of the intensity distributions in beams with diameters of (a) 3, (b) 7, and (c) 10 cm (F is the number of readings in the given intensity interval).

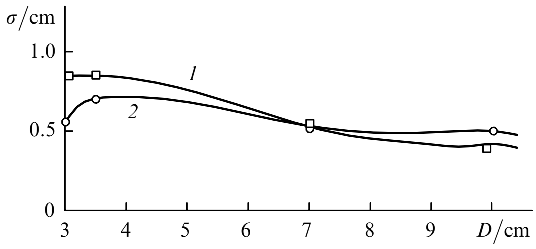

Figure 3. Rms deviations σ of the CG of the output beams in the (*1*) horizontal and (*2*) vertical planes as functions of their diameters D.

In order to characterise random shifts of the beams' CG, we calculated the correlation R between the intensity distributions for the beam images in the first and subsequent exposures of random video-record samples. The behaviour of this quantity for one of the signal realisations is shown in Fig. 4. At a small-aperture beam, significant correlation overshoots are observed, while the correlation is more stable in large-aperture beams. This correlation behaviour is explained by the fact that shifts of the CG for a small-aperture beam are comparable to the transverse beam size, being much less than the size of a large-aperture beam (this is clearly seen from the positions of consecutive beam images in Fig. 1).

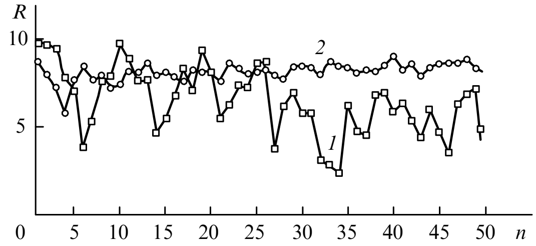

Figure 4. Correlation R of the intensity distribution in beam images between different frames (n is the frame number) at $D = 3$ (*1*) and 10 cm (*2*).

2.2 Characteristics of beams under conditions of SST intermittence

At the second stage, we studied specific features of the displacements of beams with different diameters under conditions of the development of SST. The earlier experiments in [6, 7] were usually performed with narrow collimated beams and did not allow the effects of SST on beams of different diameters to be correctly compared. It was established in these experiments that, under conditions of SST intermittency, a narrow collimated beam alternately changes from a quasi-regular state with an intensity profile close to a Gaussian one to a stochastic speckle-like state. It is precisely for this reason that, in the experiments described below, this beam was used as a reference playing the role of an indicator of changes in the structure of the atmospheric turbulence. This beam propagated along the path at a small distance (a few centimetres) from the beam under study. Under conditions of developed SST, the reference beam with an output diameter of 1 cm turned out to be in a stochastic state. Both the beam under study and the reference beam were formed from the expanded beam of the same He – Ne laser using two diaphragms with perforated edges.

Figure 5 shows examples of the intensity distributions in the large-diameter and reference beams under conditions of weakly and highly developed SST. The absence of highly developed SST (Fig. 5a) is confirmed by a slight deformation of the intensity distribution in the reference beam. Under conditions of highly developed SST (Fig. 5b), the intensity distributions in both the wide and the narrow reference beams take on a speckle-like character.

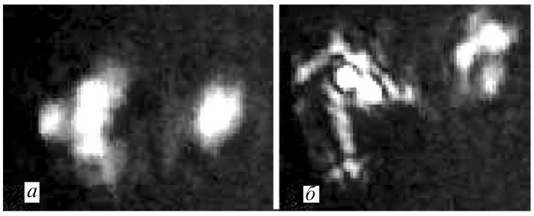

Figure 5. Intensity distributions in the large-diameter and reference beams (the left and the right images in each frame, respectively) under conditions of (a) weakly and (b) highly developed SST.

Estimates of the rms displacements σ of the narrow reference beam and the wide beam with a diameter $D = 2.4$ cm that propagates close to the former in the horizontal and vertical planes are listed in Table 1. These data were obtained on the same day as those presented in Figs 1 – 4, but the measurements were performed later (7 : 00 – 8 : 00 p. m.), when, under conditions of the falling temperature, the turbulent state became less stable and SST intermittence was observed. In the experiments performed under conditions of SST intermittence, the narrow beam, after being in a quasi-regular state for 10 – 15 s, changed jumpwise to a stochastic state, in which it remained for approximately the same time.

Table 1 lists the rms deviations σ of the beams' CG averaged over several video-record realisations. Comparing the σ values for the wide and narrow beams shows that, with allowance for the measurement errors ($\sim 10\,\%$), they virtually coincide at weakly developed SST. In the presence of developed SST, the displacements of the narrow-beam's CG increase substantially (but not drastically). No appreciable difference in the beams' CG shift dynamics in the vertical plane is observed upon sporadic development of SST.

Table 1. Displacement of the centers of gravity of the narrow (1 cm) and wide (2.4 cm) beams.

SST	$\sigma/$cm, horizontal plane		$\sigma/$cm, vertical plane	
	Narrow beam	Wide beam	Narrow beam	Wide beam
Weakly developed	0.32	0.35	0.31	0.29
Highly developed	0.42	0.30	0.46	0.33

By analysing the correlation between the displacements of the beams propagating along close paths made it possible to find that the correlation coefficient for the vertical displacements of the CG of such beams may be as large as ~ 0.4. The correlation coefficient for the horizontal shifts is, however, close to zero; i.e., the correlation is virtually absent. These data point to the presence of a certain anisotropy in the turbulence structure in the near-the-ground atmospheric layer [4].

Evaluating the effect of turbulence intermittence on the intensity fluctuations at the beams' CG is also of interest. The transformation of the intensity-fluctuation structure during the development of SST for the narrow reference beam and a 2.4-cm-diameter beam is presented in Table 2. The rms intensity deviations σ_I averaged over realizations and normalized to the average intensities for the corresponding states of the turbulence development are presented. One can see that the highly developed SST enhances considerably the beam-intensity fluctuations. Note that the fluctuation structure of the narrow beam undergoes more significant changes. This can be explained by the fact that, as SST develops, the small-diameter beam changes from a quasi-regular state to a stochastic one, while the large-diameter beam is randomised regardless of the degree to which SST is developed.

Table 2. Rms deviations of the intensity fluctuations at the centers of gravity of the narrow (1 cm) and wide (2.4 cm) beams.

SST	σ_I	
	Narrow beam	Wide beam
Weakly developed	0.08	0.12
Highly developed	0.26	0.22

Analysis of the experimental data shows that SST intermittence is also exhibited in the behaviour of the intensity fluctuations at a fixed point of the receiving aperture. The point characterising the average position of the beam's CG in the processed sequence of video frames was taken for this point. It follows from the experiment that, when SST arises, the σ_I values for the reference and wide beams increase from 0.24 ± 0.04 to 0.61 ± 0.05 and from 0.54 ± 0.05 to 0.8 ± 0.05, respectively; these values far exceed the corresponding rms deviations for the beams' CG. This is explained by the fact that the fluctuations at a fixed point of the receiving aperture are determined by both changes in the beam-intensity profile and displacements of the beam as a whole.

3. Theoretical estimates

Consider the question of the degree to which the experimental data can be described in the context of the theoretical model developed for homogeneous isotropic turbulence [3, 10, 11]. This will be done by analysing, as an example, a random walk of the light-beam's CG, using the relations

$$\sigma^2 = 2.19 C_n^2 l_0^{-1/3} L^3, \tag{1}$$

$$\sigma^2 = \frac{0.132\pi^2 \Gamma(1/6)}{3 \times 2^{5/6}} C_n^2 L^3 a^{-1/3}. \tag{2}$$

Here, C_n^2 is the structural characteristic of refractive index fluctuations ; l_0 is the inner turbulence scale; L is the path length; and a is the beam radius. Expression (1) was obtained in the geometric optics approximation and allows the beam displacements to be estimated, when no developed SST is present and the beam-intensity profile is distorted only slightly. Expression (2) characterises the behaviour of beams in the case where the diffraction effects on inhomogeneities smaller than the beam size are significant. The parameter C_n^2 for weak fluctuations appearing in (1) and (2) can approximately be determined from the expression

$$C_n^2 = \frac{\sigma_I^2}{1.23 k^{7/6} L^{11/6}}, \tag{3}$$

where σ_I^2 is the normalised variance of beam-intensity fluctuations and k is the wave number. For the case of stationary turbulence considered above, C_n^2 can be estimated from the data on the intensity fluctuations at a fixed point of the receiving aperture for a beam with a diameter $D = 3$ cm that undergoes minimum distortions. Substituting the experimental value $\sigma_I^2 = 0.49$ for this beam into (3), we find $C_n^2 = 0.6 \times 10^{-15}$ cm$^{-2/3}$. For this value, formula (2) yields $\sigma = 0.4$ cm. This value is quite close to the experimental one (see Fig. 3). Similarly to the measurements performed, formula (2) points to a rather weak dependence of σ on the beam radius ($\sigma^2 \sim a^{-1/3}$).

For the intermitting SST considered at the second measurement stage, estimating σ requires that formulas (1) and (2) be applied jointly. As is known, the inner turbulence scale l_0 may vary from 0.1 to 1 cm. Let us assume that, in the absence of SST, the l_0 value lies close to the upper limit of this range and, when SST develops and results in the narrow-beam stochastisation, l_0 is close to the lower limit. Based on this, expression (1) describes the behaviour of a narrow beam when its distortions are small in the absence of SST. Expression (2) characterises the σ value for a narrow beam under developing SST. The same expression can also be used to approximately estimate σ for a wide beam (both in the presence and absence of SST).

When estimating σ under conditions of turbulence intermittence, we assume that a change in l_0 is the main factor affecting this quantity [6]. In this case, the C_n^2 value can be assumed constant and determined using formula (3) for the parameters of a narrow beam in the absence of SST (for the experimental value $\sigma_I^2 = 0.18$, the structural characteristic of refractive index fluctuations is $C_n^2 = 0.42 \times 10^{-15}$ cm$^{-2/3}$. The estimate of the rms beam deviation yielded by (1) is $\sigma = 0.39$ cm; formula (2) yields $\sigma \approx 0.33$ and 0.28 cm for narrow and wide beams, respectively. These values are quite close to the experimental data. However, since these estimates are approximate, they do not describe all of the peculiarities of the beams' behaviour over the paths and can serve as reference values in the preliminary analysis of radiation fluctuations in a turbulent medium.

4. Conclusions

We have presented in this work the experimental data predominantly obtained in the same measurement run. However, such measurements were reproduced many times in different seasons under various meteorological conditions. These results have confirmed as a whole the basic regularities that describe changes in the statistical characteristics of laser radiation for beams of different diameters under various turbulence conditions.

A practically important result is a weak influence of aperture effects and effects related to the sporadic development of SST on the rms beam displacement. At the same time, these effects influence noticeably the intensity fluctuations.

Certain important characteristics of the radiation fluctuation structure can be explained on the basis of the theoretical model of propagation of spatially limited beams in a homogeneous isotropic turbulent atmosphere. At a number of additional assumptions, this model yields estimates of the laser-radiation parameters on urban atmospheric paths, which agree with the experimental data.

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