LASER BEAMS BEHAVIOR UNDER THE CONDITIONS OF TURBULENCE INTERMITTENCE IN THE ATMOSPHERE AND FRACTAL-LIKE STRUCTURE OF INTENSITY FLUCTUATIONS

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ABSTRACT

The results of experimental and theoretical analyses of the influence of atmospheric turbulence intermittence on the laser beam structure near the ground are presented. The multiparametric study of the experimental data obtained using paths of different geometry in the site of large city shows that the sporadic beam stochastisation is due to the fine-scale turbulence intermittence. Two beam states are observed: the quasi-regular and the stochastic and the transition from one state to another occurs by leap. More clearly this phenomenon manifests itself in narrow collimated beams with Fresnel number near to unity. Even the small increasing of this parameter leads to the prevailing of stochastic state. It is found out that the fractal structure of the turbulent inhomogeneities shows itself in fractal structure of the radiation fluctuation processes. The results of wavelet analysis are presented. The simulation of the behavior of a laser beam propagating through the moving random phase screen with fractal characteristics qualitatively approves the experimental results. This may allow to propose new approaches to the atmospheric turbulence sounding.

INTRODUCTION

Atmospheric turbulence severely degrades the performance of optical communication links as well as different metrologic devices in the near-the-ground atmosphere. The complicated underlying surface including large city area may appear the cause of different instabilities. The approaches and theoretical estimations usually used for prediction of laser beam behavior along the tropospheric paths near the ground appear to be rather rough and inadequate for practical purposes. One of the interesting problems to be studied is the influence of the fine-scale turbulence intermittence on the laser beams behavior. It is found out that the intermittence of the fine-scale atmospheric turbulence strongly affects the beam parameters[1]. The regions of rather slightly disturbed turbulence in the near-the-ground layer may alternate with peculiar "spots" of regions with small-scale turbulence. The forming of such turbulence regions results in beam stochastization and adversely affects the bulk of information transmitted and its quantity. At the Physics Faculty of Moscow State University the series of experimental and theoretical investigations were carried out to estimate the effects of turbulence intermittence on laser beams which allowed to propose new approaches to sounding of the turbulence and beam structure.

EXPERIMENTAL SETUP

To obtain the experimental results we used horizontal and slant paths typical for communications in the large city site (fig. 1). These paths were acting in radar state. Their length was near to 300 m in one direction. He-Ne laser with ?=0.63 mkm was used. Receiving and transmitting devices were settled at the height of about 25 meters above the earth. The reflecting mirror of the slant path was placed at the height of 165 meters. Receiving devices allowed measuring of amplitude-phase characteristics of the beam under different meteorological conditions. The readings of the path meteorological parameters were taken at the levels of 2.5, 25 and 165 m. That allowed getting the values of refractivity structure characteristic. Using the computer technologies gave the opportunity to produce the multiparametric analysis of the radiation and turbulence statistic parameters including the methods of fractal and wavelet analyses. To obtain the local intensity fluctuations the photo-diodes were used. Mach-Zander shift interferometer was applied to study phase fluctuations. To introduce beams images into the computer we used CCD- matrix. The experimental device allowed to change the beam diameter and the distance between the beams.

RESULTS AND DISCUSSIONS

The results showed that the sporadic changes in the state of fine-scale turbulence effect in distinctive alternation of two

Fig. 1. The experimental setup.

laser beam states. This usually occurs when the temperature gradients with height appear to be of a rather large value. One of these states – so called quasi-regular – is characterized by the weak distortions of the initial amplitude – phase profile. The second – stochastic one – reveals a speckle-like structure of the intensity distribution over the beam cross-section. The transition from one state to another occurs by leap and has quasi-periodical character. The state duration may change in the range of parts of second to several seconds this depending on meteorological conditions. More distinctly the states alternation is observed in the narrow collimated beams with the Fresnel number equal to unity. Even the small raising of the beam Fresnel number leads to the situation when the stochastic state of the beam prevails. This effect of the beam structure intermittence one may explain supposing that the beam stochastization is due to the sporadic process of small-scale turbulence development. The theoretical model used for the explanation of the results obtained is based on the suggestion that such changes of the beam structure are due to the changes of the turbulence inner scale. The analysis was carried out in the frames of Kolmogorov theory [2]. Narrow collimated beam has the smallest diffraction diameter. So it appears to be more sensitive to the changes of the turbulence inner scale close to its cross-section size.

The inner scale appears to be greater than the beam radius the turbulent broadening is insignificant and the center of gravity displacements are strong and vice versa. The experiment showed that the correlation radius decreases significantly under the conditions of stochastic beam state and a lot of helical dislocations appears in its cross-section. If one suppose that the turbulence inner scale and the intensity correlation radius are of the same order for the stochastic beam state one can get the characteristic inner scale of about (0.2 – 0.4) cm. In this case the theoretical and experimental values of the beam diameter and center of gravity displacements coincide in the limits of error. So the theory predicts and the experiment confirms that for more wide collimated beams the duration of their stochastic state is greater, the spatial structure being in this case more complicated. The critical radius of the output aperture exceeding of which leads to practically complete beam stochastization slightly depends on meteorological conditions and corresponds to the Fresnel number in the range of 0.5 – 1.5. The significant differences in the structure of intensity fluctuations under the beam transition from quasi-regular to stochastic state are characteristic to the local intensity fluctuations no matter if they are registered in the beam center of gravity or in the fixed point of the receiving aperture. This data are confirmed by the simultaneous registration of the structure of the beams propagating along the near to parallel paths (fig.2). It demonstrates the influence of the atmospheric turbulence intermittence on the laser beams structure. It can be seen that even under the conditions of weak turbulence the wide beams can get the stochastic structure (3*a*) . Under the conditions of developed fine-scale turbulence the beams stochastization is observed independently of the diameter. Using the narrow collimated beams allowed to state that their stochastization stays synchronous uptill the distance between them is approximately of about 1 m.

To describe the properties of the atmospheric turbulence and the behavior of the beams propagating near the ground

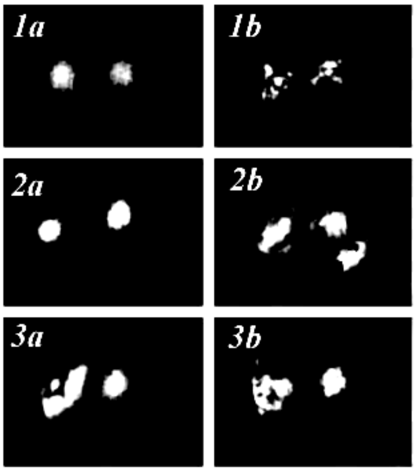

Fig. 2. The influence of the atmospheric turbulence intermittence on the structure of laser beams propagating along the near-to parallel paths. The distance between the beams centers 4.5 cm. Fresnel number ? for the right beam is equal to 1 cm. For the left beam diameter is equal to 1 cm (1), 1.6 cm (2) and 2 cm (3). (*a*) – weakly developed fine-scale turbulence; (*b*) – highly developed fine-scale turbulence

we started to use the elements of wavelet and fractal analyses. Below some results of this study are presented. Fig. 3 depicts the temporal changes of the local intensity of laser radiation (upper curve). Below there is a picture of the wavelet transform coefficients. The picture on the right represents an example of the temporal fluctuations of temperature in two points separated at the distance of 1 cm. Respectively below there is a picture of the wavelet

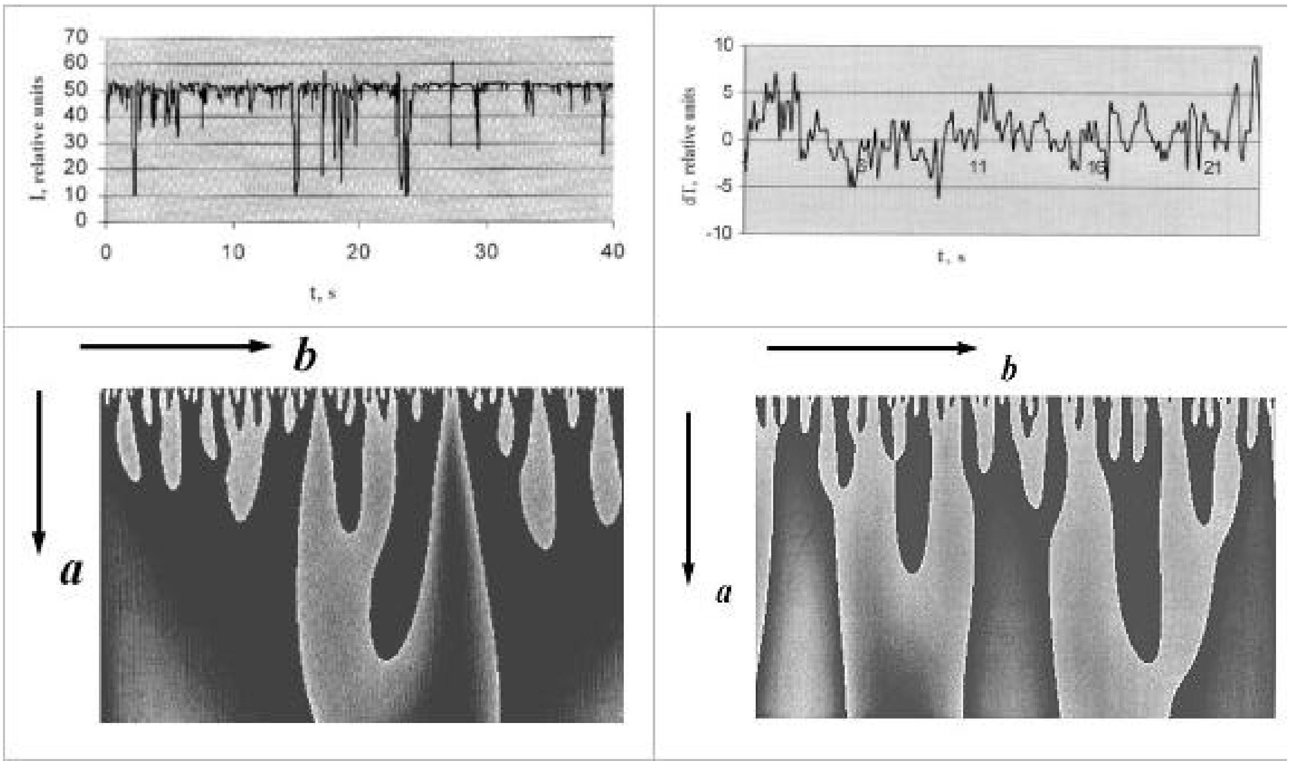

Fig. 3. Temporal changes of the local intensity of laser radiation (upper curve on the left). Below there is a picture of the wavelet transform coefficients. The upper curve on the right represents an example of the temporal fluctuations of the temperature in two points separated at the distance of 1 cm. Respectively below there is a picture of the wavelet transform coefficients (? – is a scaling coefficient, *b* – is a shift parameter).

transform coefficients (? – is a scaling coefficient, *b* – is a shift parameter). The results presented allow to see the hidden periodicity of the fluctuation process. The results of the analysis allow to conclude that the periodicity of large-scale temperature fluctuations is about the same as that of the large – scale intensity fluctuations of the beam. It is very difficult to investigate this phenomenon using other methods. It allows to use wavelet analysis for studying the intermittence of the atmospheric turbulence. The branching of the coefficients observed may appear the evidence of the presence of fractal peculiarities in the structure of turbulence and radiation.

We investigated the fractallity of the intensity fluctuations as well as that of the center of gravity displacements. The analysis was based on the relationship [2]:

$$<[X(t^2)-X(t_1)]^2>=\sigma^2|t_2-t_1|^{2H} \qquad (1)$$

Here $X(t)$ – the temporal behavior of the signal parameter, σ^2 – its variance, $|t_2-t_1|$ distance in time, H – is the so called Herst parameter. It is connected with the fractal dimension D by the following relationship:

$$D=2-H. \qquad (2)$$

By getting the logarithm of the left an right sides of (1) one can get the value of H and accordingly the value of fractal dimension. Some of the experimental results are presented in fig. 4. There are the structure of the analog signal characterizing the local intensity fluctuations under the stochastic (*a*) and quasi-regular (*c*) states. Curves *b* and *d* represent the variance of this signal increment via the time interval increment. The estimation gives H_b = 0.92 and H_d = 0.94 for the *AB* range for pictures *b* and *d respectively*. Accordingly D = 1.06 thus rejecting the existence of fractality in this range. It can be due to high frequencies filtering. In the range *BC* H_b is equal to 0.39 and 0.28 respectively. In this case D is about 1.6. So the fractality is clearly observed.

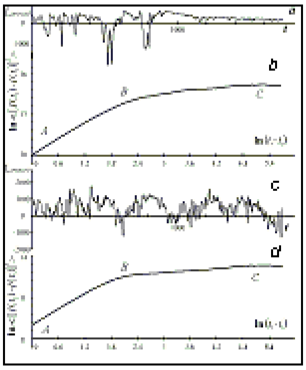

Fig. 4. Fractality features in the local intensity fluctuations

The simulation of the behavior of a laser beam propagating through the moving random phase screen with fractal characteristics qualitatively approves the experimental results.

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