CORRELATION OF THE INTERMITTENCE IN THE STRUCTURE STATES OF WAVE BEAMS ALONG SPACED PATHS AND SOUNDING OF SMALL-SCALE TURBULENCE

T.I. Arsen'yan, P.V. Korolenko, G.V. Petrova, and S.V. Embaukhov

M.V. Lomonosov State University, Moscow

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In this paper we describe the experimental data on the intermittence in structure states of laser beams along spaced paths in different directions under urban conditions. These results are compared with the characteristics of atmospheric stability on the path. It is shown that the development of small-scale instabilities in air on an optical path may be the cause of the intermittence in the beam structure states. It is found that the beam stochastization along a slant path is weaker than along a horizontal one that is due to the altitude variation of meteoparameters. Determination of a direct connection between the intermittence of turbulence and that in the structure states of laser beams makes it possible to use the method of transmitting laser radiation through the atmosphere along spaced paths for diagnostics of the small-scale turbulence structure in the atmospheric boundary layer.

As a rule, analysis of wave-beam parameters, propagated along the surface tropospheric paths, is assumes that statistically, the characteristics of the air mass along the path are uniform and isotropic.

Such an estimate of propagation conditions is rather rough and inadequate for practical purposes. In practice the turbulence distribution in the atmospheric boundary layer, in time and space, is very irregular and intermittent. This intermittence of turbulent motions strongly affects the beam surfaces. The influence of the effects producing the shift of inhomogeneity spectrum toward high-frequencies is of fundamental importance. The formation of regions with small-scale turbulence on the paths results in the beam stochastization and adversely affects the bulk of information transmitted and its quantity.

Development of theoretical models of the small-scale turbulence in the atmospheric ground layer and collecting relevant experimental data could be a subject of special concern for the researchers. Having generalized a series of investigations,[1] we can state that in a wide range of meteorological situations there occurs the process of the transition to spatial organization of small-scale turbulence in the form of isolated jet streams, globules, filaments, and the like. Peculiar "spots" of regions with small-scale turbulence in the near-ground layer can alternate with the regions of almost laminar air flows.

This paper is devoted to the consideration of the question on the extent to which the above model of small-scale turbulence is applicable to surface paths under urban conditions as well as the effect of the development of the turbulence fine structure on the evolution of characteristics of optical beams.

The following results have been obtained on the near-ground horizontal and slant location-type paths. We used the radiation of a single-mode He–Ne laser at 0.63 μm wavelength. The receiving-transmitting optics for both the horizontal and slant paths were placed at 25 m height, while the reflecting mirror of a slant path was at 165 m height. The horizontal path length was 285 m, the slant path length was 320 m in one direction. For elevation angle of the direction along the slant path was 30 degrees. During the experiment we measured the intensity and phase distributions of the beam over the input aperture as well as their time variations. For entering the images of the beam structure and its shear interferograms into a computer we used a CCD matrix and corresponding software. When recording the radiation parameters, we have also measured the meteorological quantities along the measurement paths.

From the experiments carried out during 1994–1996 we have determined the intermittence between the quasi-regular (weakly perturbed) and stochastic (strongly perturbed) beam structure states. The transition from one state to another occurred stepwise and was accompanied by a sharp decrease of the spatial coherence radius. The formation of a speckle-like intensity distribution of light beams occurred at a relatively small distance, at which traditionally the validity of the geometric optics laws could be expected.

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TABLE I. Laser beam structural state as compared with the parameters of stability of the slant path.

Data of the experiment	Altitude temperature gradient $\Delta T/\Delta h$, °C/m	Temperature variation in the Earth-paths layer $\vert\Delta T\vert$, °C	Ratio of variations of temperature and wind velocity in the Earth-paths layer $\vert\Delta T/\Delta v\vert$, °C/(m·s^{-1})	Parameter of stability of the layer B	Richardson number $\vert$Ri$\vert$	Predominant beam structure
31.10.95	0.024 stable	0.6 stable	0.6 stable	0.032 stable	0.555	stochastic
01.11.95	− 0.076 unstable	1.9 unstable	0.95 moderate unstable	− 0.916 highly unstable	− 0.441	stochastic
01.11.95	− 0.036 unstable	0.9 unstable	0.9 highly unstable	− 0.43 highly unstable	− 0.835	stochastic
02.11.95	− 0.152 unstable	3.8 unstable	0.9 highly unstable	− 0.203 highly unstable	− 0.878	quasi-regular, snowfall
09.11.95	− 0.012 unstable	0.3 unstable	0.3 neutral	− 0.016 unstable	− 0.278	stochastic
13.11.95	− 0.008 unstable	0.2 unstable	0.2 neutral	− 0.011 unstable	− 0.187	stochastic
13.11.95	− 0.06 unstable	1.5 unstable	1.5 highly unstable	− 0.08 unstable	− 1.40	equally probable every
14.11.95	− 0.044 unstable	1.1 unstable	0.44 weakly unstable	0.033 highly unstable	− 0.161	stochastic

Table I gives the results of analysis of the averaged meteorological conditions, on a slant path, as compared with the dominant structure state of the laser beam occurred under conditions with temperatures below zero. Using the meteorological data we have calculated the values of parameters used for estimating the degree of path stability (the temperature difference at points of location of the receiving-transmitting devices and mirrors, the altitude temperature gradients, the relationship of temperature difference on the path to the velocity difference at the upper and lower points of the path, coefficients of path stability, and the Richardson number). Analysis made confirmed our statement that intermittence between the structure states of the laser beams is a necessary characteristic of both stable (including inversions) and unstable states of the atmosphere with the exception for the cases when a dense water aerosol is present on the path.

Since the stochasticity of the laser beam structure is connected with the small-scale inhomogeneities, whose dimensions are compared with those of the first Fresnel zone, it can be assumed, based on the data given in Table I, that the small-scale turbulence is developed both under unstable and stable atmospheric conditions. In the first case the basic factor, resulting in the occurrence of areas with small-scale turbulent formations, is the formation of convective turbulent jets in the turbulent layer. In the second case it may be the shear effects due to the friction against the underlying surface.[1–3]

As the experiment has shown,[4] the duration of characteristic periods of stochastization is not directly related to the wind velocity. Consequently, the occurrence of turbulent spots on the path is not always determined by the wind drift. The formation of turbulent spots may be a result of the development of instabilities of the optical path in air. This agrees with the measurement data obtained earlier using aerostats and refractometers[5,6] as well as with the observational data on temperature fluctuations at a weak wind under conditions of cooling.[7]

A detailed description of the phenomenon studied needs for data on the size of the air mass volume, whose variation results in the beam stochastization. To obtain these data, the measurements on the basic horizontal path were supplemented by those on the auxiliary paths. The radiation from an independent laser source with the same wavelength was emitted along an auxiliary sounding path. During the experiments, geometry of the auxiliary optical path could be changed that enabled us to vary the distance between the paths in a wide range.

From these experiments conducted enabled us to arrive at the conclusions that:

1. Stochastization of the beams propagated along parallel paths, at the distances between the beams of several tens of centimeters, takes place synchronously,

independent of the duration of the stochastization periods.

2. Synchronism of structural intermittence occurs only at long-duration stages of stochastization while being absent at the short-duration stages with the further increase of the spacing between the paths. The trend has been revealed toward the delay of the long-duration stages of stochastization on an auxiliary path shifted relative to the basic one along the wind direction.

3. The correlation between the processes of structural intermittence in the beams completely disappears at the separation between the paths of several tens of meters.

These experimental results well agree with the results obtained in the centimeter wavelength range[4] what is indicative of same physical nature of fluctuations for the radiation of centimeter and optical ranges. This enables one to make use of the beam stochastization phenomenon at the diagnostics of the tropospheric turbulence intermittence.

The experimental data show that the fine structure of a wave beam reacts on the approaching meteorological front. A sharp decrease of temperature in winter results in the total degeneracy of the stable beam phase and only the stochastic beam state is being recorded in the experiments.

The information obtained about the correlation of the periods of beam stochastization on the spaced near-ground paths makes it possible testing models of spatiotemporal structure of atmospheric turbulence in the ground layer that are being actively developed at present. When the turbulence, in the ground layer, undergoes a change in its state relatively small-volume areas are being formed where sharp increase of the small-scale turbulence power occurs. Typical dimensions of these formations can vary in from ten centimeters to ten meters, and "the lifetimes" – from fractions of a second to several tens of seconds.

We have compared the experimental data on intermittence of structure states of the laser beams propagated along the horizontal and slant paths. Table II presents the data on the values of average intensity, the variance of intensity fluctuations, spatial correlation radii, and spatial spectrum widths in the horizontal and vertical cross sections for the stochastic states of a beam for both paths. From the data regarding the correlation radius it is evident that its value for the horizontal path turns out to be much smaller than that for the slant path. It follows from these results that the processes of beam stochastization manifest themselves stronger on a horizontal path as compared to vertical ones. That may be caused by both the existence of altitude dependence of meteorological parameters and smaller value of the effective transport velocity along a slant path. It should be noted that the widths of spatial frequency spectra for the horizontal and slant paths noticeably differ even under conditions of synchronous variations.

TABLE II. Comparison of beam characteristics at synchronous measurements along the horizontal and slant paths.

Number of recording series	Type of the path	Average intensity $<I>$	Dispersion of intensity σ_I^2	Correlation coefficient ρ, cm	Spatial spectrum width in vertical cross section	Spatial spectrum width in horizontal cross section
1	horizontal	57.0	0.22	0.3	1.4	0.7
	slant	63.0	0.32	0.5	1.1	1.0
2	horizontal	58.9	0.2	0.3	1.1	0.7
	slant	63.4	0.32	0.6	0.9	1.1
3	horizontal	70.7	0.12	0.4	1.1	0.7
	slant	62.8	0.32	0.6	0.8	0.7
4	horizontal	69.6	0.16	0.5	0.7	0.6
	slant	59.8	0.55	0.8	0.5	0.7
5	horizontal	66.1	0.13	0.4	0.5	0.6
		64.3	0.35	0.7	0.4	0.5

The existence of direct ratio between the turbulence intermittence and the intermittence of the laser beam structure states provides for good grounds to use the method of atmospheric transmission with a laser radiation, along spatially separated paths, for the diagnostics of the small-scale turbulence structure of the paths.

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