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EFFECT OF LOW-SCALE ATMOSPHERIC TURBULENCE ALTERNATION ON THE CHARACTERISTICS OF NARROW COLLIMATED LASER BEAMS

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Factors affecting amplitude and phase fluctuations in detection-and-ranging-type optical systems under alternating atmospheric turbulence conditions are considered. Experimental data characterizing, as applied to a narrow collimated laser beam, the effects of random wandering, turbulence broadening, and variation of the correlation radius of the intensity fluctuations are obtained and analyzed. The sporadic radiation stochastization observed is explained by the sharp reduction of the internal turbulence scale in comparison with the average beam size.

Upgrading the optimization techniques for the parameters of atmospheric optical data transmission channels is closely associated with generalization of available experimental data on the character of the amplitude and phase perturbations of the light beam used, as well as with the development of theoretical models adequately describing the actual mechanism whereby the propagation medium turbulence influences the radiation space-time structure. In the present work, this problem is considered as applied to detection-and-ranging-type optical systems operating with narrow collimated beams under alternating atmospheric turbulence conditions.

Comparing the experimental results and the two thirds law [1, 2] shows that, in the near-surface air layer, turbulence is more involved due to various instabilities developed therein. In this case, a spatial nonuniformity of low-scale turbulence manifests itself at the observation point [3] as the process of alternation of fast and slow temperature and refractive index fluctuations. These fluctuations are uniquely associated with the alternation of large- and low-scale turbulence.

The alternation of turbulence is observed both under stable, indifferent and unstable stratification of the atmosphere. Despite a wide variety of physical factors at work, a tendency is clearly defined toward spatial arrangement of low-scale turbulence in the from of individual jets, filaments, globules, spots, etc. When evaluating the effect of low-scale turbulence on the characteristics of radiation, the following important question remains open: Will the allowance for the effect of turbulence alternation have the character of corrections to the data obtained on the basis of the classical notions of the turbulence development [1, 4, 5], or will it necessitate a substantial revision of the existing approaches to the description of laser beam perturbations?

The experiments were conducted on a detection-and-ranging-type atmospheric route constructed in Vorob'evy Gory, southwest of Moscow [6, 7] using the buildings of Moscow State University. The route was located at a height of 25 m above the ground and had a length of 280 m in one direction. To exclude the fluctuation amplification effect, the entrance and exit apertures of the detection-and-ranging route were spaced 50 cm apart. The source of cw radiation was a single-mode He–Ne laser operating at a wavelength of $\lambda = 0.63$ μm. A telescope formed a narrow collimated beam with a Fresnel number close to unity at the exit aperture. The beam returning from the route was directed into a device that registered the phase and amplitude characteristics of the light field by means of a shearing interferometer and a CCD array. The registration equipment contained a PC graphic input device operating under a television transmission standard. To perform a multiple-parameter express analysis of the beam images and interferograms entered into the computer, use was made of custom-made software. Simultaneously with optical measurements, the meteorological parameters of the route were estimated (temperature, pressure, humidity, wind velocity and direction, and visibility range) at the locations of the registration equipment and reflecting mirrors and also in the immediate vicinity of the underlying surface. The analysis of these data made it possible to estimate the structural characteristic of refractive index fluctuations, C_n^2, by means of the relations [1]

$$\begin{aligned} C_n^2 &\cong 10^{-13} C_T^2 \langle T \rangle^{-2}, \\ C_T^2 &= 2.8 a^2(\mathrm{Ri})(K_k h)^{4/3} [d\langle T \rangle / dh]^2, \end{aligned} \tag{1}$$

where $a^2(\mathrm{Ri})$ is the universal function of the Richardson number Ri, K_k is the Karman constant, and $d<T>/dh$ is the average temperature gradient along the height h.

In the course of measurements taken in 1995–1998, it was found that on the route there occurred either weak or strong fluctuation regimes, depending on the weather conditions (the magnitude of C_n^2 varied between 10^{-10} and 10^{-17} cm$^{-2/3}$). Weak fluctuations are characteristic of atmospheric stratification close to the indifferent type, whereas strong ones, of pronounced stratification and occur, as a rule, in windy weather. The instabilities developing in the atmosphere at sufficiently high vertical temperature gradients manifest themselves as the alternation of two structural states of the laser beam [6, 7]. One, the quasiregular state, is characterized by a large intensity variation correlation radius, close to the beam radius, and a dislocation-free structure of the wave front. The other, stochastic state, the transition to which occurs in a stepwise fashion, is characterized by a smaller (sometimes by an order of magnitude) intensity variation correlation radius. In the cross section, there is observed an irregular, speckled-type intensity distribution with numerous screw dislocations in the wave front. The transitions between these states are of quasiregular character, and the lifetime of each state may vary from a few seconds to a few tens of seconds.

In the stochastic state, the beam experiences a perceptible turbulence broadening. In this state, the beam cross-sectional dimension is usually 1.5–2 times that in the quasiregular state. The stochastization of the beam somewhat reduces the random displacements of its "center of gravity", whose frequency under these conditions increases from a few hertzes to a few tens of hertzes. Experimental values of the mean beam diameter D and the mean square ρ_c^2 of the displacements of the beam center of gravity in the different structural states are listed in Table 1.

Table 1

Beam Parameters in Different Structural States

Beam parameters	State			
	quasiregular		stochastic	
	exper.	theor.	exper.	theor.
Diameter D, cm	3 ± 0.5	2.1	8 ± 1	7.2
Mean square of center of gravity displacements ρ_c^2, cm^2	8.2 ± 2.5	4.02	3 ± 1	3.6

The above data were obtained in Spring at the ambient temperature of $-1\,^\circ$C at the height of the route and $-2\,^\circ$C at a height of 2 m above the ground. The wind velocity was equal to 1 m/s. These conditions correspond to $C_n^2 = (2 \pm 0.5) \times 10^{-14}$ cm$^{-2/3}$. When experimentally determining the ρ_c^2 value, use was made of a reference system fixed to the entrance aperture of the transmitter-receiver system. The fluctuation level of the intensity and the beam diameter were determined in a reference system fixed to the beam center of gravity. After the frame-by-frame recording of the parameters of interest, they were averaged over 10–20 frames relating to the appropriate state of the beam.

When the beam is in its quasiregular state, its phase fluctuations are mainly caused by the wave front slope variations. In the stochastic state of the beam, these variations are first of all governed by the local phase variations associated with the development of screw dislocations in the wave front.

To theoretically estimate the effect of the internal turbulence scale l_0 on the structure of turbulence, use is usually made of a model of the form [1]

$$\Phi_n(K) = 0.033C_n^2K^{-11/3}\exp(-K^2/K_m^2),$$

where K is the wave number of inhomogeneities, and $K_m = 5.92/l_0$.

Within the framework of this model, the alternation of turbulence can be caused by the sporadic variations of C_n^2 and K_m and the exponent of the power spectral function $\Phi_n(K)$. We assume that the variation of the parameter K_m is the determining factor in the change of the structure of the laser beam upon its sporadic transition from one state to the other. Note that for the routes used in the experiments, which are raised high enough above the underlying surface, neither the value of the external turbulence scale L_0, nor its variations will have any perceptible effect on the beam characteristics [8, 9].

Let us specify the distribution of the single-mode laser beam entering the turbulent medium by the expression

$$u_0(\rho) = \exp[-(\rho^2/2a^2) - (ik\rho^2/2F)],$$

where a is the effective beam radius at the transmitting aperture, F is the radius of curvature of the phase front at the center of the aperture, and ρ is the radial coordinate in the beam cross section.

To describe the diffraction broadening of the laser beam en route, use is made of the diffraction beam radius [9]

$$a_g = ag/\Omega. \tag{2}$$

Here $\Omega = ka^2/L$ is the Fresnel number of the beam cross section at the transmitting aperture, L is the route length, k is the wave number, and $g^2 = 1 + \Omega^2(1 - L/F)^2$ is the generalized diffraction parameter of the beam. It follows from expression (2) that the narrow collimated beam ($L/F = 0$, $\Omega = 1$) has a minimum diffraction size. Such a beam most distinctly responds to the variations of the internal turbulence scale l_0 that occur in the vicinity of the mean cross-sectional dimension of the beam. Since the experiments described above were conducted with narrow collimated beams, the analysis of the fluctuation characteristics of radiation will be performed for the case $L/F = 0$, $\Omega \sim 1$.

If l_0 perceptibly exceeds a, the turbulence broadening of the beam proves to be insignificant. At the same time, turbulence causes substantial random displacements of the beam center of gravity. The mean square of these displacements is in that case defined by the expression [10]

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

The relative dispersion of the intensity logarithm fluctuations is [8]

$$\sigma^2 = 3.2C_n^2L^3l_0^{-7/3}. \tag{4}$$

If $l_0 \ll a$, then a noticeable turbulence broadening of the beam will occur with the magnitude of σ^2 being close to unity. This case can be described within the framework of the theory of spatially bounded beams [8, 10], which holds true for well-developed turbulence. The effective size D of the beam determined by its diffraction and turbulence broadening is defined by the expression [8, 9]

$$D = 2a[g^2 + 0.46(2.8\beta_0^2)^{6/5}]^{1/2}, \tag{5}$$

where $\beta_0^2 \cong 1.24\,C_n^2k^{-7/6}L^{11/6}$.

To estimate the mean square of the displacements of the beam in the case of its turbulence broadening, use is made of the relation [9]

$$\rho_c^2 = 1.54a^2(2.8\beta_0^2)^{4/5} - 1.78a^2(2.8\beta_0^2)^{5/8}. \tag{6}$$

The correlation radius r_c of intensity fluctuations in the beam with turbulence broadening can be found as [9]

$$r_c = r_0\left[\left(2+\frac{4}{3}q\right)\Big/\left(\frac{4}{3}+\frac{1}{3}q\right)\right]^{1/2}, \tag{7}$$

where $q = 1.22\beta_0^{12/5}$, and $r_0 = \sqrt{L/qk}$ is the spatial coherence radius of the plane wave field. The above relations may serve as a basis for calculating and optimizing the characteristics of narrow collimated beams used for detection and ranging purposes.

In evaluating the degree of suitability of the theoretical model presented above for the description of experimental data, we assume that the quantity C_n^2 entering the theoretical relations corresponds to the values found by formula (1) and is a quantity averaged over a sufficiently long time interval (much in excess of the lifetimes of the individual structural states of the beam). Relation (4) makes it possible to determine the internal turbulence scale. For a quasiregular state of the beam with an intensity fluctuation dispersion $\sigma^2 = 0.1$–0.3, l_0 ranges from 4 to 15 cm. Thus, the quasiregular state of the beam corresponds to the case where the beam size (in our experiments, the beam diameter is $2a = 1.5$ cm at the exit aperture and $D \cong 3$ cm at the entrance aperture) is inferior to the internal turbulence scale, and to describe this state, use can be made of relation (3). For the conditions corresponding to the data listed in Table 1, the mean square of the displacements of the beam center of gravity found with its help is $\rho_c^2 = 4.02$ cm^2. The discrepancy existing between the theoretical and experimental values can be considered quite acceptable, considering the quadratic character of ρ_c^2.

As shown by experiment, the transition to the stochastic state is characterized by a sharp reduction (almost by an order of magnitude) of the correlation radius of the intensity fluctuations and a perceptible turbulence broadening of the beam. If we assume that the variation of the internal turbulence scale is of the same order of magnitude as that of the correlation radius of the intensity fluctuations, then, for the stochastic state of the beam, we get $l_0 \cong 0.2$–0.4 cm. With l_0 being so high and $C_n^2 = (2\pm0.5)\times10^{-14}$ cm$^{-2/3}$ as indicated above, estimating the correlation radius of the intensity fluctuations by formula (7) yields $r_c = 0.2$ cm. The estimation of the turbulence broadening of the beam by formula (5) shows that the transition to low-scale turbulence substantially increases the beam size. In that case, the experimental and theoretical values of the beam diameter coincide to within the measurement error (see Table 1). The mean square of the displacements of the beam under its turbulence broadening is calculated by formula (6) to be $\rho_c^2 = 3.6$ cm^2, which is also in good agreement with the values found experimentally.

Therefore, the approach used in this work allows one to estimate to acceptable accuracy the variations of the narrow collimated beam characteristics upon sporadic development of low-scale turbulence. This approach may prove fairly useful in optimizing the parameters of near-surface optical routes from the standpoint of providing stable level and character of the amplitude and phase fluctuations of the beams used.

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