EXPERIMENTAL INVESTIGATION OF FLUCTUATIONS OF A SPHERICAL WAVE REFLECTED FROM A MIRROR IN A TURBULENT ATMOSPHERE

A.P. Ivanov, G.Ya. Patrushev, and A.P. Rostov

Institute of Atmospheric Optics, Siberian Branch of the USSR Academy of Sciences, Tomsk

Received June 2, 1989

The results of experimental investigations of the fluctuations of the intensity of spherical wave reflected from a circular mirror in a turbulent atmosphere are presented. It is shown that the intensity of the fluctuations are intensified and their temporal spectra undergo a low-frequency shift as the distance between the receiver and source is increased, both in the region of weak fluctuations and on transition to strong fluctuations. A simple physical interpretation of the effects studied is given.

The propagation of laser radiation on ranging paths results in the appearance of a number of effects which are not observed on straight paths.[1] The correlation of the fluctuations of the field of an optical wave, propagating through the same nonuniformities in the forward and backward directions, in certain situations results in the intensification of backscattering (increase in the average intensity),[1] intensification of intensity fluctuations,[2] and change in the temporal structure of the fluctuations. It is very convenient to study these effects theoretically for cases of so-called weak and saturated fluctuations of the intensity, i.e., essentially, for the asymptotically limiting conditions of propagation in a turbulent atmosphere. The amplification of backscattering accompanying reflection from a rough surface was studied experimentally in Ref. 4 and the intensification of intensity fluctuations was studied in Ref. 5, where the region of spatial localization of intensification of weak fluctuations was determined.

In this work these studies are continued for the conditions of propagation corresponding to transition from weak fluctuations to strong fluctuations, and the behavior of the temporal spectra of the intensity fluctuations is studied. It is shown that the temporal spectrum of the reflected signal is shifted into the region of low frequencies, and the magnitude of the shift depends on the height of the intensity fluctuations and the distance from the radiation source. A simple qualitative interpretation of the observed effects is given.

A diagram of the experimental setup on which the measurement were performed is shown in Fig. 1. The laser beam 1 was directed through a diaphragm in the plate 2 into the atmosphere, where a reflector 3 was positioned 400 m away. The plate 2 had two circular diaphragms 1.2 mm in diameter, positioned at a distance of 3 mm from one another; one diaphragm was used to obtain a quasispherical wave from the laser (the wave parameter of the emitter > 100) while the second diaphragm formed the reference channel of the reflected wave. In the measurements a high-quality circular mirror 500 mm in diameter was used as the reflector; this made possible complete interception of the incident radiation. The receiving channel of the reflected wave consisted of reference and signal channels. The signal channel was formed by the plate 4 and contained a row of rays, formed by circular diaphragms with equal diameters (0.9 mm) uniformly spaced in the plate. The distance between the diaphragms and the distance between the first and optical axis of the laser beam were equal to 3 mm. The row of beams formed by the reflecting prism 5 was directed on the photodetector 7, which was able to move in a plane perpendicular to the direction of propagation of the beams. Thus as the detector was moved signals of the reflected wave were obtained successively for different distances from the optical axis of the source. Analogously, the beam in the reference channel was directed with the help of a reflecting prism 6 onto a photodetector 8. The photodetectors in both channels consisted of FEU-79 photomultipliers with shields 10 and interference filters 9 with a transmission band of ≃ 30 Å.

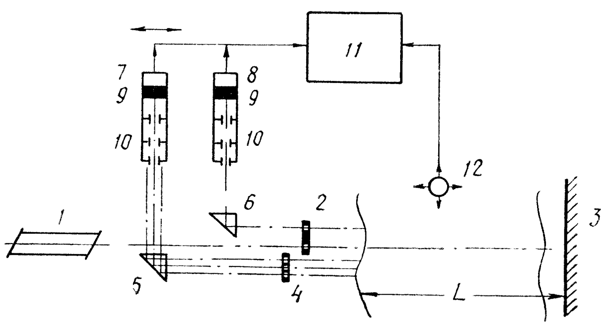

FIG. 1. Diagram of the experimental arrangement.

The electric signals from the output amplifiers of the photomultipliers were fed into the instrumentation-program complex 11 (Ref. 6), where after low-frequency filtering they were digitized and recorded on a coded magnetic device (CMD) with the following characteristics: the dynamic range was equal to 72 dB and the sampling rate in each channel was equal to 10 kHz. The recorded realizations were processed in the complex, while the spectral analysis was performed on a stationary computer using the program of Ref. 7.

The measurements were performed in October 1988 on a horizontal section of a location with a relatively even underlying surface. The path was located 2.2 m above the ground. The radiation source was an LGN-215 helium-neon laser (the wavelength $\lambda = 0.63$ μm and the power was equal to 55 mW). During the experiment more than 100 50-sec realizations were recorded and processed.

The average v_v and fluctuation $\sigma_\perp$ components of the wind velocity perpendicular to the propagation path were measured with the help of an acoustic anemometer 12 (Ref. 8), placed 100 m from the measurement pavilion, during the entire experiment synchronously with the recording on the CMD.

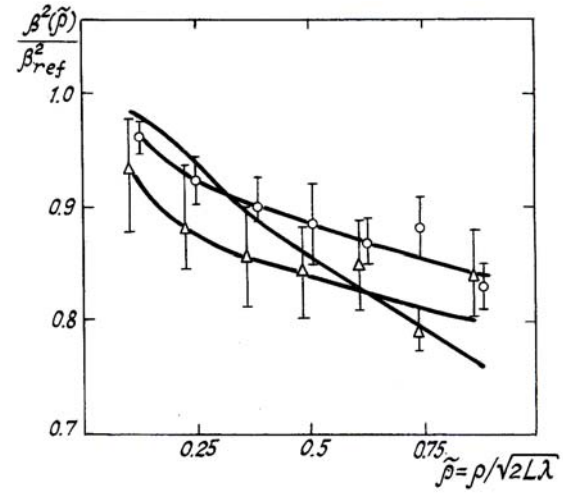

FIG. 2. Measurements of the amplification of the intensity fluctuations.

Figure 2 shows the measurements of the amplification of the intensity fluctuations. The distance ρ between the source and the receiver in a plane perpendicular to the propagation of the wave, normalized to the radius of the first Fresnel zone $\sqrt{2\lambda L}$ for a path of length 21 was plotted along the abscissa axis. The results are presented for two different atmospheric situations with $\beta_0 = 0.5 + 1.0$ (circles) and $\beta_0 = 1.1 - 1.5$ (triangles). The parameter

$$\beta_0 = [1.23 \times C_n^2 \; k^{7/6} \; (2 \; L)^{11/6}]^{1/2}$$

characterizes the degree of turbulence;[1] C_n^2 is the structure constant of the fluctuations of the refractive index of the medium, which was determined from the relative dispersion of the intensity fluctuations of the reflected wave β^2_{ref} in the reference channel; and, $k = 2\pi/\lambda$ is the wave number. The vertical bars indicate the spread in the experimental data. The solid curve corresponds to the theoretical calculation by the smooth-perturbation method.[2]

As one can see from the figure the intensification of the intensity fluctuations can be seen clearly within the first Fresnel zone, and it occurs both in the region of weak intensity fluctuations, which agrees with the results of previous studies,[5] and with the transition to strong intensity fluctuations, which was not studied previously.

The obtained temporal spectra of the fluctuations in the intensity of the reflected wave are presented in Figs. 3 and 4, where the logarithm of the dimensionless frequency $\Omega = f/f_0$ (f is the frequency and $f_0 v_\perp / \sqrt{2\pi\lambda 2L}$ is the characteristic frequency, which is related with the transport time of nonuniformities of the order of $\sqrt{\lambda L}$ in size through the beam with velocity $v_\perp$) is plotted along the abscissa axis and the normalized spectrum $U = fW(f, \tilde{\rho})\,\sigma_I^2$ is plotted along the ordinate axis ($W(f, \tilde{\rho})$ is the spectral density of the intensity fluctuations and σ_I^2 is the variance of the intensity fluctuations).

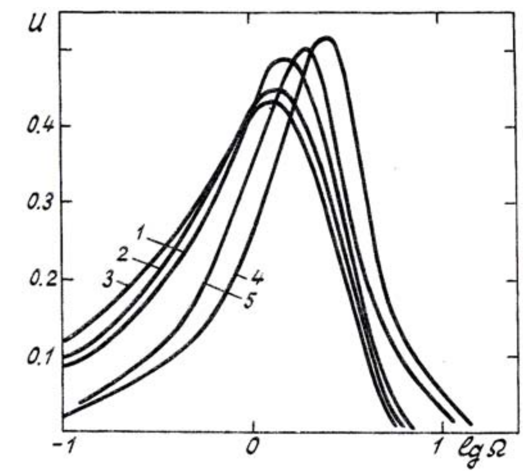

FIG. 3. The normalized spectrum of intensity fluctuations $U = fW(f, \tilde{\rho})$, σ_I^2.
$v_\perp = 3.4$–3.9 m/sec. $\sigma_v = 0{,}4$–0.7. For $\beta_0 < 1$ the experimental values are $\tilde{\rho} = 0.1$ (1), $\tilde{\rho} = 0.4$ (2), and $\tilde{\rho} = 0.9$ (3); the theoretical values are $\tilde{\rho} = 0$ (4) and $\tilde{\rho} = 0.6$ (5).

The spectra were calculated by the fast Fourier transform method followed by smoothing over segments of a realization and over the frequencies. The total number of degrees of freedom was equal to about 1000, which gave a 1–2% error in the estimation of the spectrum over the entire frequency scale. Figure 3 shows the characteristic behavior of the spectra for

$\beta_0 < 1$ (curves 1, 2, and 3), and one can see the low frequency shift of the spectrum of the reflected wave as the distance between the source and the receiver is increased. In comparing with the theory it should be noted that the temporal spectra obtained in the experiment are different from the spectra calculated in the smooth-perturbation approximation (curves 4 and 5) in Ref. 3. It is obvious that the experimental spectra are shifted into the low-frequency region relative to the computed spectra. The disagreement between the positions of the theoretical and experimental spectra on the dimensionless frequency scale is explained by the nonuniformity of the profile of the average wind velocity on the path. Special measurements performed with two acoustic anemometers showed that the components of the wind velocity perpendicular to the path could differ by 30 % for distances of 200 m between them.

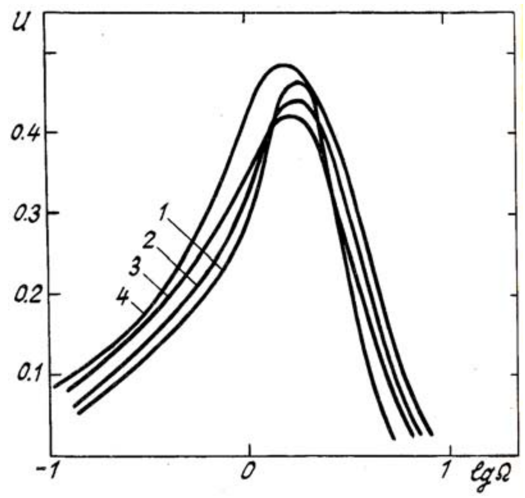

FIG. 4. The normalized spectrum of intensity fluctuations $U = fW(f, \tilde{\rho}), \sigma_I^2$.
$v_\perp = 3.4$–3.9 m/sec. $\sigma_v = 0{,}4$–0.7. $\sigma_v = 0{,}4$–0.7, For $\beta_0 > 1$ $\tilde{\rho} = 0.1$ (1), $\tilde{\rho} = 0.6$ (2), and $\tilde{\rho} = 0.9$ (3); for $\beta_0 < 1$ $\tilde{\rho} = 0.1$ (4).

The results for strong fluctuations ($\beta_0 > 1$) are presented in Fig. 4 (curves 1, 2, and 3). As one can see from the figure the low-frequency shift is also observed in this situation. However it should be noted that the entire picture is shifted into the high-frequency region compared with the case in Fig. 3. This can be seen clearly by comparing the spectra 1 and 4 in Fig. 4, where the spectrum 4 is taken from Fig. 3.

The low-frequency shift of the temporal spectrum and the decrease in the intensity fluctuations as the point of observation is shifted relative to the source of radiation 0 can be interpreted as follows. It is well known that in the case of weak fluctuations, studied here, the spatial nonuniformities of the refractive index, which are located in the region corresponding to the first spatial Fresnel zone, make the main contribution to the fluctuations. For a Kolmogorov spectrum of atmospheric turbulence the size of these nonuniformities is approximately equal to the radius of the first zone. When the point of observation is located on the source 0 the first 1 and second 1′ halves of the Fresnel paraboloid, corresponding to the direct and reflected waves, coincide (Fig. 5), and therefore the wave propagating in the forward and backward directions passes through the same spatial nonuniformities of the refractive-index field (the velocity of light is much higher than the drift velocity of the optical nonuniformities across the path). When the point of observation is displaced to a distance ρ from the source the halves of the Fresnel paraboloid, which correspond to the direct 2 and return 2′ passage of the wave, are also displaced. The tops of the halves of the paraboloid, which are shifted by ρ, rest on a common base, lying on the mirror, where their transverse dimensions are maximum. The direct and reflected waves traverse only the part of the path adjacent to the mirror through the same nonuniformities of the refractive index. The reduces the intensity fluctuations to a value corresponding to the limiting case of propagation of radiation over twice the distance $2L$.

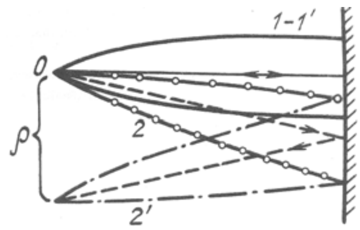

FIG. 5. The Interpretation of the intensification of intensity fluctuations and of the shift in the temporal spectrum accompanying ref lection from a mirror surface.

As one can see from Fig. 5, on the section of the path adjacent to the mirror the total transverse size of the region making a significant contribution to the intensity fluctuations changes by an amount $\rho/2L$ ($\rho \ll L$), which results in a low-frequency shift of the temporal spectrum of the intensity fluctuations as ρ is increased compared with $\rho = 0$ or with direct propagation over the distance $2L$.

We thank M.G. Bondarenko and A.V. Noskov for assistance in performing the measurements and in analyzing the experimental data.

REFERENCES

1. V.A. Banakh and V.L. Mironov, *Lidar Propagation of a Laser Radiation in a Turbulent Atmosphere* (Nauka, Novosibirsk, 1986).
2. S.O. Koval, G.Ya. Patrushev, A.I. Petrov, and V.V. Pokasov, Izv. Vyssh. Uchebn. Zaved. SSSR, Ser. Radiofiz., **23**, No. 3, 326 (1983).
3. G.Ya. Patrushev and V.V. Pokasov, Problems in Atmospheric Optics (Nauka, Novosibirsk, 1983).
4. A.S. Gurvich and S.S. Kashkarov, Izv. Vyssh. Uchebn. Zaved. SSSR, Ser. Radiofiz., 7.20, No. 5, 794 (1977).

5. G.Ya. Patrushev, A.I. Petrov, and V.V. Pokasov, Izv. Vyssh. Uchebn. Zaved. SSSR, Ser. Radiofiz., **26**, No. 7, 823 (1983).
6. A.P. Rostov, Opt. Atmos., **1**, No. 3, 125 (1988).
7. G.Ya. Patrushev and T.P. Pecherkina, Algoritmy i programmy, No. 7, 20 (1987).
8. M.V. Anisimov, E.A. Monastyrnyi, G.Ya. Patrushev, and A.P. Rostov, Prib. tekh. eksp., No. 4, 196 (1988).