ON THE SCATTERED RADIATION INTENSITY FLUCTUATIONS FOR A FOCUSED LASER BEAM IN SNOWFALL

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Some specific features of the variance, correlation function, temporal spectrum, and probability density of the scattered radiation intensity fluctuations for a focused laser beam in snowfall have been established. The measurements have been performed on a 130 m *path within scattering angles from* 0.4 *to* 0.17 mrad.

It is well known[1–4] that during the propagation of a focused laser beam in snowfall a complex spatial distribution of scattered radiation is formed in the focal plane in the form of readily observable spots or "speckles". They result from the interference of waves scattered by snow particles. Speckles change continuously, and the scattered radiation intensity fluctuates in time.

The characteristics of these fluctuations under conditions of precipitation have still received only insufficient study. However, the first data obtained in Ref. 1 at a fixed scattering angle give promise that they can be used not only for identification but also for measurements of some characteristics of precipitation.

The possibilities of optical methods harnessing the speckle phenomenon are described in a number of papers (see, for instance, Ref. 5). To assess these possibilities, we performed a run of measurements of fluctuation characteristics (extended in number) at some scattering angles in 1992–1993.

In this paper the results of joint analysis of the data obtained earlier[1–4] and new data on the scattered radiation intensity fluctuations for a focused laser beam in snowfall are presented.

Let us briefly consider the measurement procedure. (It was considered at length in Refs. 1–4.) An LGN–215 quasi–single–mode He–Ne laser was used as a source of radiation. It had a maximum output power of 50 mW at the wavelength $\lambda = 0.6328$ μm. Its radiation was linearly polarized with the polarization plane being approximately perpendicular to the earth surface. The beam was broadened and focused into a detector with a high–quality collimator being a part of the OSK–2 optical bench. Fresnel's number of the source was $\Omega = k\,a_0^2/L = 38$, where $k = 2\pi/\lambda$, α_0 is the effective beam radius in the source plane, and $L = 130$ m is the path length.

The visible beam diameter on the detector was approximately 3 mm, and the diameter of a receiving aperture placed before a photomultiplier was 0.3 mm. The total field–of–view angle of a receiving system was usually 0.01 rad, in a specific case it was 0.05 rad.

At first, the receiving aperture was visually placed at the center of the focal spot. The location of the aperture was checked by maximum of the signal from the photomultiplier. Then the whole receiving system was displaced at the distance Δl by a fine adjustment screw. The sharp decrease in the low–frequency components of the signal and appearance of its high–frequency components proved that the minimum distance Δl was larger than the beam radius in the recording plane. In our new measurements Δl changed from 5 to 23 mm which corresponded to the scattering angle $\varphi = \Delta l/L = 0.04–0.17$ mrad. In our previous experiments[1–4] Δl was 15 mm and φ was 0.12 mrad. Twelve measurements were performed in snowfall on different days. Their main results are presented below.

First of all it should be noted that the high–frequency component of fluctuations was absent in the scattered signal under conditions of haze (without precipitation and fog). However, the high frequencies appeared in the signal spectrum even under conditions of light snowfall, when the meteorological visibility range was as high as 8–10 km.

Let us consider at first the normalized variance of the signal intensity (I) fluctuations $\sigma^2 = \langle(I - \langle I\rangle)^2\rangle/\langle I\rangle^2$. Here angular brackets denote time averaging. The period of averaging was 20 seconds.

When the maximum diameter of particles $D_M = 1–3$ mm and the optical thickness $\tau = 0.3–0.45$ remain close in values, the variance σ^2 decreases as the scattering angle φ increases (see Fig. 1). Slightly different meteorological conditions ($D_M = 5$mm, $\tau = 0.25$) correspond to the last point ($\varphi = 0.17$ mrad).

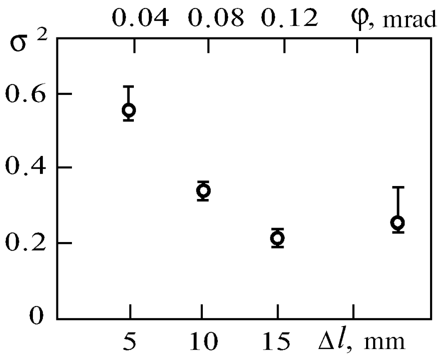

FIG. 1. Variance of the scattered radiation intensity fluctuations σ^2 versus the scattering angle φ (April 6, 1993).

The variance σ^2 was measured as a function of τ at $\varphi = 0.05$ mrad ($\Delta l = 7$ mm). The measurements show that σ^2 depends explicitly on D_M (see Fig. 2). For D_M ranging from one to three millimeters at $\varphi = 0.05$ mrad the dependence of σ^2 on τ is weak (curve *1*). For $D_M = 3–5$ mm at $\varphi = 0.05$ mrad the variance first increases with τ and then saturates (curve *2*). The similar behavior can be seen for $D_M \geq 5$ mm at $\varphi = 0.12$ mrad ($\Delta l = 15$ mm) in the absence of large flakes[1] (curve *3*). The variance saturates at a level of 0.85 at $\tau = 0.2$. By means of visual approximation of the experimental data[2] we derived the analytical expression for the dependence of the variance on the optical thickness of the form $\sigma^2 = 0.85(1 - \exp(-17\tau))$ for curve *3*. Curve *4* corresponds to a rather seldom case of precipitation of giant flakes for which D_M amounted to 3 cm ($\varphi = 0.05$ mrad). The average value of variance equalled unity.

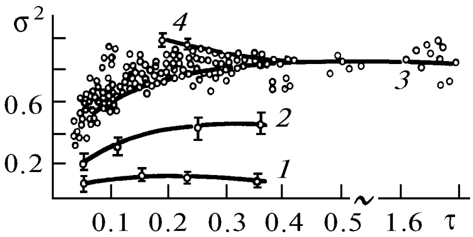

FIG. 2. Variance of the scattered radiation intensity fluctuations σ^2 as a function of the optical thickness τ.

Figure 2 shows that at $\tau = 0.2–0.3$ the variance depends on the maximum diameter of the snow particles. This is confirmed by the results presented in Table I (σ^2 denotes average values of the variance, N denotes the number of measurements, and δ is the rms value of σ^2). It is clear from Table I that the variance increases more than by a factor of 10 as D_M increases from 1 to 30 mm.

TABLE I. Variance of the intensity fluctuations versus the diameter of snow particles D_M at $\tau = 0.2–0.3$ and $\varphi = 0.05$ mrad.

σ^2	D_M, mm	δ	N
1	10–30	0.058	32
0.85	5–7	0.124	31
0.48	3–5	0.066	42
0.17	1–3	0.040	31
0.09	1	0.017	45

TABLE II.

Curves	τ	D_M, mm	φ, mrad	$V_\perp$, m/s
1	0.18	10	0.12	5/
2	0.2	5	0.12	–
3	0.12	5	0.12	–
4	0.1	5	0.12	–
5	0.36	5	0	5
6	0.1	5	0	–

The normalized spectrum of the scattered radiation intensity fluctuations $U(f) = f\,W(f) / \int W(f)\,df$ (see Fig. 3), where $W(f)$ is the spectral power density of signal at the frequency f and $\varphi = 0.12$ mrad, substantially broadens as compared to the spectrum measured at the center of the focal spot (see curves *5* and *6* in Fig. 3 and Table II).

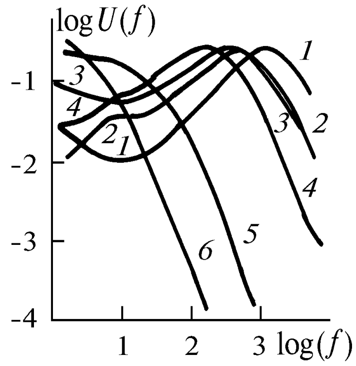

FIG. 3. Spectrum of the intensity fluctuations of the transmitted and scattered radiation[2] for $V = 5$ m/s.

An analysis of the correlation functions showed that the correlation time t_c determined at a level of 0.37 was two orders of magnitude smaller for the scattered radiation than at the center of the focal spot. The correlation time decreases as φ and D_M increase at close values of τ and wind velocity V. So, for instance, when $V = 3.5$ m/s, $V_\perp = 1.2$ m/s, $\tau = 0.3–0.45$, and $D_M = 1–3$ mm, the correlation time was 1100, 650, and 590 μs at $\varphi = 0.04$, 0.08, and 0.12 mrad, respectively. Figure 4 shows two normalized correlation functions B at $\varphi = 0.05$ mrad and close values of optical thickness and perpendicular wind velocity $V_\perp$, but substantially different D_M. The correlation time for small snow particles is two times smaller than for giant flakes. To be precise, we have thus far analyzed 25 correlation functions.

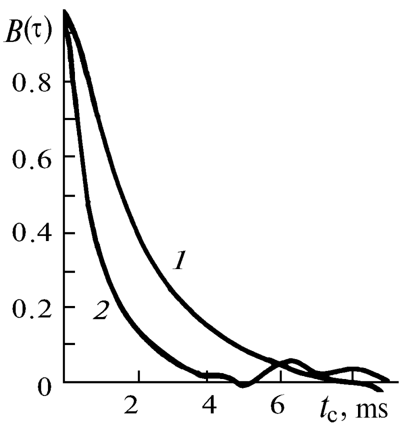

FIG. 4. Normalized autocorrelation function for the scattered radiation at $\varphi = 0.5$ mrad: 1) $D_M = 10–20$ mm, $\sigma^2 = 1.03$, $\tau = 0.2$, $V = 2$ m/s, and $V_\perp = 1.8$ m/s; 2) $D_M = 1–2$ mm, $\sigma^2 = 0.55$, $\tau = 0.3$, $V = 3.4$ m/s, and $V_\perp = 1.2$ m/s.

About 40 measurements of the probability density of the scattered radiation intensity fluctuations have been performed. All of them exhibit right asymmetry. The analytical expression for empirical distributions were adjusted by means of graphic representation of probabilities (the rectified diagram method was used). To this end, the data were plotted on a special chart paper that was reserved for chosen distribution. The proximity of the experimental points to the given straight line serves as a qualitative criterion for acceptance of a hypothesis.[6,7] Thirty three distributions are fairly well described by the gamma distribution. The lognormal distribution describes experimental data substantially worse. Figure 5 confirms visually the aforesaid. A proper scale of the probability grid corresponds to each value of α (see Ref. 7). The probability grids for α = 8, 5, and 0 are plotted on the ordinate axis in Fig. 5. The curves in Fig. 5 were constructed for the parameters indicated in Table III.

TABLE III.

Curves	α	D_M, mm	σ	τ
1	0	10–20	1.04	0.2
2	0	2	0.34	0.09
3	5	3–5	0.12	0.17
4	5	3–5	0.46	0.21
5	8	1–3	0.11	0.36
6	8	1	0.15	0.35

It follows from the foregoing that the characteristics of the scattered radiation intensity fluctuations for a focused laser beam depend on the optical thickness, size of the particles, and wind velocity and considerably differ from the characteristics within the focal spot where the atmospheric turbulence has a dominant role. These specific features can be used as a criterion for precipitation detector. On the whole, the data presented here may help to choose the efficient method of random signal processing for such a detector. Moreover, they give a good idea of temporal behavior of the signal at very small scattering angles since the focused beam is used.

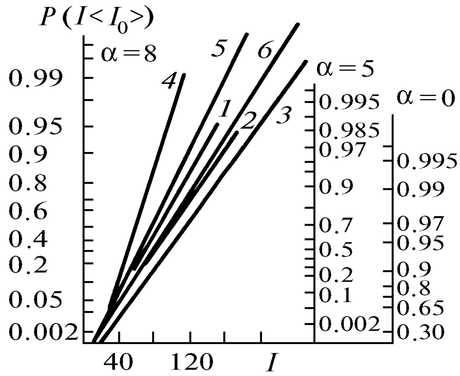

FIG. 5. Test of a hypothesis that the experimental data obey the gamma distribution (φ = 0.05 mrad).

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