FLUCTUATIONS OF RADIATION INTENSITY AND FLUX OF A LASER BEAM IN SNOWFALLS

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Received September 11, 1998

Fluctuations of laser radiation intensity and flux in snowfalls are studied. It is found that as the optical depth increases, fluctuations of both flux and intensity first increase, then saturate, and then decrease. A similar behavior is observed for flux fluctuations when increasing the path length under close meteorological conditions. The data qualitatively confirm an irregular change of the spatial scale of correlation of the intensity fluctuations with increasing optical depth in a snowfall.

This paper continues the series of our papers[1–4] analyzing fluctuations of radiation intensity[1,3,4] and flux[1,2] of a laser beam. In these papers, we have revealed three characteristic modes (regions) of fluctuations in the received laser radiation depending on optical depth and the length of the propagation path.

This paper analyzes the average level of fluctuations of the radiation intensity $\bar{\sigma}_I$ and flux $\bar{\sigma}_p$ for a narrow diverging laser beam (NDB) depending on the optical depth τ of a snowfall. It also considers the dependence of $\bar{\sigma}_p$ on the path length L under similar meteorological conditions. The measurement technique and instrumentation are described in Ref. 1.

In Fig. 1, curve *1* depicts the dependence of the average level of fluctuations $\bar{\sigma}_I$ on the average optical depth $\bar{\tau}$ with the maximum size of snow flakes being D_{max} = 1–3 mm. Analysis have involved data for nine paths of the length: $L = 130 \times N$, 964, and 1928 m, where N is the integer number from 1 to 7 inclusive. The results of σ_I measurements on these paths were already used in Refs. 1–4. In contrast to Refs. 1–4, here the data were averaged over the optical depth with the step $\Delta\tau = 0.5$. This step is larger than in Refs. 1–4, where $\Delta\tau = 0.1$. The step $\Delta\tau$ was expanded in order to increase the number of σ_I values in calculation of the average level of intensity fluctuations $\bar{\sigma}_I$ for the case of the largest values of the optical depth, for which we have only few data yet. For clarity reasons note that the first value of $\bar{\sigma}_I$ was obtained by averaging of σ_I values measured at τ = 0.01–0.5; the second one at τ from 0.5 to 1.0; and so on. Circles on the curve *1* at $\tau \le 4.5$ are for the measurements, conducted when the receiver's diameter D was equal to 0.1 or 0.3 mm; at $\tau > 4.5$ they correspond to D = 0.5 mm. We considered the receivers with such diameters as very close to the “pointB ones, because their diameters are smaller than the coherence length of the received radiation.[5,6] In other words, we believe that in this case we have measured the intensity fluctuations σ_I.

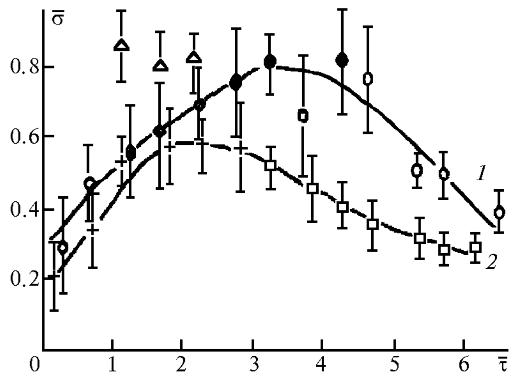

FIG. 1. Average level of fluctuations of the radiation intensity $\bar{\sigma}_I$ and flux $\bar{\sigma}_p$ vs. average optical depth τ with maximum size of snow flakes D_{max} = 1–3 mm. Curve 1: circles correspond to the cases τ < 4.5, the receiver diameter D = 0.1–0.3 mm and τ > 4.5, D = 0.5 mm; L = 964 m. Curve 2: crosses are for D = 3.1 mm, L = 130–780 m; squares are for D = 3.1 mm, L = 2048 m; triangles are for D = 3.1 mm, L = 2048 m, strong influence of the turbulence.

Curve *2* in Fig. 1 shows the measurement data obtained with the receiver of diameter D = 3.1 mm. We believe that at D = 3.1 mm the instrument measured the flux fluctuations σ_p. Squares on curve *2* show the data of measurements at the path of L = 2048 m length; while the triangles are for the values obtained at the same path under conditions, when turbulence contributed only insignificantly. Crosses are for the

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values of $\bar{\sigma}_p$ obtained in the cases of the paths 130, 260, 520, and 780 m long and at D = 3.1 mm.

All the data presented in Fig. 1 were obtained for the case when the maximum size of snow flakes did not exceed 3 mm ($D_{max} \le (1-3)$ mm) and $\Delta\tau = 0.5$. It follows from Fig. 1 that the three modes (regions) are characteristic of the fluctuations of both radiation intensity $\bar{\sigma}_I$ and flux $\bar{\sigma}_p$ with increasing optical depth. First fluctuations grow, then they saturate, and then decrease (decay). This is an important feature of fluctuations in precipitation, which distinguishes them from fluctuations in the turbulent atmosphere under clear sky weather. We have already reported this fact in Refs. 2–4. As known, in the turbulent atmosphere without precipitation, fluctuations increase, saturate, and then slightly decrease with increasing L and/or q_n^2. Here q_n^2 is the structure characteristic of the air refractive index.[6–11] It is also important that flux fluctuations saturate at lower values of the optical depth than the intensity fluctuations do. The saturation level of the flux fluctuations decreases as compared to that of intensity fluctuations. Decay of fluctuations with increasing $\bar{\tau}$ can be explained by an increase in the refracted radiation[2,3] and decrease in the spatial scale of radiation intensity fluctuations.[12,13]

The ratio δ of the average level of intensity fluctuations $\bar{\sigma}_I$ to the average level of flux fluctuations $\bar{\sigma}_p$, i.e. $\delta = \bar{\sigma}_I/\bar{\sigma}_p$, is shown in Fig. 2 at a slightly increasing optical depth τ while close values of the average optical depth $\bar{\tau}$. The circles correspond to the values obtained from curves *1* and *2* (see Fig. 1), while the triangles correspond to the case of a significant contribution from turbulence. In this case, the spectrum has two pronounced maxima.[3] The ratio δ varies almost three-fold (from 0.74 to 2.03). As τ increases, the ratio δ experiences maximum, minimum, and close values (about 1.5) at three different values of the optical depth. Moreover, δ decreases (after reaching its maximum) at $\tau > 4.5$, i.e. in the decay region of fluctuations. To explain qualitatively the noticed features in the behavior of δ as a function of τ, let us take into account the following facts. We believe that at a fixed receiver diameter the variance ratio (δ) depends strongly on the spatial correlation length of the intensity fluctuations (ρ). This assumption is valid for the turbulent atmosphere without precipitation, what follows from Ref. 7 (§53) and other papers, for example, Ref. 14. Therefore, it is reasonable to seek the physical causes for δ variation in the variations of ρ.

Let us first consider the behavior of ρ in the turbulent atmosphere without precipitation (ρ_t). Since $\bar{\sigma}_I < 1$, the measurements can be considered as being conducted in the region of weak turbulent fluctuations. In this region, $\rho_t = \sqrt{\lambda L}$. In our measurements we have $\lambda = 0.63$ μm and L = 130–2048 m and the value of ρ_t varied from 0.9 to 3.5 cm. According to Ref. 12, the correlation length of intensity in the scattering monodisperse medium (ρ_d) at $\lambda \ll d$ is estimated as $\rho_d \cong d/\tau$ at $\tau > 1$ and $\rho_d \cong d$ at $\tau < 1$, where d is the diameter of a particle. The decrease in the coherence length with increasing τ was noticed in the model medium.[13]

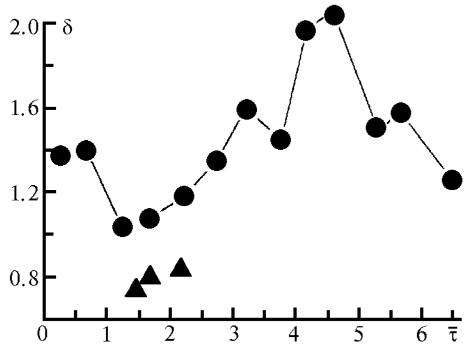

FIG. 2. The ratio δ of the level of intensity fluctuations $\bar{\sigma}_I$ to the level of flux fluctuations $\bar{\sigma}_p$ vs. the optical depth $\bar{\tau}$.

In the case being analyzed D_{max} = 1–3 mm, therefore $\rho_d <$ 1–3 mm and $\rho_t > \rho_d$ at $\tau < 1$ and $\rho_t \gg \rho_d$ at the path 2048 m long. It is also important that the contribution of turbulence into the measured fluctuations decreases with increasing optical depth for all the paths.[15] With regard for the above-listed facts, the growth of δ up to the maximum value (δ_{max}) is likely caused by a decrease in the level of fluctuations when the receiver is not a point one because of a decrease in ρ_d and the contribution from turbulence into the fluctuations. The decrease in the ratio $\delta > \delta_{max}$ is likely caused by a significant averaging of fluctuations at both point (D = 0.5 mm) and non-point receivers (D = 3.1 mm), because ρ_d drastically decreases in this range of τ. To be precise, for the refracted radiation ρ_d is approximately equal to the wavelength. Its fluctuations can be considered as very small, because they are grossly averaged even by a point receiver.[2] Consequently, the particular behavior of δ depends on the ratio of contributions from turbulence and precipitation particles into the measured fluctuations. If turbulence contributes significantly, the ratio δ can be even below unity. In Fig. 2, such values are presented by triangles. To be precise, the values of δ were obtained for the average values of $\bar{\sigma}_I$ and $\bar{\sigma}_p$ with D_{max} = 1–3 mm.

Let us consider the dependence $\sigma_p = F(L)$. To find it, we used the values of fluctuations measured in a snowfall using the receiver with D = 3.1 mm and five paths 130, 260, 520, 780, and 2048 m long (curve *2* in Fig. 1). The results obtained at close values of flakes number density in snowfall and at D_{max} = 1–3 mm were separated out from these measured data. As an equivalent to the particle number density in a unit volume, we take the optical depth of precipitation τ_0 at the path of 130 m. It was calculated from the atmospheric transmittance measured on the path 2×100 m long with the visibility range meter (RVD–3). From data obtained with the receiver of D_{max} = 1–3 mm and the path 130 m long we selected only close values of τ_0 from all the data obtained. For the sake of clarity let us refine that along the 260-m long path $\tau = 2\tau_0$, for the path 520 m long $\tau = 4\tau_0$, and so on. Among the data analyzed, we have managed to find only one value $\tau_0 = 0.34$. Similar separation of data by τ_0 and D_{max} for intensity fluctuations was done in Refs. 16 and 17, and in Ref. 3 the data were separated for flux fluctuations at D_{max} = 1–3 mm and D = 3.1 mm. For the path 130 m long Ref. 3 gives no data. The dependence of the average level of flux fluctuations $\bar{\sigma}_p$ on the path length logarithm ($\log L$) is shown in Fig. 3. The contribution from snowfall was determined from simultaneous measurements of the level and spectrum fluctuations according to the relation $\sigma^2 = \sigma_s^2 + \sigma_t^2$, where σ_s^2 is the contribution from snow flakes and σ_t^2 is the contribution from turbulence into the measured fluctuations. As seen from Fig. 3, the level of flux fluctuations first grows and then decreases (decays) as the path length increases.

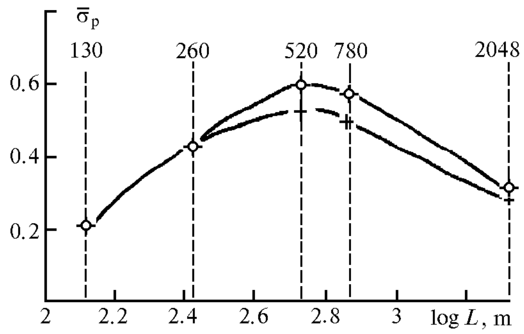

FIG. 3. Average level of flux fluctuations ($\bar{\sigma}_p$) vs. the path length logarithm ($\log L$) for D = 3.1 mm and similar meteorological conditions on the path D_{max} = 1–3 mm and $\tau_0 = 0.34$. Crosses are for the contribution from snow flakes into the fluctuations.

The results presented allow us to formulate definitely the main conclusion. Both intensity and flux fluctuations in snowfalls first grow, then saturate, and decrease as the optical depth grows (at close values of the maximum particle size). Moreover, under close meteorological conditions, flux fluctuations first grow and then decrease with increasing path length. At the same time, the data qualitatively confirm the irregular change of the spatial scale of the intensity fluctuation's correlation, what will be the subject of our further research.

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