THE INTENSITY FLUCTUATIONS OF A NARROW DIVERGENT LASER BEAM IN SNOWFALL

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Received December 30, 1990

The intensity fluctuations of a narrow divergent laser beam were measured in snowfalls on 130, 390, 650, and 964 km paths. It is shown that the fluctuations became stronger and then saturate with increase of the optical thickness of snowfall. The saturation increases as the maximum size of the snowflakes increases.

Atmospheric precipitation actively affects the parameters of a laser beam which is significantly attenuated due to scattering by the precipitation particles. In addition, simultaneously with the turbulence fluctuations in the refractive index of air, the precipitation particles cause strong fluctuations in the intensity of the received signal. The fluctuation statistics under multiple scattering have been studied insufficiently. However, it is already well known that this statistics differ from the statistics of the turbulent atmosphere in the presence of aerosol.[1-8]

It has been established experimentally[1,5] that at optical thicknesses $\tau \le 0.7$, the variance of the intensity fluctuations $s_{\rm exp}^2$ of a divergent laser beam is proportional to τ. It is also important that for identical values of τ the variance is increased substantially as the maximum size of the flakes $D_{\rm m}$ increases, i. e., $\sigma_{\rm exp}^2 = f(\tau, D_{\rm m})$. In this paper we examine the dependence $\sigma = f(\tau, D_{\rm m})$ for a wider range of τ, namely, for $\tau \le 4$, analyzing our previous data[1,5,9] together with our recent results.

The investigations made in this range of τ are important, because such atmospheric conditions are found quite often during precipitation on path lengths of several hundred meters or even longer.

The range of $\tau \ge 1$ has been studied insufficiently though the same preliminary results are available. The most important result is thought to be the saturation of the level of fluctuations $\sigma_{\rm exp}$ with increase of τ (Refs. 2, 3, 5, 9, 10, and 11).

We shall use the term saturation implying the explicit decrease or termination of increase $\sigma_{\rm exp}$ with increase of the optical thickness of snowfall. The same situation is also observed in the turbulent atmosphere without precipitations with increase of path length L and/or of the turbulence level. For example, in the day time for the path length $L = 1750$ m the fluctuation level of a divergent laser beam does not exceed 1.6 under conditions of strong fluctuations and depends weakly on the turbulence level.[12]

The theory of "saturated" fluctuations in the atmospheric precipitation is far from being completed. It must simultaneously account for multiple scattering by the optically rigid aerosol and precipitation particles and as well as for the atmospheric turbulence. The equation of the field moments was written in Ref. 2 under the same conditions of the optical wave propagation. However, we fail to derive the general form of the exact solution of this equation for the variance of the intensity fluctuations. In this connection A. Borovoi[13,14] proposed a qualitative model of the high–frequency fluctuations under conditions of the precipitation on long atmospheric paths. The latest version of this model was given in Ref. 2.

According to the model, the high–frequency fluctuations are determined mainly by a layer of the precipitation particles which is adjacent to the receiver and by the atmospheric turbulence along the path from the source to this layer. Note that with increase of the path length the fluctuation level also increases and then saturates. Moreover, the fluctuations become weaker with further increase of the path length when the effect of weakly fluctuating multiply scattered field becomes pronounced.

It is important that the largest particles are mainly responsible for fluctuations. These are the salient features inherent in the fluctuation level which follow from the model.

The specific behavior of the function $\sigma_{\rm exp} = f(\tau)$ is manifested explicitly in the model media for $\tau < 32$ (Ref. 15). At the same time the authors of Ref. 2 claim that the model under discussion provides a qualitative description of the experimental data obtained in a narrow collimated beam at $\tau = 1.5$–14 during rain on the 2. 5 km and 5 km paths.

It is natural to check the proposed model of the fluctuations under other atmospheric conditions, in particular, during snowfalls when the shape and size of the particles may vary significantly and the variations can be estimated, at least roughly, by means of the simple visual observations of the particles.

We have selected a narrow divergent laser beam for our study since the strong dependence of its characteristics on the particle size for $\tau < 0.7$ has already been established. In addition, it is more convenient to use such a beam for measuring in winter.

2. The experimental scheme and measurement technique were described in detail in our previous papers. Therefore, we omit here the unessential details and give only the information which is necessary for understanding the main points of the experiment under discussion.

A divergent laser beam was emitted from the main output of an LG–38 He–Ne laser ($\lambda = 0.6328$ mm). The total divergence angle of a laser beam was equal to $5\cdot 10^{-4}$ rad. The laser operated in a quasi–single–mode regime and had the Gaussian distribution of the radiation intensity over the beam cross section in the source plane.

Measurements were made on four paths of 130, 390, 650, and 964 m length. On the 3×130 and 5×130 m paths the measurements were carried out by means of reflection of

0235-6880/91/04 0269-04 $02.00

laser beam from plane mirrors with diameters ≥ 40 cm. In the study of the intensity fluctuations, a diaphragm with diameter 0.3 mm and a blend were placed in front of the detector to limit the field–of–view angle of the photodetector to $5{\cdot}10^{-2}$ rad. The photomultiplyer tube (PMT–38) was used as a photodetector. Signal I from the PMT–38 output was amplified and fed into a device for measuring a variance $\sigma^2 = \langle I - \langle I\rangle\rangle^2$ and an average value of the signal $\langle I\rangle$. A normalized variance $\sigma^2_{\rm exp} = \sigma^2 / \langle I\rangle^2$ and a fluctuation level $\sigma_{\rm exp}$ were calculated from the values of $\sigma^2_{\rm exp}$ and $\langle I\rangle$. Here the angular brackets denote the time averaging which was chosen to be equal to 20 sec for the conditions of our experiments. The dynamic range of the entire receiving channel was not worse than 40 dB in the frequency band 0.01–20 kHz. According to our estimates, the relative measurement error $\sigma^2_{\rm exp}$ did not exceed 10%.

We obtained the optical thickness of snowfall which was calculated from the atmospheric transparency for each value of $\sigma^2_{\rm exp}$ or $\sigma_{\rm exp}$. The atmospheric transparency was determined with an RDV–3 visibility meter, which operated on the 2×100 m path. This device was placed at the receiving end of the path. The shape and size of the largest particles ($D_{\rm m}$) were determined visually after they had been collected on a soft substrate.

3. About two thousand pairs of $\sigma^2_{\rm exp}$ and τ values were measured. We identified three ranges of $D_{\rm m}$ values, namely, the range of small values of $D_{\rm m} \approx 1$ mm, the range of large values of $D_{\rm m} > 5$ mm (the flakes), and the range of moderate values of $D_{\rm m} \approx 2$–5 mm in the entire set of the experimental points. We also included the cases of the precipitation of occasional single flakes with $D_{\rm m} > 5$ mm in the last range.

For each range of $D_{\rm m}$ values we plotted the dependence $\sigma_{\rm exp} = f(\tau)$ for three paths of 390, 650, and 964 m lengths. They are shown in Figs. 1, 2, and 3.

First of all, the analysis of these figures shows that the majority of curves $\sigma_{\rm exp} = f(\tau, D_{\rm m})$ has a similar behavior, namely: 1) when the optical thickness τ increases to a certain value τ, $\sigma_{\rm exp}$ smoothly increases and then saturates at a certain level; 2) $\sigma_{\rm exp}$ increases with increase of $D_{\rm m}$ for identical τ in the entire investigated range of τ ($\tau \le 4$). Figure 4a shows the curves obtained by averaging the data shown in Figs. 1, 2, and 3. Averaging over τ was performed with a step of 0.1. Also shown in Fig. 4a the dependence $\sigma_{\rm exp} = f(\tau)$ we obtained earlier on 130 m path for a divergent laser beam during the heavy snowstorm.[8,13] In this case we observed the strongest atmospheric turbidity for which we could perform the measurements.

The figures near each curve indicate path length. The dashed curves correspond to $D_{\rm m} \approx 1$ mm, the solid curves are for $D_{\rm m} \approx 2$–5 mm, dot–dash curve is for $D_m \approx 7$ mm. Curves *1* and *2* obtained by fitting are also depicted with dots in Fig. 4a. Note that curve *1* corresponds to the dependence $\sigma_{\rm exp} = (1 - \exp(-\tau))^{0.5}$ while curve *2* – to $\sigma_{\rm exp} = 0.65[1 - \exp(-\tau)^{1.4}]^{0.5}$. These dependences provide an adequate description of the experimental data. The saturation of the fluctuations under conditions of the snowfall without dense flakes can be distinctly seen in Fig. 4a, in addition, for $D_{\rm m} \approx 1$ mm the saturation occurs at $\tau \approx 1$ and for $D_{\rm m} \approx 2$–5 mm it is observed at slightly larger values of τ. It is also important that the optical thickness $\tau_{\rm s}$, at which the saturation occurs, is virtually the same for significantly different path lengths (964 and 130 m or 390 and 964 m).

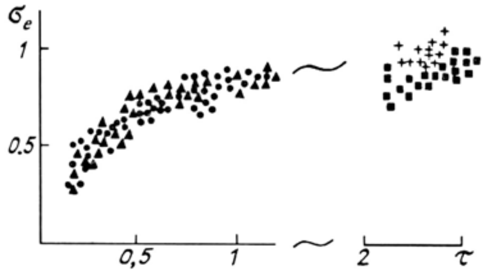

FIG. 1. The level of the intensity fluctuations on the 390 m *path: filled triangles are for* $D_{\rm m}$ = 1–3 mm, *filled squares are for* $D_{\rm m}$ = 5 mm, *crosses are for single flakes to* 2 cm *(measurements were made on April 5, 1981), and filled circles are for* $D_{\rm m}$ < 5 mm *(February 18, 1987).*

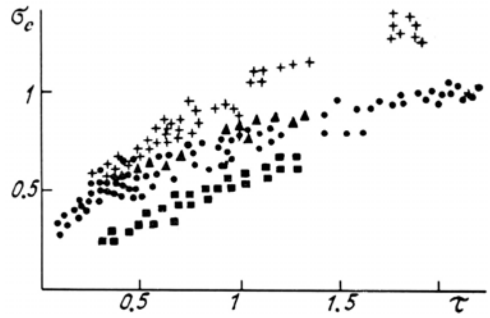

FIG. 2. The level of the intensity fluctuations on the 650 m *path: crosses are for* $D_{\rm m} \approx 7$ mm *and dense flakes (February 19, 1987), filled triangles are for* $D_{\rm m}$= 5 mm *(February 19, 1987), filled circles are for* $D_m \approx 2$–5 mm *(February 14–16, 1987), and filled squares are for* $D_m \approx 1$ mm *(April 13, 1987).*

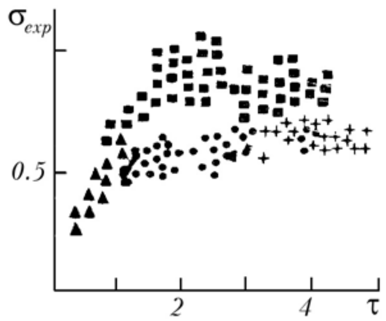

FIG. 3. The level of the intensity fluctuations on the 964 m path: filled triangles are for $D_{\rm m} \approx 1$ mm *(December 25, 1989), crosses are for* $D_m \approx 1$–2 mm *(December 25, 1989), filled circles are for* $D_m \approx 1$ mm *(December 14, 1989), and filled squares are for* $D_m \approx 3$–5 mm *(December 25, 1989).*

A large filled circle denotes $\sigma_{\rm exp}$ at $\tau \approx 0.5$ in the zone occupied by a divergent laser beam on the path of length $L \approx 130$ m during hail for $D_{\rm m} \approx 10$ mm (Ref. 8).

The data from Ref. 2 are shown by squares in Fig. 4a (rain, a narrow collimated laser beam, and $L = 2\times1250$ m, 4×1250 m). Here the saturation of the intensity fluctuations occurs at a level of 1. 2 at $\tau \approx 4$.

It should be specially stressed that for the measurements described in Refs. 2 and 3 the main contribution to the fluctuations came from the atmospheric turbulence while in our case the opposite situation was observed on the 964 m path, namely, the main contribution came from the precipitation particles.

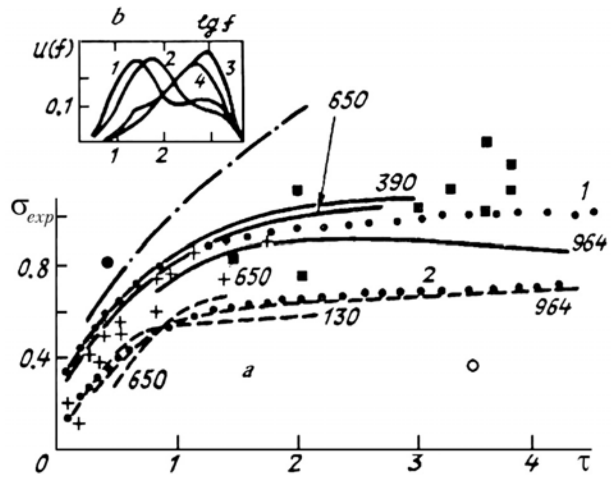

FIG. 4. The averaged curves: a) $\sigma_{exp} = (\tau, D_m)$ *and b) the spectrum of the intensity fluctuations* $U(f) = fW(f)/fW(f)df$.

Naturally, since the size D_m of the particles ($D_m \approx 1$ mm) in the course of measurements are close in value, length of the so–called zone adjacent to the receiver L_r is to differ but slightly for three paths. In fact, this implies that the optical thickness of this zone L_r for the 964 m path will be approximately seven times lower than that for the 130 m path, since the optical thickness is identical along both paths.

It is well known that for $L = L_r \approx kD_m^2$ the intensity variance increases exponentially as $\sigma^2 = \exp(\tau) - 1$ (Ref. 2). In other words, it can be expected that the level of fluctuations acquired in the nearest zone would be essentially different for different path lengths at identical τ. However, the experimental values of the variance are close in value.

All this gives rise to an idea that the fluctuations are affected not only by the zone adjacent to the receiver but also by other sections of the path.

In particular, a certain role of the sections of the path adjacent to the transmitter on which the particles screen a narrow laser beam is obvious.[9]

In addition, on the path from the source to the layer adjacent to the receiver (i.e., $L = L - L_r$) the degree of coherence of the field decreases due to the interaction of radiation field with the turbulence and the precipitation particles. Owing to the fact that the fine structure of the interference pattern depends on the coherence of incident radiation,[6] the level of fluctuations will depend on the path length L_1.

We have had no opportunity to make measurements under conditions of the precipitation with the dense snowflakes (the probability of such precipitation is low). At the same time, we claim the fact which seems to be important: in the absence of the dense flakes the level of the intensity fluctuations does not exceed 1.2 (Figs. 1–4) for $\tau \le 4$. It should be emphasized once again that the level of the saturated intensity fluctuations in a divergent laser beam in the turbulent atmosphere is generally higher than 1.2. Taking this fact into account we can assume that the intensity fluctuations in a narrow divergent laser beam in snowfall without flakes do not exceed the fluctuations in the turbulent atmosphere without precipitation. This is the basic result of the measurements which we have made. By way of conclusion it can be said that although the fluctuations in precipitation have a number of peculiarities in the spectrum and in the distribution law, we can assume to a first approximation that maximum random noise induced by precipitation does not exceed noise found in the turbulent atmosphere without precipitation.

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