RELATIONSHIP BETWEEN THE RECEIVER DIAMETER AND THE LIGHT FLUX FLUCTUATIONS IN A NARROW DIVERGENT LASER BEAM PROPAGATING THROUGH A SNOWFALL. 1. LEVEL OF FLUCTUATIONS

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This paper presents the measurement results on the level of the radiation intensity fluctuations in the narrow divergent laser beam propagating through a snowfall. The measurements were done along ten paths from 37 m *to* 2 km *long in* 122 *snowfalls and the receiver diameter of* 0.1, 0.8, 3.1, *and* 25 mm. *It was found that the level of fluctuations of the laser radiation flux is related to the receiver diameter, the optical depth, and the maximum size of particles. With increasing optical depth, the flux fluctuations first grow and then saturate at some level depending on the receiver diameter and maximum size of particles. In fine-disperse snowfall, when the maximum size of snow flakes is below* 3 mm, *the level of fluctuations saturates at lower optical depth, as the receiver diameter increases. The fluctuations of the radiation flux become lower with the increasing receiver diameter and decreasing maximum size of particles.*

1. INTRODUCTION

The fluctuations of the received radiation flux from a narrow divergent laser beam propagating in a snowfall were studied in Refs. 1–5. The experiments in those papers were performed with the receiver diameter ($D_r = 0.1$ or 0.3 mm) smaller than the maximum size of snow flakes. In Refs. 1–5, the main qualitative features were revealed for a narrow divergent beam (NDB), some quantitative relationships for the fluctuation characteristics were established, and the parameters were found that most effectively govern the fluctuations, namely, the optical depth[1–5] τ, particle number density,[4–5] maximum size of snowflakes[1–5] D_m, and the wind velocity[3] V, $V_\perp$.

The remaining atmospheric turbulence[6,7] also affects the level of fluctuations. This effect is well pronounced in the spectrum of fluctuations at low frequencies and low values of the optical depth.

From the general physical concepts, experimental data,[8] and theoretical estimates[9,10] one should expect that the increase of the receiver diameter will lead to smoothing or, as is usually said, averaging of the fluctuations of optical signal. This effect has attracted much attention due to its practical importance. Now it is well studied for the case of laser radiation propagation in the atmosphere without precipitation, see Refs. 11, 12 and references therein. It is clear from these references that the averaging effect of the objective is mainly governed by the spatial correlation function of the intensity fluctuations (B_ρ) which depends, in a complicated way, on the characteristics of atmospheric turbulence and the beam diffraction parameters.

The physical nature of the averaging effect is well known.[13] If the size of the objective is far greater than the correlation length of the intensity fluctuations, then wave front portions with opposite signs of fluctuations fall within it simultaneously. That is why the light flux passed through such an objective fluctuates less as compared to the objective with the size less than the correlation length.

As to the snowfall conditions, the spatial correlation of intensity fluctuations in this case is poorly studied, but it is natural to expect different features of the averaging effect, because the nature of fluctuations in precipitation is different than in turbulent atmosphere[3,5] without precipitation.

In this paper we present the results of analysis of measuring the light flux fluctuations level at different receiver diameter for narrow divergent laser beam propagating through the atmosphere in snowfalls. To be accurate, we should note that we do not separate here the turbulent and hydrometeorological contributions into the fluctuations measured.

2. BRIEF DESCRIPTION OF THE EXPERIMENT

Laser beam propagated in a snowfall along the path of the length L. The radiation was received with a photomultiplier, in front of which diaphragms with different diameters (D_r) were installed. Electric signal from the photodetector was amplified and then entered a pulse analyzer, a spectrum analyzer, a correlator, and a measurer of the level of signal fluctuations.

Simultaneously with the light flux characteristics, the optical depth (τ) was measured, as well as the maximum size of snow flakes (D_m) and wind velocity (V and $V_\perp$).

As a source of radiation we used the He–Ne lasers ($\lambda = 0.6328$ μm) of LG–38, LG-38A and LGM–215 types. The total angle of the beam divergence was equal to $5 \cdot 10^{-5}$ rad, the initial beam size was at $1/e$ level (3–4 mm). Such a beam is considered as a narrow divergent beam (NDB). The receiver field of view was $5 \cdot 10^{-2}$ rad. The path length varied from 37 to 1928 m. At paths lengths multiple to 130, the measurements were done with the beam reflection from plane mirrors installed 130 m apart.

In our experiments wee used a single-channel measurement system, although it is clear that a two- or multi-channel system would be more suitable. Two sets of data were analyzed. One set consists of the measurement results in different snowfalls (different τ, D_m, and V) at certain receiver diameters ($D_r = 0.1$, 0.8, 3.1, and 25 mm). The second set includes the measurements at meteorological conditions close in τ, D_m, and V (in one snowfall) but at different D_r.

The measurement statistics and important details will be presented below.

3. MEASUREMENT RESULTS

Let us note once more that we did not separate, in this work, the turbulent and hydrometeorological contributions into the fluctuations measured.

The level of fluctuations (σ) was calculated by the signal normalized variance σ^2. It is defined as

$$\sigma^2 = \langle (I - \langle I \rangle)^2 \rangle / \langle I \rangle^2,$$

where angular brackets are for time averaging; $\langle (I - \langle I \rangle)^2 \rangle$ and $\langle I \rangle$ were measured with a variancemeter in the frequency band from 0.01 Hz to 20 kHz. The operation of the variancemeter is described in Ref. 14. The relative error of σ^2 measurement was within 10%. The data were averaged over 20 s. This averaging time were chosen for best agreement between the variances in two channels of the variancemeter for the same signal.

We have analyzed numerous measurements of the level of fluctuations. Altogether we had about $1.5 \cdot 10^4$ values of the fluctuation level.

Table I (the right column) presents the number of snowfalls, in which the measurements were done for NDB at paths with the length L at different receiver diameters. A total set of 122 measurement sessions was conducted.

TABLE I.

D_r, mm	L, m										Σ number of measurements
	37	130	260	390	520	650	780	910	964	1928	
0.1	2	4	15	3	4	3	–	1	21	4	57
0.8	–	–	12	–	9	–	2	–	–	–	23
3.1	–	–	9	–	13	–	1	–	–	–	23
25	–	–	5	–	12	–	1	–	–	–	19

TABLE II.

D_r, mm	L, m										Σ number of measurements
	37	130	260	390	520	650	780	910	964	1928	
0.1	200	717	1794	160	202	230	295	160	2904	315	6977
0.8	–	–	1760	–	1347	–	212	–	–	–	3319
3.1	–	–	1147	–	1629	–	170	–	–	–	2946
25	–	–	71	–	1507	–	93	–	–	–	1671

Table II presents the number of measured values of the level of fluctuations. Most of the measurements were done at $D_r = 0.1$ mm. This number also includes a few measurements done at $D_r = 0.3$ mm. We decided not to decrease the receiver diameter (less than 0.1 mm), since with increasing τ the problem necessarily arises on providing for a sufficient signal–to–noise ratio (average signal related to the system signal at a closed source), which was, in the measurements discussed, at least 15 (even for the path 1928 m long).

We believe that the intensity fluctuations can be measured at $D_r = 0.1$ and 0.3 mm. This means, in fact, that such receivers do not average fluctuations. Although the last assumption is not proved rigorously in experiments, in our opinion, it is very close to real situation. We will designate the level of intensity fluctuations as σ_f. For $D_r > 0.3$ mm we will designate it as σ_f with the receiver diameter denoted, if necessary, in parenthesis [for example, σ_f (25), where 25 is the receiver diameter in millimeters; the letter f in subscript is a contraction of flux].

Earlier[2] it was established from analysis of a great number of measurements that σ_I depends on the optical depth τ and the maximum size of particles. And for NDB in a snowfall σ_I first increases with increasing τ and then tends to saturation at the level σ_s (the value dependent on the maximum size of particles, D_m).

At $\tau = 0.6 - 4.0$ the level of fluctuations can be described by the following expression

$$\sigma_I = \sigma_s[1 - \exp(-2\sigma_s\tau)],$$

where $\sigma_s = 0.9$ at $D_m = 3 - 5$ mm and $\sigma_s = 0.75$ at $D_m = 1 - 3$ mm. For $\tau < 0.6$, as follows from the data of four measurements at the path 130 m long,[16] the linear dependence was obtained for the intensity fluctuations:

$$\sigma_I^2 = A + N\,\tau.$$

with the coefficients: $A = 0.03$, $N = 0.67$; $A = 0$, $N = 0.55$; $A = 0.03$, $N = 0.58$ at $D_m = 5$ mm. When $D_m = 3$ mm, $A = 0.02$ and $N = 0.27$. At the path 650 m long[1] in one snowfall with flakes $D_m = 7$ mm, $A = 0$ and $N = 1$ up to $\tau < 2$. It is clear therefrom that in the first approximation, according to our data, the coefficient A can be neglected (at $\tau > 0.05$), then $\sigma = C_0\sqrt{\tau}$. The factor C_0 depends on D_m. With flakes it is close to unity and decreases with decreasing D_m. Without flakes at D_m = 3–5 mm, $\sigma = \bar{C}_0\sqrt{\tau} = 0.52\sqrt{\tau}$, where $\bar{C}_0$ is the average of N.

In this paper we present, for the first time, not the average data on σ_I at each of the ten paths (Figs. 1, 2 and 3). These figures show not all the experimental data, because some of them are very close.

Figure 1*a* gives the designations for each of the paths. Figure 2*a* gives the additional designations for snowflakes. It is seen from the figures that the number of measurements decreases with increasing optical depth. More measurements have been done at $\tau < 2$ and relatively less at $\tau > 3.5$. The data for σ_I at $\tau > 3.5 - 7$ are presented in Ref. 2, where σ_I decreases with increasing τ. The data obtained without flakes were divided depending on D_m: at $D_m = 1 \div 3$ mm and $D_m > 3$ mm (including the case of rare flakes falling). It follows from the figures that σ_I values spread over a wide range at close values of τ even in a limited range of D_m values. The level of fluctuations can differ fourfold (Fig. 1*a*) that is far greater than the measurement error.

In our opinion, such a wide spread of σ_I within the chosen D_m ranges is due to natural variations in the particle size distribution and in the internal structure of particles, which could not be properly evaluated by only visual estimation of D_m (Refs. 15 and 16). Errors in τ estimation, not followed in time, are also possible, since in precipitation the contribution of scattered radiation varies significantly within the field of view of a receiver being a part of the visibility range meter. Finally, at a very small τ the atmospheric turbidity in haze and mist, comparable with precipitation, has an effect as well as the remaining atmospheric turbulence, whose level increases with decreasing τ. Haze and mist lead to the shift of the dependence $\sigma = f(\tau)$ in the horizontal direction, while the turbulence shifts it along the vertical direction.

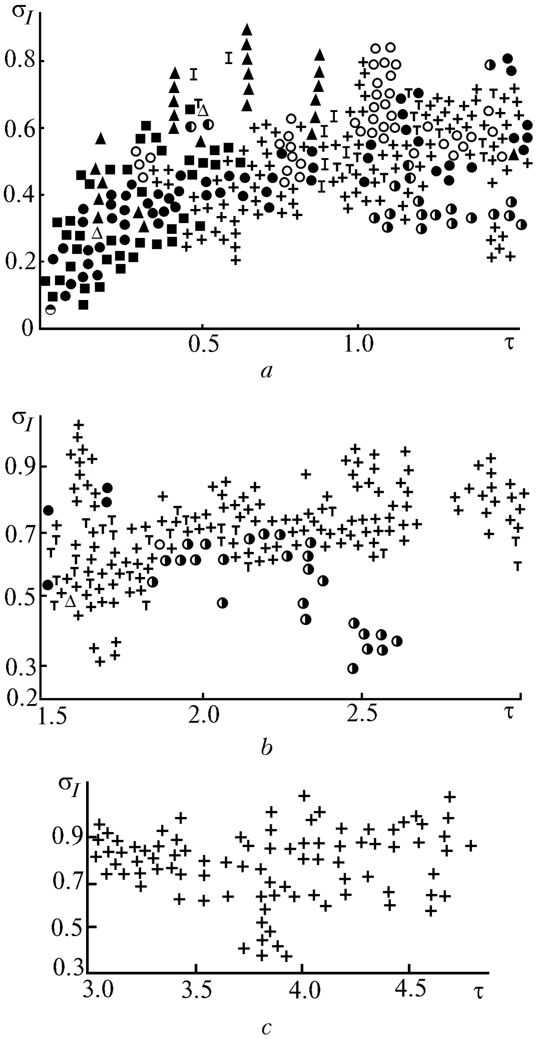


FIG. 1. The level of laser radiation fluctuations (σ_I) *against the optical depth* (τ) *at the receiver diameter* $D_r = 0.1$ mm *and the maximum size of particles* $D_m = 1 - 3$ mm. *The path length L was:* 37 (◓), 130 (•), 260 (■), 390 (▲), 520 (ɪ), 650 (▯), 780 (◑), 910 (◐), 964 (+), *and* 1928 m (ᴛ).

From the corresponding comparison of Figs. 1 and 2 at the same τ it follows that in the range $0.2 < \tau < 3$ the values of σ_I at $D_m > 3$ mm are, on the average, greater than at $D_m = 1 - 3$ mm. At $\tau > 3$ this tendency is not so well pronounced. Let us remind that the data at $\tau > 3$ are not so numerous and possibly just this is the cause of such a dependence of

σ_I on D_m. It is seen from Figs. 2*a* and *b* that in a snowfall of continuously falling snowflakes at $\tau > 0.2$ σ_I is practically always greater than without flakes. In Figs. 1 and 2 as well as in Refs. 1 − 5, the regimes of weak and strong fluctuations are clearly seen. In the first regime, the fluctuations increase with increasing τ, while in the second one they remain practically unchanged (at close D_m).

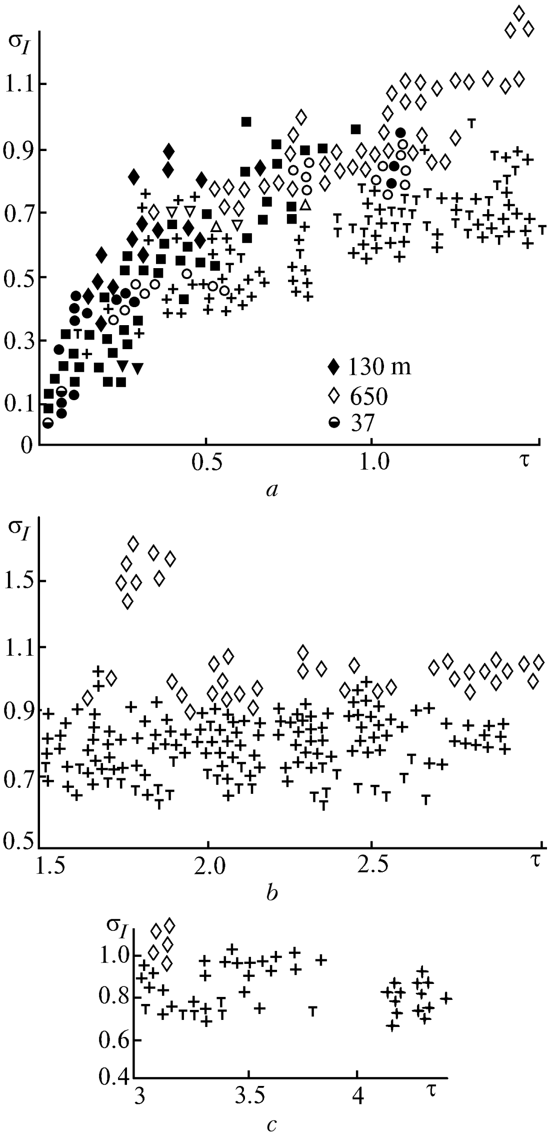


FIG. 2. The level of intensity fluctuations (σ_I) of the laser radiation received against the optical depth (τ) at $D_\mathrm{r} > 3$ mm without continuously falling snowflakes. Designations are the same as in Fig. 1. For the case of "continuous" snowflakes: L = 130 (◆), 650 (◇), and 37 m (⊖).

When looking closely at Fig. 1*a*, one can see that at close values of τ the same σ_I were measured at paths markedly different in length. For example, at $\tau = 0.6 - 0.8$ the close values of σ_I were obtained at paths significantly different in length, namely, 1928, 964, 650, 390, and 130 m long. One can find other ranges of close σ_I values at different L in this and other figures. So the "pure" influence of the path length on σ_I is not found in not averaged data, as well as in the data averaged over certain paths.[1] The influence of τ upon σ_I is clearly seen at close values of the snow particles number density and D_m (Refs. 4 and 5). In flakes, as follows from our data, the maximum observed value of σ_I is 1.4, see Figs. 2*a*, *b* ($\sigma^2 = 2$).

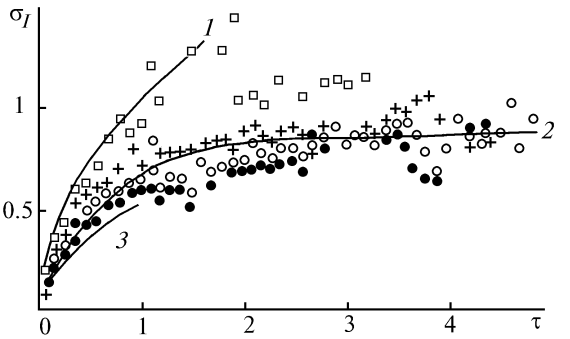


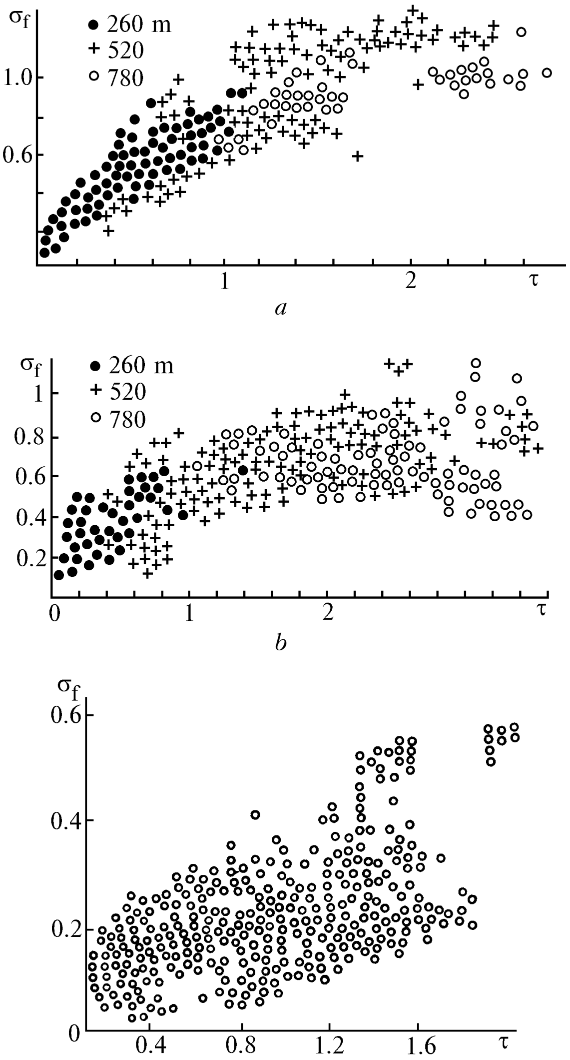
FIG. 3. Average values of the laser radiation intensity fluctuations (σ_I) at $D_\mathrm{r} = 0.1$ mm: averaged over all data except for the case of "continuous" flakes (•), $D_m = 1 - 3$ mm (+), $D_\mathrm{m} > 3$ mm (+), "continuous" flakes (□).

Figure 3 presents the average values σ_I, that were calculated with the step of 0.1 in τ. Here open circles are for σ_I over all the data without "continuous" flakes, closed circles are for the case $D_\mathrm{m} = 1 - 3$ mm, crosses are for the case $D_\mathrm{m} > 3$ mm, and squares are for "continuous" flakes. In this figure at $\tau < 2.6$ the growth of σ_I with increasing D_m is also well pronounced, and there is also no clear dependence of σ_I on D_m at τ more than 2.6. At the same time, it is quite obvious that in "continuous" flakes σ_I is greater than without them. When averaging over τ at $\tau > 2.6$, when the number of values averaged was four or less, this values were not taken into account because they were insufficient for averaging, but earlier, in Ref. 2, we took them into account. In Fig. 3, curve *1* is for the dependence of the level of fluctuations on the optical depth: $\bar{\sigma}_I = \sqrt{\tau}$; curve *2* is for the dependence

$$\bar{\sigma}_I = 0.83\,[1 - \exp(-\,1.65\,\tau)]. \qquad (1)$$

This dependence well describes the experimental results, calculated over all data without flakes (open circles). Curve *3* in Fig. 3 is $\bar{\sigma}_I = 0.52\sqrt{\tau}$. The lower values of experimental σ_I as compared to that calculated by Eq. (1) for $1.05 < \tau < 1.95$ and $3.6 < \tau < 4$ can be explained by a relatively greater weight of σ_I with small D_m in our measurement data. About a half of such data were obtained in snowfalls, when D_m was less than 1 mm. In contrast to the earlier results, Fig. 3 demonstrates the saturation of $\bar{\sigma}_I$ in "continuous" flakes. This takes place at the level somewhat higher than unity, that is comparable (but lower) with the level of saturation of a divergent laser beam in the turbulent atmosphere with aerosol.[17,18]

One should keep in mind that the nature of intensity fluctuations in precipitation is different than in the turbulent atmosphere with aerosol, where the structure characteristic of the refraction index fluctuations, C_n^2, and the inner scale of turbulence, l_0, play a crucial role in fluctuation for ND" .[17,18] For a snowfall, it is natural to add the optical depth and the maximum size of particles to these parameters.



a

b

c

FIG. 4. The level of flux fluctuations (σ_f) *at the receiver diameter* D_r = 0.8 *(a) and* 3.1 mm *(b), the path length of* 260, 520, *and* 780 m; D_r = 25 mm *(c), the path length of* 520 m.

Figure 4 shows the measurement results for the flux fluctuations, σ_f. The vertical scale in Fig. 4*c* is twice as big as that in Figs. 4*a* and *b*. One can see a specific behavior of σ_f from this figure. At D_r = 0.8 and 3.1 mm the fluctuations saturate with increasing τ and the spread of σ_f at close τ is observed. The comparison of figures reveals a common tendency toward a decrease of σ_f with increasing D_r, that is most obvious when comparing Fig. 4*a* and Fig. 4*c*.

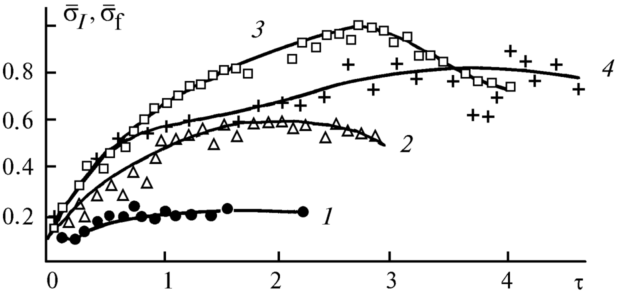


FIG. 5. The average level ($\bar{\sigma}_I$, $\bar{\sigma}_f$) *of fluctuations of radiation received in snowfall against the optical depth at* D_m = 1 – 3 mm *and* D_r = 25 *(1),* 3.1 *(2),* 0.8 *(3), and* 0.1 mm *(4). The data for curve 4 are taken from Fig. 3.*

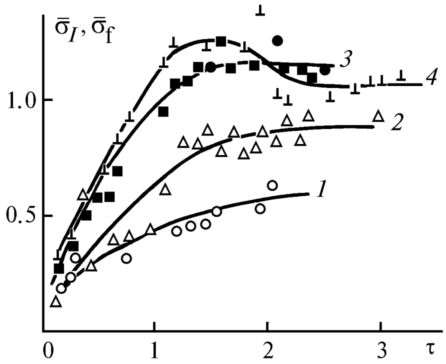


FIG. 6. The average level ($\bar{\sigma}_I$, $\bar{\sigma}_f$) *of fluctuations of radiation received in snowfall against the optical depth at* D_r = 25 *(1),* 3.1 *(2), and* 0.8 *(3) and* D_m = 5–10 mm; D_r = 0.1 mm *and* D_m = 5 – 30 mm *(4).*

Figure 5 presents the average values $\bar{\sigma}_I$ and $\bar{\sigma}_f$ for different D_r at D_m = 1 – 3 mm, and Fig. 6 presents similar data but for D_m > 5 mm and snowflakes. It is clearly seen from Figs. 5 and 6 that $\bar{\sigma}_{I,f}$ depends markedly on the receiver diameter, the maximum size of particles, and the optical depth. It is also important that as τ increases at D_m = 1 – 3 mm, the saturation of fluctuations occurs at lower values of the optical depth when D_r increases. At the same time, with larger snowflakes, the saturation, as follows from the data available, occurs at close values of the optical depth. The attention should also be paid to the fact that the level of flux fluctuations may even decrease with the increasing the optical depth (curve *3* in Fig. 5 and curve *4* in Fig. 6). Let us note once more that the decrease of the intensity fluctuations (σ_I) with increasing τ was revealed first in a heavy snowfall at the 964-m path.[2] The values of $\bar{\sigma}$ for different D_m, L, and τ, that were used when constructing the figures, have been published in the form of tables and plots in Ref. 19. Some data on σ_f were published in Refs. 20, 21, and 22.

Let us discuss now the results of measuring the level of laser radiation flux fluctuations with a varying receiver diameter in snowfalls. It should be noted that performing such experiments took at least half an hour (30 min). But, unfortunately, τ and D_m are not usually stable during such a period. Therefore it is hard to predict the conditions of beam propagation from the data available. This is also the cause why we measured only few number of dependences $\sigma_f = f(D_r)$. In spite of numerous attempts we made, we succeeded in only 14 measurements.

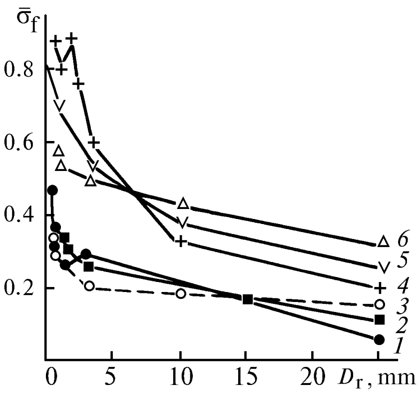


FIG. 7. The level of fluctuations (σ_f) vs. the receiver diameter:

Curve	*1*	*2*	*3*
D_m, mm	1	2 – 5	1 – 3
L, mm	260	520	520
τ	0.36 ÷ 0.41	0.27 ÷ 0.29	0.85 ÷ 1.2

Curve	*4*	*5*	*6*
D_m, mm	1 – 3	1 – 3	2 – 20
L, mm	780	520	520
τ	1.4 ÷ 2.6	0.75 ÷ 0.85	0.46 ÷ 0.57

Shown in Fig. 7 are the results of six measurements. The average values $\bar{\sigma}_f$ were calculated using ten measurement results on σ_f. One can see that at small D_m = 1 – 3 mm fluctuations obviously decrease with increasing D_r (curves *1*, *3*, *4*, and *5*), but this decrease is markedly weaker for large particles (curve *2* and *6*). The level of fluctuations at close D_m and the same D_r increases with decreasing τ (curves *1* and *3*), i.e., the measurements were done under conditions close to single scattering. These facts mean that the spatial correlation length of NDB intensity under conditions close to the single scattering grows with increasing D_m. This does not contradict the conclusion about the decisive role of the particle shadows at the path section adjacent to the receiver in the flux fluctuations.[4,5]

4. CONCLUSION

Summarizing all the abovesaid, the following conclusions can be drawn:

1. The level of fluctuations in the signal received in snowfall first increases and then saturates, with increasing τ, at the level depending on the receiver diameter and the maximum size of particles.

2. Fluctuations decrease with increasing receiver diameter and decreasing maximum size of particles.

3. In the fine-disperse snowfall (D_m = 1 – 3 mm), as the receiver diameter increases, the saturation occurs at lower values of the optical depth.

Thus, two regimes: of weak and strong fluctuations correspond to the flux fluctuations as well as the intensity fluctuations for laser radiation of NDB. In both cases fluctuations increase as the receiver diameter decreases and the maximum size of snow snowflakes increases.

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