ON THE LEVEL OF THE INTENSITY FLUCTUATIONS OF A NARROW DIVERGING LASER BEAM IN SNOWFALL

A.F. Zhukov

Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk
Received October 20, 1992

Some measurements of the intensity fluctuations of a narrow diverging laser beam in snowfall are presented. It is shown that the intensity fluctuations first increase, then saturate, and thereupon decrease with increase of the snowfall optical thickness. The fluctuations also increase with increase of the maximum size of snowflakes.

1. Experimental data obtained in Ref. 1 showed that the level of the intensity fluctuations σ_e of a narrow diverging laser beam in snowfall first increases with increase of the snowfall optical thickness τ and then tends to the saturation level σ_s depending on the maximum size of particles D_m. This is in a qualitative agreement with the theoretical assumptions of Ref. 2, which moreover predicts the decrease of the intensity fluctuations with further increase of τ. However, the analytical dependence $\sigma_e = f(\tau)$ was not determined in Ref. 2. The empirical relations between σ_e and τ were proposed for two ranges of variations of D_m in Ref. 1. They were found by way of fitting the curves obtained on individual paths of different lengths.

Recently we have performed additional measurements of the intensity fluctuations on 964 and (2×964) m paths using the method and instrumentation described in Ref. 1. On (2×964) m path the measurements were performed by means of reflection of a laser beam from a flat mirror 40 cm in diameter. In contrast to Ref. 1, an averaging over τ for the chosen size D_m was performed for the entire data set (i.e., disregarding the length of the path) to determine the dependence $\sigma_e = f(\tau)$.

The results of such an analysis are presented in this paper. We analyzed 3 000 pairs of σ_e and τ. The quantities $\overline{\sigma}_e$ averaged over all paths for two ranges of variations of the maximum particle size $D_m = (1 - 3)$ mm and $D_m > 3$ mm are shown in Fig. 1. The cases of precipitation of individual flakes were included in the second range. The data published earlier in Ref. 1 and obtained on 650–m path in the case of precipitation of continuous flakes are shown in Fig. 1 for comparison. The results of calculation of $\overline{\sigma}_e$ and $\overline{\tau}$, the standard deviation $\Delta\sigma$ for σ_e, as well as the number of averaged values (n) for each interval of τ are listed in Table I. An averaging was performed with a step of 0.1.

As can be seen from the table, the number of pairs of σ_e and τ differs at different τ, but at $\tau < 3.5$ it is still sufficient for statistical averaging. An approximation for different D_m was based on the best coincidence with experimental points. The additional aim was to find the generalized dependences for different D_m.

It can be seen from Fig. 1 that the level of fluctuations at $\tau = 0.6 - 4.0$ for the above–described ranges of D_m is approximated fairly well by the rather simple dependence

$$\sigma_e = \sigma_s [1 - \exp(- 2\sigma_s \tau)] .$$

TABLE I. The quantity $\overline{\sigma}_e$ averaged over all paths for a narrow diverging beam and $D_m = 1 - 3$ mm. Here τ is the optical thickness, n is the total number of points, and $\Delta\sigma_e$ is the standard deviation of σ_e.

σ	τ	n	$\Delta\sigma_e$	σ	τ	n	$\Delta\sigma_e$
0.14	0.08	10	0.04	0.71	2.45	23	0.01
0.19	0.14	30	0.06	0.71	2.54	15	0.03
0.31	0.25	50	0.05	0.73	2.62	1	–
0.37	0.34	69	0.03	0.74	2.79	5	0.01
0.38	0.44	85	0.05	0.86	2.87	6	0.07
0.40	0.53	62	0.08	0.81	2.96	25	0.06
0.46	0.66	77	0.09	0.84	3.04	15	0.06
0.51	0.75	134	0.08	0.80	3.14	18	0.05
0.52	0.86	31	0.05	0.80	3.24	13	0.06
0.49	0.95	25	0.06	0.78	3.33	24	0.07
0.51	1.05	51	0.07	0.87	3.43	2	–
0.55	1.16	49	0.09	0.76	3.53	5	0.08
0.60	1.26	43	0.07	0.68	3.63	3	0.02
0.61	1.35	46	0.08	0.74	3.72	3	0.14
0.64	1.45	43	0.08	0.82	3.83	7	0.14
0.57	1.53	51	0.08	0.75	3.92	4	0.12
0.62	1.66	60	0.10	0.93	4.06	9	0.10
0.59	1.74	46	0.06	0.84	4.15	4	0.12
0.67	1.84	10	0.09	0.79	4.25	6	0.13
0.70	1.96	29	0.04	0.86	4.30	3	0.08
0.71	2.08	47	0.07	0.77	4.41	6	0.13
0.55	2.15	10	0.02	0.98	4.53	4	0.04
0.68	2.22	24	0.03	0.73	4.62	16	0.14
0.71	2.34	18	0.03	0.93	4.78	3	0.06

0235-6880/93/01 19-03 $02.00

TABLE II. The quantity $\bar{\sigma}_e$ averaged over all paths for a narrow diverging beam and $D_m = 3 - 5$ mm. Here τ is the optical thickness, n is the total number of points, and $\Delta\sigma_e$ is the standard deviation of σ_e.

σ	τ	n	$\Delta\sigma_e$	σ	τ	n	$\Delta\sigma_e$
o.26	0.09	1	–	0.87	2.25	53	0.09
0.35	0.17	21	0.04	0.89	2.33	84	0.09
0.44	0.23	50	0.05	0.91	2.46	37	0.08
0.54	0.34	134	0.09	0.86	2.52	40	0.08
0.59	0.44	72	0.07	0.87	2.64	17	0.13
0.57	0.55	243	0.08	0.93	2.75	22	0.09
0.64	0.65	75	0.10	0.96	2.87	13	0.13
0.76	0.75	44	0.06	1.06	2.96	12	0.02
0.75	0.86	66	0.06	0.93	3.05	13	0.07
0.76	0.97	72	0.07	0.83	3.14	19	0.12
0.77	1.06	51	0.10	0.89	3.33	19	0.08
0.81	1.16	51	0.08	0.95	3.43	18	0.04
0.82	1.25	46	0.08	1.01	3.53	12	0.08
0.79	1.34	21	0.11	0.98	3.63	3	0.01
0.78	1.44	43	0.09	0.98	3.73	5	0.01
0.78	1.55	35	0.08	0.87	3.82	2	–
0.82	1.66	29	0.07	0.88	4.00	3	–
0.84	1.75	56	0.09	0.81	4.17	21	0.05
0.80	1.84	14	0.09	0.92	4.76	2	–
0.86	1.97	32	0.07	0.80	4.30	19	0.05
0.86	2.07	48	0.09	0.83	4.92	2	–
0.84	2.16	43	0.08	0.81	5.08	2	–

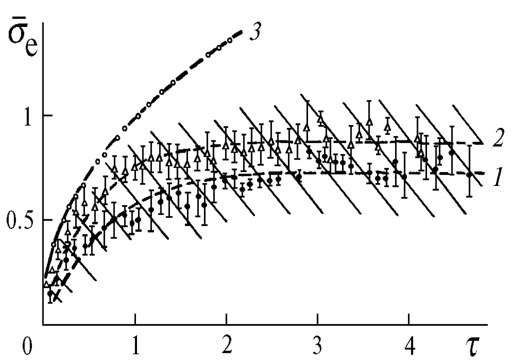

FIG. 1. Fluctuation level σ_e averaged over all paths at different τ for three values of the maximum diameter of snowflakes D_m: 1) 1 – 3, 2) 3 – 5, and 3) 7 mm on 650–m path.

For $D_m > 3$ mm, σ_s is equal to 0.9 while for $D_m = (1 - 3)$ mm, $\sigma_s = 0.75$. Curve *3* in Fig. 1 is described fairly well by the dependence $\sigma_e = \sqrt{\tau}$. This is the main result of this work.

2. During one of snowfalls we could measure τ varying from 3.5 to 7. We enlarged the receiver diameter from 0.3 to 0.5 mm to increase the signal–to–noise ratio. At the same time we performed measurements on (2 × 130) m path with the same narrow diverging beam and the receiver diameter $D_r = 0.3$ mm. Such an insignificant increase in the receiver diameter on 964–m path did not result in the noticeable smoothing of fluctuations. This conclusion follows from the results of comparison of the spectra of fluctuations on 964–m path obtained with two diameters of the receivers. Moreover, the level of fluctuations at $\tau = 3.5 - 5$ with close value of D_m ($D_m = (1 - 3)$ mm) during another snowfall was in the same range, though the measurements were performed with $D_r = 0.3$ mm. The decrease of σ_e with increase in τ, predicted in Ref. 2, can be clearly seen from Fig. 2. According to our data at $\tau = 3.5 - 6.5$, it is described by the dependence $\sigma_e = 1.13–0.11\tau$.

It is important that σ_e on 964 and 260–m paths are close in values (average value of the ratio of σ_e (260 m) to σ_e(964 m) is equal to 0.96 at $\tau = 5.1–6$. It should be taken into account that the spectra of the fluctuations $U(f)$ differ insignificantly when it is considered that the values of the perpendicular wind velocity $V_\perp$ were different (see Fig. 3). Here $U(f) = f\,W(f)/\int W(f)\mathrm{d}f$, where $W(f)$ is the spectral power density at the frequency f.

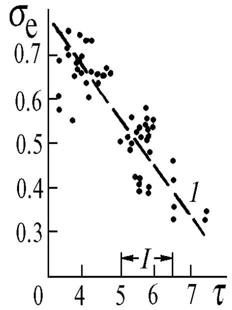

FIG. 2. The dependence of the level of fluctuations σ_e on τ at $\tau > 3.5$ for $D_m = (1 - 3)$ mm on 964–m path. The receiver diameter was 0.5 mm. The measurements were also performed on (2 × 130) m path at $\tau = 5 - 6.5$ (L = 964 m).

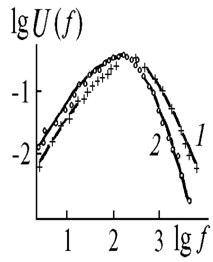

FIG. 3. The spectrum of fluctuations $U(f)$ in snowfall for $D_m = (1 - 3)$ mm: 1) $\tau = 4.3$, $V = 7.8$ m/s, $V_\perp = 2.5$ m/s, and $L = 964$ m and 2) $\tau = 1.1$, $V = 7.8$ m/s, $V_\perp = 1.3$ m/s, and $L = 260$ m.

The physical reason for these two unexpected coincidences is not quite clear. At the same time they together with the results of Ref. 3 can be considered as one more weighty argument in favour of the same main reasons for the intensity fluctuations of a narrow diverging beam on paths of different lengths. Most obvious among them are screening of a laser beam by snowflakes localized in the layer adjacent to the transmitter as well as screening of the single–point receiver by particles of the atmospheric layer adjacent to the receiver.

In Ref. 3 the intensity fluctuations of a narrow collimated beam saturated at a level of 1.2 in rain. It is nearly twice as large as the level of saturation in snowfall. These differences are due to the fact that in Ref. 3 the main contribution to the fluctuations came from the atmospheric turbulence. In our case fluctuations are almost completely due to the snowflakes, because the low–frequency maximum, corresponding to the atmospheric turbulence, is absent in the spectrum.

The author would like to acknowledge N.A. Vostretzov and N.P. Krivolapov for their participation in several measurements and R.Sh. Tzvyk and M.V. Kabanov for useful discussions of the obtained results.

REFERENCES

1. A.F. Zhukov, M.V. Kabanov, R.Sh. Tsvyk, N.A. Vostretsov, and N.P. Krivolapov, Atm. Opt. **4**, No. 4, 272–275 (1991).
2. A.G. Borovoi, Izv. Vyssh. Uchebn. Zaved. Radiofiz. **25**, No. 4, 391–400 (1982).
3. A.G. Borovoi, G.Ya. Patrushev, and A.I. Petrov, Appl. Opt. **27**, No. 17, 3704–3714 (1988).