Normalized variance of the intensity fluctuations of a divergent beam in snowfalls measured with a photodetector shifted off the beam optical axis

N.A. Vostretsov and A.F. Zhukov

Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk

Received September 2, 2005

The normalized variance ($\bar{\sigma}^2$) of the intensity fluctuations of a divergent laser beam in the ground atmosphere in snowfalls was measured with a photodetector shifted off the beam optical axis. It is shown that $\bar{\sigma}^2$ increases under these conditions because of scattering by snowflakes.

As known, shift of a photodetector off from the optical axis of a spatially limited Gaussian beam under conditions of weak fluctuations in turbulent atmosphere without precipitation results in an increase of σ^2 (Refs. 1–5). In this case, the experimental and calculated results[1,4,5] qualitatively agree quite well.[1–3]

Similar effect takes place in calculations for scattering media, when radiation wavelength is significantly less than diameters of isotropic spherical particles.[6,7]

Earlier we used one photodetector, placed near optical axis of a beam, for measurements in snowfalls. In the present study, we describe experiments with the use of two photodetectors simultaneously. One of them was placed near the optical axis, as before, and was used for monitoring atmospheric conditions during measurements. Another one received radiation from an optical cube (2.5 cm in size). First the cube was placed on the beam optical axis and then it was displaced in horizontal direction parallel to the optical axis with the step of 0.5 or 1 cm. Thus, the photodetector received radiation from different portions of a beam cross section, which were at the distance R from the beam optical axis. Detailed description of the experiment can be found in Refs. 5, 8, and 9.

The measurements have been conducted on a 130-m long path at about 2-m height above the ground surface. The initial diameter of the beam was 6 mm and the total divergence angle equaled 10^{-3} rad, radiation wavelength $\lambda = 0.63$ μm. Diameters of photodetectors were 0.1 mm, total viewing angle was $2.7 \cdot 10^{-2}$ rad. Meteorological visual range was measured with an RDV-3 device. Data of these measurements were used for calculation of the optical depth, τ, of the path. A meteorological station M63m measured wind speed. Maximum size $D_{\rm m}$ of snowflakes was estimated visually after their trapping on a piece of fur. Normalized variance of the intensity fluctuations $\bar{\sigma}^2$ was calculated using values of $\sigma^2_{\rm un}$ and $<U>$ measured with a two-channel variance meter

$$\bar{\sigma}^2 = <(U - <U>)^2>/<U>^2 = \sigma^2_{\rm un}/<U>^2,$$

where U is the voltage at the photodetector load resistor; $\sigma^2_{\rm un}$ is the unnormalized variance; $< >$ denotes time averaging. Averaging of $\bar{\sigma}^2$ was performed over 20-s interval. We measured the intensity fluctuations of laser radiation since the variance of the received radiation fluctuations does not increase with the decreasing diameter of the receiver starting from 0.1 mm.

In each channel of the variance meter, the variance error did not exceed 15% within the range of normalized variance variations from 0.01 to 1. Normalized variances, calculated using measured values of $\sigma^2_{\rm un}$ and $<U>$, differed no more than 5% for the same signals in two channels of the variance meter. Spectral functions of the intensity fluctuations $U(f)$ were calculated using average voltage at outputs of each of 38 three-octave filters making up a parallel-type frequency analyzer:

$$U(f) = fW(f) \Big/ \int W(f)\,{\rm d}f,$$

where $W(f)$ is the spectral power density at the frequency f, f is the central frequency of the filter. Time of signal averaging at outputs of filters was about 100 s. Filters were calibrated to pink-noise, which was accounted for in $U(f)$ calculations. Spectral power of the pink noise was inversely related to the frequency.

The above measurements were carried out in snowfalls at the optical depth close to 0.1.

Figure 1*a* shows $\bar{\sigma}^2$ variations for turbulent atmosphere without precipitation (curve *1*) and for small snowflakes (with the maximum size $D_{\rm m} \approx 1$ mm) (curve *2*).

Here the photodetector shift R, normalized to the effective beam radius in the receiving plane α_0, is plotted on the abscissa. Beam radius, at which the beam has the same power as the Gaussian one, is called an effective beam radius. The effective beam has the same intensity throughout the beam cross section, which is 2.72 times as low as that of a Gaussian beam at its optical axis. Curves *1* and *2* are plotted through the points that present average of

0235-6880/06/05 373-02 $02.00

nine measured values of the variance. Vertical bars in Figs. 1 and 2 show the root-mean-square deviations of the variance. RMS deviations are not shown for the detector shifts, at which they have been equal to 0.001–0.002. Average variances in turbulent atmosphere without precipitation are slightly shifted horizontally to the right.

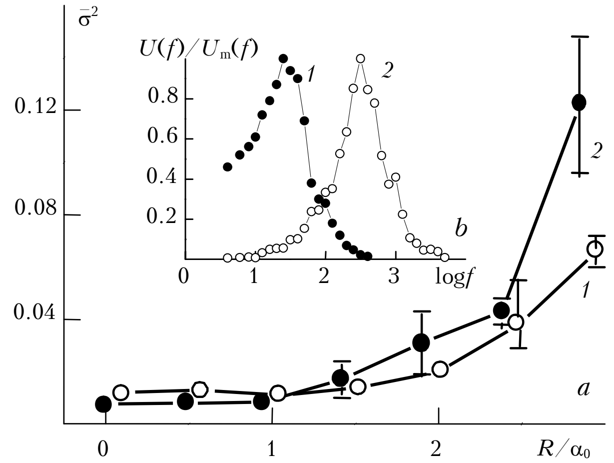

Fig. 1

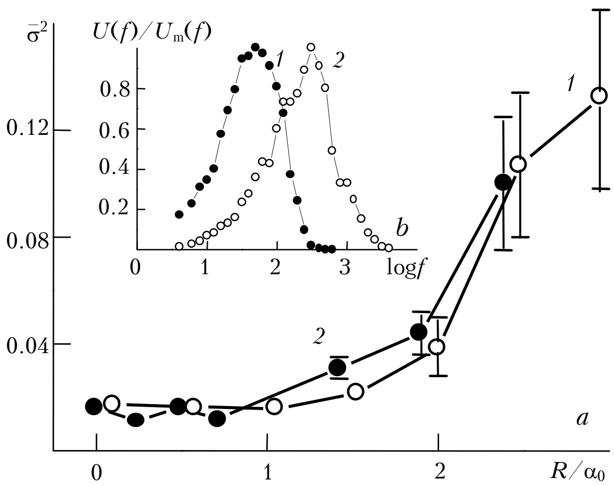

Fig. 2

Normalized spectral functions $(U(f)/U_m(f))$ obtained with the detector shifted to $R = 6$ cm $(R/\alpha_0 = 2.8)$ from the optical axis of the beam are shown in Fig. 1*b*. Here $U_m(f)$ is the maximum of the spectral function. Wind speed $V = 2$–3 m/s $(V_\perp = 1$ m/s$)$.

In Fig. 2*a*, curve *1* corresponds to turbulent atmosphere without precipitation while curve *2* to situation with large snowflakes ($D_m = 5$–10 mm). In Fig. 2*b*, curve *1* is the normalized spectral function for turbulent atmosphere at the photodetector shift $R = 6$ cm $(R/\alpha_0 = 2.8)$, curve *2* is for large snowflakes at the same shift. Wind speed and its component, perpendicular to the path, are the same as in Fig. 1.

In turbulent atmosphere, under conditions of weak fluctuations without precipitation, $\bar{\sigma}^2$ increases when moving the photodetector off from the optical axis of the beam. Similar behavior of $\bar{\sigma}^2$ was observed in snowfalls. As follows from Figs. 1*b* and 2*b*, it is caused by snowflakes. The difference by one order of magnitude between maxima of spectral functions in the atmosphere without precipitation and in snowfalls is evident from Figs. 1 and 2. This agrees with earlier determined[9] high-frequency broadening of the spectral function in the case of snowfall.

In both weather situations $\bar{\sigma}^2$ changes little within the limits of an effective beam radius (see Figs. 1*a* and 2*a*). It rises by a factor of 3 if the detector is shifted off from the beam optical axis that is much higher than $\bar{\sigma}^2$ measurement errors. Increase of D_m at the same shifts results in an increase of the variance of intensity fluctuations.[8]

It seems that increase of normalized variance at a shift of the photodetector from an optical axis of the beam is caused by simultaneous action of two factors, i.e., decrease of mean intensity and increase of a fraction of scattered radiation caused by scattering from snowflakes that are within the beam.

It is shown that the normalized variance $\bar{\sigma}^2$ in snowfalls is non-isotropic over the cross section of a Gaussian beam. It is minimum if measured near the beam axis while it takes its maxima at the beam boundary, which can be conditioned by beam swinging due to air turbulence and vibrations of the transmitter.

Acknowledgments

The authors are grateful to I.P. Lukin for useful remarks.

References

1. V.L. Mironov, *Laser Radiation Propagation in Turbulent Atmosphere* (Nauka, Novosibirsk, 1981), 246 pp.
2. V.L. Mironov and G.Ya. Patrushev, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **15**, No. 6, 865–872 (1972).
3. V.A. Banakh, G.M. Krekov, and V.L. Mironov, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **17**, No. 2, 252–260 (1974).
4. V.L. Mironov and G.Ya. Patrushev, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **18**, No. 3, 450–452 (1975).
5. A.F. Zhukov, A.V. Efremov, S.S. Khmelevtsov, and R.Sh. Tsvyk, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **17**, No. 11, 122–123 (1974).
6. V.A. Krutikov, in: *Problems of Atmospheric Optics* (Nauka, Novosibirsk, 1983), pp. 141–150.
7. S.I. Tuzova, *"Field intensity fluctuations in the cross section of an optical beam propagating in an aerosol medium,"* Dep. VINITI. 2696-B89 (1989), 8 pp.
8. N.A. Vostretsov and A.F. Zhukov, Atmos. Oceanic Opt. **18**, No. 3, 200–203 (2005).
9. N.A. Vostretsov, A.F. Zhukov, M.V. Kabanov, and R.Sh. Tsvyk, Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **20**, No. 7, 581–588 (1984).