Requirements to the technique and instrumentation for measuring fluctuations of a laser beam radiation in snowfalls

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The paper determines the requirements to instrumentation and technique for investigations of the main fluctuation characteristics of laser beam radiation in snowfalls.

Introduction

Time fluctuations of laser beam radiation in snowfalls depend on the characteristics of a laser beam, detector, and atmospheric conditions of propagation (ACP) of laser beam radiation (see Ref. 1 and references therein). The ACP in snowfalls vary significantly with time. These and other properties of snowfalls should be taken into account in the measurement technique and in the parameters of instrumentation intended for the investigation of laser radiation scintillation.

1. Some requirements to instrumentation and technique for measurement of statistical characteristics of laser radiation

1.1. Measurement of variance of signal fluctuations

It is very important to select an appropriate measurement technique. The atmospheric conditions of radiation propagation in snowfalls are characterized by slow and fast variations. The frequency boundary between them is not determined. The nature and properties of fluctuations manifest themselves in significantly different frequency ranges. Slow variations of an electric signal (at the photodetector output) on the detector load are caused by natural variations of atmospheric transmittance on the measurement path due to turbidity of any kind and by slow variations of the turbulent characteristics of the air due to snowfalls, which are quite poorly studied. Transmittance variations were studied repeatedly with the use of optical transmissiometers.[2] They are characterized by a significant time lag. This paper, as Ref. 1, considers scintillations of laser beams in a frequency range of 0.05 Hz to 20 kHz, which are caused by turbulence of the atmospheric air (hereinafter, turbulence for brevity) and by motion of snowflakes.

The characteristics of the medium along the measurement path vary arbitrarily for long time intervals. The electric signal is random and nonstationary. However, for short time intervals (Δt), ACP do not change considerably. The process of electric signal fluctuations can be considered as approximately stationary, and the corresponding algorithms can be used. In Ref. 1, $\Delta t \approx 20$ s for the variance. The cases of fast change of ACP were excluded from the processing. Changes in the signal, which occurred for any 20-s interval and caused 10% changes of the current mean value of the signal as compared to its initial value determined at the beginning of every 20-s interval, were treated as fast ones. According to our data, fast changes of ACP even for the so short time interval are possible.

Four circumstances are to be noted:

1. In the technique described in Ref. 1, the fast changes of the mean signal were excluded from the analysis, although they are characteristic of snowfalls, that is, a part of data were deliberately rejected. This should be kept in mind when analyzing the results.

2. The variance was calculated as

$$\sigma^2 = \langle (U - \langle U \rangle)^2 \rangle / \langle U \rangle^2.$$

Here U is the random voltage across the photodetector load; $\langle U \rangle$ is its average value; angular brackets $\langle\ \rangle$ denote time averaging. The values of $\langle (U - \langle U \rangle)^2 \rangle$ and $\langle U \rangle$ were measured consecutively by a precision voltmeter. The signal before the square-law generator was amplified to correspond to its dynamic range. The value of $\langle U \rangle$ was measured just for this arbitrarily amplified signal; therefore, we could not estimate the volume scattering coefficient (α) from it, but could calculate σ^2.

3. The scattering by snowflakes significantly attenuates the beam. Large α and low power of laser sources seriously restrict the capabilities of an experiment along extended paths. Therefore, it is quite natural to increase the laser power until its radiation begins to change the optical properties of the ambient medium in the beam.

4. It should be taken into account that the studies are usually concentrated at maximum possible radiation fluctuations, that is, intensity fluctuations, which actually means the small diameter of the

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detector D as compared to the spatial correlation length of the intensity fluctuations ρ_k.

For a monodisperse medium with discrete spherical particles of radius a_r, it follows from Ref. 3 that $\rho_k \approx a_r$ under conditions, when the optical thickness τ is smaller than unity, and with the increase of τ the value of ρ_k decreases, so that $\rho_k = P_0 a_r/\tau$. The proportionality coefficient P_0 is still unknown. Assume that ρ_k has the same tendency in snowfalls. Then, to maintain the identical detection conditions with the increase of τ, it is needed to decrease the detector diameter D, so that $D \ll P_0 a_r/\tau$. At a low power of a source, this may be an obstacle for obtaining reliable information about scintillations in intense snowfalls along the extended paths, because the increase of τ and the decrease of D lead to a decrease in the signal-to-noise ratio at the output of the receiving system.

According to our data,[1] the maximum variance for a narrow diverging beam was measured in sheeted snow, when snowflakes had the maximum size ($D_{\rm m}$) about 7 mm. This variance did not exceed two, which is smaller than the maximum possible variance in the turbulent atmosphere without precipitation. According to Ref. 4, the maximum variance σ^2 is about 10. For comparison, we will use just this value of the variance σ^2.

The minimum value of the variance σ^2 is taken equal to 0.01. According to our data,[1] this value is quite sufficient for revealing the characteristic features in scintillations for paths longer than 0.1 km. In studying the dependence of variance on the characteristics of the beam and the medium, it is necessary to watch the mode of scintillations[5] (growth, saturation, or decay), because the dependence can be different in different modes.

1.2. Measurement of the spectral function

The spectral function $U(f)$ in the experiments was estimated in the range from 2 Hz to 20 kHz [Ref. 1]. Here

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

where $W(f)$ is the spectral density at the frequency f. According to our data, the upper boundary $f = 20$ kHz is sufficient for the estimation of $U(f)$, while the lower boundary $f = 2$ Hz is insufficient and $U(f)$ should be also measured at $f < 2$ Hz. To find the characteristic features of $U(f)$, it is needed to carry out measurements in a frequency range from 0.05 Hz to 20 kHz with the amplitude resolution of 10%.

1.3. Measurement of the autocorrelation function

The autocorrelation function (ACF) is uniquely related to the spectrum. Spectra with two pronounced maxima should have ACF with two characteristic slopes (scales). The two-scale character of ACF was not found experimentally.[6] This is likely caused by the fact that the time shift of a signal in the correlator was fitted for the entire broadband signal with the prevalent orientation to its high-frequency part.

It would be more correct to separate high- and low-frequency components in the signal spectrum and to determine ACF separately for the two parts of the spectrum and for the entire signal. The boundary between the components can be taken in a range from 20 to 100 Hz (more exactly, at the frequency of $U(f)$ minimum between the maxima).

1.4. Measurement of the probability distribution

There are also some features in the measurements of the probability distribution of scintillations. The main task is to find the analytical dependence, describing the empirical distributions. Various criteria, for example, χ^2 [Ref. 7], are used for this purpose, but during the processing it is necessary to analyze independently (only independently) sampled values of the electric signal. The decision about their presence can be made only after the analysis of ACF. The autocorrelation function, as was shown in Ref. 6, may vary significantly and depends on the wind velocity, detector diameter, and the maximum size of snowflakes. We believe that ACF also depends on the volume scattering coefficient (α).

Another important aspect is that the electric signal can decrease to zero ("seeming" zero). Note that standard pulse analyzers respond to a signal of several millivolts. So the best way is to add some small constant value to the signal and take it into account when analyzing the measured scintillations.

2. Peculiarities of comparison of experimental and theoretical results

In comparing the results, it is very important to answer the question: how do snowflakes and turbulence affect scintillations of the received radiation: additively or in some other way? Essentially, this question is discussed for a long time, but it remains open yet.

Some papers[8–11] accept the additivity, that is

$$\sigma^2 = \sigma_{\rm T}^2 + \sigma_{\rm s}^2, \qquad (1)$$

where $\sigma_{\rm T}^2$ and $\sigma_{\rm s}^2$ are the turbulent and snow contributions to σ^2, respectively.

There is also the opposite opinion, that is, the contributions are assumed non-additive in the form[12,13]:

$$\sigma^2 = \sigma_{\rm T}^2 + \sigma_{\rm s}^2 + \sigma_{\rm T}^2\sigma_{\rm s}^2, \qquad (2)$$

or in the form[14]:

$$\sigma^2 = \sigma_{\rm T}^2 + \sigma_{\rm s}^2 - 2\sigma_{\rm T}^2\sigma_{\rm s}^2. \qquad (3)$$

I intuitively prefer Eq. (2), because in the scientific literature there is no discussion of the inconsistency between the results of Refs. 14 and 12, 13.

There are also some publications on this subject, which do not discuss the question formulated above.[15–17]

Equations (1) and (2) differ by the third term $\sigma_T^2\sigma_s^2$. The answer to the question formulated essentially consists in the value of this term. If it is small in comparison with the sum of the first two terms in the right-hand side, then Eq. (2) transforms into Eq. (1) and the answer is clear.

In comparing the experimental and theoretical results, it is important to keep in mind the following circumstances:

1. In Eqs. (1) and (2), it is necessary to know σ_T^2. It is believed that any of known turbulent calculation methods can be used for this purpose. However, C_n^2 and l_0, affecting σ_T^2 in snowfalls are known not enough accurately. Thus, actually the problem is not solved. Here C_n^2 is the structure characteristic of fluctuations of the refractive index of the atmospheric air; l_0 is the inner scale of turbulence.

2. Usually, for example, in Refs. 8–12, the theoretical solution is sought in the approximation of the near and far zones. This means that only two parts, where the corresponding approximations are fulfilled, are separated on the path. The role of other path parts in scintillations is not determined, but their significance is obvious even because they affect the mean value of the electric signal, which is used to calculate σ^2.

3. All the calculations are performed in the approximation of spherical and isotropic particles, which clearly is not true for snowfalls.

4. Snowflakes weakly absorb the optical (visible) radiation, and their refractive index is 1.33 (ice). Hence, it is clear that snowflakes are not "black" screens[13] and not "soft" particles.[9] So only qualitative agreement between the measured scintillation characteristics and the available calculated data could be expected.

5. Turbulence causes only minor variations of the refractive index of the atmospheric air around a snowflake. Therefore, the relative refractive index of a particle (with respect to the medium) varies negligibly. In this connection, the scattering by particles can be considered as scattering in the non-turbulent medium. On the other hand, the turbulent (random) phase change in the areas occupied by particles is small as compared to that in the air inhomogeneities between particles. Hence, it is clear that turbulence and particles do not prevent each other from acting on the laser beam. However, there is a relation between them. It reflects the fact that any particle is illuminated by the radiation having passed through a turbulent medium. This radiation has a random component. The properties of radiation incident on a particle manifest themselves in the scattered radiation. For example, sinusoidal modulation of radiation emitted from the source can be seen in the scattered radiation at any angle. Thus, the contributions are always nonadditive.

In the case that the spectrum of $U(f)$ has a deep minimum between maxima,[1] the values of σ_T^2 and σ_s^2 can be found from the spectral function $U(f)$. However, this method of estimation of σ_T^2 and σ_s^2 gives a large error. In general, a more accurate estimation of σ_T^2 and σ_s^2 and determination of the relation between them are quite difficult problems. Solutions are contradictory. For example, in Ref. 12 it is believed that the normal concentration of precipitation (rain) particles is small and the contributions of σ_T^2 and σ_s^2 to σ^2 can be considered additive. In Ref. 13, the opinion concerning the estimation of σ_T^2 and σ_s^2 in rain is quite opposite. It is certainly clear that specially arranged measurements are strongly desired, and their results could give a reasoned answer to the question formulated above. Such measurements should likely take into account the differences in the aerodynamic and optical properties of precipitation particles and turbulent inhomogeneities of the refractive index of atmospheric air.

To find the dependence of any fluctuation characteristic of an electric signal on the characteristics of the beam and the detector, it is necessary to compare results obtained under the same or at least close atmospheric conditions. This was made in Ref. 18. That paper studied the dependence of the snow contribution σ_s^2 on the wave parameter Ω at the optical thickness $\tau = 0.4–0.6$ and maximum particle size $D_m \le 5$ mm. It is worthy to note that σ_s^2 was estimated in different snowfalls and on significantly different path lengths L (from 130 to 1310 m). Recall that $\Omega = k\alpha^2{}_{,0}/L$, $k = 2\pi/\lambda$, α_0 is the effective radius of the Gaussian beam; $\tau = \alpha L$. Although in Ref. 18 the values of the optical thickness are close for different L, but since L are different, the results obtained at different α or different ACP are actually compared. It is just this circumstance that makes the main disadvantage of the research presented in Ref. 18.

Nevertheless, in Ref. 18 the linear dependence between σ_s^2 and Ω was found for collimated beams, which follows from theoretical calculations presented in Refs. 12 and 19.

Another circumstance is also important. Reference 18 used the measurements along the paths with reflection, having the length of 390 (3×130) m and 650 (5×130) m. Collimated beam reflected from plane mirror disks. The disk radii were larger than the beam radii. For the 390-m long path, the diameter of the disks (mirrors) was equal to 70 cm. At the 650-m long path, two first disks had a diameter of 40 cm, while two next ones were 70 cm in diameter. The reflection of the beams was used in order to average the influence of spatial inhomogeneity of snowfalls and to increase the path length. At the paths with reflection (the path length multiple of 130 m here), the radiation scattered at angles larger than the angular size of the mirror disk ($2R_d/L_d$) does not take part in the formation of fluctuations of the detected radiation. Here R_d is the disk radius, L_d is the distance from the radiation source to the disk. In other words, the reflecting disks restrict the scattering phase function from above to the angles R_d/L_d. This is, essentially, the incorrectness (disadvantage) of such measurements.

However, σ^2 values measured along the paths with reflection are in a good agreement with the results obtained along the paths without reflection 130 and 964 m long.[5,20] This indicates indirectly the possibility of using the "trimmed" scattering phase function in snowfalls,[21–23] but it is still better and more reliable to avoid measurements with reflection.

Taking the above-said on Ref. 18 into account, it is reasonable to compare only the results obtained without reflection along a path of the same length (L = 130 m), but at different Ω. In this work, such data from Ref. 18 were supplemented with the results of measurements with $\Omega = 12$ along the same path of 130 m length, carried out later. The number of data decreased obviously, but their quality increased. In general, the tendency in the behavior of the dependence $\sigma_s^2 = \sigma_s^2(\Omega)$ keeps the same: σ_s^2 decreases with the decrease of Ω. Note that σ_s^2 in this case is free of the disadvantages mentioned above.

In Refs. 20, 24, and 6, I made some mistakes. Thus, in the Table presented in Ref. 24, the cell at the intersection of the 15th row and the 5th column should contain 1.07 in place of 0.474, and in Ref. 20 $\sigma = 0.52\sqrt{\tau}$ should be replaced by $\sigma = 0.72\sqrt{\tau}$. As to Ref. 6, in Fig. 1 the horizontal axis should be marked $0.3t$, ms, rather than t, ms.

These mistakes do not change seriously the conclusions drawn in Refs. 6, 20, and 24.

Conclusions

It follows from the above-said that during the measurements it is necessary to determine the atmospheric conditions of laser beam propagation. They are characterized by three important features:

1. They have no pronounced diurnal behavior and thus differ from turbulent ACP.
2. ACP in snowfalls change fast and randomly with time even in the same snowfall. This is, perhaps, one of the main difficulties in the interpretation of measurement data.
3. As was already noted in Ref. 1, under the effect of snowfalls, not only the properties of precipitation, but also turbulent ACP vary with time.

These features should be taken into account in the measurement technique.

The requirements to the characteristics of the processing instrumentation for investigating fluctuations of an electric signal (voltage) across a load of the detector of laser beam radiation in snowfalls are quite close to those needed for investigating the influence of turbulence without precipitation. The capabilities of modern computers meet these requirements quite well.

The technique of measurements in snowfalls becomes more complicated as compared to the turbulent atmosphere without precipitation because of the need:

a) to compensate for the beam attenuation by snowfall. This can be achieved by increasing the beam power and the photodetector sensitivity;

b) to measure the atmospheric conditions of propagation faster than in the cloudless atmosphere. These conditions include the characteristics of snowfalls and turbulence in snowfalls.

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