# TIME CHARACTERISTICS OF THE INTENSITY AND FLUX FLUCTUATIONS OF A SPHERICAL WAVE REFLECTED FROM SPECULAR OBJECTS IN THE TURBULENT ATMOSPHERE

**G.Ya. Patrushev**

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

*Received November 26, 1993*

*This paper deals with an analysis of time structure of the fluctuations of the intensity and flux of a spherical wave reflected from a specular disc of large diameter and from a spatial array of closely packed ground–based corner–cube reflectors for strong intensity fluctuations. Based on the experimental data, it is shown that temporal variations in the intensity and flux of radiation caused by variations in the average and fluctuation components of the wind velocity on a path can be accounted for by introducing an effective drift velocity of the optical inhomogeneities across the propagation path. In the case of reflection from a specular disc the interval of time correlation of the fluctuations is proportional to the square root of D, where D is the diameter of a receiving aperture, while the position of the spectral power density maximum is inversely proportional to this quantity. In the case of reflection from an array of corner–cube reflectors, the temporal spectra of the intensity fluctuations are less sensitive to the intensity of turbulence on the path, and their high–frequency portion is more pronounced as compared to that in the case of reflection from a specular disc.*

The temporal spectra of the intensity and radiation flux fluctuations on ranging paths were considered in Refs. 1–4. It was shown that a low–frequency shift in the temporal spectrum of the intensity of wave reflected from specular objects occurs as compared to direct propagation. The similarity parameter which takes into account the variations of the average wind velocity $V_\perp$ perpendicular to the path and the fluctuation component $\sigma_\perp$ is the characteristic frequency $f_0 = (V_\perp^2 + \sigma_\perp^2)/(\lambda L)^{1/2}$, where $\lambda$ is the radiation wavelength, and $L$ is the path length.[3,4]

The experimental spectra of flux of radiation reflected from a specular disc for weak intensity fluctuations deviate from the calculated ones when the wind velocity fluctuations $\sigma_\perp$ are not considered.[1]

The temporal spectrum of radiation flux fluctuations on the path with reflection from a corner cube, whose size was not indicated, was experimentally investigated for weak and strong intensity fluctuations in Ref. 2. The lack of similarity among the temporal spectra of the radiation flux in the wind velocity component $V_\perp$, perpendicular to the path, followed from the data obtained for strong fluctuations. Thus, it followed from Fig. 2*b* of Ref. 2 that tenfold change of $V_\perp$, from 0.2 to 2.4 m/s, shifts a high–frequency region of the normalized spectrum from 400 to 150 Hz, i.e., by a factor of 2.7. Figure 3*a* shows that nearly sevenfold decrease of the velocity (from 4.8 to 0.7 m/s) changes the position of the high–frequency spectral region on the frequency axis only twice for the same level of atmospheric turbulence.[2]

This paper deals with an analysis of temporal spectra of the fluctuations of the intensity and flux of radiation reflected from specular objects (disc, matrix of trihedral corner–cube reflectors with hexagonal arrangement of elements in a two–dimensional spatial array) for strong intensity fluctuations with different diameters of a receiver and reflector. The experiment was conducted using the instrumentation described in Refs. 5 and 6. A channel for measuring the reflected radiation intensity fluctuations was added to this instrumentation. The horizontal component of the wind velocity on the propagation path was measured with an acoustic anemometer, and the structural characteristic of the refractive index $C_n^2$ was determined by the optical method.

We are not aware of calculations of time structure of the fluctuations of the intensity and radiation flux, which took into account cooperative effects of such factors as a diffraction size of emitter and receiver, effective velocity of wind, turbulence intensity, and reflector specifications. As a result, it is difficult to identify the joint action of the aforementioned factors in the experiment. Therefore, we have concentrated on the comparative effect of some of them.

Depicted in Fig. 1*a* are the dimensionless temporal spectra $U$ of the fluctuations of the intensity and flux of a quasispherical wave (with a wave parameter of 100) reflected from a specular disc 500 mm in diameter on 1250 m path to a reflector for strong intensity fluctuations[8] (the value of the parameter $\beta_0(2L) = [1.21\, C_n^2\, k^{7/6}(2L)^{11/6}]^{1/2} \approx 7$–8, where $C_n^2$ is the structural characteristic of the refractive index field, and $k = 2\pi/\lambda$ is the wave number). The dimensionless frequency $\Omega = f/f_0$, where $f$ is expressed in Hz, is plotted on the abscissa in Fig. 1*a*. Figure 1*b* shows the normalized temporal autocorrelation functions $b(\tau)$ corresponding to these spectra. The dimensionless time delay $\tau_{\rm eff} = \tau\, V_{\rm eff}/(L\, \lambda)^{1/2}$, which takes into account the

0235-6880/94/05 321-04 $02.00

real delay $\tau$ and the average $V_\perp$ and fluctuation $\sigma_\perp$ components of wind velocity that are transverse to the propagation path, is plotted on the abscissa in this figure.

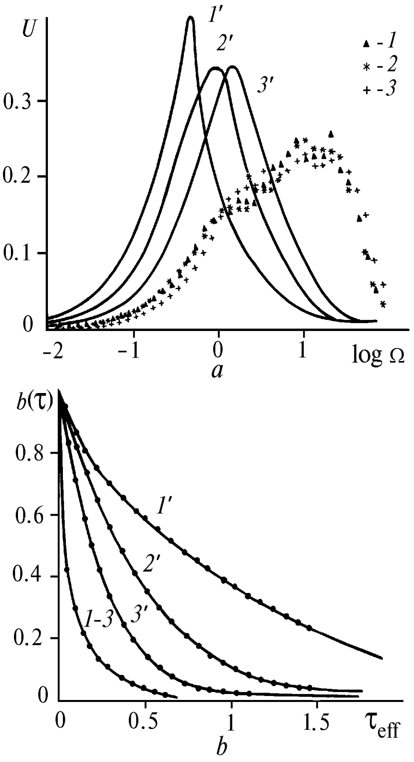

*FIG. 1. Temporal spectra (a) and autocorrelation functions (b) of the intensity (1, 2, 3) and radiation flux (1′, 2′, 3′) for different wind velocities and diameters of the receiving aperture:* $D = 500$ mm, $\beta_0(2L) = 7$, $V_\perp = 1.08$ m/s, *and* $\sigma_\perp = 0.55$ m/s *(1 and 1′);* $D = 62$ mm, $\beta_0(2L) = 8$, $V_\perp = 2.23$ m/s, *and* $\sigma_\perp = 0.65$ m/s *(2 and 2′);* $D = 31$ mm, $\beta_0(2L) = 8$, $V_\perp = 1.46$ m/s, *and* $\sigma_\perp = 0.38$ m/s *(3 and 3′).*

It is seen that the effective velocity $V_{\rm eff}^2 = (V_\perp^2 + \sigma_\perp^2)$ enables one, in a unified manner, to take account of the effect of wind velocity on time characteristics of the intensity fluctuations (Fig. 1*b* depicts only one curve $b(\tau)$ for the intensity since the remaining curves are very close to it). Unfortunately, the data for the same diameter of the receiving aperture but different mean wind velocities were unavailable to us. Such data were obtained for a two–dimensional array of 12 individual prism corner–cube reflectors with hexagonal arrangement of elements. The diameter of this array was 12.5 cm. Here the values of the regular component $V_\perp$ of wind velocity substantially differed (Fig. 2*a* and *b*), and the effect of fluctuations of the wind velocity $\sigma_\perp$ for $\sigma_\perp \gtrsim V_\perp$ on transport of inhomogeneities of the refractive index field became the decisive factor. It is seen from Fig. 2 that the similarity hypothesis is true for radiation flux fluctuations as well.

The distinctions between the intensity spectra are insignificant if we take into account that the measurements were made on different days, the wind velocity was monitored in one point close to the emitter, and the turbulence intensity was measured on an auxiliary $V$–shaped 200-m path. In measurements performed in Ref. 2 the mean wind velocity $V_\perp$ perpendicular to the path was low, and the fluctuation component $\sigma_\perp$ affecting the temporal spectrum was not measured. It seems likely that this was the reason for the behavior of the flux fluctuation spectra pointed out in Ref. 2.

Figure 1 demonstrates that the increased diameter of the receiving aperture results in a low–frequency shift of a temporal spectrum of radiation flux. In this case the position of the maximum of the dimensionless spectrum on the axis of the dimensionless frequency $\Omega$ in the first approximation is inversely proportional to the square root of the receiving aperture diameter ($\sqrt{D}$). The interval of time correlation (at a level of 0.5), in the same approximation, will obviously be proportional to $\sqrt{D}$ (Fig. 1*b*).

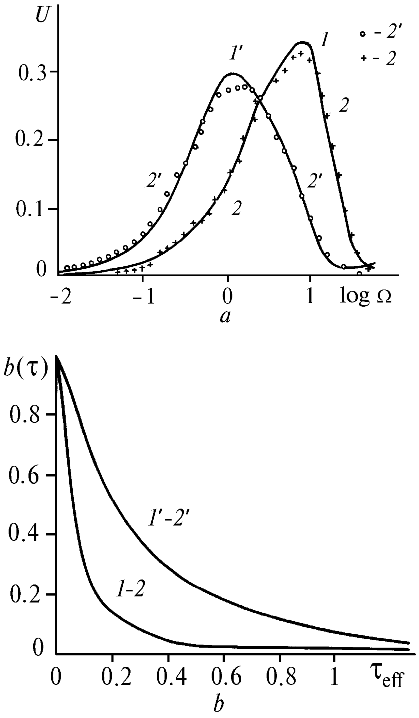

*FIG. 2. Temporal spectra (a) and autocorrelation functions (b) of the intensity (1, 2) and flux (1′, 2′) of radiation reflected from an array of 12 corner–cube reflectors for a receiver* 500 mm *in diameter:* $\beta_0(2L) = 9.8$, $V_\perp = 1.17$ m/s, and $\sigma_\perp = 0.38$ m/s (*1 and 1′*); $\beta_0(2L) = 11$, $V_\perp = 0.27$ m/s, and $\sigma_\perp = 0.47$ m/s (*2 and 2′*).

Clearly, such a dependence of time characteristics of radiation flux on this parameter disappears for the array of corner–cube reflectors since the reflection from it occurs differently, with the result that the system "a spherical wave – a matrix of corner cubes" becomes a self–focusing facility.[7]

Shown in Figs. 3 and 4 is the smoothing action of large (Fig. 3) and small (Fig. 4) receiving apertures on time characteristics of received signals for substantially different values of the parameter $\beta_0(2L)$ and signals reflected from a specular disc 500 mm in diameter. It is seen that for large receiving apertures and small apertures being much larger than the coherence length[8] the effect of turbulence intensity is insignificant as compared to its effect on the temporal spectrum of the intensity fluctuations.

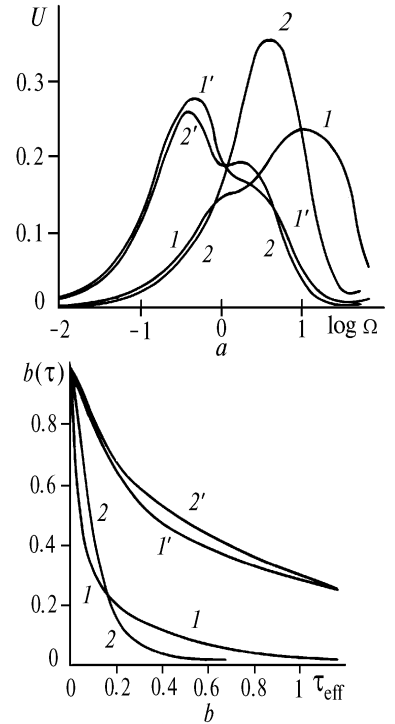

*FIG. 3. Temporal spectra (a) and autocorrelation functions (b) of the intensity (1, 2) and flux (1', 2') of radiation reflected from a* 500–mm *mirror and received by a* 250–mm *aperture for the parameters* $\beta_0(2L) = 9$, $V_\perp = 2.60$ m/s, *and* $\sigma_\perp = 0.62$ m/s *(1 and 1')* and $\beta_0(2L) = 3.3$, $V_\perp = 2.34$ m/s, *and* $\sigma_\perp = 0.64$ m/s *(2 and 2')*.

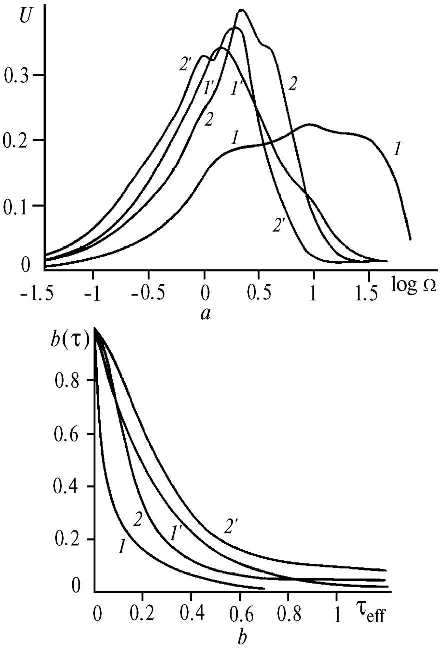

*FIG. 4. Temporal spectra (a) and autocorrelation functions (b) of the intensity (1, 2) and flux (1', 2') of radiation reflected from a* 500–mm *mirror and received by a* 31 mm *aperture:* $\beta_0(2L) = 8$, $V_\perp = 1.46$ m/s, *and* $\sigma_\perp = 0.38$ m/s *(1 and 1')*; $\beta_0(2L) = 3$, $V_\perp = 2.58$ m/s, and $\sigma_\perp = 0.82$ m/s *(2 and 2')*.

Figure 5 shows the temporal spectra of the fluctuations of intensity (*1*, *2*) and flux (*1'*, *2'*) of light reflected from a spatial array consisting of 12 corner–cube reflectors with reception of radiation by a 500–mm aperture for close values of wind velocity but essentially different values of the parameter $\beta_0(2L)$.

These data show that for strong intensity fluctuations the effect of turbulence on the temporal spectrum of the fluctuations of radiation reflected from corner cubes is much weaker than for radiation reflected from a specular disc under the same conditions (compare Figs. 3, 4, and 5). The intensity fluctuations are seen to exhibit higher frequency spectrum when radiation is reflected from corner cubes than those when radiation is reflected from a plane mirror, particularly for $\beta_0(2L) = 3$ (see curves 2 in Figs. 3, 4, and 5). For the saturated fluctuations the temporal spectra of the intensity differ substantially: the spectrum narrower for radiation reflected from corner cubes than for radiation reflected from a 500 mm specular disc. This can be accounted for by modulation of the reflected intensity with flux fluctuations due to the aperture of an array of corner–cube reflectors. However, Figs. 2*b* and 3*b* show that the intervals of their temporal correlation at a level of 0.2 differ insignificantly.

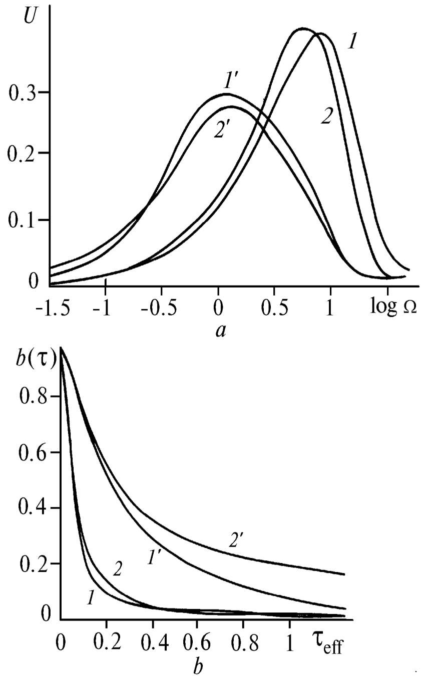

*FIG. 5. Temporal spectra (a) and autocorrelation functions (b) of the intensity (1, 2) and flux (1', 2') of radiation reflected from an array of corner–cube reflectors for different turbulence intensities:* $\beta_0(2L) = 9.8$, $V_\perp = 1.17$ m/s, *and* $\sigma_\perp = 0.38$ m/s *(1 and 1')*; $\beta_0(2L) = 3$, $V_\perp = 1.1$ m/s, *and* $\sigma_\perp = 0.6$ m/s *(2 and 2')*.

A more correct comparison between the temporal characteristics of the fluctuations of intensity and radiation flux is shown in Fig. 6. The data were obtained for reflection from a specular disc 12.5 cm in diameter, i.e., approximately equal to the diameter of an array of corner–cube reflectors. The radiation was received by the same 500–mm aperture with close values of the parameter

$\beta_0(2L)$. The intensity fluctuations of radiation reflected from an array of corner cubes exhibit higher frequency spectrum, and the fluctuations of radiation flux exhibit lower frequency spectrum in comparison with the corresponding spectra of radiation reflected from a plane mirror. Such behavior of temporal characteristics is in agreement with the fact that a spherical wave together with the array of corner–cube reflectors, whose size is larger than the coherence length of a spherical wave, form a self–focusing system.[7]

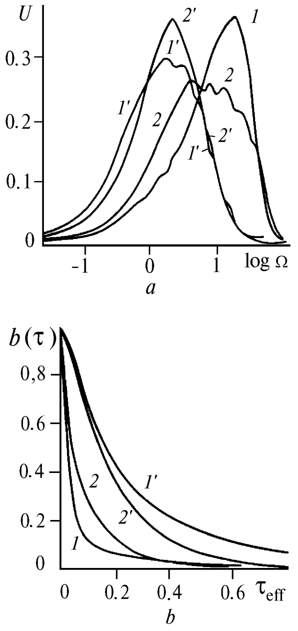

*FIG. 6. Temporal spectra (a) and autocorrelation functions (b) of the intensity (1, 2) and flux (1', 2') of radiation reflected from a* 12.5–cm *mirror (2 and 2') for* $\beta_0(2L) = 8.5$, $V_\perp = 1.91$ m/s, and $\sigma_\perp = 0.46$ m/s *and from an array of corner–cube reflectors (1 and 1') for* $\beta_0(2L) = 9.7$, $V_\perp = 0.39$ m/s, and $\sigma_\perp = 0.5$ m/s.

Thus the experiments indicated that similarity among the temporal characteristics of fluctuations of the intensity and flux in the effective velocity of wind bears for radiation reflected from a specular disc and corner–cube reflectors. The effect of turbulence variations on temporal spectra of the intensity and radiation flux is much weaker than that of wind velocity variations. Under the same atmospheric and other conditions the fluctuations of the intensity of a spherical wave reflected from an array of corner–cube reflectors exhibit higher frequency spectra than those of radiation reflected from a specular disc of equal diameter. The fluctuations of radiation flux exhibit the lower frequency spectra.

The results described above give an idea of possible variations of temporal characteristics of fluctuations of the intensity and flux of radiation reflected from specular objects in the turbulent atmosphere.

Let us now analyze the data from Ref. 2. The aforementioned behavior of fluctuation spectrum of flux of radiation reflected from an individual corner cube is typical for small values of the wind velocity component perpendicular to the path. For low winds the effect of the fluctuation component on the temporal spectrum becomes strong. This component cannot be neglected otherwise the hypothesis of similarity among the spectra becomes false. This situation was analyzed in Ref. 8 (pp. 115–117). The measurements for low wind velocities using an anemorhumbometer give a large error since the threshold of actuation of commercial instruments is approximately equal to or larger than 0.5 m/s.

One more reason may be associated with temporal and spatial inhomogeneity of the wind field. The effect of temporal nonstationarity on the results of measurement of autospectra was demonstrated in Ref. 8 (pp. 117–118). It also should be noted that in Ref. 2 the data were averaged over 10 measurements. The spread of low–frequency estimates of spectra for individual measurements was close to an order of magnitude. Moreover, the bias of spectra was not estimated. This bias depends on a relative width of a spectral window of the SKC–26 analyzer and the spectrum under study, whose width increases with variations of wind velocity and turbulence intensity.

All these factors may strongly affect the estimates of the spectra and their comparison with the calculated results or hypothesis of similarity among the spectra in the wind velocity. At the same time, they were taken into account in that paper in a manner analogous to that described in Refs. 8 and 3. However, their effect was not estimated and the hypothesis was not tested in Ref. 2. As was noted in that paper, for weak fluctuations of the intensity and large velocities of wind $V_\perp = 14$ m/s and $V_\perp = 8$ m/s, the calculations agreed with the experiment to within an accuracy being sufficiently high for practical applications. As seen from Fig. 2*a*, which shows the results of comparison, the difference between the calculation and experiment reaches half an order in a low–frequency spectral region. It can be accounted for by flux scintillation due to finite aperture of the reflector, which was not taken into account in the theory, as well as by the fact that the fluctuations of the intensity of radiation reflected from a corner cube exhibits lower frequency spectrum[4] than that for fluctuations on a direct path. Thus the results of Ref. 2 do not contradict with the conclusions of our paper.

## ACKNOWLEDGMENT

In conclusion I would like to acknowledge O.A. Rubtsova for her great help in an analysis of the measurements.

## REFERENCES

1. E.A. Monastyrnyi, G.Ya. Patrushev, A.I. Petrov, and V.V. Pokasov, Kvant. Elektron. **7**, No. 7, 1580–1582 (1980).
2. V.I. Grigor'evskii, V.N. Lomakin, and S.V. Tarakanov, Izv. Vyssh. Uchebn. Zaved., Radiofizika **29**, No. 3, 364–366 (1986).
3. A.P. Ivanov, G.Ya. Patrushev, and A.P. Rostov, Atm. Oceanic Opt. **6**, No. 5, 313–315 (1993).
4. E.A. Monastyrnyi, G.Ya. Patrushev, A.I. Petrov, and V.V. Pokasov, Izv. Vyssh. Uchebn. Zaved., Radiofizika **27**, No. 7, 907–912 (1984).
5. G.Ya. Patrushev, O.A. Pelymskii, and A.I. Petrov, Izv. Vyssh. Uchebn. Zaved., Radiofizika **32**, No. 6, 673–678 (1989).
6. G.Ya. Patrushev and O.A. Rubtsova, Atm. Oceanic Opt. **6**, No. 11, 794–797 (1993).
7. G.Ya. Patrushev, A.I. Petrov, and O.A. Rubtsova, Atm. Opt. **2**, No. 3, 221–226 (1989).
8. V.E. Zuev, V.A. Banakh, and V.V. Pokasov, *Optics of Turbulent Atmosphere* (Gidrometeoizdat, Leningrad, 1988), 270 pp.