INVESTIGATION OF SOME PECULIARITIES IN THE STRUCTURE OF LARGE–SCALE ATMOSPHERIC TURBULENCE

V.P. Lukin

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received September 23, 1992

This paper deals with the analysis of optical measurements of the atmospheric turbulence characteristics. Some conclusions are drawn on the variability of the most large–scale component of the turbulent inhomogeneities, spectrum for the atmosphere as a whole and for the boundary atmospheric layer.

This paper is a continuation of the preceding issues[1–3] dealing with the description of the behavior of the atmospheric turbulence spectrum in the large–scale region.

It is known, that the behavior of the turbulence spectrum in the low–frequency region for the ground atmospheric layer cannot be described with the help of a single parameter, i.e., the turbulence intensity C_n^2 (see Refs. 2–5) (it is generally assumed that the behavior of the spectrum in this region is not universal). The fact must be taken into account that for large–scale inhomogeneities close in size to the outer scale of turbulence the assumption on local isotropy is not strictly correct for the real atmosphere.

Nevertheless, in the practical calculations of fluctuations of the optical fields various models are used to describe the spectrum in the region of large scales.[2,3,5] These models have already had two parameters, one of which was the so–called outer scale L_0. In calculations various models of the turbulence spectrum were employed and in so doing the coincidence of the experimental data with the calculational results was achieved by adjusting the parameter L_0. As the experimental results have shown, for horizontal paths the value of the outer scale appears to be comparable to the altitude of propagation of optical radiation over the underlying surface, however there are some disagreements between the values of L_0 obtained by different authors.[2–8] Possible reasons for this disagreement is likely to be as follows. In the real atmosphere along with the small–scale turbulence (with the size below several meters) there are motions of larger scales and of different nature. These motions can be caused by the variety of radiative properties of the underlying surface, screening of the underlying surface by cloud structures and by some other factors.[3,4] In the ground atmospheric layer these large–scale formations can be treated as slow changes of the external conditions determining the generation of small–scale turbulence. In addition, both the parameters of turbulence (and of a model) of the ground atmospheric layer must change in time (and in space) with a characteristic scale typical of these large–scale structures.

For this reason, if the model parameter L_0 was adjusted based on simultaneous measurements of fluctuations of some optical parameter and the turbulence intensity C_n^2 they certainly must be followed by the measurements of the mean meteorological parameters, such as mean gradients of temperature T and the wind velocity v, transverse component of the mean wind velocity at the altitude of the optical radiation propagation $v_\perp$, and the variance of the wind velocity fluctuations.

In this paper we will analyze several many–years experimental studies:

(1) Tsimlyanskaya Scientific Station "Atmosphere" (1978),

(2) Scientific polygon of Tomsk (October–November, 1979), and

(3) Special Astrophysical Observatory of the Academy of Sciences of the USSR, Zelenchugskaya Station (January–February, 1981).

First, we will give the specifications of the used measuring facilities. In the experiments two classes of measuring devices were employed: measurers of the temperature and wind velocity at fixed altitudes (mean value of the wind velocity $v_{0.5}$, v_2, and $v_{1.5}$ at the altitudes 0.5, 1.5, and 2 m; mean temperature $T_{0.5}$ and T_2; measured quantities were used for calculating the structural temperature parameter C_T^2 and the instability parameter $B = \frac{gh}{T} \cdot \frac{\Delta T}{v^2}$ for the altitude h) and the optical meters, namely:

– A Doppler laser meter of the wind velocity manufactured by the firm DISA which allows one to measure the horizontal and vertical components of the wind velocity at the altitude $h = 1.5$ m (i.e., at the altitude of the optical beam propagation). The Doppler wind velocity measurements provide the values of the components of wind velocity (the vertical v_z and transverse v_y components) at the center of the optical path at the altitude ($h = 1.5$) of the laser beam propagation;

– An optical meter of fluctuations of the beam arrival angle recording the random angular displacements of the center of gravity of the image of the laser source along two perpendicular directions, the radiation from which propagates along a horizontal path. The data from these optical measurements allow one to calculate the spectra of the random image jitter along two perpendicular directions W_y and W_z (here z refers to a vertical component);

– An optical meter of fluctuations of the phase difference on the basis of a homodyne interferometer[2,4] ensuring the measurements of the phase difference of two mutually coherent optical beams.

0235-6880/92/12 834-07 $02.00

PHASE MEASUREMENTS OF THE OUTER SCALE OF TURBULENCE

In the first two series of the experiments the method was developed and the experimental data were accumulated for determining the outer scale of turbulence from synchronous measurements of the variance of the fluctuation phase of the optical wave σ_s^2 and the turbulence intensity C_n^2.

In fact, measured in the experiment was the structure function $D_s(\rho)$ of the optical wave phase in the case of large spatial spacing between the observation points. Our earlier measurements[7] have shown that the structure function of phase saturates, i.e.,

$$D_s(\rho \to \infty) \simeq 2\,\sigma_s^2\,,$$

where σ_s^2 is the variance of fluctuations of the optical wave phase due to the atmospheric turbulence.

In these experiments the structure function of the optical wave phase was measured interferometerically, i.e., the random phase difference was measured between two mutually coherent optical beams propagating along parallel optical paths. In the experiment the distance between beams could be varied in a wide range. The limiting spacing between the beam centers ρ_{max} = 293 cm, i.e., $\rho_{max} > h$. That is why the effect of saturation of the structure function $D_s(\rho)$ of phase could be expected.

Actually, in the experiments the random difference of phases at the centers of two limited beams was measured what is equivalent, as shown in Ref. 2, to measurements in an unlimited plane wave.

For the sake of comparison, we have calculated the structure function of phase in the approximation of the method of smooth perturbations for the plane wave with the help of the von Karman model of the turbulence spectrum. From Refs. 2 and 4 we have

$$D_s(\rho \to \infty) = 2\sigma_s^2 = \frac{24}{5}\,0.033\,\pi^2 k^2 C_n^2\,L\,L_0^{5/3} \qquad (1)$$

for the parameters of the optical experiment. The model of the turbulence spectrum being used to calculate this is

$$\Phi_s(\kappa) = 0.033\,C_n^2\,L_0^{11/3}\,(1 + k^2 L_0^2)^{-11/6}\,. \qquad (2)$$

Then simultaneous measurements of the structure function of phase in the "saturation" region and of the turbulence intensity C_n^2 (by deriving it from the data on C_T^2) allow one to estimate the von Karman outer scale L_0 corresponding to the horizontal transport of the optical inhomogeneities.

During the whole measurement cycle we have compiled 154 series of observational data. The same number of the L_0 values have been calculated using model (2). Figure 1 shows all these data in the histogram representing the frequency of appearance of some value of the outer scale calculated by model (2). We should like to remind that optical experiments were carried out at the altitude of 1.1–1.2 m above the ground. Since the scales L_0 shown in the histogram (Fig. 1) were measured under different meteorological conditions, an attempt has been undertaken[3] to classify the results of optical measurements of L_0 depending on the degree of thermodynamic stability of the atmosphere.

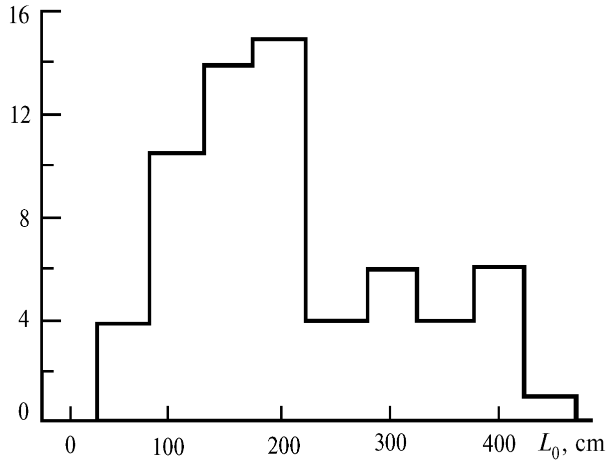

FIG. 1. Hystogram of the measured values of the outer scale of turbulence according to the model of spectrum (2).

Using the data of simultaneous optical and meteorological measurements we have calculated the following characteristic:

$$B = \frac{gh}{\overline{T}}\,\frac{\mathrm{D}T}{\overline{v}^2}\,, \qquad (3)$$

where $\Delta T = \overline{T}_2 - \overline{T}_{0.5}$ is the difference between the temperature values at altitudes 2 m and 0.5 m above the underlying surface, $\overline{T}$ and $\overline{v}$ are the mean absolute values of temperature and wind velocity at the altitude h, and g is acceleration of gravity.

This characteristic allows one to classify the data presented in Fig. 1 with respect to thermodynamic stability of the atmosphere. It was found that the values of L_0 exceeding the mean value (Fig. 2) are realized under the conditions of neutral stratification $B \approx 0$. At the same time, for the conditions of unstable ($B < -0.01$) and stable ($B > +0.003$) stratifications the values of L_0 are less than the average values.[9]

This is well explicable in the context of formation of the temperature–induced optical inhomogeneities. Thus, a high level of instability of the atmosphere, i.e., large negative values of the parameter B correspond to higher degrees of the initial flow breaking, therefore the probability of occurence of large L_0 is sufficiently small. For high stability (large positive values of B) the initial flow is weakly turbulized, therefore there is a deficit of the inhomogeneities of all scales including the inhomogeneities with dimensions of the order of L_0. Finally, high probability of occurence of large scale inhomogeneities exists for neutral stratification (for B close to zero) of the atmosphere.

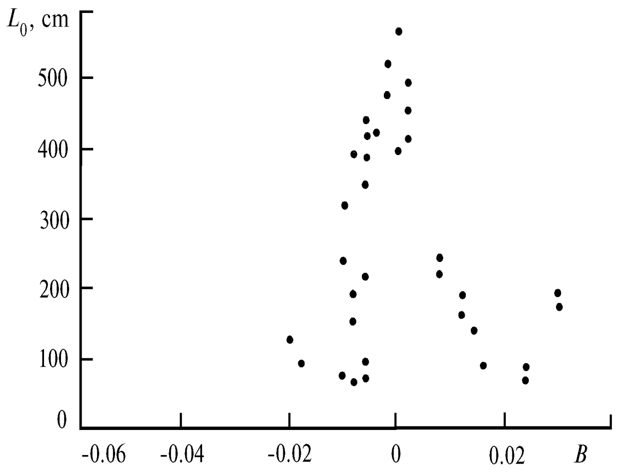

FIG. 2. The correspondence between the data of optical measurements of the outer scale of turbulence L_0 and the instability parameter B.

At the same time, if one classifies measured values of L_0 on the basis of the measured average wind velocity values it appears that lower wind velocities correspond to the larger values of L_0 and *vice versa*. This confirms the conclusion that the dynamic component of the turbulence is characterized by the smaller–scale structure than the convective component.

INVESTIGATION OF THE ANISOTROPY OF THE SPECTRUM OF ATMOSPHERIC TURBULENCE IN THE LOW–FREQUENCY REGION

Together with the dependence of the outer scale of turbulence on variations of meteorological parameters of the atmosphere, there exists anisotropy of the atmospheric properties, in other words, inhomogeneities with dimensions exceeding several meters possess the properties that depend on direction. As a consequence, the properties (correlation characteristics) of some parameters of optical waves appear to be direction–dependent. For example, random displacements of an image, which is formed by the optical radiation passed through the surface atmospheric layer along a horizontal path, exhibit such properties. It is well known that phase fluctuations are of principal importance in the process of image formation. For this reason, if the spectrum of atmospheric turbulence is anisotropic it can be expected that the effect of jittering in the low–frequency region is also anisotropic.

Neglecting the amplitude fluctuations for the variances of random (linear) displacements of the center of gravity of an image we obtain the relations

$$\sigma_y^2 = \frac{F^2}{k^2\Sigma^2}\int_\Sigma\int d^4\rho_{1,2}\,\frac{\partial^2}{\partial y_1\partial y_2}\,D_S(\rho_1,\,\rho_2)\,, \tag{4}$$

$$\sigma_z^2 = \frac{F'}{k^2\Sigma^2}\int_\Sigma\int d^4\rho_{1,2}\,\frac{\partial^2}{\partial z_1\partial z_2}\,D_S(\rho_1,\,\rho_2)\,, \tag{5}$$

where $D_s(\rho_1, \rho_2)$ is the structure function of phase, $\Sigma = \pi R^2$, R is the radius, and F is the focal length of the lens.

Investigations of the fluctuations of image displacements occurring due to the atmospheric turbulence were carried out in Tsimlyansk at the Scientific Station of the Institute of Atmospheric Physics of the Russian Academy of Sciences. The measurements were conducted along a horizontal path 40.4 m in length located at the altitude of 1.15 m over the ground surface covered with approximately 20–cm long plant canapies.

A collimated laser beam (0.63 μm wavelength and 1.3 cm diameter) was used as a radiation source. Random displacements were measured with a dissector tracking system[10] at the focus of an objective (220–270 cm focal length). The displacements of the image in two perpendicular directions were recorded simultaneously. The corresponding variances σ_y^2 and σ_z^2 and spectral densities W_y and W_z were calculated according to these measurements. All in all we have recorded 260 observational series each about 300 s long.

Meteorological measurement support of this optical experiment involved measurements of the mean temperatures and wind velocities at heights 2 and 0.5 m (T_2, $T_{0.5}$; v_2, $v_{0.5}$) and at the height of the beam propagation the pulsations of these parameters have also been measured. In addition, at this height the pulsations and mean values of the vertical v_z and horizontal v_y components of the transverse wind velocity were measured with the help of a DISA laser single–component Doppler rate meter. Mean temperature was measured with a mercury thermometers and mean wind velocity with FUS type meters with averaging over 100–200 s. The temperature and wind velocity pulsations were recorded with a resistor and hot–wire anemometer. The primary sensors of the meteorological measurement system were mounted on a mast installed in the vicinity of the optical receiver. A laser Doppler anemometer was used in the experiment for measuring alternatively the vertical or horizontal wind velocity components. These measurements were carried out in the central portion of the path.

The structure parameter C_T^2 and the instability parameter $B(3)$ as well as $T(h)$ and $v(h)$, i.e., mean temperature and mean wind velocity at the height of beam propagation, were calculated based on the meteorological measurements.

In the course of this optical experiment the corresponding variances of the image displacements were calculated with the help of a dual–channel analog variance meter[10] whose input dynamic range was 40 dB with the frequency band being from 0 to 20 kHz. Subsequent processing was performed with a modified spectrum analyzer. Duration of the processes to be handled was 300 sec. The spectra were estimated in the frequency region from 0.06 to 100 Hz. The data measured by the laser Doppler anemometer permitted obtaining exact mean values of the components of wind velocity (v_y and v_z) that must be available when interpreting the spectra of the image jitter W_y and W_z.

For estimating the anisotropy of the turbulence spectrum in the low–frequency region the comparison of the corresponding variances can be used. The so–called coefficient of anisotropy $K = \sigma_y^2/\sigma_z^2$, being obtained immediately in the experiment, varied in the interval from 0.62 to 2.57 with the mean value $K_m = 1.57$ that indirectly indicated that the temperature induced optical inhomogeneities, which produce the phase fluctuations, were anisotropic in the large–scale region. In addition, the relationship is quite obvious between the K value and the instability parameter B.

As was noted above, when interpreting the experimental results, for estimating the anisotropy of the turbulence spectrum in the low–frequency region one can use the comparison of mean values of variances of the image jitter in two perpendicular directions. Let us compare the measured variances (and their ratios) with those calculated using the model of the turbulence spectrum allowing for the finiteness of the turbulence outer scale.

In our calculations we use the formula for the correlation functions of random displacements of an image in the focal plane of a lens (F is the focal length and Σ is the area of the lens aperture). Thus for the Y axis

$$\Gamma_y(\tau) = \frac{8\pi F^2}{\Sigma^2} \times$$

$$\times \int\limits_{\Sigma}\int d^2\rho_1\, d^2\rho_2 \int\limits_0^L d\xi \int\int d^2k k_2^2 \Phi_n(\mathbf{k}, \xi)\cos[\boldsymbol{\kappa}(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2) + \boldsymbol{\kappa}\mathbf{v}\tau] ,$$

and for the Z axis

$$\Gamma_z(\tau) = \frac{8\pi F^2}{\Sigma^2} \times$$

$$\times \int\limits_{\Sigma}\int d^2\rho_1\, d^2\rho_2 \int\limits_0^L d\xi \int\int d^2k k_3^2 \Phi_n(\mathbf{k}, \xi)\cos[\boldsymbol{\kappa}(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2) + \boldsymbol{\kappa}\mathbf{v}\tau] ,$$

where τ is the time lag. It is not difficult to show that for circular aperture

$$\int\limits_{\Sigma}\int d^2\rho_1\, d^2\rho_2 \cos[\mathbf{k}(\boldsymbol{\rho}_1 - \boldsymbol{\rho}_2) + \mathbf{k}\mathbf{v}t] =$$

$$= \cos(\mathbf{k}\mathbf{v}t)(\pi R^2)^2[J_1(kR)/(kR/2)]^2 .$$

In order to simplify the subsequent calculations we first assume that the lens aperture is Gaussian, then the variances are

$$\begin{Bmatrix}\sigma_y^2\\ \sigma_z^2\end{Bmatrix} = 8\pi F^2 \int\limits_0^L d\xi \int\int d^2k \begin{Bmatrix}k_2^2\\ k_3^2\end{Bmatrix} \Phi_n(\mathbf{k}, \xi)\exp(-k^2R^2/2) . \quad (6)$$

In the numerical calculations we use the model of the turbulence spectrum $\Phi_n(\kappa, \xi)$ that makes it possible to introduce two scales for the outer scale of turbulence.

$$\Phi_n(\boldsymbol{\kappa}, \xi) = 0.033\, C_n^2(\xi)\,(k_2^2 + k_3^2)^{-11/6} \times$$

$$\times \left\{1 - \exp\left(-\frac{k_2^2}{k_{02}^2} - \frac{k_2^2}{k_{03}^2}\right)\right\} , \quad (7)$$

where κ_{02}^{-1} and κ_{03}^{-1} are the projections of the outer scales onto the Y and Z axes, respectively. The calculations will be performed under the assumption of uniform optical paths, provided that $C_n^2(\xi)$, κ_{02}, and κ_{03} are constant along the entire path of propagation of optical radiation.

Let us now consider the main contributor to Eq. (6)

$$\int\int d^2k k_2^2 \frac{\exp(-(k_2^2 + k_3^2) R^2/2)}{(k_2^2 + k_3^2)^{11/6}} \times$$

$$\times \left\{1 - \exp\left(-\frac{k_2^2}{k_{02}^2} - \frac{k_2^2}{k_{03}^2}\right)\right\} = \int\limits_0^{2\pi} d\varphi \cos^2\varphi \times$$

$$\times \int\limits_0^{\infty} dk k^{-2/3} \exp(-k^2R^2/2)\left\{1 - \exp\left[-k^2\left(\frac{\cos^2\varphi}{k_{02}^2} + \frac{\sin^2\varphi}{k_{03}^2}\right)\right]\right\}.$$

It can be easily shown that for $(\kappa_{02}^{-1}, \kappa_{03}^{-1}) > R$ and

$$k_{03}^{-2} = k_{02}^{-2}(1 + \delta)$$

one can obtain

$$\sigma_y^2 = 4\pi F^2 0.033 C_n^2\, L\Gamma\left(\frac{1}{6}\right) \times$$

$$\times \int\limits_0^{2\pi} d\varphi \cos^2\varphi \left\{\left(\frac{R^2}{2}\right)^{-1/6} - k_{02}^{1/3}\,(1 + \delta \sin^2\varphi)^{-1/6}\right\} . \quad (8)$$

Since $\int\limits_0^{2\pi} d\varphi \cos^2\varphi = \pi$,

$$\int\limits_0^{2\pi} d\varphi \cos^2\varphi\,(1 + \delta\sin^2\varphi)^{-1/6} = 2B\left(\frac{3}{2}, \frac{1}{2}\right) {}_2F_1\left(\frac{1}{6}, \frac{1}{2}; 2; -\delta\right),$$

$$\int\limits_0^{2\pi} d\varphi \sin^2\varphi\,(1 + \delta\sin^2\varphi)^{-1/6} = 2B\left(\frac{1}{2}, \frac{3}{2}\right) {}_2F_1\left(\frac{1}{6}, \frac{3}{2}; 2; -\delta\right),$$

we obtain

$$\sigma_y^2 = 0.264\pi^2F^2\Gamma\left(\frac{1}{6}\right)C_n^2L\left\{\frac{R^{-1/3}}{2^{5/6}} - \frac{k_{02}^{1/3}}{2}\, {}_2F_1\left(\frac{1}{6}, \frac{1}{2}; 2; -\delta\right)\right\}, \quad (9)$$

$$\sigma_z^2 = 0.264\pi^2F^2\Gamma\left(\frac{1}{6}\right)C_n^2L\left\{\frac{R^{-1/3}}{2^{5/6}} - \frac{k_{02}^{1/3}}{2}\, {}_2F_1\left(\frac{1}{6}, \frac{3}{2}; 2; -\delta\right)\right\}. \quad (10)$$

Let us calculate the ratio

$$K = \frac{\sigma_z^2}{\sigma_y^2} = \frac{1 - \left(\frac{k_{02}^2R^2}{2}\right)^{1/6} {}_2F_1\left(\frac{1}{6}, \frac{3}{2}; 2; -\delta\right)}{1 - \left(\frac{k_{02}^2R^2}{2}\right)^{1/6} {}_2F_1\left(\frac{1}{6}, \frac{1}{2}; 2; -\delta\right)} , \quad (11)$$

and $\delta = (\kappa_{02}^2/\kappa_{03}^2) - 1$. If $\delta = 0$ and the outer scale has equal horizontal and vertical dimensions ($\kappa_{02} = \kappa_{03}$) then $K = 1$. In this case the isotropy takes place. Alternatively, if $\delta \gg 1$ then

$$K = \frac{1 - \left(\frac{k_{02}^2R^2}{2\delta}\right)^{1/6} \frac{G(4/3)}{G(3/2)\, G(11/6)}}{1 - \left(\frac{k_{02}^2R^2}{2\delta}\right)^{1/6} \frac{G(2/3)}{\Gamma(1/2)\,\Gamma(11/6)}}$$

and we have quite a strong anisotropy.

In the general case for estimating the observed anisotropy of the image jitter K one should use formula (11). It follows from this formula that the measured K values can be explained with the help of the spectrum (Eq. (7)) as a model with two different projections of the outer scale of turbulence onto the vertical and horizontal directions.

The anisotropy of larger scales was examined in more detail with the use of spectra W_y and W_z as well as using the mean values of wind velocity components measured with the help of the Doppler anemometer, i.e., ν_y and ν_z. It is well known[2] that the spectra of fluctuations of the components of image displacements should have the characteristic maxima at the frequencies $f_{\max} \sim \nu\kappa_0^{-1}$, where ν and κ_0^{-1} are the corresponding projections of the wind velocity and the outer scale of turbulence. Measurement data on the spectra W_y and W_z are also indicative of the fact that the projections κ_{02}^{-1} and κ_{03}^{-1} are significantly different in the surface layer.

The characteristic spectral densities of fluctuations of a laser source image jitter in two perpendicular directions are presented in Fig. 3. The vertical displacements $f\,W_z(f)$ are depicted in Fig. 3*a*, while the horizontal ones $f\,W_y(f)$ in Fig. 3*b*.

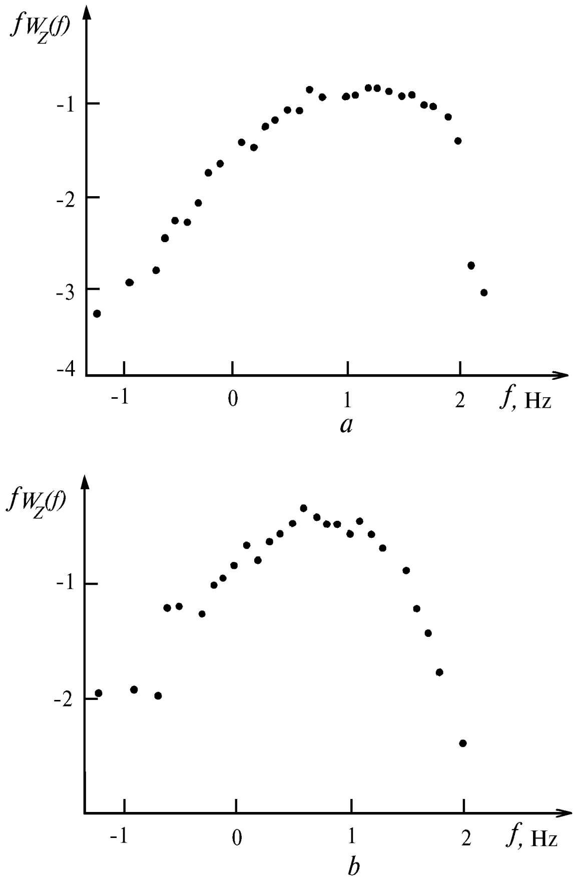

FIG. 3. Characteristic spectral densities of the fluctuations of an image jitter in two perpendicular directions: in the horizontal direction $f\,W_y(f)$, $\nu_y = 21$ m/s (a) and in the vertical direction $f\,W_z(f)$, $\nu_z = 0.60$ m/s, $C_n^2 = 0.38\cdot10^{-2/3}$.

Relating the positions of maxima of these spectra to the values of the wind velocity components ν_z and ν_y, measured synchronously by the Doppler anemometer at the center of the path, one can see that the projections κ_{02}^{-1} and κ_{03}^{-1} of the outer scale of turbulence differ significantly (by a factor of from 2 to 3). In addition κ_{02}^{-1} (vertical component) is always smaller than κ_{03}^{-1} (horizontal component). The same conclusion can be drawn from a comparison of the variances. It always happens that $\sigma_z^2 > \sigma_y^2$.

INVESTIGATION OF THE ATMOSPHERIC TURBULENCE DYNAMICS ON THE BASIS OF ASTROCLIMATIC OBSERVATIONS

Let us finally analyze the data on the astroclimatic characteristics obtained in the region of the Elbrus mountain. These measurements were conducted at the Special Astrophysical Observatory (SAO, Zelenchugskaya stanitsa) in January–February, 1981.

In our analysis of the experimental data we assume that the atmosphere is stratified and its optical (temperature) inhomogeneities have the shape of elongated ellipsoids of revolution. This implies that:

(1) In the case of vertical propagation (precisely along the zenith direction) the image jitter must be practically isotropic.

(2) If the underlying surface is isotropic then the anisotropy of the jitter of an optical source image must be maximum for the case of horizontal propagation and will be determined by the atmospheric instability.

In the experiment we have used the measurer of fluctuations of the angles of arrival of the optical waves based on the telescope ($2R = 600$ mm, with the focal length $F = 12$ m), which has a clockwork guide with the correction and a photoelectric adapter. The telescope provided operative homing to a chosen direction (azimuth and elevation angle). The photoelectric adapter was manufactured based on the dissector LI–609.[11] The parameters of the telescope and the measurer ensure the determination of angular position of the center of gravity of the focal spot with the accuracy of about 0.08″ and the measurements of its deviation in the frequency range from 0.01 to 100 Hz. A signal of 100 mV from the measurer corresponds to the displacement of the spot by 5 μm that equals to $4\cdot10^{-7}$ rad of angular deviation.

The signals proportional to the deviations of the center of gravity along two perpendicular directions were processed on a computer. We calculated the corresponding variances, spectral densities of the processes, as well as the distribution probability densities in the case of 256 levels of digitizing.

The meteorological instrumentation allowed obtaining the data for calculating the structure parameter of temperature C_T^2, mean wind velocity v at the altitude of 2.5 m above the underlying surface, the mean temperature gradient, and the wind velocity.

At the first stage, the measurements were conducted under the controlled conditions of a homogeneous horizontal path. To this end a point light source, i.e., the electric bulb supplied by a source of stabilized voltage, was placed at the distance of 1685 m from the telescope.

As a result we have obtained the values of the variance σ_α^2 of an image jitter and of the orthogonal components ($\sigma_\alpha^2 = \sigma_y^2 + \sigma_z^2$). For the case of isotropic turbulence $\sigma_y^2 = \sigma_z^2$. However, under the near–surface conditions one can expect a strong anisotropy of the turbulence that leads to the anisotropy of the jittering process. We shall use the value $K = \sigma_z^2/\sigma_y^2$, i.e., the ratio of variances, to characterize the measure of anisotropy of the image jitter process. The data of synchronous meteorological and optical measurements carried out along a near surface path, each being averaged over 16 measurements, are presented in the Table I.

$\sqrt{\sigma_\alpha^2}$	K	$\Delta T/\Delta z$ deg/m	ν m/c
4″	1.20	+0.3	1
2″	2.87	+1.4	0.5
3″, 2″	2.09	+0.20	2.5

It is obvious from the table that at small wind velocities the increase of the temperature instability (the positive growth of the temperature gradient) reduces the turbulence intensity (and, as a result, σ_α^2 decreases), but causes an enhancement of the anisotropy of the temperature field (growth of K). The earlier indications of the anisotropy of a source image jitter in the surface atmospheric layer can be found in Ref. 5.

At the next stage jittering of images of stars caused by the atmospheric turbulence were observed. During the whole observation period more than 2000 realizations (with their durations ranging from 10 to 500 s) of the star image jitters were obtained. About 40 different stars were used in the measurements. The position of an observed star is described by two angles, i.e., the azimuthal A and zenith θ angles. In the process of the jitter recording we have determined the zenith and azimuth angles of a star while its stellar magnitude was available from a catalog. The sensitivity of the photoelectric measurer provided reliable measurements of the star image jitters with the brightness as low as +4.

It is well known[11] that under conditions of uniform underlying surface the length of atmospheric column is solely the function of the elevation angle and is independent of the azimuth. In the so–called approximation of "flat Earth" the assumption is made that with the change of elevation angle the variance of an image jitter scales as $(\cos\theta)^{-1}$. In this context we can replace the measured value of the variance of a stellar image jitter along the direction θ_1 by that in the other direction θ_2 by multiplying the former value by $\cos\theta_1/\cos\theta_2$.

It should be noted that the approximation $(\cos\theta)^{-1}$ is valid with stars in two cases, i.e., under conditions of uniform underlying surface (steppe, sea) and for isolated mountain peaks.[12] This approximation must be valid for all azimuthal angles. Alternatively, if the mountain peak, at which the telescope is located, is not single but is surrounded by other peaks being even higher than the peak of the telescope location, then the characteristics of jitter of the image formed by the telescope will be dependent both on the elevation and azimuthal angles.

As the results[1] show, for the point of location of a telescope the law $(\cos\theta)^{-1}$ is fulfilled rather well in the case of a fixed azimuth. Thus, the error of recalculation from the zenith angle $\theta_1 \approx 20°$ to the angle θ_2 of the order of 70–75° is about 10%. At the same time, by varying the azimuthal angle one obtains a significant deviation from the law $(\cos\theta)^{-1}$. This means that the atmosphere at the point of location of the telescope has an azimuthal anisotropy.

In addition it was found that with increase of time interval, during which the telescope turns from θ_1 directly to θ_2, the error of transition from the characteristics measured at θ_1 to those measured at θ_2 also increases. The experimental data indicate that the "forecast" (i.e., the recalculation of the image jitter values occurring along one direction to those for the other direction) has the "lifetime" of the order of 20–30 min.

As in the case of horizontal paths, the measurements of variance of the jitter performed for the stars observed at large zenith angles (θ is of order 70–75°) are indicative of a strong anisotropy (K = 1.6–2.4). At the same time, for the stars, observed at small zenith angles θ = 20–30°, jitter is practically isotropic (K = 0.9–1.15). These data confirm my earlier assumptions.

It is difficult to obtain reliable data on the outer scale of turbulence from these measurements because the real altitude distribution of the turbulence intensity is unknown. At the same time, indirect information about the outer scale can be obtained by examining the dependence of the variance of a jitter of a star on the diameter of a receiving aperture.

It is not difficult to show that for the model of the turbulence spectrum

$$\Phi_n(\kappa) = 0.033\, C_n^2\, k^{-11/3}\{1 - \exp(-k^2/k_0^2)\}$$

the variance of an image jitter is

$$\sigma_\alpha^2 = 16\pi^2F^2 \int_0^L d\xi\, 0.033C_n^2 \int_0^\infty dk k^{-2/3} \times$$

$$\times \{1 - \exp(-\kappa^2/\kappa_0^2)\} \exp(-\kappa^2R^2/2) =$$

$$= 0.38\pi^2\Gamma\left(\frac{1}{6}\right)\int_0^L dx C_n^2(x)(2R)^{-1/3}\{1 - (1 + 2R^{-2}k_0^2)^{-1/6}\} .$$

Thus, for $2R \ll \kappa_0^{-1}$ the aperture dependence follows the power law $(2R)^{-1/3}$.

In our measurements this dependence was examined with the help of a sufficiently bright star. The diameter of the receiving aperture has been varied with the help of an aperture diaphragm, successively, diameters of the diaphragms were $2R$ = 152, 215, 313, 492, and 600 mm. All observations were performed sufficiently fast so that the stellar zenith angle could be considered constant and no significant variations of the meteorological conditions occurred.

However, the experimental data do not follow the dependence $(2R)^{-1/3}$. This failure can be justified, for example, as follows: the aperture diameter $2R$ is comparable to the outer scale of the turbulence κ_0^{-1}.

CONCLUSION

Based on our experiments it was revealed that:

(1) In the ground atmospheric layer the outer scale of turbulence is comparable to the height above the underlying surface.

(2) The value of this outer scale appears to be dependent on the atmospheric stability.

(3) In the ground atmospheric layer the most large–scale inhomogeneities of the atmospheric turbulence are anisotropic. One of the consequences of this situation is the difference of vertical and horizontal dimensions of the outer scale.

(4) From the standpoint of vertical distribution of the atmospheric inhomogeneities one can conclude that the atmosphere is a stratified medium.

REFERENCES

1. S.M. Gubkin, O.N. Emaleev, and V.P. Lukin, Astron. Zh. **60**, No. 4, 790–795 (1983).
2. V.P. Lukin and V.V. Pokasov, Appl. Opt. **20**, No. 1, 121–135 (1981).
3. V.P. Lukin, Atmos. Oceanic Opt. **5**, No. 4, 229–242 (1992).
4. M.S. Belenkii, V.P. Lukin, V.L. Mironov, and V.V. Pokasov, *Coherence of Laser Radiation in the Atmosphere* (Nauka, Novosibirsk, 1985).
5. A.S. Gurvich, A.I. Kon, V.L. Mironov, and S.S. Khmelevtsov, *Laser Measurement in the Turbulent Atmosphere* (Nauka, Moskow, 1976).
6. G.M.B. Bouricius, S.F. Clifford, J. Opt. Soc. Am. **60**, 1484 (1970).
7.V.P.Lukin, V.V.Pokasov, and S.S.Khmelevtsov, Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz. **15**, No. 12, 1861–1866 (1972).
8. R.S. Lawrence and L.W. Strohbehn, IEEE, AP–58, No. 10, 130 (1970).
9. O.N. Emaleev, V.P. Lukin, V.V. Pokasov and S.F. Potanin, *Abstracts of Reports at the Fifth All–Union Symposium on the Propagation of Laser Radiation in the Atmosphere,* Tomsk (1979), Vol. 2, pp. 144–147.
10. O.N. Emaleev, V.P. Lukin, V.V. Pokasov, et al., *Abstracts of Reports at the Second All–Union Conference on Atmospheric Optics,* Tomsk (1980), Vol. 2, pp. 97–100.
11. V.I. Tatarskii, *Wave Propagation in a Turbulent Medium (*McCraw–Hill, New–York, 1961).
12. L.N. Zhukova, Izv. Glavn. Astron. Observ. **21**, 72 (1973).