Asian Journal of Physics
Vol. 33, Nos 3 & 4 (2024) 219-238
Available on: www.asianjournalofphysics.com
ap

Atmospheric turbulence and its optical manifestations

Victor Nosov, Vladimir Lukin, Eugene Nosov and Andrei Torgaev

V E Zuev Institute of Atmospheric Optics SB RAS, 1 Academician Zuev sq., Tomsk 634055, Russia

Dedicated to Professor Anna Consortini for her significant contributions and pioneering works in the field of atmospheric turbulence and her continuous commitment to promote optics at global level

---

The results of long-term experimental studies of coherent turbulence of the mountain boundary layer of the atmosphere using acoustic and optical methods are presented. The presence of regions of coherent (non-Kolmogorov) turbulence in the atmosphere over the territories of mountain observatories, in which a single large coherent structure has a significant influence, has been experimentally confirmed. In such regions of coherent turbulence, the attenuation of light fluctuations is registered. This leads to a significant reduction in the jitter of astronomical images and to an improvement in their quality. It is established that astronomical observations are accompanied by a frequent transition from Kolmogorov turbulence to coherent turbulence. This change in the type of turbulence gives intermittency in the jitter of astronomical images. This paper (which is of an overview nature) presents results of many years of experimental studies of the effect of intermittent turbulence performed in high- mountain Russian astronomical observatories.

Doi: 10.54955/AJP.33.3-4.2024.219-238

Keywords: Turbulence, Airflow; Coherent structure, Coherent turbulence; Dispersion.

---

1 Introduction

Scattering of light by turbulent inhomogeneities of the atmosphere is one of the main mechanisms for the distortion of optical waves as they propagate through the atmosphere. Random spatiotemporal changes in the refractive index of the atmosphere [1-4] lead to distortion of the structure of optical beams and images, fluctuations in the intensity and phase of optical waves and are manifested, in particular, in blurring, jitter and flickering of images of radiation sources, as well as in turbulent attenuation of the average signal power received.

The study of these fluctuations has led to the development of methods for remote diagnostics of atmospheric turbulence. Works on laser sounding of atmospheric turbulence have been greatly developed, since the use of lasers for measuring the parameters of atmospheric turbulence has a number of advantages [4-6]. In particular, optical measurements provide greater stability and reliability of the obtained statistical data, since by their nature they are associated with additional averaging of the determined characteristic along the propagation path.

This is the reason why serious studies of the structure of atmospheric turbulence have been carried out for many years based on the analysis of fluctuations of optical waves that have passed through a layer of a turbulent medium [1-7].

Corresponding author:
e mail: lukin@iao.ru (Vladimir Lukin)

And one of the pioneers of these studies is the professor of the University of Florence (Italy) Anna Consortini. She carried out a number of important scientific studies in this area, we will single out here some of them, for example [5-7].

2 Historical background and motivation for the study of the turbulence spectrum

It is known that the most developed method for measuring the energy spectrum of refractive index fluctuations is the method of restoring the last of the measured statistical characteristics of fluctuations in the parameters of optical waves that have passed through a layer of turbulent atmosphere.

To determine the spectra of fluctuations of the refractive index of the medium [3-4] one can use the spectra and correlation functions of the fluctuations of the parameters of the optical wave propagating in a turbulent atmosphere. It is admissible when the relative fluctuations of the refractive index are small. It should be borne in mind that, as applied to light waves, one almost always considers temperature turbulence and the similarity [2] of the spectra of fluctuations of the refractive index and temperature.

When studying the spectra of atmospheric turbulence by optical methods, the question arises of the sensitivity of the measured characteristics of optical waves to the functional form of the spectral density of refractive index fluctuations. The problem is to choose such a characteristic of an optical wave that would ensure the simplicity of experimental measurements and would be extremely sensitive to the form of the spectrum in one or another of its regions of the spatial frequencies of turbulent inhomogeneities. The spectrum of atmospheric turbulence, even in the surface layer, has a large dynamic range (spatial scales range from meters to fractions of millimeters), and therefore, due to the finite accuracy of the optical measurements themselves, it cannot be reconstructed from measurements of fluctuations of any one of the optical wave parameters. Studies of the sensitivity of various parameters of optical waves to the type of turbulence spectrum in its various regions have shown that the characteristics associated with the phase of an optical wave are mainly determined by low-frequency inhomogeneities of refractive index fluctuations, while fluctuations in the intensity of optical radiation are determined by the high-frequency region of the turbulence spectrum [3,4].

In other words, measurements of fluctuations in the phase of an optical wave can be used to study the energy interval of the turbulence spectrum, and measurements of intensity fluctuations can be used to study the equilibrium interval, which includes the inertial and viscous intervals of the turbulence spectrum [6-10]. Measurements of fluctuations in optical radiation intensities are a simpler task than measurements of phase fluctuations. Therefore, the first reconstruction of the turbulence spectrum from the data of optical measurements was carried out precisely when measuring intensity fluctuations [4]. As a result, the turbulence spectrum in the dissipation interval was reconstructed from the data of optical sounding of the atmosphere [3, 8].

2.1 Features of phase measurements

Phase measurements in the optical range in the atmosphere with a large dynamic range of spatial separations of observation channels is a technically difficult task [8,9]. Therefore, only in the second half of the 70s of the last century, for the first time, sufficiently correct experimental data were obtained [8,9] for measuring the structure function of an optical wave at spatial separations of observation points comparable to the height of surface atmospheric paths. These data, as well as the correlation functions of fluctuations in the spatial position of the centers of gravity [3,10] of horizontally separated optical beams, contradicted the available theoretical calculations [4] obtained by using the purely power-law Kolmogorov–Obukhov model for the spectral density of fluctuations in the refractive index of the atmosphere.

It was in these publications [8,9] that the effect of the outer scale on the fluctuations of optical waves propagating in a turbulent atmosphere was first reported. Almost simultaneously with these measurements, similar studies were carried out in the USA [11] and in Italy [6,7]. The results of these works [5-7, 8-11] allow us to conclude that the phase structure function for an optical wave propagating in a turbulent atmosphere deviates noticeably from the power dependence corresponding to the Kolmogorov model of the turbulence spectrum.

It should be noted that for the well-known Kolmogorov model [1-4], the turbulence spectrum corresponds to the "2/3 law" for the structural function of the atmospheric refractive index. For Kolmogorov model of turbulence spectrum [1], the only structural phase function can be calculated correctly. Since other statistical characteristics of phase fluctuations of the optical wave, such as dispersion and correlation function of fluctuations for the Kolmogorov model are not determined due to the unusual behavior of the turbulence spectrum in the low-frequency region.

However, this singularity in the behavior of the spectral density of atmospheric turbulence is not significant when calculating intensity fluctuations of an optical wave propagating in a turbulent medium [3,4].

2.2 Development of the models of turbulence spectra

The Kolmogorov model of refractive-index fluctuations is frequently used for calculations in atmospheric optics [1-4]. However, this model is valid only in the inertial range of turbulence. In the early 70's, the scientists in Italy (A Consortini, L Ronchi), USA (G Bouricious, S Clifford) and USSR (V Pokasov, V Lukin) almost simultaneously discovered [6-11] the phenomenon of deviation from the power law and the effect of saturation for the structure phase function. These discoveries meant that there is a correlation for phase fluctuations, and therefore it is necessary to apply the turbulence spectrum with a finite outer scale of turbulence L_0.

This paper deals with the experimental [12,13] and theoretical studies [14-18] of optical waves fluctuations for comparing different models of the atmospheric turbulence spectra. Using the experimental data, we proposed to study the behavior of the spectral density of atmospheric turbulence in the region of large spatial scales. For practical calculations of the characteristics of optical waves fluctuations, the various models are used to describe the spectrum in the large-scale region: von Karman, Greenwood-Tarazino, and Russian model. These models have already had two parameters, one of which is called outer scale of turbulence L_0:

$$\Phi_n(\kappa,\xi) = 0.0033\, C_n^2(\xi)(\kappa^2 + \kappa_{0K}^2(\xi))^{-11/6} \tag{1}$$

$$\Phi_n(\kappa,\xi) = 0.0033\, C_n^2(\xi)(\kappa^2\, \kappa_{0G}^{-2}(\xi) + \kappa\, \kappa_{0G}^{-1}(\xi))^{-11/6} \tag{2}$$

$$\Phi_n(\kappa,\xi) = 0.0033\, C_n^2(\xi)\kappa^{-11/3}\{1 - \exp[-\kappa^2/\kappa_{0R}^2(\xi)]\} \tag{3}$$

I have obtained in papers [14-16] the relationships between the scale for its models

$$\kappa_{oG}^{-1} = 0.27\kappa_{0K}^{-1}\,,\ \kappa_{oR}^{-1} = 0.36\kappa_{0K}^{-1}\,,\ \kappa_{oR}^{-1} = 1.33\,\kappa_{0G}^{-1}$$

Thus, the calculations of the optical characteristics performed using one model of the spectrum can be result in other models. Need to say, that Russian model (Eq 3) is more suitable for analytical calculations of phase fluctuations and characteristics of images and beams random displacements of center of gravity for optical wave in turbulent atmosphere. For practical calculations of the characteristics of optical waves fluctuations, the various models are used to describe the turbulent spectrum of large scales for ground surface atmospheric layer and for spectral density averaged over the entire atmosphere.

The many-year discussion on this subject demonstrated the importance of the parameter L_0 in calculation of phase fluctuations of optical waves [6,7,12,19-26]. It should also be noted the works by A. Consortini [29-31], devoted to measuring the outer scale of turbulence.

2.3 Outer scale of turbulence and instability parameter

Also, we have made a calculations [14-16] of phase structure functions for optical plane wave on horizontal path with models (Eqs 1-3) and have obtained the formulas for restoration of outer scale of turbulence from measurements of phase structure function in saturation region

$$D_s(\rho \to \infty) = 2\,\sigma_s^2 = \frac{24}{5}\,0.033\pi^2\kappa^2 C_n^2 L L_0^{5/3} \tag{4}$$

here is $\kappa_0^{-1} = L_0 / 2\pi$, C_n^2 is a structure parameter of refractive index, $k = 2\pi/\lambda$.

Indeed from Eq (4), I obtained the nice tool for measurements of outer scale of turbulence in near surface region of atmosphere. Several measuring devices were employed in the experiments to measure the temperature and wind velocity at fixed altitudes. Data were used for calculating the temperature structure parameter and the instability parameter [1,2].

$$B = \frac{gh}{\overline{T}}(T_2 - T_{0.5})/\langle v^2\rangle, \tag{5}$$

here h is a current altitude, g is acceleration due to gravity, $\overline{T}$ is average temperature at altitude h, T_2 is temperature at altitude $2h$, $T_{0.5}$ is temperature at altitude $0.5\,h$, $\langle v^2\rangle$ is a variance of wind velocity.

We used several instruments [14,26,32]. (1) Doppler acoustical waves meter of wind velocity, which allows measuring the horizontal and vertical components of the wind velocity at the center of optical path; (2) optical meter of fluctuations of angular displacements of center of image gravity along two perpendicular directions; (3) homodyne interferometer [8,9] for measuring the phase difference of coherent optical beams.

Our simultaneous measurements [14,26,32] of the phase structure function in the “saturation” region and of the turbulence intensity allow one to estimate the outer scale corresponding to the near surface region of the atmosphere. The values of outer scale of turbulence on altitude 2 m were obtained in region about 2-4 m. Since the scales L_0 were measured under different meteorological conditions, an attempt has been undertaken to classify the results of optical measurements of L_0 depending on the degree of thermodynamic stability of the atmosphere. During optical experiments [14], I found that the outer scale of turbulence L_0 depends on the thermodynamic stability of the atmosphere. We also found that the values of L_0 exceeding the mean value are realized under the conditions of neutral stratification (for $B = 0$). In the surface layer of the atmosphere the outer scale of the turbulence can be comparable, on the one hand, with the altitude above the ground and, on the other hand, the scale is dependent on characteristics of thermodynamic instability B from Eq (5).

2.4. Investigation of the anisotropy of the spectrum of atmospheric turbulence in the low-frequency region

I would like to note that one of the most important properties of atmospheric turbulence is the continuity of motion i.e., the contribution to the fluctuations of the refractive index at each moment of time is given by inhomogeneities of all scales. The largest inhomogeneities are those caused by the decay of large-scale mean motions: zonal winds, atmospheric fronts, and radiation regime inhomogeneities [1,2]. All these motions, decaying due to instability, serve as the basis for the entire spectrum of turbulent inhomogeneities. The area of large-scale inhomogeneities is most strongly associated with all local meteorological parameters, first of all, these are the fields of wind speed, temperature and their gradients. For the atmospheric under-surface layer this range turbulent scales called the region of energy-producing vortices and is characterized, as a rule, by non-isotropic properties, i.e. these inhomogeneities have properties that depend on the space direction. A correct description of the phase fluctuations of optical waves requires taking into account the deviation of the atmospheric turbulence spectrum from the Kolmogorov–Obukhov power law in the region of low spatial frequencies [1,2,17,18]. At the same time, it is this region of the turbulence spectrum that is the most poorly studied. Undoubtedly, one of the important properties of the spectrum in the low-frequency region can be its anisotropy.

Together with the dependence of the outer scale of turbulence on variations of meteorological parameters of the atmosphere, there exists anisotropy of atmospheric turbulent spectra. The properties of turbulent inhomogeneities with dimensions exceeding several meters depend on space direction. As a consequence, the characteristics of some parameters of optical waves appear to be direction dependent. Actually, we take into account two sizes of outer scale along two perpendicular directions:

$$\Phi_n(\kappa_2, \kappa_3, x) = 0.033 C_n^2(x)(\kappa_2^2 + \kappa_3^2)^{-11/6}\,\{1 - \exp(\kappa_2^2/\kappa_{02}^2 - \kappa_3^2/\kappa_{03}^2)\},$$

$$\vec{\kappa} : (\kappa_2, \kappa_3),\ \vec{\kappa}_0 : (\kappa_{02}, \kappa_{03}) \tag{6}$$

For example, the random two-directional displacements of an image formed along the horizontal atmospheric path on aperture with radius R, which is formed by the optical radiation passed through layers, exhibit such properties:

$$\vec{\rho}_F = \frac{1}{k\sum} \int_{\Sigma} d^2\rho\, \nabla_\rho\, S(L, \vec{\rho}),\ \langle(\vec{\rho}_F)^2\rangle = (\sigma_y^2 + \sigma_z^2) \tag{7}$$

In papers [13,17,18] have been shown that for anisotropic homogeneities of turbulence, we may introduce two values K and K_1, given by Eq (8) and Eq(9).

$$K = \frac{(\sigma_y^2 - \sigma_z^2)}{(\sigma_y^2 + \sigma_z^2)}, \tag{8}$$

$$K_1 = \frac{\sigma_z^2}{\sigma_y^2}. \tag{9}$$

The value of K (Eq 8) and value of K_1 (Eq 9) may present longitudinal and transverse outer scales of turbulence κ_{02}^{-1} and κ_{03}^{-1}, respectively.

To indicate the difference between longitudinal and transverse outer scales, the following relationship can be used:

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

If the outer scale has equal horizontal and vertical dimensions ($\delta = 0$), then $K_1 = 1$ and $K = 0$. And for this case the isotropy takes place.

Alternatively, if $\delta \neq 0$, then we have an anisotropy turbulence spectra.

Our experimental investigations [13] of astroclimatic characteristics of Elbrus region presented some features of anisotropy turbulence spectra in mountain region.

2 Intermittency of turbulence in the high-mountain astronomical observations

In this part of article, which is of an overview nature, we present results of long-term experimental studies of the intermittent turbulence effect in the mountain boundary layer of the atmosphere using acoustic and optical methods. The studies were carried out at high-mountain Russian astronomical observatories. Most of the presented experimental data were obtained at the Sayan Solar Observatory.

In the conditions under which astronomical observations are usually carried out (a slightly turbid cloudless atmosphere), atmospheric turbulence becomes the main component of the astroclimate, which significantly affects the effectiveness of astronomical observations. According to [1-3,33], local surface turbulence can contribute up to 40% or more to the deterioration of the image quality. Therefore, studies of the structure of turbulent fields in high-mountain areas where astronomical receivers are located remain important and relevant.

2.1. Coherent and Kolmogorov turbulence

Experimental data revealed the existence of deterministic formations in the turbulent atmosphere – coherent structures. A detailed historical review of studies of coherent structures and coherent turbulence since the 19th century was made by us in [34,35]. Monin and Yaglom [1] defined a coherent structure as a non-random nonlinear stable superposition of large-scale turbulence components. However, the process of hydrodynamic cell decay, as established in our works [36-42], continues to the smallest vortices that can exist in the air. And the concept of "coherent structure" is expanded in [38-42].) A hydrodynamic coherent structure is a compact formation that includes a long-lived spatial vortex structure (cell) that occurs as a result of the prolonged action of thermodynamic gradients, and the products of discrete coherent cascade decay. In the extended sense, a coherent structure is a soliton solution of hydrodynamic equations (topological three-dimensional soliton, solitary wave). This is either a single-soliton solution or a single soliton in a multi-soliton solution. The coherent structure contains both large-scale and small-scale turbulent inhomogeneities. At the same time, both the large-scale vortex itself and the products of discrete cascade coherent decay (small-scale vortices with multiple frequencies) are rigidly connected (in-phase or coherent).

This definition of a coherent structure brings together the well-known turbulent cascade of energy transfer and the coherence (in-phase, consistency, dependence) of all vortices in the structure. Turbulence resulting from the decay of the main vortex is coherent and deterministic [36-46].

In the atmosphere over the territories of astronomical observatories, extended regions have been recorded, in which one coherent structure has a determining influence. Turbulence in such areas is called coherent. In this case, currents external to the main vortex of a coherent structure can transport the products of its decay over considerable distances, forming a long turbulent wake.

We list some individual properties of coherent turbulence.

Our work shows that real atmospheric turbulence can be considered as an incoherent mixture of various coherent structures with incommensurable frequencies of the main energy-carrying vortices [36, 37,47]. Such turbulence is usually called Kolmogorov turbulence and is described by the well-known Kolmogorov model. As a well-mixed collection of regions with coherent (non-Kolmogorov) turbulence, it has some isotropy properties. We have shown that the experimental one-dimensional energy spectra of the actually observed atmospheric Kolmogorov turbulence with a 5/3 – decrease in the inertial interval are the sum of the spectra of individual coherent structures of different sizes with an 8/3 – decrease in the inertial interval [36-42]. If the coherent structures have similar sizes and are "well mixed", then the turbulence isotropy described by the Kolmogorov spectrum is observed. If one of the coherent structures is significantly larger than the others, then anisotropy of turbulence is observed, which is described by the coherent turbulence spectrum.

A pressure gradient appears in the air flow behind the obstacles, and coherent structures are formed. When flowing around obstacles (for example, mountains) due to the constant generation of large vortices and the transfer of decay by an external current, the currents immediately behind the obstacles are depleted by small vortices. Therefore, just beyond the obstacle, the spectrum of fluctuations corresponds to coherent turbulence. As the some distance from the obstacle increases, vortices (which are decay products) from the turbulent traces of decaying coherent structures mix with the surrounding turbulent atmosphere, and the turbulence from the coherent one gradually passes into the Kolmogorov one [39]. At the same time, as the measurement data show, the structural characteristic of fluctuations in the refractive index C_n^2 decreases when approaching an obstacle. For example, at a distance of 1 m from an artificial obstacle, C_n^2 is usually an order of magnitude less than away from the obstacle at a distance of 3 m or more.

The coherent turbulence is detected also in the air of enclosed spaces, arising due to the existence of temperature gradients inside the premises. Stationary circulating air flows (vortices) observed in a completely closed room can be interpreted as convective Bernard cells in the air. Inside the closed specialized rooms of astronomical telescopes, we registered the intensity of coherent turbulence comparable to the external atmospheric turbulence, and the average speed of air movements can reach values up to 1 m/s.

Coherent structures were registered in all turbulence measurement experiments performed by the authors of this paper over a period of more than a decade [40]. The measurements were made at different times, in different geographical areas and climatic conditions: in the mountain regions of observatories in southern Siberia (Baikal astrophysical and Sayan solar observatories), in the mountains of the North Caucasus. Our papers [38-40] review the results of studying the properties of coherent structures published in the world scientific literature. A comparison of the properties of structures established by us with the known results shows that our data significantly expand the currently existing in the literature the concepts of coherent structures in the atmosphere.

Areas of coherent turbulence can occur due to many different reasons: behind a major obstacle to atmospheric air flows (mountains), temperature variation of the underlying surface, near coastlines, convection, etc. Kolmogorov (incoherent) turbulence is usually detected over areas with a flat underlying surface.

2.2. The effect of intermittency of the jitter of astronomic images

In optical and meteorological measurements, we found [36-39,48-50] that over the territories of mountain observatories there is a periodic change in the type of turbulence, when coherent turbulence is replaced (alternates) by Kolmogorov turbulence. This means that the effect of intermittent turbulence was registered in the experiments. It has been established that the effect occurs due to the wind moving of extended regions of air with Kolmogorov or coherent type of turbulence entirely through the territory of observatories, which leads to intermittent turbulence.

3 Experiments

3.1. Equipment and Methods

Optical measurements were performed at the Sayan solar Observatory (SSO) of the Institute of Solar-Terrestrial Physics SB RAS using an Automated Horizontal Solar Telescope (AST). Experiments confirming changes in the type of turbulence (the intermittency effect) were also performed at the Baikal astrophysical and Special astrophysical observatories (see section 3.2). The design of the AST telescope includes a system (coelostat) consisting of two flat mirrors with a diameter of 800 mm. The Brandt sensor installed in the focus of the main mirror of the telescope, which is a photoelectric jitter recorder, was used as a photodetector [51]. The accuracy of the sensor jitter measurement is not less than 0.1", the upper limit of the frequency resolution is 100 Hz. The principle of operation of the recorder is based on measuring the photocurrent, the value of which is proportional to the linear shift of the image (jitter of the edge of the solar disk) through the optical slot behind which the light receiver is installed. The measured luminous flux is calibrated based on the difference between the fluxes when the slit is fully illuminated by the Sun and when there is no Sun on the slit. The data received after processing by an analog-to-digital converter is written on the computer's hard disk. The Brandt sensor has been successfully tested for several decades and was previously used in similar studies [38,39,48-51].

In parallel to optical measurements the meteorological situation was continuously monitored by the ultrasonic autonomous meteorological complex AMK-03 [52,53] near the receiving telescope to determine the type of turbulence (coherent or incoherent Kolmogorov turbulence). The AMK-03 complex registers six meteorological parameters and calculates in real time more than a hundred statistical parameters of atmospheric turbulence. The recorded meteorological parameters include air temperature, the three orthogonal components of the wind velocity vector (and the horizontal wind direction), atmospheric pressure, and relative air humidity. They are stored in the computer's RAM memory for the time interval equal to the set averaging time, counted back from the moment of receipt of the last information package from the device. That is, there are always arrays of instantaneous values of meteorological parameters with the large number of their elements (on average for 10 minutes the sample has 48000 elements). The software for the time and observation periods specified by the operator calculates from these arrays the average values of meteorological parameters and their other statistical moments, as well as the standard numerical characteristics of atmospheric turbulence, automatically storing the results in text files. The main calculated characteristics of turbulence include the heat and impulse flows, scale of temperature (T_*) and wind (V_*) fluctuations, the scale and Monin-Obukhov's number, and also the structural characteristics of temperature fluctuations C_T^2 (deg^2 cm$^{-2/3}$), of longitudinal component of wind speed C_V^2 ((m/c)^2 cm$^{-2/3}$), of the acoustic refraction index C_{na}^2 (m$^{-2/3}$), of the optical refraction index C_n^2 (cm$^{-2/3}$).

3.2. Experimental observations of changes in the type of turbulence in high-mountain observatories

First and foremost, we are interested in features of formation of coherent turbulence in the atmosphere. Earlier, it was shown [36-45] that in the open atmosphere over the territory of high-mountain observatories often there are regions of coherent turbulence. In an unclouded atmosphere, the quality of the image received by the telescope is mainly determined by atmospheric turbulence, which introduces random distortions in the phase front of the wave. We have theoretically and experimentally established [34,36-40,43-50] that in the presence of large coherent structures in the atmosphere (regions of coherent turbulence), the effect of attenuation of phase fluctuations of light radiation in comparison with Kolmogorov turbulence due to depletion of small-scale inhomogeneities is observed. The attenuation of phase fluctuations manifests itself in a significant decrease in fluctuations in the jitter of astronomical images. Therefore, in order to improve the quality of images, for installing ground-based astronomical telescopes we can recommend areas over which there is the coherent turbulence during measurements [38,39].

(a) (b)

Fig 1. Surface profile along the main winds direction in the SSO: (a) to the North of the SSO is the Eastern Sayan mountain ridge; (b) to the South of the SSO is flat terrain and Lake Khubsugul.

The attenuation of phase fluctuations of light radiation was registered by us [6-9,18-20] in a series of optical and meteorological measurements in 2010-2019. At the Sayan solar Observatory (SSO) measurements were made using the AST telescope. Measurements of turbulence parameters made in 2005-2019 continuously (every 15 minutes) for several weeks in SSO show that the wind over this territory has a selected average preferred direction along the North-South line, similar to breezy winds.

To the north of the Observatory the Eastern Sayan mountain range stretches across the average wind direction (Fig 1a). The height of the Chasovye Hills Mountain, on the top of which the Observatory is located, is 2000 m. The average height of the Northern mountains opposite the Observatory is about 2400 m, and the distance to them at the height of the Observatory is about 14 km.

On the South side of SSO, there is a fairly flat terrain and a large lake Khubsugul, more than 100 km in length (Fig 1b). With a southerly wind (flat underlying surface), the atmospheric turbulence spectra (($W_T(f)$, f – frequency) over the Observatory area usually remain Kolmogorov spectra ($W_T \sim f^{-5/3}$). In the opposite wind direction from the Sayan, the inertial intervals of the turbulence spectra usually have 8/3-asymptotics ($W_T \sim f^{-8/3}$), which is a sign of a coherent structure. Thus, the air masses flowing down from the cold Sayan mountain ridge to the river Irkut and twisting by the slopes of the mountain Chasovye Hills, form a large long-lived coherent structure behind the obstacle in the atmosphere above the observatory SSO. The life time was 6–28 minutes.

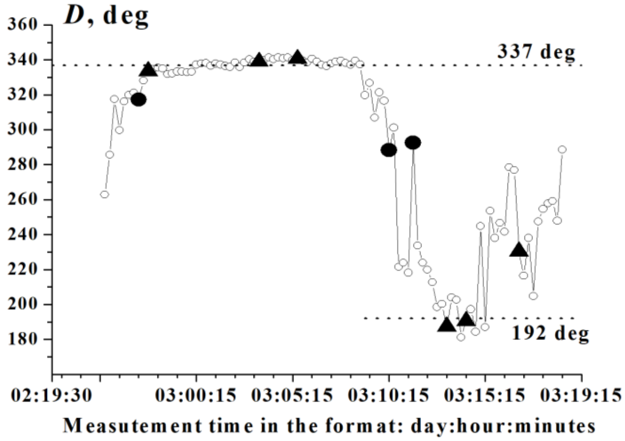


Fig 2. Average wind direction *D* Baikal, 2007.

A similar situation was observed by the authors near the receiving aperture of the Big Solar Vacuum Telescope (BSVT) installed on the top of the mountain near the coastal edge of Lake Baikal [41]. The average wind direction near LSVT differs by about 180° (measured from north through east) at night and during the day (Fig 2). With a constant wind direction at night and daytime, the obtained data are dominated by spectra with 8/3-asymptotics corresponding to Kolmogorov turbulence (dark circles in Fig 2). With a constant wind direction at night and daytime, the obtained data are dominated by spectra with 8/3-asymptotics (triangles in Fig 2, coherent non-Kolmogorov turbulence), i.e., with a stable wind, due to the inhomogeneities of the coastal relief, at the height of the BSVT receiving mirror the coherent turbulence arises.

Thus, the experimental data obtained by us show that regions of coherent turbulence are formed in the mountains in stable weather conditions characterized by a constant direction of the average wind (at night and during the day) behind large terrain inhomogeneities or artificial obstacles to atmospheric flows [1]. Changes in the mostly observed type of turbulence (Kolmogorov or coherent turbulence) occurred depending on the time of day and the direction of the average wind.

4.3. Measurements of the integral intensity of atmospheric turbulence

The intensity of atmospheric turbulence is determined, as is known, by the parameters of the structural function of temperature fluctuations and the refractive index; they are the structural characteristics of C_T^2 and C_n^2. On vertical atmospheric paths the altitude turbulence profiles play an important role.

In a previous work [9], we presented the results of optical measurements of the integral intensity of atmospheric turbulence based on high-mountain optical measurements of the image jitter of the edge of the solar disk.

For the case of Kolmogorov (incoherent) turbulence, the dispersion of image jitter σ_a^2 is expressed in terms of the integral value I_{nc} of the structural characteristic of the refractive index C_n^2 in a known way [39]:

$$\sigma_a^2 = 4.51\, a_t^{-1/3} \sec q \times I_{nc}\,,\ I_{nc} = \int_0^{\infty} \mathrm{d}h\, C_n^2(h), \tag{10}$$

where a_t is the radius of the input aperture of the telescope, q is the zenith angle of the observed object (measured at the location of the receiver from the direction to the zenith), $C_n^2(h)$ is the structural characteristic of fluctuations in the refractive index of air, depending on the height h above the underlying surface (altitude profile C_n^2). For each value of the angle q, the value of I_{nc} determines the integral intensity of atmospheric Kolmogorov turbulence on optical paths of a given slope. This formula allows us to restore the integral intensity I_{nc} of Kolmogorov turbulence from the measured values of the jitter dispersion σ_a^2 . In coherent turbulence, the spectrum of atmospheric turbulence differs from the case of Kolmogorov (incoherent) turbulence [34-47]. Therefore, the expression for the variance σ_a^2 will change. For the measurements, the estimated expression of the dispersion σ_a^2 given in [9] is used in terms of the integral value of the I_c of the structural characteristic C_n^2 in coherent turbulence

$$\sigma_a^2 = 8.06\, L_0^{-1/3} \sec q \times I_c\,,\ I_\mathrm{c} = \int_0^{\infty} dh\, C_n^2(h), \tag{11}$$

where $L_0 = L_0(h_0)$ is the outer (exponential [39]) scale of turbulence at the height of the center of the receiving mirror above the underlying surface h_0.

The main difference of this formula (Eq 11) from the expression for the case of Kolmogorov turbulence (Eq 10) is that in (Eq 11), instead of the receiver radius a_t, the outer turbulence scale L_0 appears, and σ_a^2 does not depend on a_t. The expressions for the integral intensities of the Kolmogorov I_{nc} and coherent I_c turbulences in formulas (Eq 10) and (Eq 11) are identical in form, but we can expect that the altitude profiles of the structural characteristic $C_n^2(h)$ for different types of turbulences (Kolmogorov and coherent turbulences) will differ from each other.

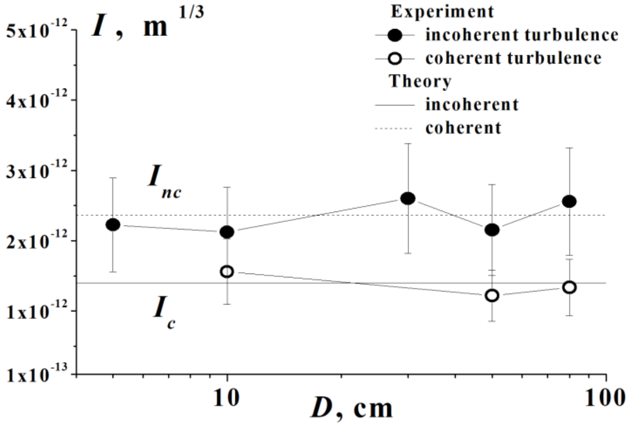


Fig 3. Integral intensity of atmospheric coherent turbulence I_c (light circles) and Kolmogorov incoherent turbulence I_{nc} (dark circles) over the territory of the SSO depending on the diameter of the receiving aperture D. June 2010.

Figure 3 shows the results of optical measurements of the integral intensity of the atmospheric Kolmogorov incoherent turbulence I_{nc}, averaged over four measurement sessions (dark circles) [39]. The measurements were carried out for five different diameters of the receiving mirror (aperture) of the AST telescope: 5 cm, 10 cm, 30 cm, 50 cm, 80 cm and for two different angular sizes of the receiving slit of the sensor recorder: 25" and 10". The zenith angle of the Sun was monitored. The solid line in Fig 3 shows the corresponding theoretical dependence of the value of I_{nc} on the diameter of the telescope receiving 0 D.

The measurement results (Fig 3) show that the presence of large coherent structures in the atmosphere has little effect on the values of the integrated turbulence intensity ($I_{nc} \approx 2.4\times10^{-12}$ m $^{1/3}$, $I_c \approx 1.4\times10^{-12}$ m $^{1/3}$). This was to be expected, since the integrated intensity accumulates along the entire optical path. In this case, the variations in the altitude profile of the structural characteristic of the refractive index, arising due to the deviation of turbulence from Kolmogorov turbulence, are smoothed out. At the same time, coherent turbulence is usually depleted in small-scale heterogeneities that increase C_n^2. Therefore, on average, the integral intensity of coherent turbulence turns out to be almost two times less than the intensity of incoherent Kolmogorov turbulence.

4.4. Measurements of the angular jitter dispersion of the solar disk edge

In this section, which is of an overview nature, we present the results of measurements of the angular jitter dispersion of the solar disk edge image carried out by the authors over a number of years (2010-2015).

4.4.1. Experiments 2010

The main averaged parameters of the optical experiment in 2010: the zenith angle of the observed object $\theta \approx 55°$; structural characteristic $C_n^2 = 4{,}2\times10^{-15}$ cm$^{-2/3}$ at a height of 4.5 m from the underlying surface; the angular radius of an astronomical source (edge of the solar disk) corresponding to the limiting angular resolution of the used receiver $\alpha \approx 0.1$ arcsec. The results of optical and parallel meteorological measurements have shown (Fig 4) [37,39,48] that when large coherent structures are present in the atmosphere (spectrum of temperature fluctuations $W_T \sim f^{-8/3}$, coherent turbulence), then our data coincide with the coherent theory ($\sigma_\alpha \sim$ const, point 2 in Fig 4).

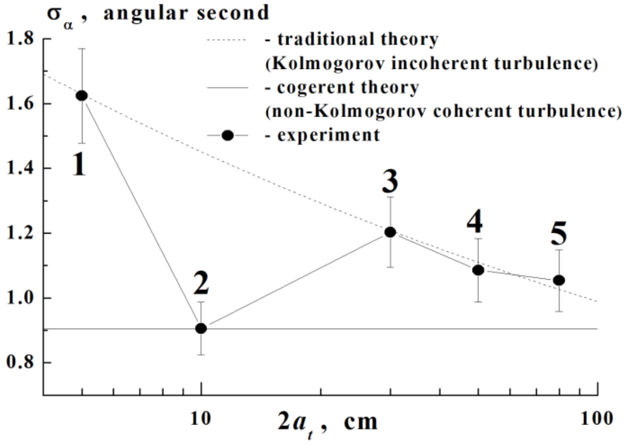


Fig 4. Root-mean-square deviation σ_α of jitter of the astronomical image of the solar disk edge depending on the telescope aperture diameter 2 a_t. Sayan. 19.06.2010. For the experimental point $2a_t = 10$ cm – $W_T \sim f^{-8/3}$, for other points – $W_T \sim f^{-5/3}$.

In the absence of large structures (incoherent turbulence, $W_T \sim f^{-5/3}$) in the atmosphere, our results coincide with the traditional incoherent theory (the inclined line and points 1, 3 – 5 in Fig 4. As can be seen from Fig 4, the standard deviation (RMS) of the image jitter of the solar disk edge in coherent turbulence is significantly less (almost 2 times) than in the case of Kolmogorov (incoherent) turbulence.

4.4.2. Experiments 2011

In 2011, we repeated experimental studies of the effect of attenuation of light fluctuations in coherent turbulence similar to those conducted in 2010 [38,39]. The zenith angle of the observed object is $\theta \approx 50°$; the structural characteristic of refractive index fluctuations at a height of 4.5 m from the underlying surface is C_n^2

= 1.2×10^{-15} cm$^{-2/3}$; the angular radius of the astronomical source (the edge of the solar disk) corresponds to the maximum angular resolution of the receiver used is $\boldsymbol{\alpha} \approx 0.1$ arcsec.

The results of astronomical and parallel meteorological measurements confirmed (Fig 5) that the jitter dispersion of the image of the edge of the solar disk in coherent turbulence ($\sigma_\alpha \sim$const, squares in the Fig 5), as well as in the 2010 experiment, is significantly smaller for the same aperture size than in the case of Kolmogorov (incoherent) turbulence (the inclined theoretical line and dark points in the Fig 5). In the absence of large structures in the atmosphere (incoherent turbulence, $W_T \sim f^{-5/3}$), our results coincide with the incoherent theory.

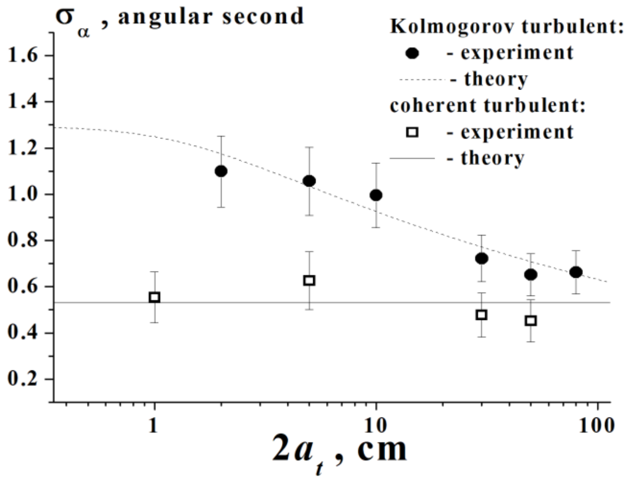


Fig 5. Standard deviation σ_α of the jitter of the astronomical image of the edge of the solar disk depending on the aperture diameter $2a_t$ of the telescope. Sayan. 04.08.2011.

4.4.3. Experiments 2013

In 2013, studies of the effect of attenuation of light fluctuations in coherent turbulence were continued [36,49,50]. The main averaged parameters of the experiments in 2013 were: the zenith angle of the observed object $\theta \approx 60$ °; structural characteristic of refractive index fluctuations at a height of 4.5 m from the underlying surface $C_n^2 = 1{,}7\times10^{-15}$ cm$^{-2/3}$; average surface wind speed 6 m/s; the angular size α of an astronomical incoherent source (edge of the solar disk), corresponding to the resolution of the used receiver, varied in the range from 0.1 to 1.5 arcsec.

The experimental conditions in 2013 were significantly different from those of 2010-2012 [49]. In contrast to the previous summer measurements, the 2013 experiments were carried out in the fall, when an unstable snow cover was present on the territory of high-mountain observatory SSO and a strong wind was observed.

The results of astronomical and parallel meteorological measurements showed (Fig 6) that when coherent turbulence is recorded in the atmosphere, then our data coincide with the coherent theory ($\sigma_\alpha \approx$ const, light simbols and line 3 in Fig 6). In the case of Kolmogorov turbulence, the results for a point source (α = 0.1 arc. sec) coincide with the traditional Kolmogorov theory (dark points and line 1 in Fig 6).

Theoretical curve 2 in Fig 6 (and the oblique theoretical line in Fig 5) is plotted for Kolmogorov turbulence taking into account the regularization of the random singular phase of an incoherent extended source. In this case, as is known [49,50], the theoretical standard deviation σ_α of the angular jitter of an astronomical image is approximately represented in the form

$$\sigma_\alpha = \sigma_{\alpha\, sp} f(\alpha_t), f(\alpha_t) = [\, 1 + (4/9)\, (\alpha h_e \sec \theta/\alpha_t)^2]^{-1/12}, \tag{12}$$

where $\sigma_{\alpha\, sp}$ is the standard deviation of the angular jitter of the image of a spherical wave (point source), h_e is the effective thickness of the optically active layer of the turbulent atmosphere ($h_e \approx 3.2$ km). Here, the function $f(a_t)$ takes into account the deviations of a real extended incoherent source (the edge of the solar disk) from a point source (spherical wave) in the image jitter.

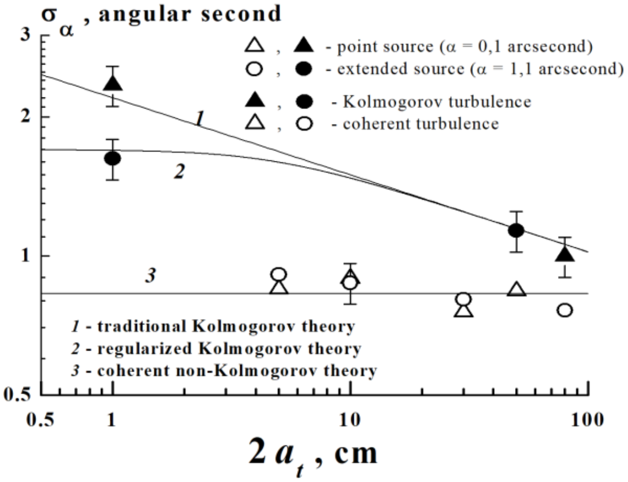


Fig 6. Standard deviation σ_α of the angular jitter of the astronomical image of the edge of the solar disk depending on the telescope aperture diameter $2a_t$. Sayan. 24.09.2013. The open circles and triangles correspond to coherent turbulence, dark ones correspond to the Kolmogorov (incoherent) turbulence. Triangles are a point sources ($a = 0.1$ arcsec), circles are an extended incoherent source ($a = 1.1$ arcsec).

As can be seen from Figs 5 and 6, there is a satisfactory agreement between the regularized theory for Kolmogorov turbulence and experiment. According to the data in Fig 6, the jitter of the image of the edge of the solar disk ($\alpha \neq 0$) tends to a constant value with decreasing receiver diameter $2a_t$. Figure 6 also shows that the standard (root-mean-square) deviation of the image jitter of the solar disk edge in coherent turbulence for the same aperture turns out to be much smaller than in the case of Kolmogorov (incoherent) turbulence (for small receivers, more than 2 times).

Thus, in the presence of coherent turbulence in the atmosphere, fluctuations in the jitter of optical images are significantly reduced. This improves the quality of astronomical images.

The 2013 experiment extended our understanding of the effect of coherent turbulence on the propagation of optical radiation in a turbulent medium. In 2013, more data were registered for coherent turbulence (eight points for the variance of image jitter, instead of four in 2011 and one point in 2010).

In the previous summer meteorological measurements of 2010-2012 long-lived (with a life time of 20-120 min) coherent turbulence over the territory of the Sayan Solar Observatory was recorded, as a rule, with a north wind (from the mountains of the Sayan ridge). In summer similar wind direction is usually observed at night. Therefore, summer night astronomical observations could be considered preferable here. However, summer nighttime optical measurements in 2010-2012 were not carried out and only daytime summer optical measurements were performed. During the day, usually a southerly wind (from the side of Lake Khubsugul, Mongolia) and short-lived coherent turbulence (with a life time of usually 6-14 min) were registered. Therefore, in the daytime summer optical measurements of 2010-2012 few data σ_α have been registered for coherent turbulence.

In the experiments of 2013, which was carried out under conditions of snow cover and strong wind (essentially under conditions of transition from autumn to winter), short-lived (with a lifetime of 2-4 min) coherent turbulence arose, as in summer, with a southerly wind (from the Lake Khubsugul), which is usually observed in the Sayan Solar Observatory during the day. At the same time, measurements of previous years have shown that Kolmogorov turbulence is usually observed in the Sayan solar observatory with a southerly wind during the day. However, compared with summer measurements of 2010-2012 in the autumn-winter measurements of 2013, the frequency of the appearance of short-lived coherent turbulence increased significantly (apparently, due to the strong wind, which transports the mixture of single coherent structures formed over Lake Khuvsgul more quickly). Therefore, in the optical measurements of 2013, much more data σ_α were registered for coherent turbulence.

In our observations in 2013, under stable meteorological conditions and wind from the side of a flat underlying surface, the time period of the presence (lifetime) of coherent turbulence in the atmosphere, during which it does not change to Kolmogorov turbulence, is from 10 to 26 minutes (Table 1). At the same time, the lifetime of the Kolmogorov turbulence is 2-4 times less and is 6-7 minutes, and the largest number of coherent points (5 points) in measurements was registered. For measurements of past years, the lifetimes of turbulence of different types are given in Table 1. For measurements in 2010, the lifetime of the Kolmogorov turbulence is approximately 2 times longer than the lifetime of coherent turbulence (only one coherent point in the measurements was registered). For measurements in 2011, the lifetimes of the Kolmogorov and coherent turbulence turned out to be comparable (this can be seen from the Table 1, in this case, 4 coherent and 6 incoherent points are registered).

4.4.4. Experiments 2014

In 2014 observations, it was possible to register a non-standard daytime wind direction from the Sayan Mountains. The measurements were taken in the afternoon and are shown in Fig 7.

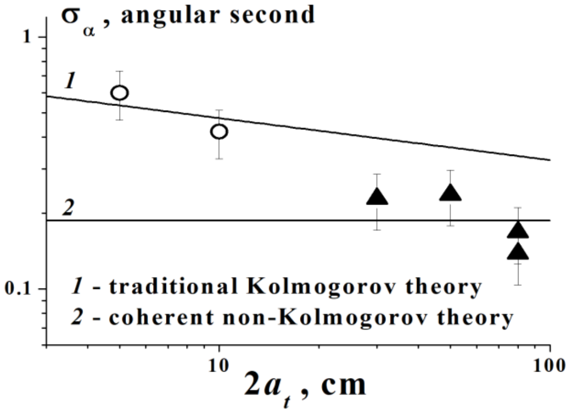


Fig 7. Standard deviation σ_α of the image jitter of the edge of the solar disk from the aperture diameter of the telescope $2a_t$. Sayan Mountains. 12.08.2014.

During the measurement period (about an hour) the turbulence type changed from coherent turbulence (dark triangles) to Kolmogorov turbulence (light circles). As can be seen from Fig 7, the standard deviation of the image jitter of the solar disk edge in coherent turbulence is smaller than the theoretical curve 1 for the case of Kolmogorov (incoherent) turbulence (more than 2 times). This confirms our earlier conclusions [36-46] about the attenuation of phase fluctuations of optical radiation in coherent turbulence in comparison with Kolmogorov turbulence (due to the depletion of small-scale inhomogeneities). Therefore, in order to improve image quality, it is possible to recommend places over which there are areas of coherent turbulence during measurements for the installation of ground-based astronomical telescopes.

In our observations (12.08.2014) under stable meteorological conditions and wind from the Sayan ridge, the time period of presence (lifetime) of coherent turbulence in the atmosphere, during which it does not change to Kolmogorov turbulence, is about 18 minutes. The lifetime of the Kolmogorov turbulence is 2-3 times less and is 7 minutes. At the same time, in the observations of 13.08.2014, with a stable wind direction from a flat underlying surface, the lifetime of the Kolmogorov turbulence was significantly longer than for coherent turbulence (Table 1).

4.4.5. Experiments 2015

In optical and meteorological measurements in 2015, we found that over the territory of the SSO there is a periodic change in the type of turbulence, when coherent turbulence is replaced by Kolmogorov turbulence. Coherent turbulence in daytime measurements usually occurred with an average wind direction from the North (from the Sayan ridge, through the deep valley of the Irkut river). The life time was 6-28 minutes. In the absence of climate anomalies (in 2015, for example, such a three-day anomaly was registered as an exception), the North wind direction in SSO is usually observed at night. With the opposite south wind direction (from a flat underlying surface and a large lake Khubsugul) is registered mainly Kolmogorov turbulence, with a lifetime of 7-35 minutes. In this case, short-lived coherent turbulence with a lifetime of 2-4 minutes also often occurred. The southerly wind direction in SSO is usually observed during the day. As can be seen from Fig 8, the dispersion of image jitter for coherent turbulence is less than in the case of Kolmogorov (incoherent) turbulence (2-4 times depending on the telescope diameter and observation time).

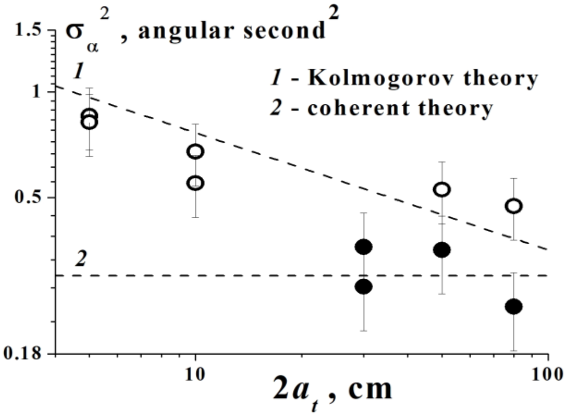


Fig 8. Dispersion σ_a^2 of the angular jitter of the solar disk edge as a function of the receiving telescope aperture diameter $2a_t$. Experimental dark circles correspond to coherent turbulence, light ones - to Kolmogorov turbulence. Sayan. 15.07.2015.

In the 2015 experiment, the times and places of occurrence of coherent turbulence regions were identified, their connections were established with the type of underlying surface and the direction of the wind speed, as well as with the type of microclimate of the region as a whole. In order to improve the quality of images, for the installation of ground-based astronomical telescopes in [34,38,39,49], the regions with areas of coherent turbulence are recommended.

In general, under the conditions of the transition from autumn to winter at the Sayan Solar Observatory, long-term daytime astronomical observations are accompanied by a frequent transition from Kolmogorov turbulence to coherent turbulence. Such a transition, corresponding to a change in the type of turbulence, gives an intermittency in the jitter of astronomical images, which manifests itself in a frequent change in the intervals of strong and weak jitter of images. Since coherent turbulence leads to an improvement in the quality of optical images [36-40], this effect can be regarded as positive for short-exposure measurements, when the best quality can be selected from a series of images obtained.

4.4.6. Results of experiments during 2010-2015

The results of the experiments carried out during 2010-2015 are summarized in Table 1, which show the lifetimes recorded in optical and meteorological measurements (by measurement sessions) of various types of turbulence.

Table 1. The lifetimes of turbulence of various types registered in optical-meteorological measurements

Measurement time	**Wind direction, deg**	**Horizon speed wind, m/s**	**Temperature, ° C**	**Time of continuous registration, min:**	
				Coherent turbulence	**Kolmogorov turbulence**
19.06.2010	190-230	4.4	19.0	10	21
04.08.2011	20-40	1.9	19.5	7-12	8-15
14.07.2012	40-70	1.7	9.4	29	13
25.09.2013	180-200	6.0	8.5	10-26	6-7
12.08.2014	5-79	1.7	17.7	18	7
15.07.2015	52	2	17.6	28	15

From the data in Table 1, it can be seen that when the wind is directed from the side of a flat underlying surface, the lifetime of Kolmogorov turbulence is more than 2 times longer than the lifetime of coherent turbulence. With the opposite wind direction (from the Sayan Mountains) the period of the presence of coherent turbulence becomes longer (up to 2-3 times). The exception is the measurements in the 2013 experiment, carried out under conditions of snow cover and strong wind (essentially under conditions of transition from autumn to winter), when short-lived (with a life time of 2-4 min) coherent turbulence arose with a southerly wind from the side of an even underlying surface. In addition, the registered large vertical velocity components correspond to the presence of rather large coherent structures in the surface layer.

4 Conclusions

Theoretical analysis and experiments confirm the presence of large coherent structures (regions of coherent turbulence) in the atmosphere of high-altitude observatories, in which fluctuations of optical radiation are significantly reduced [36-46]. Therefore, for the installation of ground-based telescopes, it is possible to recommend regions over which large coherent structures are present during measurements. Large coherent structures (regions of coherent turbulence) are detected by measurements of the jitter characteristics of astronomical images.

Analysis and comparison of the results of the measurements made it possible to draw the following conclusions.

In optical-meteorological measurements, it was established that in the presence of coherent structures in a turbulent atmosphere, a periodic change in the type of turbulence is observed, when the coherent turbulence is replaced (alternated) by Kolmogorov turbulence. This means that there is an intermittent jitter effect in astronomical images. The data in Table 1 illustrate the manifestation of the intermittency effect. The effect *arises* when the wind carries the regions of coherent (non-Kolmogorov) turbulence formed in the atmosphere; it *consists* in periodic attenuation and gain of phase fluctuations of optical radiation (with intervals from 6 to 39 min), and *is caused* by the presence of a large number of regions of coherent turbulence from the windward side (and their subsequent wind transfer). Measurements 2010-2015 [36-50] confirm the existence of the intermittency effect and clarify the conditions for its manifestation. As can be seen from Table 1, the occurrence of regions of coherent (non-Kolmogorov) turbulence, which then move to the observation point by the wind, depends on the season of the year, the direction of the wind, and the type of underlying surface.

The effect of intermittency, as can be seen from the description (and from the above measurement data for 2010-2015), characterizes the local structure of turbulence over a specific region. In a continuous turbulent field, there are regions of isotropic Kolmogorov turbulence, in which the decay products of coherent structures of similar sizes are well mixed, and regions of anisotropic coherent turbulence with insufficient mixing. These areas are separated from each other and are carried by the wind as a whole. With continuous optical registration at a fixed ground surface point, we observe intermittent turbulence characteristics (regions with different turbulence move across the optical path).

The presence of mountain massifs in the locations of astronomical telescopes leads to the fact that there is a distinguished direction of the mean wind over the territory of the observatories, due, like breeze winds, to the temperature difference (gradient) between the mountain massif and the valley, or determined by the existing relief "channels" for air masses in the surface layer. A change in the wind direction along the selected stable direction to the opposite direction leads to a change in the air masses brought to the territory of the observatory and a change in the type of observed turbulence. Changes in wind direction can be caused, for example, by a change of day to night, a change in cloudiness, meteorological conditions, etc. A predominantly coherent type of turbulence is registered with the wind direction from the mountains and predominantly Kolmogorov turbulence registered with the wind from the valley.

Thus, measurements show that coherent turbulence occurs over the territory of SSO, as a rule, with a North wind (from the mountains of the Sayan ridge, through the deep valley of the Irkut river). In summer, such wind is usually observed at night. Therefore, night observations are preferable here. The sizes of coherent turbulence regions can exceed the size of telescope towers. in our measurements, the maximum size of the vortex (reconstructed from the registered turbulence spectra) reached 80 m. The lifetime of coherent turbulence regions (during a single measurement session) is 2-4 minutes in the South wind (from Mongolia, where the underlying surface is relatively flat), and one is 6-28 minutes in the North wind (from the Sayan Mountains). With the opposite south wind direction (from a flat underlying surface and a large lake Khubsugul; it observed, as a rule, during the day) mainly Kolmogorov turbulence is registered, with a lifetime of 7-35 minutes.

Funding

The research was supported within the framework of the scientific program of the National Center for Physics and Mathematics (project "Physics of high energy densities. Stage 2023-2025").

References

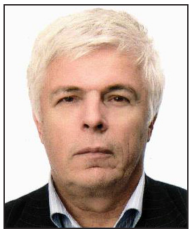
1. Monin A S, Yaglom A M, Statistical hydromechanics, Part 1. *Science. M. 1965, p 460.*
2. Obukhov A M, Proceedings of the Academy of Sciences of the USSR, Ser geophysical, 1953. No. 2. 155-165.
3. Gurvich A S, Atmosphere and Ocean Physics. Notes of Academy of Sciences of the USSR, 4(1963)160–169.
4. Tatarsky V I, Propagation of waves in a turbulent atmosphere, M: Science Nauka, 1967, p 464 p.
5. Burlamacchi P, Consortini A, Ronchi L, Time-resolved measurements of the phase fluctuations of a coherent beam at the emergence from a turbulent layer, *Appl Opt, 6*(1967)1273–1275.
6. Consortini A, Ronchi L, Choice of the model of atmospheric turbulence, *Appl Opt*, 11(1972)1205–1211.
7. Consortini A, Ronchi L, Moroder E, Role of the outer scale of turbulence in atmospheric degradation of optical images, *J Opt Soc Am*, 63(1973)1246–1248.
8. Lukin V P, Pokasov V V, Khmelevtsov S, Investigation of temporal characteristics of optical waves phase propagating in ground-boundary layer, *Radiofizika*, 15(1972)1861–1866.

9. Lukin V P, Pokasov V V, Phase fluctuations of optical waves propagating in turbulent atmosphere, Izvestia VUZov, *Radiophysics*, 16(1973)1726–1729.
10. Mironov V L, Lukin V P, Pokasov V V, Khmelevtsov S S, Phase fluctuations of optical waves propagating in a turbulent atmosphere, Izv. Academy of Sciences of the USSR, *Radio Engineering and Electronics*, 20(1975)1164–1170.
11. Bouricius G M B, Clifford S F, Experimental study of atmospheric ally induced phase fluctuations in an optical signal, *J Opt Soc Am*, 60(1970)1484–1489.
12. Lukin V, Pokasov V, Optical wave phase fluctuations, *Appl Opt*, 20(1981)121–135.
13. Gubkin S M, Emaleev O N, Lukin V P, Mutnitskii N G, Pokasov V V, Experimental investigations of astroclimatic characteristics of Elbrus region, *Soviet Astron*, 27(1983)456–459.
14. Lukin V P, Optical measurements of the outer scale of atmospheric turbulence, Proc SPIE, 1993(1968)327–336.
15. Lukin V P, Investigation of some peculiarities in the structure of large–scale atmospheric turbulence, Proc SPIE, 2200(1994)384–395; doi.org/10.1117/12.177255.
16. Lukin V P, Comparison of the spectral model of atmospheric turbulence, Proc SPIE, 2222(1994)527–535.
17. Lukin V P, Investigation of the anisotropy of the atmospheric turbulence spectrum in the low-frequency range, Proc SPIE, 2471(1995)347–355; doi.org/10.1117/12.211944.
18. Lukin V P, Antoshkin L V, Botugina N N, Emaleev O N, Investigation of turbulence spectrum in the ground atmospheric layer, *Atmos Ocean Opt*, 8(1995)993–996.
19. *Borgnino J*, Estimation of the spatial coherence outer scale relevant to long baseline interferometry and imaging in optical astronomy, *Appl Opt*, 29(1990)1863–1865.
20. Borgnino J, Martin F, Ziad A, Effect of a finite spatial-coherence outer scale on the covariances of angle-of-arrival fluctuations, *Opt Commun*, 91(1992)267–279.
21. Ziad A, Borgnino J, Martin F, Agabi A, Experimental estimation of the spatial-coherence outer scale from a wavefront statistical analysis, *Astron Astrophys*, 282(1994)1021–1033.
22. Vernin J, Mechanism of formation of optical turbulence, ASP Conference Series, 266(2002)2–17.
23. Dewan E M, Grossbard N, The inertial range “outer scale” and optical turbulence, *Environ Fluid Mech*, 7(2007) 383–396.
24. Reinhard G W, Collins S A, Outer-Scale Effects in Turbulence-Degraded Light-Beam Spectra, *J Opt Soc Am*, 62(1972)1526–1528.
25. Coulman C E, Vernin J, Coquegniot Y, Caccia J L, Outer scale of turbulence appropriate to modeling refractive-index structure profiles, *Appl Opt*, 27(1988)155–160.
26. Lukin V P, Atmospheric turbulence parameters measurements // Proc. IUA Site 2000. ASP Conference Series. 266(2002)18–27.
27. Lukin V P, Nosov E V, Fortes B.V, Effective outer scale of turbulence for imaging through the atmosphere, Proc SPIE, 3219(1998)98–106.
28. Coulman C E, Vernin J, Significance of anisotropy and the outer scale of turbulence for optical and radio seeing, *App Opt*, 30(1991)118–126.
29. Consortini A, Innocenti C, Paoli G, Estimate method for outer scale of atmospheric turbulence, *Opt Commun*, 214(2002)9–14.
30. Innocenti C, Consortini A, Method for estimating the outer scale of atmospheric turbulence and its dependence on the model, Proc SPIE, 5237(2004)25–30.
31. Sun Y Y, Consortini A, Li Z P, A new method for measuring the outer scale of atmospheric turbulence, *Waves in Random and Complex Media*, 17(2007)1–8.
32. Lukin V P, Outer scale of turbulence and its influence on fluctuations of optical waves, *Phys Usp*, 64(2021)64 (2021)280; doi. 10.3367/UFNe.2020.10.038849.

33. Tokovinin A, Where is the surface-layer turbulence?, Proc SPIE, 77331N(2010); doi. org/10.1117/12.856409.
34. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Formation of Turbulence at Astronomical Observatories in Southern Siberia and North Caucasus, *Atmos Ocean Opt*, 32(2019)464–482.
35. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, The emergence and evolution of the concept "coherent turbulence", *Journal of Physics: Conference Series*, 2020, 1499(012005).1–7.
36. Lukin V P, Nosov E V, Kovadlo P G, Nosov V V, Torgaev A V, Causes of non-Kolmogorov turbulence in the atmosphere, *Appl Opt*, 55(2016)B163–B168.
37. Lukin V P, Bol'basova L A, Nosov V V, Comparison of Kolmogorov's and coherent turbulence, *Appl Opt*, 53(2014) B231–B236.
38. Nosov V V, Atmospheric Turbulence in the Anisotropic Boundary Layer, In *Optical waves and laser beams in the irregular atmosphere*, 2nd edn; Blaunshtein N., Kopeika N, (Boca Raton, Taylor & Francis Group, CRC Press: London, New York, USA). 2018; Chap. 3. 67–180.
39. Nosov V V, Lukin V P, Kovadlom P G, Nosov E V, Torgaev A V, *Optical properties of turbulence in the mountainous boundary layer of the atmosphere*, (Novosibirsk: Publishing House of SB RAS), 2016, p 153.
40. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Grigoriev V M, Kovadlo P G, Coherent structures in the turbulent atmosphere, In *Mathematical Models of Non-linear Phenomena, Processes and Systems: From Molecular Scale to Planetary Atmosphere,* 3rd edn; Nadicto A B, Uvarova L A, Latyshev, A V, (Nova Science Publishers: N Y, USA), 2013; Chap 20, pp 297–330.
41. Nosov V V, Grigoriev V M, Kovadlo P G, Lukin V P, Nosov E V, Torgaev A V, Astroclimate of specialized stations of the Large Solar Vacuum Telescope: Part I. Part II. *Proc. SPIE* 2008. *6936*, 69360P, 69360Q.
42. Inhomogeneously Heated Surfaces. In Nonlinearity: Problems, Solutions and Applications, 3rd edn; Uvarova L A, Nadicto A B, Latyshev A V, (Nova Science Publishers: N Y, USA), 2017; Vol 1, Chap 17, pp 335–412.
43. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Grigoriev V M, Kovadlo P G, Coherent structures in turbulent atmosphere, Proc SPIE, 2009. 7296. 729609.
44. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Turbulence Structure over Heated Surfaces: Numerical Solutions, *Atmos Ocean Opt*, 29(2016)234–243.
45. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, A V Kolmogorov's and coherent turbulence in the atmosphere, Imaging and Applied Optics 2019. OSA 2019. *Paper PM3C.3*.
46. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Afanas'ev V L, Balega Y U, Vlasyuk V V, Panchuk V E, Yakopov G V, Astroclimate Studies in the Special Astrophysical Observatory of the Russian Academy of Sciences, *Atmos Ocean Opt*, 32(2019)8–18.
47. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Representation of the synoptic spectra of atmospheric turbulence by sums of spectra of coherent structures, IOP Conference Series: Earth and Environmental Science (*EES*), 2019.231. No 012040. 1–7.
48. Nosov V V, Lukin V P,Torgaev A V, Kovadlo P G, Atmospheric coherent turbulence, *Atmos Ocean Opt*, 26(2013)201–206.
49. Nosov V V, Grigoriev V M, Kovadlo P G, Lukin V P, Nosov E V, Torgaev A V, Intermittency of the astronomical images jitter in the high-mountain observations, Proc SPIE, 9292OV(2014); doi.org/10.1117/12.2074614.
50. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, The effect of intermittency of astronomical images in the high-altitude observations, *Imaging and Applied Optics. 2019. OSA* 2019. *Paper JW2A.36*; doi.org/10.1364/COSI.2019. JW2A.36.
51. Brandt P N, Mauter H A, Smartt R, Day-time seeing statistics at Sacramento Peak Observatory, *Astron Astrophys*, 188(1987)163–168.
52. Nosov V V, Lukin V P, Nosov E V, Torgaev A V, Measurement of atmospheric turbulence characteristics by the ultrasonic anemometer and the calibration processes, *Atmosphere,* 10(2019)460; doi.org/10.3390/atmos10080460.

53. Azbukin A A, Bogushevich A Y, Lukin V P, Nosov V V, Nosov E V, Torgaev A V, Hardware-Software Complex for Studying the Structure of the Fields of Temperature and Turbulent Wind Fluctuations, *Atmos Ocean Opt*, 5(2018)479–485.

[*Received*: 04.07.2023; *accepted*: 03.08.2023]



Vladimir P Lukin

Vladimir P Lukin is currently Head of Laboratory of Coherent and Adaptive Optics in Institute of Atmospheric Optics (Siberian Branch of Russian Academy of Sciences, Tomsk) and part-time Professor in Tomsk State University. His principal field of work was application analysis, stochastic field theory and problems of electromagnetic waves propagation. His principal contributions are currently in theory adaptive optical systems and phase optical wave fluctuations for in atmospheric turbulence propagation, design and algorithms of optical wave photometer, sounding of characteristics of atmospheric turbulence using optical waves, investigation of foundations of atmospheric adaptive optics systems design. He has received a number of awards; Medal "For Merit to Country" II degree, 1999, International Galileo Galilei Award and medal, **2000**, Medal by S P Korolev, **2001**, Medal “For Merit to Tomsk State University”, **2006**, was Elected SPIE Fellow, **2004**, and OSA Fellow, 2005.

Victor V Nosov graduated from Tomsk State University, Russia, and his specialties are radiophysics and optics. Since 1972, he has worked at the V E Zuev Institute of Atmospheric Optics SB RAS. He obtained Ph D in 1978 and doctor of science in 2010. He is the author of more than 630 publications, including ten books and more than 100 papers in peer-reviewed Russian and international journals. His research interests include radiophysics, optics of the atmosphere and ocean, theory of turbulence, and mathematical physics.e mail: nosov@iao.ru

Andrey V Torgaev graduated from Tomsk State University, Russia, and his specialties are physics. Since 1988, he has worked at the V E Zuev Institute of Atmospheric Optics SB RAS. He obtained Ph D in 2013 in optics. He is the author of more than 350 publications, including four books and more than 60 papers in peer-reviewed Russian and international journals. His research interests include optics of the atmosphere and ocean, physics of atmospheric turbulence, astroclimate.e mail: torgaev@iao.ru

Evgeny V Nosov graduated from Tomsk State University, Russia, and his specialties are radiophysics and optics. Since 1995, he has worked at the V E Zuev Institute of Atmospheric Optics SB RAS. He obtained Ph D in 2019. He is the author of more than 300 publications, including 4 books and more than 60 papers in peer-reviewed Russian and international journals. His research interests include radiophysics, optics of the atmosphere and ocean, theory of turbulence, physics of atmospheric turbulence and astroclimate. e mail: nev@iao.ru