Estimations of the effects of the middle atmosphere on the transmission of a high-power laser beam. Part 2. Beam distortions caused by isotropic and stratified inhomogeneities

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The effect of isotropic and anisotropic components of a random field of the refractive index on beam propagation is analyzed. To estimate the effect of isotropic component, the Kolmogorov turbulence model is used for altitudes between 10 and 20 km, and for altitudes of 20 to 50 km we use a two-component model of the 3D spectrum of refractive index fluctuations in the stratosphere developed based on occultation observations of stellar scintillations from orbiting stations. The effect of inhomogeneities on laser beam parameters is estimated analytically. The estimates obtained show that Kolmogorov turbulence is one of the major factors restricting the possibilities of Laser Orbital Transfer Vehicle (LOTV) concept. Propagation of laser radiation is simulated numerically for preset paths with the use of phase screen models. For numerical simulation of phase screens, the method of modeling stochastic fields with a wide spatial spectrum of inhomogeneities is applied.

Introduction

It should be expected that among the major factors restricting laser energy transfer to a Laser Orbital Transfer Vehicle (LOTV)[1] the most significant are broadening and wandering of the laser beam due to random inhomogeneities of the refractive index of air. In this paper we consider the effect of atmospheric turbulence on the efficiency of laser beam energy transfer under conditions (beam parameters, experimental geometry, dimensions of the transmitting and receiving apertures, etc.) determined by the LOTV concept.[1] In particular, it is assumed that the laser source is installed aboard a flying platform, whose flight altitude varies from 10 to 15 km. Therefore, in developing the model of inhomogeneities of the air refractive index, we restricted our consideration to the altitude range of 10–50 km (the effect of higher atmospheric layers can be neglected). The estimates of the efficiency of the laser beam energy transfer were based on calculation of the turbulent beam broadening averaged over rather long periods (long-exposure broadening). Random distortions of the beam energy centroid contribute significantly to the long-exposure broadening.[2,3] In developing the model of inhomogeneities of the air refractive index, it was accepted that in the middle atmosphere there are two types of inhomogeneities: isotropic inhomogeneities caused by Kolmogorov turbulence[4] and strongly anisotropic ones with a 1D vertical spectrum described by the model of saturated internal gravity waves (IGW).[5–7] Manifestations of these types of inhomogeneities were detected in observations of stellar scintillations from Mir space station,[8–12] from radiosonde temperature measurements,[13,14] and from radar[15] and other measurements.

1. Model of 3D spectrum of the refractive index inhomogeneities

For consideration of light propagation through randomly inhomogeneous media, it is necessary to specify the 3D spectrum Φ_n of fluctuations of the refractive index n (Ref. 3). Following Refs. 12 and 16, we take the spectrum Φ_n in the form

$$\Phi_n(\kappa_1,\kappa_2,\kappa_3;h) = C^2(h)\eta^2\left(\kappa_1^2+\eta^2\left(\kappa_2^2+\kappa_3^2\right)+\kappa_0^2\right)^{-\mu/2}\times$$
$$\times\exp\left(-\frac{\kappa_1^2+\eta^2\left(\kappa_2^2+\kappa_3^2\right)}{\kappa_m^2}\right), \quad (1)$$

where κ_1 is the vertical wave number, and κ_2 and κ_3 are the horizontal wave numbers; h is the height measured from the ground that serves a parameter in this case; $C^2(h)$ is the coefficient characterizing the vertical dependence of the intensity of the refractive index fluctuations; η is the anisotropy coefficient, which is determined as a ratio of characteristic horizontal scales of inhomogeneities to the vertical ones; μ is the exponent (slope) of the spectrum within the range of power-law behavior. The characteristic wave numbers

κ_0 and κ_m determine the vertical scales, at which the spectrum deviates from the power-law dependence, namely, κ_0 is associated with the inner scale of the inhomogeneities $L_0 = 2\pi/\kappa_0$ and determines the spectrum saturation in the range of large scales, while κ_m specifies the boundary of the small-scale range of the spectrum, which is determined by dissipation (molecular dissipation for the model of isotropic turbulence[3] and eddy dissipation for saturated IGW[17]).

To pass on to the model of the 3D spectrum of the Kolmogorov isotropic turbulence $\Phi_n^K(\kappa)$ (where $\kappa = \sqrt{\kappa_1^2 + \kappa_2^2 + \kappa_3^2}$ is the absolute value of the spatial wave number), in Eq. (1) we should take: $\mu = 11/3$, $\eta = 1$, and $C^2 = 0.033C_n^2$, where C_n^2 is the structure characteristic of the refractive index fluctuations.[3]

For anisotropic inhomogeneities, assuming their statistical symmetry about the local vertical, within the model of saturated IGW we can formally write the equation for the 3D spectrum Φ_n^g in the form (1) as well.[7,12,16] In this case, we should assume $\mu = 5$, $\eta >> 1$, and define the coefficient C^2 characterizing the intensity of refractive index fluctuations as

$$C_g^2 = AN^2 3\varpi_{B-V}^4/(4\pi g^2).$$

Here A is a numerical coefficient, N is the refractive index, ϖ_{B-V} is the Brunt-Vaisala frequency, g is the acceleration due to gravity. In the theory of saturated IGW, the recommended[4,6] value of A is 0.1 for the one-sided ($\kappa_1 > 0$) vertical spectrum. On the average, this value agrees with the experimental data.[8,9,12,14] The anisotropy coefficient of inhomogeneities is assumed constant all over the wave number ranges and in the selected vertical range and is equal to $\eta = 150$ (Refs. 8 and 9). To analyze the dependence of the anisotropy coefficient on the scale of inhomogeneities and the height, further investigations are needed.

For each component of the inhomogeneities, the spectrum (1), even at a given values of μ and η, includes three parameters: C_n^2, L_0, and l_0. They all depend on the height h, season, geographic latitude, etc. The experimental data available now for the upper troposphere and stratosphere are insufficient to draw these dependences even for mean vertical profiles.

The most important parameter of the Kolmogorov turbulence influencing laser beam propagation in the atmosphere is the vertical profile of C_n^2. In the altitude range of 10–20 km, we use the model of this characteristic described in Ref. 18 and based on numerous experimental data. Keeping in mind wide spread of the available data,[18] we present three versions of the vertical profile of C_n^2 for turbulence with high, moderate, and low intensity. This classification is convenient for estimation, and we will use it from here on.

In the altitude range of 20–50 km, we used the results of restoration of the structure characteristic of temperature fluctuations C_T^2 from data on stellar scintillation taken from Ref. 9. The most poorly investigated parameters in this case are the inner and outer scales of turbulence. To estimate the vertical profile of the inner scale in the range of 10–20 km, the data on the dissipation rate of the kinetic turbulent energy obtained from radar measurements[19] were used, and for the altitudes above 40 km we used the experimental data on stellar scintillations.[10] For intermediate altitudes, the dissipation rate was interpolated. The inner scale increased from 2 cm at the altitude of 10 km to 3.2 m at the altitude of 50 km. To estimate the outer scale, we took $L_0 = 0.3$ km all over the altitude range taking into account the estimated vertical dimensions of turbulized atmospheric layers forming the radar return signal (see, for example, Ref. 20).

Analysis of new data on stellar scintillations[12,21] shows that these estimates should be likely corrected toward increase of the inner scale of turbulence and decrease of the outer one at the altitudes of 25–35 km. Note that random laser beam displacements for the model of the Kolmogorov turbulence are largely determined by inhomogeneities with the scales comparable with the beam diameter.[2] If it is much smaller than the outer scale and much larger than the inner scale, then the role of these scales in the problem under consideration is insignificant. In the first approximation, this circumstance allows us to restrict the consideration to the accepted estimates of the inner and outer scales of Kolmogorov turbulence.

Besides, since of particular interest in this problem are the integral characteristics of turbulence averaged over wide altitude and time intervals, the model presented ignores parameters of intermittence characteristic of the Kolmogorov turbulence in the middle atmosphere. (The spread of C_n^2 values due to intermittence is partly taken into account in the spread of data for models with different level of turbulence). The vertical profiles of the structure characteristic $C_n^2(h)$, which were obtained by use of the approximation described, are shown in Fig. 1. As can be seen from Fig. 1, the ratio of the structure characteristic under conditions of strong and weak Kolmogorov turbulence reaches tens.

When drawing the vertical profiles of $C_g^2(h)$, for anisotropic inhomogeneities it was taken that the mean value of the constant A is 0.1, and the data spread at a fixed height due to seasonal and latitudinal variations, orography, etc. falls roughly within one order of magnitude according to data of radiosonde measurements[14,15] and stellar scintillation observations.[8,9,12] This estimate of the spread may prove underestimated and calls for refinement based on new experimental data. Analysis of stellar scintillation observations[9,12,21] shows that the eddy scale of anisotropic inhomogeneities increases roughly from ten to hundred meters in the altitude range from 25 to 50 km. Taking into account that for random laser beam displacements caused by anisotropic inhomogeneities the role of the inner scale is insignificant, we estimated it as 50 m all over the altitude range. Unlike the inner scale, the outer one in the model of anisotropic inhomogeneities is one of the main parameters determining random beam wanderings.[3] Unfortunately, this parameter is investigated most poorly. Based on the theoretical models of saturated IGW,[6] sonde measurements of temperature fluctuations,[15] and phase fluctuations at radio sounding,[22] we estimated the outer scale as 2.5 km all over the altitude range. The incorrectness in determination of the outer scale and the method of its introduction into spectrum (1) in this problem is partly justified by the fact that, as calculations show, the role of anisotropic inhomogeneities becomes significant only for close-to-horizontal paths, but such paths are inefficient from the energy point of view and because of other factors, and therefore they should be avoided in realization of the LOTV concept.

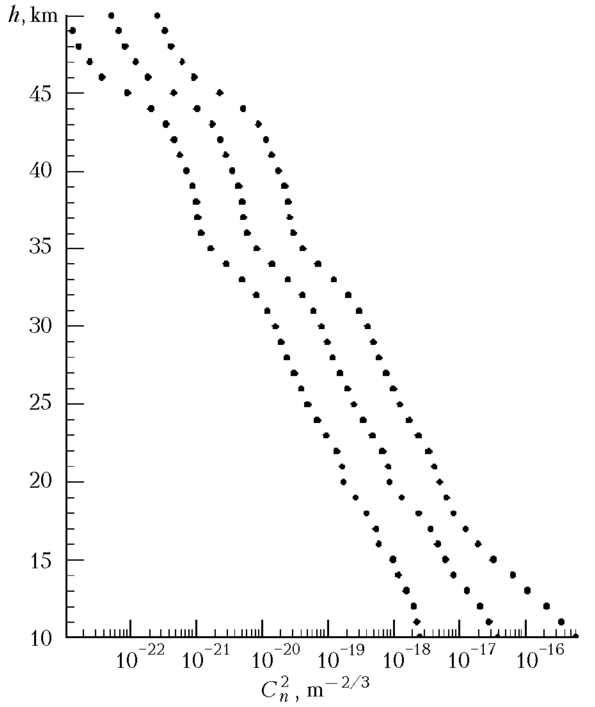

Fig. 1. Vertical profiles of the structure characteristic of the refractive index fluctuations in the model of Kolmogorov turbulence under conditions of strong, moderate, and weak turbulence.

It should be emphasized that the presented models of the Kolmogorov turbulence and anisotropic inhomogeneities are of tentative character. This is connected, in the first turn, with lacking detailed information on the structure of inhomogeneities and their statistical characteristics in the middle atmosphere. The seasonal and latitudinal variability of structure characteristics, as well as the vertical behavior of characteristic scales and the anisotropy coefficient of inhomogeneities is ignored in our models. The possibility of using the selected parameters for this particular problem was considered separately. The concepts of the models of inhomogeneities in the middle atmosphere, values of the parameters and their spread should be refined in accordance with the new experimental data.

2. Analytical estimates of the laser beam broadening

The effect of turbulence was estimated analytically for an axisymmetric beam with the initial Gaussian field distribution. The initial beam radius was taken equal to 0.75 m, the radius of the receiving aperture was 2.25 m, the source height was taken equal to 10 and 15 km, and the zenith angle θ varied from 0 to 90°. For the point of location of the receiving aperture, we calculated the diffraction R_d and the total effective R_eff beam radii. The latter one was determined through the intensity on the beam axis provided that the total energy of the laser beam is constant. The efficiency (fraction) of energy transfer was determined as an area ratio of the receiving aperture to the cross section of the beam incident on the aperture in the case that the receiving aperture is smaller than the beam cross section. All the equations needed for calculation can be found in Ref. 2 (for isotropic turbulence) and in Ref. 3 (for anisotropic stratified inhomogeneities).

Figure 2 depicts the estimated effective beam size and energy transfer efficiency for the model of Kolmogorov turbulence.

It can be seen from Fig. 2 that for the source height of 10 km (left) with the zenith angle θ = 0–45° the effective beam radius doubles as compared to the diffraction one, if the satellite height is 20000–10000 km in the case of moderate turbulence and 4000–2500 km in the case of strong turbulence. At the zenith angle θ = 70° this condition is fulfilled at the satellite height of 4000 km in the case of moderate turbulence and 1000 km in the case of strong turbulence. Weak turbulence gives no significant contribution for the angles θ = 0–45° at the heights lower 40000 km and for θ = 70° at the heights lower 20000 km. If the source is lifted to 15 km (right), turbulent effects decrease markedly. In particular, for the moderate turbulence the beam is doubled in size as compared to the diffraction one at the heights of 36000 and 15000 km for the zenith angles θ equal to 45 and 70°, respectively.

For the source height of 10 km and the zenith angle θ = 70°, the receiving mirror of a given radius receives, on the average, about 10% of the initial beam power at the satellite heights of 10000, 3000, and 500 km, respectively, for weak, moderate, and strong turbulence. At the source height equal to 15 km, the corresponding satellite heights are 20000, 8000, and 3000 km. The figures generally show that turbulent effects increase quickly with the increase of the zenith angle θ > 60–70°.

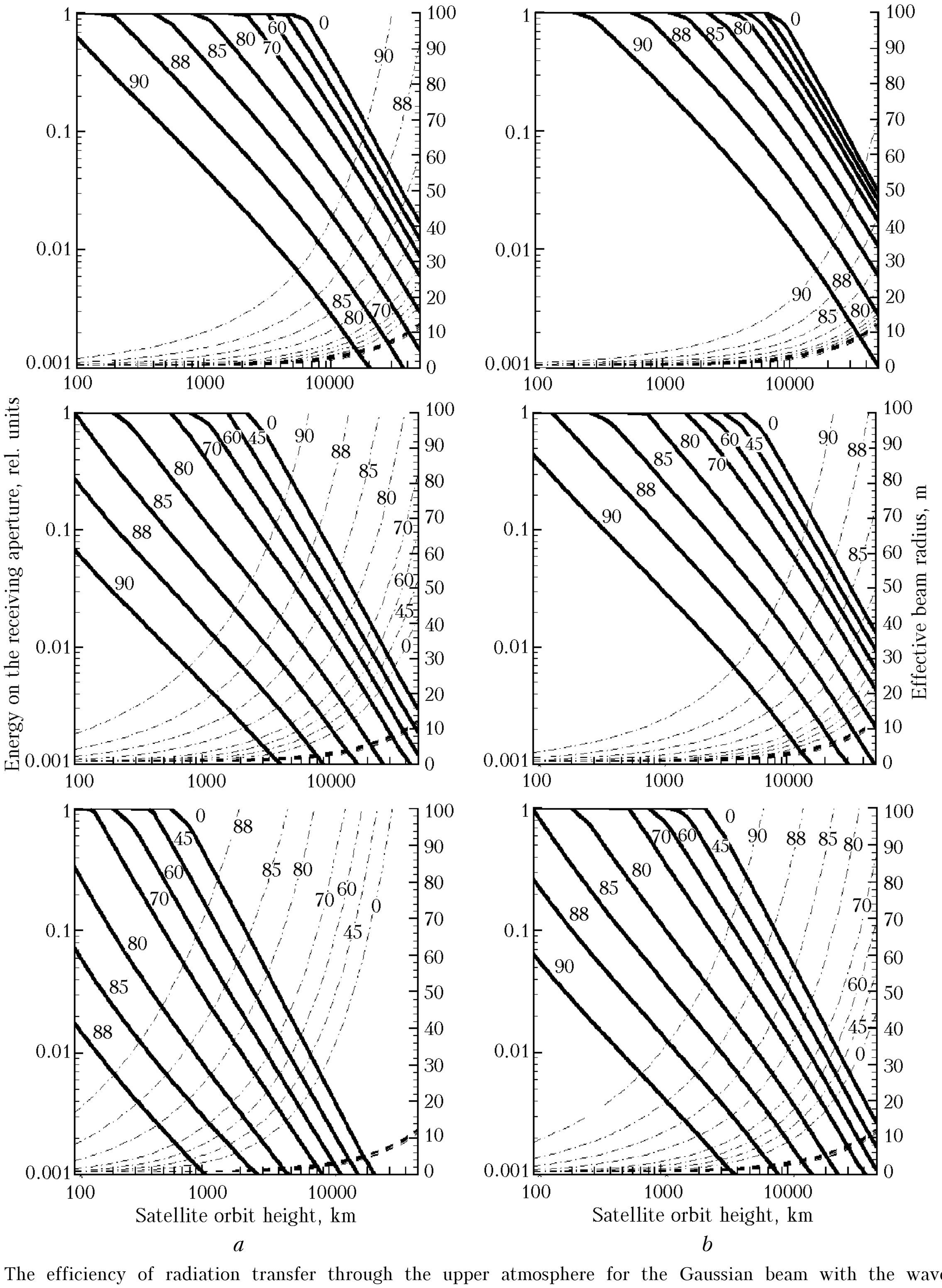

Fig. 2. The efficiency of radiation transfer through the upper atmosphere for the Gaussian beam with the wavelength $\lambda = 1.06$ μm and diameter of 1.5 m for the best, moderate, and worst turbulent conditions at two source heights of 10 (*a*) and 15 (*b*) km and different values of the zenith angle: analytical estimates of energy on the receiving aperture with the radius of 1.5 m (solid line) and analytical estimates of the effective beam radius (dashed line).

The calculations show that the use of radiation with 0.53 μm wavelength leads to both a decrease in the diffraction broadening and to a stronger effect of turbulence. Under conditions of weak turbulence, use of 0.53-μm-wavelength radiation may provide for some gain in the energy transfer efficiency. Under moderate and strong turbulence, the transition to 0.53 μm wavelength either gives no gain or even decreases the energy transfer efficiency. However, it should be kept in mind that when systems compensating for random beam distortions are applied, the use of radiation with 0.53-μm wavelength can produce gain as compared to the case with 1.06-μm wavelength because of smaller diffraction broadening of the beam.

The effect of strongly anisotropic inhomogeneities, in addition to the effects of Kolmogorov turbulence, was analyzed in the following way. The presence of large-scale stratified inhomogeneities caused by saturated IGW leads to the situation that the beam broadened due to diffraction and Kolmogorov turbulence is additionally subjected to random displacements caused by refraction in the stratified inhomogeneities. Because of strong anisotropy of these inhomogeneities, the beam randomly wanders, mostly in the vertical direction. The rms values of the beam centroid displacements along the horizontal within the framework of the selected model are at least tens times smaller than those along the vertical. Asymptotic relations for the slant and tangent paths, for which the variance of horizontal and vertical random beam displacements was estimated, are given in Ref. 3. Assuming statistical independence of isotropic and anisotropic inhomogeneities, the effective beam size along the vertical can be estimated as a square root of the sum of squared beam dimensions caused by each component of the inhomogeneities.

The estimates show that anisotropic inhomogeneities, in addition to diffraction and Kolmogorov turbulence, lead to a marked decrease in the energy transfer efficiency at the zenith angles $\theta > 80°$. This is a consequence of strong anisotropy of stratified inhomogeneities: variance of vertical displacements increases at the zenith angles close to 90°. For the zenith angles, $\theta \le 70°$ the effect of the anisotropic component of atmospheric inhomogeneities can be neglected as compared with the effect of Kolmogorov turbulence. Taking into account that the effect of Kolmogorov turbulence increases fast as the path approaches the tangent one it is worth, as the estimates show, using in the experiments the zenith angles $\theta < 60$–$70°$.

3. Numerical estimates of beam propagation through turbulent atmosphere

The estimates presented in the previous section give an idea of the effect of turbulence on the mean beam characteristics, namely, its broadening and wandering. However important factors for generation of laser jet propulsion are not only the efficiency of energy transfer, but also the instantaneous distribution of the laser beam intensity over the aperture of the receiving collector. The almost unique method for prediction of the instantaneous distributions of the field of a laser beam after propagation through a turbulent medium is numerical simulation. Usually, numerical simulation for this purpose is performed using phase screens.

Simulation of phase screens in a wide range of spatial frequencies corresponding to the problem under consideration calls for special approach. For this purpose, we used the method of generation of a homogeneous random isotropic Gaussian field based on the combination of the spectral and modal approaches.[23] The stochastic field S in this case is represented by a sum of two (or more) statistically independent fields:

$$S(\boldsymbol{\rho}) = S_{H1}(\boldsymbol{\rho}) + S_{H2}(\boldsymbol{\rho}) + S_{H3}(\boldsymbol{\rho}) + \ldots + S_B(\boldsymbol{\rho}). \quad (2)$$

Every term of the sum corresponds to the phase distribution with its own correlation function and the characteristic scale of inhomogeneities, and their combination forms the phase field with the correlation function $B(\boldsymbol{\rho},\boldsymbol{\rho}')$ corresponding to the given spectrum.

The stochastic fields S_{Hi} corresponding to the first terms of this series are formed based on the modal approach through expansion over the Karhunen–Loeve–Obukhov functions, and they correspond to low-frequency and medium-frequency components of the field to be simulated. The field S_B is formed by the method of sliding average or the spectral method, and it corresponds to the high-frequency component.

The method of representing a random field as a set of random fields corresponding to contributions with different scales of inhomogeneities is useful for studying the effect of these contributions on the simulated processes, as well as for justifying and selecting methods of correcting for turbulent distortions. Using the presented models of turbulence (see Fig. 1) and the method of generation of phase screens simulating the turbulence, we have calculated propagation of a laser beam through the middle atmosphere that demonstrated the effect of turbulence on the beam intensity distribution. The capabilities of this approach involving the method of phase screen representation as a set of statistically independent random fields corresponding to contributions with different scales of inhomogeneities are demonstrated by the model of laser beam propagation through the atmosphere (Fig. 3).

Figure 3 depicts the calculated instantaneous intensity distributions in the far zone for the laser beam with the wavelength $\lambda = 0.53$ μm and a uniform initial distribution of the intensity over the beam aperture of 1.5 m in diameter. The first five columns of the first row show different realizations of the beam intensity distribution in the far zone after beam propagation through the phase screen corresponding to the first component S_{H1} of the combined phase screen (2). The second row shows different realizations after beam propagation through the screen corresponding to the first two components $S_{H1} + S_{H2}$, the third row corresponds to the three components $S_{H1} + S_{H2} + S_{H3}$,

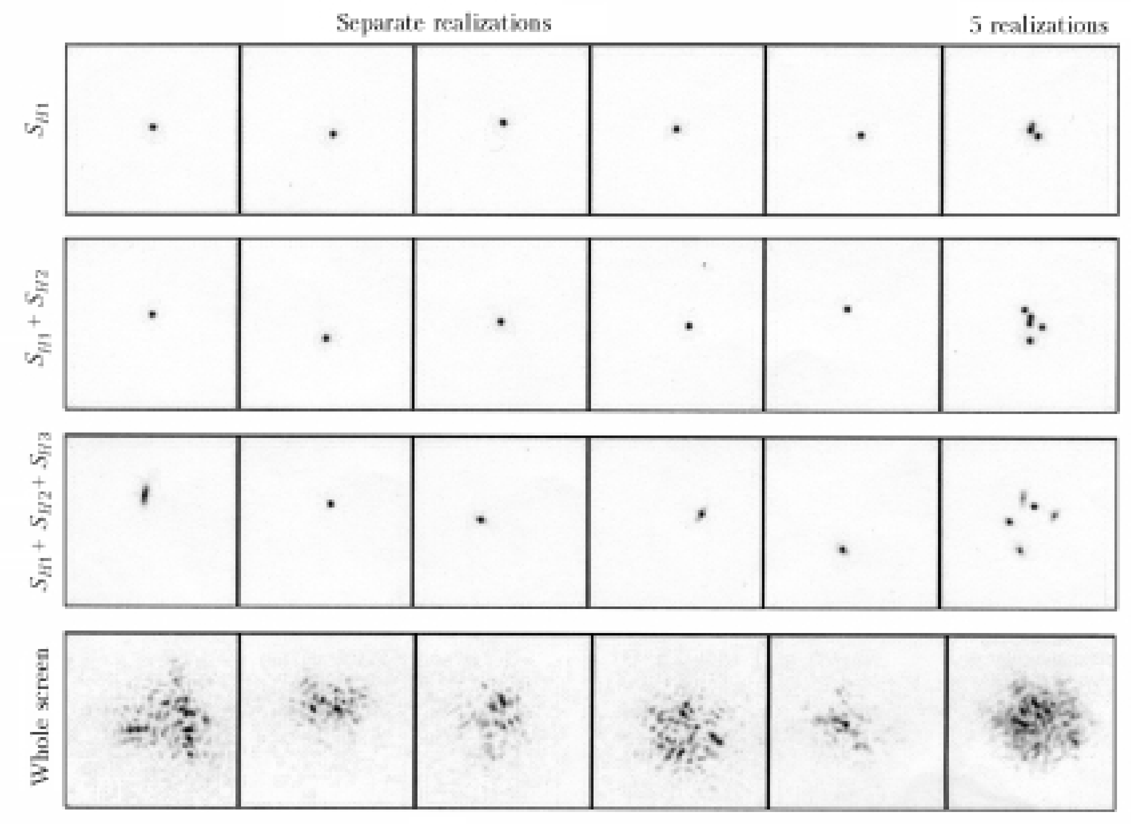

Fig. 3. Intensity distributions of the beam with almost uniform (super-Gaussian) initial distribution, diameter of 1.5 m, and λ = 0.53 μm caused by the effect of different components of a screen simulating atmospheric layer 1 km thick at the height of 15 km. Square side is 12 μrad (Kolmogorov spectrum with parameters l_0 = 0.017 m, L_0 = 300 m, $C_n^2 = 6 \cdot 10^{-16}$ m$^{-2/3}$).

and, finally, the fourth row demonstrates the effect of the combined screen as a whole. The right column presents the five realizations all together, rather than the displacement of the beam as a whole.

It can be seen that the first two components of the phase screen S_{H1} and S_{H2} simulate atmospheric distortions of the wedge type that lead to displacement of the beam as a whole, while the third component S_{H3} simulates the effect of either focusing or defocusing lenses with small aberrations. The component S_B simulating the small-scale part of atmospheric inhomogeneities leads to appearance of speckles and broadening of the beam as a whole.

The presented turbulence and phase screen models were used for calculation of the laser beam propagation through the upper atmosphere simulating the effect of turbulence on the distribution of complex amplitude of the beam. Figure 4 depicts the calculated instantaneous intensity distributions in the far zone for the laser beam of 1.5 m in diameter with the initial Gaussian intensity distribution and the wavelength λ = 1.06 μm for moderate and worst turbulent conditions. For a comparison, Fig. 4 also depicts the intensity distribution obtained by averaging over 2000 realizations of instantaneous intensity distributions. Besides, for each intensity distribution, Fig. 4 gives the fraction of the beam energy falling within a target circle of 2.25 m in radius. The source was at the height of 3000 km. Similar results for the near zone (distance of 300 km) are depicted in Fig. 5.

These results demonstrate that the beam intensity distribution in the receiving mirror has a complex structure. It is important to note that in every realization, the beam center displacement determined by large-scale inhomogeneities and the size of the beam, as a whole, determined by the diffraction at small-scale inhomogeneities are roughly equal. This circumstance allows us to conclude that to correct turbulent distortions with adaptive systems, the correction of only random beam wandering may prove to be insufficient.

We have compared the estimates of the energy transfer efficiency obtained by two methods: numerical simulation with the following averaging over 2000 realizations and analytical calculation. The estimates were obtained for the model of Kolmogorov turbulence at the radiation wavelength of 1.06 μm and the source height of 10 and 15 km for the cases of moderate and worst turbulent conditions. Figure 6 depicts these estimates for different distances to the receiver. The difference in the estimates is noticeable only for the source height of 10 km under the worst turbulent conditions.

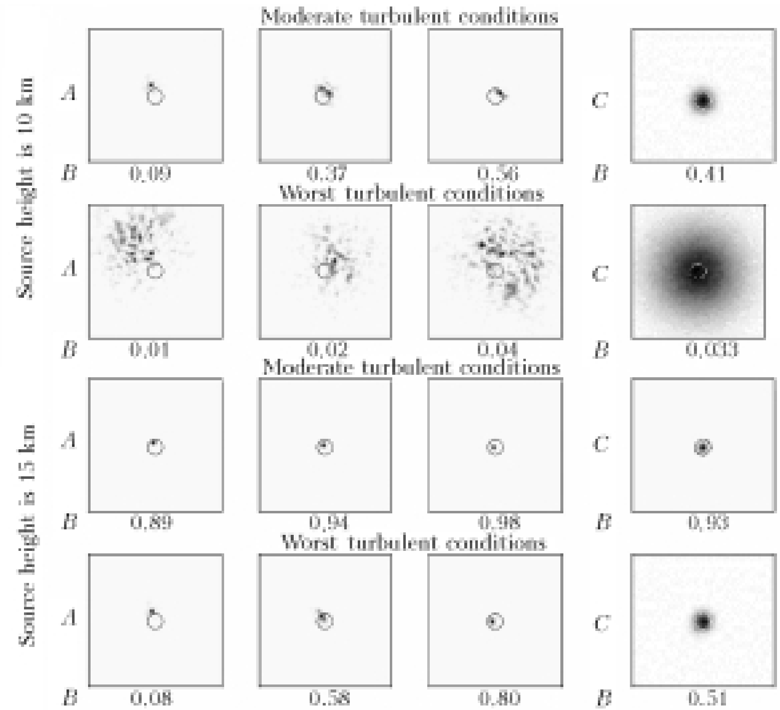

Fig. 4. Numerical simulation of the intensity distribution of the beam of 1.5 m in diameter with λ = 1.06 μm and the initial Gaussian distribution in the far zone (distance of 3000 km); the source height of 10 and 15 km; the circle stands for the receiver 2.25 m in radius: single realizations of the intensity distribution (*A*), percentage of energy falling within a circle with the radius of 2.25 m (*B*), the intensity distribution averaged over 2000 realizations (*C*).

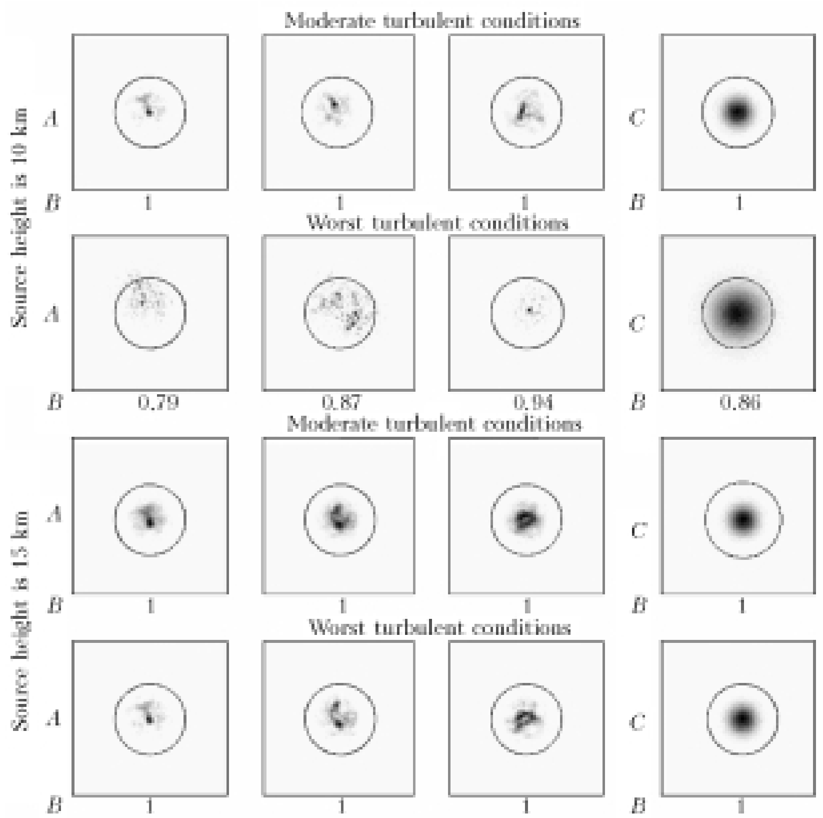

Fig. 5. Numerical simulation of the intensity distribution of the beam of 1.5 m in diameter with λ = 1.06 μm and the initial Gaussian distribution in the near zone (distance of 300 km); the source height of 10 and 15 km; the circle stands for the receiver 2.25 m in radius: single realizations of the intensity distribution (*A*), percentage of energy falling within a circle with the radius 2.25 m (*B*), the intensity distribution averaged over 2000 realizations (*C*).

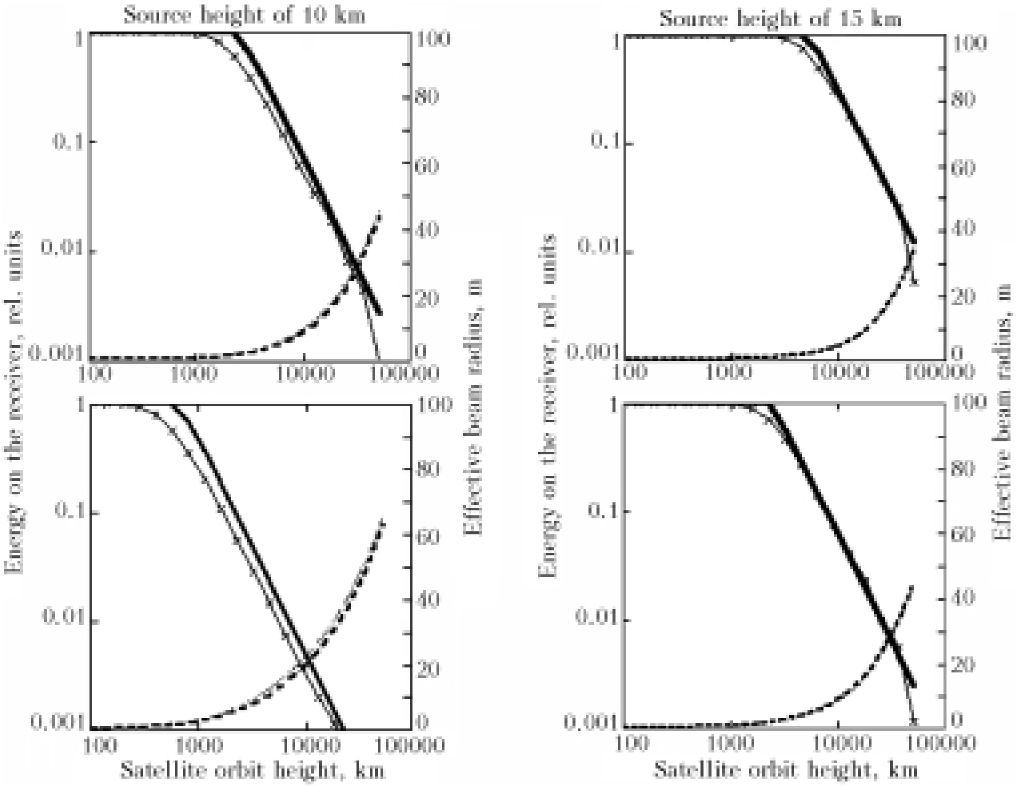

Fig. 6. Comparison of analytical and numerical estimates of the efficiency of energy transfer through the upper atmosphere for a Gaussian beam with the wavelength λ = 1.06 μm and diameter of 1.5 m under moderate (top) and worst (bottom) turbulent conditions at the zero zenith angle. The number of realizations averaged in numerical simulation was 2000: analytical (———) and numerical (-x-x-) estimate of the energy on the receiver 2.25 m in radius; analytical estimate of the effective beam radius (– –) and numerical estimate of the effective beam radius (······).

Conclusion

To estimate the effect of turbulence in the upper troposphere and stratosphere on laser radiation characteristics, the models of random inhomogeneities of the air refractive index in the height range of 10–50 km are considered. These models include two types of inhomogeneities: isotropic ones caused by Kolmogorov turbulence and strongly anisotropic inhomogeneities with the 1D vertical spectrum described by the theory of saturated internal gravity waves. It is worthy to remind that parameters of the turbulence models developed have been obtained from the experimental data available. At the same time, these experimental data are obviously insufficient for estimation of all parameters with the accuracy needed. This applies to both their mean values and, especially, to their spread caused by latitudinal, meridional, and seasonal variability, surface features, and other factors. The models themselves and the values of all their parameters call for further refinement and revision based on new experimental data as soon as they will become available. For this purpose, the Institute of Atmospheric Physics RAS is now developing a more detailed model of the 3D spectrum of random inhomogeneities of the refractive index in the stratosphere, which, in particular, will include all data on the stellar scintillations observed from Mir space station.[12,21]

Nevertheless, the models already developed give an insight into the main effects associated with the influence of tropospheric and stratospheric turbulence on the efficiency of laser energy transfer from a laser source located at the altitude of 10–15 km to a space vehicle as it moves from a low orbit to a geostationary one. The estimates obtained showed that the effects of broadening of beams with the wavelengths of 1.06 and 0.53 μm due to fluctuations of the air refractive index are among the main factors determining the feasibility of laser energy transfer from a laser to an orbiting platform. These estimates can form the basis for selection of the optimal parameters (zenith angle, source height, direction and speed of the source movement, effective radiation transfer time) of the optical path at different parts of the satellite speedup trajectory. It was shown that for the zenith angles $\theta < 70°$ the main influence is due to Kolmogorov turbulence, while the additional effect of anisotropic inhomogeneities becomes significant for paths with the zenith angles close to 90°. Turbulent effects become much weaker as the source height increases up to 15 km. For effective transfer of the laser beam energy it is worth using the zenith angles $\theta < 60$–$70°$.

Acknowledgments

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