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The efficiency of propagation of radiation from different lasers through the turbulent Earth's atmosphere

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***Abstract*. A simplified model of the propagation of intense laser beams in the turbulent Earth's atmosphere along horizontal and inclined paths is improved. The model takes into account the basic mechanisms of interaction of laser radiation with the Earth's atmosphere (molecular absorption, aerosol extinction, turbulence-induced beam spreading and wander). The application of this model demonstrates a general approach to determining the optimal radiation wavelengths for attaining the maximum intensity of focused laser radiation at a stationary object depending on the path length, angle of the path inclination, weather conditions, and diameter of the laser output beam. A simple physical interpretation of the dependences obtained is presented. The efficiencies of propagation of various high-power laser beams through the turbulent Earth's atmosphere are compared. Specific features of the energy transfer from various lasers to moving objects are analysed. It is shown that, when weather conditions change over a wide range, it is expedient to use radiation from a cw chemical DF laser.**

Keywords: *turbulent atmosphere, radiation propagation in the atmosphere, radiation absorption and radiation attenuation by aerosols.*

1. Introduction

A great contribution of N.G. Basov and coworkers to the development and investigations of a number of high-energy cw and pulsed lasers is well known. An important trend in the application of such lasers is associated with a laser energy transfer through the Earth's atmosphere over long enough distances (> 1 km) to various objects, which are located near the Earth's surface or in the air at altitudes of up to a few kilometres. This is necessary, for example, for remote cutting of materials on dangerous objects in an emergency, for protecting important objects, attacking the eyesight and navigation instruments of terrorists on aircrafts, etc. The complexity of this problem is confirmed by the ever-continuing discussion as to what laser is best suited for these purposes.

The uncertainty of the laser choice is determined by the existence of several mechanisms of the interaction of laser radiation with the near-surface Earth's atmosphere rather than a single one and also by a change in the weather conditions over a wide range. Two methods can be used to calculate the efficiency of transmission of various laser beams through the atmosphere. The first one takes into account nonlinear effects of the interaction of intense radiation with the atmosphere, which are caused by heating of the atmosphere upon absorption of laser radiation and lead to changes in the beam propagation trajectory and in its cross-sectional profile [1]. In this case, rather cumbersome numerical methods are used, in which the molecular absorption is calculated taking into account the absorption spectrum of the atmospheric molecules, their concentration, and the dependence of the molecular composition of the Earth's atmosphere on the altitude above the Earth's surface [2, 3]. These circumstances significantly complicate the comparison of the transmission efficiencies for different laser beams propagating through the atmosphere. Such a comparison can be performed only under some definite atmospheric conditions and particular paths, but this calculation method is virtually inapplicable in a general case. Using the other calculation technique based on the construction of simplified analytical models (e.g., [1, 4, 5]), it is believed that the problem may be solved in a general form, if we manage to obtain an analytic dependence of the laser radiation intensity in the far-field zone on the wavelength λ.

Here, we consider only linear mechanisms of the interaction of laser radiation with the atmosphere. The most important mechanisms are the molecular absorption (with the absorption coefficient $\alpha_{\rm ab}$) and the aerosol absorption and scattering (with the coefficient $\alpha_{\rm s}$), as well as a turbulence-induced spreading of the radiation pattern and a wander of the laser beam axis caused by turbulence. The Rayleigh molecular scattering at $\lambda > 1$ μm is small and usually neglected. When nonlinear effects of radiation–atmosphere interaction can be ignored, the averaged laser intensity in the focal spot is described by the expression

$$I(\lambda) \approx \frac{P_0}{[\theta(\lambda)F]^2}\exp[-\alpha_\lambda(\lambda)F], \qquad (1)$$

where $\alpha_\lambda = \alpha_{\rm ab} + \alpha_{\rm s}$ is the total attenuation coefficient per unit path length; F is the path length; and $\theta(\lambda)$ is the effective divergence of the laser beam.

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The influence of molecular absorption on the efficiency of the transmission of high-power laser beams through the atmosphere was studied in many papers [1–4, 6, 7]. Note that, if lasers on vibrational–rotational transitions are used (such as HF, CO, and CO_2 lasers), a low enough absorption during the beam propagation through the atmosphere is observed only for individual lines. Lasing on separate lines obtained using passive or active selection methods will surely reduce the output power of these lasers. Therefore, the possibility of using these lines for transmitting the laser energy through the atmosphere over large enough distances is questionable. A different situation takes place with the radiation of DF lasers, whose basic lasing lines are weakly absorbed by atmospheric molecules.

In contrast to the molecular absorption, the aerosol extinction due to absorption and scattering is not wavelength-selective but continuously changes with the wavelength [4, 7]. For example, the dependency of the aerosol extinction coefficient on λ in the region where the effect of water-vapour continuum is appreciable can be approximated to within a satisfactory accuracy by the analytic expression [7]

$$\alpha_s = 3.745 \times 10^{-5} \nu^{0.8543}, \quad (2)$$

where α_s and $\nu = 1/\lambda$ are measured in km^{-1} and in cm^{-1}, respectively. This formula is valid for a visibility distance of 23 km. When atmospheric conditions change, α_s changes approximately inversely proportional to the visibility range.

Table 1 lists the total extinction coefficients α_λ for radiation from different high-power lasers under various weather conditions. These data were obtained by processing the data from [1, 4, 7] and were used in calculations in this study. Note that only the lasing lines with high enough intensities and low losses during their transmission through the atmosphere were taken into account in the lasing spectra of CO and HF lasers. The data for overtone transitions in an HF laser are not presented in Table 1, because, as was shown in [1, 6], the extinction coefficient for this laser radiation virtually coincides with that of an I laser.

Table 1. Total extinction coefficients α_λ (in km^{-1}) for radiations of different high-power lasers in the near-surface Earth's atmosphere depending on the weather conditions (medium latitudes).

Laser	λ/μm	Clear (visibility of 23 km)		Hazy (visibility of 5 km)	
		Winter	Summer	Winter	Summer
$CO_2(P(20))$	10.591	0.115	0.404	0.191	0.48
$CO(P_4(15))$	4.989	0.075	0.237	0.215	0.377
$DF(P_2(8))$	3.8007	0.049	0.064	0.225	0.24
$HF(P_1(12))$	2.957	0.13	0.405	0.35	0.625
I	1.3152	0.10	0.12	0.50	0.52
Nd	1.06	0.11	0.11	0.55	0.55

The effect of turbulence on the spreading of a laser beam during its propagation along a horizontal path was evaluated in [4] for the case when the refractive index structure constant C_n^2, which takes into account this effect, was constant. In [5], such estimates were extended to inclined beam paths, when the parameter C_n^2 is not constant. Using the Kolmogorov theory of turbulence, the dependence of the structural temperature coefficient C_T^2 on the altitude h above the Earth's surface in the form $C_T^2 \sim T^2 h^{-4/3}$, and the expression $C_n^2 \sim (p/T^2)^2 C_T^2$ [8], we obtained a formula for the effective divergence of a laser beam at a level of 0.8 of the total radiation energy incident on an object [5]:

$$\theta(\lambda) = \Big\{ \Big[4.42(K\lambda/D)^{5/3} + 37.1\lambda^{-1/3} C_n^2(h_0) X_{eff} \Big]^{6/5} + 33 D^{-1/3} C_n^2(h_0) X_{eff} \Big\}^{1/2}, \quad (3)$$

where D is the radiating-aperture diameter; K is the optical quality of the output laser beam equal to the ratio of the actual beam divergence to its diffraction limit; $h_0 0$ is the altitude of the radiating aperture above the Earth's surface; and $X_{eff} = FW(\Delta h/h)$ is the effective length of the inclined path equal to the product of the actual focusing length F by a correction factor $W(\Delta h/h)$. The latter is described by the expression

$$W(\Delta h/h) = (1 - \Delta h/h)^{4/3} \int_0^1 t^{5/3} (1 - t\Delta h/h)^{-4/3} dt - 2.15 \times 10^{-4} h_0 (\Delta h/h)(1 - \Delta h/h)^{1/3} \times \int_0^1 t^{5/3} (1 - t)(1 - t\Delta h/h)^{-4/3} dt,$$

where $\Delta h = h - h_0$. The first, second, and third terms in (3) are the contributions of the diffraction, turbulence-induced beam spreading, and beam-axis wander, respectively, to the effective divergence $\theta(\lambda)$. As was pointed out in [5], expression (3) is valid under rather limited conditions: at altitudes ranging from 5–50 m (depending on particular weather conditions) to 3–5 km and distances of up to 10–15 km. A stratification of the atmosphere was neglected, and all changes were assumed sufficiently continuous.

Note that expression (3) not only takes into account the inclination of the path but also represents the actual conditions for the radiation propagation more adequately than in works [1, 4], where, to simplify calculations, Gaussian beams with a theoretically infinite aperture were analysed, and a turbulence-induced beam-axis wander and the aerosol extinction as a function of λ were neglected in the determination of the maximum intensity $I_{max}(\lambda_{opt})$.

The aim of this study is to update the simplified model by taking into account these mechanisms of the interaction of laser beams with the atmosphere and analysing limited-aperture beams. The attention is predominantly paid to the propagation of laser beams with an average power of > 10 kW.

2. General approach to the determination of the optimal wavelength for transmission of laser beams through the turbulent Earth's atmosphere

Since the aerosol extinction is not wavelength-selective, a lower limit of the extinction coefficient, which cannot be reduced by selecting λ, exists for each multifrequency laser. Therefore, for lasers that are promising for transmitting the laser energy through the atmosphere, the molecular absorption must be low compared to the aerosol extinction $\alpha_{ab} \ll \alpha_s$.

As λ increases, the coefficient α_s [see (2)] and the turbulence-induced beam spreading [the second term in (3)] decrease, which, according to (1), must lead to an increase in $I(\lambda)$. At the same time, the diffraction-limited radiation divergence increases with increasing λ, which should cause a decrease in the intensity $I(\lambda)$. This may cause the existence of an optimal wavelength $\lambda_{\rm opt}$ at which the diffraction is still small enough, while the turbulence-induced beam spreading and aerosol extinction are not large. This fact was pointed out already in [4], where the dependence $I(\lambda)/I(\lambda_{\rm CO_2})$ exhibited a distinct maximum, whose position shifted to the red with decreasing the structural coefficient $C_{\rm n}^2$.

By substituting α_λ for $\alpha_{\rm s}(\lambda)$ in (1), differentiating (1) with respect to λ, and equating the derivative to zero, we obtain the equation for determining $\lambda_{\rm opt}$:

$$F\theta^2\frac{\partial\alpha_{\rm s}}{\partial\lambda}+\frac{\partial\theta^2(\lambda)}{\partial\lambda}=0. \qquad (4)$$

Such an optimisation is completely valid only at $\alpha_{\rm ab}\ll\alpha_{\rm s}$. This condition is satisfied for DF, I, and Nd laser radiations and also for the second harmonic of an HF laser.

Comparing the results of our calculations using formula (4) to the corresponding results of [4] for horizontal paths has shown that the type of dependence of $\lambda_{\rm opt}$ on $C_{\rm n}^2$ is the same in both cases, but the values of $\lambda_{\rm opt}$ significantly differ. This is explained by the fact that, in this work, the effects of various factors are taken into account more correctly. Figs 1 and 2 show the results of calculations according to (4). One can see from Fig. 1 that the optimal wavelength $\lambda_{\rm opt}$ rapidly increases with increasing $C_{\rm n}^2$ and the distance to the irradiated object. Thus, for a long enough horizontal path ($\sim$ 10 km) in a highly turbulent atmosphere ($C_{\rm n}^2 = 10^{-13}$ m$^{-2/3}$), the optimal wavelength is $\sim$ 10 μm. However, for long horizontal paths with a moderate turbulence ($C_{\rm n}^2 = 10^{-14}$ m$^{-2/3}$) and highly turbulent inclined paths, the optimal wavelengths are close to 4 – 5 μm. Such dependences are quite understandable, because, beginning with a certain value, a decrease in λ may lead to such a rapid increase in the aerosol extinction and radiation divergence due to the turbulence-induced beam spreading that, despite a decrease in the diffraction limit, the focused laser intensity falls.

The dependences shown in Fig. 2 can be explained similarly. The larger the diameter D of the radiating aperture, the smaller the contribution of diffraction to the effective divergence of the laser beam and the larger the wavelength, at which the turbulence term begins to prevail over the diffraction term. Therefore, as the diameter D increases at other factors being equal, $\lambda_{\rm opt}$ shifts to the red.

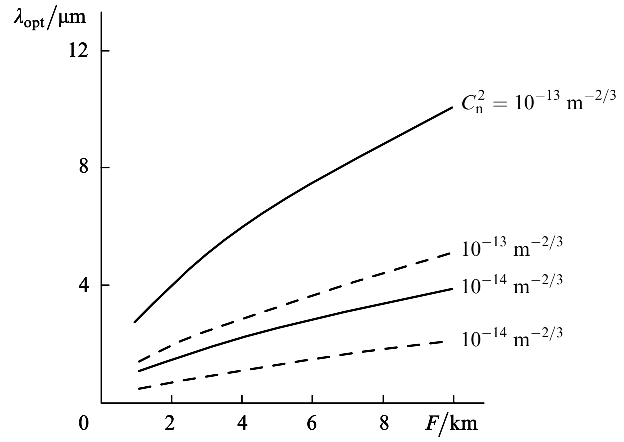

Figure 1. Dependences of $\lambda_{\rm opt}$ on the beam path length F at various $C_{\rm n}^2$ for horizontal (solid curves) and inclined (dashed curves, $h_0 = 5$ m, and $h = 100$ m) paths at $D = 0.8$ m, $K = 3$, and a visibility distance of 23 km.

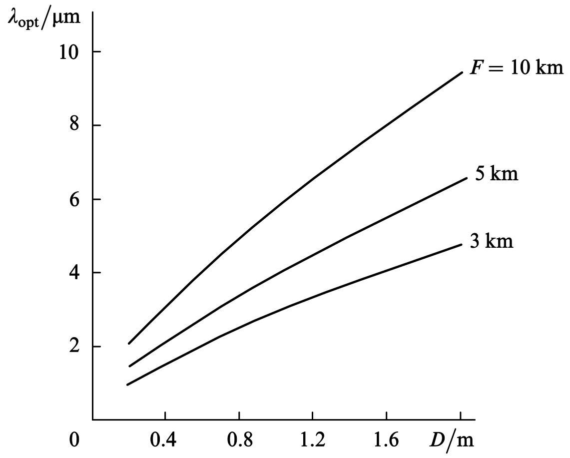

Figure 2. Dependences of $\lambda_{\rm opt}$ on the diameter of the radiating aperture D for an inclined path at $h = 100$ m, $h_0 = 5$ m, $C_{\rm n}^2(h_0) = 10^{-13}$ m$^{-2/3}$, $K = 3$, and a visibility distance of 23 km.

Let us make some refining comments. First of all, the results presented in Figs 1 and 2 cannot be extended to CO and CO_2 laser radiations, for which the majority of lasing lines are characterised by $\alpha_{\rm ab}\gtrsim\alpha_{\rm s}$. The data shown in Fig. 2 do not also permit us to assert that $D = 0.6$ m is the optimal diameter for a distance of 10 km and a wavelength of $\sim$ 4 μm, since Eqn (4) allows the intensity optimisation only in the wavelength with all the other parameters (F, $C_{\rm n}^2$, D, and $\alpha_{\rm s}$) being fixed. Moreover, analysis of expression (3) for $\theta(\lambda)$ shows that an increase in the diameter D leads to a decrease in the effective beam divergence in all cases. However, the slope of this dependence really changes and, beginning with a certain value, a further increase in D may become inefficient. This is confirmed by the curve plotted in Fig. 3.

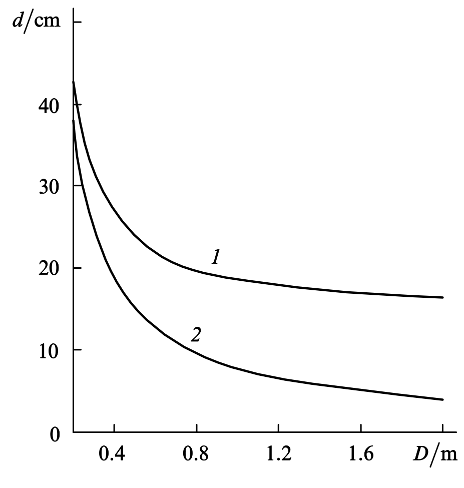

Figure 3. Diameter d of the focal spot of a DF laser beam as a function of the radiating aperture diameter D at a distance $F = 4$ km, $K = 2$, and $C_{\rm n}^2 = 10^{-14}$ m$^{-2/3}$ for (*1*) a horizontal path with $h_0 = 5$ m and (*2*) an inclined path at an angle of inclination to the horizon $\vartheta = 30°$.

3. Comparison of the efficiencies of propagation of different laser beams through the turbulent Earth's atmosphere

The relative intensities I/P_0 of radiations from different lasers focused at a stationary object were calculated from (1) (Fig. 4) taking into account for all the factors mentioned above, including molecular absorption, and fully confirmed the conclusion about a complex character of the effect of the laser wavelength on the efficiency of laser beam propagation through the turbulent atmosphere. As a result, depending on the path propagation conditions, the highest efficiency may belong to different lasers. The calculations were performed for the lasers with an average power of > 10 kW and radiation characterised by a low enough molecular absorption coefficient. These are DF, I, and Nd lasers. Because the wavelengths of the $P_{2-0}(3)$ and $P_{2-0}(4)$ overtone transitions of HF molecules and the laser transitions in I atoms are close to each other and the losses in this case are determined by the aerosol extinction, which is a smooth function of λ, the effective attenuation coefficients for these lasers and, consequently, their focused radiation intensities virtually coincide. Moreover, calculations have shown that the intensities of I and Nd lasers also have close values over the entire range of the variable parameters $C_{\rm n}^2$, Δh and $L = (F^2 - \Delta h^2)^{1/2}$. Therefore, Fig. 4 presents the calculated data only for DF and I lasers.

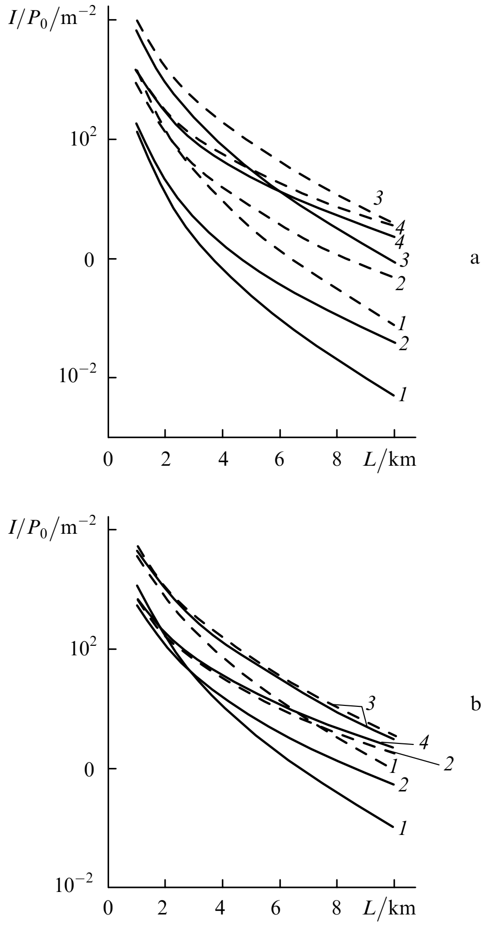

Figure 4. Relative intensity I/P_0 of the focused (*1*, *3*) I and (*2*, *4*) DF laser radiation as a function of the horizontal distance $L = (F^2 - \Delta h^2)^{1/2}$ to the irradiated object obtained at various weather conditions using adaptive systems (dashed curves) and without them (solid curves) for (a) horizontal paths and (b) inclined paths at a constant height difference ($h_0 = 5$ m, $h = 500$ m), a visibility distance of 7 km, $D = 1$ m, $K = 3$, $C_{\rm n}^2 = 10^{-13}$ (*1*, *2*) and 10^{-15} m$^{-2/3}$ (*3*, *4*).

To demonstrate the effect of using adaptive mirrors in the laser-beam formation, the introduction of adaptation was simulated by reducing the actual value of $C_{\rm n}^2$ by an order of magnitude. Note that the application of adaptive mirrors in the model considered has no effect either on the atmospheric absorption or on the aerosol extinction (scattering at angles much larger than the beam angular divergence is assumed). In this case, a compensation for the turbulence-induced beam spreading and beam-axis wander remains the basic mechanism for reducing the radiation divergence. In principle, this process can be simulated by a decrease in the constant $C_{\rm n}^2$. A more detailed quantitative description of the effects of using adaptive mirrors is beyond the scope of this study.

Typical weather conditions were chosen for the calculations: a visibility of 7 km and $C_{\rm n}^2(h_0) = 10^{-13}$ m$^{-2/3}$, which is characteristic of the atmosphere above the solid Earth's surface, and $C_{\rm n}^2(h_0) = 10^{-15}$ m$^{-2/3}$, which is characteristic of the atmosphere above sea. As follows from Fig. 4, the use of adaptive mirrors in the presence of a high atmospheric turbulence significantly (by almost an order of magnitude) enhances the object's irradiance. At a low turbulence, the effect of adaptive mirrors is noticeably lower. This especially applies well to inclined beam paths (Fig. 4b). For example, for I laser and $C_{\rm n}^2(h_0) = 10^{-15}$ m$^{-2/3}$, the curves obtained with and without adaptation are close to each other. The corresponding curves coincide for a DF laser. Hence, when a DF laser beam propagates above a sea surface, it is not obligatory to use adaptive systems for compensating for the turbulence-induced beam spreading. The explanation is rather simple. Adaptation helps to reduce the turbulence-induced beam spreading and, as long as it is large compared to the diffraction effect, its decrease leads to a significant reduction in the beam divergence and, consequently, to a higher object's irradiance. If the beam spreading due to the turbulence is inferior to the diffraction, the effect of using adaptive mirrors becomes insignificant or even negligibly small.

Here, we do not consider the problem of using adaptive mirrors to compensate for the wavefront aberrations, which are determined by thermal deformations in the elements of the optical system, jitter, etc., assuming that this refers to the laser design.

Thus, when selecting a laser for irradiating remote objects, it is necessary, if possible, to strictly determine the conditions for its application, including climatic and weather factors. Under favourable conditions (a long visibility distance and a low turbulence), short-wavelength lasers have an advantage (Fig. 1), since their wavelengths are closer to an optimal one. However, when laser radiation should be used over a wide range of environmental conditions, it is natural to consider the most unfavourable conditions. In this case, the DF laser radiation becomes more promising, which is clearly illustrated by the curves in Fig. 4a for $C_{\rm n}^2 = 10^{-13}$ m$^{-2/3}$ both with and without adaptation [curves (*2*) are higher than curves (*1*)]. The advantage of DF lasers for horizontal beam paths remains even at a low atmospheric turbulence and long distances of laser action [curves (*4*) are above curves (*3*) beginning with distances of $\sim 7 - 10$ km].

Fig. 5 helps to determine the range $r = (L^2 + h^2)^{1/2}$ of the action of a focused DF laser beam as a function of the beam inclination angle ϑ for $0 < \vartheta < 90°$. One can see that the laser-action range sharply decreases near horizontal paths at $\vartheta = 5 - 10°$. At larger inclination angles, the laser-action range is virtually independent of ϑ. As follows from Fig. 5, the intensities of focused radiation for paths with inclination angles of $\vartheta = 20 - 25°$ are observed at distances that exceed the distances for horizontal paths corresponding to the same intensities by a factor of $\geqslant 3$. Note that, as the optical quality of the output beam improves, this differences increases. For $K \to 1$, this factor may exceed ten.

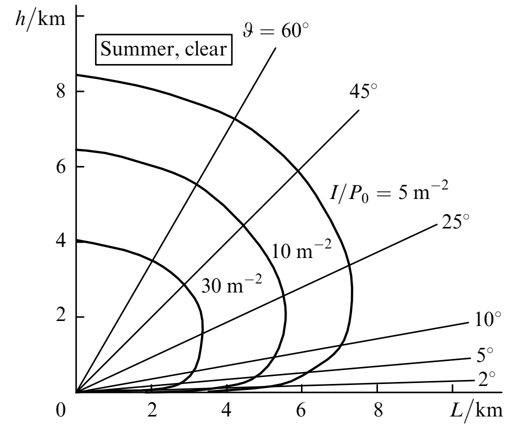

Figure 5. Lines of equal relative intensity for DF laser radiation at $\lambda = 3.8$ μm, $C_n^2(h_0) = 10^{-13}$ m$^{-2/3}$, $K = 3$, $D = 0.8$ m, and $h_0 = 5$ m.

4. Energy transfer to moving objects

We will calculate the density of the laser energy transferred to a moving object assuming that the absorption coefficient of the object surface is equal to unity, the surface is normal to the beam axis, and the centre of the laser spot is strictly fixed to the same point of the moving object. Consider the object moving in a horizontal plane ($\Delta h =$ const). The heat exchange between the object and the incident air flow is neglected. Under these assumptions, the following expression can be written for the absorbed laser energy density E_0 at the centre of the focal spot stored during the interaction time:

$$E_0 = 2\frac{P_0}{V_\parallel}\int_{F_1}^{F_2}\frac{\exp(-\alpha_\lambda F)\mathrm{d}F}{(F\theta)^2[1-(\Delta h/F)^2]^{1/2}}. \qquad (5)$$

Here, $V_\parallel$ is the projection of the object velocity on the vertical plane in which the source and object lie at a given moment; F_1 and F_2 are the distances at which the interaction of the laser beam with the object begins and terminates, respectively; and a factor of 2 is determined by the fact that E_0 is calculated at the beam axis where the radiation intensity is approximately twice as high as the mean value over the focal spot.

Specifying F_1, E_0, and other parameters included in Eqns (3) and (5), we can find F_2 and $d_2 = F_2\theta(F_2)$ from (5). The knowledge of F_2 allows us to determine Δt for which the laser beam must illuminate the object in order to obtain the energy density E_0 at the centre of the focal spot:

$$\Delta t = \frac{1}{V_\parallel}\int_{F_1}^{F_2}\frac{\mathrm{d}F}{[1-(\Delta h/F)^2]^{1/2}}. \qquad (6)$$

In order not to restrict ourselves to specifying particular values of E_0, P_0, and $V_\parallel$, it is convenient to introduce a generalised parameter of the relative energy density $\mathscr{E}_0 = E_0 V_\parallel / P_0$. Let us evaluate this parameter at some typical E_0, P_0, and $V_\parallel$ values. For $E_0 = 500$ J cm^{-2}, $V_\parallel = 300$ m s^{-1}, and $P_0 = 200$ kW, we have $\mathscr{E}_0 = 0.75$ m cm^{-2}. This dimension of $\mathscr{E}_0$ is determined by E_0 measured in J cm^{-2}, which is typical of studies of the interaction of radiation with matter, but not in J m^{-2}, as is conventional for SI units.

Fig. 6 presents the results of calculations using expressions (5) and (6) at $\mathscr{E}_0 = 0.75$ m cm^{-2} and $V_\parallel = 300$ m s^{-1} for DF and I laser beams. The analysis of these data shows that the effect of turbulence for the DF laser radiation is substantially lower. The functions $\Delta t(F_1)$ and $d_2(F_1)$ for the DF laser differ from each other to a much smaller degree than the corresponding functions for the I laser over the entire range of changing beam-propagation conditions ($C_n^2 = 10^{-13} - 10^{-15}$ m$^{-2/3}$, horizontal and inclined paths).

An increase in d_2 abruptly slows down with an increase in F_1 for both lasers, which is especially appreciable for horizontal paths with an intense turbulence. This effect is caused by a very low radiation intensity at long distances. The object has enough time to approach the source and

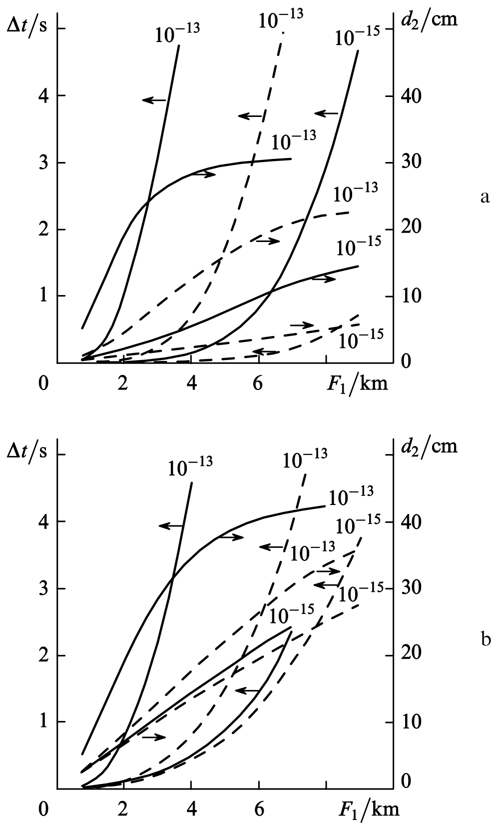

Figure 6. Duration Δt of laser action and the focal spot diameter d_2 as a function of F_1 for a moving object for an (a) I laser and (b) DF laser in the case of a horizontal path (solid curves) and an inclined path with $h = 500$ m and $h_0 = 5$ m (dashed curves) at $\mathscr{E}_0 = 0.75$ m cm^{-2}, $V_\parallel = 300$ m s^{-1}, $D = 0.8$ m, $K = 3$, and a visibility of 7 km. Figures near curves are values of C_n^2 in m$^{-2/3}$.

reach a distance, where the intensity is sufficiently high, before the specified energy density E_0 is stored. Mathematically, this means that, if $F_1 = \infty$ on the right side of formula (5) and F_2 smoothly changes, then the integral tends to zero, as F_2 increases. Hence, there exists a limiting $F_{2\,\mathrm{max}}$ at which condition (5) is still valid. At finite F_1 values, condition (5) is satisfied for $F_2 < F_{2\,\mathrm{max}}$. For all other factors being equal, $d_{2\,\mathrm{max}}$ values uniquely correspond to $F_{2\,\mathrm{max}}$ values. It follows from the plots $d_2(F_1)$ in Fig. 6 that, for horizontal paths and $C_\mathrm{n}^2 = 10^{-13}$ m$^{-2/3}$ (the values of other parameters are given in the caption), $d_{2\,\mathrm{max}} \simeq 40$ and 30 cm for DF and I lasers, respectively. These $d_{2\,\mathrm{max}}$ values correspond to $F_{2\,\mathrm{max}} \simeq 3$ and 2.3 km.

Table 2 presents several durations Δt of the laser action necessary for attaining the specified $\mathscr{E}_0 =$ 0.75 m cm^{-2}, depending on the beam-propagation conditions. As could be expected, according to the conclusions concerning the advantages of various wavelengths made in previous sections, the use of DF laser radiation with a longer wavelength is preferable in the case of a strong turbulence and a long distance to the object. For example, for horizontal paths, distances of 2 and 7 km, and $C_\mathrm{n}^2 = 10^{-13}$ m$^{-2/3}$, the durations of DF laser irradiation are significantly shorter than the corresponding durations for I laser radiation. However, already at $C_\mathrm{n}^2 = 10^{-15}$ m$^{-2/3}$, the duration Δt for an I laser becomes shorter.

Table 2. Laser action durations Δt depending on the conditions on the beam path*.

	$C_\mathrm{n}^2/\mathrm{m}^{-2/3}$	F_1/km	$\Delta t/\mathrm{s}$	
			DF laser	I laser
Horizontal	10^{-13}	2	0.73	1
		7	13.3	16
	10^{-15}	2	0.1	0.01
		7	2.4	1.65
Inclined	10^{-13}	2	0.12	0.05
($h = 500$ m, $h_0 = 5$ m)		7	3.9	5.6
	10^{-15}	2	0.08	0.003
		7	1.9	0.22

*Other parameters are identical to those in Fig. 6.

In addition, we should pay attention to a very important circumstance. The matter is that deterministic C_n^2 values were used in the calculations performed. Experiments have shown that this parameter strongly fluctuates in time and space, for example, during changes in the altitude above the Earth's surface. Therefore, the results of calculations are valid only on the average. This means that, when a run of tests is performed in approximately identical weather conditions, the experimental results (in particular, the object's irradiance) are not exactly reproduced from test to test but 'oscillate' around the values calculated according to the technique presented above. The experimental data averaged over a large number of such tests are close to the calculated values. An efficient method of improving the reliability of calculations of cw radiation propagation through the turbulent atmosphere in a single test is to compensate for turbulence-induced wavefront distortions as completely as possible by using adaptive optics. In this formulation of the problem, the calculation method considered might also be useful for determining the required range of wavefront phase corrections using adaptive mirrors depending on the operating conditions of the laser facility. Since the response speed of adaptive mirrors has a finite value, their application to pulsed lasers is limited. In this case, other compensation methods, such as the phase conjugation technique, should be evidently used.

5. Conclusions

The Kolmogorov turbulence theory and a simplified atmospheric model ($C_\mathrm{n}^2 \sim h^{-4/3}$ and $\alpha_\mathrm{ab} \ll \alpha_\mathrm{s}$) have allowed us to optimise the laser wavelength in a general form using the criterion of the maximum intensity of the laser beam transmitted through the turbulent atmosphere along horizontal and inclined paths and focused at an irradiated stationary object. The wavelength λ_opt depends on the parameters of the laser beam at the output of the laser facility (the aperture size determined by the primary mirror diameter of a laser beam – director telescope and the beam quality K) and the path parameters (C_n^2, Δh, and F).

A comparison of the focused radiation intensities produced by high-power lasers on a stationary object has shown that, depending on the weather conditions and beam path lengths, the maximum intensity can be provided by different lasers. However, if weather conditions change in a wide range, a DF laser is the most suitable source.

Consideration of the features of laser energy transfer and energy storage on a moving object made it possible to derive the expressions for determining the distance F_2 at which the energy with a given density can be stored. The limitation $F_2 \leqslant F_{2\,\mathrm{max}}$ imposed on F_2 is found.

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