Some peculiarities in formation of reference sources

V.P. Lukin

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

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Since the 1980s, the use of reference sources has been studied in application to adaptive optics systems aimed at studying the formation of laser beams in the atmosphere. The atmospheric turbulence, refraction, and thermal blooming are usually considered as the disturbing factors. The reference source is a coherent laser beam propagating backwards with respect to the principal radiation through the same inhomogeneities of the medium. The angular and spatial detuning of the reference and initial beams within the range of the isoplanatism of the propagation path is possible. It is known, from the general properties of the parabolic wave equation for media with fluctuations possessing the reciprocity, that the elementary spherical wave can be reconstructed ideally by the operation of phase conjugation only in the case that the operation is applied within an infinite initial aperture. I consider the possibility of using extended diffusely scattering objects and large-size mirror targets as the reference sources. A diffusely scattering surface (or volume) forms a reflected wave with some interesting properties, which allow the formation of an undirected reference source along almost any direction. Such a source can be a rather efficient reference source for a wide initial beam.

Introduction

References 1 to 12 present a thorough study of the application of reference sources of coherent radiation in adaptive optics systems for the formation of laser beams in the atmosphere. The atmospheric turbulence and thermal blooming of a beam were considered as the distorting factors.

The reference source is a coherent laser beam, propagating backward with respect to the initial beam through the same inhomogeneities of the medium. The angular and spatial detuning of the reference and initial beams is possible within the range of isoplanatism of the propagation path.[12] In Refs. 14 and 15, the cases were considered of a dichromatic correction, at which the wavelengths of the initial and reference radiation are different.

The aim of this study is to determine the limiting capabilities of coherent adaptive systems, operated on the basis of the algorithm of phase conjugation of fluctuations in the reference wave. The efficiency of adaptive systems is compared with the efficiency of the wave front conjugation system.

Algorithm of phase conjugation

It is one of the important principles, for adaptive optical systems, as systems with the optical feedback correcting for distortions in the structure of optical radiation, the principle of reciprocity or optical reversibility, which states the identity of fluctuations in elementary waves for the forward and backward propagation. In this paper, this principle and its consequences are used to prove the possibility of describing optical systems with a feedback by introducing the "reference" source into the unit of the current control over the parameters of a randomly inhomogeneous medium, the radiation propagates through.[10,11,13,15]

It is known that for linear media the field of a wave passed through a layer of a randomly inhomogeneous medium can be presented as a superposition of the field distribution at the emitting aperture

$$U(x,\rho) = \int d^2\rho_1 U(x_0,\rho_1)\, G(x,\rho;\, x_0,\rho_1), \qquad (1)$$

where $U(x_0,\rho_1) = U_0(\rho_1)$ is the initial field, $G(\ldots)$ is the Green's function of the problem. The operation of phase conjugation transforms the wave $U(x,\rho)$ into the complex conjugate wave $U^*(x,\rho)$. At the backward path, the optical wave passes through the same optical inhomogeneities, and the resultant field at the entrance plane is

$$U(x_0,\rho) = \iint d^2\rho_1 d^2\rho_2 U^*(x_0,\rho_1)\, G^*(x,\rho_2;x_0,\rho_1) G(x_0,\rho;x,\rho_2). \qquad (2)$$

Due to the reciprocity of the medium, the Green's functions are orthogonal:

$$\iint d^2\rho_1 d^2\rho_2 G^*(x,\rho_2;x_0,\rho_1) G(x_0,\rho;x,\rho_2) = \delta(\rho_1-\rho_2) \qquad (3)$$

and we have the following result:

$$U(x_0,\, \rho) = U^*(x_0,\, \rho).$$

Thus, in the double-pass schemes, the phase conjugation operation, which transforms $G(\ldots)$ into $G^*(\ldots)$, fully compensates for the effect of the random medium. Indeed, if the Green's function is represented in the form $G(\ldots) = A\exp(iS)$, then after the phase conjugation we obtain the reflection, in

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which the wave amplitude is reconstructed, while the sign of the total phase is changed.

As a result, the main element of image correction is the conjugation of the total phase of the field of a spherical wave, since the Green's function is just the spherical wave. Hence, it follows that such a correction can virtually correct for any fluctuations,[5,13] caused by the action of randomly inhomogeneous media.

Optimal phase correction in a randomly inhomogeneous medium

This section presents calculations of the mean intensity of a focused Gaussian beam in the turbulent atmosphere with the aid of an adaptive optical system, operated according to the phase conjugation algorithm. One of the possible choices[7,10] of the *optimal correcting phase* for the focusing of the radiation beam is considered.

As was already mentioned, for linear media the field of a wave passed through a layer of a randomly inhomogeneous medium can be presented by formula (1). The initial distribution of the field $U_0(\rho)$ can be written in the form

$$U_0(\rho) = A(\rho)\exp[i\varphi(\rho)], \tag{4}$$

where $A(\rho)$ and $\varphi(\rho)$ are the amplitude and phase of the initial field distribution. The phase $\varphi(\rho)$ is controlled by an adaptive device. If one makes use of the phase approximation,[14] for the Green's function, of the form

$$G(x_1,\rho;x_0,\rho_1) = G_0(x_1,\rho;x_0,\rho_1)\exp[iS(x_1,\rho;x_0,\rho_1)], \tag{5}$$

in which $G_0(x_1, \rho; x_0, \rho_1)$ is the Green's function for the free space, and the phase $S(x_1, \rho; x_0, \rho_1)$ characterizes fluctuations along the path, then after the substitution of Eqs. (5) and (4) into Eq. (1) we obtain:

$$U(x_1,\rho) = \\ = \iint d^2\rho_1 A(\rho_1)G_0(x_1,\rho;x_0,\rho_1)\exp[iS(x_1,\rho;x_0,\rho_1) + i\varphi(\rho)]. \tag{6}$$

If the aim of correction is to maximize the intensity functionals in the plane x_1, then we obtain the condition for the optimal phase correction

$$\varphi(\rho_1) = -S(x_1,\rho;x_0,\rho_1). \tag{7}$$

Condition (7) appears to be dependent on the observation point ρ. For the maximization of the Strehl ratio

$$I(x_1,0) = I(0) = \\ = \iint d^4\rho_{1,2} A(\rho_1)A^*(\rho_2)G_0(x_1,0;x_0,\rho_1)G_0^*(x_1,0;x_0,\rho_2)$$

the condition (7) transforms into

$$\varphi(\rho_1) = -S(x_1,0;x_0,\rho_1), \tag{8}$$

that is, the initial phase of the distribution (4) should be conjugate to the phase of a point source placed at the origin of coordinates.[7,13] An adaptive system for the correction for distortions can use the measured phase of the wave from a point guide beacon.

Thus, the phase of a reference source, used for the correction by the phase conjugation algorithm, fully coincides with the phase, maximizing the intensity functionals at the point, corresponding to the position of a point reference source. This can serve a basis for constructing an experimental correction algorithm with the use of a reference source. In calculating the efficiency of the correction algorithm, it is important which of the approximations is used to calculate the function $S(x_1, \rho; x_0, \rho_1)$.

Independent reference source

References 4 to 8 and 15 published in early 1980s have studied thoroughly the application of independent reference sources in adaptive optical systems in the problems of formation of laser beams in the atmosphere.

It can be shown from the general properties of the wave parabolic equation[7,11] that for the media with fluctuations possessing the reciprocity the elementary spherical wave can be reconstructed ideally by the operation phase conjugation only in the case that this operation is applied within an infinite initial aperture. An actual initial aperture ($\Omega = ka^2/x$) should be large enough to intercept the entire flux of scattered radiation.

The use of a finite aperture and the loss of the information about the amplitude distribution, that is, the application of the phase conjugation algorithm for the phase of the reference wave measured within the initial aperture, provide for the efficient suppression of fluctuations (in the region of "weak" intensity fluctuations) under the condition that the following inequality is fulfilled:

$$\Omega\Omega_0 < 1,$$

where $\Omega = ka^2/x$ is the wave number of the initial aperture, Ω_0 is the wave number for the aperture of the reference radiation. We obtain that the wider ($\Omega \gg 1$) is the initial beam, the closer to the spherical wave should be the reference radiation, and, on the other hand, the narrow beam ($\Omega \to 0$) requires a plane wave as a reference radiation. This equally applies to the correction of the mean intensity distribution of the initial beam and to the suppression of the residual intensity fluctuations.[5,6,12]

It has been found earlier[2,12] that for the adaptive correction under conditions of thermal blooming the narrow, in the diffraction meaning, reference source is most efficient for wide laser beams.

Figure 1 shows the calculated correction for the case of thermal blooming of a focused laser beam using a reference source of different size. It is seen that as the size of the reference source decreased, the efficiency of correction increased.

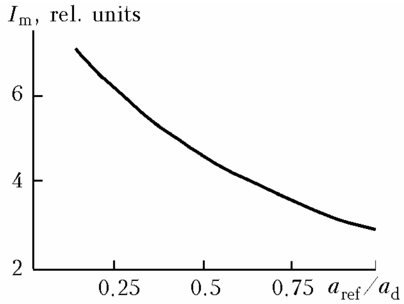

Fig. 1. Maximum intensity I_m in the cross section of a focused laser beam as a function of the size of a reference source. Abscissa shows the ratio of the size of the reference source to the size of the diffraction limited beam a_d in vacuum. The distance is $x = ka^2 = 0.25$. Under conditions of thermal blooming without correction $I_m = 1.1$.

The problem of correction occupies a particular place in astronomical applications.[9,12] Here the ideal wave (without fluctuations) is nearly plane, and therefore the higher is the point guide source, the closer to the plane wave will be the spherical wave from a laser guide star (LGS) and the more efficient will be the correction.

Reflection-based reference source

The formation of a reference source by the reflection from extended objects is an important issue of this study.[2,12] If such an object has an efficient point scatterer/reflector, then we deal with a spherical guide wave. Almost every time when we spoke about laser guide stars (LGS), we meant a point luminous object obtained by beam focusing, which was not resolved by the initial aperture.

Capabilities of extended diffusely scattering objects and large-size mirror targets are of interest as well. A particular place here is occupied by the effect of enhanced phase fluctuations as compared to a single-pass path of double length.[16,17] Some aspects of applying a retroreflector for the formation of a point source were considered in Refs. 2 and 18.

At the same time, a diffusely scattering object forms a reflected wave, having some interesting properties, which allow the formation of an undirected reference source along almost any direction. Such a source may be a rather efficient reference source for a wide initial beam.

Mirror reflection

There are certain questions in the problems of using extended diffusely scattering objects and large-size mirror targets that are still to be addressed. In the late 1970s, a certain interest was shown in the studies devoted to describing the features of phase fluctuations of waves mirror-reflected in the atmosphere, which passed through turbulence twice. Such objects include, for example, an infinite plane mirror, dihedral and trihedral corner cube retroreflectors or arrays of such retroreflectors. The problems that have been solved in this formulation dealt with the optical waves (plane, limited beam, spherical wave) passed along an atmospheric path, reflected from an infinite mirror, and traveling backwards.

A particular attention was paid to the effect of increasing the phase fluctuations[17] in reflected waves as compared to a single-pass path of the double length. For problems of adaptive optics (AO), this effect required the development of *the algorithm of optimal correction*, which was determined by the equation

$$\varphi_{opt}(\rho) = \varphi^{ini}(\rho) - A\varphi^{ref}(\rho),$$

where A is the optimal AO control coefficient, minimizing the error. It should be kept in mind that we consider only one-step correction algorithm, not including the iteration procedure. It is interesting to note that the optimal coefficient A depends on the method of obtaining the information, as well as on the parameters of the optical path and optical beam.

One of the features is the formation of the reference radiation (beacon, reference source, guide star in astronomy) from the initial radiation, reflected backwards. When the size of a reflector or individual spot on the reflector is rather small, a point reference source is actually formed, but when the reflector is extended, certain peculiarities appear in the behavior of such a wave, because the wave passes through the layer of inhomogeneities twice: on the way toward the reflector and backwards.

Consider the phase fluctuations in the approximation of the method of smooth perturbations. A limited wave beam[3] propagates along the optical axis after the reflection from a plane mirror, installed at a distance L from the transmitting aperture and normally to the axis x. The size of the mirror is selected so that the diffraction on it can be neglected. The analysis of statistical characteristics has shown that the reflected waves have a number of features, including the anisotropy of the properties. To estimate the sensitivity of the measured parameters to different-scale inhomogeneities of the refractive index, we have introduced the spectral filtering functions $f_{\chi,S}(L \leftrightarrow L, \rho)$ (χ – for intensity fluctuations, S – for phase fluctuations), which relate the correlation functions $B_{\chi,S}(L \leftrightarrow L, \rho)$ and the spectral density of turbulence $\Phi_n(\kappa)$:

$$B_{\chi,S}(L \leftrightarrow L, \rho) = 4\pi^2 \int_0^\infty d\kappa\kappa\Phi_n(\kappa)J_0(\kappa\rho)f_{\chi,S}(L \leftrightarrow L, \rho). \tag{9}$$

After calculation of the integral (9), we obtain the following analytical form for these functions:

$$f_{\chi,S}(L \leftrightarrow L, \rho) =$$
$$= \kappa^2 L[1 + \sin(\kappa^2 L/k)/(\kappa^2 L/k)][1 \mp \cos(\kappa^2 L/k)]. \tag{10}$$

The difference between these filtering functions and the corresponding functions in the wave incident on the reflector for the path of double length is shown in Fig. 2. Here curves *1* and *2* correspond to the spectral filtering functions for the path of double length ($2L$), while curves *1′* and *2′* correspond to the filtering functions in the reflected wave.

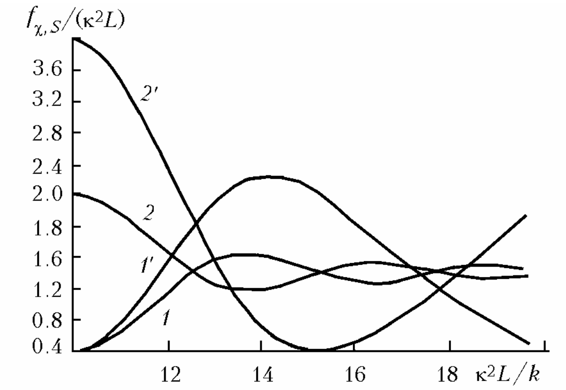

Fig. 2. Spectral filtering functions of intensity and phase fluctuations for the forward and backward propagated plane waves.

From curves *2* and *2′*, one can see a significant difference between the phase fluctuations in the reflected and incident waves: the high frequencies are suppressed stronger, while the low ones are more pronounced. Thus, the statistical characteristics of fluctuations in reflected waves have some features, which should be taken into account, for example, in developing the adaptive correction systems, which employ the algorithm of phase conjugation, that is, form the reference source formed by beam reflection.

Comparing the optical filtering functions[3,12] for the forward propagation of the initial plane wave and the wave passed twice through the atmosphere after the reflection from an infinite plane mirror, one can see that the contribution from different frequencies to the fluctuations of the forward (initial) beam and the backward reflected beam, which passed twice through the same inhomogeneities, is significantly different. This means that simple scaling cannot match these functions and the wave reflected from a plane mirror cannot be a good reference wave.

Some aspects of applying retroreflectors for the formation of a reference source were considered in Ref. 18.

Reference source based on the scattered radiation

In Ref. 19 it was shown how the general equation for the mutual coherence function of the field $\Gamma_2^0(\mathbf{R},\rho)$ emitted from a thermal source (that is, a source, for which the coherence length of the field $\rho_k \to 0$) can be approximated by the following equation:

$$\Gamma_2^0(\mathbf{R},\rho) = b^2 I(\mathbf{R})\delta(\rho). \qquad (11)$$

For this case $b = \lambda/\sqrt{2\pi}$, that is, the initial coherence length of radiation from a thermal source or a diffusely reflecting body is comparable with the radiation wavelength. For a completely incoherent radiation

$$\Gamma_2^0(\mathbf{R},\rho) = \frac{\lambda^2}{2\pi} I(\mathbf{R})\delta(\rho).$$

At the distance x from the source, in a turbulent medium, it is, as was shown in Ref. 19,

$$\Gamma_2(x,\mathbf{R},\rho) = \frac{U_0^2 k^2 a^2 \rho_k^2}{x^2}\exp\{ik\mathbf{R}\rho/x - \\ -\frac{k^2 a^2 \rho^2}{4x^2} - \frac{\pi k^2}{4}\int_0^x H(x', \rho x'/x)\mathrm{d}x'\}. \qquad (12)$$

For the absolute value of the complex degree of coherence we have

$$|\gamma(x,\mathbf{R},\rho)| = \exp\{-\frac{k^2 a^2 \rho^2}{4x^2} - \frac{\pi k^2}{4}\int_0^x H(x', \rho x'/x)\mathrm{d}x'\}. \qquad (13)$$

Consequently, one can see two opposite tendencies in the variation of the length of spatial coherence of the initially incoherent radiation. On the one hand, it increases proportionally to $d_0 = 2x/ka$ (which is caused by the decrease of the visible angular size $\gamma_s = a/x$ of the source) and, on the other hand, it decreases due to the loss of the field coherence in the turbulent medium.

The diffusely scattering surface (or volume) forms a reflected wave, having the following properties[19]: the coherence in the reflected wave in the vacuum is determined so that the length of transversal coherence is

$$\rho_k \approx \lambda/\Theta,$$

where Θ is the angle, at which the object is seen from the plane of the initial beam or its element is seen within the field of view of a sensor. We obtain $\Theta \approx d/x$. If the beam of the size a is focused at a distance x, we have $d \approx \lambda x/a$, then $\rho_k \approx a$. In the turbulent medium, the coherence in the reflected wave will decrease as in a spherical wave.

We can express the complex degree of coherence through the structure function of the phase

$$|\gamma(x,\mathbf{R},\rho)| = \exp\{-\frac{1}{2}D_S(x,\rho)\}. \qquad (14)$$

Comparing Eqs. (13) and (14), we obtain

$$D_S(x, \rho) = \frac{k^2 a^2 \rho^2}{2x^2} + \frac{\pi k^2}{2}\int_0^x H(x', \rho x'/x)\mathrm{d}x'. \qquad (15)$$

From calculations by Eq. (15) with the Kolmogorov spectrum of turbulence, we obtain, under condition that the outer scale of turbulence $\kappa_0^{-1} \gg \rho$, that

$$D_S(x,\,\rho) = \frac{k^2a^2\rho^2}{2x^2} + 2.91k^2\rho^{5/3}\int_0^x dx' C_n^2(x')(x'/x)^{5/3}. \quad (16)$$

Thus, the structure function of the phase for such a field appears to have two parts: the quadratic diffraction one, ρ^2/ρ_k^2, and the turbulent, $3.44(\rho/\rho_{tur})^{5/3}$. It is possible to perform the quadratic approximation in the second term and to reduce the result to the square dependence.

The main conclusion is that the diffusely scattering object reflects the waves, which have the properties that allow the formation of an undirected source along almost any direction, and this source can serve an efficient reference source for the adaptive formation of a wide initial beam. These analytical conclusions confirm generally the results obtained by numerical simulations.[21]

It should be mentioned that the conclusions drawn here apply only to the so-called complete phase correction, while at the partial correction (when only some modes of the phase distribution are corrected) some statements may be incorrect.

Adaptive control over the laser beam on horizontal paths in the lower atmosphere

Let us present some results obtained by numerical simulation of an adaptive optical system for the correction for the effects of turbulence and thermal blooming of radiation. The influence of the position of a reference source on the quality of correction with the use of phase conjugation has been studied using numerical analysis.

Action of turbulence and adaptive control

The initial size of a focused Gaussian beam was 0.5 m, the length of the focusing was 3 km, the path length was 3 km, the wavelength was 1.315 μm, the wind speed was $v = 2$ m/s, and the structure constant was $C_n^2 = 5.2 \cdot 10^{-15}$ cm$^{-2/3}$. It was assumed that the adaptive system operated with an ideal wave front sensor and an ideal or mode corrector. The signal reflected from the object was used as a reference radiation, that is, the boundary conditions for the reference signal are specified as follows:

$$E_r(\rho,L) = E(\rho,L)R(\rho); \quad (17)$$

$$R(\rho) = R(x,y) = R_0 \exp\left(-\frac{\left(x^2 - n_1a_0\right)^2 + y^2}{\left(n_2a_0\right)^2}\right), \quad (18)$$

where a_0 is the effective size of the diffraction-limited beam in the initial plane; n_1 is the shift of the brightest part (flare) on the reflector, normalized to the beam size, n_2 is the normalized size of the bright part (flare). Changing the values of n_1 and n_2, we can change the size of the guide source and its position.

From the numerical experiment, we have obtained the efficiency of the operation of the adaptive system, employing the reflector, in which the brightest spot, having the diffraction size ($n_2 = 1$), is shifted with respect to the axis of the system ($n_1 = 0, 2, 4$).

Table 1 presents the parameters of the beam after the correction: coordinates of the centroid x_c and y_c, the energy fraction, in per cent, within the focal spot P_d, and the power density of the radiation I_m at the point with the maximum intensity in the beam cross section. The power of the beam was 10 kW.

Table 1

n_1	x_c, mm	y_c, mm	P_d, %	I_m, kW/cm^2
0	–0.1	–0.3	22	7.68
2	9.4	0.1	0.3	7.88
4	18.7	0.0	0.1	7.92

Table 2 gives the calculated results obtained with the angular size of the reflecting spot being larger than the resolution of the system, which corresponds to the values $n_2 > 1$ and $n_1 = 0$.

Table 2

n_2	x_c, mm	y_c, mm	P_d, %	I_m, kW/cm^2
1	–0.1	–0.3	22	7.68
2	–0.3	–1.2	19	7.27
4	–0.8	–2.8	13	7.06
8	–1.0	–3.5	7	5.67

These results show that as the size of the reference source increases, the efficiency of the correction worsens sharply and the energy fraction within the focal spot decreases three times.

Consider also the restrictions, caused by the finite spatial resolution of the corrector. According to Ref. 20, residual distortions are determined by the number of degrees of freedom of the corrector, that is,

$$\Delta = C(N)(D/r_0)^{5/3}.$$

Here N is the number of degrees of freedom of the corrector, D is the size of the aperture, r_0 is the coherence length. Table 3 presents the parameters of the focal spot, obtained after the adaptive correction for distortions of a focused laser beam at different number of corrected modes.

Table 3

N	P_d, %	I_m, kW/cm^2
3	3.7	1.25
6	8.4	2.96
10	11.9	4.11
21	16.4	5.71
45	19.3	6.72
Infinite number of degrees of freedom	22	7.68

As can be seen from Table 3, when the number N becomes equal to 45, the concentration of the field in the focal spot achieves almost 90% of the maximum achievable value, while $N = 10$ is already enough to achieve 50% of this value.

Influence of the speed of control

To determine the needed speed of control, we introduce the time delay Δt into the feedback loop of the control of the adaptive system (Table 4).

Table 4

Δt, ms	P_d, %	I_m, kW/cm^2
0	22	7.60
5	15.5	5.95
10	7.6	3.02
15	4.9	1.67
20	3.3	1.13

As follows from Table 4, the efficient control is possible at the delay in the adaptive system no longer than 5–10 ms, which corresponds to the frequency band of 100–200 Hz.

Effect of thermal blooming and adaptive correction

Consider, also numerically, the correction for distortions, caused by the effect of thermal blooming of radiation, and the possibilities of adaptive correction for it. Let the initial parameters of the focused Gaussian beam be as follows: the initial beam is a truncated Gaussian beam with the size $a_0 = 0.5$ m, the focusing is carried out through the entire path, that is, $f = L = 3$ km, the wavelength is $\lambda = 1.315$ μm, the wind speed is $v = 2$ m/s, the atmospheric absorption coefficient is $\alpha = 1.252 \cdot 10^{-7}$ cm^{-1}, the initial power is $P_0 = 10$; 25, and 100 kW, the adaptive system is modeled as a system with an ideal wave front sensor and mode corrector (Table 5).

Table 5

P_0, kW	x_c, mm	P_d, %	I_m, kW/cm^2
10	−8.8	0.04	4.22
25	−18.5	0.07	3.52
100	−55.2	0.01	3.16

The reference source is a reflected signal or a source with the size smaller than the limiting resolution of the transmitter, that is, virtually a point reference source.

In these calculations, the effective size of the untruncated Gaussian focal spot was 3.54 mm. In the absence of thermal blooming, about 62% (for the untruncated beam) and 37% (for the truncated beam) of energy fall within the diffraction spot. The intensity distribution for these three beams is shown in Fig. 3. The size of the frame was 142 mm for the first two pictures and 284 mm for the third picture.

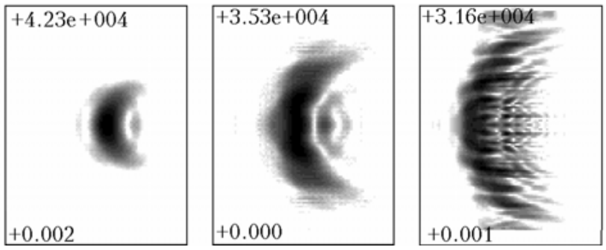

Fig. 3. Intensity distribution as a function of the source power under conditions of thermal blooming. Numbers show the minimum and maximum values.

Table 6 demonstrates the influence of different mode components of the corrector on the quality of the beam in the focus.

Table 6

N	Correction for defocusing	Correction for astigmatism	x_c, mm	P_d, %	I_m, kW/cm^2
		$P_0 = 10$ kW			
3	Off	Off	0.2	1.89	3.96
6	On	On	0.7	1.51	3.01
10	On	On	1.5	2.2	4.45
10	Off	On	0.5	2.06	4.74
10	Off	Off	2.0	2.25	4.34
15	Off	Off	1.6	2.21	4.35
21	Off	Off	1.7	2.22	4.38
45	Off	Off	1.6	2.22	4.36
		$P_0 = 25$ kW			
3	Off	Off	−1.0	1.32	3.49
6	On	On	−6.6	0.65	1.9
10	On	On	−2.5	1.05	5.24
10	Off	On	−0.6	1.34	6.68
10	Off	Off	2.2	2.71	5.76
15	Off	Off	3.0	2.34	5.23
21	Off	Off	3.7	2.08	5.25
45	Off	Off	–	–	–

N o t e . N is the number of corrected modes, the second and third columns show the presence or absence of defocusing and astigmatism during the correction, that is, the modes with numbers 3, 4, and 5.

As can be seen from Table 6, for the beams with the energy up to 10 kW the quadratic aberrations almost do not affect the efficiency of correction. At the level of 25 kW, the correction for defocusing is unstable, and the efficiency of correction decreases. The exclusion of quadratic aberrations from the control increases the resultant effect of correction. In this case, the stable adaptive control is possible starting from the time $t = D/v = 0.25$ s. Thus, the high speed of adaptive control is not that critical in compensation for the effects of thermal blooming.

Since the increase in the number of degrees of freedom of the corrector above 15 does not lead to a significant improvement of the correction, the requirements to the spatial resolution of the adaptive mirror remain quite modest.

As can be seen from Table 6, the 2.5 times increase of the source power (from 10 to 25 kW) gives only 30% increase of the energy concentration on the object. This means that the optimal power of the source at these parameters of the path is about 25 kW. And further increase of the power (say, up to 100 kW) leads to a significant increase of thermal aberrations in the beam.

Correction for thermal and turbulent aberrations

The source is a truncated Gaussian beam with the size of 0.5 m, the length of the focusing is $f = 3$ km, the wavelength is $\lambda = 1.315$ μm, the structure constant at the path is $C_n^2 = 5.16 \cdot 10^{-16}\,\text{cm}^{-2/3}$, the atmospheric absorption coefficient is $\alpha = 1.252 \cdot 10^{-7}\,\text{cm}^{-1}$, and the power of the beam is 10 and 25 kW. The adaptive system includes an ideal wave front sensor and a mode corrector. The reference source is a flare on the object, unresolvable by the transmitting aperture (Table 7).

Table 7

P_0, kW	P_d, %	I_m, kW/cm^2
10	1.93	3.94
25	2.1	4.27

For definiteness, we use a mirror flare with the size equal to the diffraction size of the beam; for the focused beam the cross size is L/ka.

We assume that for the beams with the total power $P = 10$ kW the quadratic aberration were compensated for with the aid of the control over the mirror, and for the beams with $P = 25$ kW these aberrations were excluded. The intensity distribution in the cross sections of the beams was averaged over the time interval of 0.25 to 0.5 s.

Conclusions

The results presented allow the conclusion to be drawn that the main difficulties are connected with the correction for the action of turbulence. These difficulties are caused, first, by the significant amplitude fluctuations, occurring both along the extended high-altitude paths and along the near-surface atmospheric paths at large zenith angles.

On the other hand, there exists a problem of strict requirements to the frequency pass band of an adaptive optical system. The estimates of the needed frequency band give the value (on the order of 1 kHz) higher than real systems can provide for (about 100 Hz). These restrictions are associated with the high speed of motion of the object.

The correction of laser beams by the method of "introducing predistortions" with the use of a signal reflected from an object moving with the speed close to the speed of sound gives pessimistic results even when the adaptive system has a zero delay. This is caused by the finiteness of the speed of light. The decrease in the efficiency of the adaptive correction is seen especially well in the case of extended high-altitude atmospheric paths.[21,22]

Difficulties in the correction for thermal blooming arise mostly for horizontal paths. In the examples considered, the correction for thermal blooming is stable only when the aberrations caused by thermal blooming are weak (power up to 10 kW). As the power increases up to 25 kW, the instability of the beam as a whole appears while the concentration of the energy at the object increases insignificantly as compared to the case with the power of 10 kW.

In the case of a quickly moving object, nonlinear aberrations of the beam are concentrated near the emitting aperture, and so the influence of thermal blooming is lower and the efficiency of correction becomes higher. If the correction for turbulent aberrations is possible in some scheme, then the correction for thermal blooming is possible as well. Therefore, the requirements to the adaptive system should be determined, in the first turn, by turbulent distortions.[23]

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