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Possibilities of joint application of adaptive optics technique and nonlinear optical phase conjugation to compensate for turbulent distortions

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Abstract. **The efficiency of integrating the nonlinear optical technique based on forming a reverse wavefront and the conventional adaptive optics into a unified complex (for example, for adaptive focusing of quasi-cw laser radiation) is demonstrated. Nonlinear optical phase conjugation may provide more exact information about the phase fluctuations in the corrected wavefront in comparison with the adaptive optics methods. At the same time, the conventional methods of adaptive optics provide an efficient control of a laser beam projected onto a target for a rather long time.**

Keywords: *atmospheric turbulence, adaptive optics, phase conjugation, control, coherence length.*

One of the most important problems of atmospheric optics is the increase in the efficiency of light transmission through randomly inhomogeneous media (e.g., turbulent atmosphere) based on application of modern adaptive optics (AO) methods. To this end, researchers use both conventional AO elements, working according to the phase conjugation (PC) algorithm [1], and nonlinear AO elements, implementing adaptive correction using nonlinear optical phase conjugation [2–4].

Many examples of high-speed elements (implementing wavefront phase conjugation) matched with reflecting elements have been reported (see, e.g., [2–5]). These elements are referred to as PC mirrors. An amplitude–phase control (according to the PC scheme) can be implemented, e.g., in the case of optical four-wave mixing in a nonlinear medium [6]. The advantages and drawbacks of linear AO and different realisations of nonlinear methods for adaptive correction of light distortions are well known. The unconditional advantages of linear AO are the flexibility of designing various application schemes and the possibility of working with both high- and low-power light beams. At the same time, linear AO has a drawback: low control frequencies, which are related to the use of mechanical elements for correction (flexible and combined controlled mirrors, etc.). In turn, an advantage of nonlinear AO is specifically the possibility of very fast light control; however, the lifetime of this correlated state is very short: it does not exceed several tens (maybe, hundreds) of nanoseconds. It is rather difficult to transfer high energy during this short time interval. There are some other drawbacks of the nonlinear PC technique, which limit its application.

The concept of integrating these two approaches into one device was repeatedly discussed in the literature (see, for example, [7, 8]); however, neither serious numerical analysis of its possible efficiency nor, especially, its experimental simulation has been performed. Previously, we reported the results of simulating this hybrid device [6, 9, 10]. In this paper, we present the results of numerical analysis of its efficiency as a function of the atmospheric turbulence level and some characteristics of the optical scenario. The adaptive correction of the turbulence-induced distortions of light waves was simulated with allowance for the finite operating speed of the AO system under conditions where distortions on the light beam propagation path changed with time (random turbulent inhomogeneities shifted perpendicular to the light propagation direction [5]).

One of possible block diagrams of this hybrid system, combining linear AO and nonlinear optical PC, is shown in Fig. 1. In this hybrid system, the laser (*3*) generates a reference pulse, which is directed through the atmosphere to a target object (*7*) and reflects off from it; then some part of reflected light is collected by a Cassegrain telescope (*8*) and arrives at the input of a signal-receiving PC mirror (*1*). We propose to use a nonlinear optical detector (based on four-wave mixing of light with hypersound) as an PC mirror. The results of its experimental analysis were reviewed in [11]. This detector provides amplification of optical signals and has a unique combination of parameters, specifically:

(i) rather large field of view: up to 10° (~500 × 500 image pixels);

(ii) extremely narrow frequency band of detection, corresponding to a response time of ~10 ns;

(iii) high sensitivity, limited by only the quantum noise of the input amplifiers; the minimum level of the received and inverted signal is on the order of 5×10^{-19} J (i.e., about two photons) per pixel; and

(iv) gain on the order of $10^{12}–10^{13}$.

This nonlinear optical detector makes it possible to select and receive extremely weak signals against the background of intense incoherent illumination (Rayleigh and aerosol scatterings in atmosphere, solar light, etc.).

Then the amplified signal arrives at the input of a wavefront sensor (*4*), i.e., enters the linear part of the adaptive corrector. This sensor measures the wavefront, generates

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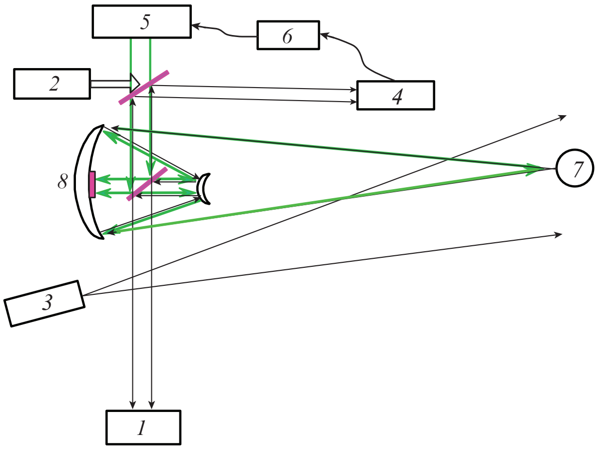

Figure 1. Hybrid focusing system: (*1*) PC mirror (nonlinear optical detector); (*2*) controlled laser; (*3*) pulsed illuminating laser; (*4*) wavefront sensor; (*5*) flexible controlled mirror; (*6*) computer that controls mirror (*5*) based on the signal from sensor (*4*); (*7*) target object; (*8*) transceiver telescope.

(using special programs) a signal for controlling the surface of the flexible mirror (*5*), and the mirror surface reproduces the wavefront of the signal received and conjugated by the nonlinear optical detector. The amplification of the signal reflected from a target and received by the nonlinear optical detector provides reliable operation of the wavefront sensor of the AO system even when the signal reflected from the target object (*7*) is very weak. If a larger part of reflected radiation is directed [through the channel of a transceiver telescope (*8*)] backward to the target, the compensation for the distortions introduced by atmosphere to the reflected radiation, as well as subsequent energy concentration on glaring target points, will make it possible to increase the signal even more (by several orders of magnitude).

The system contains also a laser (*2*), whose beam is constantly directed to the object (*7*) through a flexible mirror (*5*). The control signal supplied from the wavefront sensor (*4*) to the flexible mirror (*5*) provides constant adaptive focusing of the radiation of the laser (*2*) onto the object (*7*). During the period of 'frozen' phase fluctuations in the channel between the object and emitter, the radiation of the laser (*2*), corrected with the aid of active mirror, arrives at the object. Undoubtedly, phase distortions change in the course of time due to the presence of turbulence in the channel between the hybrid system and the object. Sooner or later, these changes become so significant that the focusing of radiation of the laser (*2*) becomes less efficient; then the cycle of compensating for distortions using pulsed radiation of the laser (*3*) is repeated. In sum, the joint use of the technique of nonlinear optical reception of the signal and linear AO for adaptive correction results in periodical focusing of radiation onto the object. It should be specially noted that the phase conjugation (with respect to the input signal) of the signal received by the wavefront sensor (*4*) does not affect the operation of the AO hybrid circuit. Note also that the optical elements of the scheme that provide projection and signal polarisation control are omitted in Fig. 1 for clarity.

Qualitatively, it is clear that the duration of the working cycle of this hybrid system will be determined by both the level of turbulent fluctuations and the rate of variation in phase fluctuations in the channel between the object and adaptive system. Here, we verified this suggestion in a numerical experiment. The cycle was quantitatively calculated using the previously developed apparatus for simulating the laser beam propagation in a randomly inhomogeneous medium [1, 5]. A numerical analysis of the operation of this system was performed using a simplified scheme, in which the sources generating reference and corrected laser beams are switched simultaneously; both beams must be initially collimated. The reason is that the distance from the device to the irradiated object is often unknown.

In the first stage of our numerical simulation, we will calculate the optical beam focusing criterion (the fraction of the beam energy enclosed within the beam diffraction diameter) in the observation plane [i.e., in the plane of the object (*7*)] without adaptive control. The calculation will be performed in some time interval, which is necessary for detecting the reference beam parameters and generate control signals. Then we will analyse the beam propagation in a random medium. To this end, the amplitude and phase distributions, caused by random factors present in the atmosphere, will be specified in the corrected beam. After some time (varied when solving the problem), a separate cycle of purely phase control will be carried out. The work of the system upon real atmospheric conditions is characterised by wind-induced displacement of turbulent inhomogeneities to the leeward side. In the numerical model, this circumstance is taken into account via transverse (wind-caused) walk off of the measured phase front. Thus, the numerical model completely imitates the work of the hybrid system.

The numerically found results of controlling the above-described system are shown in Figs 2 and 3. The total time of one control cycle in all experiments was 0.1 s at an initial beam radius of 5 cm and a wind velocity of 5 m s^{-1}; the distortions in the optical wave transmitted through a layer of the medium were controlled by setting the level of phase fluctuations (the Kolmogorov–Obukhov model for a turbulent medium [1, 6] was used). The phase-distortion level in the optical wave was set in terms of the beam coherence length (the so-called Fried length, r_0), which was varied in rather wide limits.

In the beginning of the studies, we performed a comparative analysis of the AO PC and nonlinear optical PC efficiencies when correcting steady-state distortions (i.e., when compensating for the effect of 'frozen' turbulence) [6]. The results of the numerical experiment are presented in Fig. 2, which shows the dependence of the focusing criterion on the Fried length, which is proportional to the radiation power recorded within a specified aperture:

$$J(t) = \frac{1}{P_0}\iint \rho(x,y)\, I(x,y,t)\,\mathrm{d}x\mathrm{d}y .$$

Here, P_0 is the total beam power; $\rho(x,y) = \exp[-(x^2 + y^2)/S_{\mathrm{t}}^2]$ is the aperture function, S_{t} is the aperture radius; and $I(x,y,t)$ is the radiation intensity.

The calculations were performed for atmospheric paths of different lengths. In Fig. 2, the Fried length is normalised to the initial lateral size a_0 of the beam formed. The normalised atmospheric path length Z is the ratio of the path length L to the diffraction length $z_{\mathrm{d}} = ka_0^2$, where k is the radiation wave number. Since atmosphere is a randomly inhomogeneous

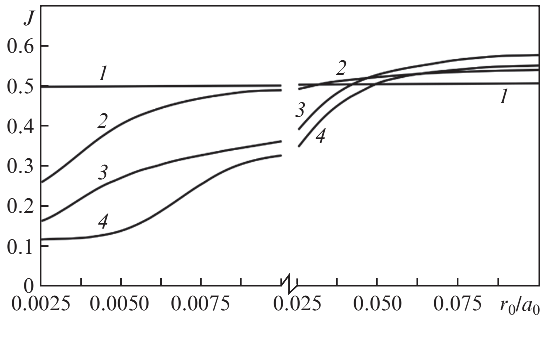

Figure 2. Comparison of the efficiencies of (*1*) amplitude–phase and (*2–4*) phase control on uniform atmospheric paths with lengths of $Z =$ (*1*) 0.5, (*2*) 0.3, (*3*) 0.5 and (*4*) 0.7.

medium, the data obtained were averaged over 50 random realisations.

It follows from Fig. 2 that the results for the PC control are independent of the turbulence intensity (the criterion is 0.5 for all Fried lengths), whereas in the case of purely phase control [curves (*2–4*)] the criterion J decreases with decreasing coherence length r_0; this decrease is more pronounced for long paths.

The algorithms of amplitude–phase control, implemented as PC, compensate for atmospheric distortions with a high efficiency; however, when using these algorithms, the correction quality is limited by the operating speed of the adaptive system [9, 12]. This feature is illustrated by the time dependence of the focusing criterion (Fig. 3), which was obtained using the AO PC and nonlinear optical PC approaches to compensate for the time-dependent distortions (the time in Fig. 3 is normalised to the characteristic transport time of inhomogeneities through the beam cross section: $\tau = a_0/v$, where v is the flow velocity). It can be seen in Fig. 3a that the focusing criterion significantly increases during the PC cycle. Then, while inhomogeneities are displaced, the fixed values of the beam wavefront amplitude and phase do not correspond exactly to the refractive index of the medium on the propagation path, and the criterion decreases. The system behaves similarly during a PC cycle; however, the criterion values are much smaller in this case than for the PC control.

The mean values of the criterion increase, and their difference for the phase and amplitude–phase control decreases with a decrease in the turbulence intensity. This trend is illustrated in Figs 3b and 3c, where the turbulence parameter is smaller than in Fig. 3a. Thus, at a relatively low turbulence intensity, the hybrid system containing a nonlinear optical detector and a linear adaptive system provides almost the same efficiency of distortion correction as the PC system.

In addition, it was found that the quality of distortion compensation can also be improved by increasing the operating speed of the system [6, 8, 9]. This is confirmed by the data in Table 1, which contains the mean values of the focusing criterion, obtained for systems with different operating speeds and different turbulence intensities. The variable parameters are the time intervals during which phase conjugation and PC formation are performed, i.e., the cycle of the system and the turbulence parameter, characterised by Fried length r_0. It was revealed that an increase in the response time of the system (decrease in its operating speed) results in reduced criterion mean values; the higher the turbulent distortion intensity, the larger this decrease is.

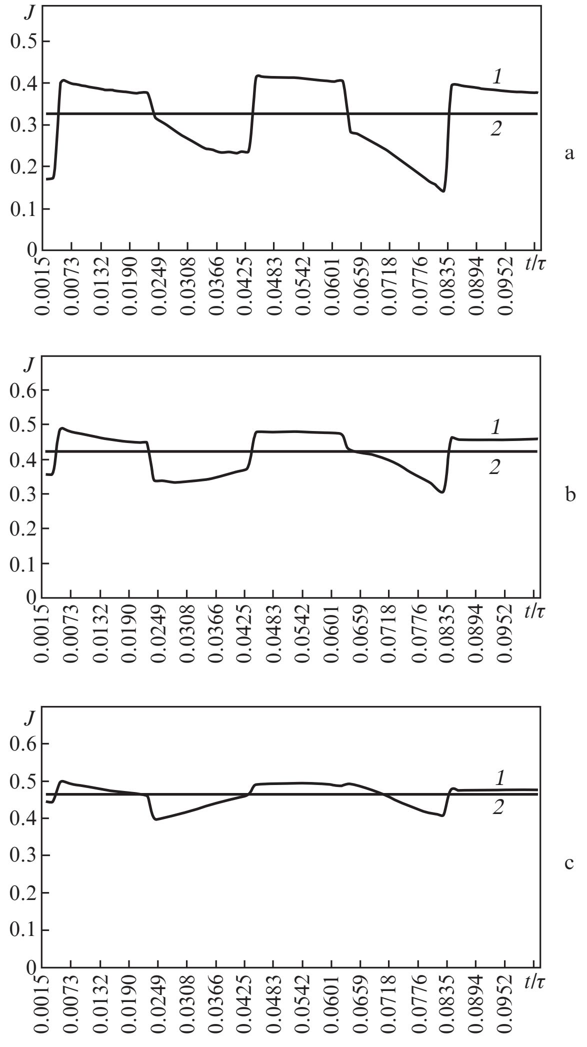

Figure 3. Time dependences of the focusing criterion in the case of joint use of AO PC and nonlinear optical PC techniques, for $r_0/a_0 =$ (a) 0.025, (b) 0.05 and (c) 0.075. Curves (*1*) characterise the operation of the hybrid adaptive system, and lines (*2*) indicate the mean value of the focusing criterion.

Table 1. Mean values of focusing criterion $\langle J \rangle$, recorded at different operating speeds of the system and different turbulence intensities (the path length is $Z = 0.5$).

r_0/a_0	Total control time/s	Response period the hybrid system/s	Mean value of focusing criterion
0.075	0.1	0.02	0.463 ± 0.072
	0.1	0.04	0.461 ± 0.091
0.025	0.1	0.02	0.325 ± 0.044
	0.1	0.04	0.279 ± 0.086

The results reported above suggest that the efficiency of a hybrid adaptive system is always lower than in the case of PC control. This decrease in efficiency is relatively small when the operating speed of the system is high and the turbulence intensity is low. At the same time, specifically a hybrid system can provide a long-term interaction with an object and transfer a high energy to it.

It is pertinent to note again that the main problem of PC application in high-power laser systems is that the PC lifetime is short (because the nonlinear optical PC technique is pulsed): in most cases, the newly formed state exists only several tens or several hundreds of nanoseconds. It is impossible to transfer a large amount of energy for such a short time. Therefore, we propose to use the PC channel primarily to form a reference source (by illumination) and obtain a reflected signal using this source.

Slow linear AO makes it possible to select preliminarily a target object. If the target is used as a reference source [13], one can select an object and form radiation in the region of interest. Currently, a method of 'advanced' correction is being developed to improve the correction quality and dynamic characteristics of adaptive optical systems. This method is based on solving the problem of prediction of the phase distribution at the next instant, proceeding from the results of phase measurements and measurements of the lateral wind velocity component at a given instant. This must be done, because an adaptive optical system designed to correct turbulent distortions of laser radiation is a dynamic system with feedback. Its response time includes the video processing time; the calculation time of control actions on the adaptive mirror; and the development time of control signals by the mirror, which is determined by its inertia and the transient processes occurring in the mirror mechanical design [1, 10, 13, 14]. The response time may exceed the allowable time (during which the turbulence is 'frozen'), which is directly proportional to the optical field coherence length and inversely proportional to the lateral wind velocity component (specifically, the evolution rate of phase distortions in the wave propagation channel).

Conventional adaptive systems cannot perform effective correction if the intrinsic response time of the system exceeds the lifetime of the 'frozen' state. One can improve the characteristics of the adaptive focusing system using, for example, the current phase profile data to predict the shape of the phase surface at subsequent instants, with allowance for the characteristic turbulence parameters and current displacements of the coordinates of centroids of the system of focal spots on the wavefront sensor. We performed a numerical simulation of the control algorithms taking into account this prediction. It was proven that the 'advanced' adaptive phase correction retains its efficiency even for slow control [1, 14].

Let us now formulate the requirements to the characteristics of the AO system, which are determined by the parameters of the problem (distance to the object, object velocity, etc.) [9–13]. We will proceed from the fact that the possible operational working range of the system is 200–500 km. The transmission of a laser beam through atmosphere on such a long path is limited by cloudiness and atmospheric turbulence.

To date, the following problems have become evident:

(i) there are almost no experimental data on the laser beam transmission along extended paths;

(ii) the known models of high-altitude run for the atmospheric turbulence intensity are unrealistic: there are barely any data on the so-called atmospheric intermittency [15]; and

(iii) one needs more detailed information about the turbulence characteristics at large heights (10–15 km above the sea level).

The developers of these systems proceeded from the following principle: a high-power laser source should operate in the absence of cloudiness along the laser beam propagation path. To exclude the influence of clouds (which significantly block light), the system for object illumination should be located at a height of 12–15 km; there are barely any clouds at these heights in middle and high latitudes. However, in the equatorial regions, clouds can be found at heights up to 20 km. The objects located on near-Earth orbits can play the role of laser-beam targets [16, 17].

When estimating the influence of turbulence on the laser beam parameters, we proceeded from the known parameters of the lasers that are candidates for the application considered here: a CO_2 laser with a wavelength $\lambda = 10.6$ μm and an iodine laser with $\lambda = 1.315$ μm. Turbulence is known to affect more strongly short-wavelength radiation. Now, one can only state with confidence that the turbulence level at heights of 10–15 km is expected to range from 10^{-17} to 10^{-18} $m^{-2/3}$.

Let us analyse the expected fluctuations of laser-beam optical parameters. We take the initial distance to be $L =$ 300 km and assume that the aperture of the main transmitting telescope is 1.5 m. Short-wavelength radiation is focused more efficiently: it can be shown that the power density in a focused short-wavelength beam (with $\lambda = 1.315$ μm) exceeds that for a focused long-wavelength beam ($\lambda = 10.6$ μm) by a factor of 65. At the same time, atmospheric turbulence is more pronounced specifically at short wavelengths. As a result, the optical-wave phase and amplitude undergo fluctuations, and the coherence length of focused laser beam decreases to 5–15 cm (which is smaller than the size of the initial laser aperture by a factor of about 10–30). In addition, intensity fluctuations arise, whose variance may be as high as 0.1–10.

Thus, even moderate fluctuations of atmospheric turbulence at distances of 200–300 km cause significant intensity fluctuations. With these intensity and phase fluctuations, any beam focusing without adaptive correction is inefficient.

It is believed that application AO systems may compensate for the turbulence effect. However, the development of a real adaptive system meets a number of problems, both technical and fundamental. One of specific problems of these systems is the necessity of providing a high operating speed. It is known from the theory of adaptive systems that an optical-wave phase correction device should operate with a frequency determined by the transport velocity of turbulent inhomogeneities through the coherent part of laser beam. At the same time, it is known that modern adaptive systems have a frequency band of 300–500 Hz. Let us evaluate the fundamental limitations imposed by this factor on the allowable object velocity and the range of reliable operation of conventional adaptive systems.

A necessary condition for efficient correction is as follows: the object must remain in the isoplanatic region during the time of one adaptive control cycle, which is equal to $2L/c + \tau_a$ [1, 16, 17]. In other words, the following inequality must be implemented:

$$\frac{v_{\mathrm{ob}}(2L/c + \tau_{\mathrm{a}})}{L} < \Theta_{\mathrm{iso}},$$

where $v_{\rm ob}$ is the velocity of lateral beam motion (or object velocity); $\tau_{\rm a}$ is the time constant of the adaptive system [it is the sum of the wavefront sensor measurement time, time of signal processing and generation of control actions on the active element (mirror), and the active-mirror control time]; and $\Theta_{\rm iso}$ is the isoplanatic angle in a turbulent atmosphere between the radiation source and the object, which is approximately equal to the ratio of the Fried length to the effective thickness of the turbulent medium.

Let us assume that our laser-optical system (radiation wavelength 0.55 μm) is aimed at an object located at the zenith and the laser beam propagates throughout the entire atmosphere. We take the value of the Fried coherence length to be about 20 cm, which corresponds to the best (with respect to the turbulence level) regions on the Earth. The effective thickness of atmospheric turbulence for observation angles close to the zenith is known to be about 2 km of the near-Earth path. Therefore, under good conditions, the atmospheric isoplanatic angle providing complete phase correction is about 10^{-4} rad. In what follows, we will arbitrarily refer to an adaptive system as 'rapid' if $2L/c > \tau_{\rm a}$ and 'slow' in the opposite case.

In sum, we have the following results:

(i) an adaptive system with a frequency band wider than 1 kHz is rapid for a path length of 150 km. For this system, the limiting object velocity $v_{\rm ob} < \Theta_{\rm iso}c/2$, at which the object can still be traced by the system, is less than 15 km s^{-1}; and

(ii) a slow system, operating on a path length of 300 km, with a frequency band of about 200 Hz, can trace an object with a limiting velocity below 6 km s^{-1}.

At the same time, the application of the PC system and any other adaptive system with an arbitrarily high operating speed is limited by the principle of optical reversibility (the PC adaptive correction is based on). In terms of mathematics, the Green's function of the problem should be the same for forward and backward beam passages along the optical path; hence, the entire system is 'frozen'. If the optical path is sufficiently long, Green's functions will differ (due to the nonzero time of flight $2L/c$), which will lead to incomplete correction. This circumstance initially limits the operational range of the system and relates the level of residual distortions, the object velocity, the transmitter parameters, and the coherence length of the system.

It is known that conventional adaptive systems need a reference source. If the role of this source is played by the object, one must take into account the fundamental limitations related to the laser beam propagation time along the path. The delay time can be estimated as $t = 2L/c$, which amounts to 2 ms for a path length of 300 km. An object moving with a velocity of 2 km s^{-1} will be shifted by 4 m for this time, i.e., by an angle of 10^{-5} rad. The allowable angular mismatch of the laser beam direction and the direction to the object (the so-called atmospheric isoplanatic angle) is known to be approximately $(5-10) \times 10^{-5}$ rad.

One must take into account that this estimate of isoplanatic angle implies complete correction. If the purpose is to correct only low-order mode components of phase fluctuations, the isoplanatic angle can be increased by a factor of two to three. For example, the spatial correlation length of wavefront tilts is $(1.2-1.8) \times 10^{-4}$ rad (for the zenithal direction). For complete phase correction, we find that the target object leaves the isoplanatic region for the delay time, as a result of which adaptive correction becomes inefficient. This factor limits again the object velocity and allowable operational range.

The only way to overcome this effect is to apply the technique of laser reference 'stars' [16]. In this case, the total delay time is shorter by a factor of about 3: the delay for sodium stars at a distance of about 100 km is 0.8 ms. In sum, the allowable velocities for rapid systems (of the PC type) can be estimated as $\sim$150 km s^{-1}. Thus, even for slow adaptive systems (with a frequency band of 200 Hz), one can trace objects moving with velocities up to 60 km s^{-1} at a distance of 300 km.

The results of this study can be used to solve the problems of controlling the laser radiation transfer and to increase the efficiency of modern optoelectronic systems used for observations in random media (e.g., in a turbulent atmosphere). The approach proposed here, which implies joint application of conventional AO and nonlinear optical technique, makes it possible to measure wavefront distortions by a wavefront sensor even when the illuminated object is weakly reflecting. It is suggested that the nonlinear optical technique provides reception of a weak optical signal and its amplification to a level acceptable for stable operation of a conventional meter (wavefront sensor). The information about the phase fluctuations 'is retained' in the system by means of a flexible active mirror until the target irradiation pulse makes it possible to renew the phase information. The information renewal rate is determined by the working conditions of the optoelectronic system. In particular, in the case of a turbulent atmosphere, the desired rate will be determined by the dynamics of phase distortions in the beam propagation channel [16].

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References

1. Lukin V.P. *Usp. Fiz. Nauk*, **184** (6), 599 (2014).
2. Zel'dovich B.Ya., Pilipetsky N.F., Shkunov V.V. *Principles of Phase Conjugation* (Berlin: Springer-Verlag, 1985; Moscow: Nauka, 1985).
3. Bespalov V.I., Pasmanik G.A. *Nonlinear Optics and Adaptive Laser Systems* (New York: Nova Science, 1994; Moscow: Nauka, 1986).
4. Dmitriev V.G. *Nelineinaya optika i obrashchenie volnovogo fronta* (Nonlinear Optics and Phase Conjugation) (Moscow: Fizmatlit, 2003).
5. Kanev F.Yu., Makenova N.A., Khokhlova T.E., Tsyro E.I. *Izv. Tomsk. Politekh. Univ*., **314** (4), 119 (2009).
6. Lukin V.P., Kanev F.Yu., Kulagin O.V. *Proc. Int. Conf. 'Laser Optics 2010'* (St.-Petersburg, 2010).
7. Berenberg V.A., Leshchev A.A., Soms L.N., Vasil'ev M.V., Venediktov V.Yu. *Proc. SPIE Int. Soc. Opt. Eng*., **4184**, 465 (2001).
8. Sprangle P., Penano J.R., Markov V., Khizhnyak A., Ting A., Hafizi B., Davis C.C., DeSandre L. *Proc. SPIE Int. Soc. Opt. Eng*., **8535**, 85350F1-10 (2012).
9. Kulagin O.V., Lukin V.P., Sergeev A.M., Peterson D., Velli M. *Trudy XVI Mezhdunar. simp. 'Optika atmosfery i okeana. Fizika atmosfery'* (Proc. XVI Int. Symp. 'Optics of Atmosphere and Ocean. Physics of Atmosphere') (Tomsk, 2009) p. 2.
10. Lukin V.P. *Proc. Conf. High Power Laser Beams* (N.Novgorod, 2006) p. 68–70.
11. Kulagin O.V., Pasmanik G.A., Shilov A.A. *Usp. Fiz. Nauk*, **162** (6), 129 (1992).

12. Antoshkin L.V., Botygina N.N., Emaleev O.N., Lukin V.P., Konyaev P.A. *Trudy XVI Mezhdunar. simp. 'Optika atmosfery i okeana. Fizika atmosfery'* (Proc. XVI Int. Symp. 'Optics of Atmosphere and Ocean. Physics of Atmosphere') (Tomsk, 2009) p. 135.
13. Lukin V.P. *Opt. Atmos. Okeana*, **27** (11), 949 (2014).
14. Fortes B.V., Kanev F.Yu., Lukin V.P. *Proc. SPIE Int. Soc. Opt. Eng*., **1628**, 253 (1992).
15. Lukin V.P., Nosov V.V., Nosov E.V., Torgaev A.V. *Proc. SPIE Int. Soc. Opt. Eng*., **9292**, 9292OV (2014).
16. Lukin V.P. *J. Opt. Soc. Am. A*, **27** (11), A216 (2010).
17. www.airborne-laser.com.