SOME PECULIARITIES OF USING THE ADAPTIVE OPTICAL SYSTEMS IN THE ATMOSPHERE

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This paper summarizes the theoretical and experimental results on the problems into the development and use of adaptive systems, obtained recently at the Laboratory of Applied and Adaptive Optics. A classification of up–to–date optoelectronic systems (OESs) is proposed as well as the place of the adaptive systems among OESs is shown. The problems of the adaptive systems evolution are underlined, i.e., developing of modern numerical models and performing of structural analysis of the most promising algorithms and loops of OESs with adaptive correction.

1. INTRODUCTION

Specific features of the optical–wave propagation in the atmosphere (as a channel of the energy and information transfer) completely determine the formation of optical beams and images.[1,2] At present the use of adaptive optical systems based on the reaction–coupling principle[3,4] is acknowledged to be the most efficient way of suppressing the fluctuations.

This paper is an attempt to determine the place of the adaptive optical systems (AOSs) among the up–to–date optoelectronic systems (OESs).

2. CLASSIFICATION OF THE UP–TO–DATE OPTOELECTRONIC SYSTEMS

The classification of up–to–date OESs is primarily needed for making their structure analysis. To my mind, the classification of OESs, based on the determination of the processes of signal processing and conversion in OESs, might be most correct from the methodological standpoint.

It seems resonable to separate out four OESs types.

a) Systems with direct detection. In these systems the photocurrent is a weighted value of instantaneous intensity of optical field incident upon the system receiver, averaged over time and the photosensitive area. In such systems the information about the optical–wave phase is lost already at the stage of recording the optical field, and only the distributions of "instantaneous" intensity are recorded.

b) OESs with a phase processing of a signal. Any optical system capable of detecting the phase variations of an optical signal falls into this class. All interference and diffraction phase meters as well as heterodyne (and homodyne) meters are among such OESs. Such systems are undoubtly of a more wide potentialities as compared with the systems of direct detection.

c) Adaptive optical systems with the reaction coupling, performed via two specific "new" elements, namely, wave–front sensor and a controlled active optical element, make up the third class of OESs. Availability of reaction coupling makes it possible, based on control of the wave–front phase, to decrease perturbing influence of medium, where the optical wave propagates, on the characteristics of optical radiation. It is a qualitatively new level of OESs, which enables the optical system to reach its limiting (limited due to diffraction) characteristics.

In its turn, not only the extension of the number of system elements, but the new approach to such a system design as well are basis for creation of adaptive optical systems.

The organization of AOSs design and operation requires much more profound knowledge of scattering properties of the atmosphere (or other medium) as a channel of optical–waves propagation.

d) Finally, the invention of systems of the fourth class, namely, learning optoelectronic systems or systems using the concept of artificial intellect, is the logical development of the up–to–date OESs. The learning systems not only adapt to the change of input optical signals in real time, but they are capable of varying the measurement strategy, operating algorithm, and own structure as well. Such systems require the expansion of our knowledge about the atmosphere, in particular, and the ability to forecast the variations in randomly inhomogeneous media.

At present such systems are only under development, but these adaptive optical systems with elements of artificial intellect will be basic OESs in the 21st century.

3. THEORY OF THE ATMOSPHERIC ADAPTIVE OPTICAL SYSTEMS

When creating the theory of the atmospheric adaptive optical systems, consideration must be given to the principal fluctuation components of the atmosphere: atmospheric refraction, atmospheric turbulence, and radiation thermal blooming due to molecular absorption.

3.1. Propagation of the optical waves in the atmosphere under adaptive control

We have investigated the feasibility of high–power radiation focusing with the use of adaptive algorithms in numerical experiment for various scenarios of radiation propagation.

Primarily we have investigated the comparative efficiency of adaptive focusing based on various control algorithms and homogeneous optical paths. The following algorithms have been analyzed: *a priori* phase correction algorithm, "quick" and "slow" adaptive phase correction algorithm based on reference radiation as well as

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algorithms of amplitude and phase correction[4–9] of the high–power laser beam distortions.

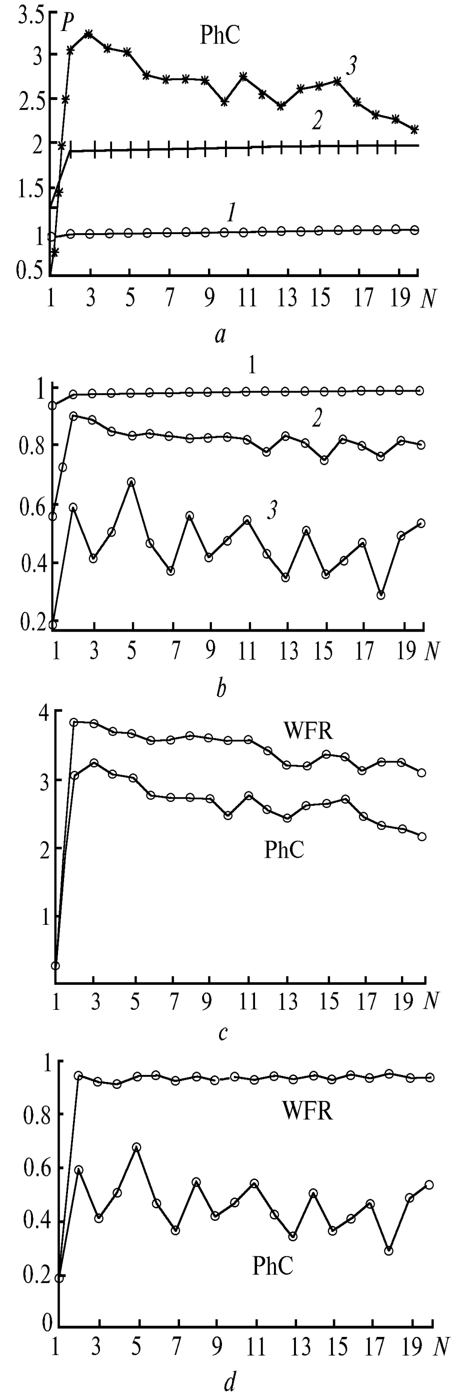

FIG. 1. Time diagrams of the behavior of the power P of a beam transmitted to the object with an adaptive system. In this case the paths are horizontal and elevated above the ground. Depicted in the figure are the comparison of efficiency of focusing using algorithms of phase conjugation (PhC) (a) for transmitter power of 1 *(1),* 2 *(2), and* 4 MW *(3); focusing with the PhC algorithm for paths of different elevations:* 23 *(3),* 25 *(2), and* 30 km *(1) (b); comparison of time diagrams for focusing using algorithms of wave–front reversion (WFR) and phase conjugation (PhC) for power of* 1 MW *(c); and, the same for power of* 4 MW *(d). Here N is the number of time iterations of the process of adaptive control.*

Let us briefly summarize the obtained results.

The efficiency of *a priori* phase correction is found to be proportional to the Fresnel number of the emitting aperture. In the near–IR range (3 μm) the atmospheric turbulence essentially reduces the laser–beam intensity at focus, whereas the *a priori* correction approximately doubles the intensity at the focus.

Adaptive optical system on a horizontal path tends to focus the high–power beam at a point ("quick" phase conjugation) and to a line ("slow" phase conjugation) near the emitting aperture. As it takes place the degree of defocusing is limited by the diffraction of the beam and the dislocations in a reference beam.[10,11]

Analyzing various scenarios of propagation, in particular, the slant atmospheric path, the homogeneous "high–altitude" paths, the scanning of high–power laser beams, we have shown at certain, that the instability is the most important effect involved in the process of focusing. In this case both the instability of the process of thermal blooming taken alone and the instability under adaptive control are of fundamental importance.

In Ref. 11 we have studied various modes of the adaptive system operation on the atmospheric paths of different types. We have revealed, that the instability transforms the process of adaptive focusing of a high–power laser radiation to iterative process with alternating "good" and "bad" iterations.

As an illustration we offer the time diagrams characterizing the efficiency of focusing of the high–power laser beam in the case of a "high–altitude" homogeneous path, depicted in Fig. 1. Figure 1 *a* is indicative of the instability in phase correction, that arises with a rise in total power of a laser. Figure 1 *b* points to the fact that the instability, that is, transformation into the iterative process arises also with increasing turbulence level at lower altitudes of propagation path. Figure 1 *c* shows that instability in adapting is connected with the loss of amplitude information; the algorithm of phase conjugation (PhC) is unstable, when the algorithm of wave–front reversion (WFR) leads to quite a stable behavior. Finally, Fig. 1 *d* shows that further increase of radiant power results in instability of WFR algorithm as well as of the PhC one.

The key to description of the optical systems instability lies in description of the phase dislocations of the wave front.

3.2. Development of the atmospheric turbulence models

The description of the optical–wave phase fluctuations in the turbulent atmosphere for up–to–date OESs needs for comprehensive investigations into the peculiarities of the behavior of the atmospheric turbulence spectrum in the range of low spatial frequencies.

In particular, the influence of outer scale of turbulence is of importance in determining the characteristics of image formed by a ground–based telescope. First and foremost it is connected with the fact that the dimensions of available and designed telescopes have been essentially increased. For instance, the Novel Technologies Telescope (NTT) has the aperture of 3.6 m, the Large Azimuth Telescope (LAT) has the aperture of 6.05 m, the Very Large Telescope (VLT) will have the aperture of 4×8.2 m and the designed telescopes of GEMINI family will have the 8–m aperture, and KECK telescope in Hawaii will have the 10–m aperture.

A number of measurements of the structure function of the phase $D_s(\rho)$ and functions related to it have been performed as well. The measurements of $D_s(\rho)$ performed in April 1991 with NTT telescope[12] are worth noting here. The results show that deviations from the power law

$$D_s(\rho) = 6.88\,(\rho/r_0)^{5/3}$$

are observed already at the distances $\rho > 30$ cm. Further the saturation of the structure function of phase at the constant level takes place. In turn, it may be interpreted as the deviation of the turbulence spectrum from Kolmogorov–Obukhov law in the large–scale region. One conceivable way for interpretation of these data is the introduction of finite outer scale of turbulence into the spectrum. One can draw the same conclusion analyzing the results of measurements of $D_s(\rho)$ with a Multi–Mirror telescope (MMT, USA, Arizona).[13] However, it should be noted that there exist some measurement data on the phase fluctuations with MARK–III interferometer.[14] The authors of these measurements state that there is no need for introducing the finite outer scale into the atmospheric turbulence spectrum. At the same time, it is known that parameters of the model of atmospheric turbulence spectrum, namely, C_n^2, L_0, and l_0 are, in turn, the values varying along the radiation–propagation path.

The concept of "turbulence spectrum averaged over the optical path" has been introduced in Ref. 18 as applied to conditions of radiation propagation along the vertical atmospheric paths, based on generalization of models of altitude behavior of C_n^2 and L_0 (see Refs. 15–20). It is assumed that the radiation propagates along the zenith direction, and the phase fluctuations measured relative to the telescope entrance pupil are analyzed.

Let us use the model from Ref. 18

$$\int\limits_0^\infty \mathrm{d}\xi\, \Phi_n(\kappa, \xi) = 0.025\, k^{-2}\, r^{-5/3}\, \kappa^{-11/3} \times$$
$$\times\, (1 - \exp(-\kappa^2/\kappa_0^2))\, \exp(-\kappa^2/\kappa_m^2)$$

and calculate the structure function of phase for a plane wave

$$D_s(\rho) = 4\,\pi^2 k^2 \int\limits_0^\infty \mathrm{d}\,\xi \int\limits_0^\infty \mathrm{d}\kappa\, \kappa\, \Phi_n(\kappa, \xi)\, (1 - J_0(\kappa, \rho))\ .$$

Under conditions

$$\kappa_0 \ll \kappa_m\ , \qquad \kappa_m^2\, \rho^2 \gg 1\ ,$$

we have

$$D_s(\rho) = 6.88\, \Big\{(\rho/r_0)^{5/3} + 2^{5/3}\, \Gamma(11/6)\, \kappa_0^{-5/3}\, r_0^{-5/3} \times$$
$$\times \Big[1 - {}_1F_1(-5/6;\, 1;\, -\kappa_0^2\, \rho^2/4)\Big]\Big\}\ .$$

It is obvious that, for $\kappa_0\rho \ll 1$

$$D_s(\rho) = 6.88\, (\rho/r_0)^{5/3}\, [1 - 0.62(\kappa_0\, \rho)^{1/3}]\ ,$$

and in the region $\kappa_0\, \rho \gg 1$

$$D_s(\rho) = 21.84\, \Gamma(11/6)(\kappa_0\, \rho)^{-5/3}.$$

Using these two formulas, one can treat the measurement data on $D_s(\rho)$ obtained with NTT telescope[12] and derive the following values: $r_0 = 0.17$ m and $\kappa_0^{-1} = 0.26$ m. Thus, "averaged over path the outer scale of turbulence" κ_0^{-1} and Fried's radius are found to correlate. Of course, these conclusions require further analysis using new experimental data.

3.3. Numerical model of the atmospheric adaptive optical system

At present, we have all necessary basis[21,22] for a 4–dimensional dynamic model of an adaptive optical system operating in the atmosphere. In particular, numerical models are developed of such components of an adaptive loop as

a) model of propagation of high–power laser beams in turbulent and refractive media;

b) model of the low–frequency range of the atmospheric turbulence spectrum (for the case of ground atmospheric layer and for the whole atmospheric column);

c) models of wave–front sensors;

d) various models of multielement segmented and deformable active mirrors;

e) model of quantum fluctuations of the radiant flux.

Using such a computer dynamic model we have studied the limiting potentials of the ground–based adaptive telescopes[23–25] as a function of the number of measurements with a wave–front sensor, the turbulence intensity and structure, and the value of a received optical signal.

It is of great importance now to proceed from the simplest models and abstractions to practicable models and schemes in AOS theory. Such a dynamic model as applied to the problems of adaptive focusing of a high–power laser radiation allows studying the temporal modes of AOS operation,[4,24] revealing the physical regularities of the instability formation under thermal blooming as well as understanding the reasons and sources of these instabilities.[10,11]

Development of such computer models makes it possible to design AOS from the standpoint of choosing the optimal configurations of a wave–front sensor and a controlled deformable mirror, to take into account such effects as the anisoplanicity in large optical systems, to model artificial reference sources as well as to analyze the efficiency of various algorithms to control of both the dynamic active mirror and the system as a whole.

4. USE OF ADAPTIVE OPTICAL SYSTEMS IN THE ATMOSPHERE

In this section we shall consider some practical implementations of our theory of atmospheric AOSs.

4.1. Design of the adaptive optical elements and systems

The performance of experiments in the atmosphere requires the use of specialized optical elements, involved in the AOS structure, for the formation of an optical loop. These elements are a wave–front sensor and an active mirror.

A number of optical elements have been developed at different times.[29,31] It is 4– and 19–element segmented mirrors, where each element has from one to three degrees of freedom. Several modifications of high–frequency deflectors[30] have been created for the control of wave–front tilts.

Different photodetectors of visible and IR radiation have been used to make a Hartmann wave–front sensor, interference phase meter as well as meters of location of the optical image center of gravity.

Various ideas allowed the performance of the schemes of phase optical meters and creating of a number of complexes for control of quality of optical products and radiation beams. INTERKON, SKIPh, TELEVVOD, SIN complexes, built of domestic components, insure the higher measuring characteristics than the characteristics of well–known American MARK–III system. All these complexes are employed at the best Russian centers for manufacturing the optical components, namely, LOMO, S.I. Vavilov State Optical Institute, Scientific–Production Association "Astrofizika". In recent years, in accordance with the creation of a 4–dimensional computer model of AOS we have performed more comprehensive analysis of the accuracy and dynamic characteristics of deformable optical mirrors.[7,8]

The problem of creating highly accurate phase meters (of interference and Hartmann types), operating under conditions of "strong" intensity fluctuations of received optical field, requires the investigations into the so–called dislocations of wave front.[11,34]

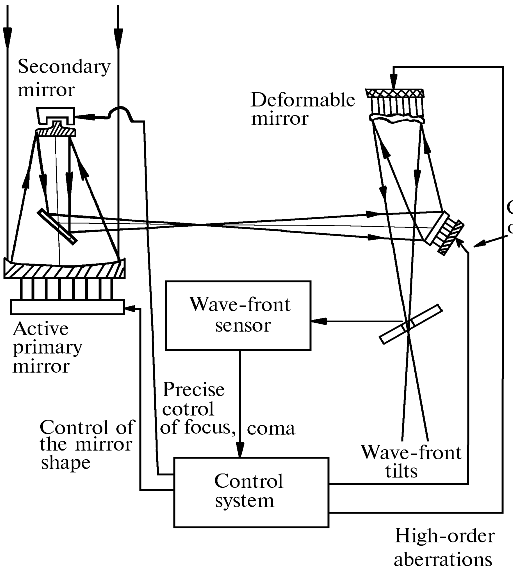

FIG. 2. Structure diagram of an adaptive telescope with the active primary mirror and two adaptive mirrors, namely, high–frequency corrector of image over two angles of tilt and deformable adaptive mirror. Secondary mirror of the telescope is for making precise adjustment of telescope.

At present we face the problem of designing not only isolated elements, but also the adaptive system as a whole. Figure 2 shows an example of a structure diagram of an adaptive telescope with several channels for correction of technical and atmospheric aberrations of the wave front.

4.2. Scientific station at IOA for investigations into boundary atmospheric layer

Development of methods and technical tools for acoustic and laser sounding of the atmosphere provides obtaining of qualitative information on profiles of temperature, pressure, density, humidity, wind velocity, turbulence intensity, concentrations of contaminating gases in the atmosphere as well as size spectrum of aerosol particles, their concentrations in clouds, fogs, and hazes. Up–to–date optoelectronic systems require prompt quantitative data on microphysical parameters of the atmosphere and their transformations at different altitudes. In particular, the information about the influence of temperature inversions occurring in lower atmospheric layers on concentration of anthropogenic products is of importance.

At present we can state at certain that estimating the efficiency of modern OESs strongly depends on the quality of our knowledge about a number of the atmospheric physical parameters.

Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Sciences develops a network of scientific stations for atmospheric studies. Two basic types of OESs (systems of direct detection and systems with phase processing) even now require the measurements of a sufficiently large number of the atmospheric parameters. Hence, the structure of measuring tools at stations is continuously expanding.

A mobile aerosol lidar is used for studying the optico–physical conditions occurring in the low atmosphere (along horizontal or slant paths). In particular, measurements of slant visual range, remote detection of aerosols in the atmosphere, investigations into relations between the aerosol microphysics and characteristics of the atmospheric turbulence are performed with this lidar as well.

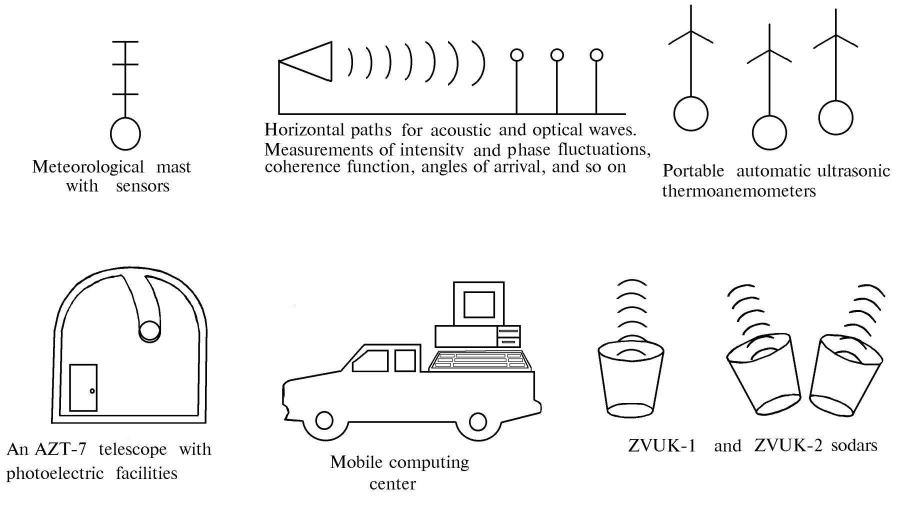

FIG. 3. Layout of measuring devices at the scientific station of the Institute of Atmospheric Optics.

Acoustic radar (sodar) enables measurements of the atmospheric parameters in lower 1–km atmospheric layer, altitude profiles of turbulence intensity and temperature stratification.

Metrological certification is provided with a mast equipped with standard meters of meteorological quantities. The unique ultrasonic anemometer developed[33] insures measuring not only of average meteorological characteristics but their fluctuations as well.

The test site has horizontal optical paths of different lengths intended for testing an OES as well as for validation of developed models of the atmosphere. The models are necessary for estimating the OES applicability and efficiency.

Figure 3 presents a layout for specialized opto–meteorological meters at the scientific station at the Institute of Atmospheric Optics.

The horizontal atmospheric paths of various lengths provide measurements of the fluctuations of basic parameters of optical and acoustic waves.

An AZT–7 telescope equipped with various photoelectric facilities is used for studying the slant and vertical atmospheric paths.

4.3. Experiments with adaptive systems in the atmosphere

At the test site of the Institute of Atmospheric Optics we perform tests of various models of the adaptive optical systems under conditions of careful monitoring of the atmospheric situation.

The first experiment on stabilization of the position of the optical beam center of gravity, based on tracking the reference image position, took place at the Institute of Atmospheric Optics.

At the beginning of our experiments on stabilization of angular shifts of laser beams we used the laser adaptive reference system designed in our laboratory. This system insured the stabilization of the laser beam axis within 0.007″ (see Ref. 4).

Then we tested the feasibility of correction for isolated mode components of phase fluctuations.[28] In Ref. 29 we pioneered the ideas of application of the so–called "two–color adaptive systems".

We have performed the experiment on correcting the image of laser radiation source spaced at 110 m by an adaptive system with a closed control loop. We used a 4–element mirror as an active optical element. Each element of the mirror insured the control of a local tilt of the wave–front section. The estimation of image–correction degree was performed on the basis of a comparison between the value of the maximum of illumination and distribution half–widths of corrected and uncorrected images. In so doing we analyzed the image averaged over 500 frames at the frame sequence frequency of 0.25 Hz.

The experiment has shown that the correction resulted in a decrease of the effective width of distribution by a factor of 1.5 and increase of the illumination maximum by a factor of 3.

At present we conduct these experiments using new modifications of the wave–front sensors and controlled optical elements.

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